09 Oct 1975

2nd Annual UMR-MEC Conference on Energy -- Entire Proceedings

University of Missouri--Rolla

PROCEEDINGS OF THE

SECOND ANNUAL

UMR-MEC CONFERENCE ON ENERGY

Theme: Energy Crisis—
Two Years Progress Towards Self Reliance

October 7-9, 1975

Volume 2

University of Missouri-Rolla

Rolla, Missouri 65401

Edited by
Dr. J. Derald Morgan
Professor of Electrical Engineering
University of Missouri-Rolla

The 2nd Annual UMR-MEC Conference on Energy

Sponsored By

THE GOVERNOR'S MISSOURI ENERGY COUNCIL (MEC)
within THE DEPARTMENT OF NATURAL RESOURCES

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FORWARD

The UMR-MEC Conference on Energy was organized in 1974 with the purpose of providing social scientists, scientists and engineers a means for rapid communication of their most recent research results in the field of energy and to offer solutions to the energy related problems of local government, business, industry and the general public. The Conference is sponsored by the University of Missouri-Rolla and the Governor's Energy Council within the State of Missouri Department of Natural Resources with the cooperation of the professional societies listed on the previous page. Much of the conference support is provided through the program of company registrations. Last year's participants in this registration program are listed on the previous page.

Papers presented at the conference are of two categories: those that are presented by invitation and those selected from papers submitted in response to an open call for papers. Papers are selected by a committee of experts, from the University of Missouri-Rolla and the Missouri Department of Natural Resourses, in the various fields of activity presented in the conference. Suggestions for papers are always welcome for careful consideration if received by April 15 in the year of the conference.

The meeting is open to all persons interested in energy resources, their extraction, their utilization and conversion, their conservation and in policy related to energy processes. The Conference provides a common meeting ground for social scientists, scientists, and engineers in universities, industry, business or government to meet and exchange ideas between themselves and with the general public. Academic sponsorship is intended to provide the freest possible discussion ranging from the most technical detail, through the economic questions and to the social and political aspects of the subject of energy.

The sponsors of the Conference and the Director in particular, thank the companies and individuals contributing to the success of the Conference. The help of the Session Chairmen, Co-Chairmen and the Organizing Committee is gratefully acknowledged. A special note of recognition goes to the many authors whose contributions appear in this tome. With their efforts the success of the Conference was assured as well as the value of the printed proceedings.

This volume is a collection of papers selected from the papers presented on the occasion of the Second Annual UMR-MEC Conference on Energy held at the University of Missouri-Rolla on the dates of October 7-9, 1975. The Conference is annually organized jointly by the Governor's Missouri Energy Council (MEC) within the Missouri Department of Natural Resources and the faculty of the University of Missouri-Rolla (UMR). This annual Conference provides a forum for the transfer of information on all subjects dealing with energy resources, their extraction, their conversion, their conservation and policy related to energy between social scientists, scientists, engineers and the interested public.

The President of the United States early in 1974 established the goal of energy independence by 1980. Since that time there has been considerable difference of opinion regarding the meaning of energy independence, and even greater differences as to how the goal of independence should be achieved. To some, energy independence is a condition in which the U.S. receives no energy through imports, and produces all of its energy domestically. To others, energy independence is a condition in which the U.S. imports some energy to meet it's requirements but only to acceptable levels of political and economic vulnerability. The definition of independence, the criteria for availability, and the technical methods d advancements for meeting the goal of ener- independence are central to the choice of U.S. energy strategy and the theme for this ar's Conference, "Energy Crisis - Two Years ogress Towards Self-Reliance".

tizens throughout our country, aware of the tion's critical dependence on its energy re- urces, are concerned about our energy supply d our need for positive action in the devel- ment of new alternatives to traditional en- gy systems and patterns of energy utiliza- on. At every level-from trying to lower en- gy consumption to the development of sophis- cated alternative resources, concerned re- archers are doing what they can to help our tion, and its future generations, achieve ergy self-reliance and stability. Papers vering the work of many of the nations out- anding researchers are contained in this lume. Through the continued research ef- rts of these and other outstanding social ientists, scientists, engineers and public rvants, I am confident that our nation will et the challenges and achieve its goal of ergy independence in the 1980's.

J. Derald Morgan
Conference Director
University of Missouri-Rolla

Dr. J. Derald Morgan, Conference Director and Mr. James L. Wilson, Director, Department of Natural Resources, State of Missouri. Mr. Wilson is presenting to Dr. Morgan the Governor's Proclamation.

Proclamation:

Office of the Governor
State of Missouri

WHEREAS, the purpose of the Annual UMR/MEC Conference on Energy is to provide a forum of exchange between social scientists, scientists, engineers, and the public on energy developments in the areas of conservation, conversion, resources, economics, and policy; and

WHEREAS, energy research and development is vital to the nation; and

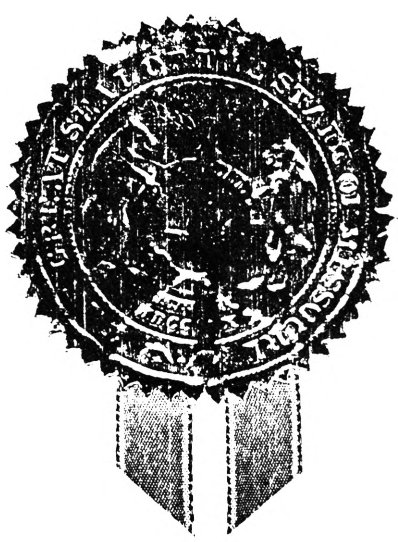
WHEREAS, the faculty of the University of Missouri–Rolla have joined with the Missouri Energy Council within the Missouri Department of Natural Resources to organize this conference on energy; and

WHEREAS, those attending this year's conference are citizens, social scientists, scientists, and engineers from all segments of our society concerned with the energy question; and

WHEREAS, this year's conference theme is "Energy Crisis–Two Years' Progress Towards Self Reliance":

NOW, THEREFORE, I, CHRISTOPHER S. BOND, GOVERNOR OF THE STATE OF MISSOURI, do hereby recognize the conference participants for their contributions and interest in providing solutions to questions of energy resources, conservation, conversion, economics, and policy for the benefit of mankind; and hereby recognize the organization committee directed by Dr. J. Derald Morgan for their efforts in preparing this outstanding energy conference; and do hereby offer a sincere welcome to the attendees of the 1975 UMR/MEC Conference on Energy.

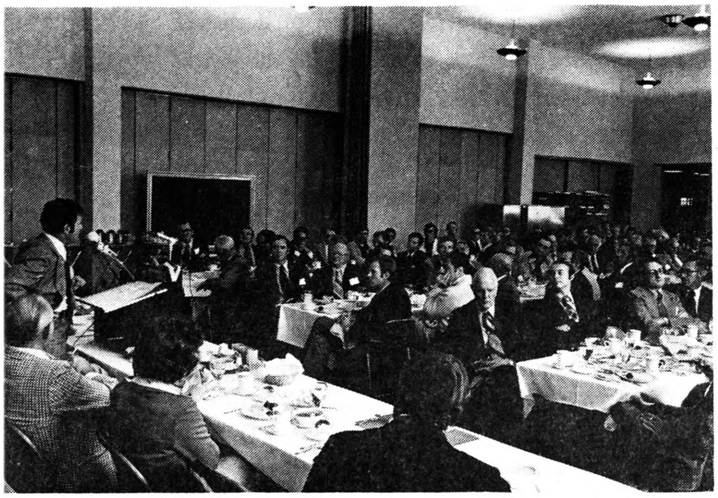
IN TESTIMONY WHEREOF, I have hereunto set my hand and caused to be affixed the Great Seal of the State of Missouri, in the City of Jefferson, this 6th day of October, 1975.



GOVERNOR

ATTEST:

SECRETARY OF STATE



Mr. James L. Wilson, Director, Department of Natural Resources, State of Missouri presenting his Keynote Speech at Luncheon.

Mr. Louis G. Hauser, Westinghouse Electric Corporation, presenting his Keynote Address.

Mr. James L. Wilson, Director, Department of Natural Resources, State of Missouri presenting his Keynote Address.

Dr. Bill L. Atchley, Dean of College of Engineering, University of West Virginia, presenting his Keynote Address.

CONFERENCE ORGANIZING COMMITTEE

Dr. J. Derald Morgan - Conference Director
UMR Electrical Engineering Department

Dr. Bill Atchley - Program Chairman
Missouri Governor's Science Advisor
UMR Associate Dean of Engineering

James L. Wilson - Chairman, Missouri Energy Council
Director, Missouri Department of Natural Resources

Mrs. Norma Fleming - Conference Coordinator
UMR Extension Division

Miss Sally White - Conference Publicity Chairman
UMR Extension Division

SESSION CHAIRMEN

General Interest Sessions

Opening Meeting

Introductory Remarks: J. Derald Morgan, Conference Director

Welcome: Raymond L. Bisplinghoff, Chancellor, University of Missouri-Rolla

Session No. 1A - Energy Management

Keynote Speaker: Dr. Bill L. Atchley, Dean of College of Engineering, University of West Virginia

Session No. 1B - Wind and Solar Energy

Keynote Speaker: Mr. William R. Cherry, Head, Agricultural and Process Heat Branch Energy Research and Development Administration

Luncheon

Master of Ceremonies: Dr. Adrian Daane, Dean, College of Arts and Sciences, University of Missouri-Rolla

Keynote Speaker: Mr. James L. Wilson, Director, Department of Natural Resources, State of Missouri

Luncheon

Master of Ceremonies: Dr. Edwin G. Lorey, Dean of Extension and Continuing Education

Keynote Speaker: Mr. Louis G. Hauser, Westinghouse Electric Corporation

Banquet

Master of Ceremonies: Dr. J. Stuart Johnson, Dean, School of Engineering, University of Missouri-Rolla

Speaker: Dr. Thomas A. Beveridge, Professor of Geology, University of Missouri-Rolla

SESSION CHAIRMEN

Technical Sessions

Session No. 1a - Energy Management

Co-Chairmen: Prof. B. R. Sarchet, Chairman, Department of Engineering Management, University of Missouri-Rolla

Dr. G. R. Cuthbertson, Department of Engineering Management, University of Missouri-Rolla.

Session No. 1b - Wind and Solar Energy

Chairman: Dr. Jack L. Boone, Department of Electrical Engineering, University of Missouri-Rolla

Co-Chairman: Dr. Ronald L. Reisbig, University of Texas-Victoria

Session No. 1c - Chemical Energy Conversion

Chairman: Dr. James L. Gaddy, Department of Chemical Engineering, University of Missouri-Rolla

Session No. 2a - Energy Management

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Dr. G. R. Cuthbertson, Department of Engineering Management, University of Missouri-Rolla

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Session No. 2c - Chemical Energy Conversion

Chairman: Dr. James L. Gaddy, Department of Chemical Engineering, University of Missouri-Rolla

Session No. 2d - Economics of Energy

Chairman: Dr. Vamon Rao, Department of Social Sciences, University of Missouri-Rolla

Session No. 3a - Energy Management

Co-Chairmen: Prof. B. R. Sarchet, Chairman Department of Engineering Management, University of Missouri-Rolla

Dr. G. R. Cuthbertson, Department of Engineering Management, University of Missouri-Rolla

Session No. 3b - Wind and Solar Energy

Chairman: Dr. Jack L. Boone, Department of Electrical Engineering, University of Missouri-Rolla

Co-Chairman: Dr. Ronald L. Reisbig, University of Texas-Victoria

Session No. 3c - Economics of Energy

Chairman: Dr. C. E. Garbacz, Department of Social Sciences, University of Missouri-Rolla

Session No. 3d - Energy Resources - Mining and Petroleum

Chairman: Dr. M. D. Arnold, Department of Petroleum Engineering, University of Missouri-Rolla

Co-Chairman: Dr. J. J. Scott, Department of Mining Engineering, University of Missouri-Rolla

Session No. 4a - Energy Systems

Chairman: Dr. Earl F. Richards, Department of Electrical Engineering, University of Missouri-Rolla

Session No. 4b - Nuclear Energy and Power

Chairman: Dr. Albert E. Bolon, Department of Metallurgical and Nuclear Engineering, University of Missouri-Rolla

Co-Chairman: Dr. Ray Edwards, Department of Metallurgical and Nuclear Engineering, University of Missouri-Rolla

Session No. 4c - Economics of Energy - Alternative Systems of Energy

Chairman: Dr. Vaman Rao, Department of Social Sciences, University of Missouri-Rolla

Session No. 5a - Energy Systems

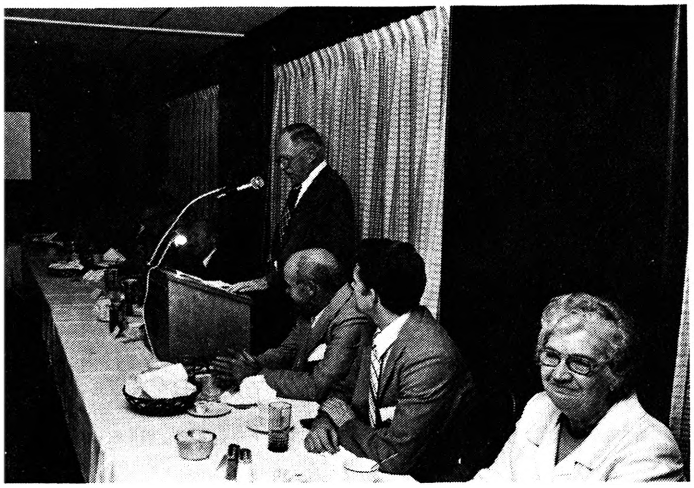
Chairman: Dr. Earl F. Richards, Department of Electrical Engineering, University of Missouri-Rolla

Session No. 5b - Energy Environment

Chairman: Dr. Ivon Lowsley, Assistant Professor, Civil Engineering, University of Missouri-Rolla

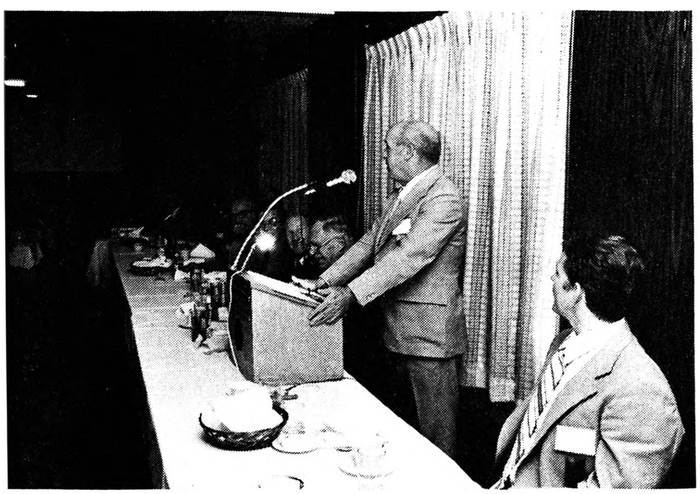
Session No. 5c - Economics of Energy - Energy Conservaton

Chairman: Prof. William Desvousges, Department of Social Sciences, University of Missouri-Rolla

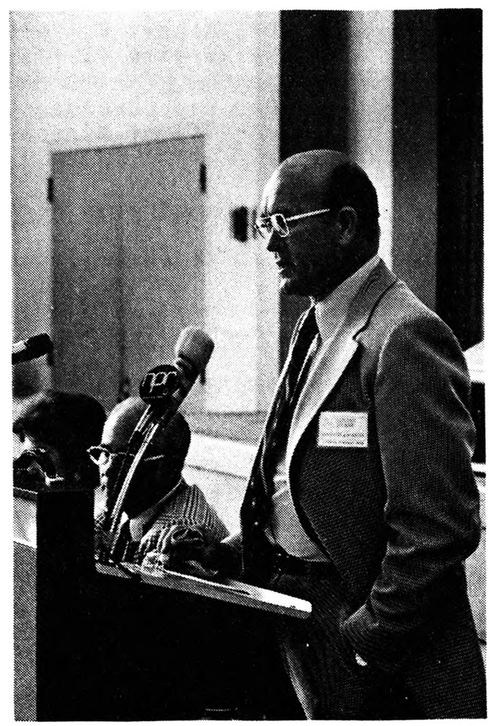


Dr. J. Stuart Johnson, Dean, School of Engineering, University of Missouri-Rolla as Master of Ceremonies for Monday's Luncheon.

Conferees at Opening Session.



Dr. Thomas A. Beveridge, Professor of Geology, University of Missouri-Rolla , Guest Banquet Speaker



Dr. Adrian Daane, Dean, College of Arts and Sciences, University of Missouri-Rolla, as Master of Ceremonies for Luncheon

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OPENING REMARKS

by

R.L. Bisplinghoff

UMR-MEC CONFERENCE ON ENERGY

October 7, 1975

You are all extended the very warmest welcome to the University of Missouri-Rolla. This four day conference on energy, the second of its kind, is filled with papers and activities that should find some interest for almost everyone involved in energy activities. All of us on this campus want you to have a rewarding four days and to enjoy yourselves as well. It goes without saying that we stand ready to aid you in every way that is possible. I want to commend the organizers, particularly Dr. Derald Morgan, for his hard and dedicated work in putting the conference together.

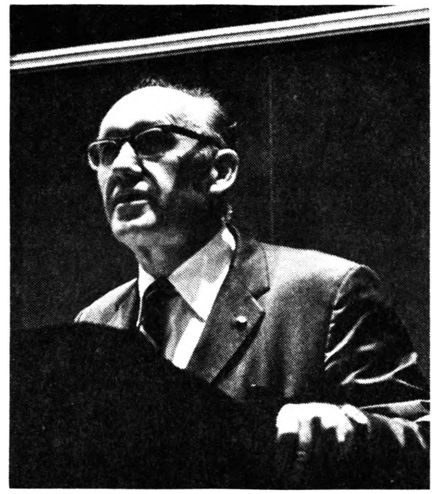
Energy and non-renewable natural resources in general will be the name of the game from now on the the United States. Since the beginning of the industrial revolution, industrial and economic growth in the United States has been coupled to growth in available energy. The two are inextricably connected. The state of Missouri and the nation will not solve their economic problems until they solve their energy problems. The most serious aspect of the energy problem now is capital formation. Capital investments now being made by business, state and local governments are not large enough to scratch the surface. Some measure of energy independence by 1985 will require at least a 600 billion dollar capital investment. The United States is clearly in a period of uncertainty and confusion with respect to the solution of its energy delemma. Few people recognize the gravity of the situation and fewer still are doing anything useful about it. During the ten minutes required to make these remarks we will have shipped a half-million dollars out of the country to pay for imported hydrocarbons. It is not necessary to be an economic genius to recognize that we will soon bleed to death.

But, the real paradox of our energy crisis is that the United States has enormous untapped energy resources and human resources with technical know-how. What it lacks are decisions, goals, and leadership. The response of our political system to the energy delemma has so far been disgraceful.

It is not true that we are running out of resources that can be easily and cheaply exploited without regard for future operations. It is <u>not</u> true that we must turn our back on economic growth. It is true that the rising cost of extracting and conserving nature's resources slows economic growth. What is true is that we have reached a watershed in our methods of management and exploitation of resources. We must face the fact that the well of non-renewable natural resources is not bottomless. We must conserve petroleum and find substitutes for it in natural gas from coal, nuclear energy and sunlight. We must accelerate programs to develop synthetic and other substitute materials in addition to creating a recycle society which reuses many materials indefinitely.

Like so many emerging national problems, the federal energy problem cannot be solved piecemeal. Federal planning policy and leadership will be required as, never before, in energy as in non-renewable raw materials. One must have the faith that trivia will not continue to triumph in Washington and that we will one day obtain a national energy policy.

Again, I wish you the very best during the course of your visit to Rolla.



Dr. Raymond L. Bisplinghoff, Chancellor of the University of Missouri-Rolla, presenting his "Opening Remarks"

CREATING THE ELECTRIC ENERGY ECONOMY

L. G. Hauser
Westinghouse Electric Corporation
East Pittsburgh, Pennsylvania

My remarks will be directed to four points:

First, that energy is the life blood of our economy, and that its use or conservation is far from a simple matter of personal habits of waste or frugality. In other words, the vital role energy plays in the production of goods and services should be distinguished from its use in their consumption.

Second, that our excessive dependence on our two scarcest energy resources -- oil and natural gas -- is the core of the energy problem, both U.S. and worldwide.

Third, that limiting our time horizon to this winter, next summer, or even 1985, will lead us to commit major blunders in formulating our energy strategy and policy.

Fourth, that shifting to an electric energy economy founded on our most abundant resources -- coal and uranium -- is the only realistic, logical, long-term solution to the energy problem; and the only way to counter OPEC's control of the availability and price of oil.

Let's begin by looking first at the relationship between energy use and the health of our economy.

Energy is an essential ingredient of economic growth. Growth rates of energy and GNP have exhibited a remarkable lock-step relationship moving in almost complete synchronism during the past 20 years.

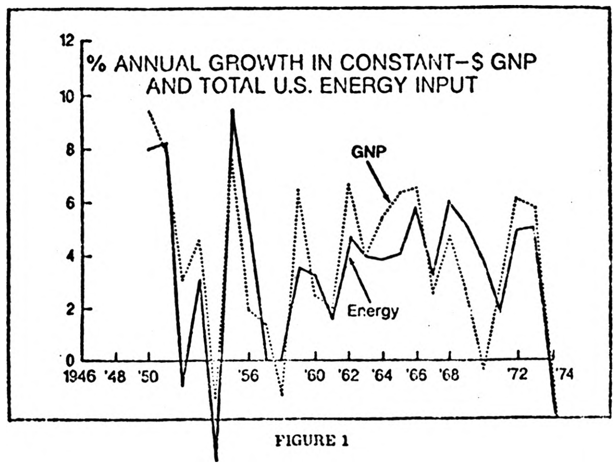


FIGURE 1

It would not be correct to say that the availability of energy causes economic growth, but economic growth certainly cannot take place unless adequate supplies of energy are available for the processing, manufacture, transportation, and sale of the various goods, products, and services that make up the gross national product. Thus the workings of the economy will be inhibited to the extent that energy is not available or is priced out of reach. It is sobering to note that during the unstable economic and energy conditions of 1974, both energy use and economic growth declined by the same two percentage points.

While a one-to-one lock-step relationship has existed between energy growth and GNP growth in the past, we believe that a modest degree of uncoupling between these variables is both possible and probable in the future. That is, some degree of energy conservation and price elasticity effect can occur without a corresponding drop in economic growth. Some housing is being reinsulated; automobile mileage will increase;

industry is taking steps to increase energy use efficiency. As a result, we project that these elasticity-conservation effects will cause the growth in energy to lag the growth in GNP by approximately 0.4 percentage point in the future.

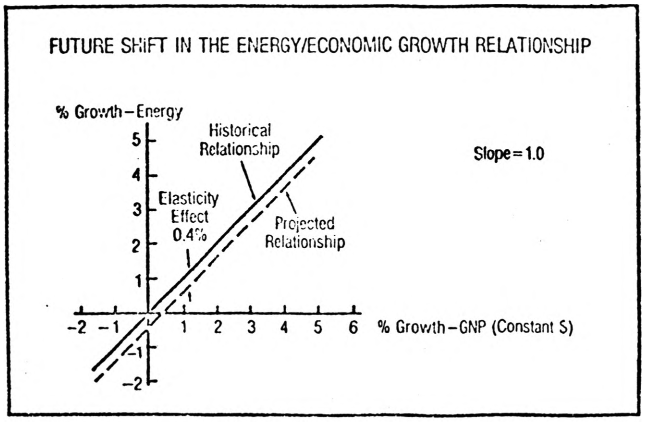


FIGURE 2

To project economic performance in the future, we have constructed a "potential GNP" as defined by the President's Council of Economic Advisors, adjusted for a 5 percent unemployment rate, reduced net productivity, and a steady decrease in labor force growth rate from the present level of 2 percent to less than 0.5 percent in the year 2000. We assumed that the economic recession would bottom out in the third quarter of this year, and that recovery would be slow. Even so, we found that the growth in constant dollar GNP over the next five years will have to average almost 6 percent per year in contrast to the historical rate of 4 percent if we are to get back to a 5 percent unemployment level by 1980.

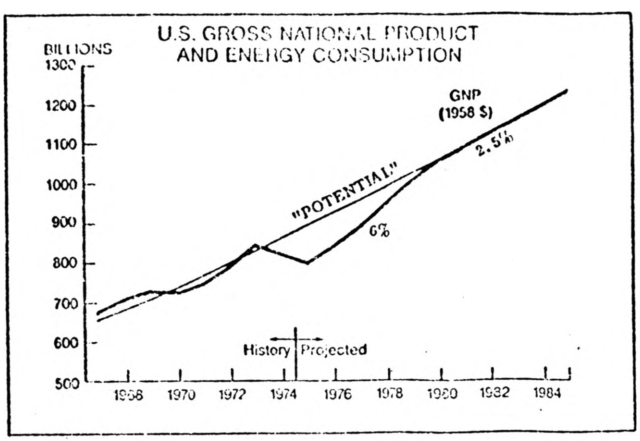


FIGURE 3

This high growth rate from the depressed starting point will have its counterpart in a high growth in energy requirements over this same period. Beyond 1980 both energy use and GNP growth should taper off to a 2-½ percent rate of growth per year in line with declines in population and labor force growth rates as projected by the U.S. Bureau of Census.

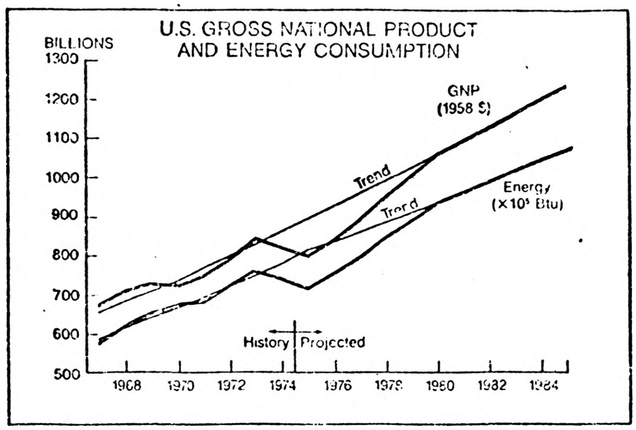


FIGURE 4

What this says, in effect, is that if economic recovery and reduced unemployment are to take place over the next five years, more energy must be made available and at a higher rate of growth than normal -- in the neighborhood of 6 percent per year compared to a recent historical growth rate of 4 percent per year. And this must take place at a time when we are facing the prospect of level or declining production of domestic energy fuels.

If we cannot make the energy available, then economic recovery will be choked off.

There has also existed a close relationship between the kilowatt-hour growth rate and the overall energy growth rate, with the kilowatt-hour rate running about 3.7 percentage points higher than the overall energy. If the economy recovers between now and 1980, we anticipate that the kilowatt-hour growth rate for this period will average approximately 9.4 percent per year in contrast to the historical rate of 7 ½ percent, in spite of both conservation efforts and the elasticity effect upon demand. The rate should drop back below the historical growth rate to an average of 6.2 percent in the first half of the 1980's.

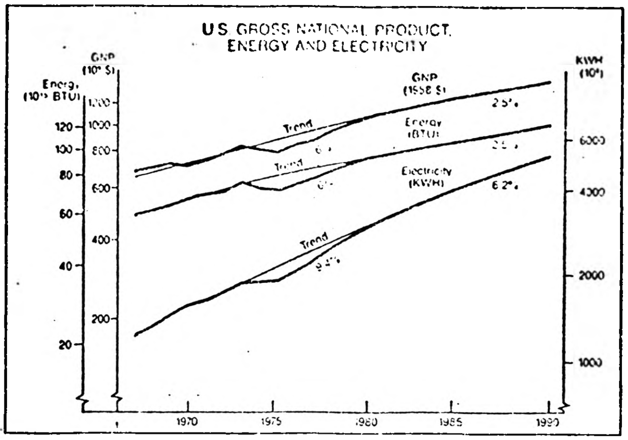


FIGURE 5

How would those kilowatt-hours be generated? After a slow start as a result of the recent cancellations and delays, nuclear energy will rapidly take on an increasing share, reaching 40 percent in 1990. Coal's share will remain relatively constant until the early 1980's, and then increase to over 50 percent in the late 1980's.

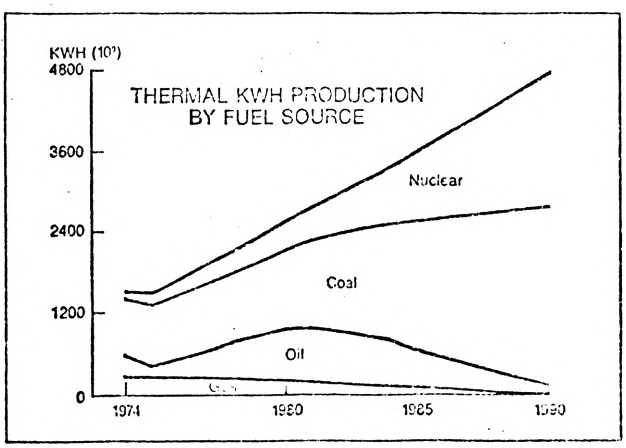


FIGURE 6

For the rest of this decade, we see natural gas declining as a fuel for power generation. The only fuel whose supply can be increased rapidly enough to provide the kilowatt-hour growth to 1980 is oil, and this increase must be imported. This unfortunate result is, of course, a direct consequence of the coal-fired and nuclear power plant delays announced last year, plus the inability to expand coal production fast enough.

Utility oil burn will have to increase by a factor of three from one point four million barrels a day, to just about four million barrels in the early 1980's. This runs directly counter to administration efforts to reduce dependence upon imports of oil, but is necessary if brownouts and economic slowdown are to be avoided.

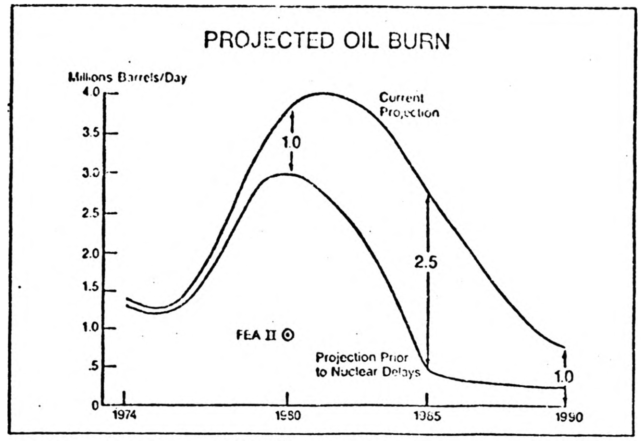


FIGURE 7

This large increase in oil consumption for electric power generation would have been one million barrels per day less had it not been for deferrals and cancellations of nuclear capacity additions last year. By 1985 the difference in the projected oil burn caused by the nuclear delays and cancellations is 2 ½ million barrels per day.

Only a massive increase in coal production and a return to an accelerated nuclear program will make it possible to bring electric utility oil consumption down to one million barrels per day by 1990. The full significance of this added burden on oil imports to meet the needed growth in electric kilowatt-hour demand is best perceived by looking at the <u>total</u> energy picture.

Examining the total use of energy in the U.S. in 1972, it is evident that ours is a fossil fuel energy economy, with direct combustion of oil and gas the dominant mode of end use. Electricity generation accounts for 25 percent of total energy input, but only 10 percent of oil consumption.

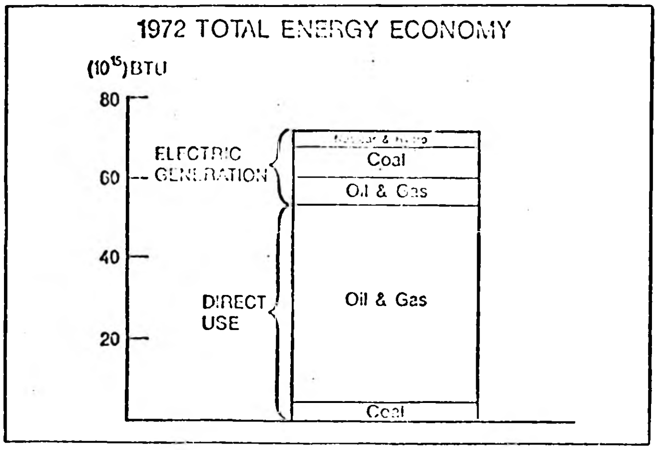


FIGURE 8

A comparison of the nation's ultimately recoverable energy resource base with our present pattern of consumption makes the root of our energy problem dramatically clear.

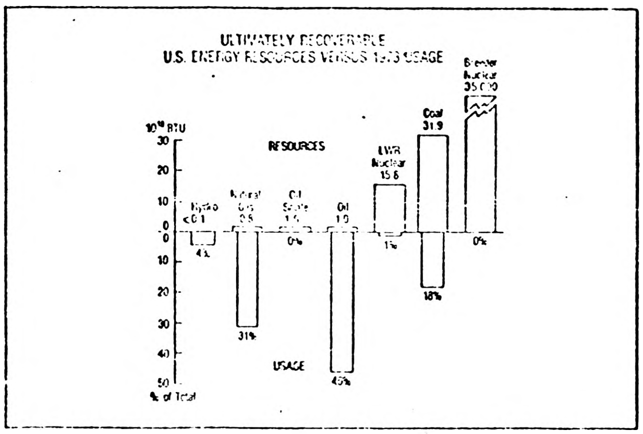


FIGURE 9

We are relying on oil and natural gas, our least plentiful energy resources, for nearly 80 percent of our energy needs, and neglecting our most abundant resources, coal and uranium. With breeder reactors, our energy resources from uranium are over one-thousand fold greater than coal, petroleum, natural gas, and oil shale combined.

At current growth rates, exhaustion of U.S. and world oil and gas resources is highly probable within 50 years. If we are to deal effectively and realistically with the coming energy crisis, we must sharply reduce our excessive dependence on oil and gas by shifting to energy sources that are more plentiful -- uranium and coal.

Let's look now at our forecast of total energy demand through 1990. It is based on full recovery of the economy by 1980, with GNP and energy growth rates tapering thereafter from 6 percent to 2.5 percent. Looking at the supply side, we assumed the maximum production rates for oil and natural gas from domestic resources would steadily decline, and that coal production could more than double. Nuclear's contribution was assumed limited to a level consistent with present utility planning, including the recent unfortunate delays and cancellations.

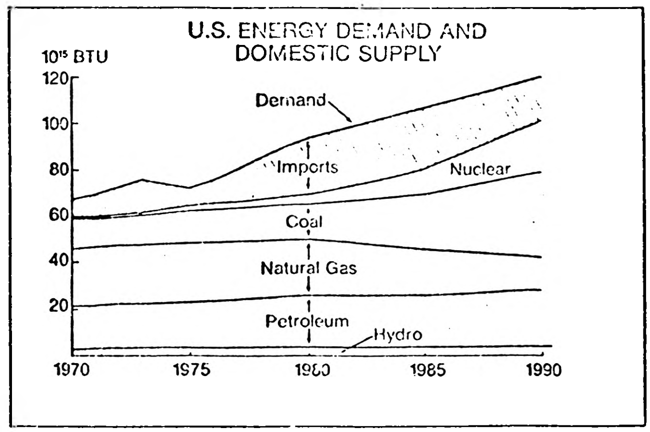


FIGURE 10

Here is the alarming picture we found. Although oil imports are projected to fall significantly this year, the start of the economic recovery will begin to drive them right back up again. By 1980, far from being reduced, they will be almost double the 1973 level at a cost of 50 billion dollars annually. Let there be no mistaking this message; if imports are choked off by tariffs, quotas, boycotts, or other actions, the ability of the U.S. economy to recover is in severe jeopardy.

Let's now look at what a true maximum commitment to nuclear power could do for this picture. When I say a true maximum commitment I mean a fully enacted and funded national policy to utilize uranium as rapidly and as extensively as is physically possible to do. A program of putting facilities in place quite similar to a NASA-type space effort, with the cessation of all legal and environmental delaying tactics which are so costly to the country today. If we would do this today, you will notice that by 1990, it is possible for us to almost reduce our imports to zero.

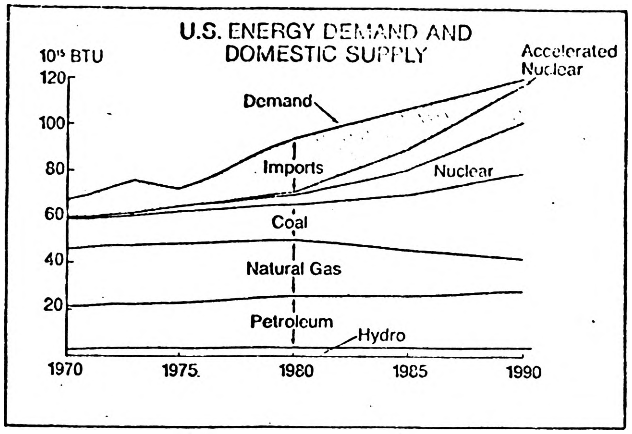


FIGURE 11

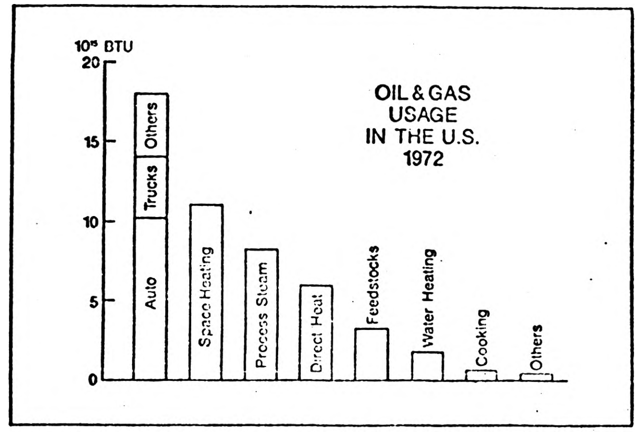


FIGURE 12

We have no real choice between now and 1980 except to live with the rapid rise in petroleum imports, but unless the proper decisions are made now, this situation will continue throughout the 1980's as well. To eliminate this perpetual high reliance on oil imports, immediate actions must be taken toward expanding the role of nuclear and coal, and to do that we will need to utilize a greater fraction of our total energy in the form of electricity.

But, the shift to an electric energy economy entails much more than merely substituting coal/nuclear for oil and gas in the generation of electricity. Instead, it also requires the substitution of electricity for the direct combustion of oil and gas at the point of energy end-use wherever this is technically and economically feasible.

Because electricity is the cleanest, most versatile, efficient, flexible, and convenient energy form at the point of use, there are many opportunities for such substitutions.

Under the policy of electric substitution, oil and gas would be reserved for critical, non-substitutable end-uses such as jet aircraft, large trucks, agricultural machinery, long-distance automobiles, drugs, fertilizers, and petro-chemicals.

Here is the way we used oil and gas in the U.S. in 1972. If we focus on the first four items -- transportation, space heating, process steam, and direct heat in industry -- we are looking at nearly 80 percent of the total direct use of oil and gas. If we are to achieve any significant reduction in the demand for oil and gas, we must do it in these areas.

Here is a summary list of some of the more important and promising opportunities for electric substitution in each energy sector. The heat pump is seen to have wide applicability, and can play a key role in res-

ELECTRIC SUBSTITUTION OPPORTUNITIES

Sector	Function	Electric Substitution
Residential and Commercial	Space Heating	Resistance Heat, Heat Pump
	Water Heating	Resistance Water Heating, Heat Pump
	All Other	Available
Transportation	Auto (Short-Haul)	Electric Auto
	Bus (Urban)	Electric Bus
	Truck (Local)	Electric Local Delivery Vehicle
	Rapid Transit	Electric Rapid Transit
	Rail	Railroad Electrification
Industrial	Process Steam	Resistance Boiler, Electrode Boiler, High-Temperature Heat Pump
	Direct Heat	Resistance, Induction, Dielectric, and Radiant Heaters, Arc Heater
	Space Heat	Resistance Heat, Heat Pump, Waste Heat Recovery

FIGURE 13

idential, commercial and industrial space heating, water heating, and process steam. It is cost competitive and more energy efficient than an oil or gas furnace. Electric furnaces are already widely used in the metals and glass industries, and will increase as gas and oil prices and availability worsen. Short-haul electric vans and buses are feasible, and can be improved as battery technolgoy progresses. These, along with greatly expanded electric mass transit systems and electrification of railroads, can gradually reduce the heavy demand for oil in the transportation sector which now amounts to over 60 percent of total consumption.

Adoption of a systematic program of accelerated electric substitution would make it possible to reduce oil imports to essentially zero by 1990. This in turn would require an additional 300 GW of electric generation, bringing the total to 1500 GW, of which 700 GW would be nuclear.

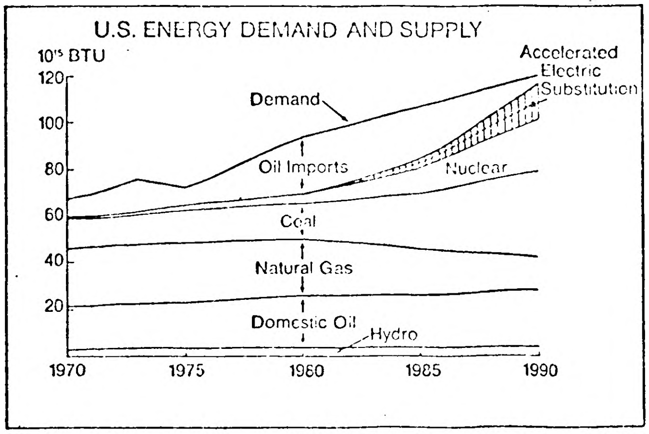


FIGURE 14

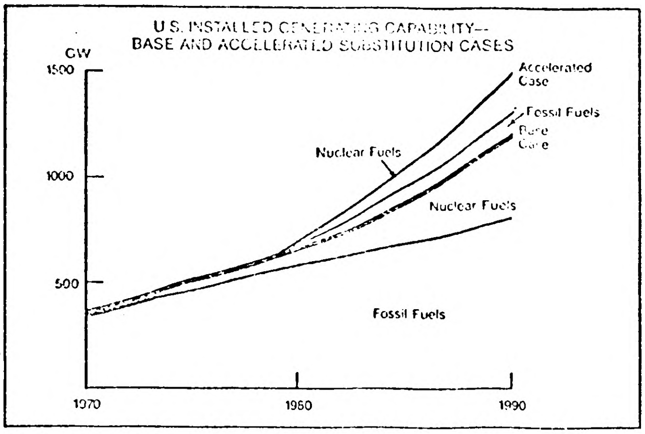


FIGURE 15

The accelerated use of electricity is the only option, the only alternative to a growing dangerous level of dependence upon imported energy and the intolerable balance of payments which that would involve.

The future of the U.S. economy is at a critical crossroads. The path to economic recovery and growth, and the steps required to assure adequate energy to support the recovery and growth, seem very clear. We must accept the necessity for relying upon increasing oil imports through the late 1970's, but we should initiate aggressive programs today to accelerate the production and utilization of coal and nuclear energy. This requires a shift to electricity as the nation's primary end-use energy form.

ENERGY EFFICIENCY AND CONSERVATION OF BUILDING HVAC SYSTEMS USING THE AXCESS ENERGY ANALYSIS COMPUTER PROGRAM

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Abstract

This paper discusses the use of the AXCESS-UMR energy analysis computer program applied to two different buildings. The monthly and yearly energy requirements of many of the commonly used HVAC systems for a single-story multi-zone building are found and compared. Energy conservation techniques are also evaluated for a two-story St. Louis office building.

1. INTRODUCTION

Heating, ventilating, air-conditioning (HVAC) and refrigeration for residential, commercial, and industrial consumers in the United States accounts for almost 30% of the total energy used by the nation. It has been estimated that as much as 40% of this energy can be saved with total application of our present technology. These energy conservation techniques would include adequate insulation, reasonable quantities of glass, sensible lighting levels, more efficient HVAC systems and controls, minimum but adequate ventilation quantities, and logical building operation and maintenance schedules.

Basically there are two categories of structures which must be considered: existing buildings with installed HVAC systems and controls and new buildings which are being designed or will be designed. All of the above mentioned energy conservation techniques can be applied to new buildings while only some of the techniques are feasible for existing buildings. For existing buildings it is normally not economical to change insulation, glass, or the type of HVAC system. However, there is potential for energy conservation in existing buildings by modifying the HVAC system controls, the quantity of ventilation air, and the building operation and maintenance schedules.

Recently, interest has developed in energy conservation techniques for HVAC systems. Some applications of these techniques to new commercial buildings were discussed by Rahme(1) and Spethman(2). Some examples of applying energy conservation techniques to existing commercial buildings were discussed by Smith(3) and to residences by Zabinski(4).

Energy consumption computer programs can be used with both new and existing buildings in order to

TABLE 1. Some of the Existing Energy Consumption Computer Programs

AXCESS	Edison Electric Institute
Westinghouse Energy	
NBSLD	National Bureau of Standards
McDonnell Automation Center	
ECUBE	American Gas Association
Post Office Program	GARD/GATX
Electric Heating Association	
NECAP	NASA/Langley
TRACE	The Trane Company
Ross F. Meriwether & Associates	
(Various computer service organizations)	

TABLE 2. Design and Operating Variables of Energy Analysis Programs

● Building size
● Building shape
● Orientation of the building
● Construction materials used in the building
● Heat storage characteristics of the building
● Infiltration rates
● Lighting schedule
● Internal load generation
● Occupancy schedule
● Internal temperature and humidity set points
● Solar load
● Hourly outside temperature and humidity variations
● Ventilation schedules
● Control and scheduling of operation of HVAC system
● Mechanical equipment part load performance
● Night set-back of inside set points
● Application of economizer cycle
● Heat recovery capability

simulate various types of changes which might be implemented for energy conservation. Several computer programs are available which simulate (with various levels of accuracy) HVAC system operation and provide estimates of yearly energy consumption for the structure. Several of these programs are listed in Table 1.

It is not the purpose of this paper to compare and/or defend the various programs listed in Table 1, since the programs use different methods of system simulation as well as varying methods of representing outdoor weather conditions. The purpose of this paper is to apply a modified version of the AXCESS Energy Analysis program to several test buildings in order to evaluate system energy efficiency and some energy conservation techniques. The cases and techniques evaluated here are only samples of what can be done with computer program energy analyses. There are a limitless number of comparisons which can be made; however, cost, space, and time dictate the number of cases presented in this paper.

Some of the design and operating variables which can be accommodated by the energy programs listed in Table 1 are shown in Table 2.

A comprehensive energy analysis program should have the capability of evaluating all of the variables specified in Table 2. In addition, it would also be advantageous for the program to have the capability of simulating internal and external thermal storage, wind effects, shading effects, and internal temperature swing.

This paper presents results obtained from the University of Missouri-Rolla version of the AXCESS Energy Analysis Program applied to two test buildings. The first test building simulated a light commercial structure and was used only to evaluate the energy efficiency of eight common HVAC systems. The systems which were simulated included the double duct (and/or multi-zone) (DD), single zone reheat (RH), variable air volume (VAV), ceiling induction with heat of lights (HOL), two pipe induction (IND-2), four pipe induction (IND-4), two pipe fan coil (FC-2), and four pipe fan coil (FC-4). Table 3 contains the salient features of each of the different types of systems.

The second test building simulated a two-story medium sized office building. In the second test building the single zone reheat system was used and the following energy conservation techniques were applied: reduction of infiltration air; change in the summer, winter, and night setback inside set point temperatures; addition of an economizer; and shading of glass areas.

2. AXCESS ENERGY ANALYSIS PROGRAM

The AXCESS [acronym for Alternate Choice Comparison for Energy System Selection] program was designed to provide accurate economic comparisons of the different energy systems which may be used in all types of buildings. The AXCESS program consists of four parts[5]:

(1) Energy analysis computer program

(2) First cost differentials among alternate HVAC systems

(3) Differentials in costs for operating personnel, maintenance, and unscheduled repairs.

(4) Financial analysis

The first section of the program is the only one of concern for this investigation.

The AXCESS Energy Analysis Computer Program[6] evaluates building energy requirements on an hour-by-hour basis for a full year (8760 hours), using typical local weather data (dry-bulb temperature, relative humidity, cloud cover), building operating profiles, and base load usage profiles. This program is not merely confined to energy requirements of HVAC systems. Although the HVAC energy is the one of concern here, the cost of energy is very much predicated on the combination of all energy using devices in the structure. AXCESS determines total energy consumption as well as demand so that a realistic comparison of HVAC systems and other energy consuming devices can be made.

The weather data which is used by AXCESS comes from U.S. Weather Bureau hourly data. The user can

TABLE 3. Features of HVAC Systems
DOUBLE DUCT (or MULTI-ZONE)
■ Has available for each zone both heated and chilled treated air. ■ Constant flow rate of air enters each zone. ■ System mixes air from each duct in order to maintain zone set point temperature. ■ Air in each duct is normally kept at a fixed predetermined value.
SINGLE ZONE REHEAT
● Constant flow rate of air to each zone. ● All air is cooled to a predetermined temperature. ● Conditioned air is reheated enough in order to maintain zone set point temperature.
VARIABLE VOLUME
▲ Air is supplied to each zone at a fixed temperature. ▲ Each zone modulates the volume flow of air delivered.
INDUCTION SYSTEMS (CEILING, 2-PIPE, 4-PIPE)
■ Treated primary air is supplied to each zone. ■ Room air is induced through coils or around lights. ■ 2-pipe either heats or cools induced air, not both. ■ 4-pipe can heat or cool induced air on demand. ■ Constant flow rate of air to each zone.
FAN-COIL UNITS (2-PIPE, 4-PIPE)
● Constant flow rate of air to each zone. ● 2-pipe either heats or cools air, not both. ● 4-pipe can heat or cool air on demand.

select any station and any year of interest. For this study the weather data for the year 1971 at St. Louis, Missouri, has been used for all calculations.

The input data for the building construction includes such items as: total roof area, net wall area, total glass, gross floor area, wall and roof construction weights, and ceiling height.

The base energy loads can include such items as interior lighting, exterior lighting, business machines, exhaust fans, vertical and horizontal transportation, cooking equipment, hot water heating, food service refrigeration, food service preparation, food service sanitation, vending machines, plumbing and fire protection equipment, machinery, and others. Up to thirty different base loads can be used in AXCESS. The base loads are input in terms of maximum electrical connected load or peak BTU together with a profile which describes the percentage use of any of the loads for up to nine types of days (seven week days, vacation day, holiday). Up to thirty profiles may be input and there is also the capability of changing the standard input profiles to a "special period" of building use (summer session, seasonal night operation, etc.)

The AXCESS program can receive the heating/cooling load data for the structure in a variety of ways. The user may input these loads for each zone calculated on an hourly basis from some other load program (NBS - Post Office, HCC-III, etc.). If these hourly loads are not available, total building design loads may be input in the form of summer and winter transmission and solar, with or without a breakdown between glass, wall, and roof values and solar loads. These loads may be further broken down to an exposure-by-exposure basis when available. If the hourly values are not input the AXCESS Program will take the building design values and back calculate to determine U-factors and solar loads by exposure.

The AXCESS program can accommodate up to 180 zones in the structure. For each zone of the structure the following information is input: inside design temperatures and relative humidity for both summer and winter, night setback temperature and relative humidity, wall area, glass area, floor area, roof area, internal heat gains from the base loads, light heat to return air, number of people, infiltration flow rate, air supply to the zone, zone number, and zone exposure.

The HVAC system simulations in the AXCESS program are divided into terminal and primary system types. The terminal systems serve sets of specified building zones. Up to twelve terminal systems can be input with up to fifteen zones assigned per terminal system. Most of the HVAC terminal systems in common use today are simulated by the program and range from simple unitary equipment to the more complex ceiling induction units utilizing lighting cavity heat. The primary systems which are specified are; chillers, boilers, heat pumps, on-site generation, etc., and are assigned to serve specific terminal systems or to serve each other. Each terminal and primary system can have its operating parameters specified as input or, in some instances standard design values can be assumed. Primary system description includes full-load, mode of operation, and part load efficiencies.

As part of the AXCESS Energy Analysis Program provision is made for assigning up to 36 energy meters which can be assigned to base loads, primary systems, and terminal systems. This allows submetering of the various loads as well as total metering of the various energy sources in the building.

The AXCESS program also has the capability of using waste heat from some base loads and HVAC loads to meet base loads and HVAC loads.

Another unique feature of the AXCESS program is that it can analyze up to six separate mechanical/electrical schemes on a single computer run. This allows the consideration of various lighting schemes, terminal systems, and primary systems for a single building with only one computer run. In this way meaningful comparisons of energy requirements can be readily accomplished.

The basic program output consists of (1) a complete print-out of input data for verification purposes, and (2) monthly and annual indications of energy usages and demands by energy source types. In addition, sample calculations for selected days, hours, zones, and schemes can be requested. This allows comparison with longhand calculations for verifying program accuracy. Also as part of the output the user can specify breakdowns of energy usage by load type, monthly total heat rejected from air cooled or water cooled primary refrigeration systems, hourly and/or monthly deficit or excess KWH for on-site generation, and hourly or daily energy usage for each meter.

The version of AXCESS which was used in this investigation was obtained from Union Electric Company (St. Louis, Missouri). This version is designated as AXCESS-UMR VERSION. This version has been revised and updated from the existing version of AXCESS issued by Edison Electric Institute in 1974.

3. TEST BUILDING ONE

The first test building considered was a single story rectangular light-commercial building containing five zones. A sketch of this building, its dimensions, zone numbers, areas, air flow rates, and lighting are shown in Fig. 1.

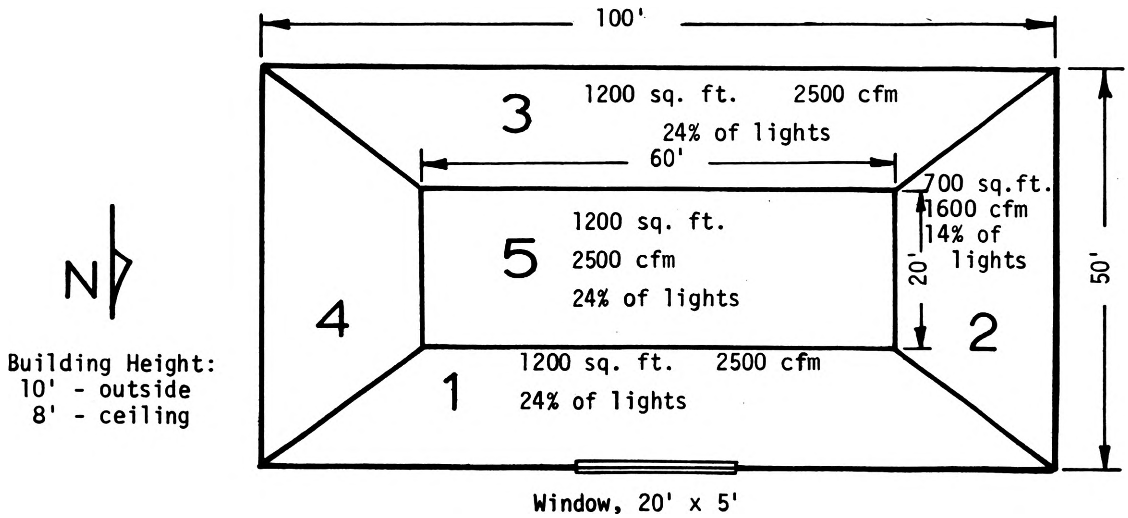

Figure 1 Test Building One

The total areas are as follows: roof, 5000 sq. ft.; wall, 2900 sq. ft.; glass, 100 sq. ft.; floor, 5000 sq. ft. The inside design conditions are: winter - 75°F dry bulb, 30% relative humidity; summer - 75°F dry bulb, 50% relative humidity. The outside design conditions are: winter - +4°F dry bulb, summer - 95°F dry bulb, 78°F wet bulb, 70°F total equivalent temperature difference, August 21, 4:00 PM, and one-half air change per hour of infiltration air. The weather station for the energy analysis was for St. Louis, Missouri, with a latitude of 38°N, longitude of 91°W and a midwest time zone. The building design solar and transmission loads in Btu/hr are as listed below.

Loads	Summer	Winter
Glass Trans	40.	4260.
Glass Solar	1280.	
Wall	12760.	41180.
Roof	70000.	71000.
Glass + Wall	14080.	45440.
Wall + Roof	82760.	112180.
Total	84080.	116440.

Zone 1 has a northern exposure area of 1000 sq. ft. Zone 2 has a western exposure of 500 sq. ft. Zone 3 faces south and has 1000 sq. ft. of exposure area. Zone 4 faces east and contains 500 sq. ft. of exposure area. Zone 5 is an interior zone with a horizontal exposure.

The only base load considered in this test building was interior lighting with a total installed quantity of 20 kw. The lights were kept on at full value for 24 hours a day every day of the year except Saturdays.

Test Building One was simulated using a boiler and chiller for the exterior zones and a separate boiler and chiller for the interior zone. Each of these units had typical full load efficiencies (gas boilers - 80%, electric chiller COP = 3.0) with typical part load degradation of efficiency. The external zones (1, 2, 3, 4) were served using

4-pipe fan-coil terminal units while the interior zone was served using different types of terminal units.

The yearly results for each of the boilers and chillers are summarized in Table 4. The results are given in terms of usage (Kilowatt-hours, or cubic feet) and demand (Kilowatts and cubic feet per hour). In addition, the various terminal systems are ranked for heating, cooling, and total energy usage for terminal system one and the total building.

The double duct (or multizone) system (DD) consistently ranked seventh in terms of minimum energy consumption for HVAC. The diagram of this system is shown in Figure 2. The system is energy inefficient because it uses reheat energy to create an additional HVAC load at off design conditions.

Figure 3 depicts the reheat system (RH) which ranked last in terms of minimum HVAC energy consumption. In this system all of the supply air is cooled to a cold deck temperature and then reheat is added as needed to maintain each zone at the set-point temperature. Like the double duct system this system uses reheat energy to create an additional HVAC load at off design conditions.

The variable air volume system (VAV) is shown in Figure 4 and it ranked fifth in terms of total HVAC energy consumption. Normally the VAV system would be more energy efficient than this, but in this simulation, the ventilation rate is set as

TABLE 4 HVAC Energy Consumption and Demand for Test Building One-St. Louis, Missouri-1971

	SCHEME	1	2	3	4	5	6	7	8
	TS-1(INT)	DD	RH	VAV	HOL	IND-2	IND-4	FC-2	FC-4
	TS-2(EXT)	4-PIPE FAN COIL							
CHILL.1	Usage(KWH)	25,554	34,379	18,394	12,766	17,060	15,761	6,001	8,068
	Demand(KW)	6	8	5	5	6	6	5	5
	Rank	7	8	6	3	5	4	1	2
BOIL.1	Usage(cf)	185,665	512,074	128,625	5,097	113,395	157,863	77,417	74,623
	Demand(cfh)	84	93	56	17	67	80	84	84
	Rank	7	8	5	1	4	6	3	2
	TERMINAL System 1 Total(10^6BTU)	273	629	191	49	172	212	98	102
	Rank	7	8	5	1	4	6	2	3
CHILL.2	Usage(KWH)	40,189	40,189	40,189	40,189	40,189	40,189	40,189	40,189
	Demand(KW)	18	18	18	18	18	18	18	18
BOIL.2	Usage(cf)	445,526	445,526	445,526	445,526	445,526	445,526	445,526	445,526
	Demand(cfh)	324	324	324	324	324	324	324	324
TOTALS	Chillers(KWH)	65,743	74,568	58,583	52,955	57,249	55,950	46,190	48,257
	Boilers(cfh)	631,191	957,600	574,151	450,623	558,921	603,389	522,943	520,149
	Total(10^6BTU)	856	1,212	774	631	754	794	681	685
	Rank	7	8	5	1	4	6	2	3

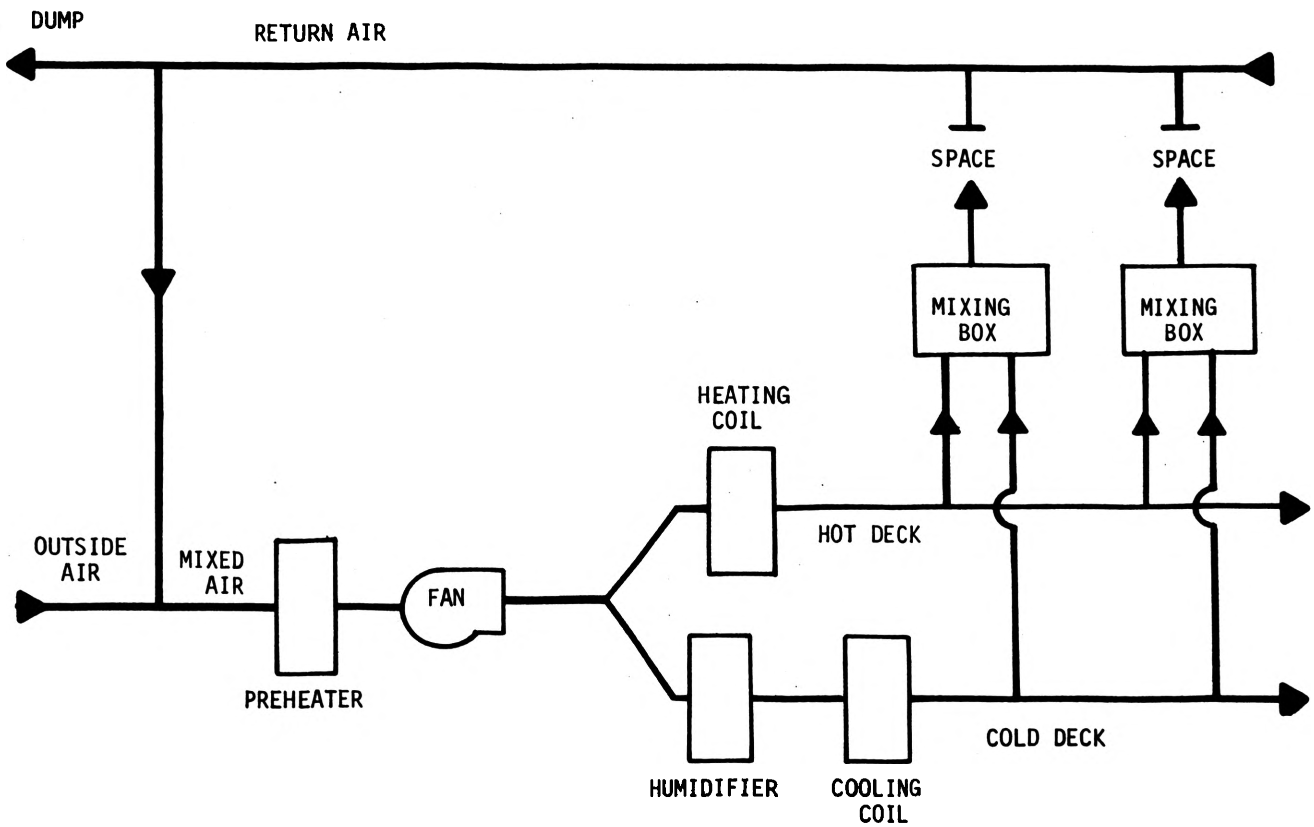

Figure 2 Double Duct or Multi-Zone System

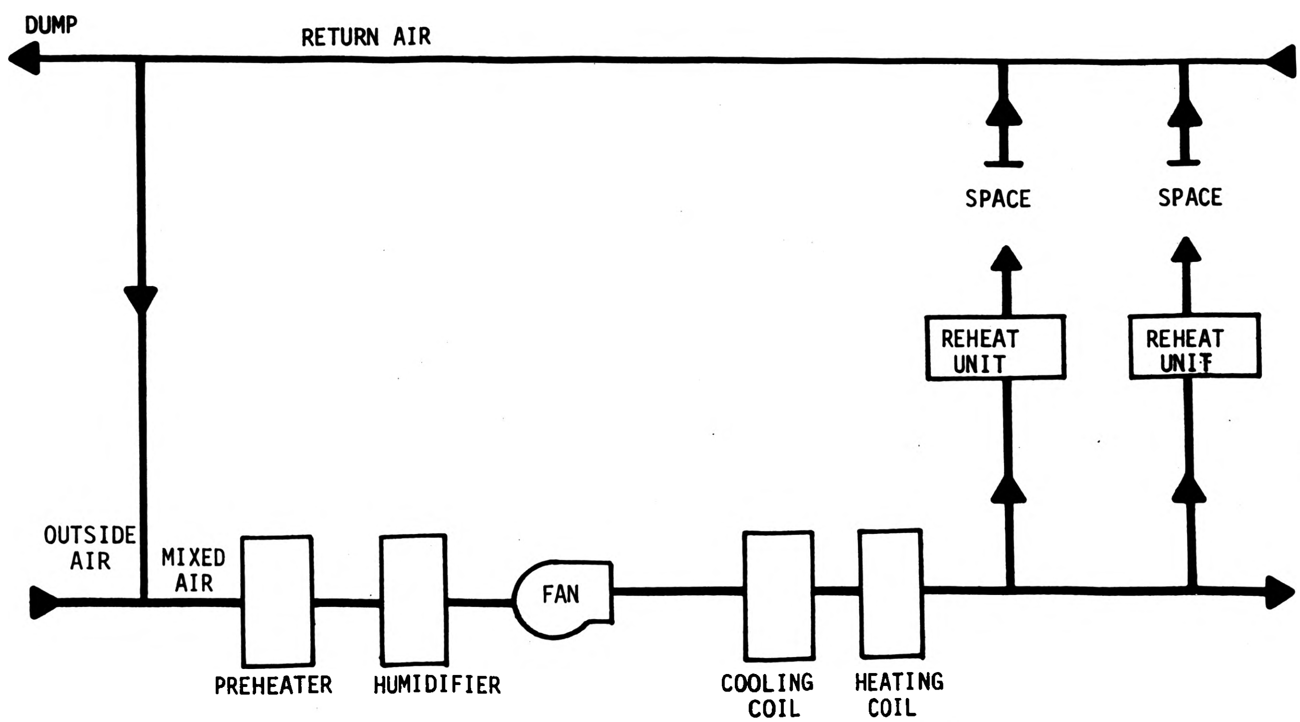

Figure 3 Single Zone Reheat System

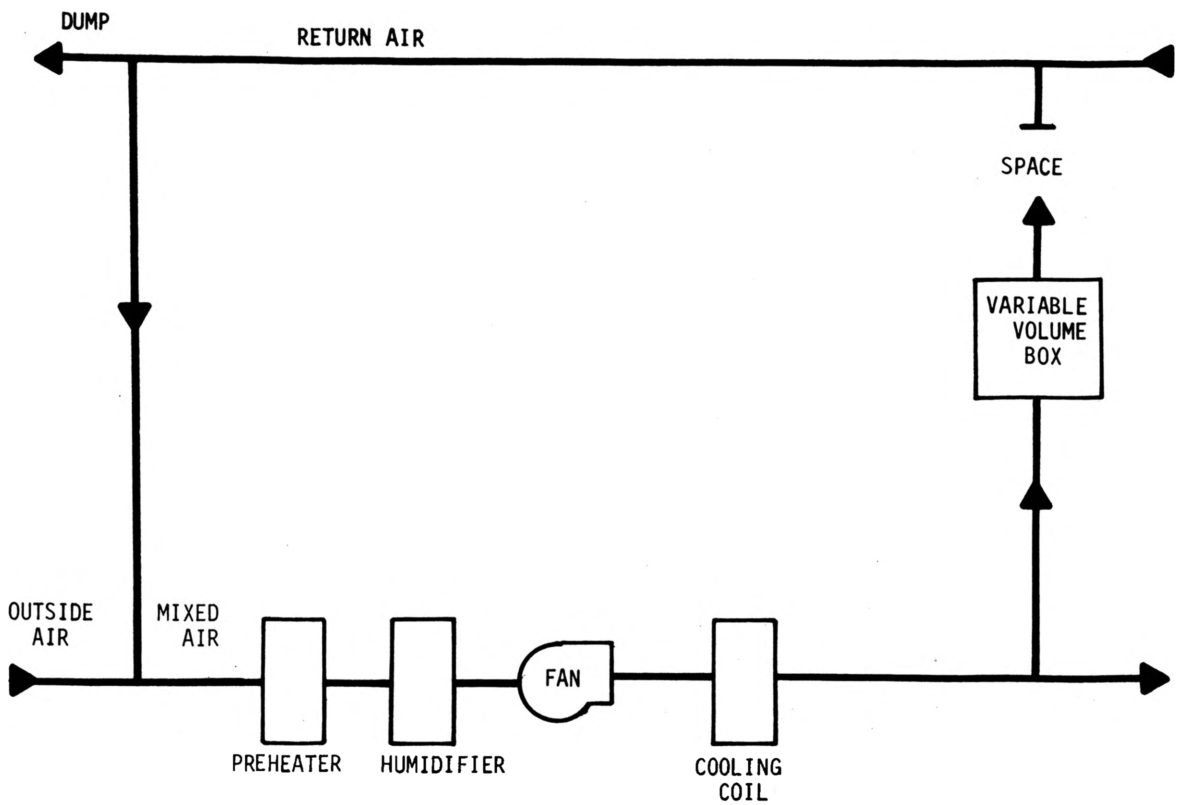

Figure 4 Variable Volume System

the percentage of the maximum supply air. This causes the ventilation load to be excessive.

The ceiling induction heat of light (HOL) system (see Figure 5) ranked first in terms of energy efficiency. This is due to the fact that much of the heat from the lights is used for heating and reheating purposes in both summer and winter.

The two-pipe and four-pipe induction systems (IND-2 and IND-4) are shown schematically in Figure 5. They ranked fourth and sixth, respectively, in terms of energy efficiency when compared to the other systems. The differences between these two systems accrue due to different primary air temperatures during summer and winter for each system as well as the fact that the two-pipe system will not always maintain the set point temperature during off design periods after switch over has occurred.

The fan coil systems (FC-2 and FC-4) are shown in Figure 6 and ranked second and third, respectively, in terms of energy efficiency for this building. The differences between FC-2 and FC-4 occur because of the necessity of having switch over days for the two-pipe system which means that there will be some days when the set point temperature cannot be met.

In general, it can be said for this test building that the HOL and FC-2 and FC-4 are the best systems for the interior zones as far as energy efficiency is concerned. It should be kept in mind however, that these results could very well change as various operating or design parameters for the building are changed.

4. TEST BUILDING TWO

The second building simulated with the AXCESS program was modeled after an existing two story office building located in St. Louis, Missouri. The building had a roof area of 22,810 sq. ft., total wall area of 9,460 sq. ft., total glass area of 7,536 sq. ft., gross floor area of 45,620 sq. ft., and a ceiling height of 9 feet.

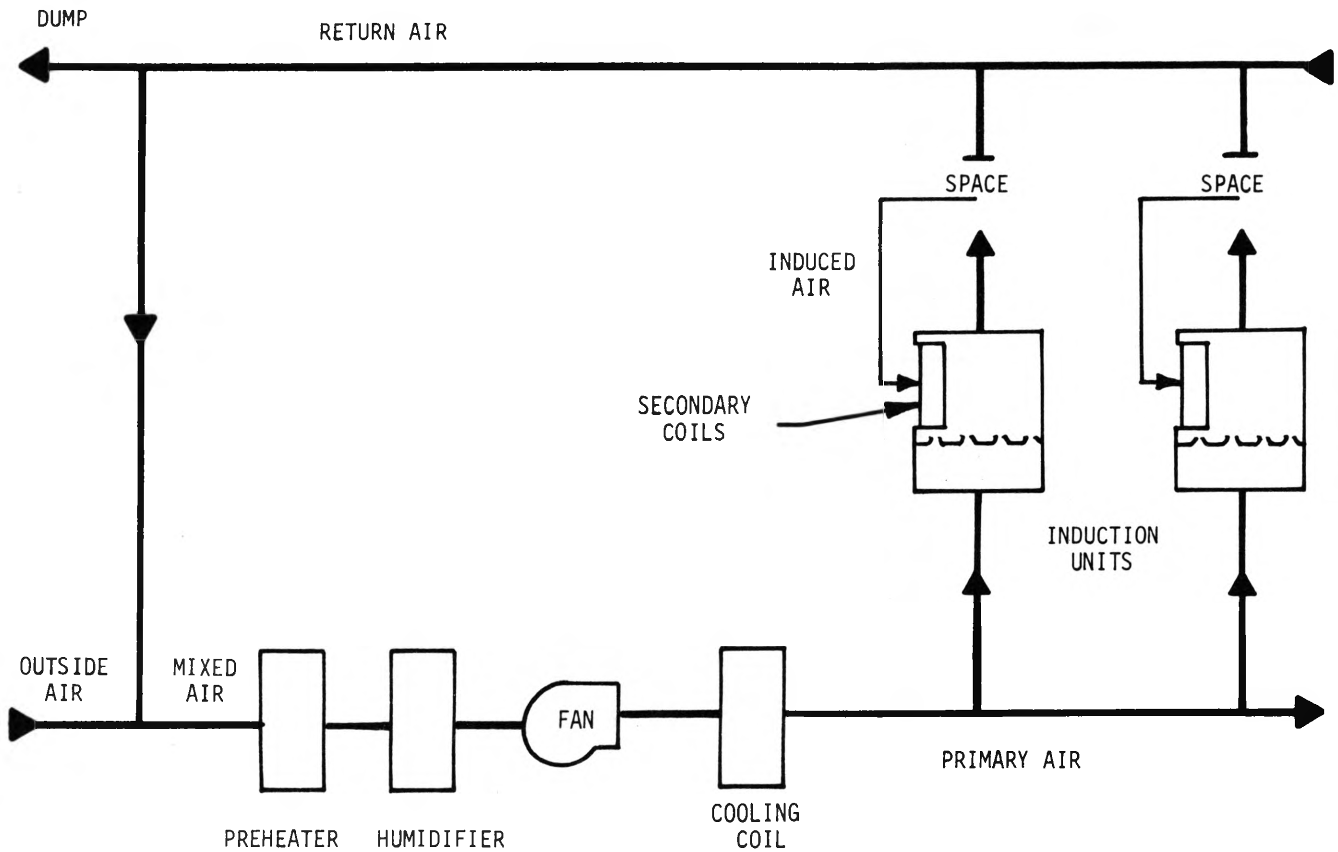

Figure 5 4-Pipe Induction System

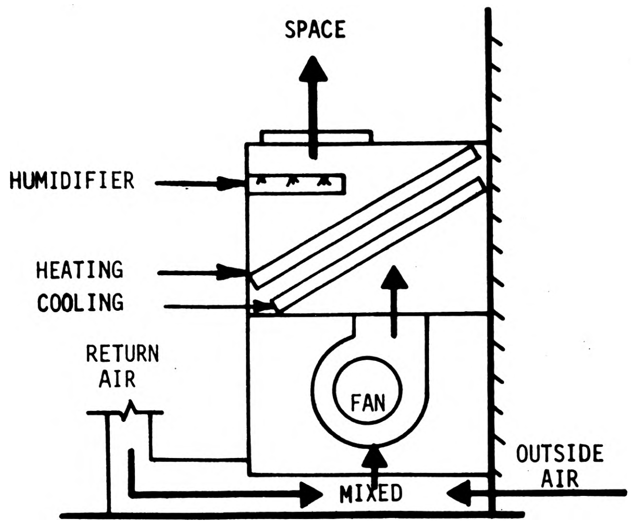

Figure 6 4-Pipe Fan Coil System

The building had four exposures with medium weight walls and roof. The building was divided into 16 zones, each served with a terminal reheat (see Figure 3) secondary system (cold deck temperature at 55°F). Each zone had a requirement of 10% minimum outdoor air, with a night heating schedule, time clock schedule, economizer, and no winter humidification.

The primary systems consisted of four air conditioning units (2/floor, 4 zones/unit) with electric reheat coils in each zone for heating and reheating. The summer indoor design conditions were 75°F-50% relative humidity while the winter indoor design conditions were 75°F-30% relative humidity with night setback conditions of 60°F and 30% relative humidity.

The building had a maximum occupancy of 410 people with an installed lighting capacity of 133 kw. Each of these base loads were applied to the zones according to the typical load profiles for the building. In addition, some special period profiles during the winter months were used. Five holidays, as well as daylight savings time, were considered in the calculations. The design heat loss/gain loads were obtained from the consulting engineer and were in the form of total values for summer and winter for glass, wall, roof, and solar. The design loads were as given below.

(1) Summer Glass Solar = 139,852 BTUH
(2) Summer Solar and Transmission-glass = 246,353 BTUH
(3) Summer Solar and Transmission-walls = 44,522 BTUH
(4) Summer Solar and Transmission-roof = 257,644 BTUH
(5) Winter Transmission-glass = 425,604 BTUH
(6) Winter Transmission-walls = 178,088 BTUH
(7) Winter Transmission-roof = 429,407 BTUH

AXCESS-UMR was run using the above data for Test Building Two and the resulting KWH for each month and full year for HVAC, heating and reheating, and cooling are given in Table 5. This set of results is referred to as the base case for Test Building Two. In the base case, zero air changes per hour of infiltration air was used. The results for Case 1 are plotted in Figure 7. The total HVAC load (heating, cooling, fans, auxiliaries) had a seasonal variation with maximum KWH required in January (141,678) and minimum KWH in June (114,085). Heating and reheating energy was minimum during June (36,848 KWH). For this test case the cooling load peaked during June at 53,057 KWH. These results are typical for this type of building and system when the economizer is in use (which it is in Case 1).

Table 5 also contains the results of four additional test runs on Test Building Two. In Case 2 one-half of an air change per hour of infiltration air was considered. In Case 3, the set-point temperatures were changed from 75°F to 80°F during the summer and from 75°F to 70°F (night setback from 70°F to 60°F) during the winter. In Case 4, 30% of the solar glass load was reduced (by natural or mechanical shading) from the existing quantity in Case 1. Case 5 represents the building operating without benefit of the economizer.

Cases 2 through 5 have been compared with base Case 1 and the results in terms of percent change of the monthly and yearly values are given in Table 6.

TABLE 5 Energy Consumption and Demand for Test Building Two-Office Building-St. Louis, Mo. - 1971

(KWH)

	Case 1 (Base)			Case 2 (Infiltration)			Case 3 (Design Conditions)		
	HVAC	HEAT & REHEAT	COOLING	HVAC	HEAT & REHEAT	COOLING	HVAC	HEAT & REHEAT	COOLING
JAN	141,678	123,606	962	152,579	134,509	962	117,114	99,194	832
FEB	123,775	100,243	6,360	131,487	108,049	6,277	99,283	76,743	5,494
MAR	131,124	103,603	7,992	138,437	110,932	7,980	101,512	75,236	6,902
APR	135,589	83,560	30,714	140,437	88,858	30,325	176,876	119,631	35,293
MAY	127,022	65,908	39,699	129,292	69,524	38,522	168,149	100,299	45,613
JUN	114,085	36,848	53,057	108,397	37,075	47,876	152,665	66,854	60,630
JUL	115,742	41,219	50,877	111,612	41,776	46,768	155,211	72,331	58,246
AUG	117,402	41,845	51,589	113,376	42,474	47,510	157,492	73,515	59,010
SEP	120,176	49,990	47,457	117,709	51,573	43,906	156,903	79,535	53,792
OCT	124,574	58,232	43,675	124,619	60,134	42,052	91,628	32,557	37,308
NOV	137,699	101,051	17,476	146,187	109,764	17,281	108,759	75,018	14,928
DEC	121,333	99,025	3,990	126,862	104,654	3,902	93,691	71,858	3,574
YEAR	1,510,194	905,132	353,848	1,540,988	959,321	333,359	1,579,281	942,769	381,620
DMD (KW)		394			394			460	
MONTH		2			2			4	

	Case 4 (30% Solar Shading)			Case 5 (No Economizer)		
	HVAC	HEAT & REHEAT	COOLING	HVAC	HEAT & REHEAT	COOLING
JAN	143,236	125,165	962	181,897	123,606	37,310
FEB	125,540	102,009	6,360	158,437	100,243	37,608
MAR	133,533	106,013	7,992	170,574	103,603	43,519
APR	138,449	86,421	30,714	151,306	83,560	44,773
MAY	129,798	68,686	39,699	131,993	65,908	44,091
JUN	116,717	39,482	53,057	114,085	36,848	53,057
JUL	118,418	43,897	50,877	115,742	41,219	50,877
AUG	119,964	44,409	41,589	117,494	41,845	51,669
SEP	122,469	52,284	47,457	121,489	49,990	48,622
OCT	126,644	60,303	43,675	128,032	58,232	46,747
NOV	139,415	102,768	17,476	164,167	101,051	41,307
DEC	122,650	100,343	3,990	163,189	99,025	41,650
YEAR	1,536,829	931,779	353,848	1,718,399	905,132	541,233
DMD		394			394	
MONTH		2			2	

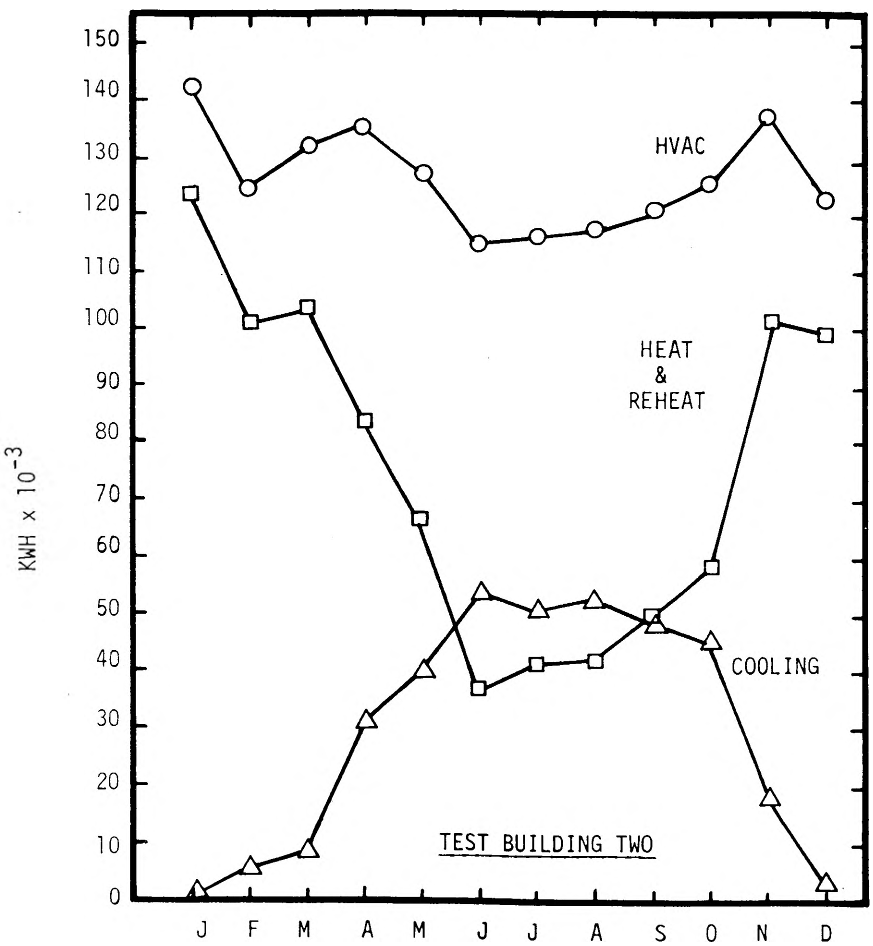

Figure 7 Monthly Energy Requirements - Base Case 1

Increased infiltration always increased the monthly heating and reheating energy requirements showing a yearly increase of 6%. The cooling requirements were always less when infiltration was present and showed a yearly decrease of 5.8%. The reason for this reduction is that the infiltration air at night (when ventilation is off) acts as a cooling source for the building. For the total HVAC energy requirements the added infiltration of 1/2 air change per hour caused a 2% increase in the yearly energy requirement. This type of sensitivity to infiltration flow rates was also demonstrated by McBride, et.al.[7] for a similar type of building.

Changing the zone set-point temperatures to a higher value in the summer and a lower value in the winter in order to conserve energy was not valid for this reheat system. As shown in Table 6 these changes resulted in an annual increase in reheat of 4.1% and an annual increase in cooling energy of 7.8% with the total HVAC yearly load up by 4.6%. For this reheat system it would be more reasonable to leave the zone set-point temperature at as low of a value as would be comfortable. This would reduce the energy required for cooling as well as the energy required for reheating. Lowering the set point by 1° for the entire year should save approximately 5% to 7% of the total HVAC energy. McBride, et.al.[7] indicated approximately a 20% reduction in energy required for a 3°F space temperature reduction. Likewise, Zabinski[4] showed that for residences a 1°F drop in space

TABLE 6 Comparison of Energy Conservation Techniques

	INFILTRATION Case 2 1/2 Air Change/hour % Change from Case 1		SET-POINT CONDITIONS Case 3 Summer 75°F-80°F, Winter 75°F to 70°F, Setback-70°F-60°F % Change from Case 1		30% SOLAR SHADING Case 4 % Change from Case 1		NO ECONOMIZER Case 5 Additional KWH over Case 1	
	Heat&Reheat	Cooling	Heat&Reheat	Cooling	Heat&Reheat	Cooling	Heat&Reheat	Cooling
JAN	+8.8	0	-19.7	-13.5	+1.3	0	0	+36,348
FEB	+7.8	-1.3	-23.4	-13.6	+1.8	0	0	+31,248
MAR	+7.1	-0.1	-27.4	-13.6	+2.3	0	0	+35,527
APR	+6.3	-1.3	+43.2	+14.9	+3.4	0	0	+14,059
MAY	+5.5	-3.0	+52.2	+14.9	+4.2	0	0	+ 4,392
JUN	+0.6	-9.8	+81.4	+14.3	+7.1	0	0	0
JUL	+1.3	-8.1	+75.5	+14.5	+6.5	0	0	0
AUG	+1.5	-7.9	+75.7	+14.4	+6.1	0	0	+80
SEP	+3.2	-7.5	+59.1	+13.3	+4.6	0	0	+ 1,165
OCT	+3.3	-3.7	-44.1	-14.6	+3.6	0	0	+ 3,072
NOV	+8.6	-1.1	-25.8	-14.6	+1.7	0	0	+23,831
DEC	+5.7	-2.2	-27.4	-10.4	+1.3	0	0	+37,660
YEAR	+6.0	-5.8	+ 4.1	+ 7.8	+2.9	0	0	+187,358
Total % Change in HVAC	+2%		+4.6%		+1.8%		+13.8%	

temperature would result in a 5% reduction in total energy required for the year. A 6% savings per 1°F reduction was also reported by Spielvogel[8].

Solar shading of the glass in this building with a reheat system also does not help to conserve energy. Comparison of Case 4 with Case 1 in Table 6 shows that the annual heat and reheat load has been increased by 2.9% with the total HVAC load increased by 1.8%. There are two reasons for the increased heating requirements. During the winter the solar load helps to maintain the inside temperature so that when solar shading is implemented, the amount of heating by the system must increase in order to maintain the 75°F indoor set point temperature. During the summer months the reheat is used to apply a load to the system in order to maintain the 75°F indoor set point temperature. As the summer solar load is reduced the reheat must be increased.

The use of an economizer in the building indicates a substantial savings in energy requirements for this system. As shown in Table 6 a large quantity of free cooling is obtained during the winter months. The total HVAC energy increased by 13.8% when the economizer was removed from the building HVAC system. The HVAC energy requirements with and without the economizer have been plotted in Figure 8 in order to demonstrate the monthly savings in energy that can result from the economizer. The largest percent savings which occurred was in December when the economizer reduced the total HVAC energy by 25%.

5. CONCLUSIONS

The following conclusions can be drawn from this analysis of computer calculated energy requirements for building HVAC systems.

(1) The AXCESS-UMR Version energy analysis program can be used to evaluate energy requirements for new and existing buildings.

(2) Each structure and system must be treated on an individual basis. General conclusions are not always valid for buildings and/or HVAC systems.

(3) The fan coil, variable air volume, and induction systems appear to be the better systems when considering energy efficiency.

(4) Not all systems respond in the same way to the common energy conservation techniques. Judgement and analysis are necessary for meaningful conclusions.

(5) The economizer appears to be one of the most promising energy conserving devices for large buildings.

6. ACKNOWLEDGMENT

The authors are indebted to Mr. George Wagner and Mr. Carl Glaser of the Union Electric Company for granting permission to use the AXCESS-UMR computer program for this paper. The financial support of the Union Electric Company and the Department of Mechanical and Aerospace Engineering at the University of Missouri-Rolla was greatly appreciated. Thanks are also due to Mr. James Ott who provided the experience necessary for carrying the machine computations.

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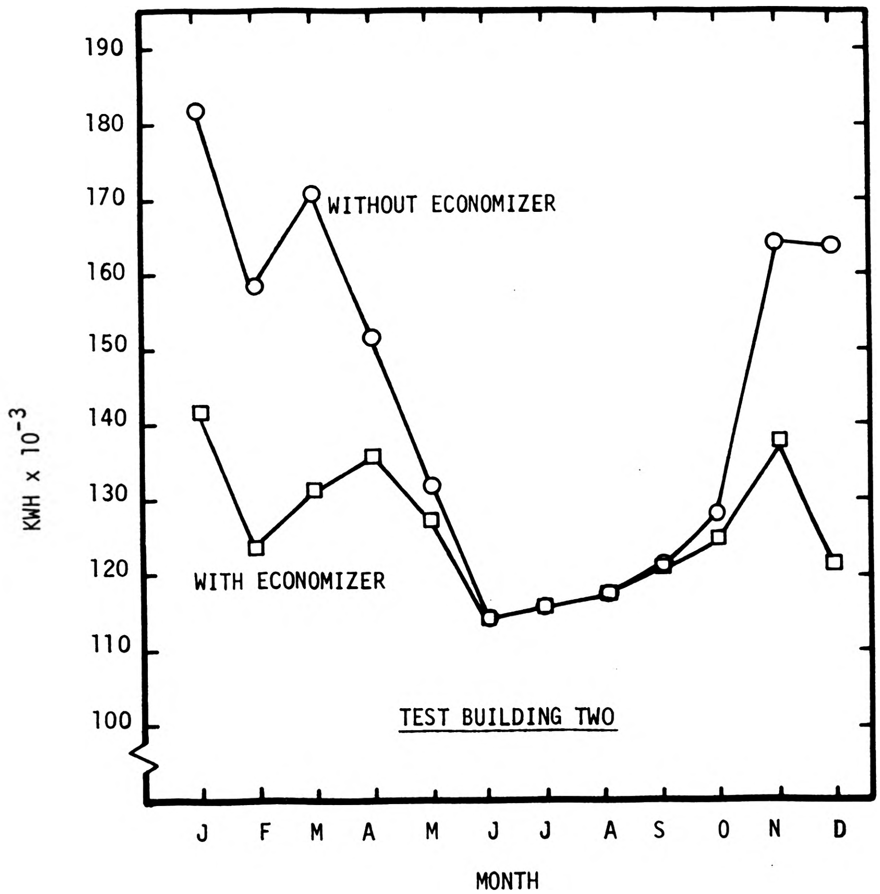

Figure 8 HVAC Energy Requirement With and Without Economizer

8. BIOGRAPHIES

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CONTROL BY CODE OF ENERGY USAGE IN BUILDING SYSTEMS

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Abstract

Space heating, air-conditioning and refrigeration accounts for over 30% of the total energy use in the U.S. ASHRAE Standard 90P, ENERGY CONSERVATION IN NEW BUILDING DESIGN, sets forth requirements for the design of all types of new buildings, covering their exterior envelopes and selection of their HVAC, service water heating, electrical distribution and illuminating systems and equipment for efficient use of energy. This paper reviews the current status, content, and implications of the proposed energy standard and reports some experience with its use.

1. INTRODUCTION

Americans use over 72 quadrillion Btu's of energy each year. Heating, air conditioning, and refrigeration for residential and commercial consumers in this country use about 26.7% of this energy. This includes approximately 18% for space heating, 4% for water heating, 2.2% for refrigeration and 2.5% for air conditioning. This is exclusive of the energy utilized in industrial heating, cooling, and refrigeration requirements. While it is true that the American people use more energy than any other nation, it is also true that this is what makes the United States the most industrialized and prosperous country in the world. Unfortunately, a large amount of the energy is wasted. The National Bureau of Standards estimates that approximately 40% of the energy used for heating is wasted while energy requirements for cooling can be reduced 30% with little sacrifice to comfort. Energy conservation must become a part of construction technology. There should be an energy standard which will eliminate the wasting of our precious energy resources, but which is workable, allows for creative engineering and has adequate technical review in its creation.

In 1973, the National Conference of States on Building Codes and Standards (NCSBCS), the organization of state building code officials, requested from the National Bureau of Standards (NBS) guidelines on energy conservation which could be incorporated into the various state building codes. In turn, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) was requested by NBS to sponsor the standard on an interim basis and later as a standard of the American National Standards Institute (ANSI) through its consensus procedures.

NCSBCS was wise to seek informed answers to the problem which confronted it as a result of the energy crisis. Too often, in the past, professional and technical organizations have not been asked to be involved or even consulted. There have been and are proposed many standards governing heating and air conditioning which are either being prepared or being proposed with good intentions, but with far less than a full understanding of the full impact of these. Proposals such as shutting down all air conditioning systems whenever the ambient outside temperature is below 75°F show lack of understanding of the technology involved, since they ignore the efficiency and comfort of the building occupants.

In February 1974, NBS presented its finished document[1] to ASHRAE in an effort to obtain broad-based, professional support and endorsement. Such was not forthcoming; however, ASHRAE did accept the responsibility of either re-writing the NBS proposal or providing an alternative standard which ASHRAE membership would support. In late June, Proposed Standard 90P[2] was submitted to public review. The review was quite extensive[3-6] The result has occasioned major revision of 90P and its re-issuance for another round of public inspection. The current version of the proposed ASHRAE Standard 90P, ENERGY CONSERVATION IN NEW BUILDING DESIGN, sets forth requirements for the design of all types of new buildings, covering their exterior envelopes and selection of their HVAC, service water heating, electrical distribution and illuminating systems and equipment for efficient use of energy.

ASHRAE has not been the only source for suggested energy standards or legislation[7,8]. National focus however, appears to reside with the ASHRAE effort. In 1973 only two states had passed legislation regulating energy in construction. Today, however, 38 states have ongoing activity related to energy conservation for buildings. At the present time seven states are considering their own energy document for implementation within their state. However, they indicated that if the ASHRAE document becomes available soon, they could consider changing from a state-developed document to the ASHRAE document. The remaining states have stated that they will wait for the ASHRAE energy standard if it is forthcoming within a reasonable length of time. It will not be long until all 50 states have legislation regulating energy in the construction field in new and existing buildings. It becomes extremely important that a national document be developed, adopted, and implemented to achieve a uniform approach to energy conservation.

2. PRESCRIPTIVE VERSUS PERFORMANCE CODES

If there is widespread realization of an energy problem, why the delay in executing a standard? One reason is the existence of two conflicting theories on how one conserves energy.

One group advocates a prescriptive type of code under which all building components influencing energy consumption would be individually specified. For example: "Glass areas shall constitute no more than xx% of outside wall areas." Prescriptive codes have advantages. They are familiar to designers, specifiers and building inspectors. They provide a go-and-no-go gauge on which even relatively inexperienced men can base approvals. However, prescriptive codes have serious drawbacks and could have a negative impact on the industry and on growth within the industry. A typical example would be a requirement for a specific thickness of insulation, which would eliminate the economic advantages of developing more effective insulating materials.

The second group favors an overall energy consumption budget for buildings expressed in Btu/sq.ft. of floor area/yr. Obviously, no single budget figure would be applicable to all types of buildings. These budgets would vary according to geographic area and conditions of occupancy and use. This group argues that the prescriptive approach to this particular problem rests on a dangerous assumption, to wit: "Maximum energy conservation will result from proper specification of each component." But, this group argues, when the HVAC, mechanical, lighting systems and the building shell, each with its own set of governing criteria, are considered to be unrelated, trade-offs between those segments would be disallowed. Without such trade-offs, maximum reduction of energy consumption may be impossible to achieve.

A discussion of as complicated a subject as trade-offs between one building system (e.g. lighting) and another (e.g. the building shell) is apt to be cloudy unless it is illustrated with specific examples.

Considering the U value of glass versus the U value of insulated masonry walls, would not the total energy consumption of the building have necessarily been lower if the glass area had been reduced? A study of energy consumption in 13 prestigious Chicago buildings, published in the September, 1974 issue of ARCHITECTURE PLUS, provides some clue to the answer.

These buildings average an annual energy usage of 264,000 Btu/sq.ft./yr. The highest energy user was found to be an older concrete building with clear glass area less than 50% of wall area, using 330,000 Btu/sq.ft./yr. The lowest energy user was the IBM Building, with reflective glass area more than 75% of wall area, using 141,000 Btu/sq.ft./yr.

The facts cast doubt on the simplistic solution of arbitrarily restricting glass area. Energy budget design quantifies and evaluates both mechanical and non-mechanical building systems in terms of their impact on overall annual fuel consumption. The energy budget provides design freedom in the case of new buildings, operating energy levels for upgrading and renovation of existing buildings, and automatic provision for the incorporation of new technologies and energy sources without necessitating standards revision.

The objection most often raised to adopting standards or legislation which include energy budgets, is a lack of hard data establishing realistic consumption levels. If the national objective is to have buildings of the future consume xx% less energy than existing buildings, proponents of the energy budget approach urge that the logical way to proceed is to find out from what base figure the reduction is to be made. There have been spot checks on energy consumption in existing buildings, but what is needed is a meaningful national data bank on a great number of buildings by location, type, and conditions of occupancy and use. The center for Building Technology, National Bureau of Standards, is now working toward that objective at the behest of the Federal Energy Administration. If it is decided that, in new buildings, a reduction in energy consumption of xx% is both attainable and dictated by the energy situation, an annual overall energy budget for each new building may be derived from such a data bank. The proponents of energy budget codes feel that each team of architects and engineers should be permitted to design within the limits of their assigned budget in any way their ingenuity and capability suggests. The national objective of energy conservation will have been served.

ASHRAE Standard 90-P, in its present form, attempts to mediate both approaches. The concluding chapters allow the designer some flexibility in an otherwise restrictive standard. The code would require all new residential, commercial, and institutional buildings to conform to the numerical values specified, for the structure and the mechanical systems, unless the designer has some better ideas. He will be permitted to deviate from the standards if he can show that the annual energy consumption will be no greater than if he had followed the standards. To prove this he must draw up a full-year energy usage analysis for the structure which conforms to the standard, and another analysis for his proposed deviations.

The second major reason for delay in establishing the standard, and probably the most troublesome difference of opinion to face ASHRAE, has been the "source energy" question. ASHRAE in developing 90P side-steps the issue on the grounds that the best expertice in the power generation field exists outside ASHRAE and that the source energy problem is thus best addressed by others. The standard "takes into account energy losses and efficiencies connected with new buildings *within the boundary of a contiguous area* under one ownership. It does not take into consideration the energy used in the extraction, processing and delivery to the building site of the basic fuels or secondary forms of energy." Hence, the current version of Standard 90 limits the subject of energy conservation to the "building line"; that is, it treats all energy sources without reference to the energy required to deliver them to the building.

3. CURRENT STATUS OF ASHRAE STANDARD 90

ASHRAE Standard 90-75 consisting of the following eleven sections was approved by the society's board of directors on August 11, 1975 and is now an official ASHRAE Standard:

1.0 PURPOSE
2.0 SCOPE
3.0 DEFINITIONS
4.0 EXTERIOR ENVELOPE
5.0 HVAC SYSTEMS
6.0 HVAC EQUIPMENT
7.0 SERVICE WATER HEATING
8.0 ELECTRICAL DISTRIBUTION SYSTEMS
9.0 LIGHTING POWER BUDGET DETERMINATION PROCEDURE
10.0 ENERGY REQUIREMENTS FOR BUILDING DESIGNS BASED ON SYSTEMS ANALYSIS
11.0 REQUIREMENTS FOR BUILDING UTILIZING SOLAR, WIND OR NON-DEPLETING ENERGY SOURCES

However, responding to pressure from groups condemning the building line approach, a special ASHRAE Presidential Committee was appointed to deal with the source energy question. This committee has recommended the addition of a twelfth section on source energy, informally called "RUF-RIF." The purpose of Section 12, ANNUAL FUEL AND ENERGY RESOURCE DETERMINATION, is "to provide a method for reporting the calculated annual burden that a proposed building would place on available fuel and energy resources." The major contents of this proposed section are: (1) a requirement that a report be made on the impact of the building on the nation's energy sources, (2) a table of Resource Utilization Factors (RUF) which gives losses and energy burdens involved in processing, transporting, converting and delivering various forms of energy to a building, and (3) the concept of Resource Impact Factors (RIF) to account for the relative desirability of using one fuel or energy resource over another in a particular location. ASHRAE would not provide RIF numbers. Section 12 was published in the July issue of the ASHRAE Journal for open review and will probably not be finalized until sometime in 1976.

There are no enforcement provisions in ASHRAE Standard 90-75. This document contains a codified list of design recommendations which can be adopted by state and local building authorities, and enforcement would be at those levels, where it is incorporated into law.

4. EXAMPLE OF EFFECT OF STANDARD 90 ON RESIDENTIAL ENERGY REQUIREMENTS

In order to roughly assess the degree of change in building construction and energy usage for compliance with the requirements of 90P, load and energy calculations consistent with ASHRAE procedures and using the AXCESS Energy Analysis Program were made on a relatively typical residence (patterned after an actual house). Details of the basic residential structure are given as Figure 1.

Excerpts from the applicable sections of Standard 90P are as follows:

4.2.3 For estimating heat loss or gain through the exterior envelope of the building the following design temperatures shall apply:

	Indoor	Outdoor
Winter	70F	97½%
Summer	80F	2½%

4.3.1.1 Equation 1 shall be used to determine acceptable combinations of wall, window and door areas, and thermal properties to meet the requirements of Table 1 ...

Equation 1

$$U_o = \frac{U_{wall} A_{wall} + U_{window} A_{window} + U_{door} A_{door}}{A_o}$$

Table 1

ONE, TWO AND MULTI-FAMILY RESIDENTIAL LOW RISE

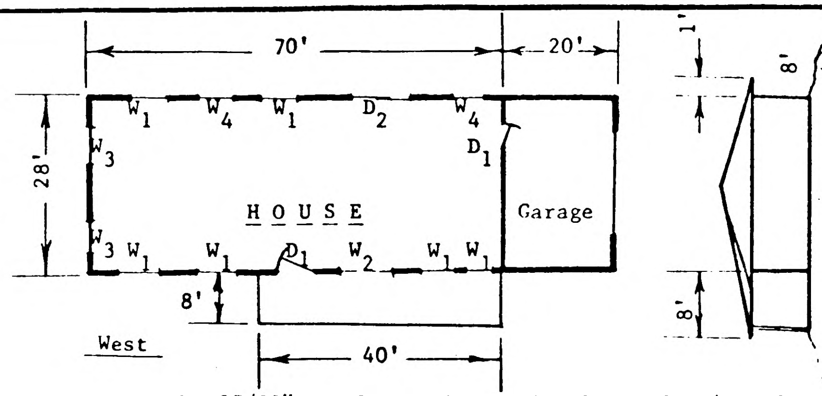
Heating Degree Days	Max.-U_o-Walls Btu/hr ft^2 F
⋮	⋮
5000	0.23
⋮	⋮

4.3.2 The thermal transmittance value for the roof/ceiling shall not exceed a value of U_o = 0.05 Btu/hr ft^2 F.

5.3.2.4 Infiltration

Unless specifically calculated otherwise, heating and cooling design load

BASIC PLAN:



Wall Construction: Face Brick, 25/32" insulating board sheathing, 2 x 4 studs on 16" centers, 3/8" gypsum board interior.

Ceiling: 2 x 6 ceiling joists, 16" oc, no flooring above, 3/8" gypsum board ceiling.

Roof: Asphalt shingles on solid wood sheathing, 2 x 6 rafters, no insulation between rafters, no ceiling applied to rafters, 1:4 pitch, 1 ft overhang on eaves, no overhang on gables.

Full basement: Heated, 10" concrete walls, all below grade, 4" concrete floor over 4" gravel.

One fireplace in living room on first floor.

Garage: Attached but unheated.

Windows: W_1 - 3' x 5' single glazed, double hung wood sash, weather stripped with stormwindow
W_2 - 10' x 5 1/2' picture window, double glazed, 1/2" air space
W_3 - 5' x 3' wood sash casement, double glazed, 1/2" air space
W_4 - 3' x 3' wood sash casement, double glazed, 1/2" air space

Doors: D_1 - 3'0" x 6'8", 1 3/4" solid with glass storm door
D_2 - Sliding patio glass door, two section, each 3' x 6'8", double glazed, 1/2" air space, aluminum frame

FIGURE 1 - BASIC PLAN FOR RESIDENTIAL TEST BUILDING

determinations for the entire structure shall include infiltration at the rate of no more than 0.7 air changes per hour for one and two-family dwellings..

5.4.2 Humidity Control

If an HVAC system is equipped with a means for adding moisture, to maintain specific selected relative humidities in spaces or zones, an automatic, space-humidity control device shall be provided. This device shall be capable of being set to prevent new energy from being used to produce space relative humidity above 20 percent RH.

In relation to the basic residential structure of Figure 1, the 90P requirements for insulation would correspond to approximately 7 inches of glass-fiber ceiling insulation but only 1/3 inch glass-fiber wall insulation due to the use of double glazed or storm windows and insulating sheathing.

The results of the load analysis are shown in Table 1 and indicate that compliance with 90P would result in considerable decrease in both furnace and air-conditioner *size* from that required for a poorly insulated residence. On the other hand, the results also show that with readily available and relatively inexpensive insulation (R = 11 for walls and R = 11 or 23 for ceilings) it is possible to better the 90P requirements.

The results shown in Table II are more significant as they reflect the *energy requirements* of the residential heating and cooling systems. Again, there is considerable savings when complying with 90P over a poorly insulated structure and yet it is very possible to do even better with standard materials on the market. Energy usage for a residence constructed in accordance with 90P would be cut almost in half for heating and by one-third for cooling compared with an uninsulated and non-weatherstripped structure. Heating and cooling energy requirements could be cut additional 17% and 5%, respectively, if nominal "full" insulation

TABLE I - EFFECT OF CONSTRUCTION ON RESIDENTIAL DESIGN LOADS		
CONSTRUCTION	HEATING Design Load, Btuh	COOLING Design Load, Btuh
ASHRAE Standard 90P (Base)	42,000	34,000
0 Ceiling Insulation 0 Wall Insulation 1.5 AC/hr Infiltration	88,000	59,000
0 Ceiling Insulation 0 Wall Insulation 0.7 AC/hr Infiltration	72,000	52,000
0 Ceiling Insulation 3½" Wall Insulation (R=11) 0.7 AC/hr Infiltration	60,000	48,000
2" Ceiling Insulation (R=7) 3½" Wall Insulation (R=11) 0.7 AC/hr Infiltration	43,000	36,000
4" Ceiling Insulation (R=11) 3½" Wall Insulation (R=11) 0.7 AC/hr Infiltration	41,000	34,000
7" Ceiling Insulation (R=23) 3½" Wall Insulation (R=11) 0.7 AC/hr Infiltration	37,000	31,000
DESIGN CONDITIONS Location: St. Louis, Mo. Outdoor: WINTER; 8°F db (97½% value) SUMMER; 95°F db, 78 F wb (2½% values) Indoor: WINTER; 70°F db, 20% relative humidity SUMMER; 78°F db, 65% relative humidity		

were used in the walls.

ASHRAE Standard 90 "does *not* incorporate specific procedures for the *operation,* maintenance and use of buildings." Thus, although the system is designed for indoor temperatures of 70°F in winter and 78°F in summer, the thermostat could still be set at other values. Since the outdoor design values (97½% and 2½%) are equalled or exceeded only 129 hours during the year, a system sized in accordance with 90P would be able to maintain 75°F an estimated 90+% of the time. Table III presents a comparison of the fuel requirements for heating for thermostat settings of 70°F and 75°F. For the insulated cases shown, the averate savings in fuel is about 2½% for each degree the thermostat is lowered. Table IV gives the effects of thermostat settings of 78°F and 75°F on the cooling energy requirements. For an insulated residence, the average energy savings for cooling is about 5 percent for each degree increase in thermostat setting.

5. CONCLUSIONS

In the time span of a few years, the majority of states will probably have energy conservation laws relating to building construction. It is imperative that this legislation be based on more than just good intentions. What is needed is an energy

TABLE II - EFFECT OF CONSTRUCTION ON RESIDENTIAL ENERGY REQUIREMENTS				
CONSTRUCTION	HEATING		COOLING	
	Gallons	% Change	Kw-hrs	% Change
ASHRAE Standard 90P (Base)	759	0	5424	0
0 Ceiling Insulation 0 Wall Insulation 1.5 AC/hr Infiltration	1487	+96	7232	+33
0 Ceiling Insulation 0 Wall Insulation 0.7 AC/hr Infiltration	1203	+58	7071	+30
0 Ceiling Insulation 3½" Wall Insulation (R=11) 0.7 AC/hr Infiltration	1010	+33	6617	+22
2" Ceiling Insulation (R=7) 3½" Wall Insulation (R=11) 0.7 AC/hr Infiltration	747	-2	5566	+3
4" Ceiling Insulation (R=11) 3½" Wall Insulation (R=11) 0.7 AC/hr Infiltration	687	-9	5342	-2
7" Ceiling Insulation (R=23) 3½" Wall Insulation (R=11) 0.7 AC/hr Infiltration	628	-17	5126	-5

OPERATING CONDITIONS
Location: St. Louis, Mo.
Year: 1971 Hourly Weather Data
Indoor: WINTER; 70°F db, 20% rh
SUMMER; 78°F db
CAC-continuous fan operation

HEATING
#2 Fuel Oil: 139,000 Btu/gallon
80% seasonal efficiency

COOLING
EER=6.84 Btuh/watt
(exc. main blower)

standard which will eliminate the wasting of our precious energy resources, but which is workable and allows for creative engineering and architecture. ASHRAE Standard 90 does provide a set of criteria consistent with available technology and materials which will result in substantial energy savings without being unduly restrictive.

6. POSTSCRIPT

On October 20, 1975, after the above paper was presented, ASHRAE Standard 90-75 was officially released. Two changes over the 90P contents which affect the results shown in this paper are: (1) Indoor winter design conditions are now 72°F db and 30 percent maximum relative humidity; and (2) an infiltration limit of 0.7 AC/hr is not specifically required.

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TABLE III - EFFECT OF THERMOSTAT SETTING ON ENERGY REQUIREMENTS (HEATING)

INDOOR TEMPERATURE / CONSTRUCTION	70°F		75°F	
	Gallons	% Change	Gallons	% Change
ASHRAE Standard 90P (Base)	759	0	873	+15
4" Ceiling Insulation (R=11) 3½" Wall Insulation (R=11) 0.7 AC/hr Infiltration	687	-9	786	+4
7" Ceiling Insulation (R=23) 3½" Wall Insulation (R=11) 0.7 AC/hr Infiltration	628	-17	715	-6

OPERATING CONDITIONS
Location: St. Louis, Mo.
Year: 1971 Hourly Weather Data
CAC-continuous fan operation

HEATING
#2 Fuel Oil: 139,000 Btu/gallon
80% seasonal efficiency

TABLE IV - EFFECT OF THERMOSTAT SETTING ON ENERGY REQUIREMENTS (COOLING)

INDOOR TEMPERATURE / CONSTRUCTION	78 F		75 F	
	Kw-hrs	% Change	Kw-hrs	% Change
ASHRAE Standard 90P (Base)	5424	0	6472	+19
4" Ceiling Insulation (R=11) 3½" Wall Insulation (R=11) 0.7 AC/hr Infiltration	5342	-2	6279	+16
7" Ceiling Insulation (R=23) 3½" Wall Insulation (R=11) 0.7 AC/hr Infiltration	5126	-5	5981	+10

OPERATING CONDITIONS
Location: St. Louis, Mo.
Year: 1971 Hourly Weather Data
CAC-continuous fan operation

COOLING
EER=6.84 Btuh/watt
(exc. main blower)

8. BIOGRAPHIES

Harry J. Sauer, Jr. is Professor of Mechanical and Aerospace Engineering at the University of Missouri-Rolla. He holds the B.S. and M.S. degrees from the University of Missouri and the Ph.D. from Kansas State University. Dr. Sauer has been active in the environmental control field for over 17 years. He has been a member of ASHRAE since 1963 and serves on several national committees of the society.

Ronald H. Howell is Professor of Mechanical Engineering at the University of Missouri-Rolla. He holds the B.S., M.S., and Ph.D. degrees from the University of Illinois. Dr. Howell has taught and conducted research in refrigeration, heating and air-conditioning for over 15 years. He became a member of ASHRAE in 1969 and serves on several national committees of the society.

THE ENERGY CONSERVATION IMPLICATIONS OF MASTER METERING OF ELECTRIC SERVICE IN APARTMENTS

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Abstract

A study has been made of the difference in electricity usage between residents of "Electricity included" apartments and those tenants who pay individual "light bills." The factors which influence owners' and builders' choices of metering service are discussed in detail.

Data taken from over 100 apartment buildings or complexes in 10 major U.S. metropolitan areas and from over 50 major electric power companies are used as the basis for the reported results. Contractors estimates of the costs to convert building service from master to individual meter and some bases for these costs are presented.

The energy conservation potential which might be realized through nationwide elimination of master metering is discussed.

1. INTRODUCTION

The purpose of this report is to compare the electric energy consumption in apartments which receive electricity through master meters with those which receive electricity through individual meters. The report will show the extent of residential master metering in 10 major U.S. cities and will discuss the factors influencing the choice of master metering. It will also give estimates of the national implication of the target city results.

The practice of master metering of electric service to apartments often allows the sale of electricity to a building or complex at wholesale rates which are usually justified by the utility company by the requirement for only one meter, one reading, and one bill for the sale of a large quantity of electricity. Furthermore, the electric utility company need not supply electrical distribution systems for the buildings. The usual alternate metering practice is individual metering.

An early review of master metering and of attitudes toward it was given by Neuhoff[1]* in 1965. The subject of master metering was addressed by the U.S. Department of Housing and Urban Development as early as 1962.[2] In addition to these two published reports, there are numerous anecdotal reports and unwritten guidelines within the electric utility industry which deal with the subject.

Master metering of residential space was relatively rare until World War II. Before that time most residential electrical service was delivered through an individual meter for each dwelling unit or was unmetered and sold for a flat monthly fee. It is not clear just when or where the practice of master metering of residences began but some of the earlier master metered apartment buildings were in Dallas, Texas, about 1950.

The growth of master metering was rapid in the 1950's as the rush to build apartments following World War II produced local over supplies, which, in turn, led to stronger competition for tenants.

* References are listed at the end of this report.

Apartment owners offered free moving of furniture, and even "free" utilities to attract tenants. Later, in the early 1960's, many electric utility companies began to feel the competition of Total Energy systems which were being promoted by the natural gas companies. They responded with promotional rate schedules offering markedly reduced electricity rates to large users, thus encouraging the bulk purchase of energy for apartment complexes. Costs per kilowatt hour under these promotional schemes were as little as one-fourth the prevailing rate for individual residences. As the cost of electricity thus became nearly negligible, many apartment and office operators took advantage of the "All Utilities Included" marketing scheme.

The master metering concept has, on the surface, elements of economic attraction for all participants. For the landlord or building owner, the block rate structure for utility services appears to offer the opportunity to purchase the same amount of electricity as would be consumed by all his tenants for less cost by his acting as a single customer. For the utility, a master meter installation reduces installation costs as well as monthly meter reading costs. It seems like a situation in which everyone benefits. However, when individual tenants no longer have monthly feedback and an economic incentive for conservation of electricity usage, their consumption usually increases. This extra consumption is held to be common knowledge by some utility marketing personnel and reported ratios of consumption by master metered versus individually metered customers range from 1.88 (Neuhoff[1]) to 1.33 (HUD[2]). Utility company load planners use ratios of from 1.15 to 1.35 for planning load requirements for master metered apartment buildings.

When utility company tariffs permit* a choice of metering in an apartment building the choice is usually made on the basis of a balance between several factors. Among them are electrical wiring costs and utility rate structures. These factors are, in turn, affected by various other factors discussed below.

Initial electrical wiring costs for an apartment building depend on the choice of metering used as well as on local building codes. Individual metering requires separate electrical feeders to each apartment, separate meter sockets, and individual meters. In most cases, much of the cost of distribution within the building is borne by the building owner. Master metering would allow elimination of many of the separate items needed for individual metering.

The share of cost of internal distribution which must be borne by the builder and whether this cost will be in favor of master or individual metering depends on utility company policies which vary widely.

Many utility companies offering service to groups of apartments under general service rates make the group service much less expensive than the total cost of individual services. The greater this difference, the more master metering is encouraged. The utility company can increase the spread between commercial and residential (individual) rates to encourage master metering if, for example, if prefers to minimize the number of customers it must deal with.

A comparison of average monthly electric bills which might apply to apartments in the various areas covered in this report is shown in Table I. The values shown include fuel adjustments but not taxes and were effective at the end of 1974. The bills would be somewhat smaller, of course, in apartment houses where certain services such as heating and air conditioning were supplied in such a way as not to appear in the monthly electric bill. Furthermore, the numbers, while showing the expected cost per apartment for electric service, are not meant to imply that the renter would be paying this amount. The electric bill might be included in the rent.

The master metered electric bills shown in Table I include approximately one-third higher usage which has been found to apply to persons receiving electricity via master meters. Under these conditions it should be noted that in only four of the service areas shown is the average charge per customer less under master metering than under individual metering and in four other areas the average bill even with 100 apartments per meter is higher for master metering than for individual metered service.

The factors of wiring costs and utility rate structures influence the selection of master metering service or individual metering service by apartment builders and owners. However, the relative importance of these various factors has been undergoing rapid changes during the past year. Utility costs

* Not all utilities permit master metering. For example, Commonwealth Edison, Company of Chicago, completely prohibits master metering for residential use and greatly restricts it for office use.

have been rising rapidly with commercial rates leading residential rates in the increases. The gap between residential and commercial rates is thus closing. Furthermore, the increased resistance to rent increases often provided by rigid rent controls has placed the owner or operator of apartments in a severe profit squeeze.

2. METHODOLOGY

This section explains the assumptions made and the various bases used for the calculations and conclusions presented in the report. The section will also discuss methods of data collection and processing.

2.1 ASSUMPTIONS

Preliminary and informal investigations prior to the beginning of this study revealed that master metering was a phenomenon found almost entirely in urban areas. It was therefore assumed that any energy consumption implications of the practice of master metering would be adequately revealed and evaluated from a study of urban buildings.

It is well-recognized that the entire collection of factors which determine the energy consumption by individual apartments or offices is too extensive and variable to be considered seriously in a comparison study. Certain factors however are well-recognized as predominant. In addition to the energy use habits of occupants, five factors--location; physical attributes of the building; heating, ventilating and air conditioning (HVAC) equipment; size and number of dwelling units; and the status of the occupants--are assumed to dominate in determining the energy use of an apartment. These five factors were assumed to be sufficient for the identification of pairs of matching apartments. It was further assumed that if pairs of apartments were matched as nearly as practicable on the basis of these five points, then differences in use habits of the tenant would be revealed by comparing the monthly consumptions of electricity between the two apartments in each pair.

2.2 SELECTION OF TARGET CITIES, UTILITY COMPANIES AND APARTMENTS

Table II shows a list of the U.S. Standard Metropolitan Statistical Areas (SMSAs) studied. Some information contained in the report was also obtained in Kansas City, Missouri.

The urban areas studied were selected primarily by size. The utility companies were chosen, somewhat arbitrarily, with the intent of obtaining information from the company which served the larger part of the principal city in the metropolitan area. Apartment houses were chosen within the utility trade areas on the basis of availability of owner information and on the requirement that only reasonably matched pairs of individual and master metered buildings could be used. Instances of metering conversion were identified by the utility companies and were included in the study on the basis of the owner's or manager's willingness to cooperate with the study. After the selection of apartment houses, individual apartments were selected for inclusion in the study on the basis of continuous occupancy for at least 12 months prior to the collection of data. Various sizes of apartments (i.e., number of bedrooms) in each complex were sampled.

The method of selection of cities, apartment buildings, apartments within buildings and utility companies does introduce a potential bias in the estimates. Such a potential bias is an inevitable consequence of real world data collection.

2.3 DATA COLLECTION

Data collection for the study was performed through correspondence with utility companies, public utility commissions, and electrical contractors; and through meetings with apartment owners and managers, and with rate and load study personnel of utility companies. We also examined kilowatt-hour records of selected tenants.

The kilowatt-hour records for individually metered apartments were obtained by fractional sampling of the individual apartments in a building or complex. The consumption information thus obtained was used to estimate the usage for the entire complex. The house meter consumption information which covers all public areas, owner's apartment, and other electrical services not indicated by the individual aparrment meters was supplied by the owners or managers.

Energy consumption information on master metered apartments was obtained either directly from managers' or utility records.

Information on the comparison attributes of different apartment complexes (such as types of heating and cooling equipment, appliances and furnishings) and information on the public facilities provided (such as swimming pools), was obtained both by interviews with the manager and by personal inspection of the facilities.

When available, apartments where metering has been coverted from master to individual or visa versa provide an idealized form of matched pair. Weather differences which might exist during the time involved before and after the conversion process and changes in the character of the apartment operation after the conversion were considered in these cases. The latter factor was avoided by eliminating from the selection of apartments where conversion was accompanied by rearrangement of space and numbers of units. Weather effects were considered through the use of records of degree days heating and cooling during the years before and after a conversion. This factor is discussed below.

2.4 STATISTICAL DISCUSSION

Electric energy consumption in apartment buildings is a complex function of many variables of which metering technique is only one. Although this function cannot be described mathematically, one can attempt to hold all of the other variables constant while varying only the metering technique and thus observe the relationship between metering technique and electric energy consumption. Aside from metering technique, it is assumed that the five factors named above under "assumptions" are significantly related to electric energy consumption in apartment buildings. Other factors involved in electric energy consumption in apartment buildings are assumed to be either insignificant or to overlap with the five chosen comparison factors.

Table III shows a summary of the kilowatt-hour consumption for the apartment complexes studied. The statistical task at hand is the estimation of the average ratio of master metered electricity consumption per apartment per month (M) to individually metered electricity consumption per apartment per month (I).

Preferred computation of consumption ratio. The nonrandom selection of the sources of these values lends statistical preference[3] to the use of Equation (1) for determining the ratio, R_1, of M/I.

$$R_1 = \frac{\sum_{i=1}^{N} M_i}{\sum_{i=1}^{N} I_i} \qquad (1)$$

where i = identifies the i^{th} apartment of a pair

N = is the total number of pairs;

instead of the form:

$$R_2 = \frac{1}{N} \sum_{n=1}^{N} R_n \qquad (2)$$

where R_n = the consumption ratio M_n/I_n of the n^{th} pair

The use of Equation (1) gives a consumption ratio which is weighted by the number of apartments whereas Equation (2) gives a ratio weighted by the number of buildings.

In the use of data from Table III to compute a consumption ratio, R_1, by Equation (1) a problem arises when the numbers of apartments in the two members of the pair do not match--see, for example, Philadelphia, where 279 master metered units must be compared to a sample of 31 individually metered units. In such cases the geometric mean of the two sample numbers was used as a weighting factor. For Philadelphia this method gives a weighting factor of 93 (279 x 31 = 93) .

The ratio of consumptions computed by using Equation (1) is $R_1 = 1.35$.

Alternate computation of consumption ratio. If it is assumed that the values of average electric energy consumption in Table III are statistically valid for each city shown, one can estimate a ratio of master to individually metered consumption which is weighted by the actual extent of master metered usage (number of master metered units and average consumption per apartment unit for all units). This ratio is of the form:

$$R_3 = \frac{\sum_{i=1}^{N} N_i E_i r_i}{\sum_{i=1}^{N} N_i E_i} \qquad (3)$$

where N_i = the number of master metered apartments in the i^{th} city

E_i = the average electric energy consumption by an apartment (master or individual) in the i^{th} city

r_i = the ratio of electric energy consumption by master metered versus individually metered apartments in the i^{th} city

Application of Equation (3) to the data in Table IV gives a consumption ratio of 1.37 which is interestingly close to the ratio 1.35 obtained by Equation (1).

The ratio of 1.35 obtained by Equation (1) is statistically preferred because it requires fewer assumptions regarding the specific applicability of the data to each city. A statistical analysis of the reliability of this ratio was carried out according to methods for "analysis of variance of ratios" as described by Cochran.[3] This analysis is more complicated than that of a single set of data because of possible covariance between the elements of data comprising the ratio. The complete analysis yielded a variance of 0.005 which indicates a standard deviation of about 0.07 (for a mean value of 1.35 for the ratio).

In summary then, the mean ratio of master metered to individually metered consumption is 1.35 ± 0.07 (standard deviation). The 95% confidence limits on the result are 1.21 and 1.49 which indicates that there is only one chance in twenty that the excess consumption by master metered tenants is lower than 21%.

2.5 EXTENT OF MASTER METERING

A combination of methods was used to develop estimates of the current extent of master metering in the target cities, and to estimate the national extent of the practice. The methods combined information obtained from utility companies with data from the 1970 Census of Housing and from the Institute of Real Estate Management.

Utility company information pertains to the company's own service area which is not always coincident with the boundaries of the target SMSA. Therefore, it was necessary to develop a method of adapting utility company service and information on the extent of master metering to the metropolitan area boundary. In carrying out this adaptation it was assumed that (1) most of the multi-family housing and most of the total residential population served by the utility were both within the urban portion of the utility's services area, and (2) that the multi-family housing was uniformly distributed over the SMSA. Also the fact that the urban portion of the utilities service area was all within the SMSA for all target cities was used. This fact and the two assumptions allow the extension of multi-family and master metering data for the utility service area to the entire SMSA by use of a simple multiplier. That multiplier is the ratio of SMSA population to utility service area population. Table V shows the SMSA populations (1970), the service area populations (1970) and the population ratios used as multipliers for the target cities.

The adaptation of utility company data on the extent of master metering to the SMSAs only provides an estimate of the extent of master metering in the SMSAs studied. The assumption that this estimate is applicable to the entire nation requires (1) that the group of dwelling units covered is a statistically valid sample of all U.S. dwelling units, and (2) that the estimate agree qualitatively with estimates from other sources. Table VI shows the total numbers of dwelling units and the numbers of dwelling units in multi-family buildings in each target city (1970 Census of Housing adjusted to 1974). It also shows the numbers of dwelling units served by master meters.

The statistical validity of the sample (Assumption (1) above) is suggested by the facts that the total sample size (15,782,087) is about 23% of all U.S. dwelling units and that the sample is entirely urban thus covering the areas where most master metering is found. It is recognized, of course, that complete statistical validity would require a random sampling of all U.S. dwelling units in all multi-family buildings--a task for beyond the scope of this project and one of little probable benefit over the present method.

The agreement of the extent of master metering (29.5%) as measured in the present analysis with that from other methods is very good (Requirement (2) above). Analysis of data collected by the Institute of Real Estate Management for 10 federal regions[4] shows 31.5% master metering and analysis of the 1970 Census of Housing shows 34.1% master metering.

2.6 WEATHER EFFECTS

The weather contributes to variations in the energy requirements in housing through changes in wet and dry bulb temperatures, wind velocities, cloud cover, and solar effects. The year to year variations in energy consumption caused by weather changes must be considered in studying meter conversion cases because of the time difference between measurement periods. Methods which are available for precise calculations of the effect of weather on heating and cooling energy needs of dwellings require complete analysis of the construction and use patterns of the building being studied.

A simplified method, the so-called "degree-day method," makes approximate corrections for the effect of temperature on heating and cooling loads and is often used when, as in the present study, the architectural and living habit information required by more complete methods is not available. This method is based on the assumption that the annual heating and cooling requirements for a building are nearly proportional to the number of degree days* of heating and cooling occurring each year. Table VII shows the differences which are estimated to have occurred in both heating and cooling requirements between the master metered period of operation and the individually metered period of operation of the conversion cases. In five of the cases shown, the heating requirements were from 2 to 13% higher but the cooling requirements were from 11 to 27% lower during the master metered operations.

Since the data needed for a detailed analysis of weather effects cannot be obtained and the degree day method does not provide sufficient basis for analytical correction of energy use records, the results shown in Table VII were used only to provide a subjective test of the conclusions regarding energy use before and after meter conversion. In all cases the cooling load was lower during the master metered period. In two cases where electric heating was involved, the lowered cooling load was found to outweigh the higher heating load. Therefore, weather differences cannot account for the higher energy use during master metering.

3. CONCLUSIONS

The conclusions presented here include the effects of master metering in nine cities, the extent of master metering in multi-family housing in nine cities and the factors influencing the choice of metering. The information regarding the extent and effects of master metering in multi-family housing for the target cities is used to provide an estimate of the national effect of master metering. Confidence in the conclusions presented is increased by the fact that information from several sources is in agreement.

3.1 CONSUMPTION DIFFERENCES ASSOCIATED WITH MASTER METERING

The annual kilowatt-hour consumption for a number of apartment buildings and complexes in eight of the target cities and in Kansas City, Missouri, is shown in Table III. It is seen there that the ratio of the consumption by master metered customers to that of individually metered customers ranges from 1.08 to 2.69.

The average ratio of master to individually metered consumptions for this group of apartments is 1.35 with a standard deviation of 0.07. There is thus, only one chance in 20 that the waste by master metered users is less than 20%.

Treatment of the individual cities with their average residential electric consumptions and their master metering extents and waste factors considered on a city by city basis yields a slightly different overall waste factor; namely 37%. While the first factor, 35% is statistically preferable as discussed in Section 2 (Methodology), the second factor, 37% has the advantage of being responsive to the city-to-city variations in extent and effect of master metering and to the rate of electric energy consumption in each city.

3.2 THE EXTENT OF MASTER METERING

The various factors used in determining the extent of master metering practice in the target cities is shown in Table VI. It can be seen that the extent of master metering of multi-family housing ranges from 18% to 77% in individual cities. For the combined population of the target cities it was found that 29.5% of all multi-family housing was master metered. This value is consistent with national estimates of 31.5% (obtained from IREM[4] data for 10 federal regions) and of 34.1% (obtained from state by state data from the 1970 Census of Housing) (three or more units per building). It is concluded that about one-third of all U.S. multi-family housing units are master metered.

3.3 FACTORS AFFECTING THE CHOICE OF METERING

<u>Initial wiring costs</u>. An accurate evaluation of the difference of cost in apartment construction which results from the choice between individual and master metering would require preparation of comparative bids for each building. This is usually not done. The decisions regarding the choice between individual and master metering are usually made before electrical wiring bids are prepared. The best available estimates of the difference in construction costs thus come from personal interviews with individuals in the electrical wiring trade.

* A degree day of heating (or cooling) is 24 hr during which the average dry bulb temperature is one degree below (or above) 65°F.

Initial wiring cost differences obtained from such interviews range from no cost difference in the Los Angeles area to $250 per unit in Washington, D.C. Kansas City contractors give values ranging from about $125 to $250 higher per individually metered apartment unit for both garden type and high-rise apartments. One Kansas City estimate which showed a range from $125 to $175 per unit higher cost for individual metering was based on a series of nearly identical, six-unit, garden apartment buildings in which the individually metered buildings cost from $750 to $1,000 higher per six-unit building that their master metered counterparts which were built at the same time. In the Washington, D.C. area, one new building of 250 units was estimated by its electrical contractor to have cost approximately $50,000 ($200 per unit) higher because of its individually metered construction. The most widely expressed estimate is about $200 per unit nationwide.

Retrofit wiring costs. A factor which does not apply to the initial choice of metering practice in a building but which can influence an owners' decision to convert to other metering styles is the cost of retrofitting for a change in metering--a small cost if the change is from individual to master metering. The costs of conversion from master to individual metering are influenced by several factors. First, those buildings which have been wired at minimum cost during construction usually have apartments and building services sharing feeder lines are more complicated to rewire for individual service. Second, older styles of buildings in which the electrical wiring is buried behind plaster or other permanent wall construction are expensive to convert because of consequent structural work and refinishing.

The wide range of conditions which prevail in building prior to conversion causes the cost of conversion to individual metering to range from $100 to $1,200 per apartment unit. The costs of electrical labor and parts differ little from city to city so these conversion costs show no geographic preference.

Retrofit costs in the $100 range apply to buildings in which the initial construction provided separate feeder circuits to each apartment or situations in which meter loops were originally installed for each apartment and the conversion only requires minor circuit changes and installation of the meter socket. The higher conversion costs prevail in those apartments where minimum cost, intial wiring was originally installed. In such situations it is generally necessary to install new feeders to each apartment and to provide a separate set of circuits for the public areas of the building. It is also necessary to install meter sockets and load centers for each unit.

It is concluded from conversations with apartment owners that the cost of conversion is a major factor preventing more widespread conversion from master metering to individual metering.

Utility rate structures. Utility rates have been used to attract customers to certain sectors of the utility market. However, the results of the present study show that the correlation between the extent of master metered service and the rate structure of utility companies is small. Table VIII compares the cost differences between general service and residential services rates for apartments with the extent of master metering in eight cities. These data also are shown graphically in Figure 1. It may be seen that two cities which offer only a small rate advantage have the highest fraction of multi-family units with master metering. The remaining six cities show a weak correlation between rate advantage and the extent of master metering for larger apartment buildings (100 units). For all eight cities, the correlation coefficient is -0.27 and for the six cities without Washington, D.C., and Houston, Texas, the correlation coefficient is 0.36. Neither correlation indicates a significant effect of price differential on extent of master metering.

From this information it is concluded that utility rate structures have a minor influence on the extent of master metering but that other factors such as company promotional and marketing activities may override this influence.

The influence of public utility commissions on master metering. Table IX shows a summary of the rules and policies of state (and Washington, D.C.) regulatory commissions on the subject of master metering. None of the regulatory commission prohibits the practice of master metering in multi-family buildings. One state does prohibit it in mobile home parks. Thirty-four of the states reporting (including Washington, D.C.) specifically report having no regulation over master-metering and four states have no state regulatory body with jurisdiction over electric utilities. In some of these states, municipal ordinances provide utility regulation. At present, state regulatory commissions exert no control over the practice of master metering of electricity.

3.4 ENERGY CONSERVATION IMPLICATIONS OF MASTER METERING

It is shown above that about one-third of all dwelling units in multi-family housing are master metered. This fact coupled with census data and information from apartment studies[5] shows that there are about 4,433,000 master metered apartments in the U.S. The present study shows that each of these apartments used about 5,940 kwh (kilowatt-hours) of electric energy per year. If these units were converted to individual metering their consumption should decrease to about 4,400 kwh per year. The total saving during the next year would be about 7 billion kwh--equivalent to about 13 million barrels of oil. With present growth rates of apartment buildings per capita electric energy consumption the annual saving by 1990 would be about 14 billion kwh per year--equivalent to about 26 million barrels of oil. The cumulative saving by 1990 due to total conversion in 1976 would be about 134 billion kwh--equivalent to about 241.6 million barrels of oil.

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4. _1974 Income and Expense Analysis of Apartments, Condominiums, and Cooperatives_, Institute for Real Estate Management, Chicago, Illinois.

5. "Residential and Commercial Energy Use Patterns, 1970-1990," Report to the President's Council on Environmental Quality and the Federal Energy Administration, Arthur D. Little, November 1974.

Mr. Gross is a physicist with 25 years of experience ranging from basic research on materials (solid state electronics and physical bases of mechanical properties) to the application of physics and physics research methodologies to practical engineering and industrial problems. He received the B.S. degree in mathematics in 1947 and the M.A. in Physics (UMC) in 1949, and has pursued other graduate studies at the University of Kansas, the University of Missouri at Columbia, and at the Rheinische Westphalische Technische Hockschule (Aachen/Germany). Mr. Gross' current activities deal with the development of engineering and managerial methods for conservation of energy in buildings and industrial operations.

TABLE I

EXPECTED COST PER APARTMENT FOR ELECTRIC SERVICE IN SELECTED CITIES (1974)*

City and Company	Average Cost Individual Meter	Expected Cost per Apartment for 5, 50, and 100 Apartments per Master Metered Apartment Building** 5 Apartments	50 Apartments	100 Apartments
Los Angeles Department of Water and Power	$14.35	$17.28	$10.93	$ 9.29
Potomac Electric Power Company	21.75	35.80	26.33	25.66
Virginia Electric Power Company	20.84	31.13	19.80	17.60
Southern California Edison	16.85	20.99	20.66	20.66
Pacific Gas and Electric	11.40	14.98	14.98	14.98
West Penn Power Company	17.50	17.29	14.14	14.14
Duquesne Light Company	16.12	19.19	13.57	12.62
Philadelphia Electric Company	23.85	23.17	22.17	22.17
Houston Light and Power	19.66	25.43	18.25	18.25
Consolidated Edison	18.00	15.88	15.56	15.48
Boston Edison	17.07	21.48	19.31	19.31
Detroit Edison	18.37	13.26	9.31	9.16

* The amount shown is the cost (less taxes and plus fuel adjustments based on the 1974 data) for the average amount of energy consumed per residence in each city listed and in the various rate situations shown (i.e., individually metered dwelling unit, or small, medium or large apartment complex) where special winter rates are offered. The average of the summer and winter rates were used in this table. The average residential consumption is based on utility company (F.P.C. Form 1) data.

** The estimates used for apartments are based on evidence that master metered customers use one and one-third times the energy used by individually metered customers.

TABLE II

THE TARGET CITIES USED IN A STUDY OF APARTMENT ENERGY USE

(Ordered by Population) Target Cities (SMSA)	1970 SMSA Population
New York, New York	11,571,899
Los Angeles - Long Beach, California	7,032,075
Chicago, Illinois	6,978,947
Philadelphia, Pennsylvania - New Jersey	4,817,914
Detroit, Michigan	4,199,931
San Francisco - Oakland, California	3,109,519
Washington, D.C.	2,861,123
Boston, Massachusetts	2,753,700
Pittsburgh, Pennsylvania	2,401,245
Houston, Texas	1,985,031
Total	47,711,384

TABLE III

RELATIVE ELECTRICITY CONSUMPTION OF MASTER METERED AND INDIVIDUALLY METERED MULTI-FAMILY DWELLING UNITS

City	No. of Units	Consumption/Apt/Year, kwh	Dates of Metering	No. of Units	Consumption/Apt/Year, kwh	Dates of Metering	Ratio of Master to Individually Metered
Los Angeles	20*	3,456	Jan 73 - Dec 73	20	1,284	Jan 74 - Dec 74	2.69
	20*	1,968	Jan 74 - Dec 74	20	984	Jan 72 - Dec 72	2.00
	9*	2,868	Jan 74 - Dec 74	9	2,664	Jan 72 - Dec 72	1.08
Philadelphia	279	9,096	Nov 73 - Oct 74	31 of 250	5,676	Apr 74 - May 75	1.60
Detroit	44	2,904	Jan 74 - Dec 74	44	1,748	Jan 74 - Dec 74	1.66
	194	9,745	Jan 74 - Dec 74	140	6,338	Jan 74 - Dec 74	1.54
San Francisco	1,683*	3,105	Nov 72 - Oct 73	1,683	2,298	Nov 69 - Oct 70	1.35
Washington, D.C.	172 of 296	3,684	Jan 74 - Dec 74	24 of 264	2,880	Jan 74 - Dec 74	1.28
	76*	4,176	Jan 73 - Dec 73	76	2,736	Jan 74 - Dec 74	1.53
Boston	208	13,032	Jan 72 - Dec 72	37	11,196	Jan 72 - Dec 72	1.16
Pittsburgh	216	17,316	Jan 72 - Dec 72	92	13,368	Jan 72 - Dec 72	1.30
	144	16,788	Jan 72 - Dec 72	207	14,376	Jan 72 - Dec 72	1.17
	21*	4,438	Jan 71 - Dec 71	21	2,658	May 73 - May 74	1.67
	20*	4,440	Jan 72 - Dec 72	20	2,733	May 73 - May 74	1.63
Kansas City	155	10,168	Jan 74 - Dec 74	135	5,412	Jan 74 - Dec 74	1.88
Houston	6	15,000	Jan 72 - Dec 72	6	13,678	Jan 72 - Dec 72	1.10
	8	10,956	Jan 74 - Dec 74	8	10,070	Jan 69 - Dec 69	1.09
	60	14,124	Jan 72 - Dec 72	6	12,444	Jan 72 - Dec 72	1.14

* Metering service conversion.

TABLE IV

CONSUMPTION RATIOS,* NUMBERS OF MASTER METERED APARTMENTS, AND AVERAGE ELECTRIC ENERGY CONSUMPTIONS FOR APARTMENTS IN SEVEN MAJOR CITIES (1974)

City	Consumption Ratio*	Number of M-M Apartments	Average Electric Consumption** kwh/year
Los Angeles, California	2.11	166,880	2,078
Philadelphia, Pennsylvania	1.60	169,065	7,386
Detroit, Michigan	1.57	54,651	6,810
San Francisco, California	1.35	33,550	2,710
Washington, D.C.	1.33	342,750	3,378
Boston, Massachusetts	1.16	63,671	12,114
Houston, Texas	1.13	140,573	12,804

* Consumption ratio shown is average ratio of master to individually metered consumptions for all apartments studied in each city.

** Average electric consumption is the average for all master and individually metered apartments studied in each city.

TABLE V

TARGET CITIES AND UTILITY COMPANIES

(ordered by population) Target Cities (SMSA)	1970 SMSA Population	Major Electric Utilities Serving Target SMSAs	1970 Service Area Population	Population** Ratio
New York, New York	11,571,899	Consolidated Edison of New York	8,614,000	1.34
Los Angeles - Long Beach, California	7,032,075	Los Angeles Department of Water and Power, Southern California Edison	2,854,739	2.46
Chicago, Illinois	6,978,947	Commonwealth Edison Company	*	
Philadelphia, Pennsylvania-New Jersey	4,817,914	Philadelphia Electric Company	2,826,178	1.70
Detroit, Michigan	4,199,931	Detroit Edison Company	3,608,600	1.16
San Francisco - Oakland, California	3,109,519	Pacific Gas and Electric Company	5,062,096	0.61
Washington, D.C.	2,861,123	Potomac Power and Light, Virginia Electric and Power Company	1,357,907	2.11
Boston, Massachusetts	2,753,700	Boston Edison	1,601,559	1.72
Pittsburgh, Pennsylvania	2,401,245	Duquesne Light Company, West Penn Power Company	*	
Houston, Texas	1,985,031	Houston Lighting and Power Company	1,849,044	1.07
Total	47,711,384			

* Service area population not developed for utilities not supplying extent data.

** Population ratio developed to adapt master metering extent data for utility service area to the SMSAs.

Source: Electrical World, Director of Electric Utilities 1974-1975.

TABLE VI

EXTENT AND TRENDS IN MASTER METERING IN 10 CITIES

City	Year	Total Number of Dwelling Units	Number of Dwelling Units In M/F Structures+	No. of Units in M/M, M/F++ Structures	Percent of M/F Which are M/M
New York	1974	3,982,298	2,331,815	837,500	36
Los Angeles	1974	2,583,354	922,426	166,880	18
Chicago	1974	2,358,971	899,157	0	0
Philadelphia	1974	1,592,667	338,130	169,065	50
Detroit	1974	1,360,097	273,255	54,651	20
San Francisco	1974	1,203,324	421,543	33,550*	8
Washington, D.C.	1974	1,072,696	439,421	342,750	78
Boston	1974	914,747	326,994	63,671	19
Houston	1974	713,933	177,940	140,573	79
Totals	1974	15,782,087	6,130,681	1,808,640	29.5**

* San Francisco data were developed using Pacific Gas and Electric Co. figures for only the number of master metered multifamily units on their DM rate schedule.

** Percentages shown in totals row are computed from numbers in totals row and not from percentage rows.

\+ Multifamily.

++ Master metered

Sources: Data from 1970 Census of Housing; 1974 values are adjusted from 1970 by demolition and construction records. Data provided by utility companies.

TABLE VII

COMPARISON OF PERTINENT HEATING AND COOLING REQUIREMENTS FOR MASTER METERED PERIOD OF OPERATION FOR CITIES WHERE CONVERSION DATA WERE USED
(Estimated by degree days from Table V)

City	Case No.	Heating Difference of Master Metered Period Compared to Individually Metered Period	Cooling Difference of Master Metered Period Compared to Individually Metered Period
Los Angeles	1	none	26% lower
	2	10% higher	17% lower
	3	10% higher	17% lower
San Francisco	(no electric heating or cooling load)		
Washington, D.C.	2	2% higher	16% lower
Pittsburgh	3	(no electric heating load)	11% lower
	4	(no electric heating load)	27% lower

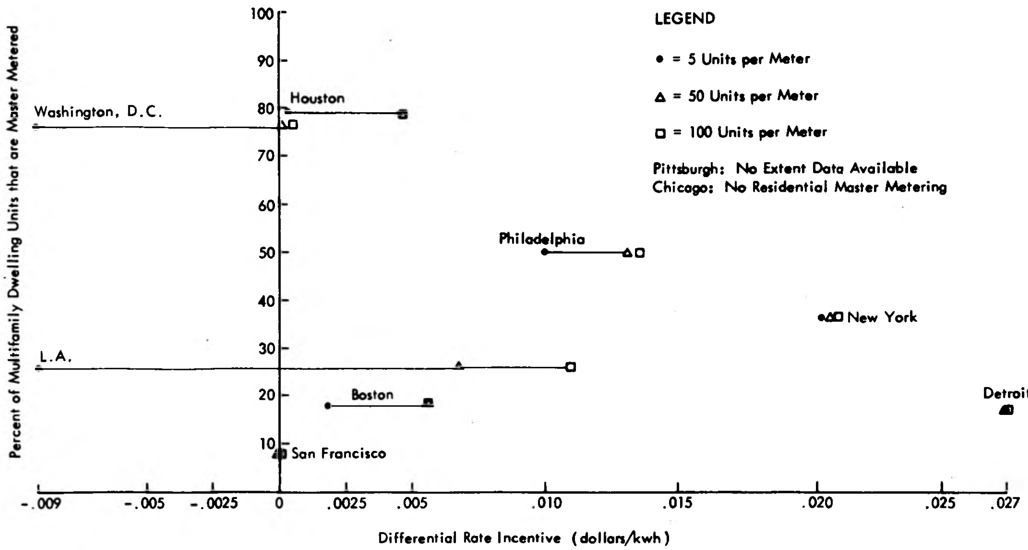

Figure 1 - Extent of Master Metering Versus Differential Rate Incentive (Residential Minus Master Metered Rate) Dollars/KwH for 5, 50, and 100 Dwelling Units per Meter

TABLE VIII

COST DIFFERENCE (PER KILOWATT HOUR) BETWEEN RESIDENTIAL AND COMMERCIAL RATES AND THE EXTENT OF MASTER METERING IN EIGHT CITIES

City	Utility	5-Unit*	50-Unit*	100-Unit*	Extent of Master Metering
New York	Consolidated Edison	0.0202	0.0210	0.0212	36%
Los Angeles	Los Angeles Dept. of Water & Power	(0.0089)**	0.0068	0.0116	26%
Philadelphia	Philadelphia Electric Company	0.0100	0.0135	0.0138	50%
Detroit	Detroit Edison	0.0270	0.0270	0.0270	17%
San Francisco	Pacific Gas & Electric	0	0	0	8%
Washington, D.C.	Potomac Electric Power Company	(0.009)**	0.0005	0.0015	77%
Boston	Boston Edison	0.0021	0.0058	0.0058	18%
Pittsburgh	Duquesne Light Co.	0.0036	0.0126	0.0141	No Info
Houston	Houston Light & Power	0.0005	0.0055	0.0055	79%

* The cost differences shown are the differences between the cost per kilowatt hour for average residential consumption (in the corresponding city) under residential rates minus the applicable general service rates for 5-, 50- and 100-unit master metered complexes.

** Residential cost less than 5-unit cost.

TABLE IX

SUMMARY OF STATE REGULATORY COMMISSION RULES AND POLICIES RELATED TO MASTER METERING

Category*	Number of States in Category
Not allowed	0
Prohibited in mobile home parks	1
Allowed	8
Discouraged	1
No regulation	34
No jurisdiction	4
No response	3

* Explanation of categories: Each category is exclusive in that it represents the total status of regulation in a state, e.g., discouraged means only that - it does not mean prohibited. The categories are:

Not allowed: Specific statements in correspondence with public utility regulatory officials indicate that the regulatory agency prohibits a practice.

Allowed: Specific statements in correspondence with public utility regulatory officials or existence of approved tariff fules for a utility in the state indicate that a practice is permitted.

Prohibited in mobile home parks: One state has a specific utility regulation which requires that each living unit (e.g., trailer) in a mobile home park be metered and receive its electricity from the utility company serving the area.

Regulated: Indicates that a practice (e.g., resale of electricity) is allowed but is subject to specific rules and regulations. The reseller is usually treated as a public utility and subjected to utility taxes, etc.

Discouraged: Specific statements in correspondence with public utility regulatory companies allow the practice in question. This position is much weaker than "not allowed."

No regulation: Specific statements in correspondence with public utility regulatory officials or a search of their published "rules and regulations" indicates that the state does not have a law or regulation pertaining to the item in question.

No jurisdiction: Specific statements in correspondence with public utility regulatory officials indicate that the state does not exercise regulatory authority over electric utilities.

No response: No response could be obtained from the state utility regulatory agency even after a followup letter.

SOLAR ASSISTED POWER SYSTEMS

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Abstract

Except for hydroelectric power, solar electric generation has not been widely used in the past to assist power system generation because of its relatively high cost. This situation has now started to change with the advent of the energy crisis as exemplified by decreasing natural gas supplies and increasing fossil fuel prices. One possible response to this situation which appears to have a relatively good chance for economic success is the utilization of wind and solar thermal energy for space and water heating loads served by natural gas or electric power. Unfortunately, a large portion of the energy collected in a typical solar heating system is lost because the received solar energy is variable and, in most cases, is not well correlated with collection site loads. This paper examines the feasibility of using the excess energy available from solar heating systems for electric power production so that power system peaking capacity and total fossil fuel consumption can be reduced. As solar electric generation becomes larger, energy storage systems will be needed to assure power system stability and reliability. At the solar collection site, thermal energy and chemical storage units in battery form are preferred. For large central energy storage facilities pumped hydro, compressed air, liquid ammonia, storage batteries, and liquid hydrogen systems are possible choices. The liquid ammonia storage system is considered the best overall choice when pumped hydro or compressed air are not feasible.

INTRODUCTION

Although it is possible to produce electrical energy from wind and solar radiation in substantial amounts, it still remains to develop economically competitive schemes for generating, storing, transporting, and utilizing this energy potential so that critical fossil fuel utilization rates may be reduced. Already, natural gas supplies have started to decline, and soon the energy needs served by this fuel will have to be shifted to other energy sources. Natural gas loads that can be shifted in some degree to solar energy include space heating and cooling, hot water heating, electrical power generation, and ammonia production. In response to higher fuel costs and in anticipation of the limited availability of natural gas, increasing numbers of solar energy heating and cooling systems are now being installed in homes, schools, and office buildings on an experimental basis. In addition, the installation of small wind turbine generators is becoming more commonplace. Unfortunately, solar systems of this type are not attractive from an economic point of view for the following reasons. First, solar energy collectors are expensive and require long term, high risk capital investment. Second, only a limited amount of collection site, energy storage capacity is feasible because of size and cost constraints. Third, a large fraction of the solar energy collected is usually lost due to the poor correlation between solar energy income and collection site load requirements. Although advances in solar collector design may help to reduce solar system energy costs in the future, it seems highly unlikely that this reduction will be greater than 10% to 15% on a relative basis. In view of this assessment, we feel that the most potentially productive approach to the problem of improving the economic position of distributed solar energy systems of this type lies in the storage and utilization of the solar energy collected that would otherwise be lost. By doing this we can help to reduce the cost of the collected solar energy and at the same time save fossil fuel supplies while using this excess energy to assist power system generation.

SOLAR POWER GENERATION

Although many different types of solar energy collection and conversion schemes are feasible, only the two most economically competitive systems are discussed in this paper. First, for wind energy collection and subsequent electrical generation, a horizontal axis wind turbine with a threshold wind speed of 10 mph and rated wind speed of 22.4 mph will be employed. Second, a rankine cycle heat engine generator using freon as a working fluid and being driven by excess heat from a flat plate solar collector will be used. A solar electric generation unit of the type being considered is shown in Figure 1. In this system some battery storage is included so that the solar electric generation can be delivered to the power grid during the period of peak load demand when other generation costs are high. In some cases local collection site battery storage may not prove feasible, and in this case all excess solar generation must be delivered when available to the AC power grid as shown in Figure 2. If the heat pump used for space heating and cooling is coupled mechanically to the heat engine generator as shown in Figure 2, then the induction motor used to drive the heat pump compressor can also be used as the generator for the heat engine. In this way the heat engine can assist space cooling in the most efficient manner and also deliver excess generation to the power grid through the same machine. Distributed solar electric generation units like those shown in Figures 1 and 2 as well as other electric generation make up what is called here a solar assisted power system. A block diagram of this system is shown in Figure 3. Included with this system is a peaking generation loop containing energy storage in the form of liquid ammonia. Note that the system above the dashed line has the flexibility to shift the production of ammonia fertilizer from natural gas to electrical energy obtained from off-peak fossil,

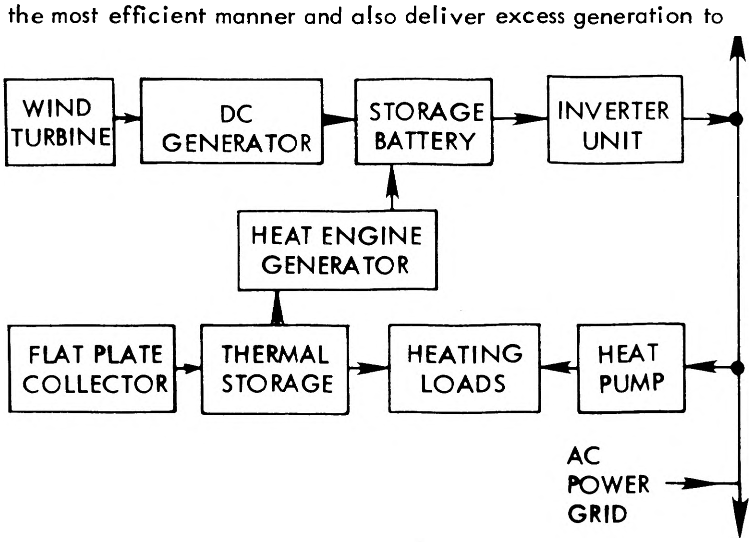

FIGURE 1. SOLAR ELECTRIC GENERATION SYSTEM

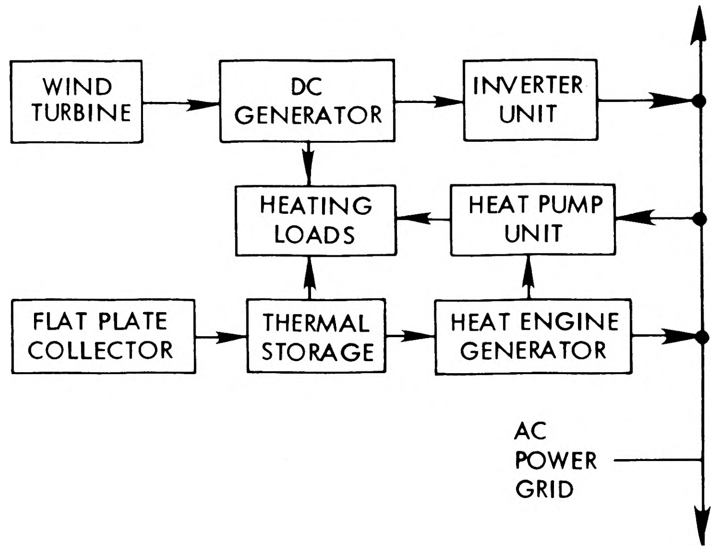

FIGURE 2. ALTERNATE SOLAR ELECTRIC GENERATION SYSTEM

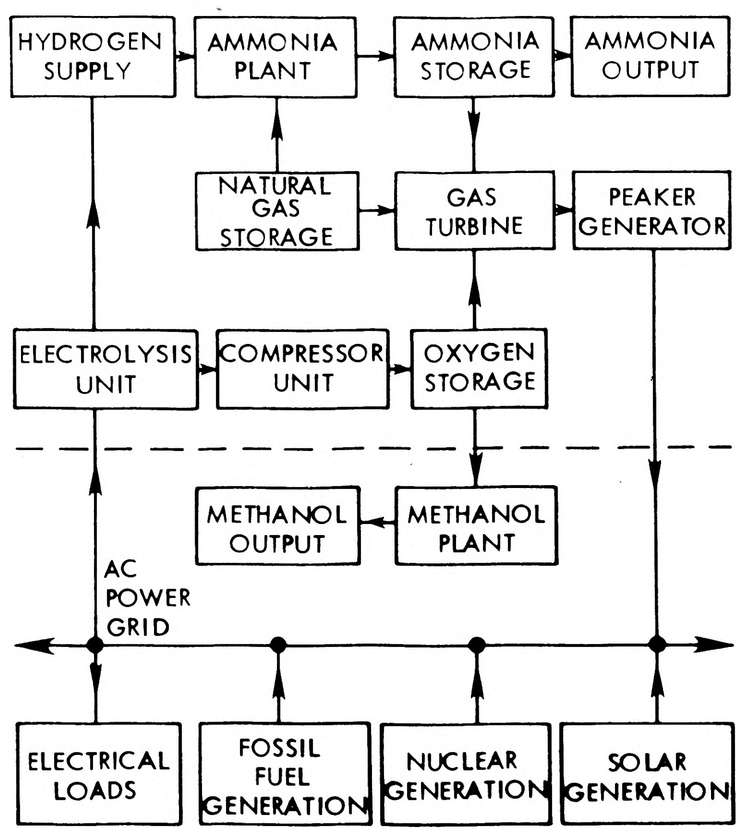

FIGURE 3. SOLAR ASSISTED POWER SYSTEM

nuclear, or solar electric generation. If electrical energy is used to produce ammonia, excess oxygen results. This oxygen could be used to support a methanol production unit (shown in Figure 3) provided a carbon source is available.

SOLAR ENERGY STORAGE

In most solar energy systems used for home heating and cooling, hot water heating, and electrical power generation, it is not practical to provide enough electrical or thermal energy storage capacity at the collection site to provide for all of the excess collectible solar energy. In order to utilize this excess energy, we propose that it be converted into electrical energy and delivered to the power system. Once put into the power grid, it can be used directly in electrical loads or stored in a central power system energy storage facility for use at some later time.

In recent years, solar energy storage schemes using hydrogen in either gas or liquid form have been proposed for locations where pumped hydro or compressed air are not feasible. Hydrogen can be stored in the form of hydrogen gas, liquid hydrogen, metal hydrides, hydrazine, hydrogen peroxide, or ammonia. Of all of these possibilities, hydrogen stored in the form of liquid ammonia is the most promising considering storage and safety problems associated with the others. Ammonia can be stored as a liquid in metal tanks, such as those used for propane, at very moderate pressures over normal temperature extremes without difficulty. From a safety standpoint, however, ammonia must be handled with care because it can cause serious skin, eye, and lung burns. On the other hand, it is routinely handled in the farm industry as a fertilizer and is much less of a fire hazard than propane or natural gas. It can be detected easily by smell at concentration levels as low as 5 to 50 ppm. It is very soluble in water and has flammability limits in air that lie in the 16 to 27% range as compared with 5 to 15% for methane. Even so, it is felt that large storage units containing ammonia in liquid form should be limited to fixed plant operations where fewer people are involved and safety precautions are routine. At the present time, ammonia is produced by using natural gas as the feedstock. As the cost of natural gas rises, the production of ammonia will probably shift to oil or coal and then to electrical energy produced by coal, uranium, or solar energy.

To illustrate why ammonia is considered to be a very advantageous solar energy storage medium, the weight and volume energy densities of several fuels are compared in Tables 1 and 2. Of the non-fossil fuels listed in these tables, ammonia has a definite advantage over other fuel storage mediums in terms of the relative energy densities, except for the weight energy density of hydrogen. Only in aircraft or space vehicles where weight is a very important factor does the weight energy density advantage of hydrogen gas storage offset its low volume energy density. Liquid hydrogen storage requires containers capable of very low temperatures and also has unavoidable no load losses. In order to compare the various electrical energy storage techniques used with peaking generation systems, Table 3 shows the weight and volume energy densities, operating conditions, life expectancy, efficiency, and estimated yearly energy cost.

TABLE 1. WEIGHT ENERGY DENSITY AT STP

Fuel	Formula	Kcal/gram
Hydrogen	$H_2(g)$	28.7
Hydrogen	$H_2(\ell)$	22.4
Methane	$CH_4(g)$	11.9
Heptane	$C_7H_{16}(\ell)$	11.50
Propane	$C_3H_8(\ell)$	11.0
Ammonia	$NH_3(\ell)$	4.45
Methanol	$CH_3OH(\ell)$	3.61
Metal Hydride	$Mg_2NiH_4(s)$	.79

TABLE 2. VOLUME ENERGY DENSITY AT STP UNLESS NOTED

Fuel	Formula	Kcal/liter
Heptane	$C_7H_{16}(\ell)$	7230
Propane (150 psi)	$C_3H_8(\ell)$	5560
Methanol	$CH_3OH(\ell)$	2860
Ammonia (150 psi)	$NH_3(\ell)$	2670
Metal Hydride	$Mg_2NiH_4(s)$	1960
Hydrogen (-425 °F)	$H_2(\ell)$	1570
Hydrogen (3000 psi)	$H_2(g)$	513
Methane	$CH_4(g)$	8.9

STP = 25 °C, 1 atm

TABLE 3. COMPARISON OF ENERGY STORAGE SYSTEMS USED WITH PEAKING GENERATION SYSTEMS

Type of Storage Medium	Type of Peaking Generator	Volume Energy Density, Kcal/Liter	Expected Life Time, Yrs	Operating Conditions, T = 25 °C P = 1 atm	Electrical Efficiency, %	Peaking Energy Costs, Mils/kWh
Pumped Hydro	Water Turbine	.720	40	600 ft Head	65	22
Compressed Air	Gas Turbine	3.68	20	600 psi	42	47
Natural Gas	Gas Turbine	8.9	20	15 psi	30	29
Liquid Hydrogen	Gas Turbine	1570	20	-425 °F	24	151
Lead-Acid Battery	Inverter	114	20	15 psi	60	105
Liquid Ammonia	Gas Turbine	2670	20	150 psi	20	100

NOTE: Storage is charged for 16 hr and discharged for 6.2 hr each day at a rate of 800 MW. Only systems with known operational characteristics and costs are included in this list.

AMMONIA PRODUCTION TECHNIQUES

Ammonia production as currently carried on in the United States depends on natural gas for both chemical feedstock and process energy requirements. The process route is traditional and consists of the following three steps:

(1) reforming of the natural gas with steam over a nickel catalyst followed by the burning of air in the efflux to introduce the required stoichiometric quantity of nitrogen,

(2) conversion of carbon monoxide to carbon dioxide, removal of the carbon dioxide, and reduction of the residual carbon oxides to methane, and

(3) compression and synthesis of the ammonia in a recycle loop. In addition, the waste heat in the reformer and the heat produced by air introduction are used to raise high pressure superheated steam which is used to drive the air compressor, the synthesis gas compressor, and the refrigeration compressor, thus holding the plant in energy balance.

If one has available hydrogen gas obtained from water electrolysis, two possible processing routes for ammonia production are possible.

(1) Air could be burned in the hydrogen atmosphere, the consequent water removed, and the synthesis gas compressed to the synthesis loop.

In this approach, a methanation step might be required to remove carbon dioxide introduced with the air, or this might be removed from the air prior to introduction. Only about 40% of the capital investment of a natural gas fired ammonia plant is required for a plant of this type.

(2) If electrical power is available, one could use it to drive an air separation unit for nitrogen production. This would produce pure nitrogen and oxygen byproduct. This nitrogen may be blended directly with the hydrogen to form ammonia synthesis gas and subsequent ammonia product.

The technology associated with operating an ammonia plant that can utilize both hydrogen obtained from natural gas and that obtained from water electrolysis in various ratios is not new. COMINCO of Trail, B.C., Canada, has in past years operated a plant of this type. Figure 4 shows a block diagram of a facility capable of this type of operation. For agricultural states, one important point to make here is the fact that one need only add to an existing ammonia plant an electrolysis unit and perhaps an air separator to make the facility serve both as an ammonia production unit and as an electrical energy storage unit. Figures 4, 5, and 6 show in block diagram the systems associated with storage and reconversion of the electrical energy used for peaking generation, ammonia production, and methanol production as shown above the power grid line in Figure 3. The conversion of electrical energy to ammonia has

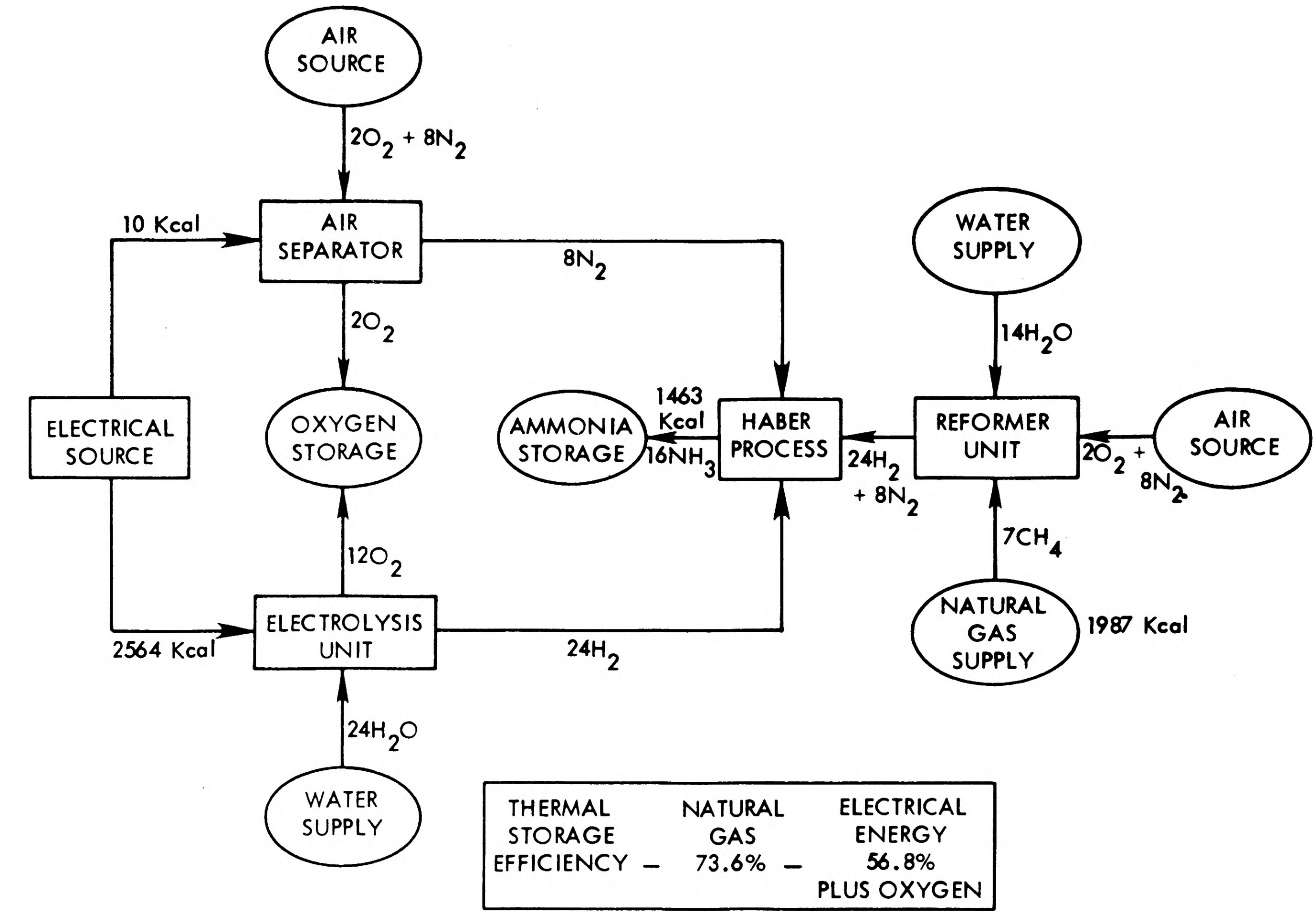

FIGURE 4. AMMONIA PRODUCTION AND STORAGE

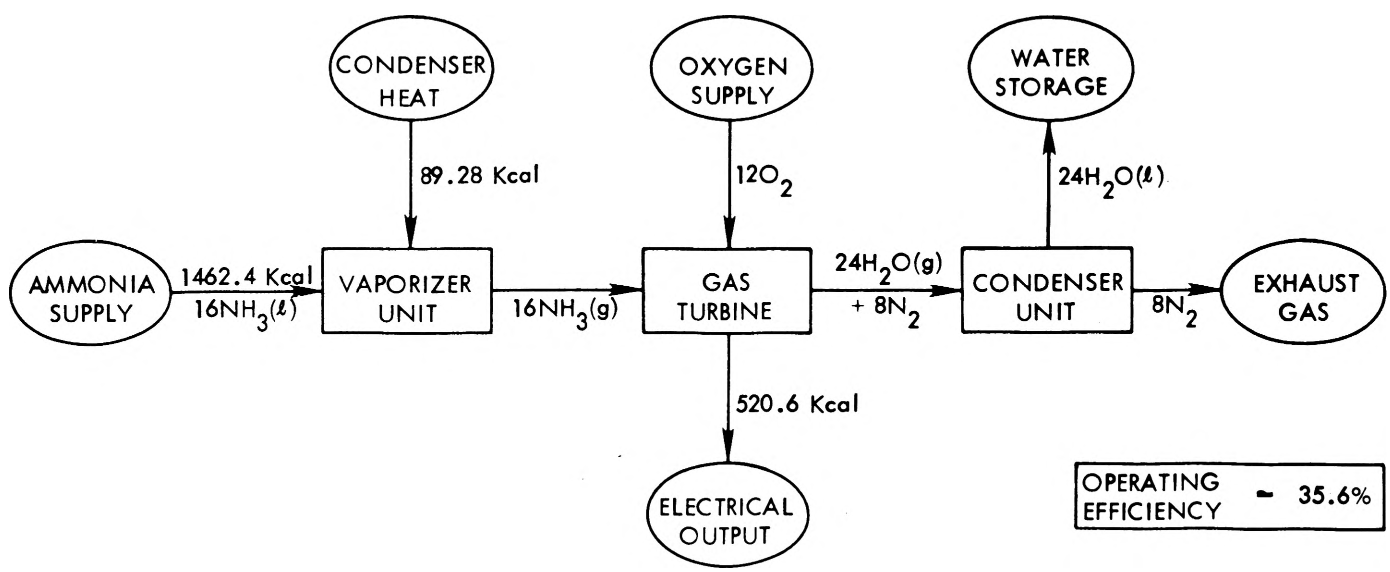

FIGURE 5. AMMONIA BURNING GAS TURBINE

a typical thermal efficiency of 56.8%, the conversion of cellulose to methanol is nearly 45% efficient, and the practical limit on peaking turbine efficiency is about 35.6%. If a methanol unit is not employed, the extra oxygen by-product obtained in this system when ammonia is produced using water and electrical energy, must either be sold on the open market or used in the ammonia plant.

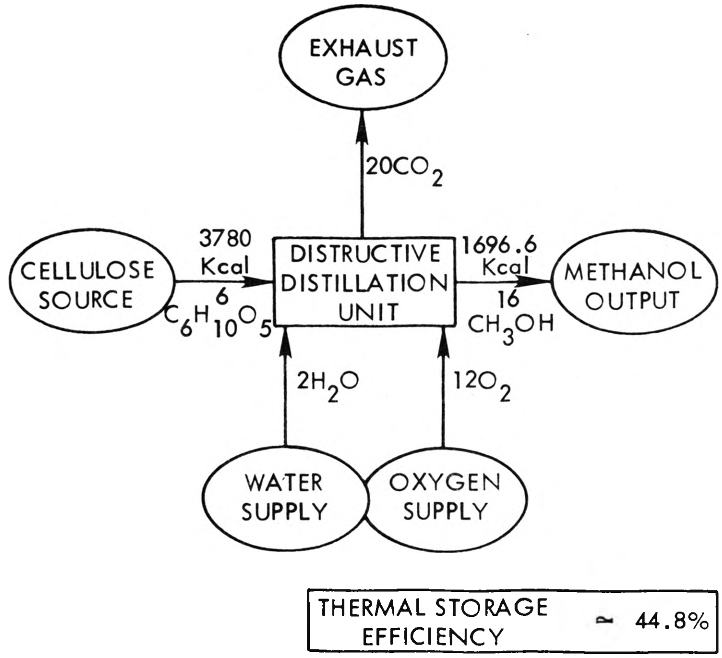

FIGURE 6. METHANOL PRODUCTION UNIT

SOLAR ENERGY RECORDING

In order to control the peaking generator, ammonia production unit, and fossil fuel generation units properly in a solar assisted power system of the type discussed in the previous sections, one must have useful and accurate solar energy density data at his disposal. For this purpose the system shown in Figure 7 has been designed and is nearly complete at the present time. A digital AC/DC kilowatt hour meter having a capacity of about one years data for each of the three types of solar collectors shown has been designed and constructed. A picture of one of these units is shown in Figure 8. For the silicon solar cell unit, we have provided a simulated battery load which tracks the cell's maximum power point. To compute energy the kWh meter multiplies voltage times current digitally and then integrates by summing this product each second. For the flat-plate collector unit, one thermal electric generator is used to keep the collector plate temperature and outside temperature differential at some desired level, while the other thermal electric generator is used to measure the rate at which heat is being pumped out of the flat-plate material. The solar thermal energy density in this case is measured by multiplying the open-circuit voltage of the heat-flow measuring thermal electric generator by a constant and summing this result each second to compute the energy density collected. For wind energy density recording, a voltage proportional to the wind velocity measured by a drag cup anemometer is cubed. This operation gives a voltage proportional to ideal wind turbine power density that is integrated to get the wind energy density available from an ideal wind turbine. The rest of this recording system involves the transmission of data received from the kWh meters mentioned above to a teletype unit where at a selected time interval the three energy density measurements along with temperature, humidity, and time are recorded.

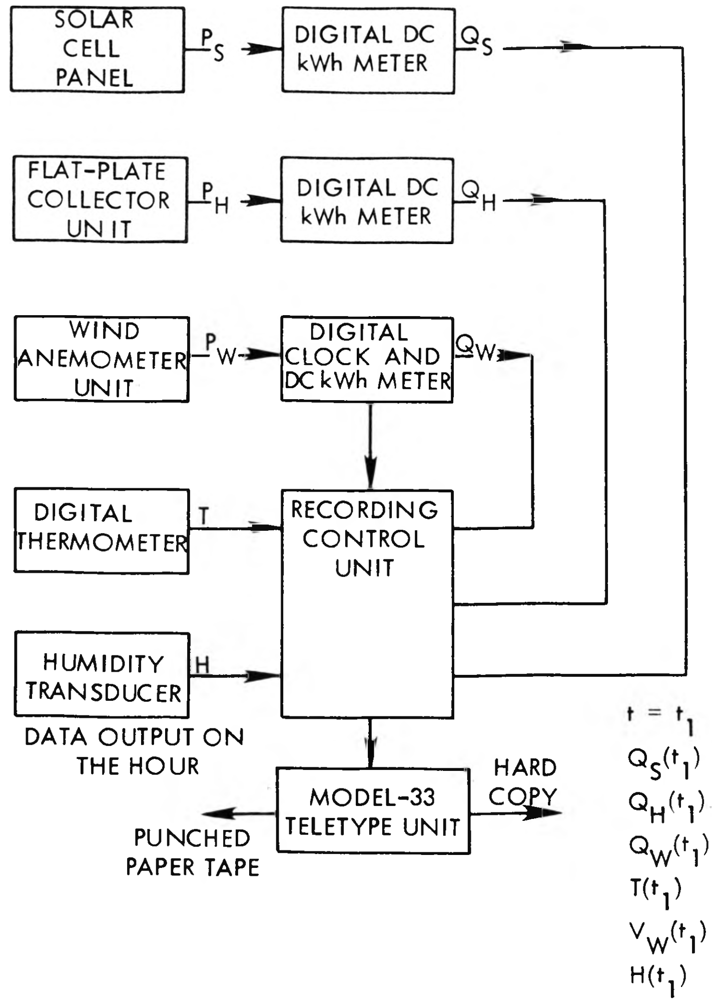

FIGURE 7. SOLAR ENERGY DENSITY RECORDING SYSTEM

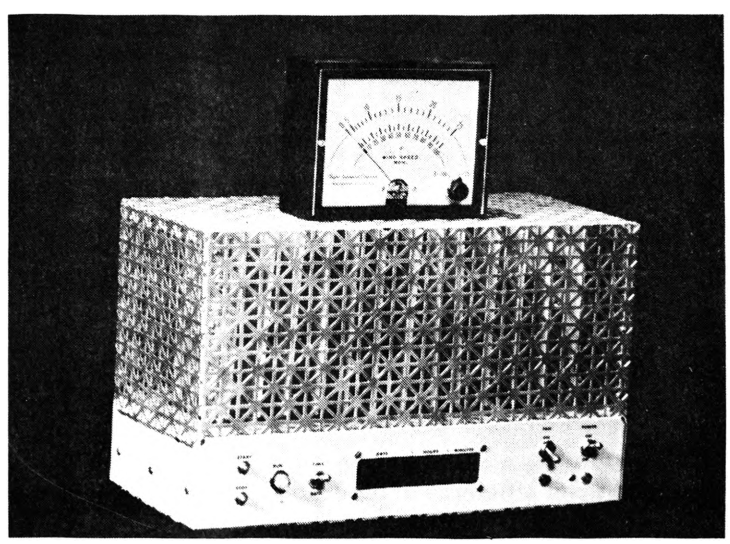

FIGURE 8. PICTURE OF DIGITAL kWh METER USED FOR WIND ENERGY DENSITY MEASUREMENTS

ENERGY COST ANALYSIS

The following economic analysis shows the cost per kilowatt hour for the electrical peaking energy delivered to the power grid on the basis of capital costs alone. At the end of this analysis an estimate of total peaking energy costs will be given. The assumptions under which these calculations are made are listed below.

(1) The peaking generator is rated at 100 MW and has an average power output of 7.14 MW during peak load operating period.

(2) An oxygen storage unit and electrolysis unit capable of converting the solar electric input into hydrogen and oxygen and storing the oxygen will be added to an existing 1000 ton/day ammonia plant.

(3) The average power output of the solar electric generators to the power system grid is equal to 77.14 MW during peak load period and 12 MW during off-peak period.

(4) The wind turbines used are two-blade horizontal axis units with a capture area of 15 m^2 that deliver 2.4 kW in a 10 m/sec wind.

(5) Each solar thermal collector contains an area of 100 m^2, and has an efficiency of 50% at a ΔT = 100 °F. All are mounted with tilt angle equal to the latitude angle facing south.

(6) One-fourth of the total solar thermal energy collected is used for space and hot water heating while the remainder is delivered to the power system via the heat engine generators.

(7) All of the wind generators supply energy to the power grid via a battery driven inverter.

(8) Solar thermal and wind generators are assumed to have a 20-year average life time.

(9) Collector, converter, and storage unit efficiencies are given below:

(a) Solar flat-plate collector (ΔT = 100 °F)	50%
(b) Heat engine, ranking cycle (ΔT = 100 °F)	12%
(c) Ammonia production facility	73%
(d) Peaker turbine generator	35%
(e) Wind turbine plus transmission	48%
(f) Electrical wind generator	85%
(g) Ammonia storage	100%
(h) Battery and inverter	74%
(i) Methanol production unit	45%

(10) The solar thermal energy income per year per unit collector area is equal to 1740 kWh/m^2/Yr with clear sky conditions at a tilt angle equal to the latitude angle. Under typical weather conditions a yearly average energy density of 870 kWh/m^2/Yr is collectible.

(11) The wind energy income per year per unit collector area is approximately 148 kWh/m^2/Yr for conditions where the average value of the wind velocity cubed is 527 $(mph)^3$ and the resulting average power density is 16.8 W/m^2.

(12) All of the oxygen generated will be used internally.

(13) Capital costs for collectors, converters, and storage units are as follows:

(a) Solar flat plate collectors	54 \$/m^2
(b) Heat engine generator units	250 \$/hp
(c) Oxygen storage units	1 \$/scf
(d) Gas turbine generator	200 \$/kW
(e) Hot water storage	27 \$/m^2
(f) Wind electric generator units	400 \$/kW
(g) Rotary inverter units	200 \$/kW
(h) Electrolysis units	360 \$/kW

(14) The capital cost of the collected solar thermal energy per collector unit is calculated below:

(a) Heat engine generation delivered to the power grid	57,942 kWh
(b) Heat energy to thermal storage	217,500 kWh
(c) Total energy used	275,500 kWh
(d) Cost of solar collectors	\$5400
(e) Cost of heat engine unit	\$1000
(f) Cost of thermal storage	\$2700
(g) Total unit cost	\$9100
(h) Capital cost per unit energy for home heating and electrical energy output	.033 \$/kWh

(15) The capital cost of collected solar wind energy is calculated below:

(a) Wind turbine generator	\$960.00
(b) Batteries and inverter	\$810.00

(c) Total system cost $1770.00

(d) Total energy collected 13,405 kWh

(e) Capital cost of wind electric generation .132 $/kWh

In order to have peaking energy storage and peaking generation capability along with the option of generating ammonia fertilizer using off-peak fossil, nuclear, and solar generation, a system like the one shown in Figures 9 and 10 is needed. Typical average operating conditions are indicated for the peak and off-peak load periods specified. In this system an electrolysis unit, peaker turbine, and oxygen storage facilities are installed at an existing 1000 T/D natural gas ammonia plant. During off-peak load periods part of the ammonia is produced using electrical energy and water as feedstock under conditions of reduced natural gas input. During the peak load period the electrolysis unit is run at a level just high enough to keep the temperature in the electrolyte at an operating level. The peaker turbine is operated as needed using ammonia or a natural gas ammonia mixture as the fuel. To get some idea of the cost of peaking power for the operating modes shown in Figures 9 and 10, the following analysis is presented based on capital costs plus fuel costs only.

ECONOMIC ANALYSIS

(1) Average cost of solar generation storage input .040 $/kWh

(2) Off-peak solar energy storage per day 120,000 kWh

(3) Cost of stored solar generation per day $4800

(4) Cost of off-peak fossil and nuclear input .010 $/kWh

(5) Off-peak fossil and nuclear energy storage per day 380,000 kWh

(6) Cost of stored fossil and nuclear generation per day $3800

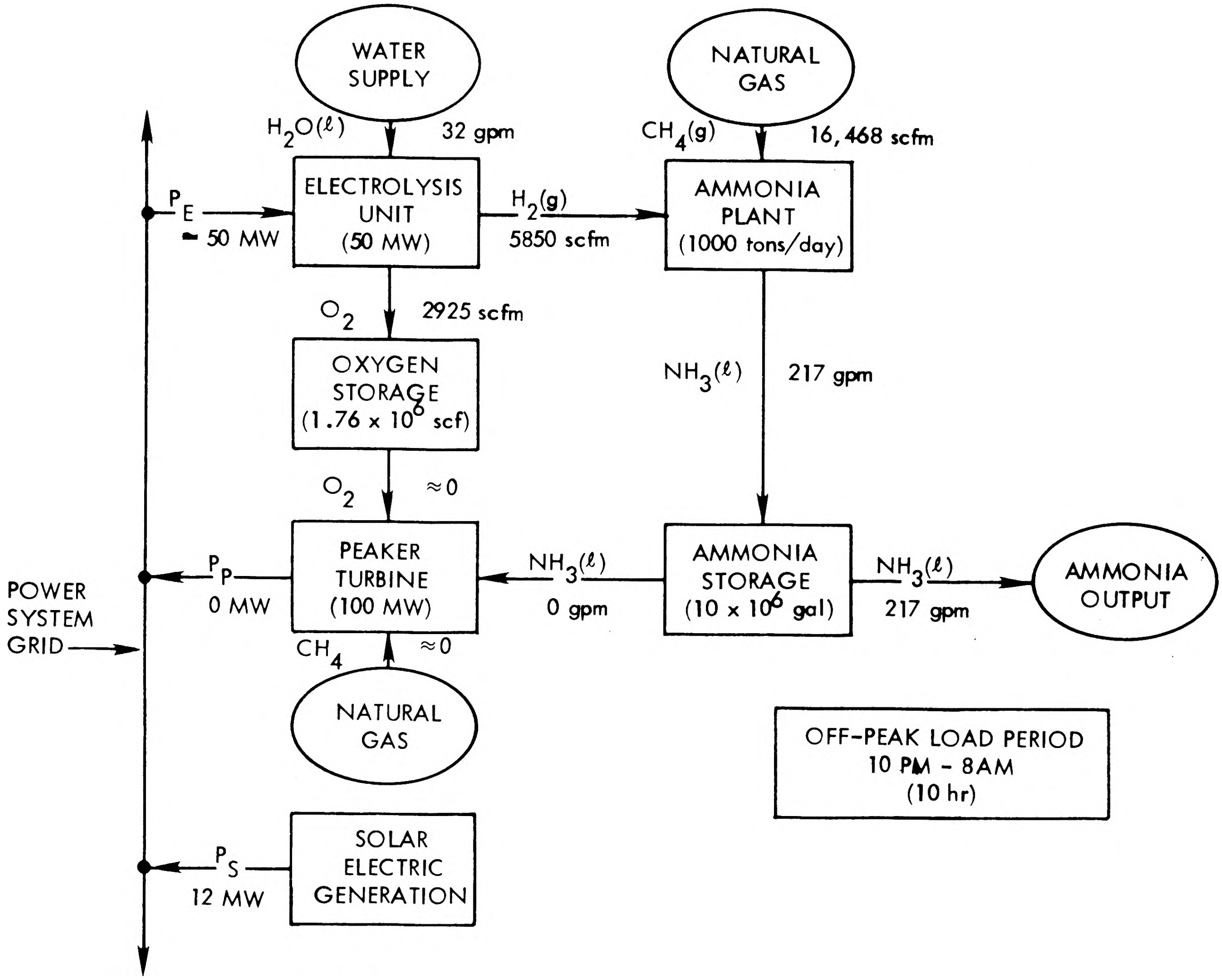

FIGURE 9. SOLAR ASSISTED POWER SYSTEM SHOWING AVERAGE OPERATING CONDITIONS DURING OFF-PEAK LOAD PERIOD

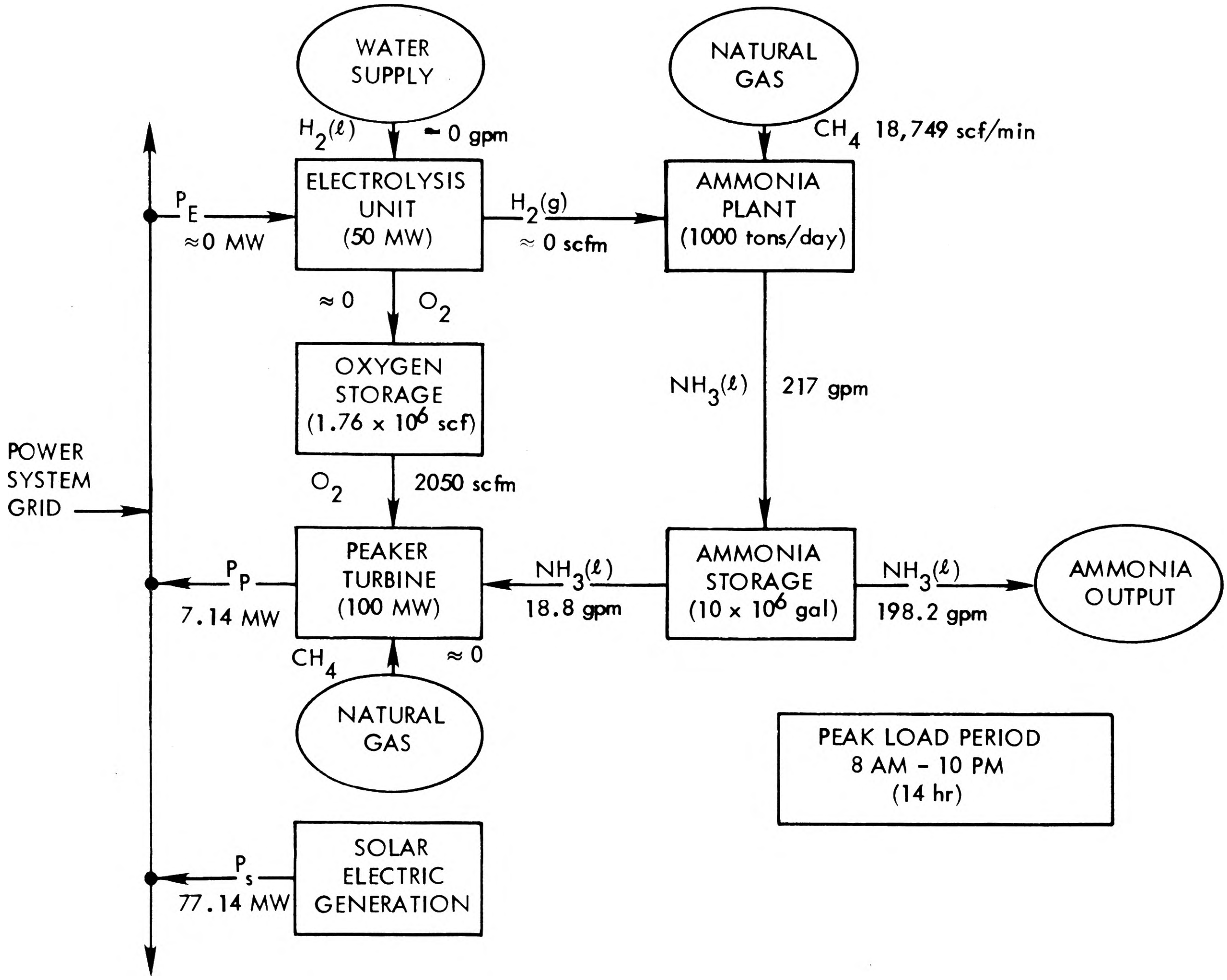

FIGURE 10. SOLAR ASSISTED POWER SYSTEM SHOWING AVERAGE OPERATING CONDITIONS DURING PEAK LOAD PERIOD

(7) Cost of oxygen storage per day $ 241

(8) Cost of peaker turbine per day $2740

(9) Cost of electrolysis unit per day $2465

(10) Peaking energy delivered per day 100,000 kWh

(11) Cost of delivered peaking energy .14 $/kWh

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ENERGY CONVERSION AND RESOURCE MANAGEMENT

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The United States has 5 percent of the world's population, yet consumes 35 percent of the total energy. This statistic reflects the availability of unlimited and cheap energy that has been enjoyed in this country. Unfortunately, this energy has been provided without much regard for the future, so that plentiful and cheap energy may not be possible much longer. A carefully formulated energy policy will be required to manage our remaining natural resources wisely and extend their longevity until other sources of energy can be developed.

There are five basic forms of energy: chemical, thermal, electrical, mechanical and radiant. Energy is consumed primarily in the thermal, electrical and mechanical forms. However, the source of almost all of our energy is chemical (petroleum or coal); so that conversions of chemical energy are necessary steps in our energy economy.

1. ENERGY CONVERSIONS

Considering the five basic energy forms, there are twenty-five possible energy conversion steps. Ten of the most common conversions are shown in Table I. Single energy conversions are usually incomplete with losses resulting from formation of undesired forms of energy. The degree of completion of an energy conversion can be expressed by an efficiency, e, defined as the net energy available in the desired form, divided by the total energy available before conversion. Table I also lists typical conversion efficiencies for several processes. For example, 88 percent of the chemical energy available in coal can be converted to thermal energy as steam in a boiler; the remainder being lost in the flue gases.

Direct conversion of the energy resource into the desired form is not frequently possible; and several conversion steps may be required. Table II lists the conversion steps required to derive electricity, heat and transportation from chemical energy sources. The efficiency of combinatorial energy conversions is given by Equation (1):

$$E = \prod_{i=1}^{N} e_i \qquad (1)$$

where E = net conversion efficiency
e = efficiency for step i

For example, electricity is generated from chemical energy by making these conversions: chem→therm (boiler), therm→mech (turbine) and mech→elec (generator). Using Equation (1) and the data from Table I, the efficiency, E, of this conversion is: (.88)(.45)(.99) = .39.

Electricity, space heating and transportation represent the largest individual uses of energy in this country. Table II gives the efficiencies of several processes for producing energy for these requirements. It is distressing to realize that the overall efficiency of our utilization of chemical energy for the above uses is only about 35 percent, not including losses in the transportation of energy (compared to an overall efficiency of 50 percent (2)). This poor efficiency suggests an examination of our conversion practices in developing an energy policy for the future.

It is interesting to observe from Table II that the fuel cell offers a means of about doubling the efficiency of electricity generation and motive power. Also, direct combustion is more efficient in providing space heat than the electric furnace. The gasoline pwoered automobile is slightly less efficient than a battery driven car, powered by electricity generated from the same gasoline.

2. RESERVES OF CHEMICAL ENERGY

Decisions as to the prudent use of our chemical energy resources cannot be made without reference to the reserve of these resources. It would not be wise for example, to use gas for space heating when out natural gas reserves are rapidly dwindling. Table III presents the proven recoverable reserves of our chemical energy resources. The life of these reserves can be estimated by Equation (2):

$$A = \frac{R}{C} \qquad (2)$$

where A = availability of reserves, yrs.
R = current quantity of proven reserve
C = annual rate of consumption of reserve

This availability is different from the usual representation of the life of resources which is computed from the current production, rather than the consumption. While it is recognized that both R and C change with time, probably increasing, it is assumed that these changes are offsetting so that the measured availability is realistic. Table III shows that our current reserves of petroleum would last only 5-11 years if all the demand were supplied by domestic production, while coal would last 275 years.

3. INTRINSIC ENERGY CONVERSIONS

The data of Table III show the heavy dependence that must be placed on coal in the future. There is incentive to convert coal into gas and oil more desirable energy forms. These are intrinsic conversions of one form of chemical energy to another form of chemical energy. These conversions are for convenience, i.e., it is more convenient to burn gas in home furnaces than to stoke coal.

Intrinsic energy conversions consume energy, resulting in a reduction of the efficiency of the converison. Table IV lists several intrinsic chem chem energy transformations, along with their efficiencies. These efficiencies should be influential in establishing a wise allocation of our resources.

4. A RATIONAL ENERGY POLICY

The availability of an energy reserve, calculated by Equation (2), is not an effective measure of the expected life of that resource, since neither the demand nor efficiency of utilization is included. A better measure is to consider the annual quantity of a resource allocated to a certain need, calculated as:

$$RA = \frac{D}{(R)(E)} \times 100 \qquad (3)$$

where RA = resource allocation, %/yr.
D = current annual demand for a particular form of energy (output)
E = efficiency of converting resource into the energy form used

For example, the demand in 1975 for space heating is 6.1×10^{15} BTU (output/yr. (input reported as 12.2×10^{15} BTU (1,5,11)). If this energy requirement is provided by gas, the resource allocation, RA is:

$$RA = \frac{6.1 \times 10^{15} \times 100}{(237 \times 10^{15})(.5)} = 5.2\%/\text{yr.}$$

Of course, it is unreasonable to assume that all of a certain demand will be met from a single energy source. The equation can accommodate the use of a fraction of demand to be allocated to a particular resource. Allocations to supply the space heating, electricity generation and transportation needs are given in Table V.

4.1 SPACE HEATING

From Table II, the most efficient means of providing space heating is by direct combustion of oil, gas or coal. To use either gas or oil for this purpose would deplete these reserves at the rate of about 5-6 percent per year. Therefore, coal should be the fuel allocated for this need. However, the use of coal for heating individual homes is certainly undesirable.

Space heating would be provided by electricity generated from coal with an overall efficiency of 39 percent and a coal allocation for heating of .4 percent per year. Coal can be converted to gas to provide space heating with an efficiency of 32 percent and an allocation of .5 percent per year. Obviously, there is little incentive to develop coal gasification for providing the requirement of space heating.* Our energy policy should clearly be directed towards provision of heating with electricity generated from coal or nuclear energy. This policy, of course, necessitates the solution of the SO_2 stack gas problem.

4.2 TRANSPORTATION

The output energy demand for transportation in 1975 is 4.4×10^{15} BTU (input reported at 17.6×10^{15} BTU (5,11)). Continued use of oil for transportation will deplete our reserves by about 9 percent per year. Conversion of coal to oil would yield an overall transportaiton efficiency of only 20 percent. However, generation of electricity with coal and the use of a battery powered auto yields an efficiency of 26 percent with a coal allocation of .4 percent per year. Clearly, an energy policy should favor the electric car and development of suitable batteries should be pursued virorously. Electric cars also are environmentally desirable, providing the environmental problems at the generating stations and coal mines can be solved.

*This comparison of heating with SNG and electricity has neglected the transportation aspects; however, the results would be little altered since the efficiency of transporting gas and electricity are about the same.

4.3 ELECTRICITY

The demand for electricity in 1975 will be about 6.1 x 10^{15} BTU (1). Reviewing the allocations of fuels for generating electricity given in Table V, it is seen that 7 to 8 percent of our petroleum would be consumed annually if used to generate electricity, while only .4 percent of the coal would be used. Coal must be allocated as the hydrocarbon fuel for electricity, and gas and oil should be phased out for this usage.

The conclusion of the above analysis is that, for maximum efficiency and resource conservation, an electrical energy economy should be pursued. Electricity can be generated from coal, nuclear or renewable energy sources. An electric energy economy is not possible without the development of new or improved technology for storage batteries, environmental protection and energy transmission.

5. COAL RESERVES

An economy, totally dependent upon coal as a source of energy, is not an altogether wise policy. Adding the allocations of coal for heating, trnasportation and electricity in Table V, it is found that 1.2 percent of our coal will be consumed annually. This allows only an 83 year life of our coal reserves. However, this life should be adequate for the full development of renewable energy sources or the breeder reactor.

Consider the achievement of energy sufficiency utilizing gas and oil from coal, by 1985, about the earliest date this technology will be available. The shortage of natural gas will amount to 8 x 10^{15} BTU annually (12). Should these shortages be made up by gas and oil produced from coal, the availability of coal reduces to about 40 years. So coal is certainly not unlimited and this resource should be managed wisely to insure its longevity.

6. PETROCHEMICAL NEEDS

Our society is dependent upon the petrochemicals derived from oil and gas. Plastics, synthetic fertilizer, pharmaceuticals and many hundreds of other products come from oil and gas. While we have alternative sources of energy, there are few alternative sources of carbon for petrochemicals. Oil and gas can no longer be used as a source of energy and particularly as a source of heat.

The demand for chemical feedstocks is currently about 10 percent of our total energy usage (5,13). If petroleum were reserved solely for petrochemical needs, (and aircraft transport) the availability of oil and gas could be lengthened to only 46 years, not a particularly bright future. Each year of continued use of petroleum for energy, shortens the time until alternative sources of chemical feedstocks must be developed. Oil from shale and tar sands (although more expensive) will undoubtedly lengthen this horizon, but continued hesitation to implement a policy of conservation will hasten the day of total depletion.

7. CONCLUSIONS

The most efficient use of our remaining chemical energy resources can be achieved by development of an electric energy economy. This transition cannot be made immediately and without technological advancement in electric cars and environmental protection at the generating stations and coal mining facilities. However, this technology is perhaps more rapidly achieved than coal gasification, nuclear fusion or solar energy storage.

Coal gasification and liquefaction are inefficient and offer no advantage over electricity generation with coal. In fact, the efficiency of coal conversion processes must be above 80 percent before becoming competitive with electricity. Petroleum should not be depended upon as a source of energy and should be reserved for petrochemicals.

For a fifty year horizon, an energy policy emerges as follows:

1) Encourage generation of electricity with coal, even at the expense of increased SO_2 emissions. Accelerate development of stack gas scrubbing and coal mining procedures. Develop uses for waste heat at generating plants.

2) Offer incentives for electrical space heating. Phase out generation of electricity and heating with petroleum.

3) Accelerate the development of advanced storage batteries and fuel cells.

4) Develop efficient urban mass transit systems based on electric power.

5) Continue development of renewable sources of energy and implement their use as economics permit.

Quite obviously, the transition from a petroleum energy economy to a coal-electric economy could not and should not be immediate nor complete. Time is required to replace refineries with power plants, internal combustion engines with batteries, gas furnaces with electric, etc. Some uses of petroleum for energy will be necessary for many years (aviation). However, unless the transition is begun soon, heavier dependence upon imported energy and petrochemicals will result; and energy sufficiency will be impossible in the near future.

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TABLE I. DIRECT ENERGY CONVERSION EFFICIENCIES[1]

ENERGY CONVERSION	PROCESS	CONVERSION EFFICIENCY (%)
CHEM→THERM	BOILER	88
	HOME FURNACE	50*
THERM→MECH	STEAM TURBINE	45
MECH→ELEC	GENERATOR	99
ELEC→MECH	MOTOR-SMALL	62
	LARGE	92
ELEC→RADIANT	INCADESCENT LAMP	5
	FLOURESCENT LAMP	20
	GAS LASER	40
ELEC⇆CHEM	STORAGE BATTERY	72
CHEM→ELEC	DRY CELL BATTERY	92
	FUEL CELL	60
RAD→ELEC	SOLAR CELL	10
THER→ELEC	THERMOCOUPLE	8
THER→MECH	GAS TURBINE	35
	AUTO ENGINE	25
ELEC→THER	RESISTANCE HEATER	100

*Home furnaces rated as high as 75 percent, but applied efficiency usually 35-50 percent.[1]

TABLE II. COMBINED ENERGY CONVERSIONS

REQUIREMENT	EXAMPLE	ENERGY CONVERSION PROCESSES	COMBINED EFFICIENCY (%)
ELECTRICITY	POWER PLANT	CHEM→THERM→MECH→ELEC	39
	GAS TURBINE GENERATOR	CHEM(GAS)→THERM→MECH→ELEC	32
	FUEL CELL	CHEM→ELEC	60
SPACE HEATING	ELECTRIC FURNACE	CHEM→THERM→MECH→ELEC→THERM	39
	GAS, OIL OR COAL FURNACE	CHEM→THERM	50
TRANSPORTATION	INTERNAL COMB. ENG.	CHEM(OIL)→THERM→MECH	25
	BATTERY POWERED	CHEM→THERM→MECH→ELEC→CHEM→ELEC→MECH	26
	FUEL CELL	CHEM→ELEC→MECH	55

TABLE III. AVAILABILITY OF U.S. CHEMICAL ENERGY RESERVES

CHEMICAL ENERGY FORM	PROVEN RECOVERABLE RESERVES, R, 10^{15}BTU	CONSUMPTION, C 10^{15} BTU/YR***	AVAILABILITY, A YRS
GAS	237*	23	11
OIL	204*	38	5
COAL	4400**	16	275

*Exxon Data (3)

**Hottel (4), conservative estimate

***Exxon Data (5)

TABLE IV. EFFICIENCIES OF TYPICAL CHEMICAL-CHEMICAL CONVERSIONS

PROCESS	EFFICIENCY	REFERENCE
COAL→GAS	64 (average)	(6,7)
COAL→OIL	80	(9)
OIL→GAS	90	(8)
GAS→LNG	80	(10)

TABLE V. ALLOCATION OF U.S. CHEMICAL ENERGY RESERVES

CHEMICAL ENERGY FORM	ENERGY PROCESS	ALLOCATION, RA, %/YR		
		SPACE HEATING	TRANSPORTATION	ELECTRICITY
GAS		5.2	-	6.6
OIL		6.0	8.7	7.7
COAL	COAL→HEAT	.3	-	.4
	COAL→GAS→HEAT	.5	-	-
	COAL→OIL→MECH	-	.5	-
	COAL→ELEC→MECH	-	.4	-
	COAL→ELEC→HEAT	.4	-	-

COAL CONVERSION TECHNOLOGY

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Abstract

Energy consumption is rapidly increasing throughout the world and the United States is no exception. Efforts to reduce the dependence on oil imports have focused on utilization of our coal resources. This paper examines various coal conversion processes and presents a method for evaluating their contribution to energy production.

1. INTRODUCTION

Demand for energy in all forms is rapidly increasing. The United States gas and oil consumption over the past 20 years is representative of this increase and is shown in Figure 1.

This increased demand in the face of a limited supply has been one of the factors driving up the cost of both gas and oil. Despite the great increase in both the amount of gas and oil used and its high cost, there are large reserves of coal in this country that remain relatively untapped as energy sources.

One of the major reasons for this lack of interest in coal is the Clean Air Amendment Act of 1970. The Environmental Protection Agency suggested ambient standards for sulfuroxide content in the air, and these were incorporated into the Clean Air Act in 1970. The primary standards (i.e. health related standards) set by the 1970 Amendment specified an annual mean output of 80 milligrams of SO_x per cubic meter and a maximum output of 365 milligrams per cubic meter for twenty-four hours. These standards have often posed problems for facilities with conventional coal-fired boilers.

One way of meeting these standards is by burning low sulfur coal. However, domestic reserves of low sulfur coal are extremely limited. Another alternative is stack scrubbing. Much advancement has been made in this technology, to the point where the Environmental Protection Agency is recommending the use of scrubbers as a solution to the pollution problems of utility companies. However, in the opinion of Donald Cook, Chairman of American Electric Power Company, the work has not yet reached optimum costs, reliability, and feasibility.

A third alternate is to convert existing high sulfur coal into a Synthetic Natural Gas. This alternate provides clean fuel which is acceptable within air quality regulations and standards. There is an additional benefit from such a conversion in that it may help close the gap in natural gas supply and demand. Figure 2 represents the sources of U.S. natural gas supply and illustrates the need for a fuel source to replace shrinking domestic production.

Coal gasification is being studied worldwide and the importance and urgency of the research is becoming increasingly evident. As stated by Dr. Abbas Fallah (Iran), Hormoz Petroleum Co.:

> "...petroleum is a raw material too valuable to be burnt for its destined use as feedstock for chemical and petrochemical industries... We should immediately devote full attention to development of new technologies for coal gasification/liquifaction.."

From the study of the gasification and desulfurization of coal, many different processes have emerged. Each of these processes has singular characteristics, advantages, and disadvantages. There are four classifications of coal conversion processes: pyrolysis, solvation, hydrogenation, and production of synthesis gas. Nearly thirty processes have been developed within these categories.

The purpose of this paper is to present a structured comparison of coal conversion processes. This comparison will take into account not only the quantitative characteristics of the process, but also the qualitative factors that could affect the success of the conversion of coal to a clean, convenient fuel or to a synthetic feedstock.

There are three distinct types of process characteristics which are involved in the comparison. These are as follows:

(1) Operating costs and revenues
(2) Process efficiencies
(3) Qualitative desirability factors

The first two of the above items are self-explanatory. The third item consists of investigating and comparing such things as:

(1) Sensitivity to product prices
(2) Public acceptance
(3) Labor requirements
(4) Etc.

This paper uses a structured evaluation model to compare existing coal conversion processes and illustrates how a more in-depth process comparison can be made.

2. DISCUSSION

2.1 PREVIOUS DEVELOPMENTS IN COAL PROCESSING

The first gas was made commercially from coal in the nineteenth century. This gas was produced by heating coal in the absence of air. Before being replaced by electricity late in the century, this gas was used for lighting cities, homes, and buildings. Afterwards, it was primarily used for cooking.(1) One by one, markets for both coal and gas made from coal disappeared as natural gas became more available.

Many companies worked on coal gasification during the mid-twentieth century, but most of these companies ran into problems which proved either insurmountable or uneconomical to solve. As natural gas shortages evolved, interest in coal conversion has awakened with renewed vigor as scientists strive to discover relief from the energy shortage.

2.2 DESCRIPTION OF COAL CONVERSION PROCESSES

Many types of coal conversion processes have been studied. Some of the processes have many variations, such as the number of stages, the temperatures, and the pressures of operation.

Scientists have succeeded in producing a synthetic natural gas from coal and have developed methods of refining the gases produced in certain of the conversion processes into methane. Figure 3 represents steps involved in gasification. Other conversion processes using coal as a raw material, result in the formation of synthetic crude oils which are suitable refinery feedstocks.

2.2.1 Processes Used in the Production of Synthetic Natural Gas

The following processes include all of the basic technology; however, some variations which have been made on certain processes were eliminated to prevent repetition.

Pyrolysis reactor of Garrett Research and Development Co. This experimental system included a one-inch diameter by eleven-foot reactor, coal feeder, product collection equipment, and gas sampling apparatus. The reaction temperature ranged upward from 1,500°F (below the ash-softening temperature of the char), and heat was supplied by electricity. Sub-bituminous coal (<200 mesh) was fed horizontally to the reactor then transported upward in dilute phase with nitrogen. Each run took about four hours. A filter bag and water cooled condensers were used to remove the tar. Product char was removed by cyclones.(2)

At 1,700°F, and after recycling the tar to the reactor for extensive cracking, the total equivalent yield was approximately 8,500 standard cubic feet of pipeline gas per ton of coal.

"From a commercial standpoint, sulfur reduction is most meaningfully expressed on an equal BTU basis, defined as: Sulfur reduction (equal BTU basis) = 100 x (lb. S/BTU of coal - lb. S/BTU of char)/(lb. S/BTU of coal). On this basis, sulfur reduction of 30% to 45% were obtained."(3)

Both the pipeline gas and the char have high heating values compared to those of other processes.

Clean Coke process-carbonizing and hydrogenating of U.S. Steel Corp. This process may be used to produce clean coke, low-sulfur liquids, and gaseous fuel byproducts from high-sulfur, high-ash coals.

This process combines carbonization and hydrogenation of coal. After sizing in a coal-preparation plant, part of the coal is processed through a carbonization unit. Here, the coal is devolatilized and partially desulfurized. The product is used to provide the base material for coke production. The rest of the coal is slurried with a carrier oil and hydrogenated to convert most of the coal to liquids. These liquids are processed into low-sulfur liquid fuels, chemical feedstocks, and three oil fractions that are recycled to other process areas. The char and pitch coke is slurried with one of these oils, formed into pellets and baked to produce metallurgical coke with a low-sulfur content. The vapors of the coke-preparation are collected and returned to the process.

Preliminary evaluations show that a plant constructed to process 6.5 million tons/yr of as-mined coal would produce 2.2 million tons/yr of coke pellets, 2.3 billion lb/yr of chemicals, 8 million gallons/yr of liquid fuels and approximately 6 trillion BTU/yr of fuel gas.

Lurgi process. Among the few processes currently in commercial operation is the Lurgi process. This is a fixed-bed process in which a sized, non-coking coal is fed into a pressure gasifier of up to twelve feet in diameter. The gasifier uses a rotating grate underneath the coal bed for feeding steam and oxygen which cool the grate and prevent clinkering of the ash. Coal is spread evenly over the bed by a distributor at the top of the gasifier where temperatures range from 500°F to 800°F. The rotating grate at the bottom allows ash to be collected in a hopper. The temperatures at the bottom of the gasifier are less than 2000°F. Raw gases leave at the top at 850°F and are scrubbed and cooled.(1)

The counter-current flow of reactants in the fixed-bed reactor allows the efficient use of the heat that is released during the oxidation of the coal near the base of the gasifier. Since this method also operates under pressure, the reported thermal efficiencies are on the order of about 70%.

Koppers-Totzek Process. This process contains an entrained bed of reactants: coal, steam, and oxygen. Two or four opposing burners may be used for commercial gasifiers. Four burners can handle up to 850 tons/day of coal. The raw gas leaves the gasifier at temperatures up to 3,300°F. Therefore, the consumption of oxygen per unit of gas is significantly higher than for fixed-bed reactors. There is a slag collected at the bottom of the gasifier.

Any rank or type of coal may be gasified by the Koppers-Totzek process. All of the coal, even the fines, may be used. Since there are no phenols, tars, or light oils produced during the operation, there are fewer environmental problems than with other processes. The thermal efficiencies of the process are reported to be about 77%.

Winkler process. This atmospheric, fluid-bed gasifier uses oxygen and steam as media. Temperatures for the operation range from 1,500°F to 1,850°F. Unreacted carbon, ash, and product gas are carried out of the bed. The unreacted carbon is reacted with more steam and oxygen in the disengaging space above the fluid bed. The gases are cooled by a radiant boiler in the upper portion of the gasifier.

Sixteen plants, in a number of countries, use this process. The largest plant has a capacity of 1.1 million standard cubic feet per hour.

This process can handle all sizes of coal, but it cannot handle a strongly coking coal which is not pre-treated. The process boasts very few environmental problems and has an average oxygen consumption compared to other processes. The overall thermal efficiencies are reported to be about 75%.(1)

Hygas process. The Office of Coal Research has sponsored the development of the Hygas process by the Institute of Gas Technology. At the present time, a large pilot plant is being tested.(4) A high-BTU gas is produced by the process by reacting hydrogen (supplied by steam-carbon and water-gas shift reactions and by reacting steam with char at 1,900°F) with coal at 1,000 to 1,500 pounds per square inch. Coal is fed into the hydrogasifier at the top, and hydrogen is fed in at the top, and steam is fed in at the bottom. The hydrogasifier is made up of two fluid beds. The upper bed operates at 1,200°F and the lower bed at 1,700°F. The reaction rate of the process and the amount of methane at equilibrium in the product gas is optimized by this method.(1)

There are three methods which may be used to produce the hydrogen needed for the Hygas process. These are electrothermal, steam-oxygen, and steam-iron. The three methods were proposed by the Institute of Gas Technology.

CO_2-Acceptor process. The CO_2-Acceptor process was also introduced by the Office of Coal Research and is being tested in a pilot plant. In this process, coal is fed into the gasifier and, after being devolatized, is reacted with steam in a fluid-bed gasifier. Operating pressure ranges from 150-300 pounds per square inch. Hot dolomite is introduced into this reaction. The dolomite provides heat to the steam-carbon reaction by absorbing carbon dioxide formed by the decarboxylation of the lignite feed.(4) The product gas leaves at the top of the gasifier. The spent dolomite and unreacted char are removed at the bottom. Then the unreacted carbon is burned with air and the heat produced carbonates, and the dolomite is regenerated.

Synthane process. This two-stage process has been tested only in small pilot plants; however, there is a 70 ton per day plant scheduled for completion by late 1974. This method used a pressurized gasifier developed by the Bureau of Mines, in which the coking properties of the coal are destroyed with oxygen and steam. This may be accomplished by either a free-fall stage or in a fluidized bed. The coal is carbonized and gasified with steam and oxygen in the lower section. Product gas leaves at the top, and char and ash are removed at the bottom. The operating temperature at the top of the bed is about 1,100°F and ranges from 1,750°F - 1,850°F at the bottom.

Bigas process. The Bigas process involves a super-pressure method developed by Bituminous Coal Research, Inc. The process uses a two-stage, entrained bed. In the upper section, coal is heated by hot gases produced in the lower section. The distillation gases from coal carbonization leave the gasifier along with the gases produced in the lower section of the vessel. The raw gas and part of the char is recycled to the lower section where it reacts in an entrained state with steam and oxygen to produce synthesis gas(1) The lower section operates at 2800°F and the upper vessel operates at temperatures ranging from 1,400°F to 1,700°F.

Union Carbide-Battelle process. This process is operated at 100 pounds per square inch pressure and requires no oxygen. In one stage (of the two-stage process), a fluid-bed combustor is used to burn part of the carbon with air to form coal ash agglomerates. A gasification reaction between steam and carbon takes place in a second vessel where the hot pellets are circulated to provide the heat for the reaction. Some of the pellets are recirculated and reheated in the first vessel.

Hydrane process. The U.S. Bureau of Mines developed this hydrogasification step, which is very similar to the Synthane process. A pressurized gasifier, using steam and oxygen as the reactants, is used as the second stage of a counter-current process to react devolatilized char from the first stage with hydrogen at 1,650°F.

Atgas process. This process was developed by the Applied Technology Corporation. It is a low-pressure process which uses a molten iron bath and limestone with either air or oxygen for the reaction. Using air, the process produces a sulfur-free, low-BTU gas. When oxygen is used in the reaction, a medium or high-BTU gas is produced.

Molten Salt process. This process, developed by the M. W. Kellogg Co., employs a molten-carbonate gasification system. Gasification is accomplished by steam-carbon and carbon-oxygen reactions, which may occur simultaneously or in a divided vessel.

Steam-Iron process. This process is a hydrogasification process which produces carbon oxides, hydrogen, and nitrogen by passing steam and air over a bed of hot carbon. When these gases come into contact with iron oxide, iron is formed. Then steam is passed over the iron, resulting in the production of hydrogen. This process lends itself to a continuous process and studies are underway in this area. The following equations represent the process(5):

$$2CO + 2H_2 + Fe_3O_4 \rightleftarrows 3Fe + 2H_2O + 2CO_2$$

$$4H_2O + 3Fe \rightleftarrows 4H_2 + Fe_3O_4$$

Work on this process was sponsored by the Fuel Gas Associates, an organization that represents several energy companies.(4)

Bituminous Coal Research process. In this process, ground, dried coal is gasified at 1,100 pounds per square inch (gauge) with oxygen to produce methane. Heat from this stage is used to supply the steam carbon reaction heat in the gasifier. The process involves a shift converter, gas purification, and methanation. The process requires oxygen for the gasification and heat for the slag of coal ash at the bottom of the gasifier.(4)

Methanation process. After coal has been gasified, it is possible to produce a largely increased amount of methane from the products of this gasification. The process involves the production of methane from hydrogen and carbon dioxide by use of a catalyst. Figure 4 illustrates the methanation process.(4)

Toscoal process. This process is an adaptation of technology utilized in the production of oil from oil shale. Partially heated feed is heated to carbonization temperature by contact with heated ceramic balls. A trommel screen is used to separate the solid carbonization residue from the ceramic balls, which are recycled for reheating. The hot residue is cooled and this heat is used to produce steam needed to remove tar and water from gaseous components of product stream from pyrolysis drum.(6)

2.2.2 Processes Used in the Production of Synthetic Crude Oil

Much current research is concerned with coal liquefaction due to the need for substitute refinery feedstocks and clean fuel for direct use in boilers.(1) Some of the processes discussed are in operation; some are in development.

Bergius process. This is a German process which boasts 55% overall efficiency.(1) The hydrogasification technique reacts a mixture of finely ground coal and a hydrocarbon liquid with the hydrogen at $850^{\circ}F$ and 10,000 pounds per square inch. The product is separated into light, middle, and bottom portions. The middle portion requires further refinement using a catalyst. The bottom portion is strained and the liquid being used in the feed mixture. This process is very expensive.

COED process. The Char Oil Energy Development Process(7) employs a multi-stage fluidized-bed pyrolysis to yield a synthetic crude oil, a char product and a gas stream which can be processed to produce hydrogen, fuel gas, and liquid hydrocarbons. The process uses various numbers of states depending upon the type of coals. The product oil is hydrotreated to produce a synthetic crude. This process will easily lend itself to commercial use if the economics permit.

Fischer-Tropsch process. This process is a synthesis gas process in which coal is gasified completely to a product of a state which depends on the variable ratio of hydrogen to carbon monoxide. Different type products may be purified and passed over different catalysts in a temperature range of 570°F to 640°F at a pressure of about 450 pounds per square inch. The result is a mixture of paraffinic and olefinic products. The process has an overall conversion efficiency of about 38%. One existing process employs fixed-bed Lurgi gasifiers. "The major engineering problem is the removal of the large volumes of heat that are released when the gas is converted to a liquid by the catalyst."(1)

Project gasoline process. This process produces a refinery feedstock by first converting coal to liquid by hydrogen-transfer recycle solvent. Then a fluid-bed catalyst reactor is used to react the liquid product with hydrogen. The solvent is separated from this final product and recycled.

H-Coal process. This process is a Hydrocarbon Research, Inc. variation of the H-Oil process. A hydrogenator using an expensive cobalt molybdate catalyst produces a liquid-solid mixture and hydrogen. A flashdrum is used to treat the product. The ultimate product is a low-sulfur refinery feedstock.

Synthoil process. Like the H-Coal process, the Synthoil process is a low-ash, low-sulfur process. The hydrodesulfurization uses the turbulent flow of hydrogen (an excess amount of recycled hydrogen) to move a slurry of coal in a recycled portion of the product oil through a bed of cobalt-molybdate pellets at 2,000 to 4,000 pounds per square inch and 800°F. The sulfur is removed in the form of hydrogen sulfide which is converted to elemental sulfur for storage.

As the process may be operated at a much less extreme pressure than the Bergius process, the resultant produce should be much less costly.(1)

Pamco process. Another low-sulfur, low-ash fuel process, the Pamco process involves the hydrogenation of finely ground coal dissolved in a recycle stream at 1000 pounds per square inch. The product is a solid at room temperature and a liquid at 350°F; therefore, it may be burned as a boiler fuel if preheated. Two pilot plants which use this process are now being tested.

2.2.3 Overview of Process Capabilities

Even with this vast amount of research being carried on in the field of coal conversion, it is difficult to secure information on the processes, their efficiencies, and their economics. Many processes, such as Cogas, are in the development phase in which the security of proprietary information is of the utmost importance. For various types of coal, frequently reported efficiencies for coal gasification processes range from 56% to 77% thermal efficiency, with capital investment ranging from $275 million to $490 million in 1975 dollars. For coal liquifaction, reported efficiencies range from 60% to 75% and investment ranges from $265 million to $570 million. The processes for the production of methanol from coal have reported thermal efficiencies of 60% to 67% and capital investments of $318 million to $470 million.

2.3 DEVELOPMENT OF A SELECTION MODEL

Economic analysis is a wide-spread policy for decision-making. However, when making a management or engineering decision, one should realize that, if there are many factors which are pertinent to the decision, it is frequently very difficult to quantify all of these factors in dollars or any other common denominator.

Energy independence is very important to this country's future. Coal conversion is an alternative route to this goal. However, when considering the increasing awareness of industries' social responsibilities, it becomes obvious that economics is only one basis for evaluating coal conversion alternatives. In addition to an economic analysis, one must study the efficiency of the processes and all intangible factors. Utility theory can be used to analyze these factors.

The first step in this analysis is a determination of the intangible factors which could possibly affect the decision-making situation. See example below.

TABLE I

DESIRABILITY FACTORS

(1) Reliability (maintainability)
(2) Reserve Situation
(3) How Well Process Meets Pollution Requirements (Environmental)
(4) Do Products Meet Market Requirements
(5) Are There Markets For By-Products
(6) How Easily is Product Transported
(7) Input Requirement
(8) Adaptability
(9) Health and Safety
(10) Residue Disposal
(11) Management
(12) Public Acceptance
(13) Capacity Expansion
(14) Labor Requirement
(15) Plant Siting
(16) Conversion Technology
(17) Ecological Efficiency
(18) Back-up and Storage
(19) Sensitivity to Product Prices

A set of criteria for each factor should be established. For example, operating costs should be minimized. The criteria should be established according to the situation specifications. These criteria will be used in evaluating each process with respect to the given factor.

In any given situation, some factors will be more important to the decision-maker than other factors. Since all factors are not of equal importance, it is necessary to assign importance ratings(8) which will be used to rank the factors according to their relative importance. A scale of 0 to 1 or 0 to 100 may be used.

These ratings may be adjusted in order to improve the consistency of the importance ratings. Since there are 19 factors to be considered in the utility function to be used in evaluating coal conversion process, the following adjustment procedure is recommended:(8)

(1) List the factors in order of descending importance.
(2) Select one factor at random and assign an importance rating of 100 to it.
(3) Assign each remaining factor to one of several groups of about equal size. Add the selected (Step 2) objective to each group.
(4) Assign importance ratings to each factor by groups, keeping the rating of the selected objective at 100, and arrange in descending order.
(5) Compare the importance of the first factor in each group to the importance of all the rest together and follow the procedure outlined here. (Do not change the rating of 100 assigned to the selected factor.)

(a) If the first factor is more important than all the rest of the factors together, adjust its rating so that it is greater than the sum of the ratings of all of the other factors.

(b) If the first factor is of equal importance to all of the other factors put together, adjust its rating so that it is equal to the sum of the ratings of all of the other factors in the group.

(c) If the first factor is of less importance than all of the other factors put together, adjust its rating so that it is less than the sum of the ratings of all the other factors in the group.

(6) If 5a or 5b is the case, omit the factor in question and apply the fifth step to the next lower factor in the list.

(7) If 5c is the case, compare the importance of the factor in question to the sum of the importance ratings of all but the lowest factor in the list and proceed as in the fifth step. If 5c is still applicable, compare the factor in question to take the sum of all but the lowest two ratings, and so on, until the factor in question is being compared to the sum of the two ratings closest to the sum of the factor in question. At this time, proceed to Step 6.

(8) Continue the procedure until the rating of the third from the lowest factor has been compared with the sum of the two lowest ratings in the group.

(9) Make a combined list of the factors in order of descending importance. Adjust any difference in ranking from the initial list if that list is thought to be correct.

(10) Find the sum of all of the ratings and divide this into each rating and multiply by 100 in order to rank the importance of each factor on a scale of 0 to 100.

After the desirability factors have been properly weighted according to their relative importance, a measure of the desirability of each process may be given for each factor. An overall weighted utility score may be calculated to indicate the desirability of each process using the formula:(9)

$$U = \sum_{i=1}^{N} \left(W_i \sum_{j=1}^{M} D_{j,i} \right)$$

where U = utility

$i = 1,2,3,\ldots,N$ desirability factors

W_i = the weighted importance rating for i^{th} factor

$j = 1,2,3,\ldots,M$ alternative processes

D_j = the desirability score for the j^{th} alternative process

This model is a simple linear non-interacting mathematical model.

The last step in the development of the utility function is to list the processes in descending order according to their overall utility scores.

3. CONCLUSION

Coal conversion will play a major role in our future. This paper presents a thorough model for examining alternative routes to synthetic gas and oil from coal.

Efficient, practical coal conversion is one major step toward self-reliance.

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5. BIOGRAPHIES

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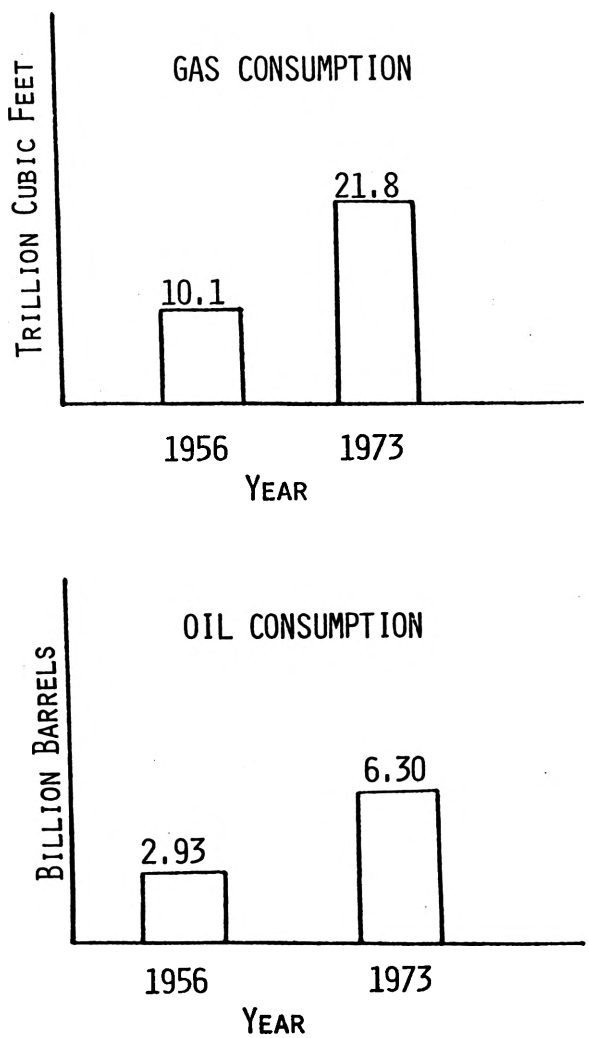

FIGURE 1.

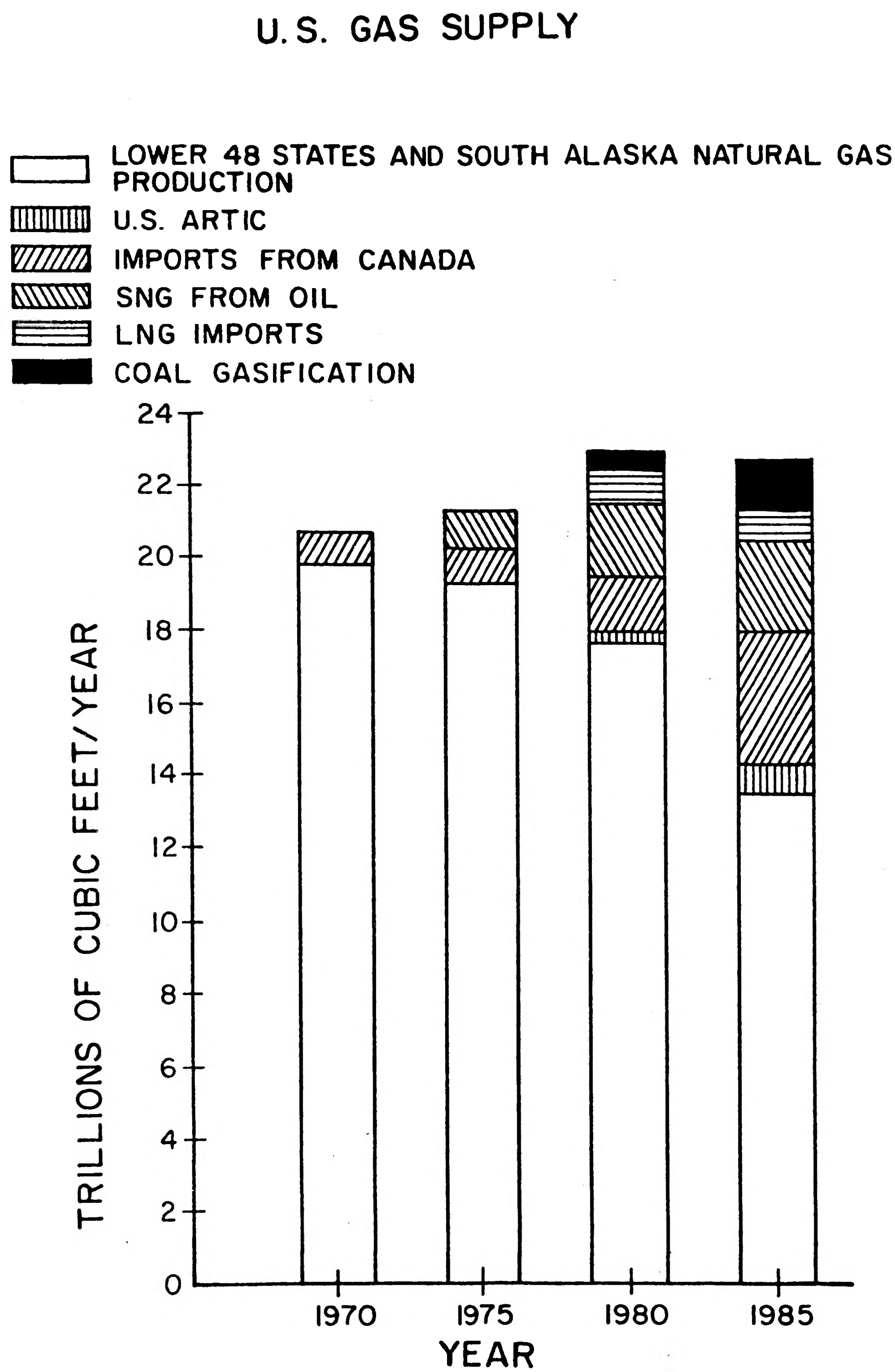
U.S. GAS SUPPLY
LOWER 48 STATES AND SOUTH ALASKA NATURAL GAS PRODUCTION
U.S. ARTIC
IMPORTS FROM CANADA
SNG FROM OIL
LNG IMPORTS
COAL GASIFICATION
TRILLIONS OF CUBIC FEET/YEAR
0
2
4
6
8
10
12
14
16
18
20
22
24
1970
1975
1980
1985
YEAR

FIGURE 2.

GENERAL GASIFICATION PROCESS STEPS

1. COAL $\rightarrow$ C + CH_4 + a mixture of liquids and gases

2. $C + 2H_2 \rightleftharpoons CH_4$

3. $C + 2H_2O \rightleftharpoons CO + H_2$

4. $C + O_2 \rightleftharpoons CO_2$

5. $CO_2 + H_2 \rightleftharpoons CO + H_2O$

Figure 3.

GENERAL METHANATION PROCESS STEPS

1. $\text{COAL} \xleftrightarrow{1000-1500\,°F} CH_4 + C + \Delta H$

2. $\Delta H + C + H_2O \xrightarrow{1700\,°F} CO + H_2$

3. $CO + H_2O \rightleftharpoons H_2 + CO_2 + \Delta H$

4. $C + 2H_2 \overset{1700\,°F}{\rightleftharpoons} CH_4 + \Delta H$

5. $3H_2 + CO \overset{\text{Ni CAT. } 700\,°F}{\rightleftharpoons} CH_4 + H_2O + \Delta H$

Figure 4.

Energy Conservation In Uniroyal, Inc.

By

John C. Madigan
Uniroyal, Inc.
Middlebury, Connecticut

ABSTRACT

In the last year, rapid developments have led to the establishment of industry conservation goals and monitoring by the Department of Commerce and the Federal Energy Administration, via the various industry associations.

Since 1972, Uniroyal has progressed more than half way toward the 1980 goal of 15% established for the rubber and chemical industries. This paper will describe details of the program with emphasis on new input, such as the computerized tracking method now in use.

Plant studies have provided an assessment of "base" loads vs. process loads, important when considering unit energy consumption. These vary, particulary with the climate and with the ratio of electrical to fuel energy inputs. Also, in-plant metering of steam has produced some surprises. Priorities for projects and lines of attack for conservation depend upon such analyses.

Of great importance is the energy content of raw materials and programs to reduce or recycle rejected portions.

A study of organization for conservation in various other companies was made to develop recommendations for improving the Uniroyal program. A composite of the best features will be presented.

INTRODUCTION

During the year 1974, the Federal Energy Administration and the Department of Commerce have been working closely with various industry groups to bring the matter of energy conservation into better focus. In most cases, the linking pin for this activity has been the appropriate industry association. Most manufacturers belong to industry associations and furnish them figures on various subjects, and often use these associations to assemble information and deal with matters of mutual interest--in particular with government bodies.

Thus, it was natural to use this connection to establish goals for conservation and to establish a format and channel for measurement of progress toward these goals. It was also thought by many that the establishment of voluntary goals and monitoring would reduce the likelihood of mandatory or arbitrary action on the part of the government.

Almost any measure of conservation has its own pitfalls. The preferred measure is unit consumption; that is, total energy consumption in Btu divided by pounds of production. The biggest pitfall in this is the problem of base load, as we shall see later. Another trap is change in product mix. Radial tires consume more energy in their production than conventional crossply tires, and the percentage of radials has been increasing right along. While radials save more than enough energy on the road to offset this, the tire producers' figures on unit consumption are penalized.

Btu's in fuels used are added to the equivalent electric power usually taken at 10,000 Btu/kwh. Adjustments are made for product mix and for OSHA/EPA required devices using energy.

Uniroyal, being in a variety of businesses, reports through several industry associations --for textiles through the ATMI, for chemicals through the MCA, and for rubber products through the RMA.

GOALS, 1974 RESULTS, AND FUTURE PLANS

Uniroyal has set a goal to reduce unit energy consumption 15% by 1980, using 1972 as the base year. This is in keeping with goals established by the various industry associations, after considerable discussion with the United States Department of Commerce and the Federal Energy Administration. That is not to say that we will necessarily be satisfied with that level of performance once it has been achieved. We intend to continue our efforts indefinitely.

Although our operations in other countries are also participating in the overall Company conservation program, they are not involved in the specific goals established for the United States. In Canada the government has begun similar activity through various industry associations, although this has not yet reached the same stage as in the United States.

Our facilities in the United States operated in 1974 at a unit energy consumption about 7% below that of 1972, in spite of the dips in the economy in the last quarter of the year. Where heating and air conditioning loads represent the major portion of the load, some rather striking accomplishments were recorded. Some examples:

1. In a large industrial park / warehousing complex which we operate in Ohio, we used 17.5% less electric energy in 1974 than in 1973. An even greater reduction was made in fuel over the 1973 heating season--average coal usage was reduced from 52 to 18½ tons/day.

2. In the new corporate management and research complex in Connecticut, electrical energy in 1974 was reduced 16% from 1973 and oil consumption, 42%. Both of the above kinds of reduction were made largely by changing operating criteria and establishing close policing of the operations.

3. A new computer-controlled, load-shedding system is being installed in the Connecticut complex and is expected to save an additional 15% in energy. The cost of installing such a system in any facility depends to some extent on the amount of centralized wiring and controls already existing. In this case, we had just about everything but the computer unit and soft-wear itself--therefore, the payout is very fast. We are evaluating the advisability of installing load-shedding systems in two factories, one of which is new and has a rather complete and integrated wiring system--the other is older and will require considerable wiring. In the older plant, about one-third of the cost would be in installation, including wiring. Nevertheless, a payout of less than two years is anticipated. Interestingly, not all of the energy to be saved is electrical. For example, some of the devices subject to periodic shedding are air-moving units (fans and blowers), many of which, when operating, are bringing in cold air and exhausting heated air. In these instances, electrical load-shedding will also reduce fuel consumption.

4. Other steps taken or planned by various plants include much more complete steam metering to pinpoint usage (which has already produced a number of surprises), reduction of air flow in buildings, substitution of low-energy fluorescent lighting for higher intensity fluorescent lamps, relocation of air intakes, tuning up boiler operation, installing stack gas heat recovery devices, changing to spot from area lighting, repairing broken glass windows with plastic, use of air-cleaning devices to allow more recycling, flash steam recovery, automatic shutdown valves on major equipment, replacing oversized motors, installing or extending condensate recovery systems, preheating raw water makeup with exhaust steam (e.g., from steam-driven pumps), reduction of mixing and curing cycles, improved cooling water systems and heating coil arrangements.

Our goals for 1975 are much more specific than last year and the year before, and our total company goal is an actual weighted composite of the goals of each plant. These, in turn, are made up of savings from specific projects, each of which has a time schedule and follow-up plan.

INFORMATION FLOW - COMPUTER PROGRAM

Early in Uniroyal's energy program, it was decided to redesign the format of the log sheets used at the factories, to accomplish four main objectives:

1. Establish uniformity of terminology and system.

2. Provide the plant engineer with data he needs.

3. Allow for monitoring by corporate engineering.

4. Build a data base for engineering design and for utility contract negotiations.

This redesign was done in a workshop held at Company headquarters in October, 1971, by a task force made up of plant, divisional, and corporate engineers, and placed in use at the beginning of 1972.

The result was a series of four log sheets for each plant so designed that they can be kept running for a full year. Each month's information is entered on a new line below that for the previous month. Samples of these log sheets are shown in Figures 1, 2, 3, and 4.

Initially, the key data from these log sheets were plotted on graphs. By the end of 1972, it was possible to include a 12-month's moving line for each of the factors being plotted:

Electrical Load Factor

Kilowatt Hours Per Pound of Product

Pounds of Steam Generated Per Million Btu Fuel Burned

Pounds of Steam Per Pound of Product

Several typical graphs were displayed at the April, 1974 UMR-MEC Conference. The maintenance of these graphs for 80 factories consumed excessive time, and at the end of 1973, a program was written to suit our computer configuration and provide a monthly printout. This printout presents data for the latest month and for 12-months moving, so that seasonal variations are eliminated. All plants and Divisions are included, and copies of the printout for each Division and plants within the Division go to each Divisional Coordinator and are available for use by corporate engineering staff. This is the general source of information on energy usage for management, industry associations, and government.

Besides the four factors mentioned above, the printout shows considerable other useful information, including Divisional progress toward goals. Sample divisional and plant pages are shown in Figures 5 and 6.

A diagram of the information flow described above is seen in Figure 7.

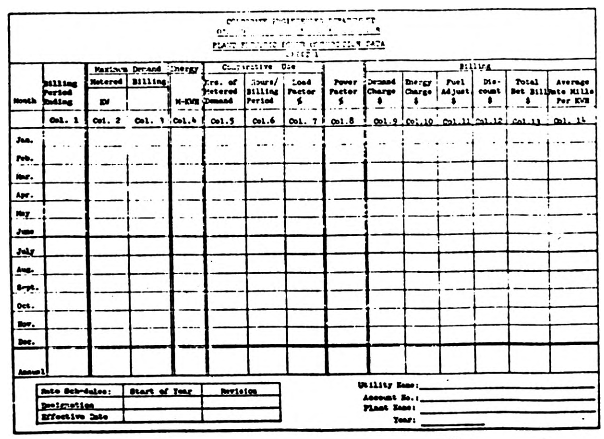

FIG. 1

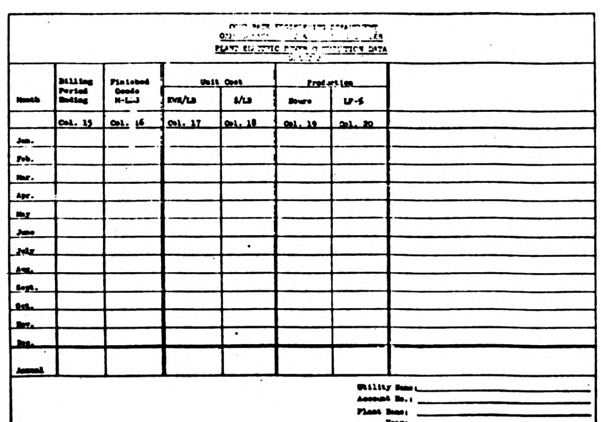

FIG. 2

[illegible]

POWER SERVICES REPORT

Steam and Water

Month	Prod. M lbs.	Steam Generated M lbs.	Fuel* Consumed	Fuel* Consumed	Fuel* Cost M $	Fuel* Cost M $	$ Steam / MM BTU	$ Steam / # Prod.	Fuel* Cost / MM BTU	Fuel* Cost / MM BTU	City Water / M Gals	City Water Cost $	Cal.C.V. / #Prod.	City Water Cost($) / M gal.
Jan.														
Feb.														
Mar.														
Apr.														
May														
June														
July														
Aug.														
Sept.														
Oct.														
Nov.														
Dec.														
Total														
Aver.														

*Enter Fuel category and units of measure for primary and secondary boiler fuel.

Utility Name: ____

Account No.(If Any): ____

Plant Name: ____

Year: ____

FIG. 3

[illegible]

NON-BOILER FUEL REPORT

Month	Fuel No. 1				Fuel No. 2				Fuel No. 3				Total Cost Boiler and Non-Boiler Fuel	Remarks
	Type (1)	Qnty. (2)	Cost (3)	Cost / MM BTU	Type (1)	Qnty. (2)	Cost (3)	Cost / MM BTU	Type (1)	Qnty. (2)	Cost (3)	Cost / MM BTU		
Jan.														
Feb.														
Mar.														
Apr.														
May														
June														
July														
Aug.														
Sept.														
Oct.														
Nov.														
Dec.														
Annual														

(1) Indicate Type: e.g., oil, coal, gas, etc.
(2) Indicate Units: tons, gals., lbs. (of fuel).
(3) Cost: Total dollars for this fuel.

Utility Name: ____

Account No. (If Any): ____

Plant Name: ____

Year: ____

FIG. 4

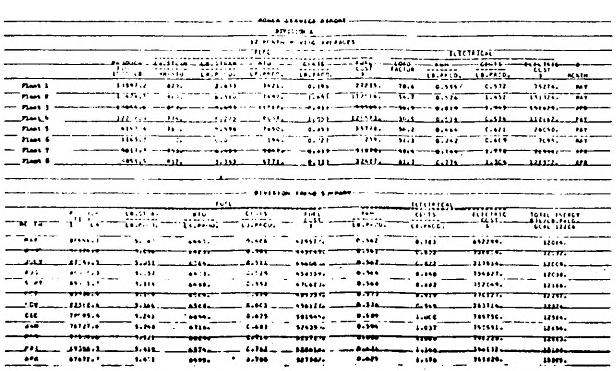

FIG. 5

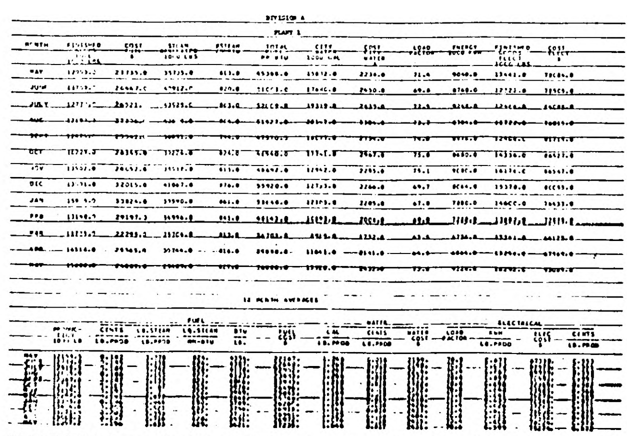

FIG. 6

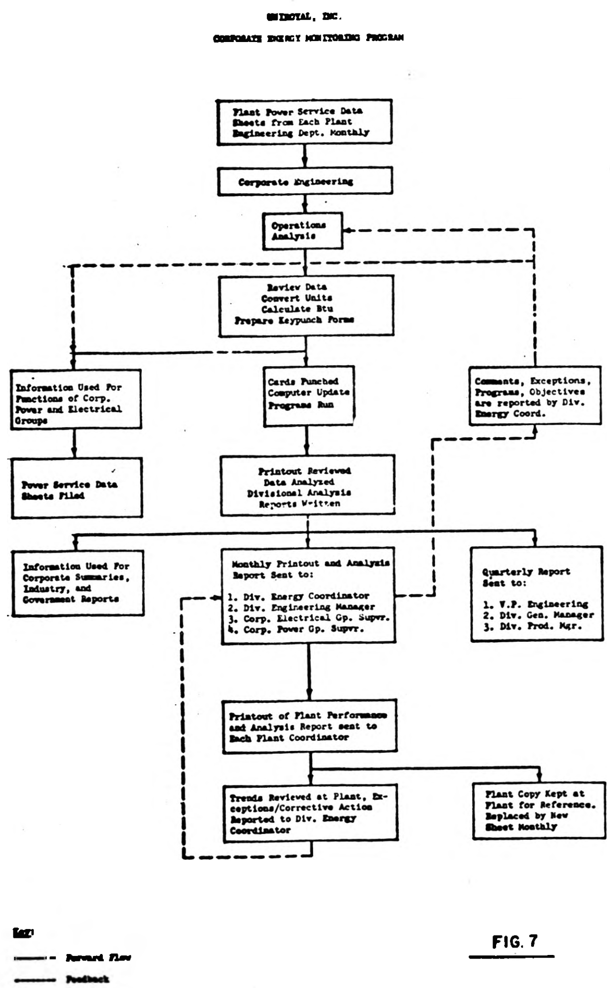

FIG. 7

BASE LOAD

Intuitively we would expect that energy consumption in a factory has both fixed and variable components. The variable portion goes up and down pretty much with the rate of production, while the fixed portion stays relatively stable. I say relatively because if we count building heating and lighting in the fixed portion, this will obviously vary with season of the year and with climate. To illustrate, the graphs in Figure 8 show the unit usage, in one division (for plants) of electricity and steam varying substantially with production rate. At the lower production end the unit usages become asymptotic--there is a base load that is required regardless of production. As production increases, the usage gets better and better, the rate of change being of function of the base load.

To get at this in greater depth, our Power Services Department determined the Sunday (no production) steam loads for various seasons, production loads at various production levels, and "degree days" for each day in the year at a number of factories.

The Sunday load in summer can be considered as the closest figure available to represent base load, because it is the residual load on a non-production, non-heating day. In summer, the Sunday load is strictly base load, but in winter it is base load plus heating load. By plotting Sunday loads against atmospheric temperature, we obtain a curve which is flat at temperatures above 65 degrees F and sloped at temperatures below 65 degrees F. This indicates that heating systems are turned on at 65 degrees F, and the heating consumption follows a linear relation to outside temperature. From the slope of the curve, we can compute the increase in hourly load per degree drop, which when multiplied by 24 represents steam consumption per degree day. Knowing the number of degree-days for the area, we can compute the steam consumption used for heating. The average Sunday load in summer also represents idling steam consumption on weekends and holidays. Having derived total heating steam consumption and total idling steam consumption, we can say that the balance of the steam generated during the year was used for production, which can be computed by difference.

This kind of analysis can help one to decide whether, in spite of low production levels, a plant is actually improving its energy consumption performance. Also, it can help to point the direction for concentration of effort.

Graphical representation of typical figures obtained for various plants which are generally similar are shown in Figures 9 and 10. A tabulation of the numbers is also given in Table 1. At this point we can make the following judgments:

Plant B needs to sharpen up its weekend (no load) situation; Plant C should look to its production operation; Plant D seems out of line on heating load; base load in all plants looks like fertile ground for searching out improvements.

ENERGY IN MATERIALS

Opportunities for energy conservation lie not only in the manner of use of conversion energy (that is, the fuel and electric power expended) in making a product from raw materials but also in the materials and supplies themselves. Here we are concerned with the amount of energy that has already been expended to bring the materials from their natural sources to the factory door, including extraction, transportation, and processing. Alternatively if the materials are substitutes for or derivatives of fossil fuels, heats of combustion can be used. This would be on the assumption that a saving of material would relieve the shortage of fossile fuels by an equivalent Btu content somewhere in our economic system.

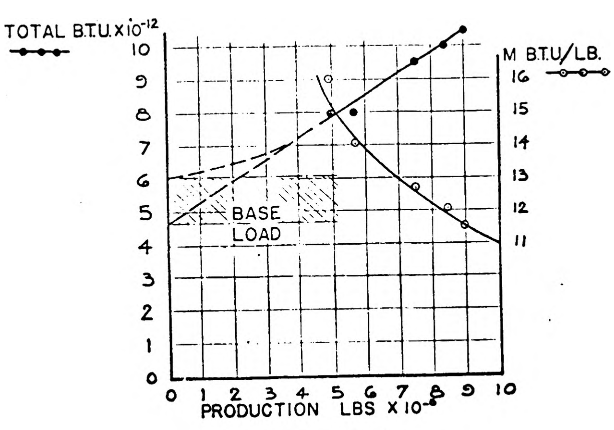

FIG. 8

STEAM LOAD CHART
NORTHERN PLANT

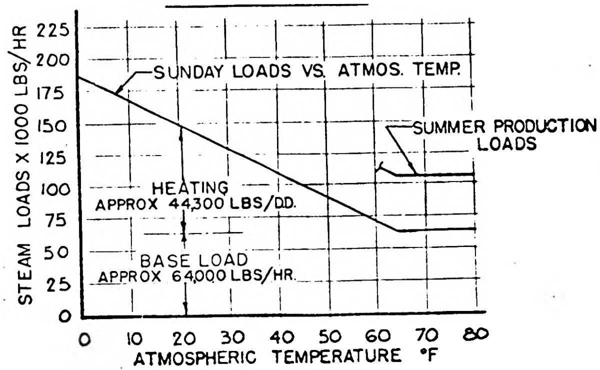

FIG. 9

STEAM LOAD CHART
SOUTHERN PLANT

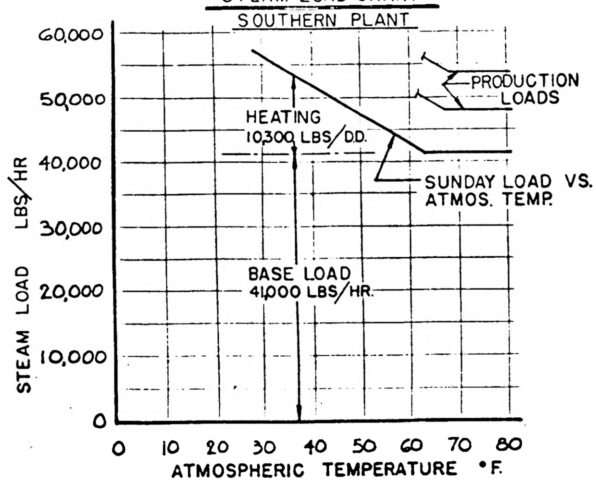

FIG. 10

TABLE 1

STEAM LOAD ANALYSIS

PLANT	A	B	C	D	E
Peak Summer Load Lbs/Hr.	82,000	75,000	210,000	130,000	58,000
Normal Summer Load Lbs./Hr.	70,000	51,000	170,000	108,000	45,000
Weekend Load Lbs./Hr.	19,000	41,000	85,000	64,000	17,000
Weekend Load / Normal Load	27%	80%	50%	59%	38%
% Steam for Production	87%	70%	66%	47%	64%
% Steam for Weekend & Holidays	10%	24%	17%	16%	10%
% Steam for Heating	3%	6%	17%	37%	26%
No. of Degree-Days	3,500	2,200	5,989	7,839	7,020
Plant Floor Area Sq. Ft.	1,056,700	1,379,719	3,080,995	1,752,321	1,167,185
Steam Required Per Degree-Day	3,927	10,300	33,000	44,300	14,400
Steam Required Per Degree Day Per $Ft.^2$	.004	.007	.011	.025	.012
Cost of Steam $ Per M Lbs.	$ 0.71	$ 0.84	$ 1.05	$ 1.58	$ 1.55
Boiler Effic. %	83%	82%	81%	76%	83%
Total Steam Generated 1974 - M Lbs.	473,429	413,193	1,363,076	1,015,061	417,461
Steam for Production (W.E.'s & Htg. Excl.)	411,883	289,235	899,630	477,079	267,175
Total Product 1974 M Lbs.	159,029	130,882	180,516	170,713	81,952
Lbs. Production Steam / Lb. Product (1974)	2.59	2.21	4.98	2.79	3.26

TABLE 2

ORGANIZATION FOR ENERGY CONSERVATION

SUMMARY OF FACTORS BY COMPANY

Company	1974 Sales*	No. of Plants	No. of Employees	Chief Exec. Support	Formal Policy Council	Responsible Staff Official	Corporate Coordinator Dept.	Corporate Coordinator Staff	Corporate Coordinator Time	Corp. Engin. Service	Results Affect Line Pay	Plant Goals Set By	Div. Coord.	Plant Coord. Individual	Plant Coord. Committee
A	3,498	65	60,926	Yes	Yes	Engineering Director	Engineering	3	Full	Yes	No	Plant	Yes	Yes	Yes
B	4,939	142	53,300	Yes	No	Exec. V.P. Manuf. & Engineer'g.	Tech. Center Admin.	0	Full	No	No	Plant	Yes	Yes	No
C	1,744	76	38,000	Yes	No	V.P. Corp. Develop't.	Development	0	Part	No	No	Plant	Yes	Yes	No
D	5,320	500	110,000	Yes	Yes	Executive V.P.-Staff	Feedstock & Energy Planning	0	Full	No	Yes	Plant/Division	Yes	Yes	Yes
E	899	9	5,820	Yes	No	Director Corp. Engin.	Engineering	1	Part	Yes	No	Plant	-	No	Yes
F	961	31	15,300	Yes	No	Vice Pres. Manuf'g.	Manufacturing	0	Part	No	No	Plant	No	No	Yes
G	1,929	39	54,410	Yes	No	Vice Pres. Manuf'g.	Manufacturing	1	Part	Yes	No	Plant/Division	Yes	Yes	Yes
H	5,256	105	154,166	Yes	No	Exec. V.P. Manuf'g.	Engineering	-	Part	Yes	No	Corp. Engin.	No	Yes	Yes
Uniroyal	2,301	89	64,000	Yes	No	Vice Pres. Admin.	Engineering	3	Part	Yes	No	Plant	Yes	Yes	Yes

* Millions of Dollars

Three possibilities, at least, present themselves as energy saving through materials--namely, substitutions of material with lower energy contents, reduction of waste and recycling. The first of these considerations depends on the assumption that material cost reflects energy content and, other things being equal, we seek the lowest cost raw material. The other two would obviously be important at any time, regardless of energy content.

Now, however, the skyrocketing cost of energy (and also of materials) as well as the increasing shortages of fossil fuels emphasize a dimension of materials and supplies that is becoming more and more prominent. Consequently, we have embarked on a program of accounting for materials on the basis of energy content as well as on cost. Programs to reduce scrap, increase recycling, and substitute materials are now being considered in the light of energy conservation and reported on as adjuncts to conversion energy savings.

To give a measure of the significance of this, we have found, for example, that the energy content of the materials contained in a tire are approximately twice the amount of energy (fuels and electric) that we use to produce a tire from them.

As we get further into this question, interesting ramifications develop. For example, it is a pretty well accepted fact that production of a radial tire consumes more conversion energy than production of a cross-ply tire, perhaps as much as 15% more. On the other hand, a set of radial tires on an automobile may increase gas mileage by up to 10% and a radial tire will out last a cross - ply tire by quite a margin. The amount of energy saved in operation of the car is considerably more than the additional energy used to produce the set of tires.

When we think of material substitutions to save energy, one that comes to mind is natural rubber as against synthetic. On the other hand, natural rubber usually takes more energy for breakdown and mixing into a compound. There are controlled viscosity types of natural rubber available but these are more costly. Obviously, this kind of tradeoff has to be worked out with some care.

As an example of a supply item that has offered an opportunity for energy conservation is the solvent used for making rubber cements. Primarily for environmental considerations, many plants have switched to water-based cements and in so doing have saved the heat content of the solvents, which were usually petroleum-based, representing a not inconsiderable quantity of energy.

ENERGY BALANCE - PILOT PROGRAMS

The concept here is simple -- first to subdivide a process into all of its steps, determine the energy input and output of each step on a "textbook" basis, add up all the pluses and minuses, and arrive at a "textbook" net energy usage; and second, to actually measure the energy input (or output) step by step and see how close it is to the theoretical.

The point is that this kind of an analysis will reveal something beyond what we have been measuring up to now -- which has been the actual usage of energy on a current basis, compared to some base period, such as 1971 or 1972. While we may be doing better than 1971 or 1972, we may be missing some rather large opportunities for real conservation.

If the above approach is taken carefully for each step of the process, we believe the results will pinpoint areas for intensive study and for process modifications.

We are presently doing this on one of our chemical processes and one process that involves mixing and vulcanization, not primarily chemical. We can only say at this time that we expect the pilot studies to enable us to polish the technique and tell us whether it is worthwhile to carry it out on all of our various processes.

ORGANIZATION FOR CONSERVATION

In a large company consisting of several divisions and numerous plants, it is important to have a chain of command that is concerned with energy conservation from the top of the house down to each factory worker. This is such a specialized and important effort that each organizational level needs someone assigned specifically to look out for it. Most companies recognize this.

Beyond this generality, however, we noticed that there were some variations from one company to another in the way they were organized, and we decided to look into this a little further. We selected eight large companies which were reported by various government agencies to have accomplished more than the average in conservation, and obtained a description of their organization. Our idea was to determine what seemed to be the best features of each and then to use these to improve our program, if applicable.

The results are shown in Table 2.

None of the companies except Uniroyal is identified. While there are a number of details behind this summary, the best features seem to be as follows:

Formal Energy Policy Council

Engineering Vice President Responsible for Conservation

Full-Time Coordinator in Corporate Engineering Department

Divisional Coordinators

Plant Coordinators

Plant Committee or Task Force

Good features that some or all companies had, in addition to the specific organization structure, included:

Personal Involvement of the Chief Executive

Conservation Included as a Factor in Line Management Compensation

Joint Goal-Setting (as against super-imposed goals)

Some of the above features obviously depend on the basic company structure. If there is no Corporate Engineering Department, the Corporate Coordinator must be under some other Corporate Vice President. If there is no formalized management-by-objective compensation plan, there would be no way to include a factor related to energy conservation

As a result of this analysis, a recommendation was made to establish an Energy Policy Council in Uniroyal. This is receiving consideration at this time. Otherwise, our organization pretty much incorporates the applicable good features found in this investigation.

ENERGY CONSERVATION PROGRAM AT RALSTON PURINA

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Abstract

While the food industry as a whole uses only about 5 per cent of total manufacturing energy, we at Ralston Purina Company recognize our dependence upon energy and the importance of a strong energy management program. Last year, as part of this program, we established and implemented an energy conservation program designed to identify opportunities for conservation.

The major thrust of this program has been directed at manufacturing facilities where usages can be traced, wastes detected, and appropriate action taken. These are separate from a general overall corporate effort to make employees more energy conscious in every phase of their duties.

Manufacturing facilities are surveyed by a conservation team. From these surveys, economic evaluations are made to determine justification of adding heat recovery equipment on steam generators, changes are reviewed in production procedures to optimize energy usage, and improved maintenance procedures are evaluated to eliminate waste.

The title of my paper has been listed as "Energy Conservation at Ralston Purina," but I feel that a little background discussion of energy usage in our industry might be of interest to all of you.

The food industry uses only about 5% of manufacturing energy and has been ranked as fourth in usage when compared with primary metals, chemicals, and petroleum refining.

Some interesting informational data on the consumption of energy in the U.S. food system was presented in an article by Dr. John S. Steinhart and Carol E. Steinhart in SCIENCE magazine dated April, 1974. A lot of complex data beyond the scope of today's meeting is presented in the article, but two charts based on that data are being presented to help emphasize the importance of energy conservation in the food industry. Figure 1 shows total energy used in the U.S. food system. Commercial and home, farm, and processing industry have been accented to show their relative values. Our (Ralston Purina) usage would be a portion of the processing industry group. Figure 2 shows how energy subsidy to the food system is increasing. The continued upward slope of the curve should be of concern to all of us.

Ralston Purina does have an active conservation program which is designed to be effective in reduction of energy use throughout the corporation by use of good operation, maintenance, and design practices. The major thrust of this program has been directed to manufacturing facilities where energy consumption is monitored, conservation efforts applied, and results reported for evaluation. Energy conservation surveys have been made by Corporate Engineering teams at many of our operating plants to assist them in locating areas of conservation challenge and with implementation of conservation ideas. Each major plant has its Conservation Committee and each domestic operating division has its own Energy Coordinator who reports to our Corporate Energy Department headed by an executive officer. The divisional Energy Coordinators are high level operating management people who have the responsibility for efficient use of energy in their respective divisions.

For the most part, the operation and maintenance category involve an analysis of energy-using equipment by the Corporate Engineering survey team to determine optimum performance. Functional process changes are also analyzed by our Process Engineers for energy-saving potential.

The biggest use of purchased oil and natural gas fuels is in steam generation. The steam generation is by boilers that would be small when compared to industrial packaged water tube boilers of the 10,000 #/hr. to 200,000 #/hr. category. Corporate-wide, our boiler sizes range from 1,000 to 75,000 #/hr. With the exception of one coal-fired unit, all are gas- or oil-fired. As a conservation effort diligent effort has been made to increase the efficiency of these boilers by reduction of excess air in the process of combustion. The combustion control systems are of the positioning type which were chosen for their simplicity which contributes well to safety and reliability (Figure 3). A little extra flexibility was added to some of these systems in the past by having a little extra excess air in case it was needed. A careful analysis of these boilers with a continuous portable test analyzer, monitoring for free oxygen and combustibles in the products of combustion will allow excess to be reduced to optimum. An example of what excess can do to fuel savings is shown in Figure 4. Resulting savings in our plants varied from 1 to 4% on the boilers analyzed.

Electrical energy usage is primarily related to motor loads for grinding, pelletizing, extruding, conveying, and pumping. Motor sizes vary from 2 to 200 HP. Good design practices have been implemented to keep from oversizing electrical motors, thereby eliminating low efficiency and low power factor. Plant power factors are always evaluated for improvement. During plant energy conservation surveys, the plant's electrical contract is reviewed to determine if we are obtaining the most energy for our dollar and if our production schedules can be modified to allow the utility to best use their available generating facilities. Off-peak operation is always evaluated. We have gotten cooperation of the utilities in analyzing these possibilities. Some of the easiest savings, however, are realized by good conscientious programs of turning off idle equipment.

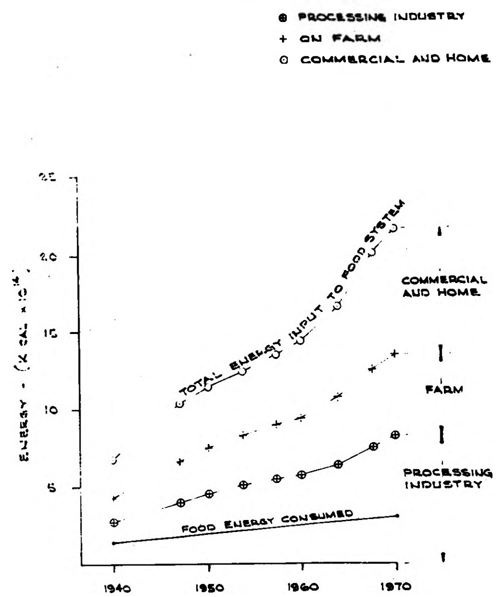
Steam is an indirect source of heat to some processes but some of our products require heat at higher temperatures than that achievable from saturated steam pressures available. Specifications of quality, texture, cleanliness, etc., require natural gas to be fired direct into an air stream to provide high temperature air for the process. The limited supply of natural gas in some plant areas has led to fuel-conversion studies in design that allow us to save premium fuel such as natural gas but increase the total fuel usage (Figure 5). Relating this back to Figure 2 shows that we have now increased the energy intensity by approximately 2.0 and the energy cost factor by 5.0. This is a conservation measure that does not have immediate economy payback but allows us to keep operating our plant at an increased cost of product.

The previous examples show that

under present-day fuel situations, efforts at conservation and fuel conversion may have the net result of an increase in energy consumption.

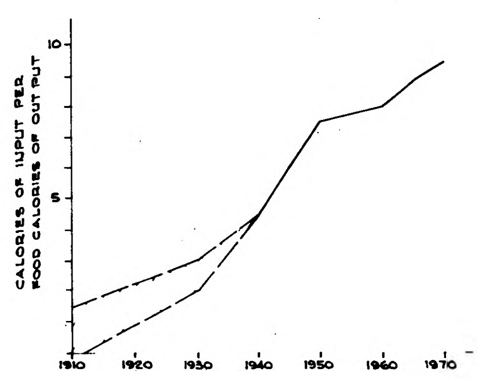
Emphasis has been placed on energy conservation by top-level management at Ralston and it is getting attention at all levels down to the individual Energy Conservation Committees in our plants. A few examples of Ralston Purina Company total efforts have been given in this paper. These examples have been limited to those in which I have been directly involved. I have not defined the work of our R & D Department which is continuously looking at new and old products for the least energy-intensive manufacturing route. I have not covered design efforts made by other members of our Corporate Engineering Department, all of which contribute to our total Corporate effort.

In conclusion, we might take another look at Figure 1 to re-emphasize the total challenge of which each of us is part. Each time any of us drives 5 blocks to the supermarket in his 300 HP automobile to get a loaf of bread, he adds to the energy-intensity of the system; each time the farmer delivers to the market, a load of dirty grain which must be mechanically cleaned, he adds to the intensity. Each time any of us demand that our food be packaged more conveniently to make our lives easier, we can add to the intensity. Finally, I would like to quote a statement by the aforementioned author as a closing thought. "Food production starts with a natural material, however later modified. Injections of energy (and even brains) will carry us only so far. If the population cannot adjust its wants to the world in which it lives, there is little hope for solving the food problem of mankind. In that case, the food shortage will solve our population problem."



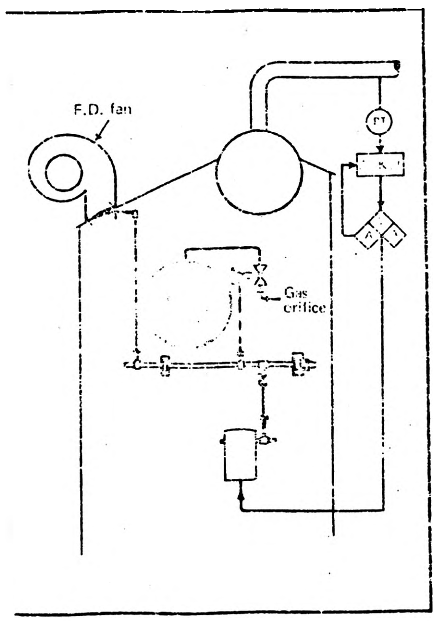
ENERGY USE IN FOOD SYSTEM

Figure 1



ENERGY SUBSIDY TO FOOD SYSTEM

Figure 2



Jackshaft combustion control

Figure 3

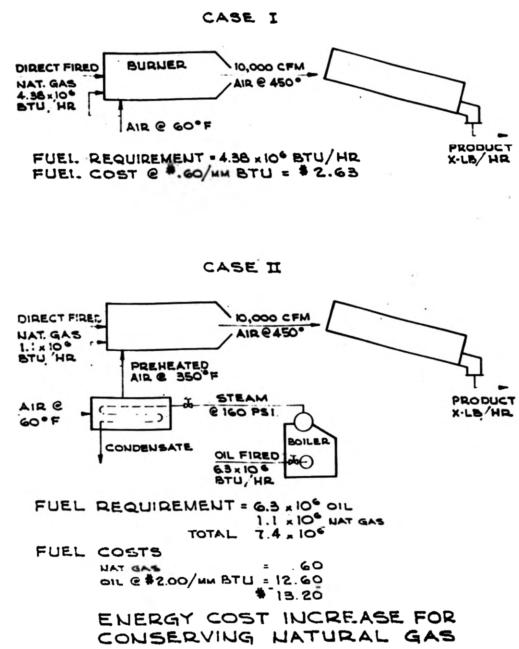


Figure 5

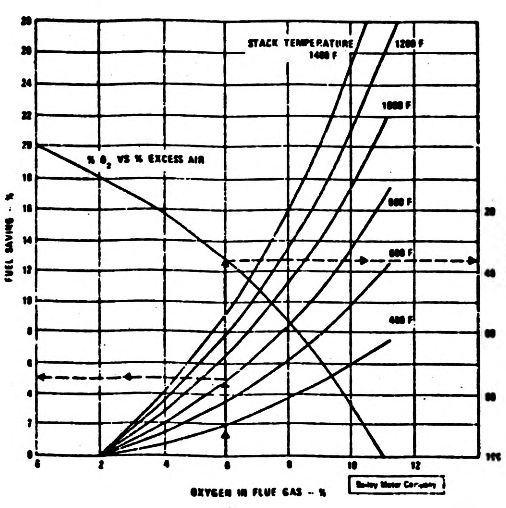


Figure 4

BIOGRAPHY

GEORGE A. BOSSMAN earned his B.S. in Mechanical Engineering from the University of Missouri, Columbia, in 1953. He is registered in the State of Missouri; a member of the St. Louis Engineers' Club and the Instrument Society of America.

Mr. Bossman has worked as a Design Engineer at Laclede Stoker Division, Tower Grove Foundry and as Sales and Service Engineer, dealing with the application of Control Equipment at Bailey Meter Company Division, Babcock & Wilcox Company.

He is presently Energy Conservation Engineer for Ralston Purina Company, promoting energy conservation programs and training personnel in the conservation of energy.

ENERGY CONSERVATION AT MONSANTO

Ray E. Doerr
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We at Monsanto want to thank you for the opportunity to tell you about our energy conservation program. We are proud of our accomplishments to date, and are very optimistic regarding plans for the future in energy conservation.

Through our five operating companies and supported by corporate departments, Monsanto directs the conservation efforts at 50 locations in the United States. We also have a very active conservation program in Canada and Europe.

As you can imagine, we are a very large consumer of energy in the forms of electricity, oil, coal and natural gas. Our annual U.S. expenditure for purchased energy in these forms will approach $250\overline{M}$ in 1975.

As a successful company over the years in a highly competitive industry, we have had utility and process improvement programs. The motivation of these programs was to reduce our operating costs and improve profits. However, these programs did result in substantial energy savings. Now Monsanto has no choice but to be committed to energy conservation because of the potential energy savings in the face of sky-rocketing energy costs. Today many of our plants have experienced a 300% increase in their fuel costs since 1970, and some plants as high as a 500% increase. Insofar as the United States is concerned, we are also committed to a Federal Energy Administration, chemical industry, energy conservation goal. Therefore, Monsanto must have a strong conservation goal.

Monsanto's formal conservation program was organized in August 1973. Monsanto assigned the responsibility for organizing and coordinating our corporate energy conservation program to our Corporate Engineering Department. As coordinator of the program, I report to an Energy Advisory Board. This board is made up of representatives from our five operating companies, Corporate Engineering Department, and Energy Materials Management. This advisory board deals with energy conservation, fuel selection and energy utilization. Each operating company is responsible for the implementation of its own conservation program.

The Federal Energy Administration has a chemical industry goal which Monsanto participates in. The FEA goal is to reduce our energy consumption rate (BTU's per unit of output) by 15% between 1973 and 1980 as compared to the base year of 1972. The government has made it very clear that some companies will have difficulty achieving 10%, while others must achieve 25% if the overall chemical industry is to meet the 15% goal. The FEA program is a voluntary program, but industry has been warned that if it does not cooperate, FEA will make the program mandatory. FEA has requested information on companies' energy conservation programs. Also they are soliciting a commitment from each company to establish a higher, long range, conservation goal. FEA representatives have visited one of our larger plants and our world headquarters in St. Louis to informally review our conservation program. As energy conservation results from industry begin to emerge, FEA will audit companies' conservation programs. The evidence is mounting that we will be living daily with the FEA, just as we do now with EPA and EEO agencies.

The Manufacturing Chemists Association has an agreement with FEA, whereby initially MCA would develop a measurement system, based on BTU's per unit of output as compared to 1972. Also, each chemical company would report its energy savings to MCA. MCA would average the savings and report the overall chemical industry performance to FEA. In March 1975, Monsanto made its first report to MCA. MCA averaged the chemical industry's performance through 1974 as compared to 1972 and reported an 8% savings to FEA.

When we started our conservation program, we did not have sufficient data to use the BTU per unit of output method, and consequently, to obtain a rapid response, we went to the activity method. This method measures BTU's of energy saved during the year from conservation, as compared to the energy used.

Monsanto now uses the FEA energy rate method (BTU per unit of output). The activity method generally gives a higher percent savings than the energy rate method. One of the reasons for the difference is that the energy rate method does not compensate for changes in energy efficiency as the production rate varies. Changes in production rate will have a major effect on percent energy savings. Therefore energy savings, using the energy rate method, will be low in 1975 because production rate has been low in 1975 as compared to 1972, even though conservation results were outstanding. The activity method is not affected by changes in production rate because it deals only with energy savings resulting from conservation activities.

To achieve the FEA goal by 1980, Monsanto management has approved certain positive actions relative to conservation. The first deals with reducing energy consumption in our existing plants. The routine energy saving activities like dialing down thermostats and repairing steam leaks have been essentially completed. Also some of the more obvious process changes have been completed. The tougher problems are ahead of us. We are now intensifying energy audits of our major energy consuming plants, and identifying and approving projects to further improve the efficiency of our operations to save energy. Many of those projects have been identified.

The second thing we are doing is developing processes and designs that will consume 15% less energy per unit of output. In most cases this will involve even more long range planning of projects, involving early consideration of energy requirements during research or process development. For every capital project, an energy statement has to be prepared. The statement must cover:

(1) Energy availability
(2) Energy and utility costs for evaluating project capital alternates
(3) Product energy rate for the project and the existing product energy rate
(4) Percent reduction in energy rate

As a result of increased energy costs, new technology, and energy awareness programs, it is not uncommon for the energy rate of new projects to be reduced by 30%.

For our existing plants, Monsanto is committed to capital programs to improve the energy efficiency of our existing processes. Also computers are being used to monitor utility usage to determine load optimization, efficiency, and scheduling of overhaul due to drop off in equipment efficiency. At one location, a computer is used to monitor the plant electrical load and to shed non-critical electrical loads on a selected basis to prevent establishing a higher electrical demand. This is another approach to saving energy.

At Monsanto's World Headquarters this past year, a change was made in our refrigeration system for air conditioning to save electrical energy. A thermocycle system was installed on two 2000 ton refrigeration machines at the Research Center complex. The thermocycle system will permit shutting down a 2000 horsepower motor and operating a 10 horsepower motor in its place to supply the winter refrigeration load. The thermocycle system will save 2 million kilowatt hours a year, reducing Monsanto's electric bill by $50,000. Part load refrigeration capacity is made available during the winter without the use of the compressor by the use of cold cooling tower water.

A large number of innovations have been made to reduce the energy consumption in our process departments. For example, one operating company research and development department, working with Engineering, developed a manufacturing process change that in 1974 saved over one trillion BTU's/year or $1.5 million in electricity and fuel at one of our plants.

Also in 1974, at another Monsanto plant, $1.2 million savings in purchased energy resulted from the installation of a new low pressure process, replacing the old inefficient high pressure process. In another plant, $364,000 in purchased gas was saved by the installation of additional heat recovery surface in the reformer convection section, and by the burning of off gas in the reformer furnace. In another department, a $354,000 saving was realized by the replacement of carbon steel superheater tubes with alloy tubes. This permitted higher temperature process operation, resulting in reduced steam usage and higher conversion with increased production.

In 1974, $2.7 million energy savings have resulted in our steam generation facilities from improved combustion efficiency mainly by the reduction in excess air for combustion in twenty plants, burning of waste streams and off gases in place of primary fuel in three plants, and the installation of heat recovery surface in four plants.

As a part of our conservation program, we have developed employe awareness programs. One such program was the employe energy conservation ideas contest held during February, March, and April 1975 for more than 80 Monsanto United States locations. Monsanto's president, John W. Hanley, announced the program in a letter sent to employes. Elements of the program included specially prepared bulletin board posters, paycheck stuffers, localized news releases and an energy display. Fifty $500 U.S. Savings Bonds were awarded to employes submitting the best energy saving suggestions in on-the-job or off-the-job categories.

Monsanto has also produced a 25 minute film on "Energy Conservation At Monsanto". This film is intended primarily for showing to plant employes. It is designed to build an awareness for energy conservation and to communicate ways through which it can be achieved. In the film, Mr. J. W. Hanley, president of Monsanto, strongly emphasizes conservation and urges all employes to participate.

WIND ENERGY CONCENTRATORS*

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Abstract

This paper presents two alternatives to the shrouded propeller wind energy concentrator. Their operation is based on generating a low pressure area, with high local wind velocity, around the windmill rotor.

The two types of wind energy concentrators considered are: (1) the "obstruction type" concentrator where a vertical cylinder or vertical flat surface is used to produce high local velocities around two counter-rotating vertical axis rotors, and (2) the "vortex type" concentrator where a horizontal vortex is generated by a vertical high lift wing of finite span. The high local wind kinetic energy inside the vortex is harnessed by a horizontal axis rotor.

The performance parameters such as the power concentration ratio and the associated area ratio have been determined theoretically. Some preliminary experimental data are included.

Nomenclature

a = radius of maximum rotational velocity in vortex.

A = dimensionless total concentrator plus turbine area = $1 + \frac{4S}{\pi d^2}$.

AR = wing aspect ratio $2b/c$.

b = semi wing span.

c = mean aerodynamic wing chord.

C_L = average wing lift coefficient.

c_p = pressure coefficient based on free wind speed.

c_{pav} = average pressure coefficient around windmill rotor.

D_i = semi wing span induced drag.

d = windmill rotor diameter.

e = span wise loading efficiency factor.

f = rate of vortex rotational kinetic energy passing through an area with diameter d and divided by D_i.

K.E. = kinetic energy.

p = pressure.

R = wind power concentration ratio.

r = radius in vortex.

S = concentrator wing area = bc.

U_∞ = free wind velocity.

V = local velocity.

V_{av} = average velocity at rotor inlet.

V_θ = vortex tangentional velocity.

$V_{\theta av}$ = average vortex tangential velocity at rotor inlet.

w = width of two dimensional concentrator.

Z = ratio of induced drag to free wind kinetic energy at turbine inlet.

Γ_o = bound vortex strength.

δ = boundary layer thickness.

ρ = density.

INTRODUCTION

The search for finding more economical methods for harnessing available wind power has found renewed interest in view of the rising fuel costs. Commercial type wind power generating stations must be large in size because of the generally low density of the wind

*Research in part funded by NSF Grant Number: AER 7500367-000

kinetic energy. This results in a low power output per square foot of wind machine. The existing commercial type wind power generating stations require large rotor frontal areas with high capital investment and maintenance cost. A large rotating rotor might not be aesthetic in appearance and the environmental impact of wind power generating stations may limit their use. These problems might be reduced if the available wind energy is concentrated locally by either natural or man-made nonrotating objects, such as mountain tops, mountain passes, corners of buildings, the top of a sloping wall, etc.

None of these natural or man-made wind energy concentrators increase the total pressure of the wind, but they create an area of low pressure around the windmill rotor. The local wind kinetic energy increases in this area of low pressure and the amount of wind power harnessed per square foot of the rotor area can be increased two to five fold. This increase is named the concentration ratio R. The area of low pressure around the rotor can be created by a nonrotating wind energy concentrator adjacent to the rotor. The area of low pressure around the rotor should be exposed to the incoming wind with a minimum of viscous losses. None of these nonrotating wind energy concentrators increase the stagnation pressure of the wind. Only the dynamic pressure is increased locally by lowering the static pressure around the rotor. There are basically three methods by which a local area of low pressure can be generated.

(1) A mountain pass, when aligned with the wind experiences a venturi effect with high velocity in the narrow passage. Shrouded windmill propellers are designed to operate on the same principle with the rotor placed at the minimum area inside the shroud, see Reference 1 and Figure 1. The flow passage must be properly aligned with the direction of the wind. The wind energy concentrators based on this principle are here referred to as "Venturi Types."

(2) Single mountain peaks present an obstruction to the flow. The air is forced to deflect and flow around the obstruction. The resulting flow curvature sets up a pressure gradient perpendicular to the surface and creates high and low pressure regions on the windward side of the mountain. The flow around a cylinder at the point of maximum cross section, would speed up to twice the wind velocity if the flow were inviscid. In a real fluid the point of maximum velocity occurs slightly upstream of the maximum cross section. A flat plate placed perpendicular to the wind also experiences a very low pressure near the edges (see Figure 2 taken from Reference 2). Note the cylinder can remain stationary but the rotors and the optional flat plate sections must align themselves with the wind direction. The wind energy concentrators based on this principle are here referred to as "Obstruction Types".

(3) Tornados are vortex type rotational flows. The curvature of the flow sets up a radial pressure gradient which results in a low pressure region in the center of the vortex. One can also think of the centrifugal force creating the vacuum in the core of the vortex.

Vertical vortices like tornados lack the high axial velocity and flow required for high power extraction. Some power could be extracted if the tornado was kept stationary, and air was ducted through a turbine and exhausted in the low pressure core of the vortex. The inlet of the duct should align itself with the direction of the wind so as to get maximum total pressure at the inlet of the turbine.

Horizontal vortices like those trailing behind the wing tips of an aircraft have a similar low pressure region in the core, but in addition, also a high axial velocity and mass flow rate in the core of the vortex. Due to viscous effects the velocities in the core of the vortex are limited (see Figure 3). The wind blowing over a finite length stationary wing can convert a great deal of its kinetic energy to generating a wing tip vortex with a low pressure in its center (see Figure 4). The wind energy concentrators based on this principle are here referred to as "Vortex Types". The trailing vortex system, shed from aircraft wings, has been treated extensively in the literature.[3] [4] These vortices are created by the cross flow around the tip of a straight wing or the leading edge of a swept wing. The cross flow goes from the high pressure bottom surface of the wing to its low pressure upper surface. The corner of a building facing the wind experiences similar leading edge vortices as a swept wing. An excellent flow visualization of these vortices is shown in Reference 2 and reproduced here as Figure 5. The angle of attack of the flat roof is created by the upward flow deflection as the wind has to flow over and around the building.

Of the three types of wind energy concentrators outlined above, only the symmetric "Obstruction Type" in combination with one or more vertical windmill rotors can be utilized as a stationary wind energy concentrator (see Figure 6). All other types of wind energy concentrators have to align themselves with the wind direction.

Both the "Obstruction Type" and the "Vortex Type" wind energy concentrators are under development at West Virginia University. An overview of their performance limitations in terms of wind power concentration ratio R and associated total area ratio A is presented herein. The power concentration ratio R does not incorporate the efficiency with which power is harnessed by the windmill rotor. The power concentration ratio R is defined as the increase in kinetic energy flow rate per unit area. If one compares a conventional windmill rotor with a rotor operating in conjunction with a nonrotating wind energy concentrator, then the rotor must be reduced in area by the ratio R in order to have the same rate of inflow of wind energy as the conventional rotor.

The total projected area of the nonrotating concentrator and that of the rotor is designated by A when nondimensionalized by the rotor area. Therefore, the total projected area of the concentrator and the rotor is A/R times greater than the conventional rotor projected area.

POWER CONCENTRATION LEVEL

As was mentioned before, none of these wind energy concentrators increase the total pressure of the wind, but they create an area of low pressure and therefore, high local wind kinetic energy available for harnessing. The magnitude of the low pressure obtained is usually expressed by a pressure coefficient: $c_p = \frac{p - p_\infty}{\frac{1}{2}\rho U_\infty^2}$ where p is the local static pressure and p_∞, ρ, U_∞ are the undisturbed wind static pressure, density, and velocity. Viscous effects have a major influence on the generation, magnitude, and location of the low pressure area. However, only a small portion of such a low pressure area suffers total pressure loss due to viscous effects and usually most of the wind energy can be extracted in the low pressure area with nearly inviscid flow. For inviscid incompressible flow the pressure coefficient c_p is related to the local velocity by the Bernoulli equation: $c_p = 1-(\frac{V}{U_\infty})^2$. The wind energy concentrator produces a power concentration ratio which can be expressed as a function of the average value of both the pressure coefficient c_{pav} and velocity V_{av} at the rotor inlet.

Consider first the "Obstruction Type" concentrator with one or more rotors placed in the local low pressure area. Assume the velocity V_{av} to be an average local inviscid velocity at the rotor inlet. The local wind power density available for harnessing is given by the kinetic energy times the mass flow per unit area $= \rho V_{av} (\frac{V_{av}^2}{2})$. Without wind energy concentrator the power density available $= \rho U_\infty (\frac{U_\infty^2}{2})$. Thus the power concentration ratio R, defined as the ratio of power densities is:

$$R(\text{obstruction type}) = (\frac{V_{av}}{U_\infty})^3 \cong (1-c_{p_{av}})^{3/2}$$

Note that if all the kinetic energy $(\frac{U_\infty^2}{2})$ would be harnessed then the mass flow through the rotor $\sim\rho U_\infty$ and the power output would reduce to zero. Consequently, for maximum power output one can only harness a portion of the available kinetic energy with the obstruction type concentrator. For unseparated flow over a cylinder as in Figure 2A, the theoretical maximum value is $V=2U_\infty$ or $R=(2)^3=8$. Due to actual flow separation R will be limited to about 4.

Next consider the "Vortex Type" concentrator. A rotor, placed coaxial with the vortex axis is used to harness both rotational and axial kinetic energy in the vortex. Assume inviscid flow and $V_{\theta_{av}}$ to be the average tangential velocity at the rotor inlet and approximate the axial velocity by U_∞. The average pressure coefficient is $c_{pav}=1-(\frac{V_{\theta_{av}}^2+U_\infty^2}{U_\infty^2})$. At the rotor inlet the wind power density available for harnessing is given by the kinetic energy times the mass flow rate per unit area $= \rho U_\infty(\frac{V_{\theta_{av}}^2+U_\infty^2}{2})$. Note for the vortex type concentrator all the rotational kinetic energy $\frac{V_\theta^2}{2}$ can be harnessed without reducing the mass flow through the rotor. Without wind energy concentrators, the power density $= \rho U_\infty(\frac{U_\infty^2}{2})$. Thus the power concentration ratio defined as the ratio of power densities is:

$$R(\text{vortex type}) = \frac{V_{\theta_{av}}^2+U_\infty^2}{U_\infty^2} \cong 1-c_{pav}$$

Viscosity limits the magnitude of c_p in the vortex. Experimental values of c_p in the vortex over a building roof are shown in Figure 5. This is similar to the trailing vortices shed from a delta wing with low aspect ratio; see Reference 5.

The magnitude of the pressure coefficients measured inside the trailing vortices is nearly linearly proportional to the wing lift coefficient C_L^2/e. Low aspect ratio wings, have a low maximum lift coefficient and correspondingly limited magnitude of c_p and R. Medium and high aspect ratio straight wings, see Reference 6, can generate high lift coefficients and therefore, large magnitudes of both the pressure coefficient inside the vortex and the power concentration ratio R. The application of inverse wing taper and twist can generate more uniform spanwise loading and further increase the lift coefficient of the wing. Aircraft do not use this because the associated increase in induced drag D_i has to be overcome by engine thrust. Vortex type wind energy concentrators benefit two ways from more uniform spanwise wing loading. First it increases C_L and R as mentioned above and secondly most of the trailing vorticity will shed near the wing tip so that it rolls up more rapidly into a single vortex.

OBSTRUCTION TYPE CONCENTRATORS

A few possible configurations of "Obstruction Type" concentrators in combination with two Savonius rotors are shown in Figures 6, 7, and 8. Figure 6 shows a cylindrical type concentrator. Due to the symmetry of the cylinder it can remain stationary for all wind directions: Two counter-rotating windmill rotors are placed in the areas of minimum pressure, the location of which depends on the wind direction. Thus the rotor bearings have to be mounted on a pivot system which orients itself to the wind direction (see Figure 9). Small scale wind tunnel experiments conducted at WVU showed that the indicated direction of rotation of the rotors produced slightly higher power concentration than when they are reversed. Placing the rotors slightly forward of the 90° position was found to be optimum, and the rotors should be kept outside the boundary layer thickness δ. Another configuration tested was the pivoting flat surface as shown in Figure 7. A slight improvement was noticed while using sharp corners. A combination of a pivoting flat surface and a stationary cylinder is shown in Figure 8. The WVU wind tunnel model uses a belt drive system as shown in Figure 9, to couple the two rotors; this eliminated the rpm fluctuations of the individual rotors, which was measured by a tach-generator. The tunnel dynamic head was measured with a pressure transducer with digital display. The wind tunnel blockage and the rotor rpm and torque were maintained constant for both tests, with the cylinder in place and with the cylinder moved six rotor diameters downstream. Then, for these two cylinder positions the wind tunnel dynamic heads were compared. By assuming the rotor efficiency and thus the power available at the rotor to be the same for both tunnel speeds, one can compute the power concentration ratio R from the third power of the tunnel velocity ratio, see Figure 10. Only two cylinder diameters and one rotor diameter were tested at WVU. Consequently only two test points are shown. Each point represents the average value of R over a wide range of tunnel speeds.

VORTEX TYPE CONCENTRATOR

Any finite lifting wing has associated with it a bound vorticity which varies in strength along the span. All this vorticity is shed in the form of a trailing vortex sheet. The spanwise intensity of the trailing vorticity is proportional to the rate of change in spanwise wing loading.

A wing with inverse taper and twist and thus nearly uniform spanwise loading has nearly all the trailing vorticity shed near the wing tip. The trailing vorticity rolls up, at each wing tip, into a strong vortex with its axis in the direction of the free stream. The rate of roll up of the vortex sheet can be computed as a function of wing loading as is shown in Reference 7. In the case of an elliptically loaded wing, as much as 40% of the vortex sheet is rolled up into a single vortex at one chord length downstream of the trailing edge. For a wing loaded nearly uniformly along its span, almost all of the vorticity will be rolled up at that distance. The trailing vortex system induces a downwash velocity on the bound-vortex in the wing, which results in an induced drag, designated by D_i for a semi-span wing. Due to the high stability of the trailing vortex system, the vortex rotational velocities can still be measured hundreds of wing spans downstream. Experimental data for the far field vortex system are given in Reference 3. The following numerical quantities are computed using these data. Even in the far field the axial momentum deficit in the vortex is small and accounts for less than 10% of the induced drag. More than 90% of the induced drag is in the form of a pressure drag created by the vacuum in the vortex. Centrifugal effects in the rotating vortex maintain this vacuum up to great distances from the vortex core. The core is in near solid body rotation and defined by the maximum tangential velocity $V\theta_{max}$ at radius (a). Significant viscous effects extend to about 4.5 times the core radius from the center and the circulation at radius (a) is only about half that in the irrotational part of the vortex.

Only 16% of the induced drag is due to the vacuum level in the viscous region, while 74% of the induced drag is due to vacuum in the near inviscid irrotational part of the vortex. It is interesting to note that inside the irrotational outer part of the vortex, the pressure drag due to the vacuum equals the local rotational kinetic energy, which can be derived from the Bernoulli equation. However, inside the viscous region of the vortex the rotational kinetic energy is only 63% of the pressure drag due to vacuum in that region. Therefore, only 84% of the induced drag manifests itself in the form of rotational energy of the wing tip vortex. Similar numbers can be obtained by using analytical models of Newman[8] or Batchelor.[9]

A wind turbine with an impulse type rotor can be used to harness the rotational vortex kinetic energy captured. The amount of vortex rotational kinetic energy entering the turbine depends on its diameter d and has been computed as a fraction f of D_i as shown in Figure 11:

$$f = \frac{\int_0^{\frac{d}{2}} \frac{1}{2}\rho V_\theta^2\, 2\pi r\, dr}{D_i} = \frac{\text{vortex rotational K.E.}}{\text{semispan induced drag}}$$

To compute the power concentration ratio, one needs to define Z as the ratio of the induced drag to the free wind kinetic energy in a streamtube of cross-sectional area equal to that of the turbine inlet.

$$Z = \frac{D_i = \frac{1}{2}\rho U_\infty^2\, C_{D_i}\, bc}{\frac{1}{2}\rho\, U_\infty^2\, \frac{\pi}{4}\, d^2} = \frac{C_{D_i}\, AR}{\frac{\pi}{2}\left(\frac{d}{c}\right)^2} = \left(\frac{C_L^2}{e}\right)\left(\frac{1}{\frac{\pi^2}{2}\left(\frac{d}{c}\right)^2}\right)$$

Here e is the spanwise loading efficiency, which should be as small as possible. The power concentration ratio R can then be computed from:

$$R = \frac{\text{axial wind K.E.+rotational K.E.}}{\text{free wind K.E.}} = 1 + f.Z$$

The corresponding total area ratio of wing concentrator plus turbine, to that of the turbine is given by

$$A = \frac{bc + \frac{\pi}{4}d^2}{\frac{\pi}{4}d^2} = 1 + \frac{2\, AR}{\pi\left(\frac{d}{c}\right)^2}$$

Both R and A have been computed for a uniformly loaded high lift semi-span wing with the turbine placed at a distance of one mean aerodynamic chord downstream of the trailing edge and concentric with the vortex centerline. The vortex core radius a/c at that location is found from experiments to be .03. Using this value one can proceed to compute f, Z, and R as a function of C_L^2/e and turbine diameter d/c. The results are plotted in Figure 12 for various values of C_L^2/e. To get high values of R it is essential that one needs high lift coefficients, which means also a high aspect ratio. Unfortunately, as the aspect ratio increases, the corresponding area ratio A increases.

To find the optimum aspect ratio which controls both R and A one must perform an economic tradeoff study. The maximum value of R is found for d = 3a, then R can be computed to be

$$R_{max} = 1 + \frac{2}{3}\left(\frac{V_{\theta max}}{U_\infty}\right)^2 \simeq 1 + .24\, C_{p_{min.}} \simeq 1 + .5 C_L^2/e.$$

Because a/c is small, the maximum value of R has a high area ratio associated with it.

A shroud around the turbine is recommended to stabilize the vortex and to maintain the low pressure at the turbine outlet even after the rotational velocity has been harnessed. The presence of the turbine will have an adverse effect on the obtainable maximum lift coefficient of the wing. Using lifting line theory it is estimated that the presence of the turbine at a distance of 1 chord length downstream reduces C_L^2/e by 13%. In Figure 13 is shown a model of a high lift wing vortex type concentrator. The airfoil chosen was a modified Liebeck airfoil as is described by Smith.[10] It is anticipated that the addition of a Gurney flap and turbulence generators might create a maximum lift coefficient C_L=4.0 or better. However, the associated high drag might increase the blockage effect and lower the effective free wind speed. It is expected that with an aspect ratio AR=5 and a turbine diameter of .75c one can achieve a concentration ratio R=2.5 and a corresponding area ratio A=6.5. Note that R does not reflect the higher efficiency with which rotational kinetic energy can be harnessed as compared to axial kinetic energy.

CONCLUSIONS

All wind energy concentrators mentioned herein such as "Venturi Types," "Obstruction Types," and "Vortex Types" operate on the same principle. They are nonrotating and generate an area of low pressure and high kinetic energy in which the rotor is placed. The application of a concentrator permits a reduction in rotor area by an amount R without change in power output. The total area of the concentrator plus rotor is then A/R larger than the original rotor where A is larger than R.

The application of a concentrator is governed by the economic and aesthetic tradeoffs. In many designs the concentrator finds additional use as support structure for the rotor and generator. Rotors operating in conjunction with a concentrator have a smaller diameter and torque but a higher angular velocity; this may produce savings in gearbox and transmission costs. The obtainable power concentration ratio R varies between 2 and 4 and the corresponding area ratio A varies between 3 and 10. At this stage no clear cut advantages are shown by one concentrator over the others. The few encouraging results justify a continued effort in the development of new economical and efficient wind energy concentrators and improving the existing ones.

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BIOGRAPHY

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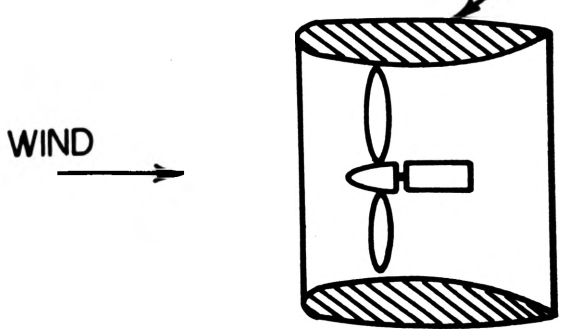
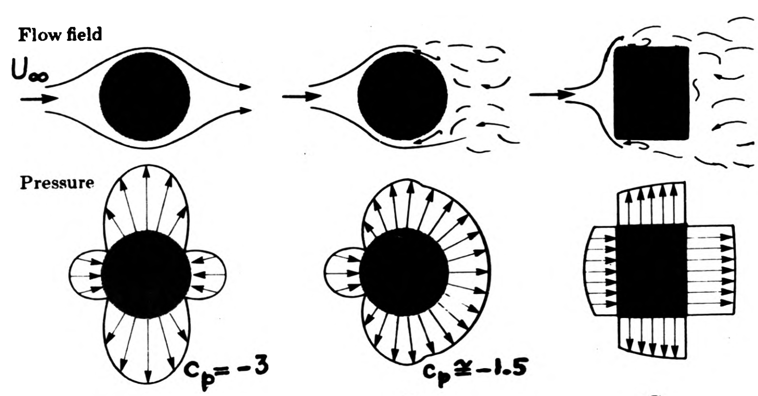
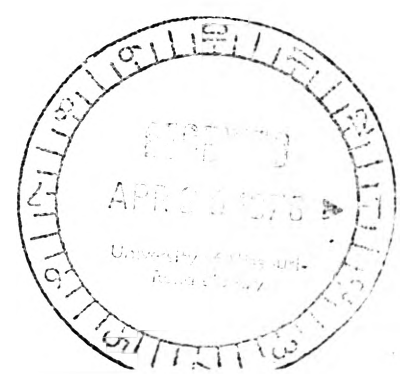
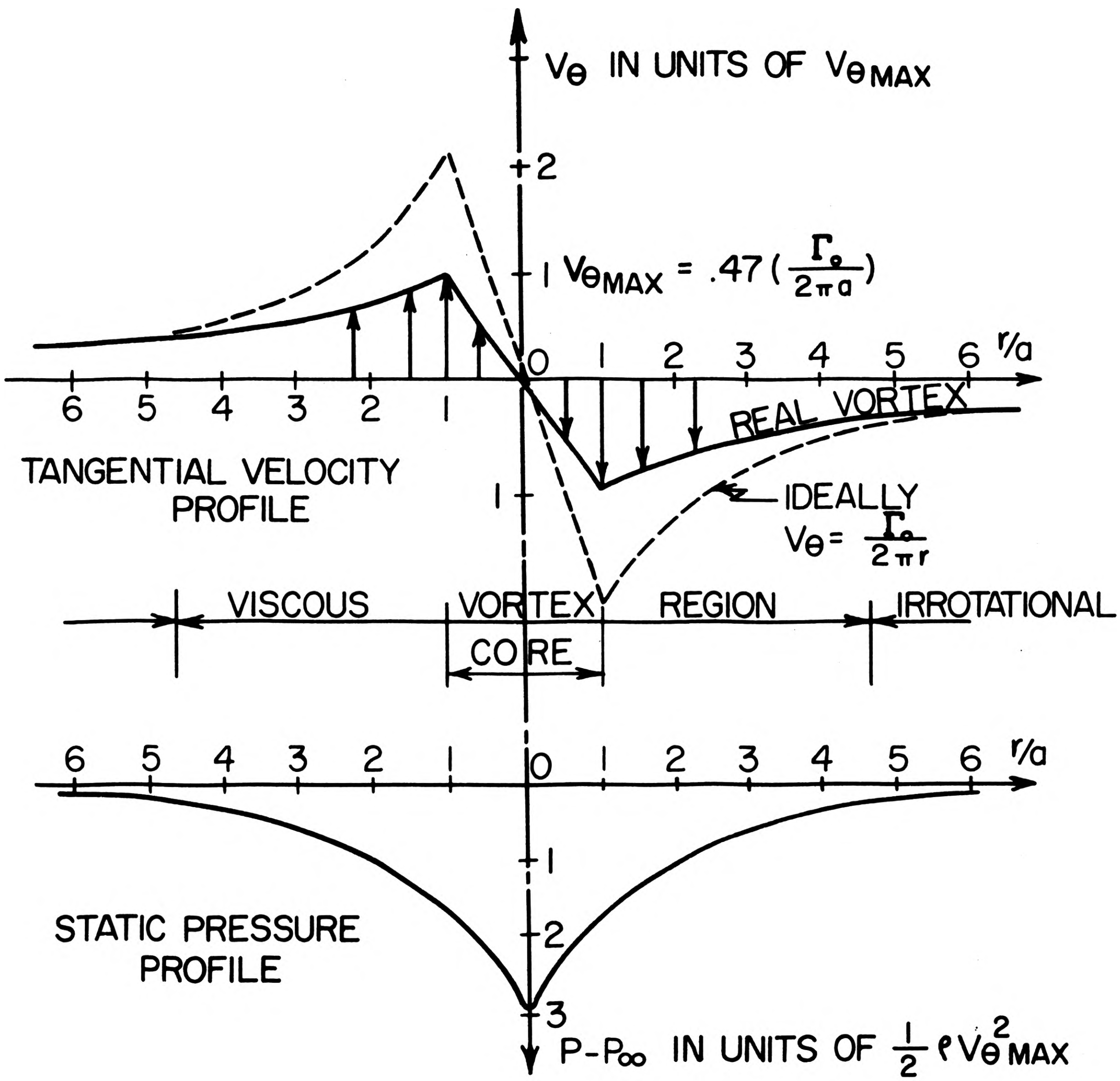


SHROUDED PROPELLER

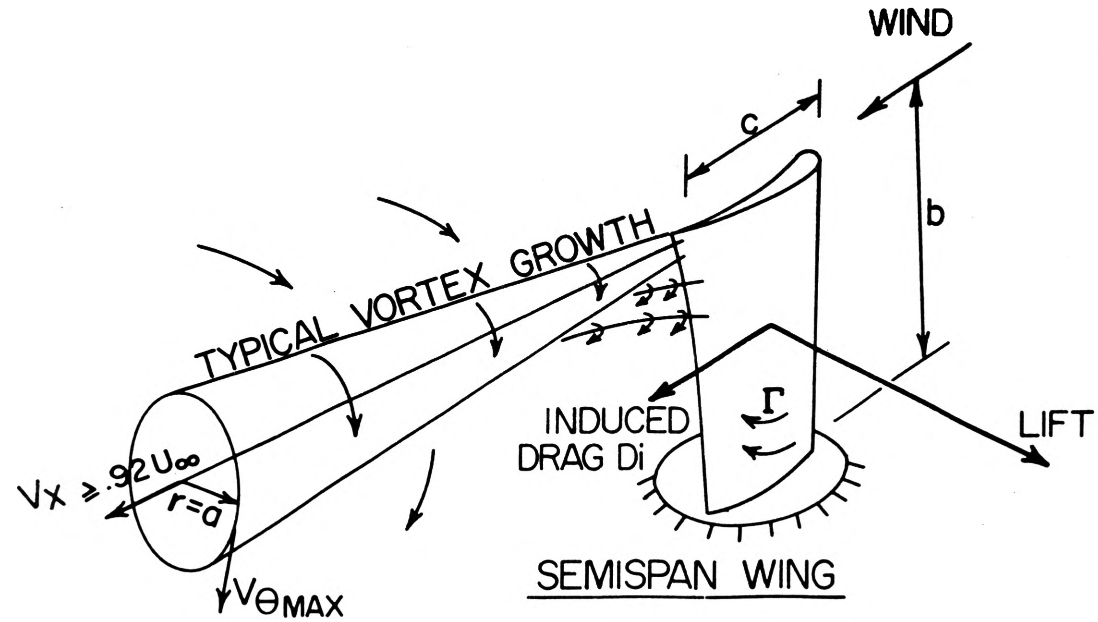


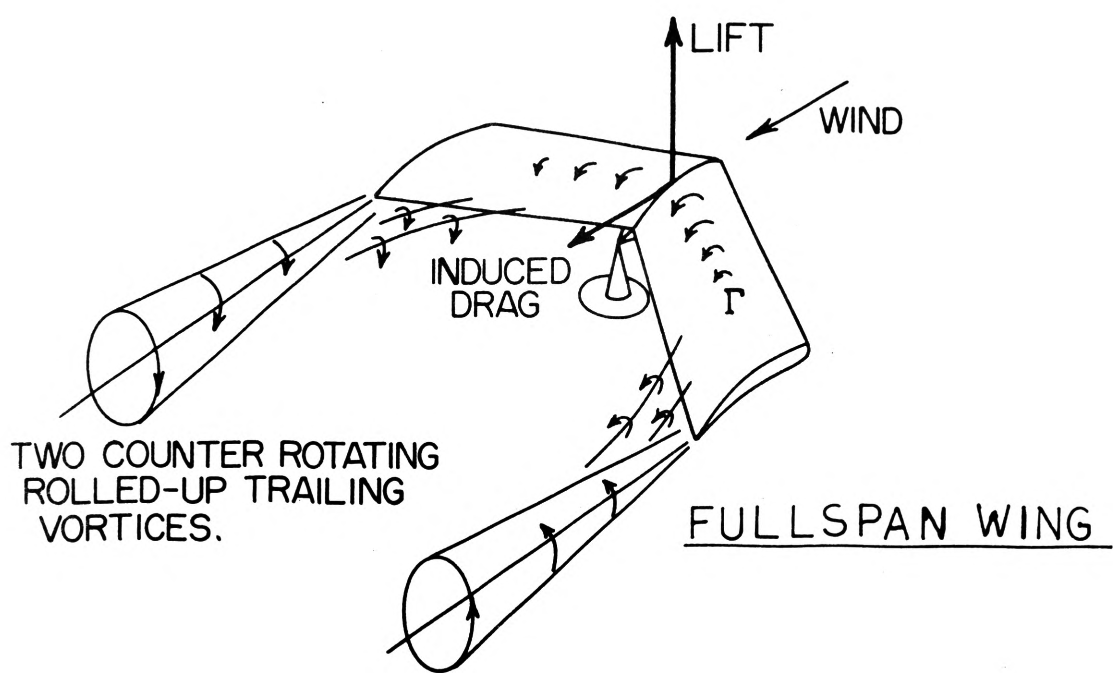
A B C

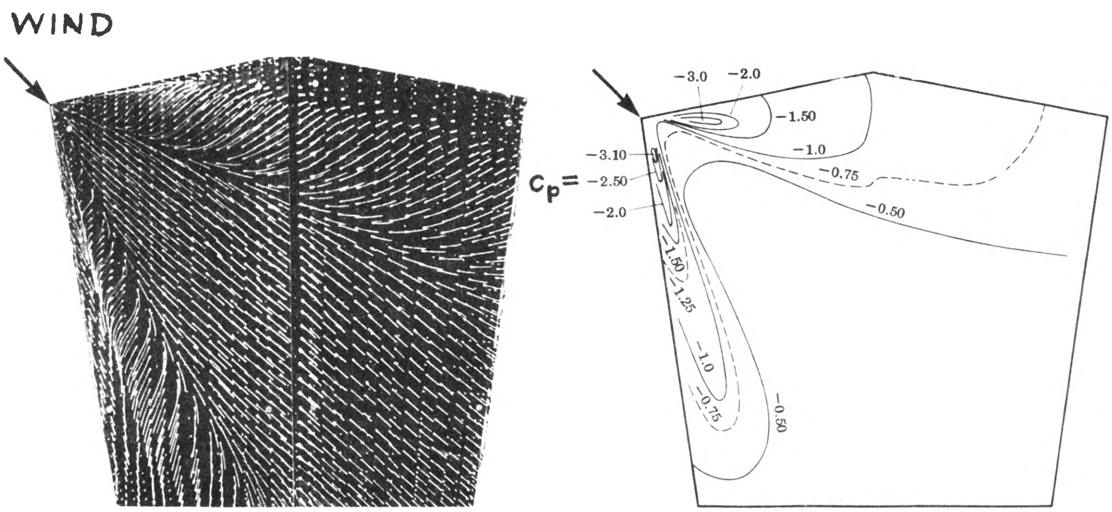




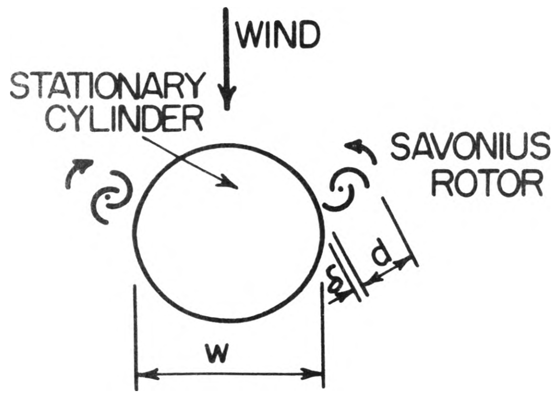
TYPICAL VORTEX PROFILES

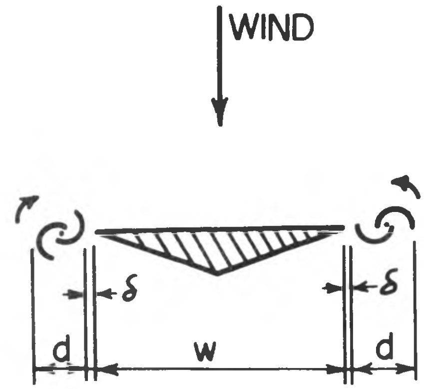

WIND
c
b
TYPICAL VORTEX GROWTH
INDUCED
DRAG Di
Γ
LIFT
Vx ≥ .92 U∞
r=a
VθMAX
SEMISPAN WING

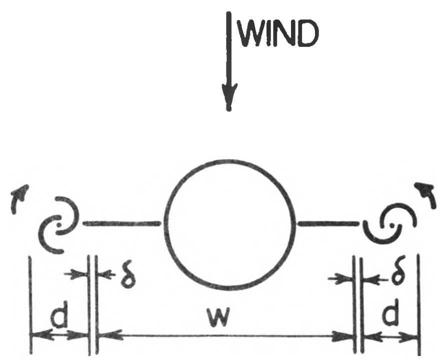

LIFT
WIND
INDUCED
DRAG
Γ
TWO COUNTER ROTATING
ROLLED-UP TRAILING
VORTICES.
FULLSPAN WING

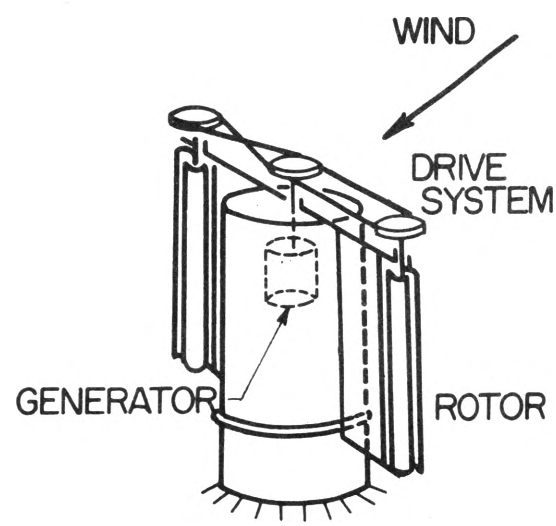


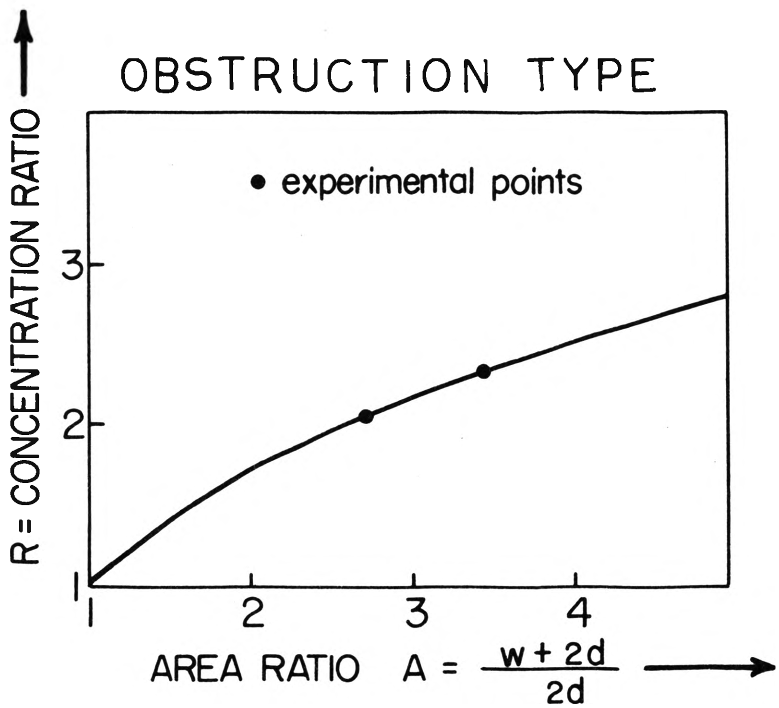
VORTICES ON BUILDING ROOF

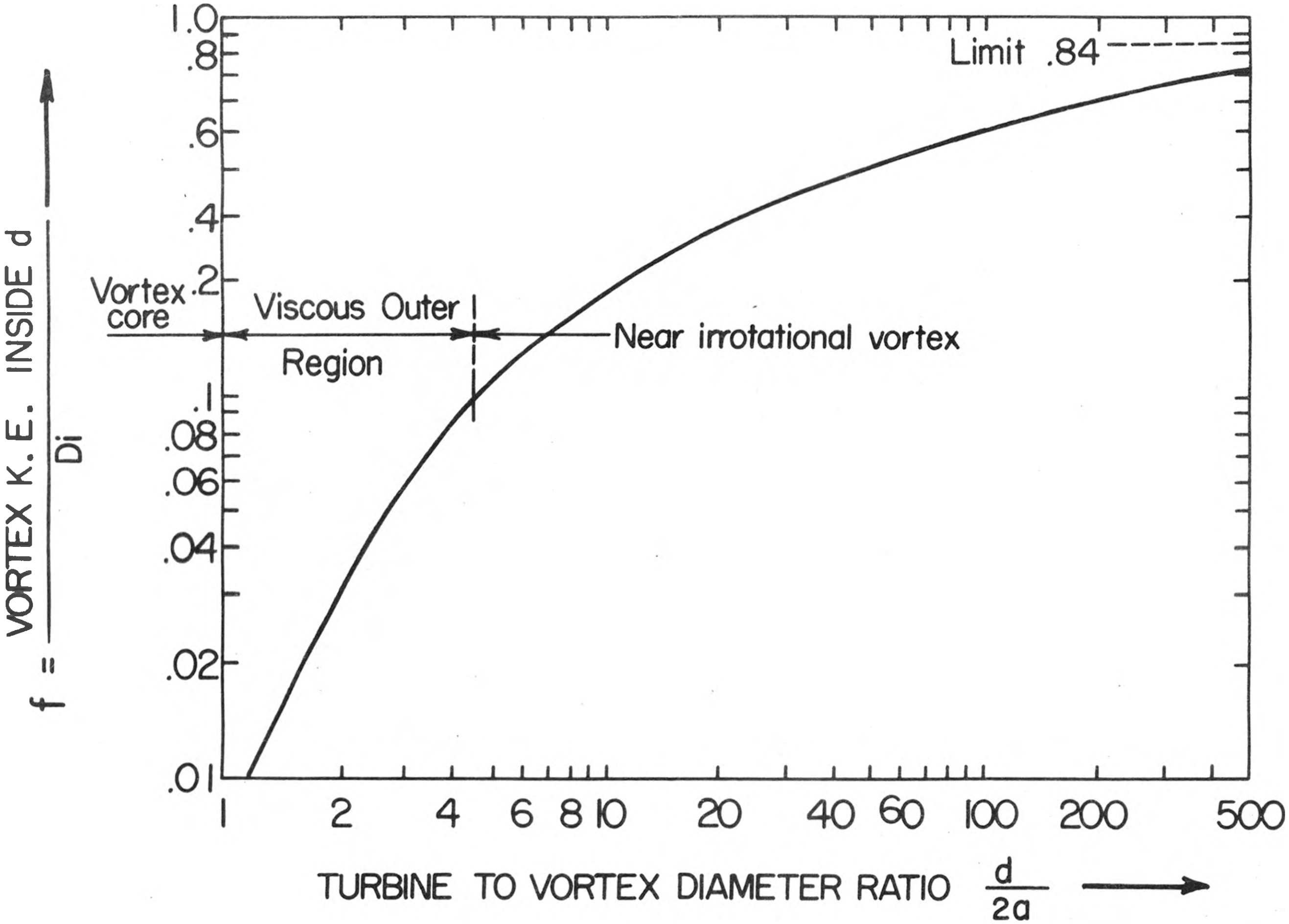

WIND
STATIONARY
CYLINDER
SAVONIUS
ROTOR
d
δ
w


WIND
δ
δ
d
w
d


WIND
δ
δ
d
w
d


WIND
DRIVE
SYSTEM
GENERATOR
ROTOR


OBSTRUCTION TYPE
• experimental points
R = CONCENTRATION RATIO
1
2
3
1
2
3
4
AREA RATIO A = (w + 2d)/2d



f = VORTEX K.E. INSIDE d / Di
1.0
.8
.6
.4
.2
.1
.08
.06
.04
.02
.01
Limit .84
Vortex core
Viscous Outer Region
Near irrotational vortex
1
2
4
6
8
10
20
40
60
100
200
500
TURBINE TO VORTEX DIAMETER RATIO d/2a

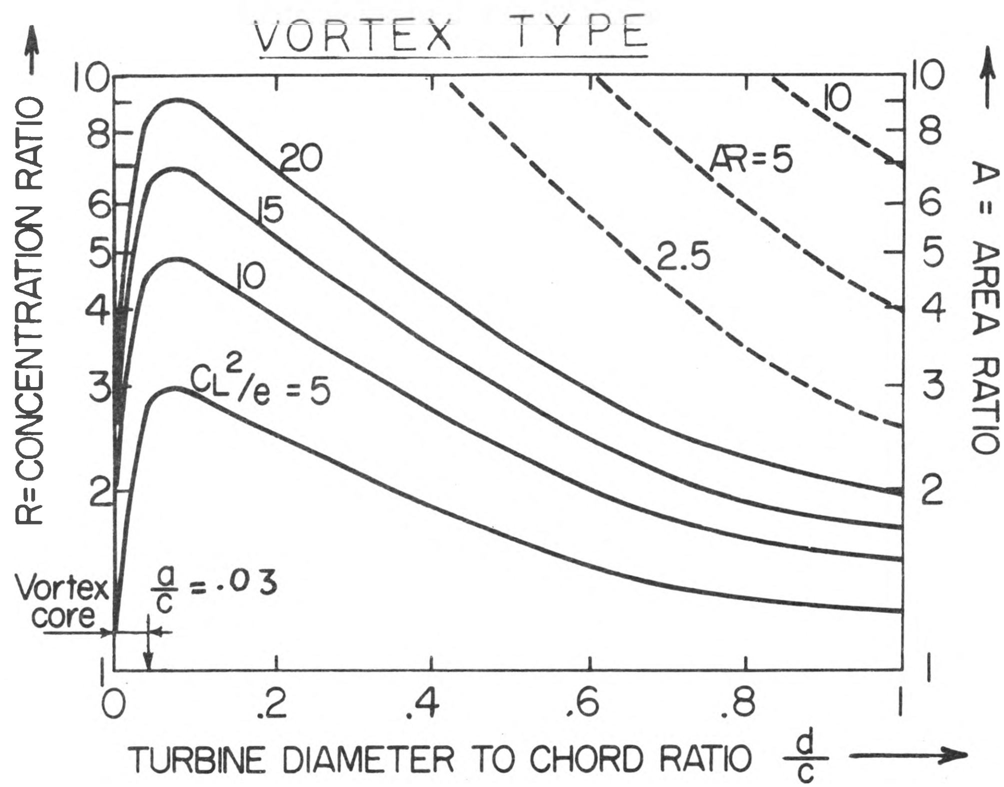

VORTEX TYPE
R=CONCENTRATION RATIO
A = AREA RATIO
20
15
10
$C_L^2/e = 5$
AR=5
2.5
10
Vortex core
$\frac{a}{c} = .03$
0
.2
.4
.6
.8
1
10
8
6
5
4
3
2
1
TURBINE DIAMETER TO CHORD RATIO $\frac{d}{c}$

Fig. 13. "Vortex Type" wind energy concentrator model, using a high lift Liebeck type airfoil and a shrouded rotor.

CENTRALIZED SOLAR WIND
HOME HEATING

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ABSTRACT

In the immediacy of national goals for energy independence, the need emerges to use dialectic methods to diminish the energy consumptive characteristics of the typical home.

At the cutting edge of resourceful progress are the residential developments which embrace alternative and conservative energy techniques. In conjunction with such a planned, low impact community, this paper proposes a cluster-centralized system which utilizes wind energy in combination with solar thermal energy for space and domestic water heating.

A description of the random solar-wind resource embodies a matching problem that in turn reveals the benefits of the combined mode of energy collection. Though solar and wind energy systems have been coincidentally advanced, their mutual and unified application remains novel. The combined system demonstrates an appealing ability to fulfill the heating requirements.

INTRODUCTION

The typical dwelling is conspicuously energy consumptive. The largest portion of the energy consumed is for space heating with the second most significant portion for water heating. Together, these thermal demands account for nearly 80 percent of the total residential energy consumption (1). Space heating of buildings consumes 20 percent of the nation's fuels (2), usually non-renewable natural gas and fuel oil. Electrically heated homes are particularly raw-resource costly if the inefficiencies of electric generation and transmission are properly included along with the more apparent dwelling requirements.

Endeavors to abate this typical dependence on fossil fuel to meet the residential thermal requirement should involve both thermal conservation schemes and the use of indigenous energy resources. Building designs symbiotic with the local environment and the engineering techniques outlined in this paper incorporate building methods and materials to reduce the net thermal effluxion to the surroundings. Replenishment of both wind and solar thermal energy is proposed for inclusion in the heating scheme because the two resources are diffusely distributed to the site local, inexhaustible, clean, and complementary. The logical extension of these heating plans is their integration into a total-coordinated thermal development (TCTD), which is a complex of conservative structures clustered with a centralized solar-wind heating system.

One of the few planned residential developments embracing these energy conservative and alternative techniques is Orient Meadow Project (3). The design for the Orient Meadow TCTD is to reduce the dwelling heating consumption of non-renewable raw resources to less than one fifth of that of a commensurate, standard, residence. This reduction is accomplished in two ways. Energy conservative tectonics reduce the heat loss from the standard residence by 50 percent. In addition, the solar plus wind alternative delivers a minimum of 60 percent of that diminished requirement, which is a more stringent standard than those professionally recommended for the solar only alternative (4).

In conjunction with this TCTD Project, this paper conveys the concepts and initial feasibility inquiry for a cluster-centralized solar-wind heating system. Though stemming from the plans for a clustered community, this central heating plant is a candidate, in the proper context, for numerous commercial applications.

ENERGY CONSERVATION

CLUSTERED HOUSING

A typical autonomous dwelling with a single total life support system serving only one family is the hyperbole of an energy costful human shelter. Such residences are often designed with minimal attention given to bioclimatic principles and promote gross wastefulness due to profit motivated construction. Furthermore, these dwellings exacerbate resource exhaustion by requiring extrinsic fuel support systems such as refineries and distribution networks. Energy necessary to maintain such a life style at commonly inflated levels of comfort is being increasingly hard to justify.

Prognosing a possible trend toward a multiplicity of families living in cooperative and energy resourceful arrangement, the Orient Meadow Project will provide a low impact, clustered community setting in which the habitants share a centralized solar-wind heating system and other life support functions. The arrangement of the living units is influenced by zoning limitations and marketing considerations and consists of a satellite array of single and duplex dwellings around a community center. The center houses community activities in addition to being a garage, laundry, and powerplant.

CONSERVATIVE DWELLINGS

Various energy conservative techniques incorporated into the individual residences are illustrated in Figure 1. Though each residence has some unique features, the basic units are of similar design. The dwelling shapes for example, are consistently two storied and have a 1 to 1.2 east west elongation as recommended by V. Olgay (5). The east and west walls receive a minimum of direct summer sun. The south wall receives nearly twice as much radiation during the winter as during the summer. The buildings, in many cases, are situated at the site so that partial subterranean construction reduces the northern exposure and a low horizon to the south increases solar exposure.

The construction is basically of wood because of its lower environmental impact, good strength and thermal characteristics, and aesthetic appeal. As suggested by Curtiss Johnson (6), conductive losses through the shell are reduced by using 8 inch foil faced fiberglass batts of insulation with a polyethelyne vapor barrier. Also, the foundation and subterranean walls are insulated at the outer surface so that in addition to reducing the losses, they increase the interior thermal capacitance. Double thickness roof insulation and the extension of berm to roof areas, where practical, reduce upward heat losses. Insulated doors and window shutters are employed. (The fact that the shutters, for example, are owner operated encourages the reunion of peoples actions with their consequences and emphasizes that environmentally sound habitation will probably demand modification of present social behavior.) Tightness of construction, air lock entry vestibules, weather stripping, and high quality casements or sealed windows all reduce infiltration losses.

Window area per wall is determined in proportion to the radiation gain versus wall losses in that direction as based on current calculations (7) (8). All windows are at least double glazed and in some cases insulating glass is used.

Calculations, in accord with the ASHRAE Handbook of Fundamentals (9), show that the TCTD goals for conservation are achievable. Though each Orient Meadow residence possesses a unique thermal behavior, (dependent upon its specific architecture, siting, and occupancy), an average reference dwelling unit is calculated to demand 15,500 Kwhr in a 7000 degree day climate. This unit compares favorably with present technology (10) and multiples of the unit are used in calculation to represent the various clustered arrangements.

HEAT DISTRIBUTION IN THE RESIDENCE

FORCED HOT AIR

A radial forced-draft system is employed to distribute heat throughout the home. Forced hot air (as opposed to hydronic which is forced hot water), is a more direct and effective heating medium. The convective currents reduce response time and can use lower temperatures to achieve a given comfort level. Forced convection schemes also afford increased design flexibility for environmental control by allowing the straightforward integration of recirculation and reclamation ductwork. For example, an air intake in the loft area is incorporated to circulate the warm loft air to the cooler lower rooms and reclamation ductwork around the Jotul stove pipe acts as a low complexity economizer. In addition, a humidifier is placed in the hot air distribution plenum, but could not be integrated with the hydronic system. The generally lower efficiency of air distribution is acknowledged but is accepted in favor of its other advantages.

To maintain comfort, all the homeowner must do is set the temperatures and humidity controls. By automatically lowering the nighttime temperature by 8°F, the thermal capacitance in the structure relinquishes a major portion of the heat otherwise required.

DOMESTIC HOT WATER

The domestic hot water continually circulates in an insulated loop, providing hot water on demand and reducing the transitory losses of heat and water. Flow controls also limit the squandering of hot water (11). During the noncritical night hours, the hot water temperature is reliant upon the solar-wind energy input only.

ENERGY ALTERNATIVES

Unlike the non-renewable fuels, solar radiation and its atmospheric by-product, the wind, are clean and inexhaustible resources appropriate for local and low temperature applications in the order of 100° to 200°F range. Their characteristic unsteady nature however, is the disadvantage that necessitates an interruptible load or some form of an energy flywheel.

Solar energy has been favorably assessed as a national resource (12) and a mushrooming number of buildings demonstrate the use of solar radiation for space and domesting water heating (13).

SOLAR HEATING

Solar home heating is usually accomplished by mechanically transporting a working fluid through a system to transfer heat from a collector (flat plate) to a distributor with the aid of thermal storage. A comparison of solar radiation and heating load information is indicative of the extensity required of the system to achieve a given heatability. Practical solar heating systems are not designed to carry the full heating load all of the time.

The dominant distribution of useful solar power depends upon the angle of collector tilt from the horizontal and the heat gain from even an optimally tilted collector does not simulate the home heat loss over the entire heating season. An economic analysis is required to determine the collector size which utilizes its area to the fullest extent in paying for itself in fuel savings. Locally for example, such a collector area is roughly equivalent to one half the heated floor space for a well insulated structure and supplies about 70 to 75 percent of the heating load. The result is that during the fall and spring, the mean solar input more than suffices for home heating but during the mid-winter months, background auxiliary heating is mandatory. As an example, the useful solar output of an appropriate 450 square foot flat plate collector is given for the reference heat load in Figure 2. In addition, locally characteristic spells of prolonged and intense cold and cloudiness require expanded thermal storage capacity and a full capacity back-up system. Because solar home heating is limited to partial success, the use of wind energy is examined as a complementary resource.

WIND POWER HEATING

Wind power technology is a subject of considerable renewed interest (14) and investigation (15) but the direct application of the resource to residential heating is the subject of but a few studies or applications.

A productive wind field can be successfully exploited for home heating purposes. Wind power heating utilizes a "wind furnace" which is a wind turbine, a convector, thermal storage and distribution system to convert atmospheric kinetic energy to useful sensible heat.

The New England Wind Furnace, as proposed by Professor W.E. Heronemus, (16) is based on the concept of a 25 Kw wind powered electric generator mounted 60 feet above the ground where a minimum annual average wind speed of 10 mph would deliver at least 25,000 Kwhrs of thermal energy yearly. In one wind furnace combination, proposed by a Swedish Civil Engineer, Bengt Sodegard (17), a conventional boiler heated hydronic system is supplemented with a wind turbine-generator, immersion heater, and hot water accumulator. Other suggestions are: the superimposing of wind generated electricity on an existant electric home heating system, the use of a mechanically driven dissipation device for directly heating of stored hot water, wind driven heat pumps (18), and electrolysis and subsequent hydrogen reconversion (19).

The technical feasibility of wind power heating depends on the local windfield productivity, the overall distribution of available kinetic energy during the heating season, and the probability and duration ofoccurrence of the wind speeds. Also of importance are the characteristics of the heating load. Windfields having an annual average available energy of the order of 100 or more watts per square metre demonstrate a seasonal distribution of kinetic energy favorable for home heating purposes. Such wind patterns repeat from year to year, and have a significant increase in late winter and early spring which has a distinct advantage when compared to the increase in the mid-winter heating requirement. Such a comparison is shown in Figure 3 on a percent of seasonal mean energy basis.

The economic analysis of wind machine design parameters to determine the combination most appropriate for home heating is a tenacious task. Two influential design parameters which determine the velocity range of the turbine operation are the cut-in speed (minimum velocity) and the rated speed (speed for maximum power). The choice of these limits affects the total seasonal power output and the hours of plant operation. Selecting high cut-in and rated speeds results in a prodigious power output (a cubic function of velocity) corresponding to the high winds but is of shorter and less frequent duration. Selecting a lower operating range yields a lower total power output but operating periods of longer duration. Common practice for the economic optimization of these parameters is based exclusively on wind energy data assessment (20). The choice of high cut-in and rated speeds for a wind furnace hower, results in sporadic and extreme high temperature excursions of diminished usefulness for practical low temperature heating. Using a lower rated windspeed, however, requires a larger diameter rotor for the same total output. An optimum overall combination of wind furnace parameters will best pay for itself in fuel savings.

The useful power output of a wind furnace with a 25 foot diameter rotor is shown in Figure 4 along with the reference seasonal heat load. It is evident that the peak windfield productivity lags the thermal load thus partially limiting the success of wind powered heating. However, wind and solar conversions can be advantageously integrated.

THE SOLAR-WIND COMBINATION

Hypothetically, if it is 50 percent probable that the sun will shine on a winter day, and it is 70 percent probable that the winds will be sufficient for conversion, then it is 85 percent probable that some combination of the natural energies will be available.

The solar collector portions of a heating scheme are active during the daylight hours only. The winter nights, which would then drain much of the stored energy, are often windy enough to be beneficial for wind powered home heating. Wind powered heating also allows the wind related convective and infiltrative losses to be directly replenished by the same winds. Combining the two modes improves the conversion reliability. It is noted however, that temperature increases due to placing a wind powered heater into a solar heated storage will decrease the solar collection efficiency unless some method of isolation is incorporated to protect that efficiency. Overall, the better frequency and duration of occurrence of the combined inputs afford a reduction of storage capacity and auxiliary fuel consumption. The seasonal distribution of useful mean energy from solar plus wind convectors can more closely approximate the seasonal heat load to further reduce auxiliary fuel consumption. For example, the total useful output of the 20 ft diameter wind turbine and a 250 ft^2 flat plate solar collector is sized to the reference heat load in Figure 5.

In applying the solar-wind technology to the conservative residence, it becomes evident that the smaller the heat loss for the building, the smaller the demand on the natural energy system, hence the smaller the equipment dollars but, unfortunately, the higher the specific equipment cost (dollars per Kw-hr) becomes. Also design heat loads of less than about 9 Kw ask for an auxiliary output that is smaller than currently available conventional gas and oil fired furnaces, making a costly full capacity back up system even harder to justify for the single residence. Compounding the above economic difficulties by dividing the reduced load between the two natural modes of heating, with their inherent dual specialty of conversion, storage, and control apparatus, one observes that the costs become exorbitant.

In discussing the Orient Meadow project, three factors were focused upon in response to the economic issues: First, the proposed totally coordinated thermal development, with the centralized solar-wind heating system supplying the clustered complex of energy conservative dwellings, is intended to cut the high specific costs to a level that is economically acceptable. Second, to quote harbinger Paul Erlich, "The quality of your life will then be directly proportional to how independent you have become from the complex and fragile mechanisms that now provide most Americans with the requisites of life (21)." A recent survey reveals that many people are indeed willing to pay an exaggerated price for the security of energy independence (22). Since the project is located in a relatively affluent and progressive community it is expected to be more marketable. Third, to shift to subsidy of a new technology from the developer to more appropriate and financially able scientific agencies, outside funding is being sought.

TCTD METHODOLOGY

Prior to designing a centralized solar-wind heating plant, a resource evaluation is in order.

WIND SURVEY

Due to the sensitivity of a local windfield's productivity to the area's surface features, a detailed and integrated study of both meterologic and topographic information is required to determine which sites are best suited for wind exploitation. A gentle hill which increases the average windspeed by a factor of 1.2 for example, might increase the extracted power by 20 percent.

A three fold survey method is employed to determine the site windpower potential. First, a meso-scale examination is made of available meteorological records. Eight miles up the prevailing windstream from the Orient Meadow site for example, a complete meteorlogical survey for a proposed nuclear power plant has been recently completed and made public domain (23). The area's chorography and prevailing winds ensure that both locations are exposed to a generally similar wind regime. The second step, having evaluated the useable amount of wind energy common to the area, will be the selection of a small number of sites, one in each major topographically distinct portion of the project area. The Orient Meadow property is divisible into three such areas: (1) a wooded ridge with a western exposure, (2) an open meadow, (3) and a gentle, wooded knoll for a total of fifty five acres. On each of the three sites will be installed measuring equipment to compute and record windspeeds on an hourly basis throughout the heating season so that velocity duration curves can be made.

Third, at a larger number of well-distributed points of interest, measuring sataions, of the simple counter type cup annemometer, will be installed to compare local point velocities to the local area velocities.

These three steps indicate whether there is enough wind available for wind powered heating, the specific energy output obtainable from a given wind furnace design, and the relative merits of the local sites.

Having established candidate sites, attention must be given to minimum inter-turbine distances to prevent the placement of one turbine in an energy-depleted wake of another turbine. The downstream distance from a rotor, required to insure atmospheric replenishment of the extracted energy, is taken to be five diameters in the prevalent direction and four diameters transversly in a close packed distribution, based on a conservative average from previous studies (34). Should multiple rotors be used on a single tower, the standard 1.4 times the rotor diameter for the center-to-center spacing of the rotors will be used.

A further tower placement constraint is the maximum generator-to-load distance which prevents excessive transmission dissipation. The suggested 1000 foot limit (24) due to transmission losses is taken to be acceptable for the intermediate sized TCTD wind furnace system.

SOLAR DATA

The collection of solar data is more straightforward. Knowing that local precedents indicate the solar resource to be sufficient for home heating, but trying to avoid estimations which lack the necessary short term effect of clouds in radiation depletion, actual recorded data is obtained. Many U.S. weather bureau stations record radiation data and one is sought that lies near to the same latitude as the site locale and that has commensurate atmospheric conditions. Though somewhat distant, the Blue Hill (25) data is acceptable to represent the project's solar environment. Such data is almost consistently recorded on a horizontal surface. To represent the insolation incident upon the optimally tilted collector surface, the data is mathematically transposed by the methods of B.Y.H. Liu and R.C. Jordan (26), thus requiring a knowledge of the direct, diffuse, and reflective components of the data (27). This new data base is used for calculating the specific solar output for a given solar collector and system design. Corresponding data useful for solar heating calculations include ambient temperature, cloud cover, and windspeed. These are often available on an hourly basis from the same weather station.

TCTD LAYOUT

The actual TCTD layout as planned is a result of a myraid of considerations such as zoning laws, topography, environmental protection, accessibility to the natural resources, and marketability. Development of the knoll as the first phase is shown in Figure 6. A central location has been chosen near the crest of the knoll where the wide and open southern exposure ensures uninhibited solar collection. At this site, a common garage and enclosed laundry and central mechanical area provides the structural base for the flat plate solar collector. The maximum feasible collector area is 1500 square feet. The dwellings are placed about the central building in a close packed fashion to prevent excessive energy transport losses. The closeness of the homes is limited by environmental design considerations, the major of which is the need for solar collection clearances between structures. The south facing walls of the individual dwellings require an open range sweep of the southern sky to ensure successful passive solar collection. Dwellings placed downslope to the north require larger inter-dwelling clearances due to increased shadow lengths. Solar angles tabulated by the American Institute of Architects are useful in making TCTD layouts (28). A total of six dwellings are to be built in phase one, two pairs of which will be connected in duplex fashion by a common greenhouse. The two windplant locations are based on the wind survey, the choice of a single masted New England Wind Furnace prototype, available land, and local zoning laws.

THE CENTRAL SOLAR-WIND HEATING SYSTEM

The central heating plant consists of an array of liquid type flat plate solar collectors and two wind turbine-generators heating tanks of stored water. Heat, hydronically circulated to fan-coil units at the dwellings, is obtained from four sources in the central mechanical area: (1) a pressurized 3000 gallon high temperature reservoir, (2) a pressurized 3000 gallon medium temperature reservoir, (3) a separate 2500 gallon low temperature water tank incorporating a 5 ton heat pump, and (4) a 225,000 BTU auxiliary hydronic heater.

Heat for the domestic hot water is obtained through heat exchangers placed in the first two hot water reservoirs with the temperature boosted as necessary by the auxiliary domestic water heater. The central heating plant is shown schematically in Figure 7.

The central heating scheme can be divided into six basic parts: (1) wind conversion, (2) solar collection, (3) hydronic space heating and storage, (4) domestic water heating, (5) auxiliary heating, and (6) automatic controls.

WIND CONVERSION

Two 25 Kw wind turbine generators power electric immersion heaters located only in the high temperature storage tank. The design of the wind turbine is based on continuing research and development at the University of Massachusetts (16) (29). The rotor with a 32.5 foot diameter is placed at a 60 foot height. Coupled to a three phase a.c. generator, it should cut-in to generate useful power in winds as low as 5mph and reach the 25 Kw rated power in a 26 mph wind. Pitch control is employed for maximum momentum exchange up to the rated speed. The turbine-generator is connected through a load controller to a bank of submerged resistors which dissipate power (heat) as soon as the wind machine begins to generate. The resistance is controlled to keep the output of the generator plus load just below the maximum output of the rotor. The parallel wiring of resistor sets prevents instantaneous unloading should an element fail electrically. The immersion heaters are placed only in the high temperature tank to protect the solar collection efficiency related to the lower temperature reservoirs. Natural convection distributes the heat throughout the tank of stored water. Overall, the directly connected and interruptible load of heating stored hot water is a very effective use of windpower. Its simplicity eliminates unwieldly and costly alternatives such as batteries and its load conversion efficiency approaches an outstanding 95% (11).

SOLAR COLLECTION

The south facing 1500 ft^2 flat plate solar collector is optimally tilted to 57.7 degrees corresponding to the 42.5 degree north latitude. Double glazing covers the flat black absorber plate through which a water-ethylene glycol solution with a -10°F freezing point is pumped. The collector downcomer delivers the solution to a selected sequence of heat exchangers placed near to the bottom in the hot water tanks. The high, medium, and low temperature tanks receive high, medium, and low grade solar heat such that no stored water will be degraded. The collector feed pump draws from the low temperature tank and operates whenever the collector temperature exceeds the low grade water temperature by ten or more degrees. Before passing into the collector, the solution passes through a getter to minimize the corrosion problems prevalent with aluminum.

HYDRONIC SPACE HEATING AND STORAGE

Whenever the outdoor temperature falls below 65°F and a fan-coil thermostatic control indicates a space heat demand, hydronic circulation commences and the circulation temperature is then maintained in the 100 to 120°F range. After giving up heat at the fan-coil units, the degraded returns feed into the medium temperature storage tank (tank 2). From there the hot water passes back to the hydronic circulating pump or into the high temperature storage tank (tank 1), depending on the mode of operation. If the output of tank 2 falls below 110°F, the high temperature storage (tank 1) bypass closes and tank 1 is then placed in series with tank 2. Combining the two reservoirs immediately results in a higher hydronic circulating temperature and increased thermal capacitance. If thermal depletion continues, such that the output temperature of tank 1 falls below 110°F, the auxiliary hydronic heater boosts the circulating temperature. If the temperature of the low grade water tank (tank 3) permits the economical operation of the heat pump, it is used to maintain the proper circulating temperature. If necessary, the heat pump and auxiliary heater operate in series. Should solar-wind thermal replenishment resume, and the two reservoir temperatures eventually reach 120°F, the bypass valve will again isolate tank 1 and return tank 2 to independent circulation. If the replenishment be wind powered or a high grade solar output, the temperature of the high grade tank 1 increases to a limit related to domestic water heating at which point tank 1 and tank 2 return to series operation. Essentially, there is both an upper and lower limit to the usefulness of the segregated storage. The upper limit is controlled by the domestic water heating demands.

DOMESTIC WATER HEATING

The delivery of hot domestic water is accomplished by the continuous recirculation of the water between the homes and the central heating plant. A sequence of heat exchangers, placed near the top and inside the two stored hot water tanks, is selected to heat the domestic water in such a manner that it will not be degraded or over heated. The medium grade tank normally acts as a preheater and the high grade tank as the last stage heater necessary to maintain the 130 to 140° domestic water temperature. If the temperature of the high grade tank reaches the maximum useful limit for domestic water heating (160°F), tanks 1 and 2 combine in series operation. The equilibrium hydronic temperature is still sufficient for total solar-wind powered domestic water heating but reduces excessive storage losses due to otherwise higher temperatures and improves the overall efficiency. Should the solar-wind output be insufficient to maintain the proper domestic water temperature during the critical hours, the auxiliary domestic water heater utilizes the non-renewable resources to boost the temperature. During the late night hours, the auxiliary heater is automatically inactivated and heat is obtained from only the thermal storage.

AUTOMATIC CONTROL

This total flow control scheme efficiently interrelates the seemingly independent solar and wind thermal outputs and the space and domestic water heating demands.

Having set the comfort controls, the system electronically monitors and controls itself. A single mini-processing integrated circuit cartridge is being designed (31) which performs the entire multiplicity of necessary functions. Should one of the units fail, its replacement will be as simple as replacing a fuse. Finally, whenever space heat is being supplied by auxiliary resources, the residents are discreetly notified and may elect to stoke up their Jotul 118 wood stoves.

PERFORMANCE SIMULATION

The initial calculations indicated that the solar-wind output can be expected to meet about 88% of the space and water heating requirement. The seasonal distribution of the solar-wind output is shown with the requirement in Figure 8.

Before the design specifications are finalized, detailed hour by hour digital computer tests must be made to simulate the dynamic performance of the total coordinated system. This program will be synthesized from the research already developed by the Alternative Energy Group at the University of Massachusetts (29) (32).

CONCLUSION

This paper proposed a Total-Coordinated Thermal Development to meet the heating needs of a planned, low-impact community. The design methodology used to generate this proposal is actually a three fold attack on the conventional, non-renewable fuel consumption patterns. The first step is to design to conserve energy. The project architect, Tullio Inglese of NaCul Environmental Center is to be acknowledged for his contributions in this area (33). The second step is to determine the dialectic energy alternatives. Wind and solar energy, locally available in good measure, inexhaustible, and clean, were the obvious resource candidates for the low temperature heating needs. Their unified application required a unique scheme but offered favorable performance characteristics. The third step is the integration of energy conservatives and alternatives into a coordinated cluster of dwellings about a central heating plant.

While fulfilling national goals toward energy independence, the TCTD approaches its own thermal energy independence. Such a central plant might also be used in commercial low temperature applications such as heating a group of stores or a light industrial plant to further abate non-renewable fuel consumption.

Should the final cost lie within the means of the developer, perhaps the remaining difficulties will be the lack of precedent, true expertise, and presently available equipment necessary for the successful implementation of the wind furnace. If the construction of the intermediate scale New England Wind Furnace is delayed, the central heating plant could become operable on the solar-only output, though requiring increased auxiliary fuel consumption during the interlude.

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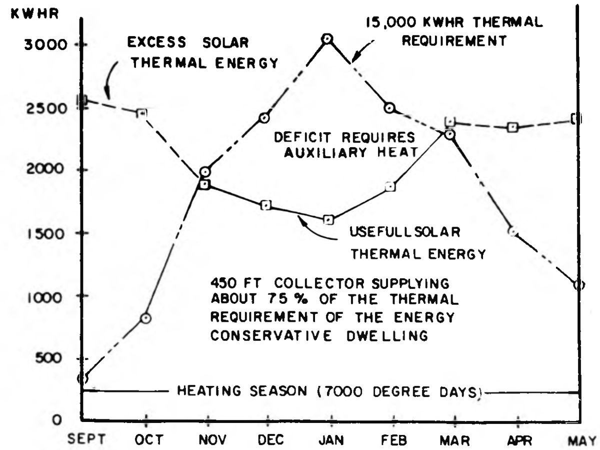


FIGURE 2 SOLAR COLLECTOR OUTPUT

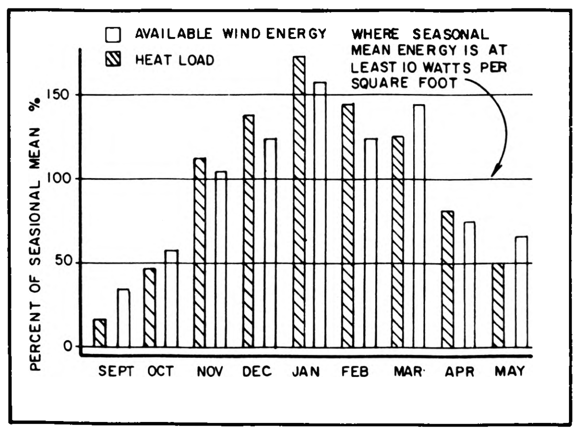
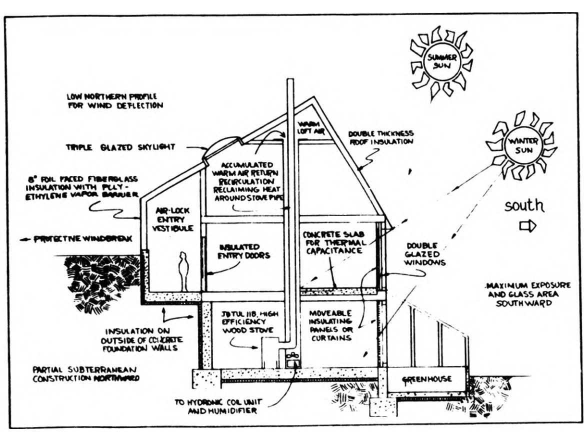


FIGURE 3 AVAILABLE WIND ENERGY FOR HEATING



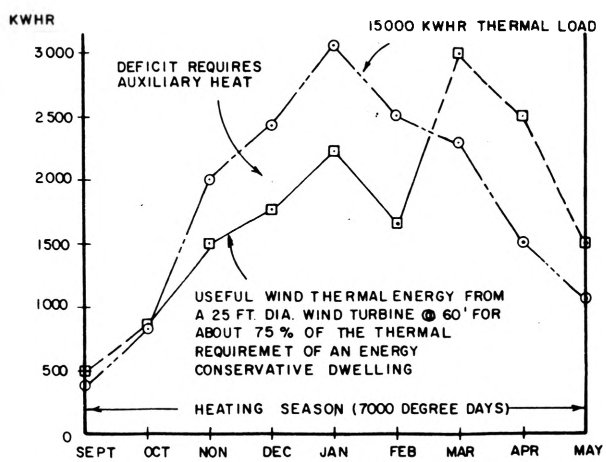


FIGURE 4 WIND TURBINE OUTPUT

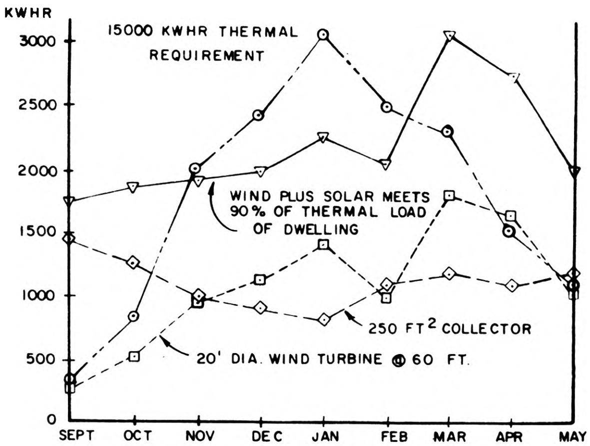


FIGURE 5 SOLAR-WIND OUTPUT

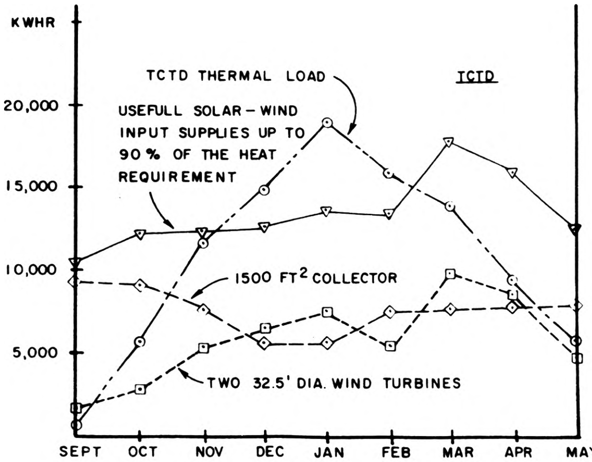
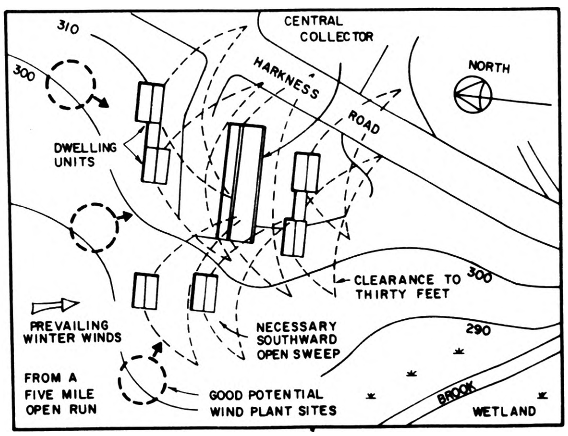


FIGURE 8 TCTD SOLAR-WIND OUTPUT

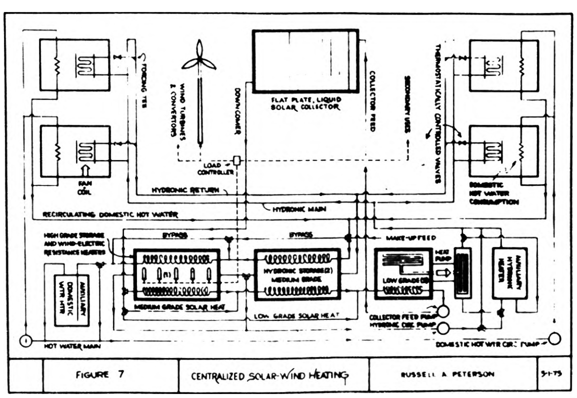
FIGURE 6 TCTD SITE LAYOUT



BIOGRAPHIES

Mr. Russell Peterson as an undergraduate mechanical engineering student at the University of Massachusetts at Amherst has been active in solar and wind power research under an NSF Undergraduate Participation Grant.

Dr. Duane Cromack, Associate Professor of Mechanical Engineering at the University of Massachusetts is currently Project Coordinator for an NSF funded grant "To demonstrate the feasibility of heating a residence by wind and solar energy."



SMALL WIND POWER MACHINE
FOR RURAL AND FARM USE IN THE STATE OF MISSOURI

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Abstract

This paper describes work in progress to develop a prototype wind power generator for use by small farms, rural and isolated homes. It is anticipated that the wind power generator may supply power (1 to 10 kw) as base electric power (including energy storage), supplemental power, or in other forms (e.g. water pumping, nitrogen or hydrogen manufacture, and direct mechanical drive). The objective of this study is to produce a system(s) of high efficiency, low construction cost, and minimum maintenance requirement. Preliminary wind tunnel tests have been completed on several blade designs. A tower system is under construction on campus that will provide for the continuous testing of the full size prototype wind power generators.

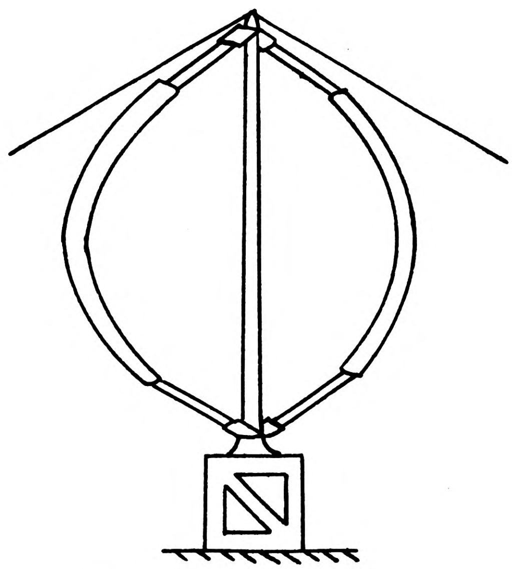
1. INTRODUCTION

The power of the wind, though potentially destructive, has been harnessed by man for centuries to do useful work. His first use of wind was probably in sailing ships and it was not until much later that windmills were first utilized to pump water, grind grain, etc. The windmill was used for centuries as an important source of power until the development of power systems utilizing low cost fossil fuels. Interest was renewed in windmill systems in the early part of this century as a candidate for furnishing power to remote areas.

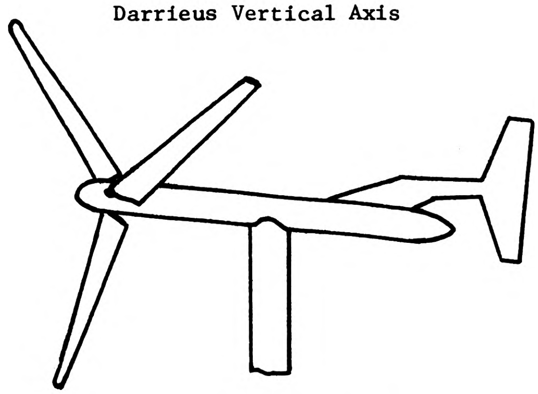
Atmospheric winds are an attractive energy source because they are virtually pollution free and constantly replenished by solar heating. However, operational and economic factors tend to hinder immediate utilization of this energy source on a scale that is significant in comparision to our current conventional sources of energy. Amoung these are the fact that wind velocity can fluctuate widely in magnitude and direction and the energy absorbing capability is low (about 59% of the energy available in a moving airstream can be absorbed for power production). Thus, windmills are hampered by a relatively large size in comparison to power output, problems with structural integrity under high wind conditions, and a fluctuating level of power production. Technologies developed in recent years are being applied to these problems so that wind power can be harnessed as a viable and economic source of energy for mankind.

Although the production of large-scale power (10^3 kw) from the atmospheric winds requires relatively large sized windmill systems, the production of power in the range from 1 to 10 kw presents much less of a problem with respect to system size. Many types of wind power systems have been developed in recent years as contenders for low power level generators. Two of these types are shown in Figure 1 as the vertical-axis wind power generator developed at the Canadian

National Aeronautical Establishment[1] from an invention in 1927 by Darrieus, and a rather standard propeller system that has evolved over the years. As an example of size and power output, it will be possible to generate about 1 kw of power with a 15-ft. diameter rotor operating in a wind of 15 mph.



Darrieus Vertical Axis



Conventional Propeller

Figure 1. Basic Wind Power Rotor Systems

It is the purpose of the recently initiated study here at the University of Missouri-Rolla to develop a prototype wind power generator for use by small farms, rural and isolated homes. It is anticipated that the small wind power generator may supply power as base electrical power (including energy storage), supplemental power, or in other forms (e.g., water pumping, nitrogen or hydrogen manufacture, and direct mechanical drive). The study will seek to produce a system(s) of high efficiency, low construction cost, and minimum maintenance requirement.

2. EXPERIMENTAL PROGRAM

Any attempt to design an economic windmill system must incorporate many important factors. These factors include a high aerodynamic blade efficiency, a high velocity ratio (rotor rotational tip speed/wind speed), and a simple and inexpensive design. Before describing the experimental program it is important to look at the energy available in the wind, and to determine what fraction of this energy can be extracted.

2.1 POWER AVAILABLE IN THE WIND

The power in the wind stream, P_s, of cross sectional area, A, is given by the equation

$$P_s = 1/2\ \rho A V^3$$

where

ρ = air density

A = cross sectional area

V = wind speed

However, even the ideal or optimum windmill cannot extract all of this power. It has been shown by Glauert[2] that the maximum power that can be extracted from a wind stream, P_m, is 59.3% of the power available in thet stream. The power coefficient for the windmill, C_p, is defined as the rotor (actual) power output divided by the power available in the wind stream, P_s, and is given by the equation

$$C_p = \frac{\text{Power Output}}{1/2\ \rho A V^3}$$

The value of C_p for modern windmills approaches 0.42, a value which is about 70% of the power that can be ideally extracted from the wind.

It is apparent that for a given windmill blade design the amount of power that can be generated depends principally on the wind speed, V, and the area swept by the blades, A. Since the power increases with the wind speed cubed, there is considerably more power available in high winds than in low winds. For example, there is four times the power available in a 16 mph wind than in a 10 mph wind. In addition, an increase in blade diameter of 40% would double the power available for a given wind speed.

2.2 TEST TOWER

A 40-ft. tall self supporting tower (see Figure 2) is now being erected at a test site on campus to provide the facility for continuous testing of the full size prototype wind power generators. The tower, a one-man fire watch tower acquired from the Clark National Forest, is rectangular in cross section with four legs, 11 ft. on a side at the base and 3-ft. on a side at the top. This basic test tower will be a permanent installation and will allow for long time testing of the various wind generator blade designs. Initial design work has been completed on the basic power system and windmill shaft to be designated as the standard test bed.

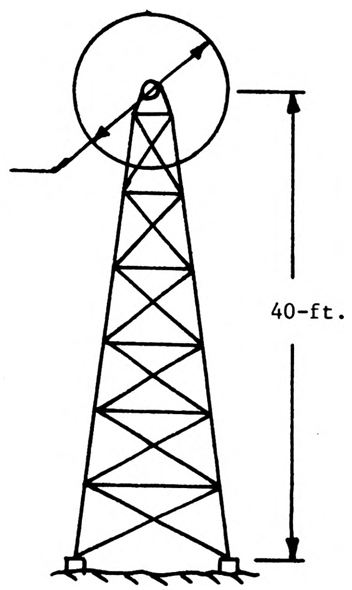


Figure 2. Tower Arrangement

2.3 BLADE DESIGNS

The basic blade designs to be tested are illustrated in Figure 1. The rigid-blade conventional propeller and the vertical-axis Darrieus designs will be tested in both a two-bladed and three-bladed configuration. Preliminary wind tunnel tests[3,4] on models of these designs suggest the need for prototype testing of the two-bladed and three-bladed designs to best satisfy the test objective of developing a system of high efficiency, low construction cost, and minimum maintenance requirement. It is anticipated that blade construction will follow two methods: (1) fiberglass skin bonded to a paper honeycomb core assembled on an aluminum tubular shaft[5], and (2) wood ribs assembled on an aluminum shaft, with urethane foam filling rasped to shape after pouring, then covered with a fiberglass skin[6].

The conventional propeller with three-blades may be necessary (as compared with the two-bladed type) to prevent excessive vibrations when a shift of wind direction requires a rotation of the propeller system to alter its facing direction on the tower. This will be a particularly important consideration for the proposed tests since it is planned to use a vertical tail vane in some cases to keep the propeller axis in line with the wind.

The blade airfoil section to be chosen must produce a high lift to drag ratio, L/D, in order to produce a high output torque and low blade drag. The new general aviation series airfoil sections generate high L/D at high lift coefficients. The first generation airfoil of this family, the GA(W)-1, will be used for the conventional propeller blade section.

Figure 3 is included to show the comparative performance of various blade systems. Note that the maximum or ideal power that can be extracted (C_p of 0.593) is only approached when the tip speed of a windmill exceeds about 4 times the wind speed; that is, when the tip speed ratio exceeds about 4.

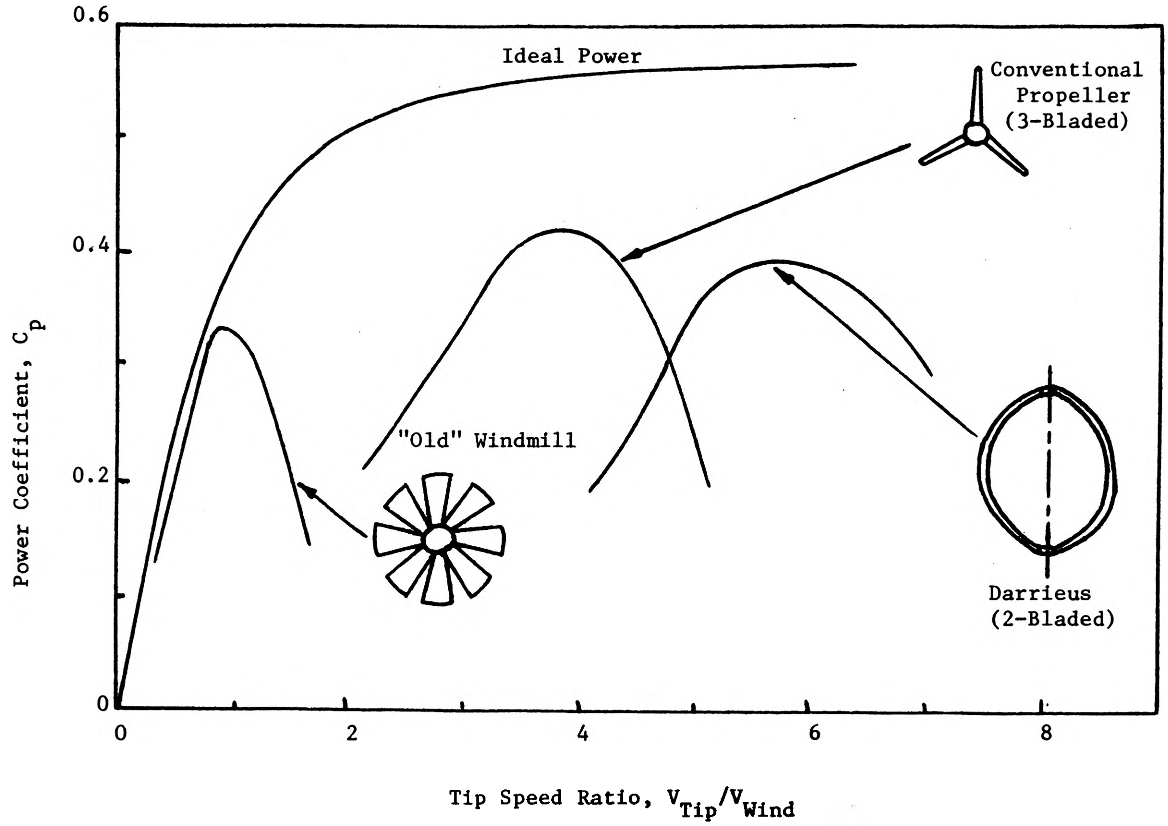


Figure 3. Blade System Performance Comparison

2.4 WIND DATA

In small size applications of wind energy the general rule is that the tower site is determined by the geographical location of the user and is not selected because it is a particularly windy place. Thus, siting is a matter of determining whether or not there is sufficient wind at a given place to economically justify installation of the wind power generator. Although the acquisition of wind characteristics for a one-year period is desirable for proper design and/or selection of a wind generating unit, it may be possible to acquire the needed wind data in a much shorter time utilizing a technique suggested by Thomas[7]. This method requires a few months measurement of average wind speed and very little data analysis. By either method the data available on an hourly basis is compiled to yield a wind frequency curve giving the number of hours for which the wind lies within a given speed interval. From this the available energy for a year for each speed interval per unit area is obtained for the site. Wind speed and direction data is currently being gathered at the site to accomplish this task.

2.5 POWER TRAIN

Energy input from the wind into wind energy conversion systems is a variable one resulting in variable speed of the prime mover unless rotative speed is regulated by a change in (for example) angle of attack of the propeller blades. Such mechanical systems designed to convert to constant rotative speed require dissipative conversion mechanisms resulting in reduced efficiency. Furthermore, since the wind power available varies as the cube of the wind speed, it would be more cost effective to allow the prime mover to rotate at varying speeds and extract a larger percentage of that available power. Not only is energy extraction improved but a simpler design of the mechanical elements is realized.

The basic factors to be considered when examining the electrical technology associated with converting wind energy to electrical energy are: (1) type of output (D.C., variable or constant frequency A.C.), (2) propeller system rotative speed (constant or variable), (3) utilization of the electrical energy output (battery storage, other storage forms, interconnection with an A.C. grid).

The utilization of the electrical energy output for interconnection with an A.C. grid requires a close examination of existing generator systems, especially if it is desired to obtain constant frequency output for a variable speed shaft. Such systems fall into two broad categories: (1) differential methods (mechanical techniques to get constant speed and then employ synchronous generators, or electrical techniques to get constant frequency), (2) non-differential methods (static frequency changes, i.e., AC-DC-AC, or rotary devices).

The proposed series of tests will begin by utilizing a D.C. generator of approximately 1 kw output. This simple system will allow for the needed time early in the test program to get the system operating. Once the system is operating effectively prototype testing will begin utilizing existing generator systems described above.

3. SUMMARY

The purpose of the recently initiated study at the University of Missouri-Rolla is to develop a prototype wind power generator for use by small farms, rural and isolated homes in the state of Missouri. The emphasis will be on optimizing the blade number and configuration to obtain maximum power output for a given wind speed range while maintaining simplicity in design and construction technique for low initial and maintenance cost. These objectives will be realized through: (1) the establishment of a standard method for the continuous testing of full size prototype wind power generators on top of a 40-ft. tall self-supporting tower located at a test site on campus, (2) the performance of long term tests on blade systems developed through wind tunnel tests, (3) establishing a set of design criteria for blade system selection based on site location, wind conditions (average and peak speeds, wind direction, duration, etc.), (4) the development of a prototype "portable" wind power generator for demonstration at selected sites throughout the State.

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OSMO - POWER

OSMOTIC WORK; ENERGY PRODUCTION FROM OSMOSIS OF FRESH WATER/SEA-WATER SYSTEMS

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It is imperative that new and ecologically acceptable energy sources are made available. Solar energy is a source which seems to be inexhaustible and free of pollution hazards. One vast source, which can be considered to be a solar energy source consists of the system fresh water/sea water. Fresh water is continually removed by the hydrological cycle where water evaporates from the ocean due to solar radiation and is eventually precipitated again in the form of fresh water feeding various rivers. Fresh water and ocean (salt) water mix when rivers flow into the oceans. The different chemical potentials are equalized due to this mixing in estuaries not producing any work similarly as when gas escapes into a vacuum. However, the difference in chemical potentials of sea water and fresh water can be utilized and made to produce work if the mixing is allowed to proceed via semipermeable membranes, that is to say if use is made of the osmotic process. This would be equivalent to producing work letting steam move a piston which has a counter pressure slightly lower than the steam pressure. This work can be transformed into electrical energy. In other words use is made of the osmotic process.

A simple osmometer is illustrated in Fig 1. In the past such osmometers have been used for measuring osmotic pressure - i. e. the equilibrium pressure which is obtained by placing an osmotic cell containing a solution into pure water. Molecular weights of polymers can, for instance, be measured in this way. Nobody looked at osmosis as a source of energy. However, osmosis can produce work; the simplest ways of doing this would either be (1) to let the liquid rise to a certain height utilizing the potential energy by just dropping the liquid to a lower level thus producing electrical energy by means of a turbine, or (2) to cut the tube in which liquid rises near the surface of the fresh water making the opening into a jet and the liquid emerging from the jet drive a turbine producing electrical energy. These two cases will be discussed in some detail in this paper.

The maximum (reversible) work,

$$- W_{max} = \int_{n_1}^{n_2} RT \ln a_w \, dn \qquad (1)$$

where n_1 and n_2 are the initial and final numbers of moles of salt solution; a_w is the water activity, R and T are the ideal gas constant and absolute temperature, respectively. Eq. (1) can be evaluated for dilution by one mole of fresh water in the form,

$$- W_{max} = \Pi_o v_1 \qquad (2)$$

Here Π_o is the osmotic pressure of the saline solution and v_1 is the partial molar volume of water (i. e. 18.0 ml/mole).

A saline solution of 35g of NaCl for each kg of solution has similar osmotic properties to those of average sea water and has an osmotic pressure of $\Pi_o = 24.8$ atm. at 20^oC.[1]. This pressure represents the weight of a water column of one square centimeter cross section 256.2 m high (or 250m of saline water of density 1.025). Osmotic pressure has a small temperature coefficient; the osmotic pressure for the above case is 23.1 atm. at 0^oC.

The maximum (reversible) work which can be obtained if $1\ell = 1000\ cm_3$ of fresh water enters a large amount of this saline solution (i. e. large osmotic cell, so that dilution is negligible) is 2.562×10^2 kgm or 6.98×10^{-4} kw hr. The same result can also be obtained by considering the following thought experiment: consider a very large (infinite) amount of the saline solution (i. e. sea water) in an osmotic cell to which a tube is attached in which the liquid rises due to the osmotic pressure of the solution. The sea water is separated from fresh water by a semipermeable membrane. The tube has a height which is a differential shorter than the equilibrium height for the osmotic pressure. Assume that this height has been reached by the solution; the tube is open at the top. One liter of water passes the semipermeable membrane and enters the osmotic cell infinitely slowly. At the same time one liter must emerge from the top of the tube. This is equivalent to lifting 1ℓ of the solution through the height h_o i. e. the equilibrium height for the system. The work done by the osmotic pressure in this case is $W_{max} = 2.562 \times 10^2$ kgm. This work is equal to that given by eqs. (1) or (2).

Thus there is a practically inexhaustible supply of energy near any location where fresh water (i. e. river water) flows into sea water (i. e. near estuaries and also at locations where salt deposits and river water are available). One can utilize this energy by mixing fresh water with sea water (i. e. equalizing their chemical potentials) using semipermeable membranes in a similar way as steam can produce work pushing a piston and not just being released into a vacuum. It is visualized that fresh water is diverted in large pipes to sites where it meets sea water, separating them by semipermeable membranes. Either potential or kinetic energy or both could be obtained in this way. The slightly diluted sea water could be channeled back to the sea where it mixes with further river water which was not used in the osmotic process. It is clear that fast enough membranes (i. e. membranes with sufficiently high fluxes should be available). All the practical experience of membrane technology which has been developed for reverse osmosis

(i. e. desalination) can be utilized for this purpose. It is also possible, in principle, to use the somewhat diluted sea water and the energy obtained from the osmotic process for desalination of this diluted sea water. Not only can lower pressures be used for this reverse osmosis process because of the dilution of sea water but the energy from the osmotic process can also be utilized for this purpose.

A plant which makes use of the kinetic energy produced during the osmotic process can be pictured in simple terms as follows: [2)]

Fresh water is diverted near an estuary in a large diameter pipe to a point near the coast and sea water is diverted similarly. Another possibility is to place a series of osmotic cells which have connections with sea water directly into a river near an estuary (see Fg. 2). Each cell contains a large amount of sea water and a large membrane area (i. e. the membrane areas of such a series of cells could amount to one or more km^2). The osmotic pressure in each cell is equivalent initially to 256.2m columns of water at 20°C. However, the tube in which the saline water would rise is cut off very near the surface and shaped into the form of a jet. The water stream which is ejected can drive a turbine - i. e. Pelton Wheel. Each cell has such a jet and turbine; the turbines in turn are fixed on a single axle. As soon as the sea water is diluted a few percent with fresh water in an osmotic cell it is replaced by new sea water. Meanwhile, however, other cells continue ejecting liquid so that continuous energy production is maintained (see Fig. 2 for details).

Continuity and stirring of this process can also be obtained as follows. A slow stream of salt water flows continually into the osmotic cell near the membrane surface under a hydraulic pressure somewhat greater than the total back pressure from the nozzle. Hence volume v_1, originating from the continuous influx and v_2 due to osmosis are ejected per time unit from the nozzle. This does away with exchanging the salt water in the osmotic cell and also provides "stirring" near the inside membrane surface. The diameter of the nozzle has, of course, to be such that it matches the total ejected volume per time unit (i. e. $v_1 = v_2$) (see later).

This whole process can be evaluated quantitatively. The assumption has to be made, which is practically always fulfilled, that the energy provided by entering of fresh water into the cell at a certain rate can be as rapidly utilized.

(A) ENERGY PRODUCTION (NEGLIGIBLE DILUTION OF SEA WATER)

All losses are neglected for the present discussion, i. e. only the ideal case is considered. It is assumed that fresh water enters through the membrane, diluting sea water at a rate of $\left(\frac{dV}{dt}\right)_{h=o}$ ℓ/sec. The surface area of the membrane is $A_m m^2$ and the back pressure is zero, as h = 0. The maximum (reversible) power is provided by such a system where the solution is sea water or its equivalent (35g NaCl/kg of solution). If the liquid in the osmotic cell, however, is allowed to rise in a tube to a height of h meters, then the flux through the membrane is diminished in the proportion h_o-h/h_o where h_o is the equilibrium height corresponding to the osmotic pressure Π_o. In such a case the power output consists of a potential and a kinetic energy component,

$$P_{max} = \dot{m}gh + \frac{\dot{m}}{2} v_{\ell h}^2 \left(\frac{Nm}{sec}\right) \qquad (3)$$

Here $\dot{m}$ is the mass flow rate, g the acceleration due to gravity, and v_ℓ is the linear velocity in the tube (friction is neglected here; see later). Eq. (3) can also be written in the form,

$$P_{max} = 2.562 \times 10^2 \left(\frac{dV}{dt}\right)_{h=0} \left(\frac{h_o - h}{h_o}\right) \left(\frac{h}{h_o} + 1\right) \frac{kgm}{sec} \qquad (3a)$$

Here 2.562×10^2 kg m/sec is the available power, if one liter of fresh water enters the osmotic cell during one second when h = 0; $\left(\frac{dV}{dt}\right)_{h=0}$ is the actual volume flow rate in ℓ/sec at h = 0 entering the cell. As already pointed out the hydrostatic pressure (back pressure caused by the column of liquid of height h) reduces the volume flow rate by $\frac{h_o - h}{h_o}$; further, the potential energy is decreased in proportion of the actual height h to the equilibrium height h_o. This accounts for the term $\frac{h}{h_o}$.

The potential power component becomes a maximum for $h = h_o/2$, however the energy which can be extracted goes up linearly with h and at h_o the maximum available energy can be obtained in principle; however this would take place infinitely slowly. Thus, if time is not of paramount importance, more than half the maximum (reversible) energy can be extracted from the potential energy. This can be done by having a reservoir of height h where liquid is collected. This liquid can be dropped (similarly as water flows down a mountain side) driving turbines producing hydroelectric power.

Energy is lost due to friction in the tube. In this paper osmotic cells will mainly be discussed which have only short nozzles, i. e. where kinetic energy only is utilized in the form of jet streams ($h \cong 0$). In such cases back pressure is negligible and friction is small.

If the nozzle is located at the side near the top of the osmotic cell then the maximum flow rate of liquid exiting from the orifice is given by,

$$\frac{m}{2} v_\ell^2 = \frac{dV}{dt} \Pi_o = \frac{\dot{m}}{\rho} \Pi_o \frac{cm^3}{sec} \frac{dyne}{cm^2} \qquad (4)$$

Here ρ is the density of the solution.

The dilution of the saline solution takes place practically in a reversible manner. The linear velocity of fresh water entering is extremely small therefore large membrane areas are needed (e. g. $\frac{dV}{dt} = 4.2 \times 10^{-3}$ ℓ/sec m^2 or 4.2×10^{-6} m/sec and $v_\ell = 70.9$ m/sec, see later). This maximum linear flow rate has to be matched by the cross-sectional area A_{or} of the orifice. If A_{or} is too large, kinetic energy is lost; if it is too small then back pressure is generated.

The matching orifice area is given by,

$$A_{or} = \left(\frac{dV^1}{dt}\right) \frac{1}{v_\ell} \quad m^2 \qquad (5)$$

V^1 is here expressed in m^3
($1\ell = 10^{-3} m^3$)

Actually the orifice diameter or cross section is quite critical as Fig. 3 shows where the power output is plotted against the ratio R/R_o.

R_o is the radius which just matches the power input of the osmotic cells (zero back pressure). It may be possible to install an adjustable orifice which can compensate by automatically adjusting the diameter of the orifice for the bulk dilution and dilution near the membrane (see later).

The fact that the diameter is so critical makes the extraction of potential energy for this process somewhat more attractive. An application which can be envisaged, as already stated above, is the desalination of sea water. It is first diluted extracting energy during this process. The diluted sea water could then be subjected to desalination using the energy gained by the osmotic process. In addition less pressure is needed for this desalination by reverse osmosis due to the dilution of the sea water. Thus there is a substantial economic advantage in such desalination which is coupled with the osmotic process.

The maximum or reversible flow rate through the membrane can also be obtained on the basis of purely hydrodynamic considerations. A large osmotic cell filled with sea water (saline water), having a small orifice at the side near the top is immersed in fresh water (see Fig. 4).

At present, friction is not considered and dilution of sea water is assumed to be negligible during operation. v_o and v_ℓ are the linear velocities of fresh water entering the cell through the membrane and of saline solution exiting through the orifice, respectively; p_o is the ambient atmospheric pressure and Π_o is the osmotic pressure which drives fresh water through the membrane on account of the difference in chemical potentials of saline and fresh water, respectively.

The following hydrodynamic equation holds for this case considering mass unit flow rate,

$$\frac{1}{2} v_o^2 + \frac{P_o}{\rho} = \frac{1}{2} v_\ell^2 - \frac{\Pi_o}{\rho} + \frac{P_o}{\rho} \qquad (7)$$

As $v_o \cong 0$, eq. (7) reduces to,

$$\frac{1}{2} v_\ell^2 = \frac{\Pi_o}{\rho} \qquad (8a)$$

If one considers the total mass flow rate, eq. (8a) becomes,

$$\frac{1}{2} \dot{m} v_\ell^2 = \frac{\dot{m}\,\Pi_o}{\rho} \qquad (8b)$$

The total volume flow rate $\frac{dV}{dt}$ through the membrane is given by,

$$\frac{dV}{dt} = \frac{1}{2\Pi_o} \dot{m} v_\ell^2 = K A_m \Pi_o \qquad (9)$$

Here $K = \frac{v_\ell}{\Pi_o}$ and $A_m \Pi_o = \frac{1}{2} \dot{m} v_\ell$

(B) ENERGY PRODUCTION WITH DILUTION OF SEA WATER

During the process the saline solution will be continuously diluted i. e. the osmotic pressure will decrease in power. This, in turn, will also diminish the flux through the semipermeable membrane.

If the osmotic cell is very large it can, in principle, be operated in a way so that the dilution is always kept small (i. e. a few percent), that is, the sea water is renewed after quite limited dilution.

However, the dilution effect can be treated quantitatively. The dilution factor is $(V_o - V)/V_o$ where V_o is the volume of the osmotic cell completely filled with saline solution and V is the volume of fresh water which has entered the cell via the semipermeable membrane during time t. Hence, the flow rate is (this is valid for small dilutions only),

$$\frac{dV}{dt} = K\, A_m\, \Pi_o \frac{V_o - V}{V_o} \qquad (10)$$

Integration of eq. (10) yields,

$$V = V_o\ (1 - e^{-K\, A_m\, \Pi_o t/V_o})$$

Eq. (3) for h = 0 in terms of work becomes then,

$$W_{max,\ t} = 2.562 \times 10^2 V_o \times (1 - e^{-K\, A_m\, \Pi_o t/V_o}) \quad (kg\ m) \qquad (11)$$

(C) NUMERICAL EXAMPLE

As always the saline concentration is C = 35g NaCl/1 kg of solution; this is a solution osmotically equivalent to average sea water. A relatively small flow rate is assumed, i. e. $dV/dt = 4.2 \times 10^{-3}$ ℓ/sec for each m^2 of membrane area. Present-day ultra thin membranes can have flow rates ten to twenty times larger than this.

It can be calculated from eq. (3) that a power output can be obtained of $P_{max} = 1.055 \times 10^{-2}$ kw/m^2 or 1.076 kgm/sec m^2 if h = 0. Further, the mass flow rate is $\frac{\dot{m}}{2} = 2.1$ g (mass) and

$v_\ell = 70.9$ m/sec which gives a matching radius for the orifice of $r = 1.37 \times 10^{-2}$ cm. The back pressure on the membrane for this case amounts to $2\, \dot{m}\, v_\ell/A_m = 5.8$ dyne/cm^2, or about 6×10^{-6} atm. This is completely negligible. This back pressure is independent of the size of A_m. For $V_o = 10^6 \ell$ and $A_m = 100 m^2$ one obtains: $P_{max} = 1.06$ kw or 1.076×10^2 kgm/sec, $v_\ell = 70.9$ m/sec and $r = 1.37 \times 10^{-1}$ cm. In actual practice the osmotic cell and the membrane area will be much larger. If $V_o = 10^6 m^3$ and $A_m = 10^6 m^2$, an osmotic cell of quadratic cross section for such a case has an edge of 1 km length and a height of 1 m. The power output would be 1.06×10^4 kw, $v_\ell = 70.9$ m/sec and r = 13.7. The linear velocity through the membrane is so small (i. e. 4.2×10^{-6} m/sec) that, as mentioned above, the dilution proceeds essentially reversibly. Hence $\Pi_o\, dV/dt = 0.104\ell$ atm/sec or 1.076 kg m/sec for each m^2 of membrane area.

Present-day reverse osmosis membranes can deliver a power for the last case discussed above of 10^5 to 10^6 kw.

(D) LOSSES DURING OPERATION

Power losses are due to (1) dilution of sea water near the membrane (this is equivalent to polarization during reverse osmosis), (2) frictional losses in jets, (3) losses suffered during conversion of kinetic into electrical energy.

Losses due to dilution near the membrane can be minimized by stirring (e. g. a strip of the width of the osmotic cell can be moved slowly to and fro across the membrane).

Frictional and turbulent losses also occur. The flow in the short nozzle is turbulent. For a membrane area of $10^4 m^2$ ($v_\ell = 70.9$ m/sec, 2r = 2.74 cm, $\eta = 10^{-2}$ poises) Reynolds number amounts to 1.9×10^6. The percent frictional loss in a pipe of length L - 2cm is given by Darcy's equation[3],

$$\%\ loss = \frac{100\ f\ L}{2\ r} \frac{\dot{m}\ v_\ell^2}{2} \Big/ \frac{m\ v_\ell^2}{2} = \frac{f\ L}{2\ r}$$

$$= 100 \times 0.02\ \frac{2}{2.74}\% = 1.5\%$$

The above equation is not valid for short pipes. It is generally agreed, however, that the turbulent loss in short pipes is not larger than about 4%. The conversion of mechanical into electrical energy in a turbine (i. e. Pelton Wheel) is better than 90%.

Thus is seems fairly safe to assume that the total losses are not larger than ca. 25% of the ideal (maximum) power output.

(E) OSMO-ENERGY FROM POTENTIAL ENERGY

A continuous method for obtaining energy from lifting liquid can be imagined as follows. A bundle of tubular membranes has a common salt water inlet and outlet respectively, i. e. an outlet tube where the liquid can rise due to osmotic pressure. This bundle is submerged in fresh water. Salt water is introduced under a pressure P from a tube located at the level of the onset of the outlet tube. The liquid rises due to the osmotic pressure, say, to a height $\frac{h_o}{2}$ equivalent to $\frac{\Pi}{2}$. In this case P must be somewhat larger than $\frac{\Pi}{2}$. The volume of liquid is collected at $h_o/2$ corresponding to $\frac{\Pi}{2}$ consisting of the volume introduced through the inlet tube plus the volume obtained by osmosis. The water can then be suitably dropped from the height $h_o/2$ driving a turbine (see Fig. 5).

(F) ECOLOGICAL CONSIDERATIONS

The ecology of the estuary would be upset if the whole river is dammed up by the osmotic power plant. However this is not envisaged. The osmotic cell only occupies part of the river (see figure 2) and the diluted sea water is either used for desalination by reverse osmosis or taken back to the sea. Thus any ecological disturbance should be minimal.

(G) ECONOMICAL ASPECTS

The cost of the osmo-power process can be estimated by considering the cost of producing fresh water by reverse osmosis (desalination). The main difference of the osmotic and the reverse osmotic process is due to the high pressures needed for desalination, which requires costly pumping equipment. The cost of membrane material and its support is practically nil for ultrathin membranes[4]. Such ultrathin membranes are suitable for the osmo-power process as the pressures involved are small compared with those needed for desalination of sea water.

An estimate can be made on the basis of the cost estimate given in Sourirajan's book "Reverse Osmosis"[5]. This estimate includes fixed charges, amortization, operating capital, interest on working capital, and operating costs (labor, electricity, supply and maintenance materials).

A cost of $0.246 is calculated for producing one kgal of fresh water, using a membrane which has a flux of 1.295×10^{-6} g mole H_2O/cm^2 sec atm or 12.26 gal/ft^2 day at 24.8 atm. Electrical energy is taken at a cost of $0.005/kw hr resulting in $0.10 for each kgal of fresh water. Membrane and membrane assembly costs in Sourirajan's estimate amount to $0.069/kgal. As the membrane and its support costs for ultrathin membranes are practically zero (see ref. 4) this amount can be subtracted for our case from the costs. Similarly 90% of the power costs can be subtracted as high pressure pumping is not required for the present process. This results in $0.087/kgal. If 1 kgal of fresh water enters the sea water in the osmotic cell through the membrane, then 2.64 kw hr of energy are produced ideally. Hence the cost per kw hr amounts to 3.3 cents. However, present day ultrathin membranes have a flux of 41 gal/ft^{2}day[6]. Hence the cost is reduced by a factor of 12.3/41 which results in 1.1 cents/kw hr. It has further to be considered that if an osmo-power plant is built in the near future, it would start operating in a few years' time. A recent article[7] estimates the cost of electricity produced by nuclear power as 1.5 c/kw hr in 1981. This would result in a cost of electricity generated by the osmotic process of 1.3 c/kw hr calculated in the same manner as outlined above. This cost compares favorably with the cost of producing electricity from nuclear power in 1981 and even more favorably with the cost of electricity from oil and coal due to the increasing costs of fossil fuels. If it is assumed that there is about a 25% loss in the osmotic process, the cost would then amount to 1.7 c/kw hr. i. e. slightly higher than the cost of electricity produced by nuclear power in 1981. It is anticipated that further developments in membrane technology will decrease the cost still further. The pressure involved in producing osmotic work is only 350 p.s.i. which allows one to use, in principle, extremely thin membranes as the mechanical stresses are much smaller for the osmo-power process than for desalination by reverse osmosis. Such osmo-power could be used not only near estuaries but in any location where salt deposits and fresh water are available.

CONCLUSION

Cost of electrical power or osmo-power obtained from the osmotic process compares favorably with the cost of producing power from nuclear power and more so with power from coal and oil. Osmo-power plants could be constructed in such a way that they have a minimal effect on the ecology of estuaries. In addition, the osmotic process does not produce any air or water pollution and does not present any hazards due to radioactivity.

The six largest rivers in the United States which flow into oceans have a water volume flow rate of about 9.8×10^5 c.f.s.[8] which could produce osmo-power of 7×10^7 kw. The total electrical power production in the United States during 1970 was 4.2×10^8 kw[9]. Hence a considerable amount of power could be provided by the osmotic process.

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Synopsis

Processes are discussed of extracting energy by mixing fresh water (river water) with electrolyte solutions (sea water) via semipermeable membranes. The energy from the process can be converted to electrical energy. Osmo-power can be based on utilizing kinetic or potential energy or both. Kinetic energy is obtained by locating a nozzle (jet) near the surface of an osmotic cell; the liquid jet emerging from such a nozzle can drive a turbine producing electrical energy. Potential energy can be obtained by raising the liquid by osmosis to a suitable height (i. e. 125 m) and letting it fall to zero height level driving a turbine. Both processes can be made continuous. Detailed calculations and plant models are presented. The osmotic process can also be coupled with desalination. Osmo-energy can be extracted and subsequently this energy can be utilized in the desalination of diluted saline water obtained by the osmotic process. Cost estimates indicate that the cost per kw hr of electrical energy from the osmotic process compares favorably with electrical energy obtained from nuclear energy and even more favorably with electrical energy produced from fossil fuels (i. e. oil and coal). Improvements in membrane technology will decrease the cost of osmo-power still further. The six largest rivers in the United States can, in principle, produce a maximum of 7×10^7 kw (the total production in the U. S. was 4.2×10^8 kw in 1970). Osmo-power can be obtained not only near estuaries but also at any locations where salt deposits and fresh water (rivers) are available. Any ecological disturbances in estuaries can be minimized by using only part of a river and by conducting diluted sea water back to the mouth of the estuary. The osmotic process does not produce any air or water pollution and presents no hazards due to radioactivity.

LEGENDS FOR FIGURES

(1) Osmotic Cell

(2) Osmo-Power Plant: A $\sim$ jet, B and C saline water outlet and inlet valves, D sea water, E fresh (river) water, (B) $\sim$ cross section, M $\sim$ membrane.

(3) Power output as function of orifice radius (R_o $\sim$ matching radius for maximum power output)

(4) Π_o initial osmotic pressure, v_o $\sim$ linear velocity through membrane, p_o ambient pressure, v_ℓ linear velocity at orifice

(5) Osmo-Power Plant for utilizing potential energy. The membranes are tubular. Sea water is continuously passed through the tubes and lifted to a height equivalent to $\Pi_o/2$ in addition a volume equivalent to that entering by osmosis is lifted to the same height.

FIG. 1

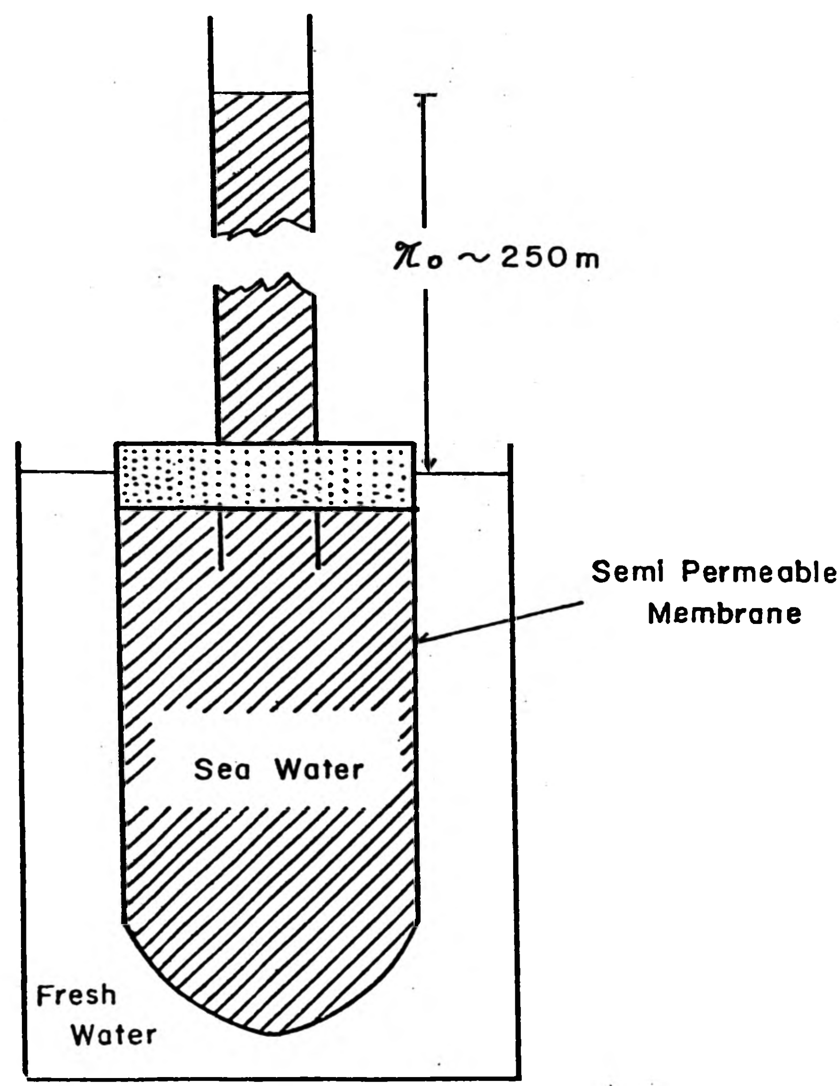
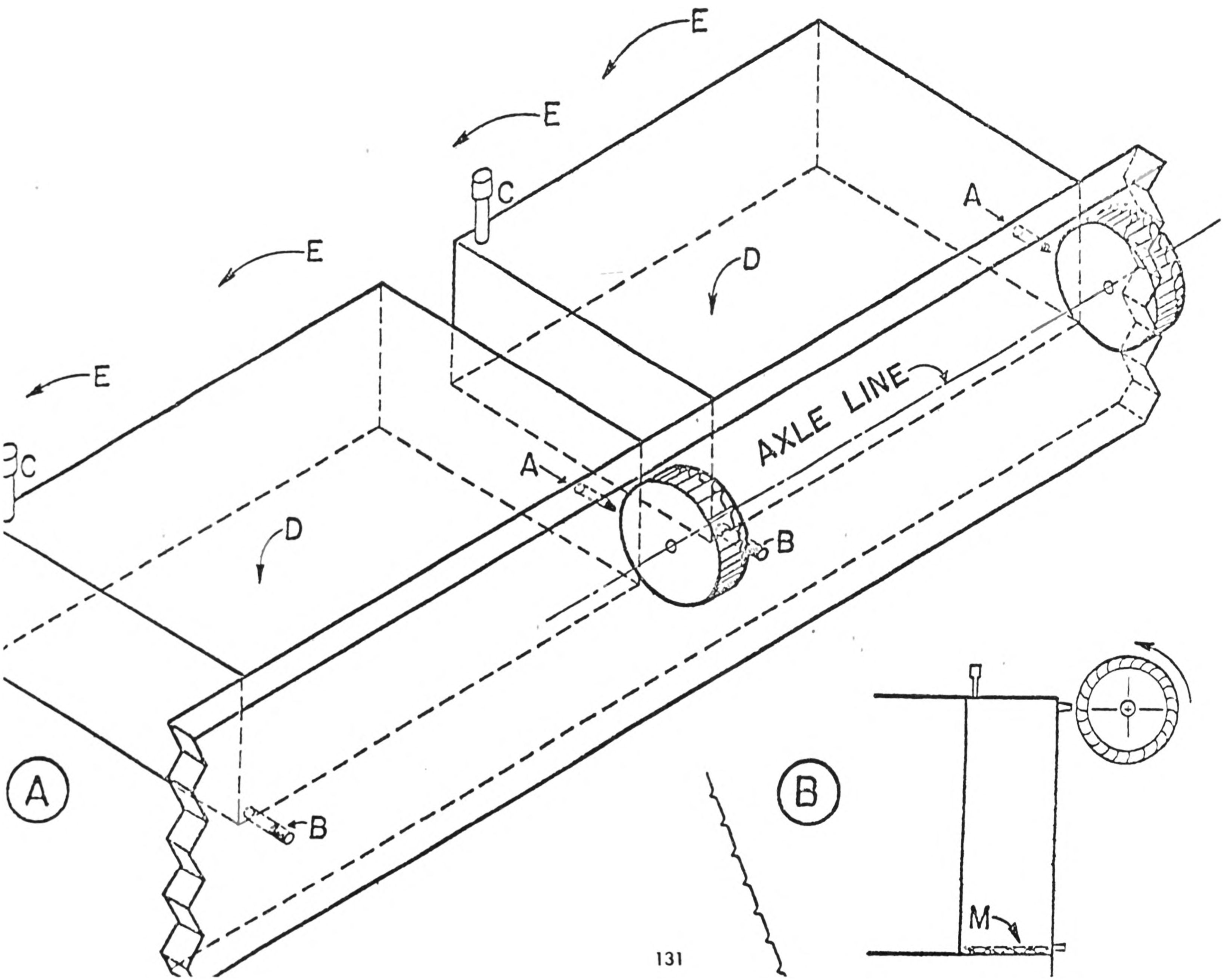


FIG. 2



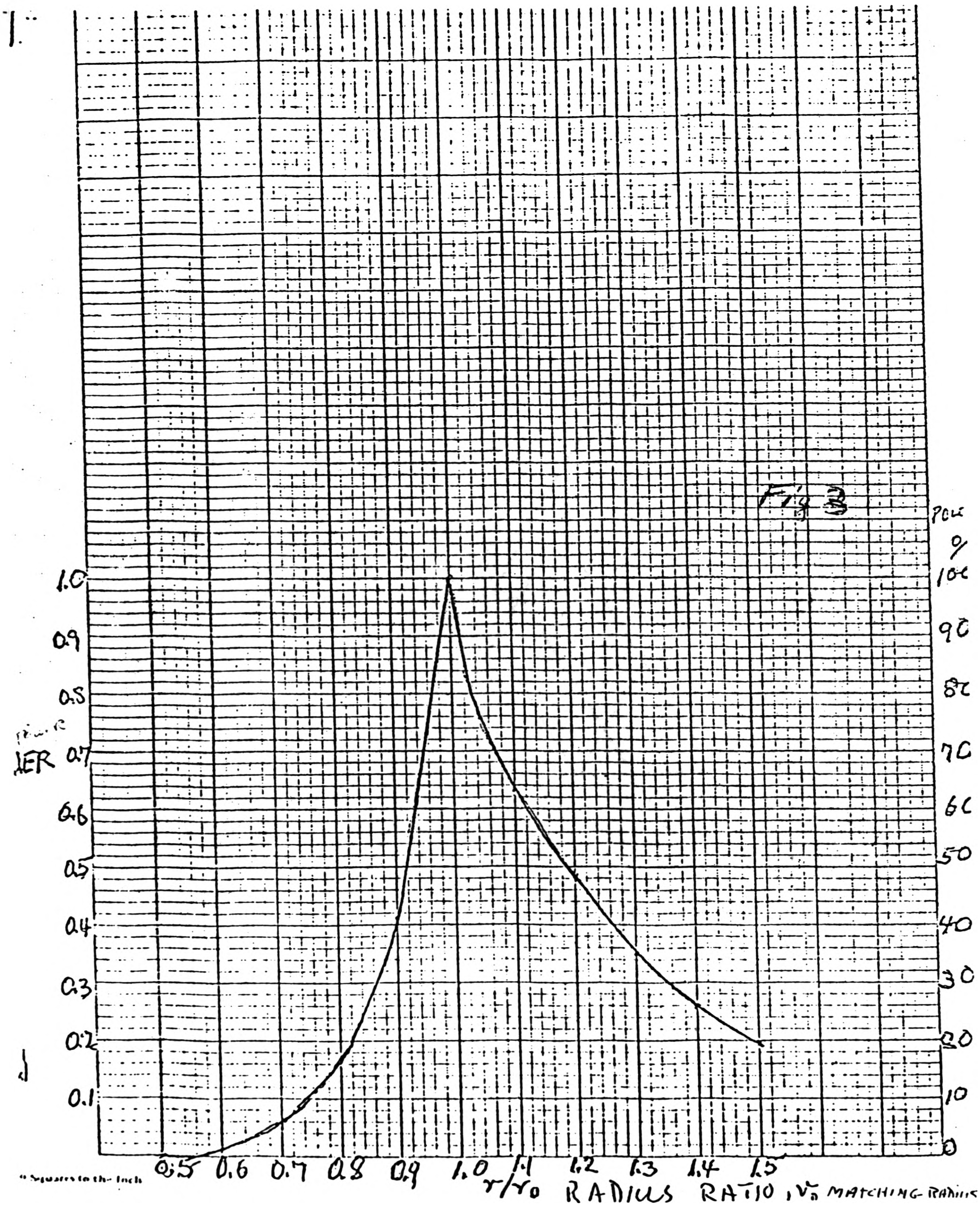


Fig 3
POWER
%
100
90
80
70
60
50
40
30
20
10
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
r/r0 RADIUS RATIO, r0 MATCHING RADIUS

FIG. 4

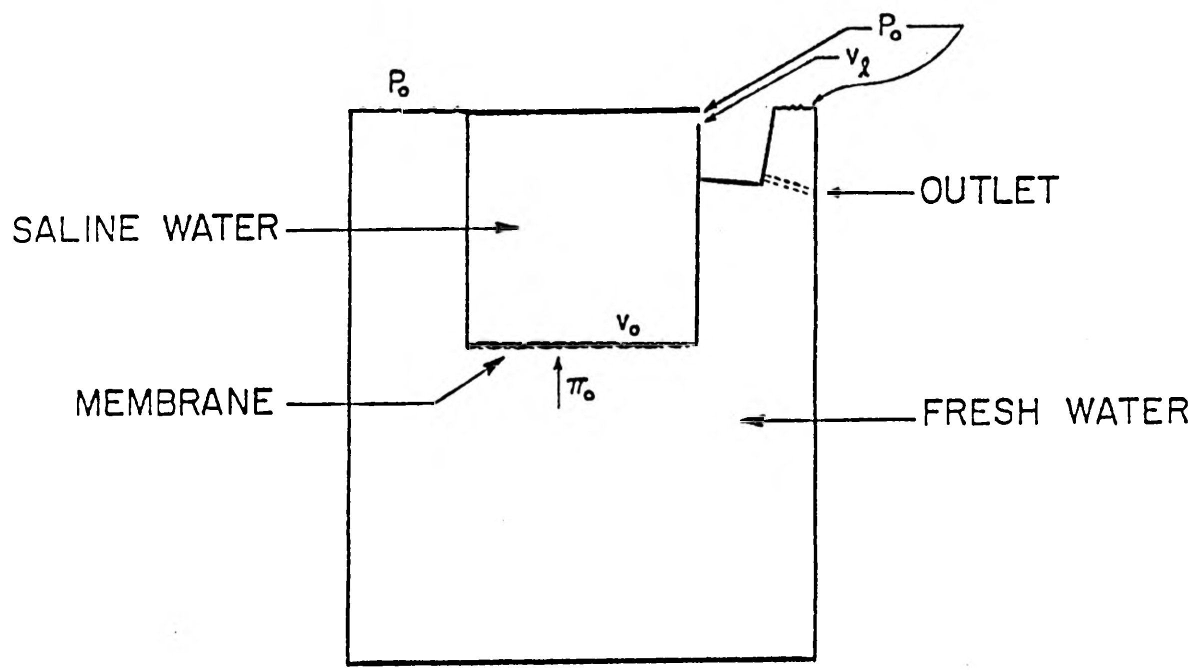
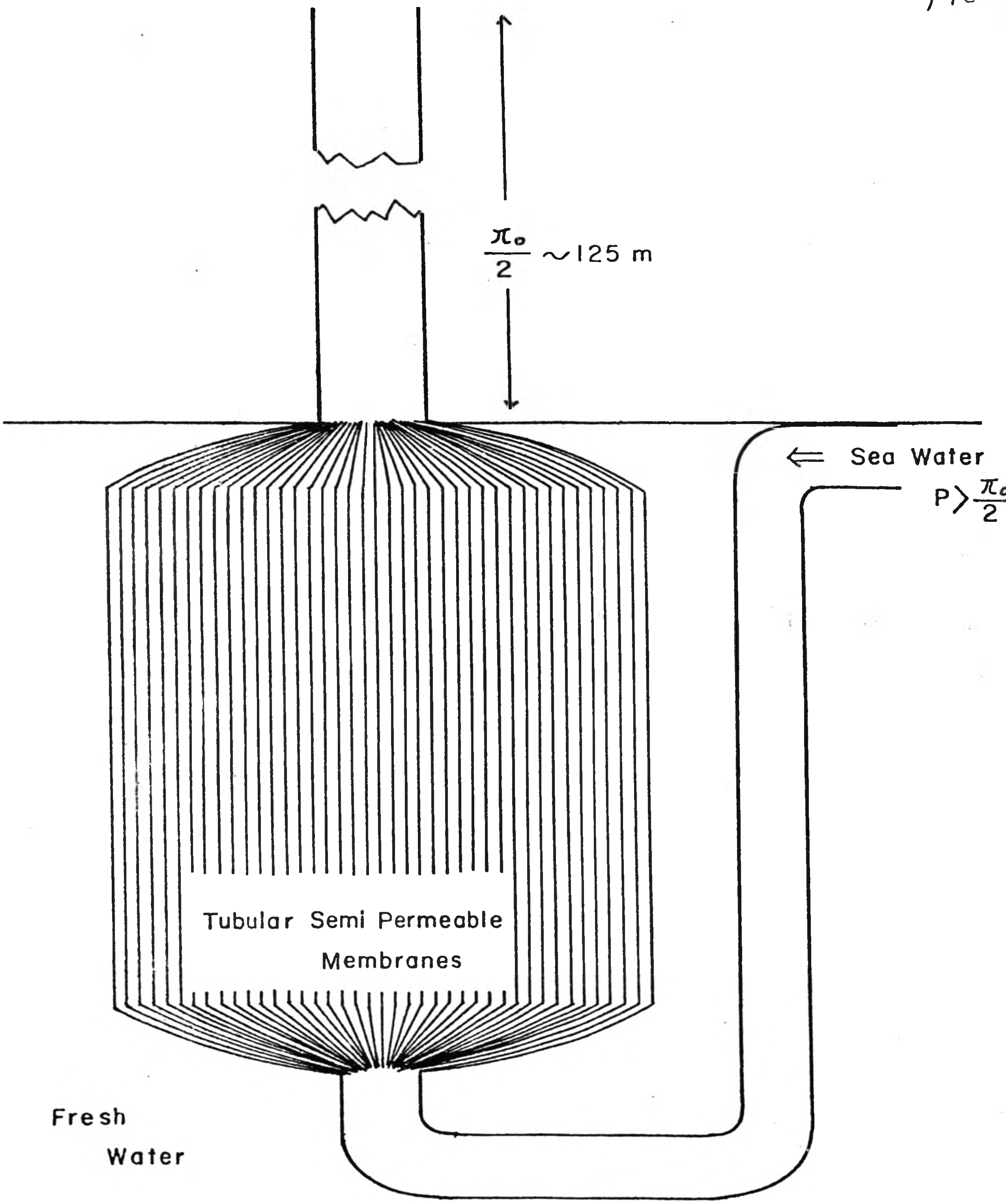


FIG. 5



$\frac{\pi_o}{2} \sim 125$ m
⇐ Sea Water
$P > \frac{\pi_o}{2}$
Tubular Semi Permeable Membranes
Fresh Water

ENERGY FROM AGRICULTURE

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During the past few years, the demand for energy and petrochemicals has grown at a pace so rapid that our reserves of fossil fuels, once considered inexhaustible, are now being quickly depleted. To help lessen this impending problem, alternative sources of energy must be rapidly developed.

Of the many new sources of energy being studied, solar energy, undisputedly, is the most inexhaustible. Energy from the sun, incident upon the earth's surface, exceeds by nearly three orders of magnitude the total energy consumption today. Furthermore, it is not subject to nationalistic boundaries and its use would be compatible with our environmental goals.

Several methods of using solar energy are under investigation. Photovoltaic and photo-thermal methods both require large land areas and large capital investments. In addition, energy storage must be provided to assure an uninterrupted supply. Significant progress is being made in resolving these problems, but it appears that it will be a number of years before these methods are economically attractive enough to receive widespread use.

A third means of collecting the sun's energy is by photosynthesis. Most of the fossil fuels we now burn originated from plants produced by photosynthesis. Plant matter can, of course, be used as a source of energy today. This means of capturing the sun's energy has several advantages:

1) energy storage in the plant, available for use upon harvest
2) readily developed with existing technology and manpower
3) ecologically inoffensive
4) economically beneficial to put idle land into productivity

The efficiency of converting sunlight into fuel by photosynthesis is rather poor Table 1 shows that conversion efficiencies for common crops range from about .2 percent for a pine forest to 1 percent for a corn or sugar cane field. However, if cropping systems were developed specifically for the production of fuel, much higher efficiencies would result. Based upon a collection efficiency of .8 percent and a heating value of 6500 BTU per pound, a land area of about 100 sq. mi. would be required to supply the fuel for a 250 mw generating station, operating with a 55 percent load factor.

Food represents only a small part of the energy available from much of our agricultural crops. Large quantities of corn stalks, wheat straw, soybean foliage etc.

represent an unused source of energy. Estimates of available crop wastes vary, but are around 400 million tons annually. If half of this could be collected, it would represent 2.6 x 10^{15} BTU annually, or about 3 percent of our total energy requirement.

Clearly, crop wastes are an important source of energy, but will not be adequate to make us energy sufficient. Fortunately, there are vast acreages of marginal or unused land that could be placed into production of uncultivated energy crops.

Crop matter is an inconvenient form of energy. It can be burned directly, but the high moisture content produces inefficient combustion. Also, storage and transportation of crop matter is inconvenient and expensive. These difficulties can be overcome by converting crop matter to gas. Pyrolysis and hydrogasification are two methods for making gas from organic matter. These processes operate at elevated temperatures and pressures, and, although not fully perfected, suffer from low conversion efficiencies.

1. BIOCONVERSION OF PLANT MATTER

Plant matter can be converted to methane by anaerobic digestion. This process is carried out at ordinary temperature and pressure with a conversion efficiency of 94 percent. Conversion of organic matter to methane by anaerobic digestion is a biological or bioconversion process. Micro-organisms convert solid organics first to soluble carbohydrates, fats and proteins; then to organic acids, aldehydes and alcohols; and, finally, methane and carbon dioxide are produced by metabolism of anaerobic bacteria.

Most investigations of anaerobic digestion have been concerned with disposal of sewage and feedlot waste and considerable data is available on these substrates. Data are somewhat more limited on the production of methane from agricultural products; although it has been shown that anaerobic digestion of such material as cannery wastes, molasses, algae and municiple refuse is feasible.

Recent studies at the University of Missouri-Rolla have demonstrated quantitatively the feasibility of producing methane from hay, oak leaves and comfrey. These investigations, covering a period of about two years, indicate that 19.5 cubic feet of methane can be obtained per pound of carbon digested. The carbon content of most plants is 35-40 percent. Carbon destructions of 80 percent are achieved, so that 5-6 cubic feet of methane would be available from each pound of dry crop matter.

2. ECONOMIC POTENTIAL OF BIOCONVERSION

Bioconversion could be applied on a small scale to the production of energy for a single farm. The method could also be used to produce large quantities of methane for distribution in existing natural gas pipelines. The equipment for a large process is shown in Figure 1. The crop matter is put through a shredder to reduce the size, then mixed with water and fed to reactors, where a culture of bacteria is maintained to produce methane. Carbon dioxide and hydrogen sulfide are removed by scrubbing with monoethanol amine and the remaining methane is compressed to the desired pressure. Effluent from the reactors is expected to be a good fertilizer, since it would contain all the minerals and nitrogen from the plant.

Table 2 presents the availability of crop wastes in Missouri. There are ten million tons of residue available from the production of corn, soybeans and small grains. Over half of this tonnage is available in NW Missouri, around Chillicothe. A bioconversion plant, as shown in Figure 1, could be built in Chillicothe to use waste in that area. A plant to produce 50 million cubic feet per day would require 1.5 million tons of crop residue annually, or about 30 percent of the available quantity. This amount of gas would generate 250 mw of electricity continuously, or the residential requirement of the city of Kansas City.

The economics of this plant are presented in Table 3. An investment of $35 million is required for the reactors, compressors, scrubbers, grinders and miscellaneous equipment. Reactors are based on series operation and a first order kinetic rate coefficient of .2 hr^{-1}, as measured in the UMR laboratories. Reactors are 5 million gallon floating head steel insulated tanks. Heating and agitation are by gas recirculation. As noted, a contingency of 30 percent has been included in the estimate.

The energy balance on the process shows that 10 percent of the methane is consumed for power, compression and steam. Revenue from the sale of gas at $2 per mscf is $33.5 million annually. Operating costs are $12.5 million, including collection of the crop residue, utilities, maintenance, labor and depreciation. Collection and transport of the crop waste were estimated at $5 per ton.

A respectable 35 percent return on investment is available from this project. If the gas price was $1.50 per mscf, the return would reduce to only 23 percent. With a raw material cost of $10 per ton the return is 25 percent. Clearly, the production of methane from crop wastes is an economically attractive energy alternative.

Table 4 presents the economics for the same size plant using hay as a feedstock. A value of hay of $15 per ton is used. This is based upon a collection cost of $5 per ton in large one ton bales. Wheat straw or hay from idle grasslands would be used. A return of 14 percent is available from this operation.

It should be pointed out that anaerobic digestion has not been studied extensively from the standpoint of production of methane; rather this process has been studied primarily as a waste treatment method. Therefore, considerable improvement in gas yields and reaction rates are expected. These matters are under study in our laboratories.

The economics of methane produced by anaerobic digestion are highly dependent upon the price of raw materials. Studies are planned to determine the most efficient photosynthetic collectors and the digestion characteristics of various materials. Also, the economics may be further improved if the reactor effluent can be used as fertilizer and investigations of the fertilizer value are planned.

3. SUMMARY

Bioconversion of crops or crop residues to methane can provide the energy source to fill the gap. Technology is available, and being rapidly advanced, to make use of this energy source now. The process is economically attractive at todays fossil fuel energy prices, a potential that few other alternative energy schemes can match.

TABLE 1. SOLAR EFFICIENCIES OF VARIOUS CROPS

PLANT TYPE	LOCATION	FUEL VALUE BTU/LB	DRY YIELD TONS/ACRE·YEAR	TOTAL RADIATION FALLING UPON LOCATION[A] BTU/FT^2	ESTIMATED SOLAR ENERGY CONVERSION PERCENT
OAK - PINE FOREST	NEW YORK	7000[C]	5.4[E]	4.24×10^5	0.41
SOUTHERN PINE	SOUTH U.S.	7000[C]	2 - 5[B]	5.34×10^5	0.13 - 0.33
HYBRID POPLAR	PENNSYLVANIA	5625[B]	4 - 8[B]	4.35×10^5	0.24 - 0.47
SYCAMORE	GEORGIA	5800[C]	1.6 - 11.2[C]	5.34×10^5	0.09 - 0.61
REED CANARY GRASS	U.S. MIDWEST	6500[C]	6.32[C]	4.65×10^5	0.29
BERMUDA GRASS	ALABAMA	5625[B]	8 - 11[B]	5.34×10^5	0.42 - 0.58
ALFALFA	U.S. AVERAGE	6500[C]	2.85[C]	4.65×10^5	0.18
CORN	U.S. AVERAGE	6500[C]	11.2 - 17.9[E]	4.65×10^5	0.72 - 1.15
SUGAR CANE	LA. & FLA.	6500[C]	20[C]	5.34×10^5	1.11
CATTAIL SWAMP	MINNESOTA	6500[D]	11.2[E]	3.76×10^5	0.88
MARINE ALGAE	NOVA SCOTIA	6500[D]	9.0 - 11.7[E]	4.24×10^5	0.63 - 0.74
SEWAGE POND	CALIFORNIA	6500[D]	25.1[E]	5.56×10^5	1.34

[A]ESTIMATED FROM W. GORCZYNSKI, COMPARISON OF CLIMATE OF THE U.S. AND EUROPE, 1945, NEW YORK.

[B]CLINTON C. KEMP AND GEORGE C. SZEGO, THE ENERGY PLANTATION, A.I.CH.E. SYMPOSIUM ON SOLAR ENERGY UTILIZATION, MARCH 20, 1975.

[C]GEORGE C. SZEGO AND CLINTON C. KEMP, ENERGY FORESTS AND FUEL PLANTATIONS, CHEM. TECH., MAY, 1973.

[D]ESTIMATED

[E]A NEW LOOK AT ENERGY SOURCES, ASA SPECIAL PUBLICATION NO. 22.

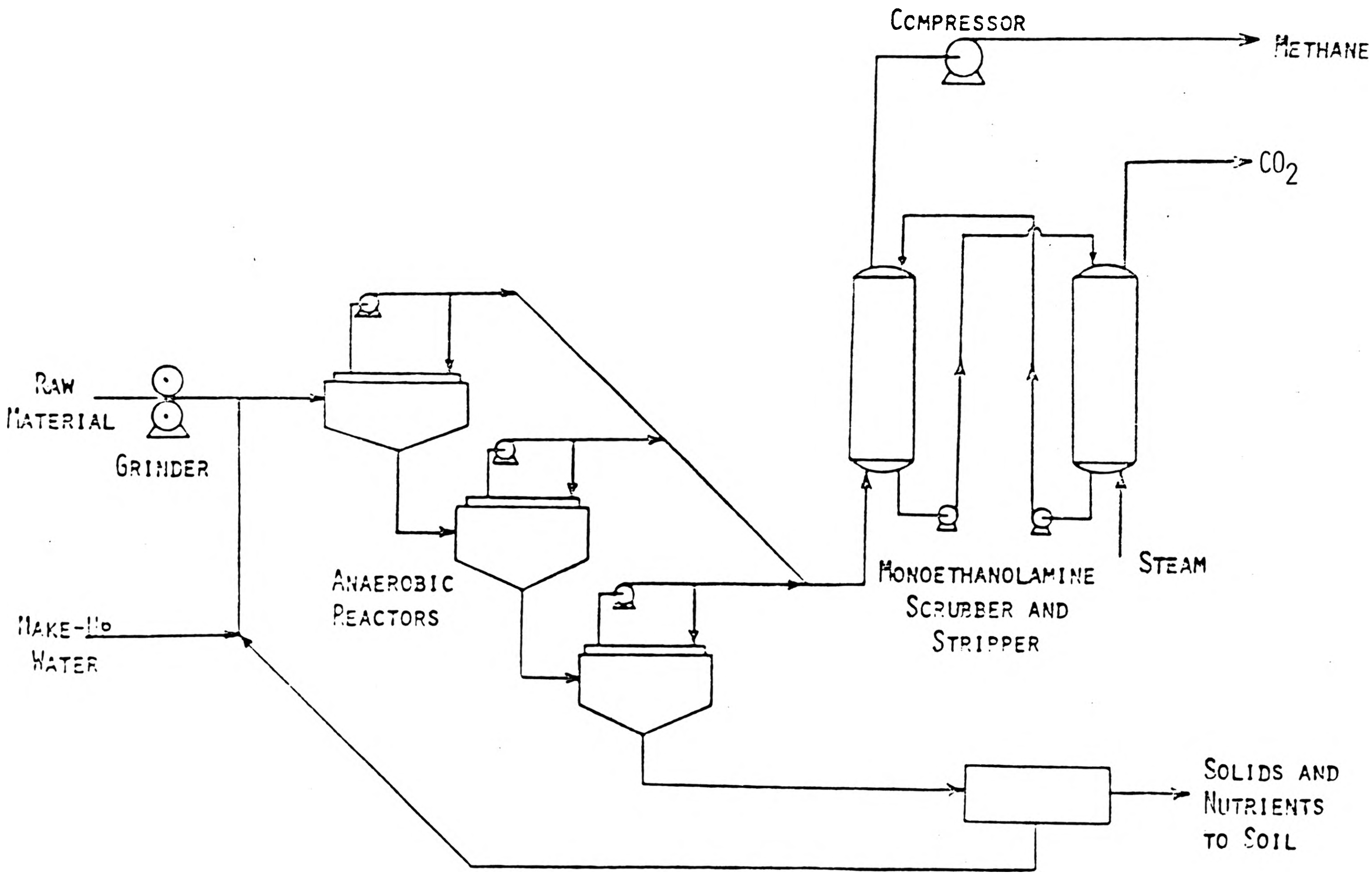

FIGURE 1. Process for Producing Methane by Anaerobic Digestion

TABLE 2.

AVAILABLE WASTE MATERIAL IN MISSOURI

AND THE CHILLICOTHE AREA*

	10^6 TONS/YEAR	
	MISSOURI	CHILLICOTHE AREA
SOYBEANS	2.4	1.2
CORN	5.4	3.0
SMALL GRAINS	1.4	0.9
SORGHUM	0.6	0.3
COTTON	0.2	---
TOTAL	10.0	5.4

* DR. J. W. NELSON, AGRONOMIST, UNIVERSITY OF MISSOURI-COLUMBIA.

TABLE 3.

ECONOMIC ANALYSIS OF METHANE PRODUCTION
FROM CROP WASTE IN NORTHWEST MISSOURI

		$\bar{M}$$
CAPITAL INVESTMENT		
DIGESTORS		22.0
COMPRESSORS		1.3
MEA SCRUBBERS AND STRIPPERS		0.3
GRINDING AND STORAGE		1.8
PUMPING AND PIPING		2.0
CONTINGENCY (30%)		7.6
	TOTAL	35.0
		$\bar{M}$ $/ YR
REVENUE ($2/MSCF)		33.5
OPERATING COSTS		
RAW MATERIAL		7.3
POWER		0.6
LABOR		0.3
MAINTENANCE		1.8
TAXES AND INSURANCE		0.7
DEPRECIATION		1.8
	TOTAL	12.5
GROSS PROFIT		21.0
NET PROFIT		10.5
RETURN ON INVESTMENT		35.1%

TABLE 4.

ECONOMIC ANALYSIS OF METHANE PRODUCTION FROM HAY

CAPITAL INVESTMENT		$\bar{M}$\$
DIGESTORS		22.0
COMPRESSORS		1.3
MEA SCRUBBERS AND STRIPPERS		0.3
GRINDING AND STORAGE		1.8
PUMPING AND PIPING		2.0
CONTINGENCY (30%)		7.6
	TOTAL	35.0
		$\bar{M}$\$/YR.
REVENUE (\$2/MSCF)		33.5
OPERATING COSTS		
RAW MATERIAL		21.9
POWER		0.6
LABOR		0.3
MAINTENANCE		1.8
TAXES AND INSURANCE		0.7
DEPRECIATION		1.8
	TOTAL	27.1
GROSS PROFIT		6.4
NET PROFIT		3.2
RETURN ON INVESTMENT		14.3%

LEAN BURNING SPARK-IGNITION ENGINES --AN OVERVIEW

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Abstract

Means of improving the thermal efficiency of spark-ignition internal combustion engines through fuel-lean combustion at part-load are discussed. For purposes of comparison and evaluation, lean-burning engines are classified as modified conventional engines, stratified charge engines, and engines using alternative fuels. Particular attention is given to automobile applications because of their importance for conservation of fuels.

1. INTRODUCTION

The four stroke-cycle spark ignition (SI) engine with gasoline as fuel has been dominant in the light-duty vehicle field in the United States for more than fifty years. The reasons for the so-far secure place of the SI engine are both technical and economic, and although various alternative engine designs, both internal combustion and external combustion, may become commercially available for vehicle applications by the end of the century, it is obvious that no wholesale replacement of the reciprocating SI engine will occur in the near future. Thus, it is pertinent to examine ways by which the efficiency of energy utilization of such engines can be improved.

The terminology "efficiency of energy Utilization" is meant to imply a broad viewpoint. This is important because the efficiency (η) of most energy conversion devices is a function of load. That is the efficiency varies with power output. This is as true of electric motors, for example, as of SI engines. Ultimately, therefore, it is the speed-load-efficiency characteristic of a given energy converter which must be considered, along with its intended application. In this review, attention will be focused on light-duty applications, specifically automobiles, because of the great importance of the automobile as a consumer of hydrocarbon fuel stocks.

The brake thermal efficiency of a typical automobile engine at its optimum operating point is perhaps 30%--a not unreasonable value when compared to other Carnot-limited heat engines, although certainly not as high as can be achieved with some. However, other off-optimum combinations of engine speed and load give lower efficiencies, hence, in a vehicle application, greater fuel consumption. At the extreme of idling, the efficiency is of course zero, if the work used to drive accessories is ignored. Both vehicle configuration--inertia, aerodynamics, rolling resistance, transmission and rear axle design--and driving cycle--starts and stops, acceleration rates, cruise speeds--then affect the resultant overall efficiency of energy utilization, or fuel economy, for a given vehicle in a given application. In this respect, questions of fuel consumption must be approached similarly to those of exhaust emissions, where driving cycle tests, with their transient conditions, have replaced steady-state testing for most purposes. Average efficiency levels for current automobiles over typical driving cycles are much less than the 30% which can be achieved at the optimum point; depending upon vehicle design, values in the range of 6% to 13% are found [1].

Strategies for improving the fuel economy of passenger cars then involve such measures as reducing vehicle weight and altering gear ratios, as well as changing the powerplant characteristics. For example, considering Fig. 1, a typical engine performance map representative of a full size American automobile [2, p. 446], we see that the points of greatest efficiency (lowest brake specific fuel consumption, bsfc*) are at relatively high loads (high brake mean effective pressure, bmep) and low speeds. Such conditions are encountered only rarely in automobile applications--for example, during rapid accelerations or climbing steep grades, which may in themselves be wasteful because, although the engine is operating efficiently the work or power required is high, perhaps unnecessarily so. The zero grade road load curve shown on Fig. 1 represents combinations of load in terms of bmep and speed typical of cruising conditions. Note that the engine is operating relatively inefficiently for all cruise conditions but most especially in the lower load/speed ranges. Of course, lower speeds require less power output and the fuel economy of an automobile thus tends to improve at lower cruising speeds--down to perhaps 30 or 40 mph [1] -- hence the present statutory 55 mph speed limit. Nonetheless, the figure makes clear the potential improvements in vehicle fuel

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*Efficiency and specific fuel consumption on either a brake or an indicated basis are related by

$$\eta = \frac{2545}{sfc.Q_c}$$

where Q_c is the heating value of the particular fuel in Btu/lbm. In the discussion below, various fuels will often be compared; thus it is generally convenient to refer to efficiencies rather than sfc's. In converting the sfc's given in many of the references to efficiencies, the lower heating value for the particular fuel has always been used.

economy possible as a result of lowering (numerically) rear axle ratios--a long term trend still in progress--and decreasing rated power levels. There seems little reason for the performance capabilities of many present-day automobiles when Fig. 1 indicates that decreasing power ratings would both move common operating points closer to the maximum efficiency points and decrease the average power levels, hence fuel flows, in stop-and-go driving if judiciously combined with decreased vehicle inertias. A complementary approach would be transmission designs which keep the engine operating near the point of greatest efficiency. It should be possible to achieve overall gains despite the reduced mechanical efficiency which might result from a more complex transmission.

Such a systems approach to the problem of increasing the energy efficiency of automobiles is much too broad an area to be treated further here, involving, as it does, the inter-related concerns of engine, transmission, and vehicle package design, as well as problems of occupant safety--more difficult in smaller, less massive cars--and powerplant emissions. Patterns of automobile use together with speed limits and other constraints which may affect overall automobile energy consumption totals are also important. The discussion that follows concentrates on thermal efficiencies of engines and, unavoidably, will often be based on peak efficiency values. However, we must remember that this is only part of the fuel consumption problem, and that any final evaluation of an alternative engine design must be based on consideration of the complete vehicle system.

2. LEAN ENGINE OPERATION

While many alternative engine designs, including Rankine (steam or other vapor), Stirling, and Brayton (gas turbine) cycle engines have been discussed in recent years as possible automobile powerplants, often because of their potential for low emissions, this review will treat only SI internal combustion engines (ICE's), sometimes termed Otto cycle engines. Specifically, we will concentrate on prospects for improving the efficiency of SI engines by means of lean combustion. Lean-burning engines typically also offer low exhaust emissions--important because of the difficulties presently being encountered in achieving both good fuel economy and low emissions, conflicting requirements in conventional engines. Before discussing ways of accomplishing fuel-lean combustion let us briefly mention the major determinants of the efficiency of ICE's.

At the most elementary level, that of air-standard cycle analysis, the theoretical efficiency of an SI engine is a function only of compression ratio:

$$\eta = 1 - (CR)^{1-k}$$

η = efficiency
CR = compression ratio
k = ratio of specific heats, c_p/c_v

Taking a value for CR of 8, typical of engines designed to operate on lead-free gasoline, and k constant at 1.4, the theoretical efficiency η is 56.5%; a plot of η as a function of CR for such an air-standard cycle is included in Fig. 2. We can easily see that this is not a realistic value, for we have already pointed out that actual SI engine efficiencies are not more than 30%. However this equation is nonetheless important because the CR is in fact among the most important variables affecting ICE efficiency.

Although neither this equation nor the plot in Fig. 1 applies directly to a compression ignition (CI) or diesel engine, the higher values of CR--by a factor of 2 or more--used in CI engines are an important reason for their greater efficiencies. Unfortunately CR's in SI engines are limited by the onset of detonation, or combustion knock, which occurs with high CR and/or low octane fuel. Use of unleaded gasoline, now required for emissions control, has resulted in lower engine efficiencies because the added tetraethyl lead had served to inhibit detonation. Without it, the octane rating of gasoline decreases, and lower CR's must be used. Lower CR's, retarded ignition timing, and exhaust gas recirculation--all adopted for emissions control--are the major causes of reduced operating efficiencies of automobile engines over the last few years. This efficiency decrease, together with greater vehicle weights and other factors such as increased accessory loads, contributed to fuel economy decreases of about 20%, on the average, in the period 1967 to 1973 [3]. Given the present situation, it seems unlikely that efficiency increases by means of increased compression ratios can be achieved in the near future using gasoline-fueled engines of conventional design.

Returning to the efficiency equation above, we can see that it is unrealistic because it assumes the working fluid in the engine to be air. Actually, air plus fuel is compressed in the engine; chemical reactions occur during and following combustion, and the products of combustion then expand, along with the inert constituents, primarily nitrogen, of the intake air. The thermodynamic properties of the actual constituents at any point in the cycle must be used for a more exact analysis. Furthermore, the specific heat ratio k, which remains important for efficiency calculations, is not constant, but decreases with increasing temperatures, tending to decrease the calculated efficiency. At the high temperatures generated by combustion, dissociation of the gases in the cylinder also occurs. Dissociation of the products of combustion (primarily CO_2 and H_2O) requires energy; this results in a decrease in their internal energy, some of which is transformed into chemical energy of the dissociated products. The net result is a decrease in the energy available to do work on the piston, hence again a lower efficiency. By considering such phenomena it is possible, using considerably more complicated procedures, to arrive at more realistic calculated thermal efficiencies. Such a procedure is called fuel-air cycle analysis or, sometimes, ideal cycle analysis. By such means, an indicated thermal efficiency of 43% can be calculated for a CR again of 8 using isooctane fuel at the stoichiometric air-fuel ratio (AFR) [4]; results for η as a function of CR from fuel-air cycle analysis are also shown in Fig. 2. The curves are for several different AFR's. These are best expressed for later comparisons with other fuels as equivalence ratios. The equivalence ratio (ER) is defined as the actual AFR divided by the stoichiometric AFR, that AFR at which just enough fuel is available to combine with all the oxygen in the intake charge. As indicated efficiencies, the curves in Fig. 2 do not include mechanical or pumping losses and therefore cannot be directly compared to brake efficiencies. They are clearly much closer to being realistic results, however.

Given the limitations on compression ratio of SI engines, it is necessary to look for other means of improving thermal efficiencies. An attractive procedure is to use fuel-lean mixtures--i.e., considerable excess air--at least for part load operation. This is the way a CI engine operates and is another of the reasons for its higher efficiency. The efficiency increments possible from lean operation result in part from lower temperatures in the combustion chamber; therefore losses due to decreased specific heat ratio, dissociation reactions, and heat transfer from the combustion chamber all decrease. Together, the losses due to dissociation and to the changes in the specific heats result in a decrease of about 14 percentage points from the air-standard cycle efficiency at CR = 8 (56 1/2 minus 43%; also see Fig. 2). Heat losses from the combustion chamber may, on a similar basis, lower actual efficiencies by as much as 5 percentage points [5]. Obviously only a portion of these "losses" can be recouped in an operating engine, but the possible gains are real and achievable, as is indicated by the pair of curves in Fig. 2 which result from fuel-air cycle analysis using lean AFR's. The higher of these two curves, for ER = 2.5, corresponding to an AFR of 36.9, shows indicated efficiencies about halfway between the stoichiometric (ER = 1) curve and the air-standard cycle result. This gives an indication of the magnitudes of efficiency improvements which might be gained by lean burning without, however, considering pumping losses.

A second related area where efficiency improvements can result from lean burning is through a decrease in pumping losses as a result of the use of an unthrottled or only partially throttled intake tract. Pumping loss, which has not been included in the fuel-air cycle calculations mentioned above, is a measure of the work required to induct mixture into the cylinder during the intake stroke. It depends among other things upon the average difference in pressure between the exhaust and intake tracts, $p_e - p_i$. With an unthrottled intake p_i will never be appreciably below atmospheric pressure, the pumping work, which is directly proportional to $p_e - p_i$, will decrease on the average, and efficiency will increase. In a conventional SI engine, pumping losses vary inversely with load; at light load conditions the pumping work can be comparable to the brake work output of the engine [6]. However a typical average figure for the decrease in efficiency due to pumping losses might again be 5 percentage points [5].

The loss categories which have been discussed are, in general, the only ones which lean combustion can serve to reduce. The percentages assigned above to these losses correspond roughly to operation at 30% to 40% of full load; their sum is 24 percentage points. If these losses could be eliminated entirely the efficiency of the engine would be almost doubled. Obviously the actual gains to be expected must be smaller; perhaps an increase in efficiency by 10 percentage points, an improvement of 1/3, is a more reasonable ultimate goal. It must also be remembered that, as the load increases, the advantages of lean combustion diminish, until at full load, the efficiency can be no better than in a conventional engine with the same fuel. Indeed, the efficiency at full load may well decrease, which, however, is not important from a practical standpoint because virtually all automobile engine operation is at part-load. Indeed, governing devices to constrain operation to high efficiency regions might prove a practical expedient.

Unfortunately it is not a simple matter to run an SI engine with a lean AFR. Mixtures of hydrocarbon fuels in air will ignite at AFR's ranging from about 8 to 20 on a mass basis. The stoichiometrically correct ratio for gasoline is about 14.9; conventional spark ignition gasoline engines are limited in power output by their air capacity; thus somewhat rich mixtures have often been employed at full load to ensure that all air ingested is utilized. Part load operation obviously requires less fuel; however conventional spark ignition engines, whether carbureted or fuel injected, must burn (nearly) homogeneous fuel-air mixtures. This is necessary to insure a combustible mixture at the spark plug. Thus at part load in a conventional engine the mass of air ingested must also be limited. This is accomplished by throttling: lowering the pressure in the induction tract, which, as we have seen, causes large pumping losses.

Conventional SI engines with gasoline as fuel are then limited to AFR's no leaner than about 18 or 19 regardless of load level. Such an AFR corresponds to an equivalence ratio, ER, of about 1.3. This lean limit results from the onset of poor combustion and misfiring. And in practice the efficiency of conventional engines reaches a minimum at some AFR richer than the lean limit because of slow and incomplete combustion. Herein lies the source of the conventional SI engine's poor part load efficiency--the need for providing a relatively constant AFR which results in high combustion temperatures with their consequent losses, as well as pumping losses. In CI engines, in contrast, there is no need for a homogeneous mixture. Diesel engines can operate unthrottled, ingesting a constant mass of air regardless of load; fuel flow only is regulated. In other words the AFR is varied and in general the lean limit is only fixed by the amount of fuel which must be burned to overcome engine friction at idle. Similar behavior is desirable to achieve part-load efficiency increases in SI engines; it is necessary to extend the lean limit, allowing unthrottled or partially throttled operation, while retaining good combustion.

There are three general strategies for extending the lean limit in SI engines:

-- modifications to fuel and air delivery systems, and usually to the ignition, while retaining a homogeneous mixture.
-- charge stratification (inhomogeneous fuel-air mixture).
-- use of an alternative fuel which has an extended lean limit compared to gasoline.

These three approaches to greater thermal efficiency will be discussed in turn; however no attempt at exhaustive coverage will be made because of space limitations.

3. BURNING HOMOGENEOUS LEAN MIXTURES

It is possible to extend the lean limit somewhat in an otherwise conventional, gasoline-fueled SI ICE by modifying the fuel and air induction and ignition systems. While this is in principle the simplest approach to lean operation, the benefits to be expected are relatively small because of the eventual flamability limitation on homogeneous mixtures.

At the simplest level measures to extend the lean limit in conventional multi-cylinder engines are directed at ensuring uniform AFR's in each cylinder. In an automobile installation the practical limit of lean operation is set by the leanest cylinder. Quite wide AFR variations from cylinder to cylinder are common unless special measures are taken. Considerable effort involving improved intake manifold and port configurations, manifold heating, and, in some cases, the adoption of fuel injection, has recently been directed at the problem of cylinder to cylinder mixture variations, primarily to give reasonable driveability with the lean mixtures being used for emissions control. A further step in this direction may come with the development of feedback control systems able to detect changes in the composition of the exhaust gas and adjust the mixture strength accordingly [7].

If uniform AFR among the cylinders of a multicylinder engine is achieved, there still remain cycle-to-cycle variations in combustion which cause poor running at lean mixtures. While not well understood, the difficulties seem to involve random fluctuations in overall AFR in a given cylinder and also inhomogeneities in mixture distribution within the combustion chamber, together with randomness in the turbulence present in the chamber [8]. It seems clear that the practical lean limit in an actual engine is not intrinsic to the particular fuel but occurs at AFR's which depend upon the details of engine design and operation. Among the variables which have been studied, the spark plug type and location have been found to be important, together with the timing of the spark and its duration, as well as combustion chamber design and the associated turbulence [9, 10]. By using such methods, AFR's as lean as 24 have been shown to be possible [11]. This corresponds to an ER of 1.6.

To go beyond this point with nominally homogeneous mixtures may prove difficult. It appears that the important limitations lie not in igniting a lean mixture but rather in propagating the flame front [12]. Although the poor combustion which ensues as the lean limit is approached is not understood in detail, it is clear that partial misfires often occur. Here the flame front is evidently extinguished after propagating some distance from the point of ignition. Aside from changes in combustion chamber design and turbulence, there seems little that can be done to overcome this problem.

Because of the poor combustion qualities of lean homogeneous mixtures, eventual efficiency gains may prove small; however, as long as misfires do not occur the advantages with respect to emissions control will remain. Although Ryan et al [11] found worthwhile brake specific fuel consumption (bsfc) decreases at an AFR of 20 with a modified CFR engine, other work has not seemed particularly promising from an efficiency standpoint [12]. While claims of improved fuel economy have been made for various lean-burn systems, particularly special carburetors, few of these systems have evidently been subjected to rigorous experimental evaluation. However there seems every reason to believe that small but significant gains in fuel economy can be eventually achieved with conventional engines modified for lean operation.

Some of the more radical schemes for igniting lean mixtures become similar to stratified charge concepts, where the fuel-air mixture is made intentionally inhomogeneous. An example is the plasma jet ignition principle [12]. Here a cavity surrounding the spark plug serves to trap a portion of the mixture, which, after ignition, issues through an orifice as a stream of hot gas to fire the remainder of the charge. Such a configuration is somewhat like a stratified charge engine of the prechamber type except that no intentional charge stratification takes place.

4. STRATIFIED CHARGE ENGINES

A fuel-air mixture of controlled inhomogeneity characterizes the stratified charge (SC) concept. In the vicinity of the spark plug, an ignitable mixture is present. However, the AFR falls off away from the spark plug (at part-load) allowing overall lean mixtures to be burned. With proper design the resulting pressures and temperatures will be sufficient to cause burning to occur throughout the combustion chamber even though the overall AFR may be 60 or higher. Throttled intakes are thus not in general necessary and combustion can occur with excess air. The idea of charge stratification goes back more than fifty years; progress up to 1964 has been previously reviewed [5] and will be briefly summarized before treating more recent developments.

There are two basic approaches to achieving charge stratification: either through use of a divided combustion chamber, or prechamber, usually with a separate intake valve, or by employing controlled air swirl in a more normal open combustion chamber to create a gradient in the AFR. These two basic SC engines types can be considered analogous to prechamber and open chamber diesel engines. In fact, the SC engine is sometimes regarded as an "intermediate" type between SI and CI engines --one combining several of the features of each.

Modern divided chamber SC engines share most of their essential features with Ricardo's early design shown in Fig. 3 [13]. This approach to the problem of charge stratification employs physical segregation of rich and lean mixtures. Ricardo's engines inducted a rich mixture into the upper chamber through an automatic inlet valve. When the spark plug in the prechamber fired, the flame front would shoot into the main portion of the chamber, consuming the weak mixture. The Honda CVCC system, Fig. 4, presently in mass production is remarkably similar in concept, also using three valves and a separate carburetor for the prechamber [14].

The other stream of SC engine development --segregation by means of controlled air swirl in an open combustion chamber--can be traced back at least to the Hesselman engine of the mid-1930's [5, 15]. The furthest development of this engine featured a cupped piston crown as shown in Fig. 5. Fuel injection was used, with swirl in the chamber prior to the injection of fuel provided by means of an angled inlet tract. Gasoline was injected into the swirling air during the compression stroke; the spark came as the air swirl brought the rich portion of the swirling mixture across the plug. With a compression ratio of 7.5 the cupped piston version of the Hesselman engine achieved a best brake thermal efficiency of about 31%. Some intake throttling was necessary for smooth running at low speed and/or light load. Basically similar engines have been under development for many years by several groups.

In recent years, there has been a resurgence of interest in SC engines of both general types, primarily because of their potential emissions advantages. A comprehensive outline of the various approaches which have been taken is included in Ref. 16. Several of the systems which have received the most attention are discussed in more detail below.

4.1 DIVIDED CHAMBER SC ENGINES

As mentioned above, the Honda CVCC engine now commercially available uses the divided chamber principle. The primary impetus has been emissions control and, in a vehicle installation, the CVCC engine gives fuel economy comparable to a conventional engine of otherwise similar design [17].

Claims have been made for quite high efficiencies in some divided chamber engines. The Broderson engine, patented in 1952, initially used propane injected into the auxiliary chamber. The best results, at about half-load, were claimed to include an indicated thermal efficiency, η_i, of approximately 45% at an AFR of slightly over 20 [5]. Although injection of a gaseous fuel has efficiency advantages, because inducting only air gives a greater volumetric efficiency, this efficiency seems higher than would be expected. In later work with the Broderson concept gasoline was used as fuel with the prechamber inserted into the Knockmeter opening on a CFR engine [18]. The prechamber incorporated a third valve and also the injection nozzle and spark plug. The best η_i's in this case were 43% at an AFR of 40 and a CR of 10. This engine was capable of operating at AFR's of more than 140, corresponding to ER's greater than 10.

However other, more recent work with prechambers, also using CFR engines, has not seemed so promising [19, 20]. Newhall and El Messiri [19] measured η_i's of about 35% at ER's between 1.7 and 2.0, comparable to a conventional engine. Wimmer and Lee's results [20] were not as good, the best indicated efficiency being about 31%, as compared to η_i = 33% for the same engine without the prechamber. Of course, the prechambers used in these three CFR engines are all of different designs; however, the results of Bascunana and Conta [18] continue to seem anomolously high. It should also be pointed out that many authors are not at all explicit concerning experimental procedures. For example, there has long been controversy over how to treat the pumping losses when presenting indicated performance data [6]. As Wimmer and Lee [20] point out, how the pumping loop is handled can make a considerable difference, especially when comparing unthrottled SC engines to conventional engines, because an important advantage of the SC engine is precisely the elimination or minimization of the pumping loop. If this pumping loop is not considered in computing indicated performance, some of the very real advantage of unthrottled operation is ignored. Unfortunately, few investigators state clearly the disposition of the pumping loop for their results.

There have been a number of other divided chamber SC engines for which developmental results have been reported; mention of several will be found in Ref. 16.

4.2 OPEN CHAMBER SC ENGINES

While physical segregation of mixture via a divided chamber has the attraction of conceptual simplicity, there are disadvantages such as mechanical complication and heat loss from the large combustion chamber surface area. An open chamber design can avoid some of these difficulties, although bringing new problems characteristic of this type.

The Hesselman open chamber design has already been mentioned. The two best-known open chamber SC engines have been developed by Texaco and by Ford. The engines are alike in that intake air swirl is used to provide the stratification; they are similar in concept though not in detail to the Hesselman engine.

The progress of the Texaco engine, termed the "Texaco Controlled-Combustion System" (TCCS) has been recently reviewed [21]. Development of the TCCS engine has been underway since 1949. A section through the combustion chamber perpendicular to the bore is shown in Fig. 6. The air swirl is produced by a shrouded inlet valve during the intake stroke and must continue throughout the compression stroke. Fuel is injected into the swirling air as the piston approaches top center and is ignited by a timed spark coordinated with the start of injection. Once burning begins, the flame front remains in an approximately stationary location past the spark plug, with fuel being consumed essentially as it is injected. There is no throttling of intake air; load control is achieved by changing the duration of injection. In these respects the TCCS engine operates much like a diesel.

TCCS engines have been operated successfully on a wide variety of fuels, ranging from kerosene to aviation gasoline. Because of the multifuel capability, much of the development has been directed towards military applications. Tests have shown insignificant variation in torque output and efficiency among the fuels used. It is also claimed that TCCS engines can operate at any compression ratio consistent with the mechanical strength of the engine without preignition or detonation. This feature would have obvious potential for additional fuel economy benefits beyond any achieved by lean operation. Indicated efficiencies of about 44% have been achieved with a single cylinder TCCS engine at a CR of 10; increasing the CR to 12 resulted in an η_i of 49% [21]. In-car tests have given the results shown in Fig. 7.

Early versions of the TCCS engine were smoke-limited, again like diesels, to AFR's less than stoichiometric. There have also been problems with smoking at idle [5]. It is not clear that these difficulties have been fully overcome.

The Ford engine program--now called PROCO (Programmed Combustion)--began in 1960 with laboratory engine experiments [22]. More recent developments are described in Ref. 23. The combustion chamber is in the piston crown, Fig. 8, similar to the Hesselman engine. Air swirl is provided by a shroud adjacent to the valve seat. Early engines operated unthrottled; however throttling to an AFR of 15.5 was adopted for emissions control in later versions. A performance map for one of the unthrottled developmental engines is shown in Fig. 9. This can be compared to Fig. 1, a marked improvement in bsfc being apparent. Indicated efficiencies as high as 44% to 48%, comparable to the TCCS engines, have been achieved with the unthrottled Ford engines [22]. The best efficiencies came at AFR's of 30 to 40, ER = 2 to 2.7, with both richer and leaner running giving greater fuel consumption. The later throttled PROCO engines have not done as well because of the greater pumping losses and the various measures adopted to control emissions.

A third generally similar charge stratification system, again using air swirl and fuel injection, was patented by Witzky in 1958 [5, 24]. Development of this engine has been carried out at the Southwest Research Institute. The Witzky engine is shown in Fig. 10. The similarity to the other swirl-stratified systems is evident. Fuel injection is against the direction of air swirl, rather than with it as in the Ford engine; the TCCS system uses injection perpendicular to the air velocity. The direction of injection and the means of producing the air swirl appear to be the principal differences between these three engines. A vane in the intake port is used to produce the swirl in the Witzky engines, which have operated unthrottled at AFR's down to at least 60 and have multifuel characteristics much like the TCCS engines. Witzky engines have given efficiencies 3% to 4% better than otherwise similar conventional engines at part load [5].

There are several other open chamber SC engines that might be mentioned. Another swirl stratified engine with the combustion chamber in the top of the piston has been under development in Japan for low power utility applications [25]. Some work has also been done with SC rotary (Wankel) engines [26]; while fuel consumptions comparable to reciprocating engines have been attained, this merely nullifies the Wankel's inherent efficiency disadvantage. That a SC Wankel could do as well as a SC reciprocating engine, even with further development, seems doubtful.

To summarize the present status of SC engine systems, let us first recall that the two major streams of development--the divided chamber engines stemming from Ricardo's work and the open chamber engines based on the Hesselman concept--have both been underway, albeit sporadically, for more than thirty years. However, it has taken the exhaust emissions requirements of recent years for these engines to move beyond curiosity status. While recent development has been more intensive--obviously in the case of the Honda CVCC engine--the practicality of SC engines for improved economy, as opposed to emissions control, has yet to be conclusively demonstrated over a wide range of vehicle types and operating conditions. Nonetheless, stratification appears a promising avenue for efficiency increases, particularly the open chamber versions, which have in general lower heat losses because of their simple combustion chamber shapes, and which can probably operate leaner provided satisfactory fuel injection characteristics can be achieved. That high compression ratios can be employed in engines such as the TCCS without a high fuel octane requirement offers a very worthwhile additional economy benefit. Multifuel capability is another obvious attraction in these days of uncertain energy supply. The principal difficulty with open chamber swirl-stratified engines seems to have lain in the nature of the fuel injection system and its controls required for satisfactory operation over the wide range of conditions presented by automotive applications. The spray pattern is critical; the fuel must not penetrate past the spark plug, yet it cannot be deflected excessively toward the plug by the swirling air, as this would give an over-rich mixture which might not ignite. The widespread recent adoption of electronically controlled fuel injection in conventional SI engines may provide useful background for improving SC engine technology in this area.

5. ALTERNATE FUELS FOR LEAN COMBUSTION

Many fuels besides gasoline--itself of course a blend--have from time to time been considered for SI engine use. The first ICE's, after all, ran on gunpowder. Recent work with alternative fuels has largely stemmed from interest in their effect on emissions. Supply difficulties with petroleum base fuels have also created interest in other fuels, particularly those which can be produced from coal or agricultural products.

Again without attempting to be exhaustive, some of the more widely considered alternative fuels are tabulated, together with their lean flammability limits, in Table 1. Where possible actual engine test results have been referred to for the lean limit conditions. As is true for gasoline, the lean limits for the other fuels in the table would be expected to depend upon the details of engine design; however, lean limits have not been carefully investigated for several of these fuels.

Table 1 shows that hydrogen has by far the greatest tolerance for lean mixtures. The other fuels fall into the same general range as gasoline in terms of ER when gasoline engines modified for lean-burning of homogeneous mixtures are included. Hydrogen has therefore received much attention as an ICE fuel in the past several years, in part because of the popularization of "hydrogen economy" scenarios. While different fuels give somewhat different efficiencies even at their stoichiometric AFR [6], these differences are typically a few percent or less, relatively insignificant compared to the possible benefits of very lean combustion.

5.1 HYDROGEN

Early work with hydrogen as an ICE fuel was reviewed by King *et al* [32]. More recent developments are summarized by Finegold *et al* [33] and deBoer *et al* [34].

Fagelson et al [35] have used fuel-air cycle analysis to calculate the efficiency expected for hydrogen compared to isooctane using a CR of 8 in both cases. The results are shown in Fig. 11. While such calculations overestimate the efficiencies which can actually be achieved, as mentioned previously, because they neglect some of the losses such as those due to heat transfer, the comparison remains edifying. Lean combustion, with the associated lower temperature and absence of throttling, results in much higher part-load efficiencies for hydrogen. As full load is approached, the differences diminish. The curve for injection of hydrogen is above that calculated for carburetion of hydrogen because injection into the cylinder gives a higher effective volumetric efficiency.

Experimental work with hydrogen-fueled engines bears out their efficiency advantages. A number of investigators have studied hydrogen using CFR engines. deBoer et al [34], employing hydrogen injection on a CFR engine with several different compression ratios, measured η_i's as high as 42% at an ER of 4.2 and a CR of 14. However their results for lower CR's were generally below 30%. Extensive work with a carburetted CFR engine on hydrogen has been reported by King and his co-workers [32, 36]. They measured η_i's which increased from 35% to 44% as the ER was varied from 1.0 to 2.2 using a CR of 10 [36]. These are higher values than found by deBoer et al, but were measured at higher speeds. In later work, King et al [32] extended their range of CR's for operation on hydrogen to 20, where an η_i close to 52% was achieved for ER = 2.6. Our own work in progress at Wichita State University has been focused on comparison of hydrogen and isooctane, both carburetted, under identical operating conditions, also using a CFR engine. We have thus far found that the efficiencies are 2 to 3 percentage points higher with hydrogen for comparable intermediate load levels at moderate CR's.

Because of the very lean mixtures which hydrogen tolerates--down to idle without throttling in typical engines--there has also been interest in adding hydrogen to other fuels as a means of extending their lean limits. The first mixed-fuel work involving hydrogen appears to be that of Lee and Wimmer [31], who used a mixture containing methane and hydrogen, along with several other constituents. With a CFR engine using this fuel, but with partial throttling, η_i's as high as 34% were found, a 13% improvement compared to gasoline.

More recent studies have concentrated on mixtures of hydrogen and gasoline. With a variable percentage of hydrogen in the mixture, the lean limit can be extended to an ER of 5 or more--that for pure hydrogen. Stebar and Parks [28], using such a variable composition mixture for CFR engine tests, were able to achieve η_i's of 38 to 40% for ER's greater than 1.7 at a CR of 8. They also report on automobile tests using hydrogen-gasoline mixtures; but no meaningful fuel economy results are given. Vehicle testing of hydrogen-gasoline mixtures has also been performed by the Jet Propulsion Laboratory [30, 37]. The flow rate of hydrogen has been held constant, so that the engine idles on pure hydrogen, while as the load level increases, the ER decreases, more gasoline being mixed with the hydrogen [37]. Part load η_i improved from 32.5% to 37.5% after conversion to the hydrogen-gasoline mixture, while driving cycle fuel economy was claimed to be improved by 25% [30].

Although claims for efficiency improvements of as much as 50% have sometimes been made for hydrogen-fueled engines [38], the results discussed above indicate that such claims are probably somewhat high, and that improvements of perhaps 35% amounting to 10 to 12 percentage points, are more likely of achievement unless very high CR's are used. It should again be emphasized that the efficiency gains depend upon load level, and that any realistic assessment must be based on typical load conditions for the particular application--i.e., for an automobile, a representative driving cycle. It should also be pointed out that investigators working with hydrogen-fueled engines have frequently reported problems with engine knock due to very rapid combustion, and with backfiring. These difficulties are most serious at high load levels but would seem not to affect engines using hydrogen-gasoline mixtures with low hydrogen percentages. Finally, large-scale use of any alternative fuel would obviously have to be based on favorable conversion efficiencies during production as well as competitive dollar costs.

5.2 OTHER FUELS

As with hydrogen, the alcohols have a long history as ICE fuels. Of the alcohols, methanol has been most widely used and will be the only one discussed here; there is current interest in methanol-gasoline blends as well as neat methanol.

Table 1 indicates that methanol can be used without special ignition or induction systems at somewhat leaner ER's than gasoline; though with a lean limit ER of about 1.7, throttling is obviously necessary. However, methanol also has a much high latent heat of vaporization than gasoline; this means that the intake charge will be cooler, increasing the volumeetric efficiency. Most and Longwell [27] have provided a brief review of work with methanol.

Pefley et al [39] compared methanol to gasoline in a CFR engine. At full throttle, operation on gasoline gave a slightly higher indicated efficiency--less than 3 percentage points better--for lean mixtures. ER's of about 1.4 were the leanest used with methanol; the objective of the work was primarily the study of emissions. Ebersole and Manning [40], also using a CFR engine, found indicated efficiencies 2% higher with methanol than with isooctane. Methanol gave an η_i near 38% for a CR of 7.5 and an ER of about 1.4. Somewhat lower efficiencies were measured by Most and Longwell [27], who also compared isooctane to methanol, as well as to blends of methanol and water, in a CFR engine. Indicated efficiencies were about 32 1/2% for isooctane and 33 1/2% for methanol with a CR of 7.82 and no throttling. ER's for best efficiency were nearly the same--about 1.3--for both fuels. For CR = 12, methanol gave η_i = 38%, while for methanol plus 5% water by volume, the efficiency was 37%. Greater percentages of water gave lower efficiencies but also lower emissions of nitrogen oxides. With a CLR engine intended for testing oils similar results were found [27]. Greater efficiency advantages were evident at part throttle using methanol as compared to gasoline, for example 36% best η_i with methanol and 28% with isooctane at 1000 rpm with a manifold pressure of 20 in. Hg. Taking into account that methanol can be used at higher compression ratios than lead-free gasolines because of its high intrinsic octane rating, Most and Longwell [27] estimate that overall improvement in efficiency of 26% to 45% (about 8 to 14 percentage points) can be attained by using methanol rather than current low CR engines.

Several testing programs using conventional automobiles with methanol-gasoline blends have also been undertaken [41, 42]. By volume 10% to 15% methanol has been used, which gave improvements in economy on an energy content basis of typically 1% to 4%, some automobiles showing a slight decrease. In these tests carburetion has been unaltered.

Propane, butane and other gaseous hydrocarbon fuels are also suitable SI ICE fuels. Lee and Wimmer [31] have measured efficiencies in a CFR engine using both propane and methane. At a CR of 8, propane gave an η_i close to 39% for ER's of about 1.3, while methane showed η_i = 36% for ER's near 1.5. Gasoline, in comparison, gave η_i = 35% for an ER of 1.1. All these figures are for a 90% throttle condition. These results are roughly comparable to those observed with methanol, not surprising because the lean limits are similar.

6. SUMMARY AND CONCLUSIONS

While stratified charge engines operating on gasoline, for example, may seem superficially rather different from otherwise conventional engines fueled with hydrogen, it is useful to consider all such methods which allow combustion to take place at lean AFR's as comprising the family of lean-burning engines. This is because the primary advantages of these various engines all have the same two sources:

lower combustion temperatures resulting from lean combustion, and less intake throttling. Both result in greater thermal efficiencies, hence less fuel consumption. Similarly, lean-burning engines all have potentially good emissions characteristics because the excess air promotes complete combustion of hydrocarbons and carbon monoxide, while the lower temperatures result in reduced reaction rates for the formation of nitrogen oxides.

Efficiencies which have been reported in the literature for various lean-burning SI engines are summarized in Table 2. Comparisons between the same or a similar engine for conventional operation and lean-burning are seldom available. For those cases where comparisons are possible there is one instance of an efficiency decrease and three cases of increases --all changes being relatively small. Direct comparisons among the various lean-burning engines in the table are also difficult because not only do the engine designs vary, but so do the CR's, operating speeds, ER's and other test conditions such as intake charge density, cooling water temperature, and so on. Some insight can be gained by inspection of Fig. 12. Here are plotted data for the various lean-burning engines as contained in Table 2 along with data from several sources for variation in indicated efficiency with compression ratio measured in conventional engines. Also included are curves repeated from Fig. 2 for the calculated efficiencies of air-standard cycles as well as fuel-air cycles with two different ER's. The measured indicated efficiencies for conventional engines include a band of data from Kerley and Thurston's work [6] which encompasses three different combustion chamber designs and also the work of Gish et al [43] and of Caris and Nelson [44]. All of this conventional engine data is at full throttle and the maximum economy AFR for the particular engine. Figure 12 shows a general trend for the lean-burning engines to give efficiencies somewhat higher than conventional engines at the higher CR's. Of course this figure mixes different engine designs and ER's. The improvements at a given CR--say 12--of perhaps 15%, are reasonable considering the predictions that might be made based on theory; it should be recalled that pumping losses are not included in this figure because the curves for conventional engines are all at full throttle; part-load comparisons would increase the spread between lean-burning and conventional engines from that shown. It should also be noted that the conventional engine results of Caris and Nelson [44] are surprisingly high, particularly at the lower CR's. The reasons for this are not clear; the leveling out of their curve at high CR's was attributed to combustion delay. Of course it should be remembered that current conventional engines cannot operate at CR's of even 10 because of the octane limitations on unleaded gasoline. Some lean-burn engines are not so limited and comparisons should therefore be based on the knock-limited CR for a given engine type. Such comparisons give certain of the lean-burn engines such as the open chamber SC or some alternate fuel engines considerably greater potential efficiency advantages. A cautionary note should also be added concerning exhaust emissions. Lean-burning engines may need various modifications such as exhaust gas recirculation to meet current or proposed standards just as do conventional SI engines. This is particularly likely at higher load levels. Modifications to lean-burning engines to achieve emissions standards may cause efficiency decrements compared to the results in Table 2 and Fig. 12. However, the conventional engines for which data is presented in Fig. 12 are uncontrolled, while some, but not all, of the lean-burning engines have been optimized for low emissions. In general, comparing lean-burning engines to conventional SI engines modified for emissions control would be expected to show the lean-burning engines to possess an even greater fuel economy advantage.

Again examining Table 2, we can see that the ER's employed in most of the lean-burning engines fall in the range of 1.3 to 2.0. For gasoline this corresponds to AFR's of 19 to 30. It seems likely that with modification to ignition and induction systems, otherwise conventional SI ICE's will be able to operate satisfactorily in the lower portion of this range. Such modifications are relatively easy to introduce into large scale production for automobile applications because they involve rather minor changes and not internal engine redesigns. Thus conventional engines modified for lean-burning appear quite desirable for rapid introduction of fuel-saving measures.

On a longer term basis, however, other schemes are more attractive. This is not only because somewhat leaner operation is possible, but, more importantly, because they may allow higher CR's--perhaps in the range of 10 to 12--to be re-introduced. This would bring significant additional fuel savings provided engines were decreased in displacement or otherwise altered, perhaps by governing, to keep power outputs at reasonable levels. Use of CR's in this range would seem to require either SC engines of the open chamber type using fuel injection to avoid detonation on low octane gasoline or else the use of some fuel other than gasoline. Divided chamber SC engines, while attractive from an emissions standpoint, are knock-limited to CR levels similar to those for conventional engines. While fuels such as the alcohols can clearly be used at high CR's, there are obvious supply problems involved with any plan for their widespread use. Low percentages of alcohols mixed with gasoline appear not to give significant efficiency benefits. Supply problems are also present with hydrogen; in addition, the practicality of hydrogen in vehicle applications, particularly at higher CR's, has not yet been conclusively demonstrated. While the alternative fuels discussed will no doubt have a place in long-term strategies for replacing fuels derived from petroleum, their economy advantages do not seem sufficiently compelling to warrant attempting rapid changeover.

Therefore over the relatively short term future--say the next 10 to 20 years--the most attractive of the SI ICE's appear to be lean-burning conventional engines and open chamber SC engines. The latter would obviously require more time to introduce; there are also some questions concerning their ultimate suitability for use in automobiles. In the longer term, alternatives to the SI ICE must also be considered. This is not the place to discuss these; however, it should be noted that even in the short term the CI (diesel) engine may prove competitive in automobile applications. Finally, we should recall that powerplant design cannot be isolated from consideration of the entire vehicular system, and in fact the road network over which it is used. Coordinated redesign of passenger automobiles can yield large gains in efficiency of energy utilization, of which increased engine efficiency will provide only a part.

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Table 1

Lean Limits of Various Fuels

Fuel	Chemical Formula	Lower Heating Value (Btu lbm)	Stoichiometric AFR	Lean Limit AFR	Lean Limit ER
Gasoline	C_8H_{17}[a]	19,020[b]	14.9[b]	18-24	1.2-1.6
Methanol	CH_3OH	8,580 [b]	6.45[b]	> 11	> 1.7[c]
Hydrogen	H_2	51,600[b]	34.2[b]	190[d]-345[e]	6-10
Propane	C_3H_8	19,900[b]	15.7[b]	24	1.5[f]
Methane	CH_4	21,500[b]	17.2[b]	27	1.6[f]

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[a]Approximate.

[b]Ref.2, pp. 46,47

[c]Ref. 27 (Estimated).

[d]Ref. 28.

[e]Refs. 29, 30.

[f]Ref. 31.

Table 2

A Summary of Reported Efficiencies for Lean-Burning SI Engines

Lean-Burn Type		Engine Description	Compression Ratio (CR)	Fuel	Equivalence Ratio (ER)	Best Indicated Thermal Efficiency(%)	Comments	Ref.
Modified Ignition and Induction System							No results found in open Literature	
Stratified Charge	DIVIDED CHAMBER	Honda CVCC		gasoline		27.2	50 m.p.h. cruise condition	14
		Broderson	10	gasoline	2.7	43	Approximately half-load	18
		CFR with prechamber	8	gasoline	1.7-2.0	35	1600 rpm	19
		CFR with prechamber	6.46	gasoline	1.4-1.6	31	1000 rpm; 33% efficiency in normal operation with CR = 6.0	20
	OPEN CHAMBER	Single Cylinder	10	gasoline		44		21
		Texaco TCCS	12	gasoline		49		
		Ford, single cylinder	10.3	gasoline	2-2.7	48	Unthrottled	22
		V-8, 430 in^3		gasoline		44		

Table 2 (cont.)

Lean-Burn Type	Engine Description	Compression Ratio (CR)	Fuel	Equivalence Ratio (ER)	Best Indicated Thermal Efficiency (%)	Comments	Ref.
Alternate Fuel	CFR	14	hydrogen	4.2	42	hydrogen injected into combustion chamber	34
	CFR	10 12	hydrogen hydrogen	2.2 2.2	44 47	1800 rpm	36
	CFR	12 14 16 18 20	hydrogen hydrogen hydrogen hydrogen hydrogen	2.8 2.8 2.8 2.6 2.6	48 49.3 50.6 51.3 51.7	1800 rpm	32
	CFR	8	hydrogen plus isooctane	>1.7	38-40	1200 rpm	28
	CFR	9.2	methanol	1.4	32	unthrottled, 900 rpm	39
	CFR	7.5	methanol	1.4	38	1000 rpm; 90% throttle; 36% efficiency for isooctane	40
	CFR	7.82 12 12	methanol methanol methanol plus 5% water	1.3 1.3 1.2	33 1/2 38 37	32 1/2% efficiency for isooctane at CR=7.82	27
	CLR	8	methanol		36	20 in. Hg manifold pressure; 28% efficiency with gasoline	27
	CFR	8 8	propane methane	1.3	39 36	35% efficiency with gasoline; 90% throttle	31

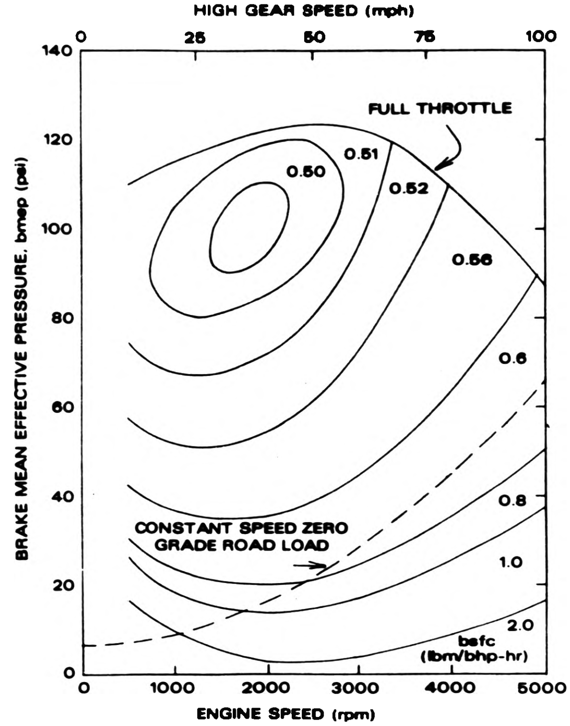

Fig. 1. Typical Performance Map for Conventional SI Automobile Engine (adapted from Taylor [2, p. 446]).

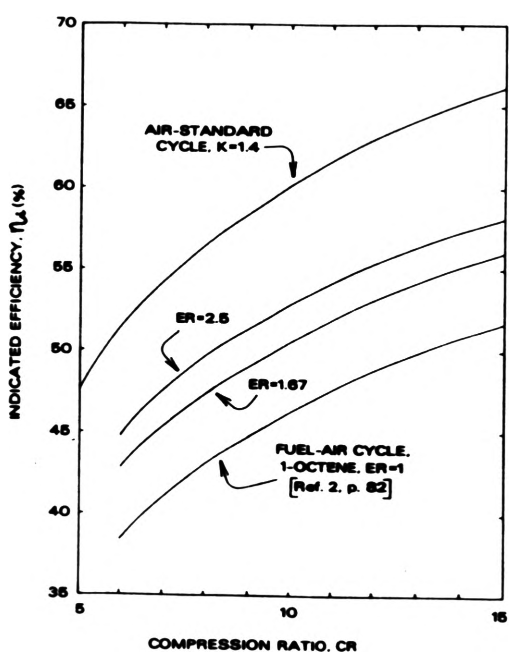

Fig. 2. Calculated Efficiencies for SI Engine Cycles.

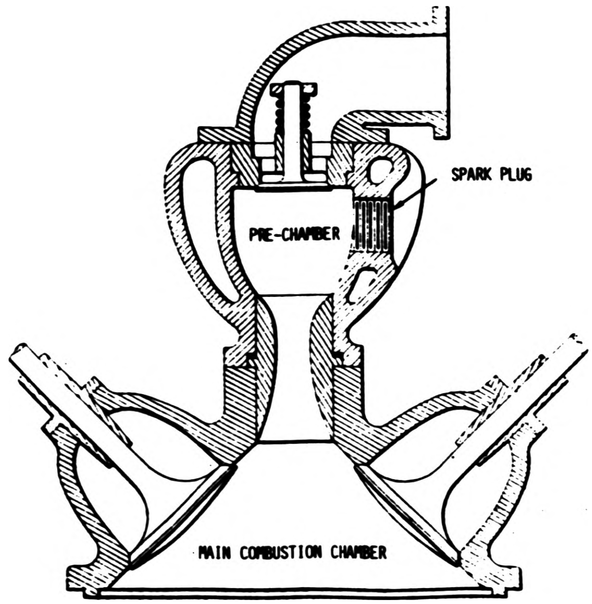

Fig. 3. Ricardo's Early Divided Chamber Stratified Charge Engine (from Ricardo [13]).

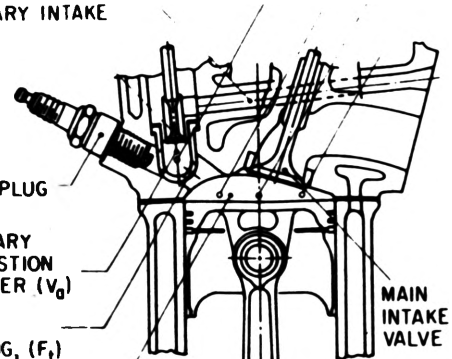

Fig. 4. Honda CVCC Stratified Charge Engine, Currently in Production (from [14]).

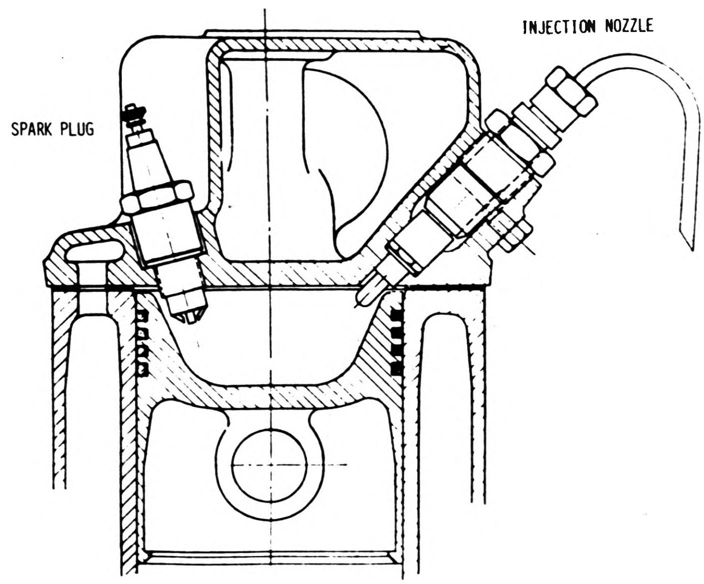

Fig. 5. Hesselman Open Chamber Stratified Charge Engine (from Dillstrom [15]).

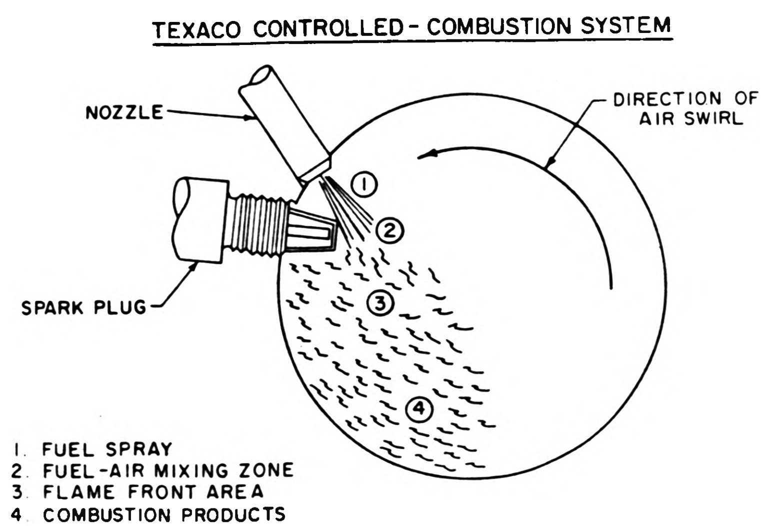

Fig. 6. Air Swirl Combined with Fuel Injection to Provide Charge Stratification in the TCCS Engine (from Tierney et al [21]).

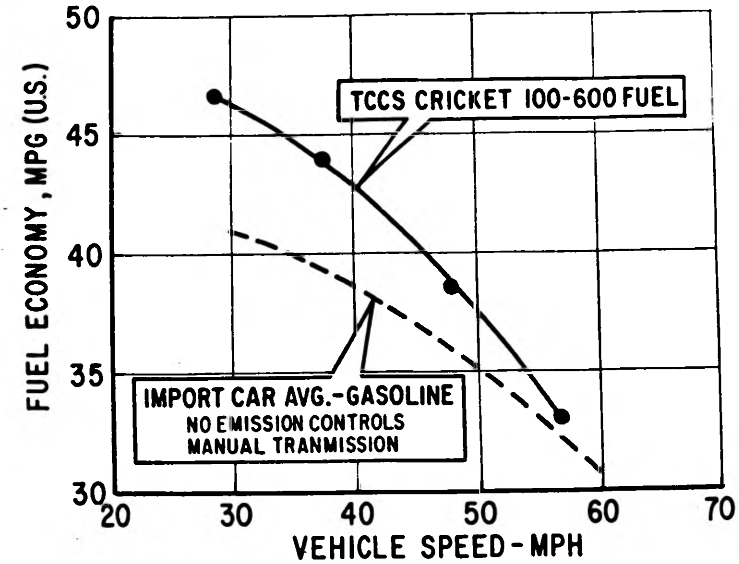

Fig. 7. Fuel Economy of TCCS Engine Installed in Subcompact Automobile (4 cylinder, 141.5 in^3 displacement, CR = 10, with automatic transmission) (from Tierney et al [21]).

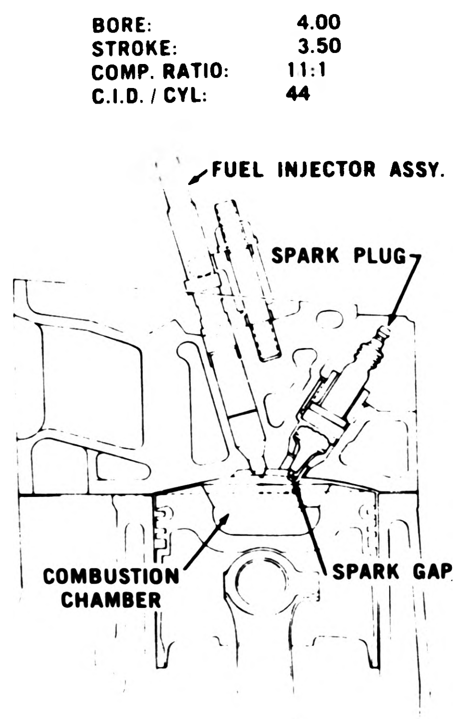

Fig. 8. Ford PROCO Stratified Charge Engine (from Simko et al [23]).

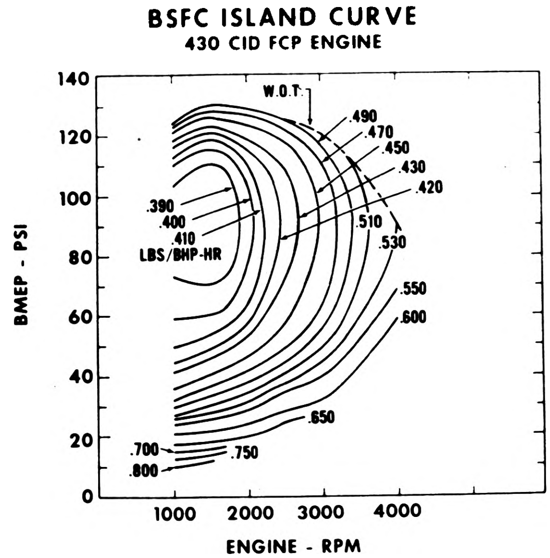

Fig. 9. Performance Map for Unthrottled Ford SC Engine (V-8, 430 in^3 displacement) (from Bishop and Simko [22]).

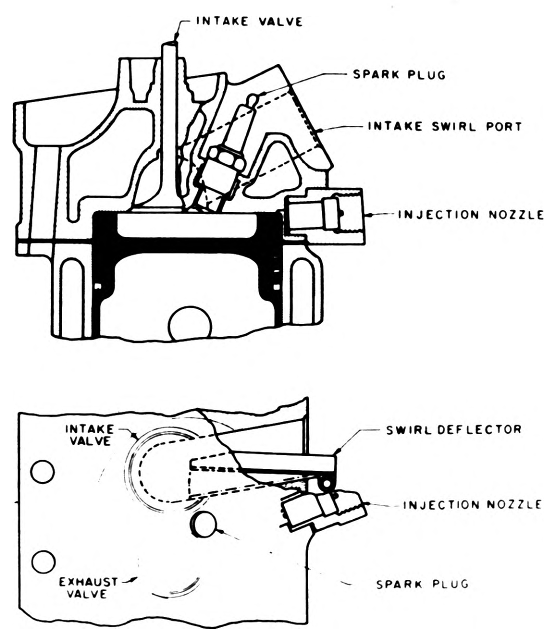

Fig. 10. Witzky Stratified Charge Engine (from Witzky and Clark [24]).

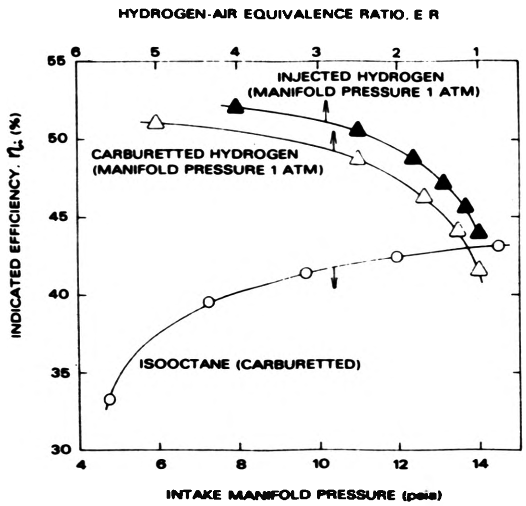

Fig. 11. Calculated Efficiency for Hydrogen (unthrottled) Compared to Isooctane (throttled to stoichiometric AFR) for Comparable Power Outputs (CR = 8) (after Fagelson et al [35]).

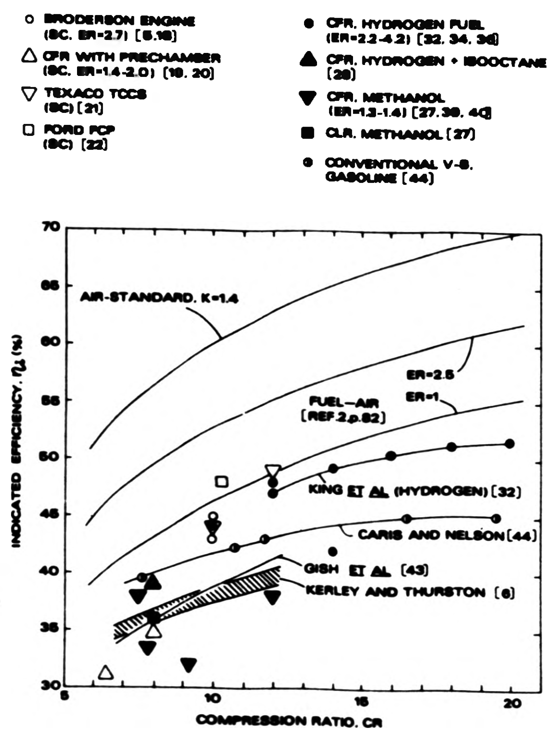

Fig. 12. Influence of Compression Ratio and Equivalence Ratio on Indicated Efficiency.

ALCOHOL ASSISTED HYDROCARBON FUELS: A COMPARISON OF EXHAUST EMISSIONS AND FUEL CONSUMPTION USING STEADY-STATE AND DYNAMIC ENGINE TEST FACILITIES

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Abstract

This paper presents experimental data which exemplifies the differences in emission level testing on internal combustion engines when dynamic engine tests are used instead of steady-state engine tests. A comparison of the two test methods is made using hydrocarbon fuels with varying amounts of methanol. Emissions measured include the nitric oxides, unburned hydrocarbons and carbon monoxide. Emission levels and fuel consumption are reported for the various volumetric percentages of methanol in the fuel.

Of special significance are the different trends the emission levels establish when subjected to a dynamic engine test as compared to the results for the steady-state tests. Dynamic tests provide a realistic automobile simulation (accelerations and decelerations) while maintaining the laboratory testing accuracy.

1. SUMMARY

Results from the testing program indicate that methanol-gasoline fuels, with up to 15 percent methanol, have a slight decrease in the exhaust emissions CO, NO_x and unburned hydrocarbons. The higher concentrations of methanol further decrease the exhaust emissions but the engine begins to suffer from lean misfire. It is doubtful that the average motorist would accept the automobile's performance under these operating conditions.

Fuel consumption on a total energy usage basis remains unchanged. The methanol has approximately one-half the energy per unit volume which means the engine will consume a greater volume of fuel but the efficiency of the engine will remain constant.

Of prime interest to the motoring public is "Will it have any effect at the gas pump?" Economically the use of methanol stands as the most attractive alternative to gasoline. A 10 percent shortage of petroleum based gasoline could be alleviated with the mixing of 10 percent methanol. Presently technology is available to produce methanol from coal and available figures show methanol can be produced at a cost equivalent to gasoline (1).

2. INTRODUCTION

Considerable attention has been given in recent years to "alternative energy sources." Much of the attention has been to solve the mobile power requirements of a mobile America. Energy sources other than gasoline and diesel fuel have long been neglected because of the low cost and apparently limitless availability of these sources. The relatively recent realization of limitations on the availability of petroleum based fuels has created a flurry of interest and study of non-petroleum based fuels (2 - 9). Michael (2) has made a comparison of various synthetic fuels for use mentioning hydrogen as very attractive for the long term but handling problems dictate immediate attention to a liquid fuel. One suggestion with good potential is methanol or methyl alcohol. It has been predicted by Stiles (1)) that "In addition to using coal-based products in industry, it is my prediction that, within the next five years or so, all of us will be burning a little bit of alcohol in our cars. Within 10 to 15 years we might possibly see a large number of vehicles powered almost completely by methanol alone or in mixtures containing higher alcohols."

Studies of methanol as a fuel have tended to emphasize specific aspects of the fuel but have been limited in general application. As a result, apparently conflicting data have been published. For example, the study of Garrett and Wentworth (3) emphasized the study of methanol as a replacement for natural gas and fuel oil in industrial furnaces and gas turbines. Ebersole's study (4) concerned tests made only in a single-cylinder engine. The studies of Garrett and Wentworth and Ebersole showed lower NO_x concentrations as did an AEC synthetic fuel panel (5). Studies by Pefley (6) indicated no change in NO_x but a significant decrease in unburned hydrocarbons and carbon monoxide. Tests of methanol by Adelman (7) in a Gremlin automobile demonstrated the ability to meet all of the '75 - '76 federal standards. Tests by Lerner (8), using mixtures of gasoline and methanol on unmodified cars were tested and operated. Fuel economy increased by 5 to 13 percent, CO emissions decreased by 14 to 72 percent, and exhaust temperatures decreased from 1 to 9 percent. Acceleration of the automobile was also seen to increase by 7 percent. Conflicting results were obtained by Ninomiya (9) where up to 25 percent methanol was added to gasoline. The addition of the methanol showed no change in the concentration of carbon dioxide, carbon monoxide or nitric oxide. Ninomiya concluded that methanol-hydrocarbon blends do not reduce exhaust hydrocarbons when the engine is operated at a performance level comparable to the methanol-free blend.

3. TEST PLAN AND EQUIPMENT

The cause for the apparent conflicting data reported was attributed to the widely varying conditions of the investigations. A more controlled set of conditions would be necessary to remove the variations caused by manual operators. The test plan must include transient conditions for acceleration as well as steady state driving.

The requirements for an engine test facility can easily be established. A review of the literature, both popular and technical, would indicate the following criteria:

(1) instrumentation for economy and performance

(2) instrumentation for pollution evaluation and study

(3) capability to utilize liquid and gaseous fuels

(4) full manual operation for standard economy and performance testing

(5) capable of testing with accelerations and decelerations typical of actual driving cycles (for example, the California 7 mode cycle, the Federal cycle)

(6) capable of testing engines loaded as in typical vehicles including transmissions, equipment and loading.

The first criterion was established because even with pollution control, performance and economy are still important. In fact, loss of performance and economy with the addition of pollution controls has been a strong complaint of many automobile owners. The growing concern and emphasis on the "energy crisis" indicates not only a desire for economy but a distinct demand for conservation. The remaining criteria were required by the definition of the problem.

Test facilities have been largely concentrated in three types:

(1) dynamometer equipped engine cells with manual control for predominately steady state tests

(2) chassis dynamometer equipment where the full system is tested

(3) standard automobiles used in road tests.

Each of these facilities normally requires the manual control of an operator and one of them would furnish the type of control required for the experiment planned. A computer actuated control system appeared to have the desired features and the system was designed as shown in Figure 1. An EPI 118 minicomputer provides control with feedback from engine speed monitors and dynamometer load monitors. The minicomputer makes any adjustments to the throttle or dynamometer as necessary to bring the engine to the predetermined loading cycle being analyzed. The system is capable of laboratory engine tests for any predetermined loading cycle such as the Federal cycle, and the California 7 mode cycle. It has been shown that with the elimination of driver, vehicle, and chassis dynamometer, test reproducibility with respect to exhaust emissions and engine performance was significantly improved.

Exhaust emissions were measured with a four channel set of Beckman Infrared Analyzers. The exhaust gases of interest and those which can be monitored are NO_x, CO_2, CO and unburned hydrocarbons as N-hexane.

The outputs from the Beckman analyzer were recorded on a six channel brush recorder together with the engine speed and torque level from the dynamometer. Fuel consumption by the engine was measured by a separate weighing and timing device.

The test program was designed to use a conventional automobile engine. A 1970 Ford 302 CID engine as equipped for the general market vehicle was used.

4. COMPUTER CONTROLLED DRIVING CYCLES

The results given in this paper are for a driving cycle modified from the California 7 mode driving cycle. The California cycle is shown in Figure 2.

The first modification was to simplify the cycle by assuming that no shifting occurred so the simulated vehicle would always be operating in high gear. A rear end gear ratio of 3.7:1, and a tire size of H78 x 15 was used. The engine speed deviated from the ideal specified but the same cycle was repeated for each blend of fuel. Figure 3 shows the engine parameters as they vary throughout the modified cycle.

5. RESULTS

The information obtained on the recorder included the simultaneous plotting of the exhaust emission gases, NO_x, CO and unburned hydrocarbons along with the engine RPM and dynamometer torque. Figure 4 is a typical set of test data for the dynamic test runs. The exhaust gas results plotted on the chart are not the instantaneous values, as are the RPM and dynamometer torque, but are subject to a time delay of approximately seven seconds. This time delay is due to the exhaust having to move from the exhaust manifold through the exhaust piping and finally through the Beckman sampling tube.

Five different types of data points were taken from each test for each mixture of methanol and gasoline. These were called the "first acceleration" level, "second acceleration" level, "average power" level, "maximum power" level, and "gas bag" level. Each of these levels and their trends with increasing amounts of methanol are significantly different. An explanation of each of these levels and how they are measured follow.

Observation of the data in Figure 4 shows that during the acceleration and loading of the engine, the pollutants exhibit maximum values. The driving cycle is such that there are two acceleration periods and there corresponds two maximum pollution points.

The maximum pollution values at each of these acceleration periods are used for the "first acceleration" and the "second acceleration" levels.

To obtain a "gas-bag" analysis of the exhaust emissions the curves for instantaneous gas concentrations were integrated using a planimeter. This procedure gives an average concentration for the exhaust gases. The "average power" level was obtained while running the engine steady-state at the average power required for the entire modified California driving cycle. The "maximum power" level was that obtained when running the engine steady-state at the maximum power output needed during the cycle. The average power was 24 hp and the maximum was 47 hp. Concentrations of unburned hydrocarbons, carbon monoxide and nitric oxides as a function of methanol content for the tests are shown in Figures 5, 6, and 7 respectively. Volumetric fuel consumption for the two steady-state power levels and the dynamic tests are shown in Figure 8.

Trends established by the dynamic test results in Figures 5 through 8 indicate that, (1) the volumetric fuel consumption increases by 20 percent as the methanol content increases from 0 to 30 percent, (2) the maximum carbon-monoxide concentration decreases from 4 percent by volume to 1 percent by volume or a decrease of 75 percent when the methanol content is increased to 30 percent, (3) the maximum nitric-oxide concentration decreases by approximately 15 percent as the methanol content increases from 0 to 20 percent. The maximum nitric-oxide concentration then increases by 18 percent when the methanol content increases from 20 percent to 30 percent, (4) the maximum hydrocarbons concentrations exhibit different phenomena with the two accelerations. The first acceleration shows a slight decrease in the maximum concentration of unburned hydrocarbons as the methanol content increases from 0 to 5 percent but then an 80 percent increase is observed as the methanol content is increased from 5 to 30 percent. The maximum concentration during the second acceleration decreases approximately 10 percent while increasing the methanol content from 0 to 30 percent. The "gas bag" analysis shows (1) the unburned hydrocarbons to increase by 40 percent as the methanol fuel percentage is increased from 0 to 30 percent, (2) the carbon monoxide will decrease by 68 percent during the increase of methanol, and (3) the nitric oxides will decrease by 31 percent as the methanol content is raised from 0 to 30 percent.

The dynamic data presented in Figures 5 through 8 represent a total of 98 individual tests. The methanol content was varied in steps of 5 percent volumetric changes from 0 to 30 percent, thus giving 7 distinct data points. Each of these 7 data points represents the average of 14 tests performed at that particular methanol content.

From Figures 5 through 8, the data for the steady-state engine tests suggest the following trends: (1) The nitric oxides, carbon monoxide, and unburned hydrocarbons decrease 72 percent, 75 percent, and 40 percent, respectively, as the methanol content is increased from 0 percent to 40 percent for the 24 hp level; (2) The volumetric fuel consumption increases 20 percent for the same power level as the methanol content increases from 0 to 30 percent; (3) At the 47 hp level the nitric oxides, carbon monoxide, and unburned hydrocarbons decrease 69 percent, 84 percent, and 82 percent, respectively, as the methanol content increases from 0 to 40 percent; and (4) The fuel consumption increased on a weight basis from 7.5 to 9.4 oz/min or an increase of 20 percent as the methanol content increases from 0 to 30 percent.

6. DISCUSSION AND CONCLUSIONS

Explanation of the results shown previously require the use of two factors, the increase in the volumetric percentage of methanol in the fuel and secondly the effect the content of the methanol has on the air:fuel ratio. The theoretical air:fuel ratio for gasoline is 15.1, while that of methanol is 6.4. For the maximum volumetric percentage of methanol in the fuel, that being 30 percent, the theoretical fuel ratio will be 12.5. For equal steps between 0 and 30 percent, methanol content in the fuel, the theoretical air:fuel ratio will vary linearly from 15.1 to 12.5.

The carburetor used in the experiments was a standard model from Ford Motor Company and was jetted for use with paraffin fuels such as gasoline and was not adjusted to the specifications required by the alcohol fuels. Using this carburetor with the methanol loaded fuels produced a lean fuel mixture. The increased concentration of methanol increased the excess air from 0 to approximately 20 percent.

Combustion products from common fuels include carbon monoxide and at higher combustion temperatures the oxides of nitrogen. As the amount of excess air is increased, certain trends regarding the concentration of these gases are followed. The amount of carbon monoxide found in the exhaust gases will decrease while the amount of nitric oxides will increase initially then decrease as the temperature drops. Examining the results from both steady-state and dynamic tests, the concentration of the carbon monoxide is seen to decrease as predicted by Stinson and Smith (11). However, the percentage of decrease found in the experimental test was much higher than predicted for constant mixtures of fuels. The additional decrease shown by these tests can be attributed to the fact that less carbon is actually entering the engine. The gasoline structure shows eight carbon atoms per molecule while the methanol molecule has only one atom.

The increase in nitric oxides as the excess air increases as shown by Smith and Stinson (11) is caused by the additional oxygen associating with the free nitrogen radicals. To lower the concentration of nitric oxides requires lowering the combustion temperature and pressure. Other experiments (8) have shown that methanol, with its relatively high mass for its heating value does have the ability to decrease the charge temperature. This factor and the lower temperature from a lean air:fuel mixture are responsible for the lower nitric oxides as the methanol content is increased. The results from these experiments validate previous work in showing that the methanol does have a cooling effect and does in turn decrease the concentration of the nitric oxides in the exhaust from an internal combustion engine. There is one exception, however, and it is shown in Figure 7. At a concentration of 20 percent methanol by volume the nitric oxide concentration reverses its downward trend.

To explain this phenomenon first consider the performance of the carburetor. The carburetor is adjusted to deliver fuel and air under a constant fuel:air ratio except at two positions, (1) closed for idle, or (2) when the throttle is wide open and the power valve is opened. When the throttle is wide open, the engine will induct essentially a constant and limiting amount of air, controlled primarily by the piston displacement, while the amount of liquid fuel to be added is increased by the power valve opening. As the restricted air flow and the power valve opening allows the fuel mixture to become richer, this increase in fuel flow and corresponding increase in fuel:air ratio will increase the MEP and the temperature of the combustion process (11). The increase in temperature and pressure are the prerequisites for the formation of the nitric oxides. In observing the action of the throttle during the two acceleration periods of the modified California driving cycle, the throttle was never driven to a wide open position until the higher concentrations of methanol in the fuel were tested. The initial downward slope of the curve in Figure 7 is caused by the lean air:fuel mixtures and also by the cooling effects of the methanol. The reversal and upward slope is caused by the engine trying to follow the acceleration of the driving cycle. The fuel mixture is too lean to supply adequate power for the engine to follow the acceleration curve, hence the throttle is pushed wide open and remains there in a fuel rich condition until the dynamometer load is dropped. The temperature increase due to the fuel-rich burning in the cylinder will offset the cooling effects of the methanol. The increase in the maximum point for the concentration for nitric oxides at high methanol content would not have been noticed in a steady-state test or in a driving test where a gas bag analysis of the exhaust emissions was used.

The concentrations of unburned hydrocarbons with an increase of methanol in the fuel were generally observed to decrease. The decrease in unused fuel is directly attributable to the addition of methanol which produced a lean mixture. The excess air contributed to a more complete combustion process. The one exception to this general trend is observed in Figure 5 where a large increase in the unburned hydrocarbons is observed when the volumetric percentage of methanol in the fuel increases from 10 to 30 percent. The large increase is seen to occur only for the initial acceleration, which is twice as severe as the second acceleration in the modified California driving cycle. The first acceleration also has to start the engine from an idle condition while the second starts at a higher RPM. As additional methanol is added to the fuel using the standard carburetor, the power output is seen to drop off, a fact which is directly attributed to the lean fuel mixture. When the driving cycle requires the engine to perform this acceleration, the carburetor produces a highly fuel-rich condition and a degradation of the combustion process results, hence the higher concentrations of unburned hydrocarbons.

The corresponding gas bag analysis for the unburned hydrocarbons indicates the increase in unburned hydrocarbons. These trends would not have been determined by a steady-state engine test.

Examination of Figure 6 shows the concentration of carbon monoxide to decrease as the volumetric percentage of methanol in the fuel increases. The maximum concentration of the CO during the dynamic testing is shown to be approximately five times as great as the steady-state test run at 24 hp. An examination of the CO concentration during the dynamic testing shows the concentration to be a factor of ten greater when the engine is running at constant speed. The dynamic testing provides this type of result that would not be detected in a steady-state test.

The curves for nitric oxide concentration show that the gas bag analysis for the dynamic tests are approximately 65 percent less than for the average power steady-state run. The difference can be attributed to excessive nitric oxides which are produced for only 15 to 20 seconds of the total 140 second duration of the driving cycle while during a steady-state test, the nitric oxides are produced the full time. Leaner fuel mixtures cause the decrease in unburned hydrocarbons that are shown in Figure 5, but an increase in the fuel:air ratio caused by a maximum throttle condition causes the one dynamic test plot to increase, another trend unrecognized in steady-state testing.

Fuel consumption for all the dynamic and steady-state tests was seen to increase on a volumetric basis as shown in Figure 8. This would be expected since the heating value of the methanol is approximately 50 percent that of the gasoline. Reducing the volumetric fuel consumption to a total BTU usage showed no significant change in total energy consumption, hence no change in efficiency of the engine.

Qualitatively speaking, the author has used methanol blends of up to 10 percent in his personal automobile and has observed no adverse performance problems. In fact, the methanol seems to have a smoothing effect on engine performance similar to the addition of tetra ethyl lead.

A summation of the experiment falls in three general areas:

(1) The driving cycle used in making fuel tests and pollution studies has a significant effect on the fuel economy and exhaust emissions of the internal combustion engine and will give different and more

relevant data than a steady-state test.

(2) The use of a computer-controlled engine-dynamometer system is highly feasible and necessary to define operation of engine add-on devices and the performance of fuels, and will give the controlled testing environment needed.

(3) The use of methanol-blends of up to 10 percent can be used with no modification to existing engines and drivers should experience no performance losses.

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8. BIOGRAPHIES

8.1 Dr. John Simonsen

Dr. John Simonsen received his B.S. degree at the University of Utah and his M.S. and Ph.D. degrees at Purdue University. Upon completion of the Ph.D. degree he joined the engineering faculty at Brigham Young University where he served as Department Chairman for 9 years. Presently he is on a leave of absence from his teaching assignments and is serving as Vice-President of Engineering for Valtek Corporation.

8.2 Dr. Dwight Bushnell

Dr. Dwight Bushnell received his B.S. and M.S. degrees from the University of Utah. Leaving the University he was employed by Hercules, Inc. as a Development Engineer where he was involved in finite element stress analysis and later, moving to Bio-Logics, Inc., he was involved with design engineering and had responsibilities as a Design Group Manager.

Returning to school he received his Ph.D. degree from Brigham Young University and then joined the faculty at the University of Missouri - Rolla. Currently he is teaching in the area of Engineering Mechanics and is involved in research with the Rock Mechanics and Explosives Research Center.

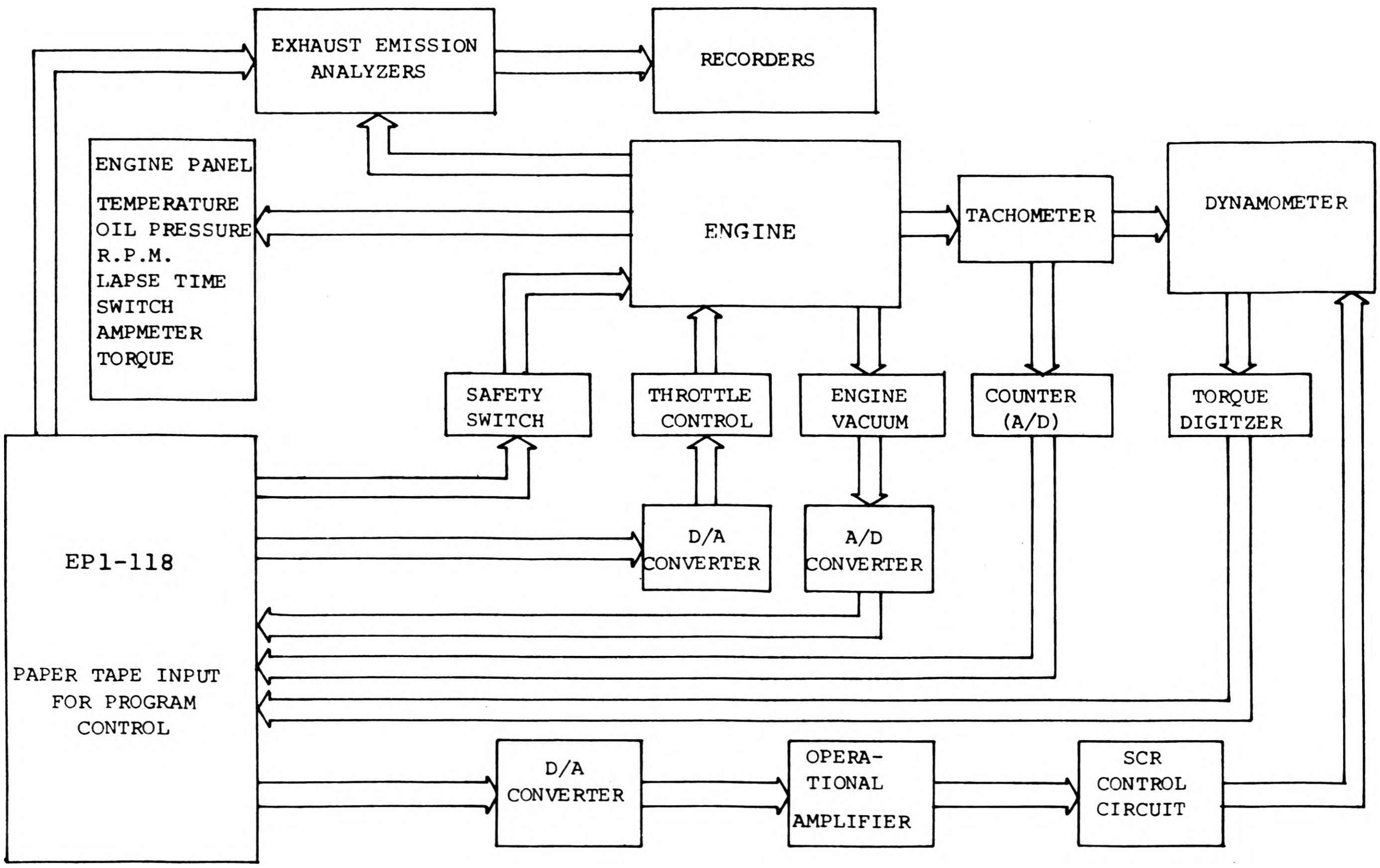

Figure 1. Computer controlled engine and dynamometer.

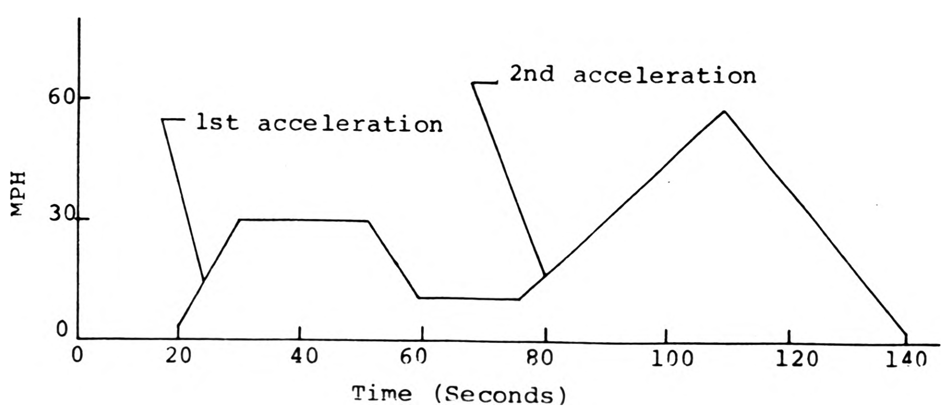

Figure 2. California driving cycle.

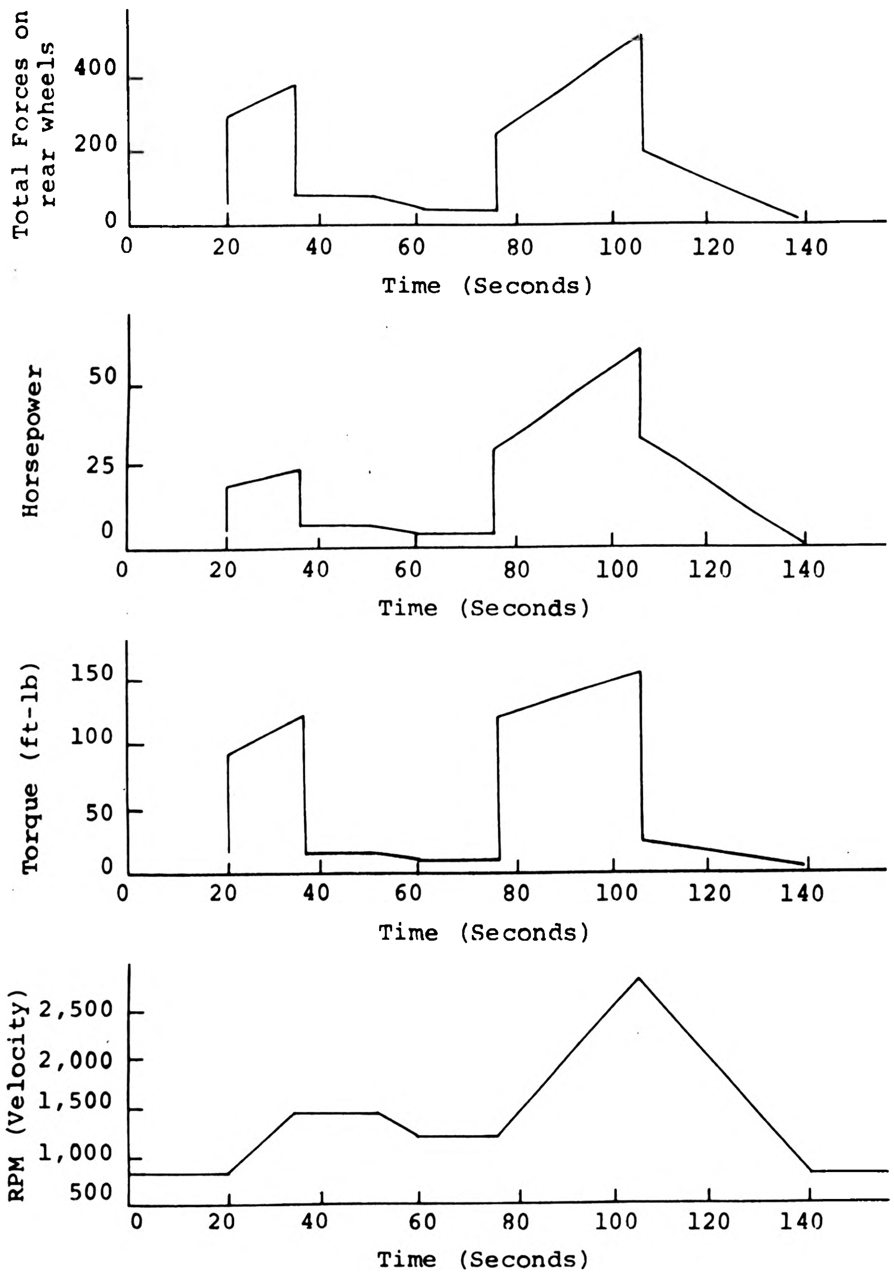

Figure 3. Total force, horsepower, dynamometer load and RPM diagrams for modified California driving cycle (no gear shifting).

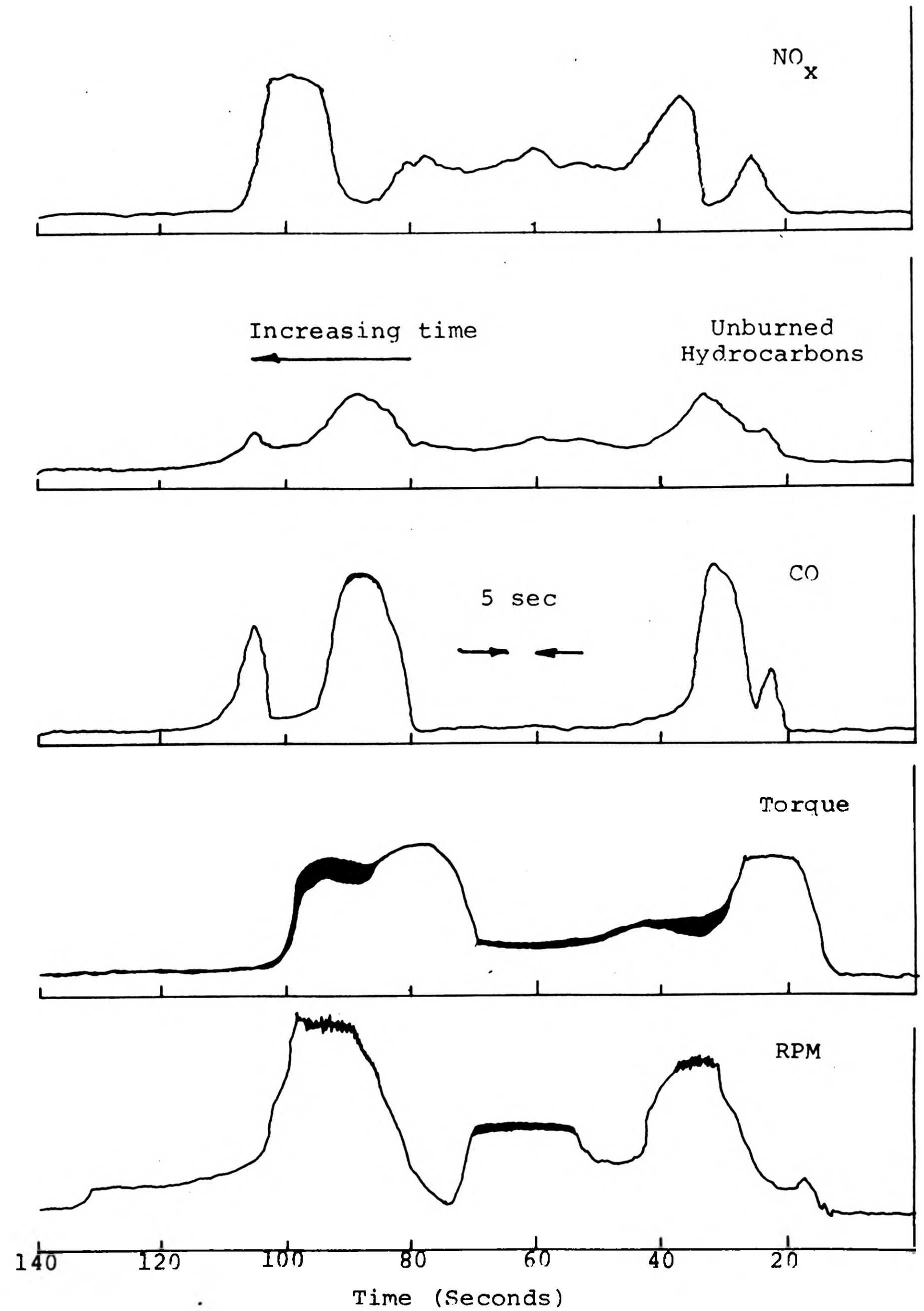

Figure 4. Test data from recorder output.

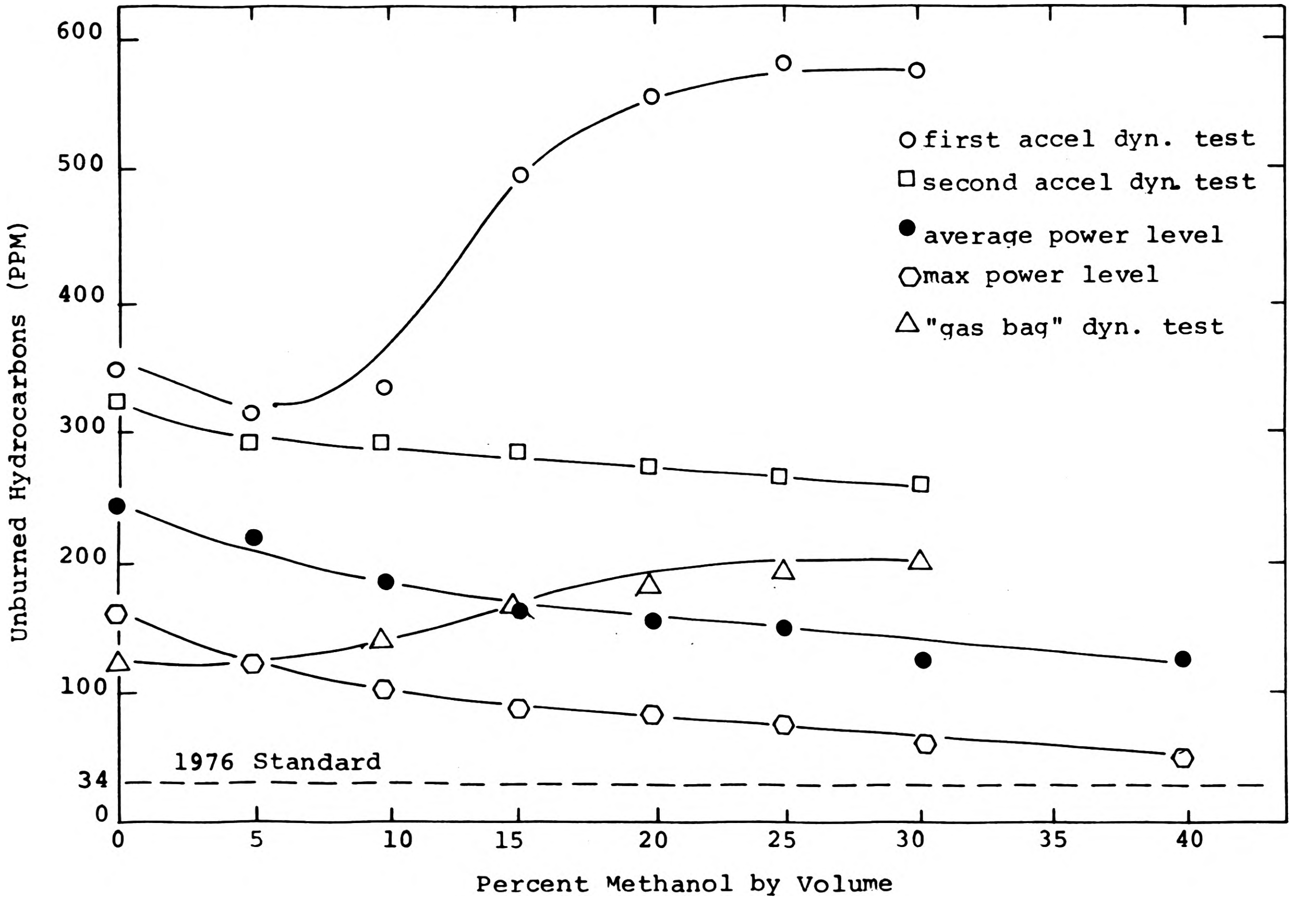

Figure 5. Unburned hydrocarbon concentration for steady-state, dynamic and gas bag test methods.

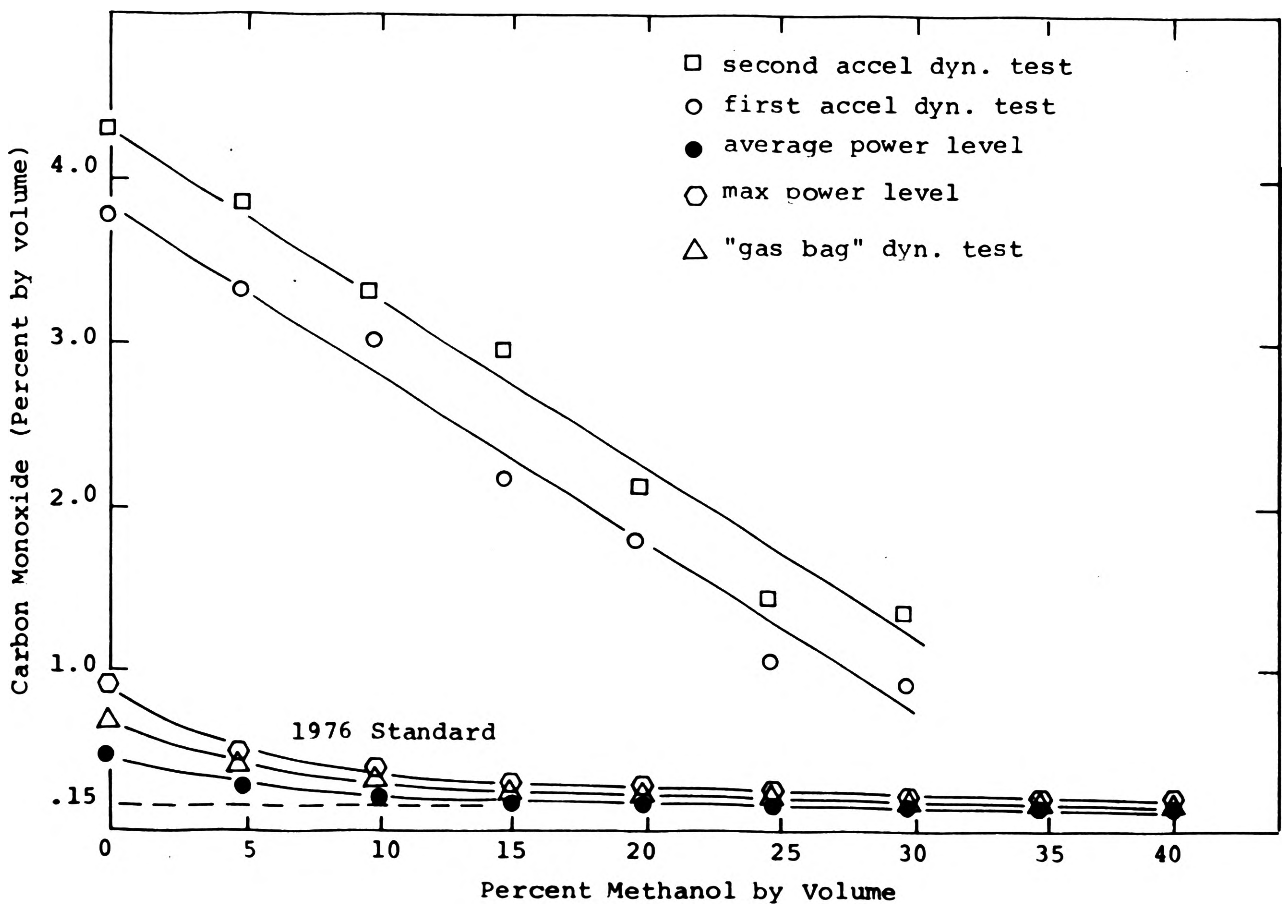

Figure 6. Carbon monoxide concentrations for steady-state, dynamic and gas bag test methods.

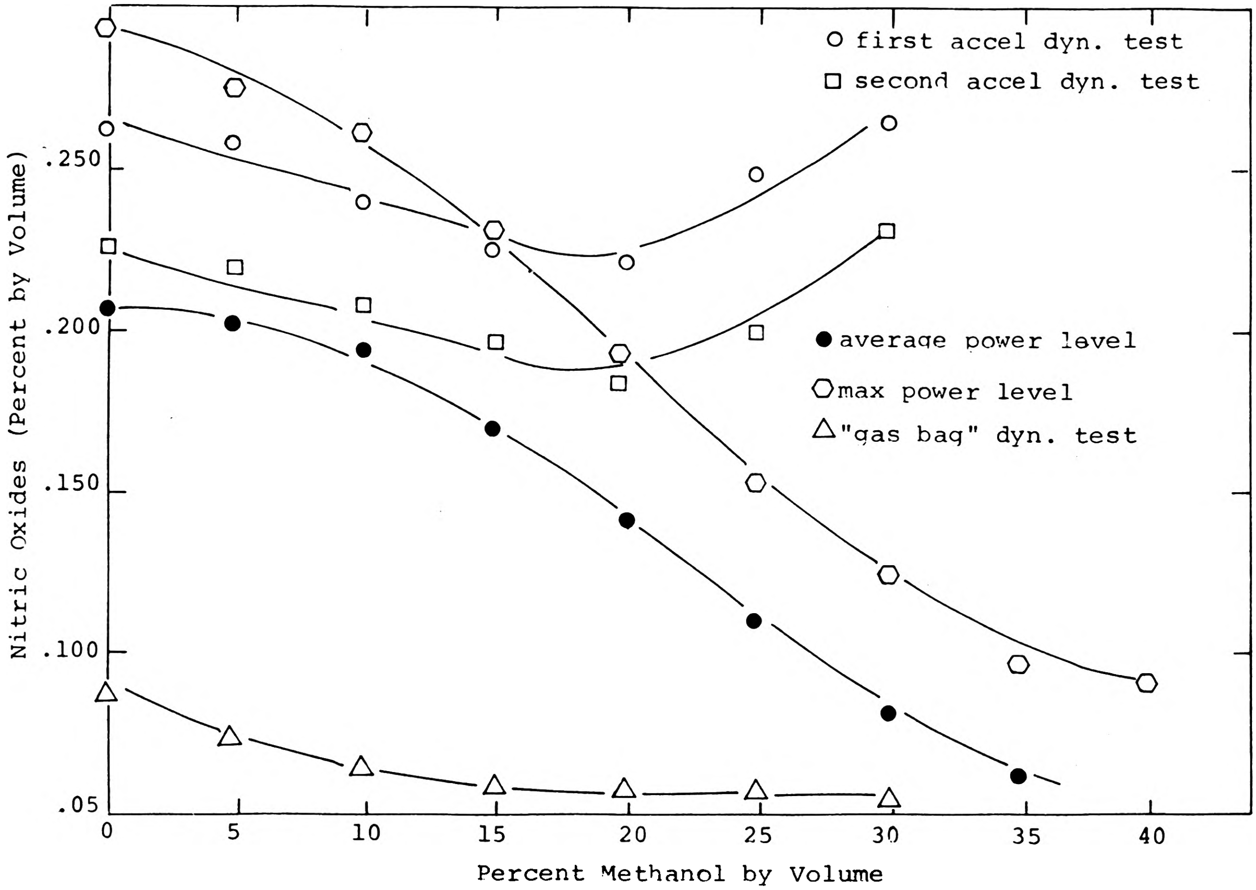

Figure 7. Nitric oxides concentration for steady-state, dynamic and gas bag test methods.

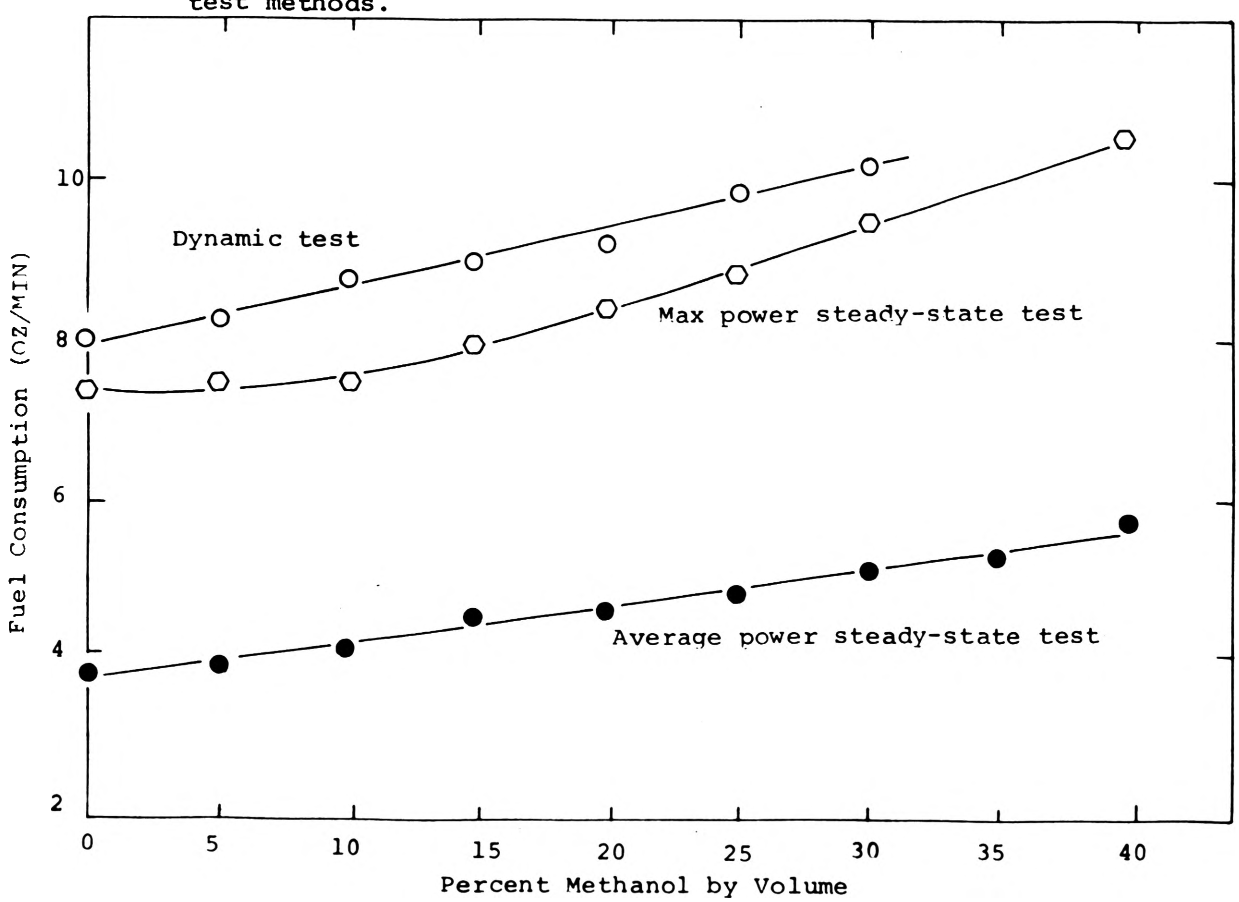

Figure 8. Fuel consumption as a function of methanol content for dynamic and steady-state engine tests.

ENERGY AND TRANSPORTATION POLICY

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Abstract

Energy shortages of recent years suggest a re-examination of national transportation policy. The lack of a coordinated approach to the solution of urban cogestion inhibits potential short-run responses to gasoline shortfalls. Longer-range policy, particularly in the context of severe financial constraints, must be carefully integrated with demonstrated patterns of urban travel and population and employment densities. Given these considerations, metropolitan areas now planning or constructing rapid rail facilities may be selecting inappropriate responses to the problem of urban access.

I. INTRODUCTION

This paper is an analytical discussion of energy considerations in the planning of urban transportation systems. Recent developments in energy availabilities, federal funding programs, and actual system operations suggest that criteria have become particularly essential in the selection of viable candidate cities for future federal and local investment in high cost, fixed route technology.

Short-run energy impacts on transportation in major American cities were examined by the author in a recent paper[1] under these hypotheses:

(1) that the worker's place of employment and residence are fixed (in the short-run),

(2) that the availability of more energy efficient vehicles is extremely limited (in the short-run),

(3) that car pooling and the use of alternative transportation modes (i.e., buses, rapid rail transit, taxicabs, etc.) are only feasible to the experience at the top end of the interquartile range (i.e., seventy-fifth percentile) in an array of such cities.

The results attained indicate that, on average an eight to ten percent shortfall of energy would be resolved through increased public and private mass transit patronage, car pooling, and more efficient driving and engine operation.[2] Although any nationwide shortfall substantially in excess of ten percent would appear to result in a reduction of non-work trips such as shopping and vacation travel, the analysis for any particular city would have to proceed on the basis of the attributes of that city.[3]

It is the purpose of this study to discuss the implications of energy and federal policy constraints on longer-range transportation planning practice. Various researchers have concluded that mass transit is more efficient than the automobile by multiples ranging from about two to about ten, depending on the assumptions incorporated in the specific analysis (see Table 1). Given the overwhelming predominance of the automobile in urban travel,[4] predictions of tremendous energy savings have been made if this pattern could only be altered nationwide.[5] A more rational and successful approach to the analysis may be to determine factors of consumer demand for transportation energy and to develop economical responses in a finite number of locales. The methodology employed in this study is to examine journey-to-work patterns in three representative American cities, and to determine the appropriateness of highway, rail and bus solutions given the specific attributes of each.

Although the work trip constitutes the largest portion of urban passenger travel,[6] prior to the 1970 Census of Population little data had been systematically collected by any federal agency on work communtation habits or on other travel activities.[7] The recent publication of journey-to-work data[8] provides some basis for our analysis of urban travel demands, although it is acknowledged that non-work trips are excluded from the discussion. However, public transit use is primarily for commutation, and non-work purposes constitute only a small protion of such activity.[9] Thus, journey-to-work analysis is highly relevant to the question of transportation planning.

II. RECENT FEDERAL POLICY ON URBAN TRANSPORTATION

It is unnecessary for the purposes of this paper to review the lengthy history of federal participation in the development of urban transportation.[10] Briefly, city growth has been influenced by three major trends in transportation: the unimodal concept of funding, with the primary emphasis on highways; the deterioration of the railroads and public transit facilities; and, despite some local planning impetus initiated by the federal government,[11] a general inaction by local governments in innovative planning. Although one may hold that the national government should, logically, adopt the viewpoint of the interest of society as a whole,[12] it has become apparent that the complexity of the American economy will not permit this "public interest" to be generally understood and incorporated in the national transportation planning process.[13]

Thus, some federal policy initiatives have recently been considered for return to state and local control. For example, the Federal-aid Highway Act of 1973 and the National Mass Transportation Assistance Act of 1974 delivered major impetuses for a multimodal approach to planning, as cities are now permitted to divert a portion of their highway trust fund money to mass transit capital and operating expenditures. Of particular significance to this discussion has been the growing participation by local governments in the federal aid process fostered by the Urban Mass Transportation Administration (UMTA). Numerous cities have come to Washington with proposals for a portion of the limited bus and rapid transit funds, and criteria for approval or rejection appear to be either nonexistent or changing depending on the political vicissitudes of the moment.

The lure of eighty percent federal funding of the planning and capital costs of rapid transit induced the development of grandiose construction programs by several urban areas, including Baltimore, Los Angeles, Miami, Denver, Atlanta, and others. These actions were encouraged by frequent assurances from the past U.S. Department of Transportation Secretary, John A. Volpe, of governmental support, provided the local matching share of the money could be guaranteed. For example, Volpe told Denver officials on October 12, 1972, that the initial experimental work would be federally financed. Furthermore, if the local share were raised, "We stand ready at the Federal level to provide two-thirds of the cost. . ." for the initial phase of the system. Denver residents subsequently approved a transportation bond issue on the basis of this implied promise.[14]

The current U.S. Department of Transportation position is that limited UMTA funds require selective approval of recipient cities based on "cost effective" analysis of alternative transportation systems, and that past "promises" are not necessarily to be construed as definite commitments.[15] Federal officials cite as justification such disappointments as the recurring technological failures and cost overruns of San Francisco's Bay Area Rapid Transit (BART) and the Morgantown (West Virginia) experimental personal rapid transit (PRT) system, as well as the continued nationwide reduction in transit patronage despite the expenditure of some three billion dollars on programs of urban transportation assistance.

Local reaction to this changing federal posture has been, as expected, heated. Atlanta Mayor, Maynard Jackson, stated: "We stuck our necks out. . ." because the city received ". . . not only the go-ahead but actually the aggressive encouragement of the Federal Government. . ." to build a transit system. Now Atlanta is being told that aid may not be forthcoming, a situation tantamount to ". . . our being on a limb, and the Federal Government behind us sawing if off."[16]

Governor Marvin Mandel of Maryland, on learning of this apparent change in policy,[17] stated that ". . . all the indications . . ." point to a federal withdrawal from Baltimore rapid transit. ". . . [T]hey have led Baltimore city right down the dark alley again and . . . I think this is the most disgusting performance of bureaucracy I've ever seen . . . There is no way the City of Baltimore or the State of Maryland could make up these funds in order to keep the project going."[18]

III. CONSIDERATIONS OF POPULATION MOBILITY

The goal of any transportation system should be to provide a satisfactory level of movement for people (and goods) so that delays, congestion, pollution, and energy consumption are minimized. Too frequently, it appears that policy makers and government officials have sub-optimized the decision-making process; that is, they have failed to consider all factors in the selection of transportation systems and in the promise of funds for the construction of such systems. This is particularly apparent with regard to rapid rail transit, for as each new urban or energy crisis occurs, this magical solution is suggested.

The hard facts, however, are that rapid rail transit is:

(1) expensive (Baltimore's first two legs of a proposed six legged radial system, now costing over one and one-quarter billion dollars, inflated nearly one hundred percent in thirty months);[19]

(2) technologically imperfect (BART's trans-Bay run was long-delayed in receiving approval of the California Public Utilities Commission, due to various operating malfunctions);

(3) not self supporting (BART will never reach a self-supporting level of operations, even with 220,000 passangers per day);[20]

(4) not a limitation on congestion (the Montreal, Milan, and Stockholm systems have not removed traffic congestion, while ninety percent of Toronto's patrons are converts from the old bus system);[21] and,

(5) subject to rather rigid federal funding limitations.

Most important, fixed rail rapid transit assumes a relatively stable combination of jobs and population, which is not the typical situation in Twentieth Century America. Recent U.S. Bureau of the Census analysis confirms that population movement from the city and suburbs is continuing to sections further out in exurbia. Employment in metropolitan areas outside the central city is increasing faster than the population, and workers can therefore commute more easily from housing now developed beyond metropolitan-area boundaries.[22]

This continuing dispersion of population and jobs beyond the central city follows the trend begun following the Second World War with the availability of the automobile and improved highways. When planners decry the "irrationality" of urban commuters in choosing other than the most cost efficient transportation mode for their journey-to-work,[23] it must be remembered that the trip duration to work is considerably longer by transit than by auto.[24] Thus, with this great dispersion into exurbia, it becomes difficult to justify transit on the basis of projected patronage estimates.

Furthermore, this changing and mobile pattern does not suggest the implementation of high cost, long-run solutions, particularly given the social and aesthetic disruptions inherent in extensive right-of-way acquisition and construction of trackage and stations.[25] This is especially true considering the extremely long planning period prior to implementation; i.e., a ten to fifteen year period is typical in the state of California, whereas the city of Baltimore has been planning its system for more than a decade.

Finally, the potential for a reversal in this pattern of migration is rather unlikely, ". . . except by a degree of compulsion incompatible with a free society."[26] While the hopes of rapid transit proponents may be to halt the decay of the central city by increased suburban commutation,[27] the facts are that people, jobs, and shopping are increasingly oriented to locations outside of the central city. "The conventional concept of the urban community. . . has to be reconsidered. . . Increasingly the movement of people within urban complexes will be multidirectional on relatively low-density traffic corridors."[28]

IV. TOWARD FIXED RAIL CRITERIA

Despite these rather definite reasons against the indiscriminate use of fixed rapid rail, the lure of the federal money has proven irresistible to many cities. Given the limitation of funding, on what criteria should approval be based? Many schemes have been suggested for the integration of land use and transportation models for the selection of the optimal policies from a broad range of plans with varying economic and social effects.[29] However, existing practice still cannot incorporate axiomatic interrelationships between these sectors,[30] while newer modelling and computer technologies may only serve to permit predictions of distant years with a larger order of errors.[31]

Little else exists in the literature to provide guidance on the planning of transit systems. Comments do appear regarding suggested minimum densities, such as a central city of at least 10,000 persons per square mile,[32] or at least 40,000 patrons per day and metropolitan areas with a population of at least one million.[33] Thus, into this seeming vacuum comes the high cost, technologically complex solution: build everywhere, or at least until the money runs out.

The important consideration in this context should be the retention of mobility in the journey to the central city in those areas where future central city activity justifies fixed rapid rail transit. Of special significance in this determination, given our inability to forecast the future (despite simulation model builders' claims to the contrary), is the existing pattern of employment concentrations within the central city. The basic assumption, then, is that cities of highly dispersed employment are less able to justify commuter fixed rail tranist systems than are central cities of concentrated employment.

Table 2 presents data on the concentration of employment in the Standard Metropolitan Statistical Areas (SMSA's) and central city's of thirty major metropolitan areas, including the ratio of central city employment to SMSA employment and a ranking within the array. Table 3 presents data on the use of transit modes for the journey-to-work in each SMSA, including bus and streetcar patronage; the percentage of in the SMSA using these transit modes for the journey-to-work; and a ranking within the array.

For purposes of further analysis, it is necessary to select a limited number of these cities of varying attributes of worker concentration and transit use. From these tables three cities are selected to illustrate varying stages in economic-transportation development:

(1) Sharply reduced central city worker concentration with average transit ridership (characteristic of older urban areas with a declining central city base of dense work attractions): Baltimore, Maryland.

(2) Somewhat reduced central city work concentration with low transit ridership (characteristic of maturing urban areas with some loss of central city economic activities): Kansas City, Missouri.

(3) Continuing high central city worker concentration but low transit ridership (characteristic of newly developing urban areas with intact central cities): Phoenix, Arizona. Thus, in descending order is arrayed the oldest to the newest city forms, which is also consistent with the present magnitude of demand for fixed rapid rail transit from each city type (see Table 4).

V. BALTIMORE: TOO LATE FOR RAPID RAIL

The city of Baltimore, Maryland, responded to the urban decline of the Post-War period with the construction of downtown office buildings and shipping facilities, and the redevelopment of the Baltimore harbor area. However, the pattern of central city worker dispersion was not arrested, and was likely exacerbated by the substitution of "white-collar" employment for the more concentrated "blue-collar" factory work which was largely eliminated during the renewal process. Thus, the concentration of workers in 1960 in the central city of 64.8% (Table 5) had declined to 42.1% (Table 2) by 1970, as denser work "attractions" were systematically moved to outlying locations.

Planning began during this time for rapid transit to serve the central city commuter. The final suggested configuration was a six-legged steel wheel on steel rail system, with each leg extending from the center of Baltimore City (Charles Center), to population centers in the surrounding suburban areas. Final engineering grants for the Northwest and Southern lines were made in 1972, based on an estimated cost of $656 million (now estimated at $1.2 billion) with the local share of this expenditure guaranteed by the Maryland General Assembly. Total costs for the completed system are unknown, but may run to several billion dollars.

The bus system in the metropolitan area was absorbed by the Maryland Department of Transportation, and received renewed support through the multi-model funding authority of that agency. During the fiscal year of 1972, 370 new buses were delivered, reducing the average age of the bus fleet from fifteen to six years, while a two year rehabiliation program to repaint and repair 250 later model vehicles continued. This governmental interest, together with an apparent tradition of public transit patronage, resulted in 100 million riders for fiscal 1972, an increase of 1.1 percent over the preceding year.[34]

While the primary and secondary highway construction programs also continued during this period, a controversy developed surrounding the city's planned expressway system. At the present time, this "3A" system of interstate and commuting roadways is estimated to cost $1.25 billion (with a local contribution of twenty percent), while construction costs rise at a significant rate.[35] The existing expressway inventory in the entire SMSA is 144 miles, including the Baltimore Beltway (I-695), the Jones Falls Expressway (I-83), the Kennedy Memorial Highway (I-95 North), I-95 South (to Washington), and I-70 North (to Frederick), in addition to some expressway-standard construction on the primary system. Thus, a rather extensive highway system is planned, under construction, or in operation, accommodating in several places as many as 100,000 + vehicles of daily traffic.

The short-run impact of the energy crisis on journey-to-work trips in the Baltimore metropolitan area has previously been determined as a relatively low, five percent diversion to carpools and alternative transportation modes.[36] Any fuel shortfall greater than about five percent of demand will lead to a significant reduction in non-work trips. However, this predicament does not support the planned rapid transit expenditures, but does seem to imply the wisdom of continued bus schedule expansion (and highway reconstruction). The reason for this paradox is that the finite amount of available federal transportation dollars delimits possible capital improvements to those projects more "cost effective"[37] in times of fuel shortages, and that a rapid transit system is not an appropriate investment given the residence-employment mix in the Baltimore area. Instead, the availability and flexibility of the bus and highway modes appear to make these the superior choices.

VI. KANSAS CITY: THE TIME FOR RAPID RAIL

The Kansas City, Missouri - Kansas area responded to the problems of urban decay later than did the city of Baltimore, with the "coerced" creation in 1966 of the Metropolitan Planning Commission - Kansas City Region (Metroplan) following the federal denial of Section 701 planning grant money. This delay may ultimately work to the advantage of Kansas City, as it has allowed sufficient time for the mistakes and wrong turns of other cities to have been examined and rejected. However, one expert has stated: "The city has not learned the lessons about growth that Eastern cities have. Industry is leaving the central city rapidly and the blacks are frozen out. There is no low-to-moderate income housing out there along I-435, the ring highway, and no rapid transit to take them out. . ."[38]

As in Baltimore, the concentration of workers in the central city had declined from 1960 to 1970, from 58.6% (Table 6) to 53.3% (Table 2), although the rate of decline was substantially slower. Thus, sufficient time may yet exist for a correction of this trend, provided appropriate action is taken by the planning officials of the region. Mechanisms do exist for such policy implementation, for Metroplan works concurrently with the Mid-American Council of Governments (MACOG), established in 1967, which has the more general perspective and political ability to implement such plans, and with the Kansas City Transportation Authority, established in 1965, which has jurisdiction over passenger transit.[39]

To this time transportation planning has been subordinate to land use planning, although the Kansas City Transportation Authority in 1969 did purchase and now operates the private Kansas City Transit Company, after threats of termination of service. However, the major thrusts of the past decade have been a constant flow of planning ideas from Metroplan oriented toward the control of urban sprawl,[40] and the development of such attractions as the Kansas International Airport, a new stadium, a sport arena, a downtown convention center, new shopping areas, and other civic attractions.

With only thirty-one percent of total metropolitan area mileage now traveled by Kansas City, Missouri-Kansas residents to Kansas City employment and a continuing pattern of horizontal growth spreading outward from the central core, specific plans are under consideration to direct investment toward more acceptible developmental patterns.[41] For example, the Metro/Center concept envisions a series of new towns of ". . . high activity core area(s) that would offer employment opportunities, retail outlets, services and recreational facilities necessary to serve about 200,000 people, all within 15 or 20 minutes of the Metro/Center core.[42]

Loci of these centers include the central business districts of Kansas City, Missouri and Kansas, the Plaza (a shopping-commercial center), and eight other sites chosen on the basis of origin and destination zonal projections.[43] Careful selection and land use controls could foster the building of corridors of sufficient travel demand to enable rapid rail transit, such as the Kansas City International Airport complex-to-downtown corridor which is expected to generate 125,000 + trips daily by 1990. Present access plans are for 70,000 to 90,000 average daily traffic on highways I-29 and U.S. 169, with the suggested purchase of rights-of-way for exclusive busways and, ultimately, rail rapid transit.[44]

The short-run impact of the energy crisis on journey-to-work trips in the Kansas City metropolitan area has previously been determined as about a fifteen percent diversion to carpools and alternative transportation modes.[45] This situation (an approximately average result) does not per se eliminate or support rail transit. The important consideration is that Kansas City has not suffered a permanent loss of central city employment and has begun efforts to define land use along specified corridors of potentially dense activity. This may be the very situation which justifies some rapid rail, in that the central city can be preserved while permitting the growth of selected radial corridors. Unfortunately, little support is thought to exist for such an undertaking from civic and business groups, although Mayor Charles B. Wheeler, Jr., is a strong advocate.[46] Perhaps Kansas City is doomed to repeat the mistakes of the older Eastern cities.

VII. PHOENIX: TOO EARLY FOR RAPID RAIL

Urban problems are rather new phenomena to the city of Phoenix, Arizona, and, consequently, recognition of the situation has come only recently. The central city was a small and charming desert "oasis" some thirty years ago, whereas today it services a metropolitan area containing several municipalities, more than one hundred shopping centers, and a population of nearly one million.[47]

This type of explosive development does not permit orderly land use control, and as a result, Phoenix ". . . is suffering the worst case of urban sprawl in the U.S. . . "[48] with no sign of correction in the near future. While environmentalists may decry the loss of a lifestyle based upon fresh, dry air and open land,[49] the virtually unrestricted economic potential does not suggest limitations on sprawl devleopment and urban decay. Employment concentration in the central city actually increased during the decade of the Sixties, from 60.4 percent (Table 7) to 62.5 percent (Table 2), an increase partially attributable to the sheer size of the city, 187.6 square miles, as compared to the cities under study: 130.3 square miles in Kansas City and 78.3 square miles in Baltimore. However, "leapfrog sprawl" now characterizes the metropolitan area and new communities appear on previously open land beyond the locational control of Maricopa County.[50]

An early return to central city development does not seem likely according to various Arizona observers.[51] Residents have resisted high density development as well as freeway construction, and appear to desire small town life in the big city. Some calls for controls on future growth are being made, but these may not occur for some time. "As we sit and talk about what to do with Arizona's increased population, the people still keep coming . . . People worry about this becoming another Los Angeles [or older Eastern city?] . . . the way we're going now, it won't be as good as L.A."[52]

Transportation planning in the Phoenix area has been oriented toward the existing highway system, and prevailing evidence is that downtown traffic is relatively stable and operating some forty percent under potential capacity.[53] Planning for rail rapid transit has never been attempted due to ". . . the lack of a series of traffic origins going to a common destination in any transportation corridor,"[54] and the low density of population resulting from urban sprawl.

The short-run impact of the energy crisis on journey-to-work trips in the Phoenix area was previously determined to be a twenty-four percent diversion to carpools and alternative transportation modes.[55] Given this extremely high opportunity for a compensatory response in times of fuel shortages, but particularly in the light of a continuing pattern of uncontrolled sprawl and an underutilized central city street system, rapid rail transit does not appear to be a justified expenditure in the forseeable future.

VIII. SOME CONCLUSIONS AND THOUGHTS ON TRANSPORTATION BALANCE

The study of three cities of varying development patterns leads to certain inductive conclusions. It is apparent that urban centers are not uniform in terms of economic and land-use problems, with the logical conclusion that transportation-energy solutions to those problems cannot be uniformly applied. Furthermore, it is clear that criteria are necessary to determine the appropriate mix of transportation investments for each type of metropolitan area, for purposes of both local planning and for federal policy.

Specific criteria do not easily fall out of these discussions. However, it may be concluded that older cities of low or falling worker concentration in the central city are not logical condidates for rail rapid transit but should be bus and highway oriented, whereas cities of substantial downtown employment may be more suitable choices for fixed route systems. Thus, the fourth column of Table 2, containing a ranking of the thirty cities selected for comparison, may be an appropriate guide, with cities in the first third being logical candidates, while those in the second third worthy of additional study. Furthermore, the planner would be advised to investigate local activity toward the termination of sprawl development, with the selection of specific radians or centers of denser industrial-commercial activity.

Given these criteria, some current rapid transit programs appear to be counter to good planning logic: the BART System, as San Francisco ranks 27th of 30 in central city worker concentration; the District of Columbia METRO System, as Washington ranks 25th of 30; and possibly, the MARTA System, as Atlanta ranks 19th of 30. Certainly these cities have congestion problems, but the dispersion of their populace can only mean that fixed rail rapid transit will not serve a sufficiently high percentage of metropolitan area workers to justify the enormous expenditures. Table 8 provides some evidence for this conclusion for the Baltimore region, in that only 496,000 miles of a total of nearly two million miles, or twenty-eight percent, are traveled by city dwellers to city employment. The remaining seventy-two percent of total mileage is traveled by city workers from outlying suburban counties, and thus many will not be attracted to a system whose nearest station is perhaps miles distant from their homes.

The indicated solutions in these cities are improvements in bus systems and continued highway construction. While the bus solution is not disagreeable from either the energy[56] or socio-economic[57] perspectives, frequent adverse commentary has been voiced regarding the automobile. While it is true that this latter mode is energy inefficient by a substantial factor,[58] it is likely that political and macroeconomic considerations alone will prevent any substantial reduction in automobile use.[59]

There is no reason that more efficient engines and lighter, more aerodynamic body design cannot significantly increase gasoline mileage, allowing full mobility within the context of the suburban orientation of our metropolitan areas. As petroleum grows scarcer and dearer to use for the private vehicle, it is completely reasonable to assume that the automobile will eventually be powered by other fuels, most notably, coal and atomic energy, through electric batteries or other storage methods.[60] These developments may be appropriate to considerations of environment and sociology, as well as energy and economics.

The policy and energy constraints now developing on planning for metropolitan areas demand the application of rational criteria to the selection of balanced transportation systems.[61] This paper has reviewed the present status of such constraints and has suggested a methodology for the planning of such systems. Energy crisis impacts vary depending on the specific situation within each region given the potential of carpooling and the availability of alternative travel modes. However, in the longer-run, the viability of the various transportation solutions to fuel shortages is closely related to developmental patterns and central city worker concentration.

ESTIMATES OF TRANSPORTATION ENERGY EF[illegible]NCIES

BTU's Consumed Per Passenger Mile

Mode	Rice[1]	Myers[2]	Hirst[3]
Bus	1090	600 - 800	3800*
Railroad	1700	400 - 700	3000*
Automobile	4250	5000 - 10000	8000*

*Estimated from Figure 1.

[1] R.A. Rice, "System Energy as a Factor in Considering Future Transportation," Proceedings of the American Society of Mechanical Engineers, December 1970.

[2] Phillip S. Myers, "The A's, B's and C's of Transportation in the 80's," Automotive Engineering, LXXIX (December 1971), pp. 26-28, at 27.

[3] Eric Hirst, "Transportation Energy Conservation: Opportunities and Policy Issues," Transportation Journal, XIII (Spring 1974), pp. 42-52, at 44.

FIGURE 1

Historical variation in energy-intensiveness of passenger modes.

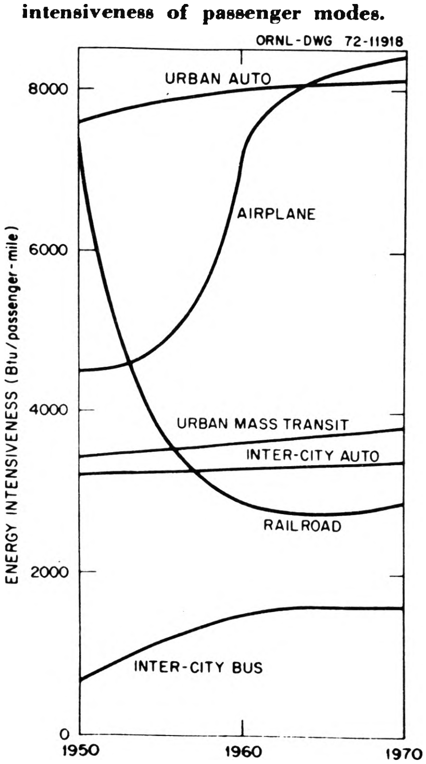

TABLE 2

EMPLOYMENT CONCENTRATION IN SELECTED SMSAs AND CENTRAL CITIES, 1970

	(1) No. of Workers in SMSA	(2) No. of Workers in Central City	(3) % of Worker Concentration in Central City (Col. 2 ÷ Col. 1)	(4) Ranking of Worker Concentration %s (from Col. 3)
Atlanta	580,960	205,104	35.3	19
Baltimore	819,597	344,801	42.1	14
Boston	1,122,516	259,781	23.1	28
Buffalo	495,141	164,952	33.3	23
Chicago	2,817,276	1,345,485	47.8	10
Cincinnati	514,216	171,832	33.4	22
Cleveland	806,222	278,983	34.6	21
Dallas	652,339	365,556	56.0	6
Denver	493,566	211,494	42.9	12
Detroit	1,525,548	537,724	35.2	20
Houston	786,106	507,193	64.5	3
Indianapolis	438,430	295,014	67.3	2
Kansas City	515,758	274,860	53.3	7
Los Angeles	2,757,759	1,267,714	46.0	11
Miami	504,345	144,597	28.7	24
Milwaukee	562,468	294,024	52.3	8
Minneapolis	741,326	315,885	42.6	13
Newark	744,421	130,698	17.6	30
New Orleans	363,821	205,022	56.4	5
New York	4,496,534	3,106,170	69.1	1
Philadelphia	1,863,897	741,907	39.8	16
Phoenix	365,896	228,509	62.5	4
Pittsburgh	853,151	187,994	22.0	29
Portland	393,331	153,429	39.0	18
St. Louis	883,200	224,899	25.5	26
San Diego	544,348	283,596	52.1	9
San Francisco	1,262,673	318,741	25.2	27
San Jose	402,230	157,179	39.1	17
Seattle	544,351	221,696	40.7	15
Washington	1,239,455	335,344	27.1	25

Note: Certain SMSAs are identified in the Census by a "two city" name, with the smaller city excluded in the above listing. These are: Los Angeles-Long Beach, Minneapolis-St. Paul, and San Fran-

Source: U.S., Bureau of the Census, Census of Population: 1970, Vol. 1, Characteristics of the Population; Table 82, Mobility, Commuting, and Veteran Status, for Areas and Places: 1970 (Washington: U.S. Government Printing Office, 1973).

TABLE 3

MASS TRANSIT COMMUTATION IN SELECTED SMSAs, 1970

	(1) Bus and Streetcar Patronage	(2) Subway, Elevated Train, and Railroad Patronage	(3) % Using Mass Transit for Journey-to-Work in SMSA	(4) Ranking of Worker Concentration %s (from Col. 3)
Atlanta	51,805	156	8.9	14 (tie)
Baltimore	105,642	1,235	13.0	11
Boston	129,516	87,596	19.3	5
Buffalo	50,029	212	10.1	13
Chicago	389,821	254,289	22.9	2
Cincinnati	40,518	132	7.9	18
Cleveland	100,374	5,736	13.2	10
Dallas	39,847	334	6.2	21
Denver	20,228	447	4.2	27 (tie)
Detroit	120,520	1,269	8.0	17
Houston	40,279	347	5.2	25 (tie)
Indianapolis	23,847	122	5.5	23 (tie)
Kansas City	26,545	143	5.2	25 (tie)
Los Angeles	149,488	2,691	5.5	23 (tie)
Miami	44,080	399	8.8	16
Milwaukee	66,240	351	11.8	12
Minneapolis	65,647	128	8.9	14 (tie)
Newark	100,666	34,483	18.2	6
New Orleans	71,846	80	19.8	4
New York	513,292	1,596,681	46.9	1
Philadelphis	245,684	135,129	20.4	3
Phoenix	4,256	129	1.2	30
Pittsburgh	121,076	1,018	14.3	9
Portland	22,354	155	5.7	22
St. Louis	65,833	245	7.5	19
San Diego	13.069	9,694	4.2	27 (tie)
San Francisco	183,595	8,268	15.2	8
San Jose	4,640	4,414	2.3	29
Seattle	37,316	133	6.9	20
Washington	190,187	2,131	15.5	7

Source: U.S., Bureau of the Census, Census of Population: 1970, Subject Reports: Journey to Work, PC(2)-6D, Final Report; Table 2, Characteristics of Workers by Residence and Place of Work...(Washington: U.S. Government Printing Office, 1973).

TABLE 4

HIGHWAY AND TRANSIT CAPITAL IMPROVEMENT PLANS, FOR SELECTED CITIES, FOR THE PERIOD 1974-1990[1]

	Highway Expenditures (Millions of 1969 Dollars)[2]	Public Transportation Expenditures: Total (Millions of 1969 Dollars)	Public Transportation Expenditures: Rail (Percent)
Atlanta	1,110	798	92
Baltimore	2,080	1,838	93
Boston	2,058	1,157	66
Buffalo	687	173	81
Chicago	5,097	1,482	68
Cincinnati	491	231	0
Cleveland	1,216	709	82
Dallas	3,071	462	75
Denver	696	446	0
Detroit	3,764	848	0
Houston	2,548	494	70
Indianapolis	313	63	0
Kansas City	947	183	80
Los Angeles	7,063	1,319	50
Miami	940	197	90
Milwaukee	679	119	0
Minneapolis	1,419	898	95
Newark		NOT AVAILABLE	
New Orleans	1,189	117	69
New York	7,941	7,031	90
Philadelphia	2,783	1,914	93
Phoenix	796	33	0
Pittsburgh	1,100	841	86
Portland	812	155	0
St. Louis	1,248	638	92
San Diego	922	242	0
San Francisco	2,850	1,641	77
San Jose		NOT AVAILABLE	
Seattle	1,121	340	0
Washington	2,707	2,147	96

Notes:

[1] These estimates were developed by the various States in response to a U.S. Department of Transportation request for spending intentions under specified limits of federal aid ("Alternative III"). Therefore, particularly with reference to rail transit, they are not necessarily representative of actual plans.

[2] Not including local roads nor the costs of completing the Interestate System.

Source:

U.S. Department of Transportation, 1972 National Transportation Report, (Washington: U.S. Government Printing Office, 1972), p. 252.

EMPLOYMENT CONCENTRATION IN BALTIMORE, MARYLAND, CENTRAL CITY, 1960

Place of Residence	Automobile or Carpool	Bus Streetcar	Railroad
in Central City	147,455	92,211	79
in Surrounding SMSA Counties	87,522	13,874	127
Outside SMSA Counties	4,837	354	386
Total, Central City Workers		396,501	
Total, SMSA workers		611,918	
Percent, Central City Workers to SMSA Workers		64.8%	

Note:

The "Private Automobile, Drivers" and "Private Automobile, Passengers" categories of the 1970 Census were combined as above in the 1960 Census.

Source:

U.S., Bureau of the Census, Census of Population: 1960, Subject Reports: Journey to Work, PC (2)-6B; Table 2, Metropolitan Status and Location Relationships of Place of Residence and Place of Work of Workers During the Census Week (Washington: U.S. Government Printing Office, 1963).

TABLE 6

EMPLOYMENT CONCENTRATIONS IN KANSAS CITY, CENTRAL CITY, 1960

Place of Residence	Automobile or Carpool	Bus, Streetcar	Railroad
in Central City	100,756	33,463	37
in Surrounding SMSA Counties	73,997	6,925	12
outside SMSA Counties	9,131	336	185
Total, Central City Workers		224,842	
Total, SMSA workers		383,513	
Percent, Central City Workers to SMSA Workers		58.6%	

Notes and Sources: See Table 5.

TABLE 7

EMPLOYMENT CONCENTRATIONS IN
PHOENIX, CENTRAL CITY, 1960

Place of Residence	Automobile or Carpool	Bus, Streetcar	Railroad
in Central City	106,388	6,445	7
in Surrounding SMSA Counties	17,602	328	0
outside SMSA Counties	1,285	73	28
Total, Central City Workers	132,156		
Total, SMSA Workers	218,668		
Percent, Central City Workers to SMSA Workers	60.4%		

Notes and Sources: See Table 5.

TABLE 8

JOURNEY-TO-WORK TRIPS AND MILEAGE
IN BALTIMORE, MARYLAND, SMSA, 1970

County of Residence -County Seat	(1) No. of Workers in Central City -Drivers and Passengers	(2) Mileage, County Seat to Central City *	(3) Journey-to-Work Miles (Col 1 x Col. 2	(4) Car Pooling Ratio (Drivers ÷ Passengers ÷ Drivers)	(5) No. of Workers in Central City - Transit Patrons
Anne Arundel -Annapolis					
drivers	16,367	26	425,542	1.18	1,187
passengers	2,914				
Baltimore City					
drivers	99,330	5	496,650	1.32	64,894
passengers	32,202				
Baltimore County -Towson					
drivers	77,567	7	542,969	1.19	9,468
passengers	15.124				

TABLE 8
(continued)

Carroll					
-Westminister					
drivers	1,625	31	50,375	1.20	36
passengers	325				
Harford					
-Bel Air					
drivers	3,412	23	78,476	1.14	131
passengers	494				
Howard					
-Ellicott City					
drivers	3,182	9	28,638	1.11	166
passengers	346				
Outside SMSA	3,890	40	179,360	1.15	256
drivers	594				
passengers					
Total					
drivers	205,373				
passengers	51,999				
Journey-to-Work Miles			1,802,010		
Transit Patrons					76,138

Notes:

*The County Seat was selected as an approximation of commuter residences for each county. Baltimore City mileage to the central city was obtained based on the location of residential neighborhoods within the city. Mileage from outside the SMSA was based on estimates from major towns lying beyond the SMSA counties.

Sources:

Maryland Department of Transportation, State Highway System and Connections (State Map), 1972.

U.S., Bureau of the Census, Census of Population: 1970, Subject Reports: Journey to Work, PC(2)-6D, Final Report; Table 2, Characteristics of Workers by Residence and Place of Work... (Washington: U.S. Government Printing Office, 1973).

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55. Sagner, op. cit.

56. See Table 1.

57. See, for example, the excellent analysis in Edward Smith, "An Economic Comparison of Urban Railways and Express Bus Services," Journal of Transport Economics and Policy, VII (January 1973), pp 20-31.

58. See Table 1.

59. Based on a transportation model simulation, two University of Maryland researchers concluded that energy conservation is better accomplished through the use of small automobiles than wide spread mode switching. The latter activity would be disruptive and would have "...inconsequential impact on energy conservation." Curtis C. Harris, Jr., and Stanley J. Hille, "Rail, Truck, or Small Car - Which is the Energy Saver?" Business Horizons, XVII (December 1974), pp. 57-64, at 64.

60. See Ralph E. Lapp, "The Hard Energy Choices Ahead," essay in The Wall Street Journal, April 23, 1974, p. 26.

61. For example, modal split models could be written to incorporate assumptions of minimum travel times and energy constraints, to allow the determination of the energy consequences of alternate transportation plans. See, Kenneth R. Yunker and Kumares C. Sinha, "Energy Considerations in Urban Transportation Planning," Traffic Quarterly, XXIX (October 1975), pp. 571-592.

WAYS TO REDUCE PEAK ELECTRICAL DEMAND IN SOUTH LOUISIANA

by S.J. Gold, M.D. Bakewell, G.E. Guidry, E.F. Lewis, L.J. Naquin and B.P. Whitney

Abstract

This study analyses alternatives for coping with the peak electrical demand of hot summer afternoons. Economic and Political aspects, as well as technical feasibility, are included. It is concluded that South Louisiana may indeed be able to trim peak demand to 5% below what is anticipated by 1980, thus making one of the coal fired stations scheduled then unnecessary. However, the contingencies (Natural Gas Shortage, Another Oil Embargo) would make a coal-fired station very desirable.

1. INTRODUCTION

The authors worked together as an interdisciplinary Systems team this summer, analysing the problem of Peak Electrical Demand that occurs on hot summer afternoons in southern Louisiana. The Systems Approach is an attempt to optimize the solution of the whole problem by bringing all aspects into focus together. One way to begin is to draw a block diagram of the problem, putting short word descriptions in each block. This is done for the electrical peak demand problem in Fig. 1.

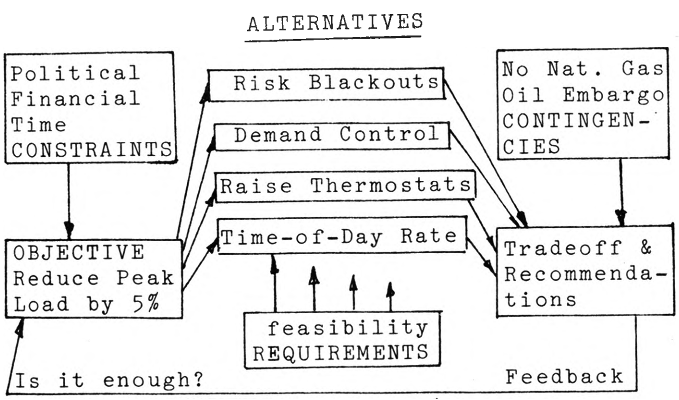

Fig. 1. Block Diagram of the Electric Power Peak Demand Problem; Showing Objectives, Constraints, Alternatives, Requirements, Tradeoff, Result, and Impact Assessment.

2. BACKGROUND INFORMATION

The 'contraints' are the pieces of background information that a researcher must understand in order to attack the problem intelligently. The words listed in the CONSTRAINTS block of Fig. 1 are discussed below.

2.1 By Existing Plants we imply both the existing set of electric generating plants, and the existing electrical load, especially air conditioners. Air conditioners are important because during the hour of peak demand (which is usually somewhere between 3 - 5:00 on a weekday afternoon after July 15 and before August 10), the load is about 35% air conditioning, and it could be 40% on an extraordinarily hot day.

At the beginning of the summer, we visited the various suppliers of electricity to the region-in-question (See Map, Fig. 2).

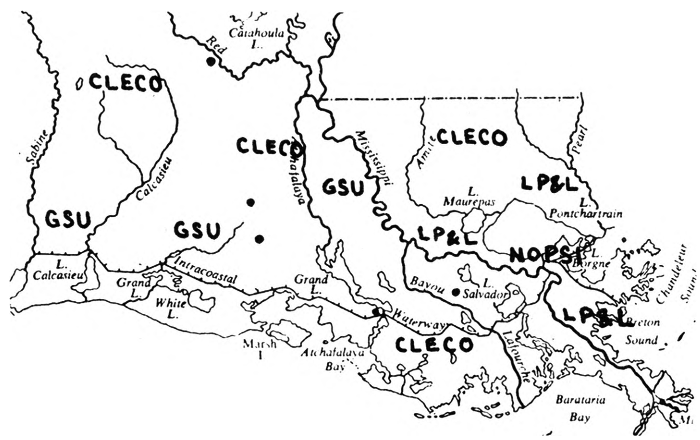

Fig. 2. Map Defining 'South Louisiana' and Showing Regions Served by the Major Electric Utilities.

There are three types of utilities in the region: investor-owned, municipal, and cooperatives. The size of each utility, and their peak demands, are given in Table 1.

The investor-owned utilities now generate about 88% of the KWh consumed in south Louisiana. In the past two or three years, their Load Factors* (except NOPSI) have gone down. CLECO's load factor dropped from 0.587 in 1972 to 0.509 in 1974. The declining load factors must be largely attributable to conservation efforts by residential and industrial users. Cutting back on lighting, hot water use, and general waste of electricity decreases the total amount of kilowatts used in a year, but peak demand is still driven primarily by the temperature of the hottest weekday.

$$\text{*Load Factor} = \frac{(\text{Total Kwh generated/year})}{(\text{Max Kw})\,(8760\text{ hrs/year})\ \ 1\text{ hr.}}$$

Investor-Owned Utilities

	Generation Capacity, MWe		Peak Demand, MWe		
	Present	By 1980	1973	1974	1975
CLECO	1328	1858	782	818	846
Gulf States	5132	6098	3782	3896	3989
L.P.&L.	3569	4429	2563	2692	
NOPSI	1257	1200	936	869	
Major Municipal Utilities					
Lafayette	188	368	109	130	159
Alexandria	178	200 (1)	109	119	
Morgan City	67	95 (2)	37	38	
Houma	64	64	37	39	
Thibodeaux	52	80 (2)	n.a.	33	
Opelousas	49	77 (2)	n.a.	28	

(1) If gas turbine purchase approved
(2) If four-cities multi-fuel plant approved

Cooperatives

Cajun Coops (3)	230	1310	n.a.	n.a.	
SLEMCO	None (buys from Gulf States)		150	160	

(3) A group of 12 R.E.A. co-ops throughout Louisiana

Table 1. Generating Capacities and Peak Loads of Utilities Serving South Louisiana (from Stockholder Reports and interviews)

2.2 <u>Existing Air Conditioners</u>. Nearly all of today's electric-powered air conditioners work on the principle of a reverse rankine-cycle heat engine, depicted in Fig. 3.

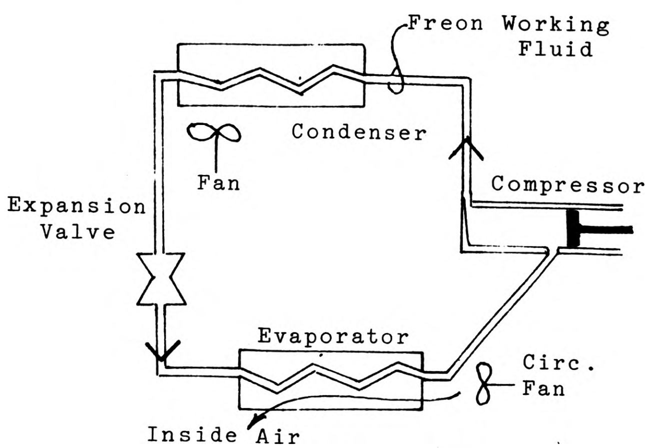

Fig. 3. Schematic Diagram of Reverse-Rankine Air Conditioning Cycle

Large stores, office buildings, and industrial complexes usually have 2 or 3 large air conditioning units. Because of their size, these units are generally designed to run continuously. Turning them on and off is a complicated operation, and usually done only a few times per year. Hospitals, office buildings, and shopping malls that were built before 1970 are sometimes equipped with separate reheat coils. The air is cooled to a low temperature (perhaps as low as 55°F) to cause condensation of some of its water vapor. The air is then reheated, by passing it over either hot water tubes or electrical resistance heaters, to the desired temperature. This mode of operation has led, in some cases, to an energy conservation scheme where the reheat coils are turned off. The result is an uncomfortably cold building.

Most central air conditioners for homes and small commercial buildings are designed for intermittant operation. Their size ranges from more than 10 Tons* (for very large homes) to 5 tons for a large 4-bedroom home, thru 3-ton units for typical 3-bedroom homes, to 2-2 1/2 tons for typical apartments. Window-mounting units are available in sizes up to 2 tons, but sizes above 1 ton require 230V. outlets. The compressor is controlled by a thermostat. If the unit is undersized, and heat (Q_{inside} in Fig. 3) is entering the building faster than the evaporator can remove it, then the compressor won't turn off till nightfall. In this case, raising the thermostat setpoint won't have any effect during the heat of the day.

The market for air conditioners is nearly saturated. Gulf States' marketing department estimates that 85% of its customers in the Baton Rouge area have either central or window air conditioners, and 7% of the remainder have electric fans. L.P.&L. indicates that 40% of its residential customers have central air conditioning. Those few poor people who do not yet have air conditioning will probably be

*1 Ton of air conditioning = 12,000 BTU of cooling per hour slow in acquiring it because of the recession, inflation, and the high price of electricity. Additional electric demand from new air conditioners will grow no faster than new buildings are erected.

The insulation in the walls and ceilings of buildings in the area is often absent. Many of the older frame homes in New Orleans have only a couple of inches of insulation in the attic, and none in the walls. Only since 1973 have the Federal Housing Administration (FHA) and the department of Housing and Urban Development (HUD) begun requiring insulation standards in new construction. Some low interest loans have been made available for insulating older homes, but not much has actually been done. If the price of energy continues its steep climb, better insulation of existing buildings may evolve.

2.3 Operational Constraints. It has been the standard operating policy of the utilities to serve whatever load the customers impose regardless of its time relationship. Some of the larger customers have a Demand Meter; if their consumption rate exceeds the agreed upon KW level, then a very expensive ratchet is imposed. The power companies say that the demand charge has the effect of limiting peak demand from large customers. Of course it does, but the constraint is put on these users whether it is day or night, hot weather or cool, irrespective of the system load (although some users have 'forgiveness' clauses for nighttime excesses).

More than 95% of the electricity in south Louisiana is now derived from burning natural gas. Gas-fired boilers with their associated turbo-generators used to cost about $65/KW as recently as 1967. Typically, a gas generator would be bought, run for a few years in base or intermediate load service, and then as more efficient larger generators came on line, it would be relegated to short run operations (perhaps only a few days in the heat of summer). Ultimately, these generators will be relegated to emergency standby status.

There are very few gas turbines in south Louisiana. NOPSI has two, and the city of Alexandria is thinking of buying one. Usually the utilities will fire up their old units for peak power. These units cannot be subjected to diurnal on-off duty because thermal cycling of the boiler and turbo-generator causes breakdowns. Therefore, they run at low load (and lower efficiency) all night. (See Fig. 4)

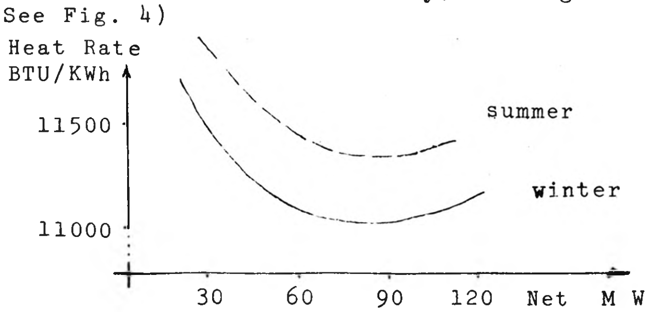

Fig. 4. Summer and Winter Heat Rate Curves for 100 MWe Gas-Fired Turbo-generator Unit.

2.4 Political Considerations. The investor-owned utilities and the coops are under the jurisdiction of the Louisiana Public Service Commission (PSC). The municipal utilities are under control of their respective mayors and councilmen. These elected officials must please the voters or be ousted. They must also keep the utilities viable.

The price of electricity is becoming a volatile issue with consumer groups. Organized consumer opposition to the utilities caused the state Attorney General to order the Public Service Commission to hold public hearing to air the reasons for the large recent increase in Fuel Price Adjustments. These moves will probably delay revenues and rate increases the utilities need to expand.

The Interstate Commerce Commission affects utilities operations by controlling the amount of natural gas they can get from interstate pipelines. In the past 2 years, NOPSI, Gulf States, and L.P.&L. have all been affected by curtailments. They had long-term, low-price (20-25¢/MBTU) contracts with United Gas Pipeline Company, which United has not been able to honor. There will be no such contracts in the future; now gas prices average about $1.00/MBTU, contracts are for two or three years at most, with price to be renegotiated annually. Before long, the price of gas will probably be nearly the same as oil for equivalent energy, namely $2.50-$3.00/MBTU. That will mean that electricity will cost 3.7¢/KWh for residential consumers (up 40%). The Stevenson Bill, introduced in the U.S. Senate, would have placed intrastate gas under control of the Department of Commerce, too. However, after 15 months, that bill is still in committee, and it is doubtful if it will be enacted any time soon.

The utilities in southern Louisiana are part of the Southwest Power Pool, which is a control region of the Federal Power Commission. They are also under the jurisdiction of an international body, the North American Power Systems Interchange Commission (includes Canada). These bodies regulate the frequency and flow of power between neighboring utilities, and also set reserve requirements for reliability.

The Louisiana PSC does not review the utilities' plans for expansion, other than requiring them to use standard accounting procedures to recover the expense of new power plants. In contrast to many other states, the PSC has not seen fit to assign service territories to the various utilities. The only rule is that if a prospective customer wants power, and only one utility has a line within 300' of him, he must buy from them. If more than one company has a power line that's close to him, or if no company does, then he can negotiate with different companies. Thus utilities, which are supposed to be regulated monopolies, are not really monopolies at all. The history of this competition has resulted in gerrymandered and still unsettled boundaries between companies.

The coops can get low-interest loans from the

Rural Electrification Administration, and the cities can sell tax-free bonds, which makes it easier for them to expand. Sometimes cities boundaries expand and take customers from surrounding rural areas; the city of Lafayette engulfed 7000 of SLEMCO's customers in the last decade.

2.5 Economics and the state of the local economy weigh heavily when decisions are made about expanding electrical capacity. Whereas generating facilities used to cost less than $70/KW, now new coal-fired stations with pollution controls cost more than $300/KW, and an additional large investment is required for unit trains or coal slurry pipelines. Nuclear plants cost $600/KW, but their fuel is almost free compared to fossil fuels. The new plants come in large sizes (500-600 MWe is typical for a coal-fired unit, and 850-1150 MWe for a nuclear plant), and the capital required to build one is beyond the capability of the municipalities or any but the largest investor-owned utilities. Some joint ventures are being discussed. Morgan City, Opelousas, Thibodeaux, and Natchitoches are looking into a jointly-owned 115 MWe plant (site unspecified) that would burn petroleum coke, coal, or any other fossil fuel. Cajun Co-ops, a consortium of 12 R.E.A. cooperatives, has a thriving generation enterprize going at New Roads, Louisiana; they have two 115 MWe gas/oil units going now, and two 540 MWe coal-fired stations planned for late 1978 and early 1980. The 1978 (or '79) unit will be the first coal-fired station in south Louisiana.

The price of electricity is rising more rapidly than general inflation. Most of this is due to higher fuel costs, but a good share is due to the high cost of expansion. (See Table 2) Most of the estimates (made eight or ten years ago) of how much electricity would be needed in 1975 were based on exponential extrapolations of then-current growth rates of 12-14% per year. These far-sighted plans overshot the mark, and the result is

	Fuel Cost	Res. Price	Ave. Use Per Cust.
		1973	
L.P.&L.	.314¢/kwh	1.99¢/kwh	11594 kwh
Gulf States	.378	2.45	10819
CLECO	.297	2.54	8937
NOPSI	.310	2.28	9398
		1974	
L.P.&L.	.414¢/kwh	2.17¢/kwh	11249 kwh
Gulf States	.614	2.85	10549
CLECO	.510	2.90	8733
NOPSI	.714	2.92	8538

Table 2. Fuel Costs, Residential Price, and Average Residential Consumption of Electricity in 1973 and 1974. (ref. 3)

that most utilities in the region are overbuilt. CLECO has 49% excess capacity, L.P.&L. has 33% excess capacity, and the city of Lafayette will soon have 140% excess capacity. As can be seen for Table 2, while the price of fuel is increasing rapidly, it still only accounted for 20.7% of the cost of electricity in 1974.

The long-term projections did not consider the elasticity of electrical demand with price. Besides short-term conservation (doing without), over the coming decade there will be a strong incentive to improve efficiency by putting insulation in buildings, replacing worn out appliances with new ones that can do the same job with less energy, and architectural improvements.

The economic future of Louisiana is somewhat clouded by the fact that our number 1 industry is running out of gas. The unemployment rate in the state has been less than the national average so far in the present recession, because the state's industrial economy is based on natural gas and oil. (52,000 persons are employed directly in oil and gas exploration and production, and many more in industries using them.) However, production of both gas and oil have been declining since 1970; see Table 3.

	1974	1973	1972	1971	1970
Oil (Thou BBls / day)	888	1039	1201	1296	1303
Nat Gas (10^9 ft^3/day)	11.77	13.34	14.58	14.77	15.06

Table 3. Oil and Gas Production in Louisiana Since 1970

It is doubtful if oil and gas will continue to provide employment in the state; the reverse is more likely--shortages of gas and oil may cause people to move. It is also very possible that these fossil fuels may be legally and forcefully phased out of use as boiler fuels within the next decade, if price alone is not sufficient to accomplish this end. The Texas Railroad Commission has already (June, 1975) held hearings on the advisability of outlawing use of natural gas as a boiler fuel. The Federal Energy Administration actively intervenes whenever a utility proposes to build a new gas-fired generation plant. However, since new facilities are so costly, and fuel costs are rising sharply, the unamortized cost of the old cheap generators will become less significant.

2.6 Resources. Everyone can see that gas and oil are going to be increasingly hard to get, particularly if intrastate commerce gets expropriated for national use. Gulf States' philosophy is that nuclear is the way to go, although they are also planning a coal-fired station near Lake Charles. L.P.&L. also had big nuclear plans but on June 26 they announced cancellation of two reactors that were to have been built near Rosalie, Louisiana. Louisiana is blessed with several large rivers, including the Mississippi and the Atchafalaya, which could supply cooling water for several nuclear power stations. Unfortunately, there isn't much topographical gradient to enable harnessing all that water for hydroelectric generation.

Coal must be shipped from Wyoming or Montana. The railroads aren't adequate to handle the volume that would be required, and there are no navigable waterways that go the whole distance. South Louisiana also has underground salt domes; these might be valuable storage resources for crude oil or compressed air (see Energy Storage below), even though their oil reservoirs (if any) have been depleted.

2.7 The Demographic constraint is: How many people will live in the area, and what socioeconomic class will they be in? It is impossible to predict what effect migration will have on south Louisiana's population, but over the thirty years it takes to amortize a power plant, it would seem that out-migration is at least as likely as in-migration, due to the aforementioned depletion of oil and gas. Therefore, considering only intrinsic growth and a continuation of present trends in birth rates, Table 4 was created. Table 4 indicates that population growth in the state will slow. Although deaths will probably not exceed births for several decades, the birthrate is now very close to the replacement level. The rate was about 2.35 children/woman for the five years prior to the 1970 census, and it has declined appreciably since then. The effects of these changes in the population will be:

1. More, but smaller homes
2. More people in the workforce; hence, more spending money for this group
3. More older people on limited budget

Item (1) will tend to increase base and peak loads and will probably decrease the load factor.

Item (2) will increase the base demand, but may well improve the load factor, if such things as electric cars become popular. However, a larger percentage of workers in service jobs instead of heavy industry, or a shortened work week may worsen the load factor.

Item (3) will tend to decrease per capita consumption of electricity, but the load factor will also decrease.

Whether upward mobility of people from the lower classes to the middle class, and the middle class to the upper class will continue remains to be seen. In the face of general economic malaise and a declining industrial base, it would seem that substantial improvements are no more likely than status quo, or perhaps even regression.

2.8 Reliability. The power companies are tied together as part of the national electric grid. They are committed to help each other in times of unscheduled outages. In order that blackouts be prevented, 'spinning reserves' of 6% above the maximum hourly load, and standby reserves of 10% additional (or equal to the size of the largest regional generator, if that is more) are required. Since the big New England blackout of 1966, the FPC has mandated that companies on the national grid have selective load-shedding relays (underfrequency-tripped). These relays make a few scattered local blackouts more likely than a blackout of an entire system.

2.9 The climate on the Gulf Coast is warm and humid. About one hurricane hits somewhere in the region each year. The daily weather is apparently a random process (with auto-correlation extending about three days, and spatial correlation at least as large as south Louisiana) superimposed on the regular day/night cycle. Successful attempts have been made to correlate peak demand with weather variables (ref. 1,2). Our group is attempting to simultaneously extract weather correlations, the effect of 'conservation consciousness', price, and market saturation on electrical demand. As of this writing, the results are not in; but hopefully they will be done before October.

The climate was apparently cooling down prior to 1970. Since then, it has been holding fairly steady. See Fig. 5.

Environmentally, natural gas was good. With the exception of trace elements, its combustion products are water and carbon dioxide. There was some concern about the environmental effects of waste heat; but the abundance of bayous and rivers in South Louisiana has kept that problem almost unnoticeable. Nuclear plants increase the amount of waste heat per kilowatt by 25-30%, but there should be no problem getting cooling water at selected sites in Louisiana.

	Age Groups						
Year	0 - 14.9	15.0-24.9	25.0-34.9	35.0-44.9	45.0-64.9	65 +	Total
1970	881.2	514.2	314.2	299.4	515.8	234.3	2759
1975	812.2	543.8	392.0	309.7	526.7	277.7	2862
1980	748.4	536.2	444.3	345.6	539.7	312.6	2927
1985	679.7	511.6	466.8	403.6	571.3	341.6	2975
1990	630.4	477.0	466.8	439.5	618.5	369.7	3002
1995	596.7	441.8	450.9	457.5	670.9	400.2	3018
2000	568.4	438.2	426.9	458.3	718.3	433.5	3044

Table 4. Projected Population (Thousands) of South Louisiana, 1975-2000, by age groups.

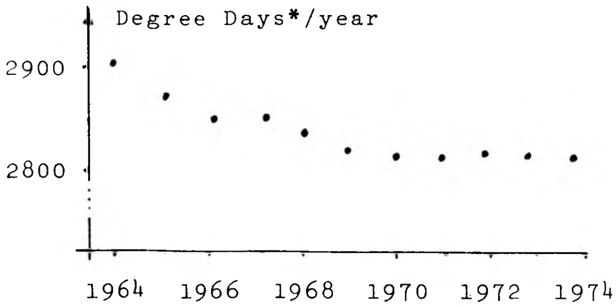

Fig. 5. Twenty-year Running Average of Degree Days* of Cooling Measured in New Orleans (Ref. 3)

The high humidity makes cooling towers less attractive in this climate than in dryer places. Some are used, however, for small power stations such as those in the city of Lafayette. Occasionally, these will cause fog on winter days, but almost never ice.

Coal will be a new experience for utilities in Louisiana. It is known to be messy, and the containment of acidic seepage from coal storage piles will be a worse problem here because of our 50-60 inches of rainfall per year. Controlling stack emissions will be especially critical for the Nelson Station plant Gulf States if planning to build in Lake Charles, because that area is already heavily industrialized. The Louisiana State Department of Conservation is firmly in favor of nuclear plants, instead of coal. However, electricity is necessary; and electricity from coal is better than no electricity at all.

2.10 Life Styles. Besides air conditioning, there are several other factors that contribute to electric load peaking. Foremost among these is the diurnal work cycle that most businesses and some industries adhere to. Having all the office workers on duty Monday-Friday from 8:00 a.m. to 4:30 p.m., and most commercial establishments open from 9:00 a.m. to 6:00 p.m. is primarily a matter of custom, rather than necessity. The superposition of the business/industrial load on top of residential loads causes peak demands on weekdays, never on weekends. It might be feasible for some offices to be open from 6:30 a.m. to 3:00 p.m.; and others from 9:30 a.m. to 6:00 p.m. Some businesses might find it profitable to schedule a siesta break from noon to 2:30 p.m. The incentive to stagger work hours could be largely taken from the need to curtail commuters' traffic jams in New Orleans, Baton Rouge, and Lafayette.

Usually, the peak hour seen by the utilities in this region has been 4:00 or 5:00 p.m.; occasionally, 6:00 p.m. This coincides closely with the time many people cook supper. Well publicized peak-load pricing might cause some gradual evolutionary changes in the way people live, but it won't happen overnight. The experiments the Federal Energy Administration is sponsoring in Vermont, Arizona, Arkansas, Connecticut, Los Angeles, New Jersey, and Ohio trying various schemes to cut back on peak power demands are being followed with great interest. (Ref. 5)

*Degree-days = (Daily mean dry bulb temp. -65° F) x (No. of Days Temp. Exceeds 65°F)

2.11 Lead Times. Because of impending fuel shortages, and no place to build, NOPSI is planning to fade out of the business of making electricity. The planning horizon for electric utilities has usually been 5-10 yrs. in the future for generators. L.P.&L.'s Waterford #3 Nuclear Plant will have taken 12 years to come to fruition when it is finally ready in 1981. Gas-fired units used to be conceived, planned, and built in about four years. Now that the utilities are faced with the need of knowing their generation needs a decade in advance, and coping with the economic, political, resource availability, and demographic uncertainties (not to mention major disrupting events, such as a war); they may as well look a little further. With the population approaching a stable condition, and conventional energy resources being rapidly depleted, perhaps someone in the utilities' planning departments needs to ask the question: What is the probability that our system load will exceed the present value by say, 40%, 10 years from now, and continue to exceed it for at least 30 years after that?

3. OBJECTIVE DEFINITION

After some discussion, the group decided that a reasonable objective would be as shown in Fig. 1: To cut the peak demand for electricity in South Louisiana by 5% below the anticipated peak for 1980. From the official forecasts of the major utilities, and estimation of the load growth for the municipalities and coops, a total maximum load of 13.5 GWe in 1980 is expected. Based on what happened last year (a decline in average use per residential customer--Table 2), this figure used is probably too high. 12.0 GWe will probably be closer to the truth; even that represents a 38% increase over 1974's peak. 5% of 12.0 GWe is 600 MWe, which is about the size of any one of the four coal-fired stations (Gulf States' plant at Lake Charles, CLECO's plant at Nachitoches, or either of Cajun Co-ops' two units at New Roads) being scheduled for completion within the 1979-1981 time frame. Hopefully, if one of these generators isn't needed, that will save $200,000,000 besides avoiding pollution. An alternate view is if they are built, then 600 MWe of gas-fired generators can be phased out earlier, which may be necessitated by a fuel shortage. In the absence of proscriptive legislation, the former is more likely than the latter; since $200,000,000 will buy eight years' worth of natural gas for a pair of 300 MWe generators, even if gas costs 1¢/kwh. If the coal-fired generating plants are built, then the old gas/oil-fired plants will still be there and available for peaking service; and shortage of peaking capacity would be no problem, unless there is no fuel available. Thus, the primary target of a peak-shaving effort in South Louisiana would be to save the utilities from heavy capital investment in new plants, not to save scarce fuels.

4. CONSIDERATION OF ALTERNATIVES

4.1 Modify the Rate Structure. The existing rate structures are of the declining block type. Typical is the one now in effect for the city of Lafayette (see Table 5).

First 50 kwh per/mo. costs	$.0475/kwh
Next 50 kwh per/mo. costs	.0400/kwh
Next 200 kwh per/mo. costs	.0275/kwh
Next 150 kwh per/mo. costs	.0225/kwh
All over 450 kwh per/mo.	.0145/kwh

Table 5. Residential Electric Rates for the City of Lafayette (1974)

Lafayette also gives all-electric homes the following price breaks: **May through October**, all kwh above 300 are billed at $0.012/kwh. November through May, all kwh above 300 kwh/mo. are billed at $0.01/kwh.

The rates for commercial users are similar but higher. (see Table 6)

First 100 kwh per/mo. costs	$.06/kwh
Next 200 kwh per/mo. costs	.045/kwh
Next 1700 kwh per/mo costs	.03/kwh
Next 8000 kwh per/mo. costs	.025/kwh
All over 10,000 kwh per/mo.	.02/kwh

Table 6. Commercial and Small Industry Rates in Lafayette (1974)

The large industries' rate is less. (see Table 7)

First 50,000 kwh per/mo. costs	$.015/kwh
Next 150,000 kwh per/mo. costs	.0125/kwh
All over 200,000 kwh per/mo.	.008/kwh

Table 7. Large Commercial and Industrial Rates in Lafayette (1974)

In addition to energy consumption (kwh), large users must pay $2.00/kw for their highest 15-minute demand at any time during the month, and $1.50/kw for each maximum kw above 40.

The rates in the tables above are basic rates; there is an additional 'Fuel Cost Adjustment' (which was $.00524/kwh in June, 1975) which is added to everybody's bill.

There have been several ways suggested to change the rate structure. These are discussed below, along with their probable result with respect to peak demand. Other significant consequences are also mentioned.

The first type of change is simply a blanket increase of all rates, retaining the declining block structure. This would spread the the burden equally among all customers, and nobody would see a pronounced increase if his usage remained constant. However, increasing prices would precipitate year-round conservation efforts. Refraining from putting up Christmas lights or turning off a few lights at night won't cut peak demand at all, but if will decrease the utilities' load factor.

Another type of change would be to flatten the rate structure; leave the first blocks unchanged, but increase the rate in the higher-usage blocks. This would penalize the big users, particularly in the months when they are using a lot. Summertime conservation in homes with central air conditioning would be one result. There would also be a lot of complaints from people who see a pronounced increase in their bill. An increase in the bill to industries or commerce would have to be passed on to their customers (who may not live in Louisiana). Closely related is the suggestion that subsidies to all-electric homes be dropped; if done to existing homes as well as new ones, this would cause some people's electric bills to nearly double. Furthermore, in the decades ahead, all-electric homes may be a necessity unless solar homes are marketed.

The 'lifeline' concept, which calls for lowering the first block while raising the others, is a way to subsidize poor people--to shield them from the effects of rising energy prices. In Lafayette, only 8% of the residential customers used less than 100 kwh in July, 1971 and 26% were less than 400 kwh. Therefore, it is unlikely that a 'lifeline' rate structure would have much effect on total energy consumption. The people who would see the biggest percentage increase in their bills would be the middle class, those whose maximum consumption is around 2000 kwh in July. The effect on them would be the same as a blanket increase (see above).

The declining block rate structure, together with the Fuel Price Adjustment, is an attempt to bill fairly. There are three components of cost to be recovered.

(1) Billing fee. This includes at least the cost of the meter, the cost to read the meter, and the cost to mail the bill and deposit the payment. In practice, it also includes a substantial part of the general office and operation overhead costs.

(2) Demand charge. This is where the capital investment in distribution lines and transformers, transmission lines, and generators must be recovered. Generally, this equipment must all be sized for the maximum demand, and the cost is there whether the demand is or not.

(3) Energy charge. This should be just the cost of the fuel; it should already be separated out as the Fuel Cost Adjustment.

An increasing block rate structure has been suggested as a way to promote conservation of energy. It probably would do that; but in order to cut peak demand, it would have to induce people to turn off their air conditioners on the hottest day of the summer. If imposed on large industries, it would impel them to put in their own generators.

Finally, a seasonal rate structure has been suggested. Ideally, such a rate structure should look like Fig. 6.

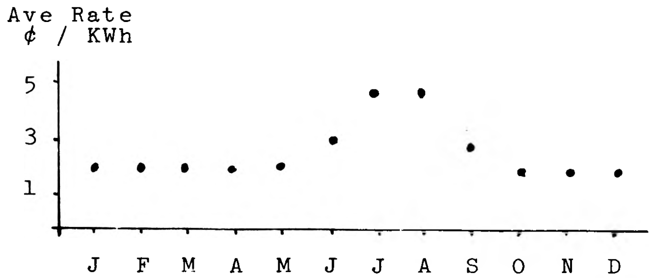

Fig. 6. A Seasonal Rate Structure Designed to Curb Peak Demand and Improve Load Factor

The structure shown in Fig. 6 would call people's attention to the fact that summertime peak demands are the biggest reason their electricity costs so much. But such a drastic price rise would probably cause a consumer revolt, such as the one that occurred in Thibodeaux, Louisiana, this year when people got their June bills. These protests would undoubtedly lead to the suggestions that the summertime costs be blended into bills for the whole year, which would miss the whole point.

All the rate structures discussed so far have the advantage that they could be implemented using existing metering equipment. But they share a common disadvantage in that they don't really focus on the problem. The peak demand only occurs once/year, usually there are fewer than 14 days per year when the peak demand is within 5% of the maximum--these are hot weekdays. Those are the only days when anything needs to be done about peak demand. All of the rate schedule changes mentioned will cause someone to cut back more during times when it doesn't help (evenings, cool days) than during the hours when a cutback is really needed.

It would be possible to install more Demand Meters on small businesses and even residences. However, since the composite load is the sum of randomly switched small loads, a Demand Meter would penalize at random unless positive steps were taken to assure that major electrical appliances were not being run simultaneously. In an all-electric home, one could set up a S.P.D.T. relay to assure that the water heater and the air conditioner did not run simultaneously, and another to supply the dryer or the range. This would result in some inconveniences.

When one considers the whole system, it is doubtful if Demand Meters would do much to trim the maximum peak unless the sum of the individual allotments was not much bigger than the system peak. This is because peak demand is driven by the sun, the time of day, and the day of the week; when these are all in conjunction, everybody will be wanting electricity, and they will take all they can have.

Time-of-day pricing for electricity has been suggested. This would require new meters in most places, although some large customers are already sufficiently instrumented. Suppose, for instance, that Gulf States imposed time-of-day rates on SLEMCO. That would really be no different than the normal costs-of-operation that the nature of the system imposes on Gulf States when they have to generate peaking power. What would SLEMCO do? They would probably inform their customers via their monthly magazine. What would SLEMCO's customers do? Probably nothing, because each would tell himself that whatever he might do would make such a small subtraction from the system load that it would not even be noticed. If each customer had his own time-of-day meter, it would be different: his actions would make a noticeable difference in his bill.

The problem with this is that the meters cost too much. The best scheme using present equipment has two meters and a timer; the timer turns on one meter at night and the other during the day. The timer is electrically driven with a mechanical spring backup in case of a power outage. Some modifications of this meter are suggested: use a photo-electric sensor and daylight as the timer, instead of an electric clock; this gets away from the re-synchronization problem, and it also would put a seasonal component (due to short days in the winter) into the rate schedule. It may also be worthwhile to run both meters part of the time, to accentuate the cost of peak power. Also, a seven-day timer might be used to allow use of low priced electricity all day on the weekends. (see Fig. 7)

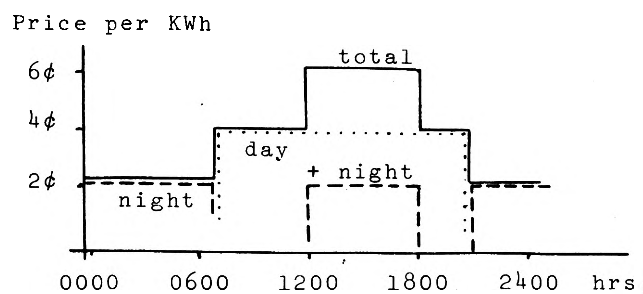

Fig. 7. Suggestion for Using Two Meters for Time-of-Day Pricing. Meter #1's Reading Cost 2¢/kwh and Meter #2 Cost 4¢/kwh.

A double meter with timer costs about $60.00. If we consider this as a goal, then it would seem that the problem could be solved by a meter based on a digital microprocessor. Electronic adding machines with 8-digit LED readouts now sell for less than $10.00, so a mass market for sophisticated kwh meters could produce a reasonably low price. Conceptually, the meter would consist of a battery with recharger, wrap-around current-sensors similar to a clamp-on ammeter, voltage pickoffs (say, a 1KΩ resistor in series with a 50Ω resistor connected between each of the hot wires and the neutral). There would have to be a solid-state differential amplifier which could be connected in turn to each of the four input busses (two currents, two voltages) using solid state switching. The microprocessor could be programmed to do an analog-to-digital conversion for one voltage; and then, one cycle later, read the corresponding current. It could then calculate their product and store it. The sampling instant could be timed so that different portions of the waveform were sampled in succession, to give the true RMS product. The same thing could be done for the voltage and current in the other incoming line. A few times per hour, the accumulated product (watts) could be multiplied by easily-generated weighing factors to get weighed time-of-day kwhr. It would be feasible to have weekly, monthly, and semi-annual changes in the weighing factors built in with no additional hardware. The batteries would keep it running through power outages without losing track of time. It would probably be necessary to control the temperature environment in which the microprocessor works, and there is some question whether it would run for a decade or more without attention. But if time-of-day metering is desirable, particularly sophisticated time-of-day metering with gradually-tapering rates that cuts out weekends and focuses on the hottest part of the summer, then microprocessors look good.

The cost of time-of-day meters, even for residential customers, need not be prohibitive. It would only be about $1.00/month if amortized over 8 years. Furthermore, not everybody needs to have a meter. An announcement that time-of-day rates will be used, based on meters in substations supplying residential areas, may be sufficient. If an individual customer has reason to believe that his usage is significantly different than the average, and he's willing to pay $1.00/month to prove it, he can have his own time-of-day meter.

A possible problem with block-jump rate structures such as that shown in Fig. 7 is that they may prompt the use of automatic load controllers by many customers; this in turn, means that lots of loads will be turning off or on just before or just after the price break time. This could have devastating consequences to the transient stability of the power system. Gradual transitions could be implemented using microprocessor meters, or by assigning different break times to different customers.

By itself, time-of-day metering would cause the following reactions: Residential users would set the thermostat up during the afternoon and perhaps delay the cooking of dinner until after the price break. Those with electric water heaters might install timers to keep them from turning on during peak hours, if the timers were simple to install and didn't cost more than a few dollars. Some commercial users might turn off part of their lights during peak hours, as well as set the thermostat up. Some industries and governmental establishments might go so far as to install load programmers that would allow or inhibit starting of some pumps, compressors, fans, etc. depending on the time of day. There would probably be a strong market for time of day meters with auxiliary contacts for automatically controlling loads as well as the meter. If the rate differential were 3:1, it might be reasonably expected that an average residential user could trim his average daily maximum by 10%. However, on the hottest day of the summer, the peak would be trimmed less than that (perhaps 5%) because undersized air conditioners would be running continuously even though their setpoint was raised.

If the time-of-day rate structure were kept in effect all year, it would cause some load flattening with attendant increase in the efficiency of the generators being used. Also, all-year operation of time-of-day metering will tend to habitualize load scheduling. However, people are bound to question the necessity of doing something all year to cope with a problem that occurs only on weekdays in July or August.

4.2 More Efficient Air Conditioning. An examination of the ARI date (ref. 4) reveals that there is some room for improvement in efficiency. For example, a Bryant 3-ton central air conditioner takes 6.8 KW, while a Westinghouse 3-ton unit requires only 5.1 KW. However, most brands are between 5.7 and 6.3 KW, a variance of only 10%. Heat pumps are slightly more efficient; the best 3-ton heat pump listed needs 4.4 KW. These savings are too small to attract the attention of most customers. They are more interested in price and immediate availability. With the present price of electricity, and assuming 5 year ownership of the unit, the difference in price between the most efficient unit and an average unit would have to be less than $150 for there to be an economic advantage for the efficient unit. Air conditioner dealers do have ARI's Energy Efficiency Rating book available for customers to look at; but according to Pat Richard at Marine Electric, few of them take the trouble to do it. Unfortunately, most people go shopping for an air conditioner when the heat's on; either their air conditioner is broken, or they are buying their first one; either way, it's usually important to them to get immediate relief. Shopping for an air conditioner under these conditions is like going into a grocery store ravenously hungry.

Maintenance can help improve the efficiency of an air conditioner. Changing the filter once a month (at a cost of about $.80) can increase the efficiency of the unit 20% by improving heat transfer from the evaporator coils (possible savings, $4.00 per month for an average central air conditioning unit). Periodic preventive maintenance (cleaning the coils, rebuilding the compressor) could also enhance the efficiency of an air conditioning system. However, according to Mr. Richard, fewer than 1/4 of the people who own air conditioners do anything other than change filters; they just wait until it breaks down. The average life-expectancy of a central air conditioning unit in South Louisiana is 8-12 years. Implying from the growth record of electric demand that a lot of new air conditioners were bought in the period between 1965 and 1970, it follows that this next five years will bring a strong replacement market. If advertisements for air conditioners included running costs as well as purchase price; and if it were mandated that the price tag should also carry that information, then there would be a potential gain of about 10% in efficiency, which would translate to a decrease in peak demand of about 1.5% on the hottest day of the summer. Better maintenance would contribute another 2% reduction.

Putting the air conditioner in the shade lowers the ambient temperature to which heat must be rejected, and enhances the efficiency of the unit about 9%, for 10°F of difference in the ambient temperature surrounding the condenser coils. Drawing draperies on the sunny side of the house helps some, particularly if the drapes are equipped with reflective backing. However, awnings or trees to shade the outside of windows help more, since visible light is degraded to infrared when it encounters objects inside the building, and infrared cannot exit through glass (greenhouse effect).

Another thing that can be done to improve the efficiency of the air conditioning system in homes is to cool the attic. In the absence of ventillation, some attics get as warm as 150° on a hot summer afternoon. Wind powered ventillators help some, but the hottest day of the summer is usually characterized by negligable wind speed; therefore, it is questionable how much wind-turbines would trim the peak demand. An on-going research project being pursued by Mr. Bakewell and Mr. Whitney of our group is an investigation of a house model. In this model, various parameters such as the attic temperature will be varied to determine what effect they have on the heat transfer rate into the house. On the other hand, a powered roof ventillator can cool the attic to about 95°. This can cut the cooling requirement by as much as 1/3. A powered roof vent costs about $120, including installation (a do-it-yourselfer can put one in for about $75). The potential saving would be about $10/month (based on today's electricity prices) for the three hottest summer months, and less for other cooling months. The fan motor itself consumes about 2 kwh/day in the hot months, and an estimated 1 kwh/day in April, May, and September, or about 450 kwh per season (cost is approximately $12.00). Therefore, it would take about 4 years of operation for a power ventillator to pay for itself. Higher-priced electricity would cut that to one or two years.

Better insulation would also help. If ceiling insulation is increased in thickness from 2" to 6", that will cut vertical heat transfer in half, which would trim the overall heat load by 20-30%, depending on the shape of the house. Better insulation in the walls could trim the heat load by another 10%, but the cost-effectiveness of putting insulation in walls is less, since the sun strikes them obliquely and only for part of the day. The cost to insulate an attic is about $200 for an average home (half that for do-it-yourselfers). Therefore, in a trade-off between an attic ventillator and more insulation, the ventillator looks better when only cooling requirements are considered. However, insulation saves energy and money in the wintertime, too.

One simple suggestion that appears to have merit is to install a leaky pipe along the apex of the roof. With water trickling over the roof, the sun's heat would go to evaporate the water instead of heat the house. Evaporating 5 gallons of water per hour takes about 36,000 BTU, which is equivalent to a 3-ton air conditioner. That much water would probably not be a burden for the municipal water system. We have no data on how much this would cut electric consumption, but it would be an interesting experiment.

An insulation standard should be written into the building code, and no one should be allowed to buy or rent a dwelling that doesn't meet the standard. This code could be applied retroactively to existing structures by requiring an inspection when there is a change in occupancy if the building has not been previously inspected.

4.3 Energy Storage. Several possible ways of storing energy at night for use in the daytime were considered. Storing water behind dams is done in Oklahoma (which supplies about 25MW to the R.E.A. coops in the region); also, TVA has a seasonal interchange arrangement with Gulf States (about 75MW). The Toledo-Bend reservoir on the Sabine River between Texas and Louisiana can supply about 50MW of peaking power. All together, the hydro-storage potential amounts to only about 2% of the maximum system load, and it cannot increase much.

One way the municipalities could store energy would be to construct surface storage facilities for water. Most of the culinary water used in cities and towns in South Louisiana comes from wells several hundred feet deep. If a million gallons were pumped into a tank at night from a depth of 600', that would represent 1.8×10^3 kwhr of stored energy. This could take the place of 300 KW spread across six hours of hot afternoon. The 300 KW are worth $600 apiece, so a million gallon surface storage tank would be worth $180,000. New pumps may not be needed if it were decided to run the existing pumps all night to fill a new tank. The cost to build such a tank would probably be around $150,000, so it might be worth doing.

A scheme has been proposed and is under active investigation by the Middle South Utilities (see ref. 7) in which compressed air would be forced into a salt dome formation at night. During the afternoon, the air would come out through a low pressure turbine that would supplement the torque of a conventional steam turbine on the same shaft. No one has tried this scheme yet, and until someone does, any attempt to guess how efficient it might be would be premature.

It has been suggested that solar energy be stored in hot water. The size of a 1.5KW (maximum when the sun hits it squarely) solar water heater would be about $4m^2$, if it were optimally oriented. For a do-it-yourselfer, the materials would cost about $400-500 ($200 for copper tubing, $50 for support frame, $50 for night-bypass controls, and $150 for a storage tank). For this investment, the owner could harvest about 2000 kwh of 'free' solar energy per year, or enough to heat about 10,000 gallons of hot water per year. This, of course, would have to be supplemented by the regular hot water heater; since several cloudy days in succession are common in Louisiana. At 3¢/kwh, it would take almost 10 years to recoup the cost of the investment in the water heater. The plumbing provisions of the building codes would have to be modified to allow putting solar water heaters on roofs. An alternate suggestion would be to embed some pipes in the driveway. It wouldn't be an optimal orientation, and they would have to be drained in the wintertime to prevent freezing; but it would not be unsightly. Inasmuch as only about 15% of the residential customers in Louisiana have electric hot water heaters, it is doubtful if solar hot water heaters curtail the electric peak load by a significant amount in the forseeable future.

However, for those customers that do have electric hot water heaters, it may be worthwhile to install large (at least 100 gal.) storage tanks that could be filled at night. If such tanks were well-insulated (or put in a hot attic), it would be possible to turn the water heater off during the day. The usage of hot water by residential customers during the peak hours (2-6PM) is less than in the morning or evening; so the contribution of water heaters to the peak demand is quite small. Hot water storage could trim peak demand by about 0.5% if everyone with electric heaters refrained from turning them on during the peak hours.

Electric energy storage in batteries was considered; but the cost of batteries to store, say, 20 kwh of energy would be more than $1000, and the inverter and charger would cost about $300 more. The batteries wear out and the life expectancy of the electronics is short compared to 30 years. Even as a source of emergency power after a hurricane, this scheme is not economical. Similarly, fuel cells for small scale installations are prohibitively expensive. Large fuel cells stations, capable of producing several dozen MW, have been considered by some utilities in New England. The capital investment and maintenance cost have so far been prohibitive, but with the price of new generation approaching $600/kw, there may be a resurgance of interest. With both the battery and the fuel cell, the conversion efficiency is important. About 1.5 kwh must be put in for each 1.0 kwh returned later.

Kinetic energy storage in high speed flywheels has been considered in California (ref. 8). The economics of this proposal are not known. However, the safety of such devices is a bigger concern.

4.4 Demand Control. In the past, utilities used to sell 'deferrable' power to some industrial customers. NOPSI still has two customers with such contracts, but L.P.&L. does not do it anymore because it causes too much hassling with customers: who is qualified for special rates, and when; how much notice is required before a cutback; might it violate some OSHA regulation; who is responsible if it causes an accident. In today's situation of surplus capacity, there is little incentive to negotiate such contracts.

Demand control probably represents the most direct attack on the specific problem of power peaking. When (and only when) the system load gets precariously high, selective load cutbacks can be initiated until the load is within bounds. In the future, instead of investing $600/KW for new generation facilities, the utilities might consider shopping around for 'negative kilowatts', which should be considerably cheaper. Maximum demand metering should be retained, but in addition large users should be encouraged to look around their places of business to find some good-sized blocks of power that could be shut off for about an hour without causing much hardship. The electric company would then install (or send instructions for the plant electrician to install) automatic shutoff devices such as the F-M receivers used by Buckeye Co-ops in Ohio (ref. 9) on residential water heaters. When necessary, power company dispatchers could send out signals to start shedding loads. By rotating the priority, it could be arranged so that no firm would have anything cut off for more than an hour (and that only about 3-5 times per year). The types of loads that might be deferred are water heaters, deep well pumps, compressor motors, reheat coils, ventilation fans, part of the lights, and other service equipment not directly involved in the production or business.

Let the power companies bargain with industrial/commercial/governmental users thus: "We (the power co.) will install automatic cutoff devices in your plant on equipment you select, at our expense. Further; we agree that no shutdown will last more than one hour, nor will more than five shutdowns be initiated by the power company in any calendar year. The power company will deduct from your bill 40¢/KW, for quantities of at least 100 KW, each time it is necessary to shed some of your load." The cutback devices could be equipped with counters and timers to verifty what the power company did. The power company would only be paying about $2.00/KW/year to those customers who agreed to this arrangement; or about $10.00/KW/year to all deferrable customers if they spread the 5-hr peak load among several. This would amount to about $300/KW over a thirty-year period, with half of the expense deferred more than 15 years. The initial cost of the cutout devices will, of course, vary with the size of the load being shut down; $20/KW is estimated. The maintenance cost of something the F-M receivers is not known, but their life expectancy could be extended if they were only activated two months per year.

Compressor motors of residential central air conditioners are another possibility for load control. They represent a load of about 6KW each, and an F-M receiver (or some other type of controller) could shut them down if necessary. Since the peak periods of Louisiana are of fairly long duration (4-6 hours), it would be necessary to spread a cutback among several residences. If an air conditioner were shut off for an hour, then allowed to run again, it would run longer before reaching its set-point. On the hottest days, many would not reach their set-point until after dark, which would tend to broaden the peak. However, if a person's air conditioner were cut off all afternoon, his house would get uncomfortably warm and he would complain. To avoid complaints, several 'banks' of sheddable load should be lined up; perhaps, as in the case of Buckeye Electric's water heater controls, by using different modulation frequencies for each bank. About a dozen banks would be advisable in each area. First priority would be assigned on a rotating basis, and outages limited to one hour. Only in very hot periods, or in case of an emergency, would the same customer be cut off two days in a row. Installation of the cutout devices could be done in the off-season by air conditioner repairmen paid by the power companies. Perhaps, if a 'Free Inspection and Cleaning' were offered as part of the deal, many people would be willing to sign up. A carefully planned advance publicity campaign would, of course, be desirable. The cost for the F-M receivers is about $90. Allowing $10 for other parts, and $50 for installation labor, the cost per controlled compressor would be about $150. Twelve such, to be called up in rotating order, would cost $1800 for 6 negative kilowatts. This is only half the cost of a plant to generate 6 positive kilowatts. Again, the maintenance cost of the receiving units is an unknown; but maintenance could be minimized by activating them only two months of the year.

4.5 Building More Power Plants. This is included as an option because that is what the power companies have been doing to cope with peak demands. The advantages are that there are engineering staffs trained to do this job, there are construction companies that stand ready to build the power plants, and a power plant lasts for 30-50 years. Customer complaints are minimized because there is no inconvenience or penalties imposed on their use of electricity. Also, by concentrating on one large unit, the number of interfaces with the public is minimized. Another advantage now that gas and oil are getting scarce is that new plants using coal or uranium fuel will have to be built sooner or later; and the sooner the better. The disadvantages are the huge capital investment required, and the necessity for forecasting need 10 years in advance. Right now, the two disadvantages seem to outweigh all the advantages.

4.6 Some Lifestyle Changes that would help the problem, besides changes in working hours would be:

1. Washing clothes and dishes at night or early morning
2. Dressing to be comfortable in 80°F or 85°F temperatures
3. Living in smaller dwellings, or air conditioning only part of a home or office. In this case, however, there would be heat transfer through the inner walls as well as ceiling and outside walls; the dead air space in unused rooms is essentially better insulation between the cooled part and the outside environment. Perhaps three thermostats in strategic locations in a house, with the air conditioner turning on only after two of the three setpoints had been exceeded, would help; or individual room thermostats that controlled the ducts into that room.
4. Energy consciousness. People will have to develop the habit of turning off lights when they leave a room, and perhaps turning the room thermostat off too.

If some national emergency made it necessary to ration electricity, this could be done by alloting a particular number of kwh/mo. to each home, depending on the type of home and the number of people who live there. But it would take the wisdom of Solomon to decide how much each could have. Businesses could be put on similar allocations. At least it would be easier than rationing gasoline, because the measuring apparatus is already in place. Black market electricity might come into existence if people started bypassing their meters.

One way to elicit the desired response to this particular problem would be to have the 10:00 p.m. TV newscaster put in a 45 second announcement, saying: "Tomorrow will be a bad day to use electricity, because it looks like our utility will be overloaded due to the hot weather. If, just for tomorrow, you would set home thermostats to 80°--you don't have to turn the air conditioner all the way off, although if you would do that, it would be greatly appreciated--you will save the power company from having to invest $200 million in a new coal-fired power station and shipping coal all the way down here from Wyoming. The trains won't block the street on your way to work in the morning, and you won't have to pay your share of that $200 million: $10 per year for the next 20 years. If you will only set your thermostat to 80°, just for tomorrow. Thank you." This should be followed up with 10 second reminders of TV and radio the next afternoon. This should be done in the spirit of a public service announcement, like a tornado warning. Also, it would lose its effectiveness if done too often; five times a year may be too many.

Without price inducements or noticeable shortages, it is felt that the effect of jawboning will be minimal. Lifestyle changes because of a widely discussed 'Energy Crisis' have been slow in coming. Electricity conservation on peak days will probably be even slower. The Public Service announcement has been tried by some utilities on the East Coast, but quantitative assessments are not available; we estimate that if timed properly, it could trim the peak of the worst day by something approaching 1%. Also, since it doesn't cost much, it would certainly be worth trying.

4.7 Reducing Voltage is done by some power companies (not in Louisiana) to cope with unexpected peaks. If the voltage is reduced 2-2 1/2%, the power consumption drops by about 1%, primarily because resistance heating ($P=V^2/R$) would go down about 5%. Induction motors also run slightly slower. However, since some transformers are equipped with automatic load tap changers, which might boost the secondary voltage if the primary voltage is reduced too much, reducing the voltage may be counter-productive in some cases. Also, on hot summer days the voltage is already lower than normal on most parts of the system, due to heavy line loads. Further voltage reduction may cause damage to some equipment, although 115 volts should be well within the tolerance range of most home appliances. If done regularly, it would cause complaints.

The utility companies could achieve about 0.5% reduction in power by deliberate voltage reduction. However, the 'brownout option' is probably best saved for emergencies and not relied on as a standard practice for peak shaving.

4.8 Spinning Reserve Requirements could be relaxed if the overall reliability of the power supply is not too critical. If one of the large generating plants tripped off the line, it would be necessary to shed some loads to keep the system from collapsing (ref. 10). If the spinning reserve requirement were reduced from 6% to 4% above the maximum peak load; there would still be only about 30 hrs. per year when the demand would be within 6% of the ready reserve. The probability of losing any of the large plants (loss of a small plant could be tolerated) within those 30 peak hours is estimated to be less than .05 for any given year. 13 years might be expected to pass without it happening at all; and if it did happen, there would be localized blackouts for a few hours in zones chosen to be relatively insensitive to the effect of a blackout, such as residential neighborhoods. Blackouts from this cause would be less likely than blackouts from violent weather or nuisance tripping of relays. The time has come to ask "Is this increment of reliability worth as much as it costs?"

There should be no cause to worry about standby reserves in Louisiana for the foreseeable future, unless it becomes illegal to store oil in tanks to use to make electricity in an emergency. Most of the existing oil/gas-fired generators will still have useful life left in them, and could be brought on-line in less than 12 hours.

4.9 Raising Thermostats is perhaps the simplest thing that could be done to curtail peak demands. There have been some doubts about how effective this would be, because on the hottest day of the summer undersized units run continuously. We examined consumer survey data for Gulf States customers in the Baton Rouge area for their peak day last year (Monday, July 29). The maximum temperature that day in Baton Rouge was 96°F. From the recorders producing good data, we deduced that in 49 households, the air conditioner was apparently running continuously throughout the afternoon. In 37 households, the air conditioner was apparently cycling, and in 47 households the air conditioner was apparently off, either because the inhabitants turned it off when they left for the day, or they had gone on vacation, or the dwelling was vacant. Thus, about 40% of the home air conditioners that were on were cycling on the worst day in Baton Rouge. We do not know what the setting of the thermostat was in those homes. However, if there was an average of 18° difference between the outside temperature and the thermostat, it can be concluded that setting the average thermostat to 80° would maintain the same margin of 40% cycling on even the hottest day of a decade. Approximately 30% of the total load on the hottest part of a summer day is due to residential air conditioning. Using the estimate that a 1% increase in setting will save 5% of the energy (ref. 6) consumed by the fraction who have some reserve margin, it can be inferred that a 1% increase in setting would cut the peak load by 0.6% on the hottest days of the summer, (vs. about 1.5% on more moderate days).

Thus, if people could be convinced to raise their thermostat settings 3°, that would trim the worst peak by about 2%. They would also trim their total energy consumption by 15% throughout the summer, and their bill by about $5.00/month. That is not enough financial incentive to attract most people's attention. The big problem with raising thermostats is how do you get people to do it?

4.10 Increasing Night Usage would inevitably cause some slight increases in daytime usage, too. However, the savings from operating the generators more efficiently, and the fact that an improved load factor would decrease the average cost per kilowatt hour, makes this an attractive option. Industries using electrochemical processes could be designed to run only at night. The transportation industry may eventually use a lot of electricity at night to charge batteries or make hydrogen. Bargain rates for night time electricity may cause such evolutionary changes in the transportation industry, particularly if the price of gasoline keeps climbing. The cost to separate 1500 g of hydrogen (containing about 210,000 BTU, about as much as 1 gallon of gasoline) would be about $2.50 if electricity cost 1¢/kwh. It is much cheaper to extract hydrogen from natural gas, or burn bottled gas in cars, than to burn gas to make electricity, then use the electricity to make hydrogen to burn in cars.

5. TRADEOFFS AND RECOMMENDATIONS

Two alternatives are recommended as having the most direct impact on the particular problem of power peaks with a minimum of unwanted side effects:

5.1 Relaxation of the Reliability Requirement would require no capital investment, only an administrative decision. A reasonable goal would be have the expected number of customer blackout hours from this cause-loss of a power plant during the peak demand period--to be about one-tenth of the number expected from violent weather.

5.2 Demand Control. Contracting for 'negative kilowatts' from governmental, industrial, and commercial establishments appears to promise the biggest payout per dollar invested. Cutout controls on residential air conditioners also appear worth considering, although about 50,000 such cutouts (costing perhaps $75 million) would be required to get 300 MWe lined up to be trimmed.

Other ways that would trim peak demand, but also decrease load factor are:

5.3 Raise the thermostat setpoint.

5.4 Improve the efficiency of air conditioning systems.

It cannot be expected that power companies will actively promote these ideas, since the loss of revenue from kwh's not sold would hurt them more than the trimming of the peak would help. Government, consumer, and conservation groups will promote them, and the public will start to respond as the price of electricity increases.

5.5 Finally, time-of-day metering, first of large users; and then gradually of smaller users would tend to decrease peak use and improve the load factor. The cost to equip everybody in South Louisiana with a time-of-day meter would be about $200 million, or about the same as one coal-fired power station.

It is felt that (1), (2), and (3) on the list above would be sufficient to reduce peak demand in south Louisiana by 5% before 1980; (4) and (5) would reduce it at least another 5%. The other alternatives would make lesser contributions, but in aggregate, they too, could result in a further 5% decrease. It is, therefore, concluded that the objective can be met.

6. CONTINGENCIES

Of the major disrupting events that could occur in the near future, four stand out as quite significant in the context of peak electricity demands. First, there is a strong possibility of another oil embargo. Mid-east wars occurred in 1948, 1956, 1967, and 1973; and the pot is still boiling. It appears likely that another war will break out within the next decade, perhaps within a year. In that event, an oil embargo would probably be erected within hours. Indeed, it is possible that an embargo may come even if war doesn't. The fuel that our Louisiana utilities burn would be more critically needed elsewhere in the nation; they would be put on curtailed operations. Shutting down inefficient units and operating the others at maximal (near full load) efficiency around the clock would be sought for. Anything done now to level the load would be beneficial in the event of such a crisis.

Another thing that might happen is that natural gas and oil will get so scarce (due to growing worldwide demand) that their use as boiler fuels will be proscribed by law. Indeed, there does not appear to be much question whether this will happen, only when. If it happens abruptly, by emergency decree from the President or the Governor, then the state will need coal or nuclear power plants to supplement whatever power might be available from T.V.A. or Missouri. Relying on our existing power plants is very risky in this context. Ultimately, of course, it is generally felt that oil and gas will be too expensive to burn in boilers, even in the face of the large capital investment in existing plants.

A nuclear moratorium, precipitated perhaps by a terrorist group capturing a nuclear power station somewhere in the world, and extorting ransom or other concessions from the local government, could happen. In that case, no new nuclear power plants would be built, and even those in early stages of construction might be cancelled. This would leave Louisiana dependent on its existing plants, unless sufficient coal-fired stations were available. On the other hand, it is conceivable that the United States might embark on an all-out nuclear power plant building program. In that case, Louisiana might be the site of several plants, and we would have abundant electricity like T.V.A. used to have. However, nuclear power is good for base load only; those plants are not amenable to daily cycling like boilers.

Louisiana would be better-prepared to survive any of these contingencies if the electric load were more nearly level; in three of them, the state would be better off with another coal-fired power station than some way of doing without it.

7. IMPACT ASSESSMENT

In this section, the side effects of doing without one large coal-fired station will be explored.

First, since the plant won't be built, the people at an Engineering/Architect firm and a crew of construction workers won't have a job. In today's climate of high unemployment, and with so many people in their early 20's trying to get started, this is indeed a significant impact. It is estimated that about 600 man years of engineering effort goes into the design and construction supervision of such a plant, and 5 million man-hours of skilled craftsmanship goes into building it (not counting design and labor at vendors' plants). About 50 operators' jobs would also be eliminated.

Not building the plant would ease the strain on transportation facilities. The quality of the railroad track in Louisiana has degraded until now, several derailments per month are reported in the newspapers. Two unit trains per day is small compared to the total rail traffic, but coal cars are heavy (some of the new ones weigh more than 100 tons when loaded). A coal slurry line, with its attendant right-of-way problems, might also be avoided.

Environmentally, not having a plant--particularly a coal-fired plant--is preferrable to having it. The coal mine, even if it is in the deserted part of Wyoming or Montana, will probably leave a permanent scar on the earth. Particulate and sulphur-oxide emissions (even if it is low-sulfur coal) and ash disposal will pose problems in the vicinity of the power plant. The plant will add noise and soot to the air, and acid to rain runoff waters.

Financially, some utility might save half the cost of such a plant. But some money will have to be spent arranging for something else instead; negative kilowatts might be cheaper, but they would not be free. The saving would mean less money would have to be borrowed (at high interest rates), and the consumers' bills would not rise quite so fast. With high inflation, being in debt for something may be better than waiting to buy it later. The utility that decides not to build may be buying power from its neighbors (paying for the neighbors' power plants), instead of paying for its own plant, but the payout will be delayed five years.

Socially, Demand Control or Peak Pricing may cause some places of business to open at odd hours. They will promote more conservation consciousness, particularly with regard to air conditioning. Such a change will unfortunately be accompanied by a lot of haggling and wounded feelings; the small claims courts must gird for an avalanche.

8. CONCLUDING REMARKS

In this paper, we have explored the possible ways of reducing peak electrical demand in South Louisiana. We conclude that by relaxing reliability requirements, contracting for 'negative kilowatts', and raising thermostats about 3°, it would be possible to shave the peak by 5%. By improving the efficiency of air conditioners, and instituting peak load pricing, it would be possible to cut it a lot more; indeed, if all the things that were discussed were done simultaneously, a peak-shaving of 20% could probably be achieved.

However, when the utilities invest money in peak shaving, that seems to imply that they are going to try to get along by using their existing generating facilities instead of investing in new plants. The existing plants run on natural gas and oil. Unless substantial new supplies of these apparently diminishing commodities appear from Alaska or off the Carolina coast within the next decade, Louisiana's utilities won't be able to get by with their existing plants. Nuclear or coal-fired power stations appear to be necessary to carry the base load as soon as possible. If such plants are built, then the larger, more efficient gas-fired generators will be available to operate for 2-4 months in the summer.

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ALTERNATIVE APPROACHES TO ENERGY MODELING*

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1.0 INTRODUCTION

The effects of government and private sector energy policies are varied and interrelated. Before implementing research and development programs, new technologies, environmental and price regulations, import quotas, and other energy-related policies, the consequences of these programs must be identified and quantified on a regional basis. To evaluate the regional impacts of energy policies, we need to consider production costs, transportation costs, and the location of reserves, as well as the demands for energy and nonenergy goods. Developing techniques for analyzing these factors was the objective of many previous research efforts. The strengths and weaknesses of the resulting models are discussed in this paper and areas for future research are outlined. Only those models that consider more than one fuel and sector (i.e., residential, utility, etc.) are reviewed.

The models examined are the Battelle Columbus-EPA Energy Quality model,[1] Baughman's Dynamic Energy System model,[2] the Brookhaven National Laboratory Energy models,[3] the Energy Management Simulation and Analysis System,[4] the Hudson-Jorgenson Energy model,[5] Kalter's Parametric Models of Fossil Fuel Markets,[6] the Project Independence Evaluation System,[7] and the Wisconsin Energy model.[8]

Most of these energy models have been formulated for use on a national level. Because of differing energy markets in various regions of the country, these national models may be inappropriate for assessing regional energy-policy impacts. Regional models may also be designed inadequately if they do not account for interregional transactions of energy-related goods.

A framework for evaluating current models is presented in the next section. It identifies features that should be included in a comprehensive and logically consistent regional energy model. In Section 3 the features of the eight energy models reviewed are summarized. These models are compared and their strengths and weaknesses are discussed. Areas for future research are identified and the analytical techniques incorporated in each model are delineated. In Section 4 potential uses of these models are discussed.

2.0 FRAMEWORK FOR EVALUATING REGIONAL ENERGY MODELS

An evaluation of energy models cannot be conducted without first defining the criteria on which the evaluation is based. Three sets of criteria are used: model comprehensiveness, economic aspects of the model, and model capabilities. The model comprehensiveness section defines the scope of the models in terms of the spatial, energy-supply, and energy-demand details. The economic aspects of the models considered are the determinants of total demand and supply, interfuel competition, and interregional competition. The ability of a model to simulate the effects of policy or technology changes are considered in the capability section. These three sets of criteria, therefore, define the eight characteristics used to evaluate each model. These characteristics are listed in Table 1. In this section, the criteria used and the reasons why these model characteristics are considered desirable are presented. To aid in the discussion of the importance of these criteria, a schematic of an energy model is provided in Figure 1.

TABLE 1. Criteria for Evaluating Energy Models

Criteria	Examples
Comprehensiveness	
Spatial Detail	States, census regions, nation
Supply-sector detail	Coal, oil, natural gas, high- and low-sulfur fuels
Demand-sector detail	Industrial, transportation, lighting, space heating
Economic Aspects	
Total demand and supply determinants	GNP, income, energy prices, reserves
Interfuel competition	
Interregional competition	
Capabilities	
Policy actions	Import quotas, environmental regulations, conservation
Technology changes	Solar energy, coal gasification, electric cars

The first set of criteria (model comprehensiveness) is important because the models should be useful in assessing the regional and sectoral impacts of policy and technology changes on energy production and consumption. Without adequate detail in the model, these separate effects cannot be evaluated. Furthermore, the impacts estimated with a highly aggregated model may err significantly because they do not account for variations in regional and sectoral markets.

The minimum level of spatial detail is not easily defined since it depends in part on the policy under consideration. For example, the environmental impacts of alternative energy consumption patterns may be highly localized within a particular state. In this situation a state-level analysis may be insufficient. On the other hand, some technology changes or federal policy actions may have significant regional impacts at only the "Census Region" level of aggregation. Because of the importance of spatial detail in many analyses and the varying levels of detail required, and because it is generally easier and more accurate to aggregate data, a model that has greater than a Census Region level of detail is desired.

Because there are practical cost and data limitations, a model that considers coal, oil, and natural gas as primary fuels, and electricity as a secondary energy source, is considered to have adequate supply detail. Without at least this level of detail, interfuel competition cannot be modeled. On the demand side, a model should include industrial, residential, commercial, and transportation demands. The industrial sector should include manufacturing, agricultural, and utility energy demands. These levels of detail are viewed as minimum requirements for a comprehensive energy model.

Since most energy-related policy actions or technology changes affect the energy market, an energy model should simulate market behavior adequately. The demand for nonenergy goods affects energy demands in two ways: (1) the demand for energy is in part a derived demand resulting from the use of energy as an input in the production of goods and services; and (2) energy and nonenergy goods compete against each other; i.e., given a fixed budget, the more people spend on energy, the less they will be able to spend on nonenergy goods.

Because economic prosperity is strongly related to energy prices, an energy model should reflect this relationship. That is, the model should consider the feedback effect of energy prices on the demand

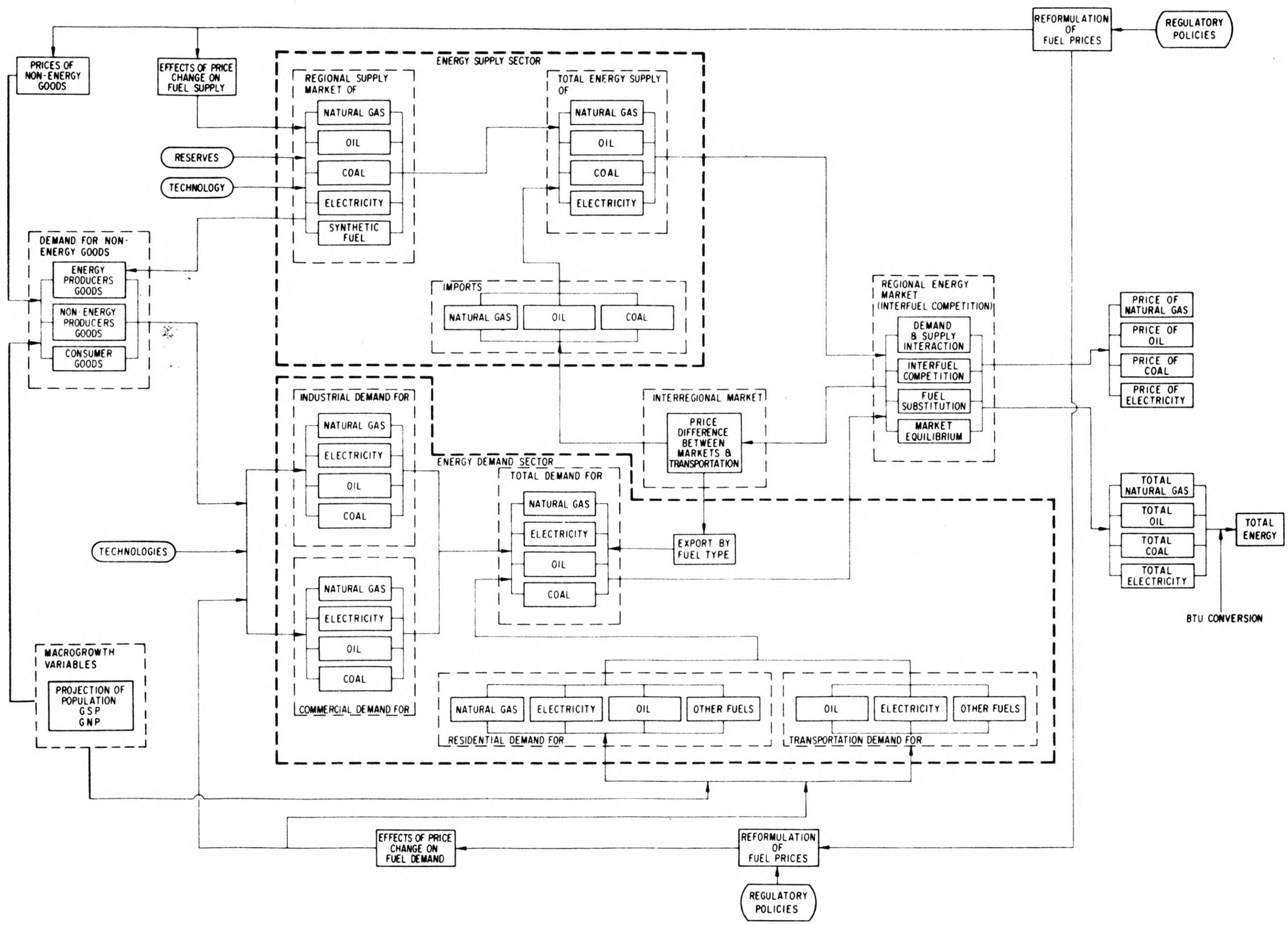

Figure 1. Regional Energy Model System

for goods and services (as shown in Figure 1). Energy prices also affect levels of exploration, the economic feasibility of alternative production processes, and ultimately the supply of energy. These relationships should be explicitly accounted for in a comprehensive energy model.

Given the total demand and supply of energy, market shares of each fuel must be determined. Market shares are a function of relative fuel prices, stocks of capital goods, consumer preferences, and other variables that affect interfuel competition. Because the availability of fuels at a given market price varies significantly between regions of the country, the interfuel competition aspects of the model may be meaningful only if the model is regionalized. To emphasize this point, the interfuel competition aspect of the schematic model in Figure 1 is labeled as a regional energy market.

Interfuel competition is an essential part of any model used to analyze the impacts of oil import quotas, sulfur dioxide control regulations, strip-mine reclamation regulations, deregulation of natural gas prices, coal gasification technology advances, and other perturbations of the energy market that will affect the price of some fuels more than others. A model that does not take into account market adjustments resulting from these policies may estimate incorrectly their relative advantages or disadvantages.

Equally important to interfuel competition is interregional competition. Differences between regions include costs of production, quality of the fuels, and proximity to markets. Production costs may be different because of the type of mining used (strip- vs. deep-mine) or the depth or level of depletion of the reserve. Varying production costs affect the prices suppliers are willing to accept for their products. The quality of the fuel is important when environmental regulations are being considered or when the production process dictates special fuel characteristics. In particular, the heat values and sulfur and ash contents of the fuels are important. Because of environmental regulations, some sources of energy cannot be used without expensive control equipment, the net effect being an increase in the cost of using those sources of energy. Proximity to markets has been a major factor in regional differences in fuel consumption patterns. In some instances, transportation costs represent the major portion of the selling price of a fuel. To be capable of simulating interregional competition, the model must consider all competing regions, hence a national or state model would clearly be inadequate for this purpose.

The final set of criteria, model capabilities, deals with the problems to which the models can be applied. Policy options, which consist of regulatory, funding, and priority-setting decisions, as well as technology advances, will affect energy supplies and demands and thus the price that must be paid for energy. In this analysis, a model that does not endogenously simulate the effects of policy or technology changes is classified as one that does not have this capability. Some models can simulate the energy impacts of changes in the economy if the resulting price, cost, demand, GNP, etc., changes are provided exogenously. Such models are easily adapted for policy analysis if auxiliary programs are constructed to simulate the impacts of the policy on these independent variables. Finally, some models may have restrictive assumptions that preclude their use for policy analysis.

3.0 STRENGTHS AND WEAKNESSES OF EXISTING ENERGY MODELS[9]

In Section 2, eight criteria were defined for reviewing the energy models. None of the models reviewed satisfy all of these desirable attributes. Unfortunately, a simple summary table identifying the criteria satisfied by each model cannot be constructed because some of the models only partially satisfy some of the criteria. Additionally, because the approaches used in the models differ, a comparison of models satisfying the same criteria becomes difficult. Finally, a complete evaluation of these models cannot be made without information on their accuracy, ease of use, computational efficiency, and other operating characteristics.

Although simple comparisons cannot be made, two summary tables have been constructed. These tables will facilitate the discussion on the state of the art of energy models and help identify areas of future research. Table 2 summarizes the economic aspects of the models. It provides a quick check of the approaches used and some of the primary data sources or driving parameters required to simulate the economic behavior within the model. Table 3 summarizes the comprehensiveness and capabilities of the models. The table identifies the principal independent variables used to drive the model when policy or technology changes are simulated. In addition, the types of perturbations that the model can simulate endogenously are listed.

Total energy demands either are provided exogenously or are estimated using trends, econometric techniques, or input/output techniques. Energy consumption is usually assumed to be a function of GNP, income, population levels, production output, or other demographic-economic variables. Energy prices (or an energy price index) are used as determinants of energy demands in the Kalter, PIES, H-J, and EMSAS models. However, none of the models explicitly considers the impacts of energy costs on the general economy. The H-J model can account for energy price effects on the economy if the prices calculated in its interindustry model are fed back into its macro-growth model as a change in the price deflator factors.

The demand for energy will change as energy costs change due to both substitution and income effects. Most models do not separate these effects. Of particular importance is the income effect and its influence on the rate of growth of the economy. Since increases in energy costs will most likely increase the costs of most commodities, the buying power of the consumer will be reduced. If this reduction is significant, it will result in a slowing down of the economy, reducing the derived demand for energy, and tending in turn to reduce energy prices. Therefore, if the income effects are not properly accounted for, a model will overestimate the demand and the price of energy. This is an area in which the state of the art could be improved.

The factors that determine the supply of fuels such as the levels of reserves, development and production costs, and exploration activities are not explicitly

TABLE 2. Summary of the Economic Aspects of Energy Models

MODELS	ENERGY DEMAND	ENERGY SUPPLY	INTERFUEL COMPETITION				INTERREGIONAL COMPETITION	
			Method	Market Lags (Dynamics)	Sectors	Fuel Prices	Method	Transportation Cost
Battelle Columbus - EPA Energy Quality Model	NPC's forecast for U S AQCR forecast taken from 1973 study by M C Cook Sartoreus and Company Other exogenous sources	Stepwise supply function applying the "minimum acceptable selling price" concept No exploration	Linear Programming	Power Plants constrained to present fuel use capabilities	Electric Utilities	Minimum acceptable selling prices are provided exogenously and adjusted upward based on shadow prices obtained from LP model	Linear programming (Objective function minimizing total systems energy costs)	Rates provided exogenously
Baughman's Dynamic Energy System Model	Demand by sector provided exogenously	Parametric engineering supply functions Exploration activity provided exogenously	Log linear equation which is price sensitive (Partly econometric and parametric)	Total demand assumes that some consumers are "locked in" to particular fuel, i e , demand for fuel is not price sensitive Supply model assumes exponented delay functions	Electric Utilities Residential/ Commercial Industrial	Equals point on supply curve corresponding to a given demand for each fuel	Not considered	Assumes that costs are constant multiples of supply prices of each fuel
Brookhaven NL Models ● Basic	Exogenously provided from other studies, extrapolation, or user's assumption	Exogenously provided from other studies	None	Not considered	Not considered	Exogenous	Not considered	Rates taken from FPC 1970 <u>National Power Survey Report</u>
● Modified	Same as above	Exogenously provided elasticity of supply (presently set at .5)	Linear Programming	Assumes no fuel conversion until capital stock has reached a given age	By functional activities (end-use) of Residential/Industrial Electrical Utilities	Derived from exogenously provided supply functions and shadow prices of LP model	Not considered	Rates taken from FPC 1970 <u>National Power Survey Report</u>
Energy Management Simulation and Analysis System (EMSAS)	Based on trends or exogenously provided (for industrial sector, it can be estimated using price sensitive econometric equations)	Parametric engineering - simulation equations (oil, natural gas) Exogenous (coal) Exploration is price-sensitive, probability of success based on historical trends	Trend analysis Econometric Market share equation (Varies by sector)	Portion of demand is assumed to be market sensitive This portion is provided exogenously Gas and oil supply models allow for lag between time when they are committed to production	Industrial Residential (single unit homes) Electric Utilities	Future prices trended or provided exogenously	User determines interregional flow of energy	Rates provided exogenously
Hudson-Jorgenson Model (H-J)	Input-Output and Macro Growth Model (technical coefficients and final demand components estimated by econometric equations)	Exogenously provided from other studies I/O coefficients	Econometric equations	Macroeconomic model is dynamic Comparative statics	Agriculture, manufacturing, transportation, communications, coal mining, crude petroleum and natural gas, petroleum refining, electric utility, and gas utility as intermediate demand, and residential, government, and commercial as final demands	Market clearing prices dependent upon demand and supply conditions	Not considered	Not considered
Kalter's Parametric Model	Dynamic parametric equation	Dynamic parametric equation	Parametric equation (substitution occurs if fuel prices differ by fixed percentage)	Assumes short-run and long-run elasticities for demand and supply (with response rate)	All sectors simultaneously	Market clearing prices dependent upon demand and supply conditions	Not considered	Not considered
Project Independence Evaluation System (PIES)	Econometric equations	Modified NPC parametric equations used to calculate the "minimum acceptable selling price" by the discounted cash flow technique (oil, natural gas) Step function where price is the "average minimum acceptable selling price" (coal) Exploration activity for natural gas and oil is provided exogenously	Market share equation (linear logit) Linear Programming	Econometric demand models developed with long-run and short-run elasticities	Residential/Commercial Industrial (Market Share) Electric Utilities (Linear Programming)	Equals market clearing price where demand equals supply	Linear Programming (objective function minimizing total systems energy costs)	Rates provided exogenously or determined by Task Force
Wisconsin Energy Model (WISE)	Trend analysis Engineering, parametric models User defined	Exogenous	Assumed change in energy intensiveness coefficients (Industrial) Assumed mixes of fuel (Electric Utilities)	Explicit consideration of age of capital equipment	Industrial Electric Utilities	Published prices from various sources	Not considered	Not considered

TABLE 3. Summary of Energy Model Comprehensiveness and Capabilities

MODELS	SPATIAL	SUPPLY	DEMAND	POLICY		TECHNOLOGY	
	Level	Fuels	Sectors	Type	Independent Variables Affected	Type	Independent Variables Affected
Battelle Columbus - EPA Energy Quality Model	92 Supply districts of fuels 233 AQCR demand region	4 grades of coal by sulfur content Natural gas Distillate and residual oil	Residential/Commercial/ Industrial Electric Utilities	SO_2 regulations	Supply availability Control costs	Power plant SO_2 Controls Fuel production technology improvements	Control costs Fuel prices
Baughman's Dynamic Energy System Model	U S	Coal Natural gas Oil Nuclear Hydro	Residential / Commercial Industrial Transportation Electric Utilities	Directly affecting price (eg , tax, tariff)	Price	Directly affecting price	Price
Brookhaven NL Models ● Basic	U S N Y City	Coal Natural gas Oil (distillate, residual, jet-fuel, gasoline) Nuclear Hydro	Residential Commercial Industrial Transportation (by end-uses) Electric Utilities	Parametric reduction of appliance or boiler efficiencies	Efficiencies	Parametric changes	Technology Trajectories
● Modified	U S	Same as above	Same as above	Environmental regulation Directly affecting price	Constraints Price	Directly affecting cost	Price
Energy Management Simulation and Analysis System (EMSAS)	State (Industrial demand) Census Region demand Supply estimates on national basis which are allocated to "fuel districts"	Coal (only utility usage) Natural gas Oil Nuclear Hydro	Residential/Commercial Industrial (2-digit SIC) Electric Utilities Natural gas feed stocks	SO_2 regulation Directly affecting price (e g , tax, tariff)	Price Control Costs	Directly affecting price Sulfur control technology	Price Costs
Hudson - Jorgenson Model (H-J)	U S	Coal Natural gas Petroleum Nuclear Hydro	9 intermediate sectors Personal consumption Government Investment Exports	Directly affecting price (e g , tax, tariff) Directly affecting macroeconomic variables	Energy price Real income	Directly affecting price	Price Productivity Real income
Kalter's Parametric Model	U S	Coal Natural gas Oil	All sectors simultaneously	Directly affecting price (e g , tax, tariff)	Price	Directly affecting price	Price
Project Independence Evaluation System (PIES)	U S and Census Region Demand Supply districts of fuels	Coal Natural gas Oil Nuclear Hydro Synthetic fuels, Solar and Geothermal	Residential/Commercial Industrial (2-digit SIC) Transportation Electric Utilities (some end-uses)	Directly affecting price (e.g , tax, tariff)	Price	Directly affecting price	Price
Wisconsin Energy Model (WISE)	State of Wisconsin	Coal Natural gas Oil (distillate residual, kerosene, LPG, gasoline) Nuclear Hydro	Residential Commercial Industrial (2-digit SIC) Transportation Electric Utilities Agriculture (by end-uses)	Parametric change in engineering efficiency Regulations such as building codes	Energy intensiveness coefficients	Changes in engineering efficiency	Engineering parameters used in demand sub-models

considered in the Energy Quality, BNL Basic and Modified, H-J, Kalter, and WISE models. Although all of these models assume that supply will be sufficient to meet demand, the WISE and Basic BNL models do not relate supply to fuel prices. The others simulate the response of supply to price parametrically rather than econometrically. In general, these models implicitly account for changes in supply by variations in fuel prices, a minimum acceptable selling price, the ratio of reserves to production, and/or I/O coefficients. Some of these variables, however, are provided exogenously as indicated in Table 2.

The Baughman, EMSAS, and PIES models explicitly consider the effect of exploration and development on future production of energy resources. The Baughman and PIES models exogenously determine exploration activity levels. EMSAS estimates the impact of prices, and other variables, on exploration activity for oil and natural gas, using historical relationships and parametric analysis.

Electricity supply determinants are considered in all of the models, except the Basic BNL and Energy Quality models. The other models assume that supply will meet demand and, therefore, the required production capacities are determined by estimating electricity demands. The PIES model incorporates an LP Program that chooses the least-cost combination of existing and incremental plant capacity to meet the demand for electricity. Although many of the models estimate electricity demands as a function of the prices of electricity and other fuels, only the H-J model considers the effects of fuel prices on the price of electricity.

As indicated in Table 2, only the WISE and the Basic BNL models do not consider interfuel competition. The most popular approaches for simulating interfuel competition are econometric techniques and linear programming. The primary variables used to determine market shares are fuel prices, which are provided exogenously or are based on trends in the EMSAS model. The other models that consider interfuel competition generate fuel prices endogenously through the supply and demand interface. The interfuel competition aspects of some of the models are restricted to a few sectors as shown in Table 2. Although Kalter's model considers all economic sectors, the model only calculates aggregate market shares; i.e., the market shares within each sector are not calculated.

A common problem in analyzing the dynamics of interfuel competition is accounting for market lags. These occur, in part, because capital equipment is often replaced when one form of energy is substituted for another. The choice between fuels must, therefore, include consideration of the capital replacement costs in addition to fuel prices. None of the models reviewed explicitly simulates the capital replacement decision. Most of the models account for market lags by separating demand into fixed and market-sensitive components in which the fixed component is a function of the characteristics (usually age) of capital stocks, or by estimating long-run demand elasticities, which implicitly account for these lags. Lags on the supply side are simulated using long-run elasticities, delay functions (e.g., exponential), or parametrically defined delays in production. Because of the importance of market lags in forecasting future energy demand and supply, more emphasis should be devoted to this problem.

Another area in which the existing models could be significantly improved is in dealing with interregional competition. Only the Energy Quality, PIES, and EMSAS models are multiregional. The Energy Quality model is limited because it considers competition between suppliers as independent of demand, i.e., demand is fixed. EMSAS, although regional, does not consider interregional competition. Therefore, only the PIES model attempts to simulate the effects of interregional competition from both the demand and supply sides.

Interregional competition is modeled in the PIES and Energy Quality models by using linear programming to minimize the delivered price of fuels. The key parameters in the model are transportation costs. The PIES model allows for different modes of transportation for each fuel. The Energy Quality model assumes that only one mode of transportation will be used for each fuel.

The most common levels of regional detail are national and census regions. The EMSAS model does estimate industrial energy demands by state and the Energy Quality model has a substate level of detail. The primary deterrent to regionalization is the lack of region-specific data. Some model structures, however, are more conducive to regionalization than others, because of their relative simplicity or less restrictive data requirements. Econometric and parametric models, such as the Basic BNL, Kalter, WISE, Baughman, PIES, and EMSAS models, are the easiest to regionalize. That four of these models have been used on a regional level exemplifies this fact. However, these techniques are not as conducive to modeling interregional flows of energy. Since this is primarily a transportation problem, a linear programming formulation, as used in the Energy Quality and PIES models, seems appropriate. The most difficult models to regionalize are those that use input/output analyses. These are the H-J and the Modified BNL models. Therefore, before these approaches should be adopted for regional studies, the advantages of using I/O must be weighed against the difficulties (data acquisition, model efficiency, etc.) of regionalization.

Because of the selection process used to identify models, most of the models surveyed have good fuel supply detail. Except for EMSAS, all of the models consider coal, oil, and natural gas as primary fuels and electricity as a secondary source of energy. EMSAS has a strong natural gas bias, but does consider oil, coal, or electricity for some sectors. The weakest aspect of the model is related to coal.

On the demand side, very few of the models are complete. The three demand sectors missing most often are the transportation, fuel oil and natural gas feed stock, and agricultural sectors. The H-J model considers most sectors, but the industrial sector is not sufficiently detailed. The EMSAS, PIES, and WISE models have good industrial (2-digit SIC) detail. EMSAS also provides for natural gas feed-stock demands; the BNL and WISE models have the best, and PIES has some end-use detail.

Although many of the authors claim their models are useful for evaluating energy policies or technology changes, these claims are often overstated. If the effects of a policy or technology change on fuel prices, costs, and availability are known, then some of the models can be used to estimate the ramification of these changes on the energy system. Only the Battelle-EPA and EMSAS models have subcomponents that simulate the effects of policy on these key parameters. The Battelle-EPA model is limited to sulfur dioxide regulation of fuels. The EMSAS model considers sulfur dioxide regulations and also has provisions for simulating the impacts of new technology. Most of the models, however, are capable of analyzing the impacts of policies that directly affect energy prices, such as taxes and price regulations. Others can simulate the effects of policies parametrically. These models with the least evaluative capabilities are the Basic BNL, Kalter, and WISE models. These models can be used to conduct only parametric studies and some regulatory policies. Yet, with sufficient modification, the BNL and WISE models can be quite useful because of their greater end-use detail.

4.0 SUMMARY AND CONCLUSIONS

This review should clearly indicate that none of the existing energy models is capable of evaluating all of the present energy issues. Furthermore, development of a tool of that degree of comprehensiveness is not recommended. To begin with, the task may be impossible. Even if it were possible to simulate the impacts of all existing energy issues, it is unlikely that all future issues could be evaluated with the model. In addition, a large comprehensive model designed for multipurpose use would most likely not only be economically inefficient, but its very complexity would make more difficult the interpretation of its results. Rather than developing a single multipurpose energy model, we recommend that a library of techniques be developed and maintained. In this way the analyst will be able to select the technique that best fits his present needs, thus avoiding excessive data collection, computer, and analytic costs.

This library should consist of two types of models. The first, referred to as "local impact models," provides a great deal of detail on end-use demands for energy; production processes of supplies; and/or environmental, social, political, and economic impacts. These models can be applied to state or substate areas. Energy requirements under a given national policy or technology scenario are provided exogenously to these models. The function of the microscale models is to simulate the impacts of decisions that affect only local markets, and to estimate the impacts of national policy or technology changes at the local level, where it has the most meaning. The second class of techniques, referred to as "national synthesis models," are designed to estimate energy supplies and demands as a function of decisions that affect the national energy market. These techniques should be multiregional and should include the entire domestic energy market with at least the Census Region level of detail provided. Three of the eight models reviewed can be classified as local impact models. These are the WISE, Basic BNL, and Energy Quality models. The other five are national synthesis models.

These two classes of models could be coupled in a number of ways. As suggested above, the national synthesis models could provide regional energy supply and demand estimates consistent with national goals and policies and consistent with each other. That is, the output of the national synthesis models would be used as inputs to the local impact models. If, however, a regional policy were expected to have an impact on the national energy market, then the output of the local impact models would be used as inputs into a national synthesis package to estimate the implications of local policy on the national energy market. In other words, the models could be used in conjunction with each other as dictated by the problem being analyzed.

This review indicates that existing models are deficient in two important areas: (1) consideration of interregional competition, and (2) integration of energy supply and demand forecasts with economic growth. None of the models reviewed is truly multi-regional, i.e., competing supply region interactions and competing demand region interactions are not considered. The PIES model is the closest to having this capability. In respect to the latter point, the effects of energy prices on economic growth are not considered in any of the models, and only a few provide for the effects of energy prices on total energy demands. The most advanced model in this respect is the Hudson-Jorgenson model. If future research efforts are devoted to these issues, then the value of energy models will be greatly enhanced.

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BIOGRAPHY

Alan S. Cohen received his Ph.D. in Industrial Engineering and Management Sciences from Northwestern University in 1971. He is presently an Environmental Systems Engineer at the Energy and Environmental Systems Division, Argonne National Laboratory, and project director for the Environmental Pollutants and the Urban Economy Program sponsored by the National Science Foundation. Other work has involved air pollution, water quality and solid waste management planning for the State of Illinois and major research responsibilities with energy, land use and socio-economic projects. Dr. Cohen has recently coauthored a book entitled Residential Fuel Policy and the Environment, Ballinger Publishing Co., Cambridge, Mass. (Coauthors, G. Fishelson and J.L. Gardner)

Kenneth W. Costello received his B.S. and M.A. degrees in Mathematics and Economics respectively from Marquette University. He has been an Assistant Economist at Argonne National Laboratory since 1974. His previous research areas include the development of an econometric model for Softwood lumber industry, and a supply analysis of the western coal industry. His present research centers on the utilization of econometrics for forecasting regional energy demand.

A VEHICLE FOR IMPROVING ENERGY MANAGEMENT FOR BUSINESS AND INDUSTRY

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Abstract

A new technical assistance program focusing on the area of energy management has been developed by North Carolina State University for business and industry. This paper describes the operation of the program and presents some typical recommendations made to industry. The impact of the energy crisis on small industry is discussed and future plans for addressing this problem are presented.

1. INTRODUCTION

The Industrial Extension Service (IES) of the School of Engineering of North Carolina State University has developed a new program of technical assistance in the area of energy. This program is designed to assist small business and industry in improving their utilization and management of energy resources.

Implementation of this program is being accomplished in two phases. The first phase -- called the "walk-through assessment" -- consists of an IES staff member making an on-location, qualitative audit of the sources of major energy losses within requesting companies. This is followed by a written report which outlines the major corrections needed to reduce energy consumption and improve energy management. The "walk-through assessment" program has been in operation for about nine months. During that time, over sixty organizations have been visited. The results to date are encouraging.

In the projected second phase of the program, the major energy losses will not only be identified but measurements will be made to help assess these losses. Based on this information, an analysis will be made and the results summarized in a final report, along with recommendations for reducing energy losses, the approximate cost for implementing the recommendations, and the expected savings. Throughout both phases of the program, the assisted companies will be encouraged to use the National Bureau of Standards Handbook 115 as a guide in establishing and maintaining their own energy management program.

This service is offered at no charge to all North Carolina business and industry by the Industrial Extension Service. However, the focus of the program is on small companies, since these companies -- with their limited technical and financial resources -- are least able to cope with the problems associated with energy management. It is envisioned that this program will be the beginning of a series of extension activities (extension education, referral services, and additional technical assistance) to aid North Carolina industry in reducing its energy needs.

2. WALK-THROUGH ASSESSMENT PROGRAM

2.1 APPROACH

A highly qualified engineer with broad, energy-related experience visits a facility and, accompanied by company representatives, makes a thorough plant tour. During this walk-through, the company representative usually describes the plant operation -- and during the ensuing questions, explanations, and discussions, new perspectives and opportunities for saving energy are often uncovered. The plant visit (which includes the walking tour and meeting with various people) usually takes from 1½-3 hours depending upon company size, complexity of operations, and the ability of company representatives to convey information. Consequently 2 or 3 companies can be visited in one day if they are located close together.

2.2 TYPES OF COMPANIES

Based on experience in the walk-through assessment program, the companies visited can be conveniently subdivided into three broad groups with respect to their energy conservation activities.*

(1) Large companies (>500-1000 employees), technically intensive with full-time, qualified staff concerned with energy conservation

(2) Intermediate to large size companies (>250 employees) with one individual who, among other duties, is responsible for energy conservation activities (Efforts at energy conservation are not based upon measurement or data but usually consist of the application of a checklist of ideas.)

(3) Small to intermediate size companies (<250 employees) with no one qualified to work in energy conservation or employed in that capacity

The last two groups of industry predominate in North Carolina (and thus in the companies visited) and consequently can profit from a program like the "walk-through assessment" program.

Since companies request the "walk-through", their representatives are usually very helpful and appreciative during the plant tour. Occasionally a plant tour is conducted by someone other than the requesting manager, and that person may at times appear defensive. Also, in some instances, the company environment (both internal and external) is either so polluted or processes so deteriorated that rational technical and economic priority dictate that they defer energy conservation considerations until other problem situations are resolved.

2.3 REPORTS TO COMPANY

After the in-plant visit, a report is written for the company to summarize observations and recommendations. The report might include the results of observation or engineering calculations, information from various references, or referrals to people or agencies. The report is written in letter form and consists of a series of paragraphs under various headings. A report varies in length from 2-6 single spaced, type written pages and usually takes 3-5 hours to write.

The following list represents a cross-section of recommendations from typical reports:

2.3.1 Recommendations pertaining to the establishment of energy conservation programs

<u>Record of energy usage</u>. As a prelude to a formal energy conservation program you should begin to keep plant and departmental records of energy usage (fuel, electricity, water, steam, etc.) on a monthly basis and compare these to production levels. This information is not difficult to

* The bulk of the facilities visited are manufacturing plants. A few commercial buildings (insurance, shopping center) and a hospital have been visited but are excluded from the above.

record and will give you a valuable perspective on the cost level and trends involved in energy usuage per unit of production.

Establishment of a company-operated energy conservation program. The most important step in conserving energy is the establishment of an ongoing energy conservation program, with a program director who is given top management support. Top management support is essential in obtaining employee cooperation and participation. The essential elements of such a program are given in a recent government publication, "Energy Conservation Program Guide for Industry and Commerce" -- NBS Handbook 115 -- put out by the U. S. Department of Commerce.

I believe your organization is totally committed to energy conservation, and now simply needs to establish and publicize an official program. It will prove advantageous if all employees of the plant are conscious that there are ways in which they can help. Most employees probably will not consider the "big picture," tending to feel that energy conservation ends at the front door. If energy conservation is to work, employees must be reminded regularly about energy conservation ideas pertaining to both the company and their lives outside of working hours. Some suggestions could be implemented with some modification in the employees habits. Suggestions falling in this category relate to: bath water temperature, dripping faucets, room temperature levels, deactivation of electrical equipment when not in use, reduced use of products manufactured from petroleum or wood, use of the refrigerator, and policies on washing. Interesting suggestions which require some equipment modification are (a) reuse of wash water for flush toilets, and (b) replacement of commodes with urinals in men's restrooms.

To more fully involve and motivate employees in the business of energy conservation, you might want to put up ENERGY SAVING SUGGESTIONS boxes throughout the plant, and then give awards for those ideas which result in substantial savings.

NBS Handbook 115 indicates that one of the first steps of any energy conservation program is keeping a monthly record of energy consumption. For employee information and motivation, you could place large bar graphs of this information in conspicuous locations throughout the plant.

2.3.2 Recommendations pertaining to changes in operations and/or procedures

Open doors. During the walk-through, we found a number of open doors leading to the outside atmosphere. As you know, large quantities of conditioned air (heated or cooled) escape through these open doors -- and this lost air represents a significant energy (and dollar) loss. I realize that the "state" of a door is the responsibility of the manager whose group is working in the area, but, somehow, these employees must be made aware of the significance of this actions. I understand that this is a difficult management problem, but it must be addressed since heating and air conditioning account for a large percentage of your energy bill.

Control of thermostats. As you know, employee control over individual thermostats can create serious inefficiencies in your heating and/or air conditioning systems. For obvious reasons, you cannot remove these thermostats. Some companies have gotten around this personnel problem by rewiring the system and placing the actual control in some other location.

Spring and fall operation. During the Spring and Fall, the climate in eastern North Carolina is quite mild. Rather than heating and/or air conditioning during these seasons, you should consider ventilating your entire plant with outside ambient air. The amount of fresh air introduced into the plant would be controlled by roof mounted exhaust fans operated in conjunction with certain outside doors. This policy has been adopted by a number of companies in your area and has resulted in significant energy savings.

Fix/maintain leaks in air, water, steam lines. I realize the difficulty of starting and maintaining a periodic maintenance program aimed at the above, particularly in the ____ manufacturing operation and in the summer, however, I think you may be overlooking a considerable savings. For instance, Charles Norton of General Motors in a paper entitled, "How to Survey Your Plant for Energy Waste" reported first year savings in an energy conservation program as follows:

> "In 1972, ona production unit basis, Livonia's water consumption declined 30%, steam was reduced 23%, natural gas 19%, and electricity 3%.
>
> It is important to note that the reductions achieved to date are not the result of technological advances or major rework and redesign of our facilities and equipment... To date we have relied upon and obtained quite satisfactory results from some rather simple but vigorous maintenance and plant engineering efforts directed at finding and fixing the energy leaks in our plants."

Similarly there are a number of examples (ECO's) in NBS Handbook 115 that indicate the monetary savings of repairing leaks in compressed air lines, steam lines, faulty steam traps, etc.

Good housekeeping. As you know, effective energy conservation is the accumulation of numerous small steps -- in a sense, it often comes down to good housekeeping. It involves such items as repairing small steam leaks, replacing insulation that has fallen off the toaster, insulating all hot water and steam lines (no matter how small), etc. In the industrial setting, I realize that most attention must be given to maintaining or improving production. However, in this day of continually increasing energy costs, I believe considerably more attention should be given to such mundane tasks as equipment maintenance --

more specifically, all equipment should be kept at an energy efficient level of operation.

2.3.3 Information from other sources

Ventilation hoods-waxing area. The one hood you have here I believe is undersized. Enclosed is a copy of the recommended ratio for a canopy hood. Note the hood should overhand 40% of the height the hood is above the process.

In most cases you should install an individual ventilation pickup at the source rather than use a general overhead fan. Consequently, I would put a hood over the small waxing machine.

2.3.4 Recommendations pertaining to building modification

Plant room (and die room) - install suspended ceiling. Particularly in the plant room where environmental conditions are getting high (65% relative humidity, 76°F temperature) you should install a suspended ceiling. You don't need the overhead space and a new ceiling will reduce the room volume by around 40% and make it much easier and cheaper to maintain appropriate conditions in these rooms.

Shipping/receiving docks. You lose a tremendous amount of "heat" in the winter by having loading docks adjacent to the building which are open and prohibit the use of "dock curtains," etc., to reduce infiltration of air. You could do one of two things. First, you could build an enclosure on the docks out to the edge so that they have a typical entry way on which you can install dock curtains. Or, second, you can remove the loading docks so that the trucks can back up to the building and be shielded with dock curtains.

Exposure between air conditioned and un-cooled areas. You have a number of situations where air conditioned areas share a common open side with un-air conditioned areas in which there is high process heat release. You exhaust from the unconditioned areas to remove fumes and to reduce the temperature levels but, in turn, attempt to keep the windows closed. This is classic example of "operating at cross purposes."

It is my opinion that you should consider isolating conditioned areas from unconditioned areas, say, with movable partitions and installing considerably more ventilation capacity in the heat release areas. In this way you could open all the windows in these areas in the summer. Hopefully, the result would be a very large reduction in the cost of air conditioning, a small increase in fan electrical consumption, and cooler and happier people in both areas. Of course I think you should seek information from other ________ plants operating under similar circumstances as well as from air conditioning and ventilation consultants.

2.3.5 Recommendations pertaining to process changes

Preheating combustion air. Another approach to reducing the radiant heat loss from the tunnel surface to the atmosphere is to enclose part of that surface (wall) with a pressurized air duct. In effect, what I am suggesting is that the surface and duct form an air preheater -- and the resulting heated air be used as combustion and/or dryer air. Two regions of the furnace envelope that appear particularly suited for this approach are the undercar zone and the burner zone. Both zones would have to be pressurized -- such that the car bearings and kiln burners are kept reasonably cool.

Most side-fired units use ambient air as combustion air to the burners. If this combustion air were heated to 550°F in the preheaters suggested above, the following energy savings would result:

FUEL: Bunker C oil
HHV = 152,000 BTU/gal or 6.58 gal/10^6 BTU
Assume: 20% excess air on oil firing → 900 lb. air/10^6 BTU. For each 10^6 BTU fired, you could expect to save approximately 100,000 BTU or .66 gallons of oil if the combustion air were preheated to 550°F.

I'm sure you will agree that a 10% saving is significant.

Kiln stack temperature. Stack temperature is one of the most important variables which influence the energy efficiency of a tunnel kiln. Under your present operating conditions, the temperature of the flue gas leaving your stack varies from 450°F to 550°F -- which is much too high for efficient operation.

For oil firing, I would recommend a stack temperature of 325°F to 350°F. The minimum temperature limitation of 325°F is imposed by the fact that the flue gas contains condensable vapors that deposit on the stack duct work, in the liquid phase, if the plant temperature falls below the dew point. In the case of sulfur bearing oil, sulfur trioxide may be formed which, in the presence of the water vapor. may in turn form sulfuric acid. The dew point of flue gas containing this acid is much higher than if water alone were present.

For natural gas firing, a somewhat lower stack temperature can be tolerated.

2.3.6 Recommendations pertaining to the purchase of new equipment

Heat recovery systems. Since your present kiln exit temperatures are considerably higher than 325°F, you may want to consider a heat recovery system in the base of the stack. In selecting the heat exchanger appropriate for your facility, you should consider the following factors:

(1) How will the recovered heat be used?
Preheated combustion air → heat wheel, heat pipe, tubular airheat
Heated air for space heating → heat pipe or tubular air heater (heat wheels usually have some leakage associated with them)
Heated water for process or feedwater heating → economizer

(2) What is the terminal difference of the heat exchanger?
Terminal Difference = (Flue Gas Temperature Leaving Heat Exchanger) - (Fluid Temperature Entering Heat Exchanger)
Note: For effective utilization of heat exchanger surface, you should design for a terminal difference of +200°F.

(3) How large is the heat exchanger? Is sufficient space available? Will the existing structure support the heat exchanger?

(4) What fuels will be fired in the furnace? The resulting flue gas will effect
(a) the type of heat exchanger surface
(b) the surface spacing
(c) the tendency to plug the surface
(d) the need for soot blowers
(e) the tendency to corrode the heat exchanger surface.

(5) Compare the cost of each type of heat exchanger on an equal recovery basis. Consider both equipment and installation costs.

(6) Is the heat exchanger compatible with existing equipment? Can the existing fans handle the additional draft loss and/or air pressure drop?

(7) What additional operating costs will the heat exchanger create? For example -- what is the draft loss across the heat exchanger and what are the operating energy costs resulting from this additional draft loss?

(8) How much energy (and money) will the heat exchanger save? As a general rule, you can expect to increase the boiler efficiency by approximately 1% for each 40°F reduction in stack temperature.

3. MEASUREMENT PROGRAM

This second phase of the overall IES energy assistance program is projected for the future. Funds are being pursued with which to buy instruments to make measurements in the key areas of combustion, stack temperature, heating, ventilating, lighting, and electrical motors. In this case, the visiting engineer would spend a minimum of one day in a facility, observing operations, asking questions, looking at records, and making physical measurements. Based on this information, an analysis will be made and the results summarized in a report, along with recommendations and anticipated savings. Approximately two weeks after the initial inspection, the IES engineer will personally review the report with the company representatives and relate the losses to specific sections in NBS Handbook 115.

In addition to initiating an energy conservation plan, each company is requested to provide IES with a quarterly record of its energy consumption -- and when possible relate this consumption to production quantities (on an absolute or relative basis) and degree days. Because uniform record keeping, reporting and energy accounting are important factors in an effective energy conservation plan, this information should be readily available.

Six months after the initial measurement and walk-through survey, each company will be contacted by the inspecting engineer -- either by phone or visit -- to evaluate the company's progress in energy conservation.

4. CONCLUSIONS

Educational programs in energy conservation tend to be applicable to people knowledgeable enough in energy conservation to extend their own abilities. As a general rule, these programs do not reach the smaller industries that oftentimes function without trained engineers. Consequently, direct technical assistance is deemed to have the most immediate effect on the energy saving capability of small companies. Also it is hoped that the money saved will serve as an inducement to these companies to consider energy conservation more seriously and eventually set up their own on-going energy conservation programs.

There are many situations in the companies visited that are tremendously wasteful of energy and yet are simple and inexpensive to rectify. Many of these situations remain unknown, usually because the affected individuals are not aware of the technical concepts involved. Even in cases where energy waste is known, the manager of a small company is often reluctant to act -- simply because he is not technically informed and therefore uncertain of the possible consequences of his actions. This individual desperately needs competent technical assistance if he is to stay in business.

The IES program of direct technical assistance in energy conservation shows promise of being an effective means for identifying energy waste and promoting energy conservation.

5. BIOGRAPHIES

Dr. Herbert M. Eckerlin is Assistant Professor and Extension Specialist of Engineering Science and Mechanics at North Carolina State University. He received his B.S. in Mechanical Engineering from Virginia Polytechnic Institute and his M.S. and Ph.D. from North Carolina State University. Dr. Eckerlin has a broad range of industrial experience, including service with Virginia Electric and Power Company, Combustion Engineering, and Corning Glass Works. He has considerable industrial experience in the design and operation of special purpose type heat exchangers, is the author of a number of technical papers, and holds 11 basic patents in fluidics and heat exchanger design.

Professor Albert S. Boyers is Expension Specialist in the Department of Mechanical and Aerospace Engineering at North Carolina State University. He received his B.S.M.E. degree at Purdue University and his M.S.M.E. at the University of Illinois and has done further graduate work in engineering and economics at the University of Michigan. At NCSU, he teaches academic courses in mechanical engineering, and organizes, conducts, and teaches continuing education courses, and does technical assistance for industry in a broad range of areas. His areas of specialization are industrial ventilation, energy conservation, and value engineering. Prior to joining NCSU in 1968, Prof. Boyers worked at Cornell Aeronautical Laboratories and the Babcock and Wilcox Research Center. He has also taught at SUNY at Buffalo.

ENERGY MANAGEMENT IN THE FOOD STORE

Paul Adams P.E.
Hussmann Refrigerator Co.

Food store refrigeration is vital to the food distribution system and consumes much of the energy used in a supermarket. The manufacturers of food store display equipment have worked long and hard to develop new ideas in supermarket energy conservation. Hussmann's studies have uncovered a number of facts invaluable to anyone concerned with energy conservation in the supermarket.

The first fact is to realize that supermarkets are different from any other retail stores. They consume more energy each year per sq. ft. of store - or per customer - or per dollar sales than other retail stores and most commercial businesses.

Supermarkets are the only retail stores in which much of the merchandise is refrigerated. In a large supermarket, the equivalent of 40 tons of air conditioning is continually mixed into the store's environment, 24 hours a day, 365 days a year.

The human factor in supermarkets is unique also. Everyone is continually on the move. Only the checkers stay in one place, but work at a rapid pace. Customers are moving about dressed for the outside environment. Therefore, heating and air conditioning is not designed in the same manner you would for an office building.

Some stores are run as low as 65^{o} in the winter. Unlike other business establishments, supermarkets use less energy as the store environment is lowered in temperature and humidity.

According to industry figures, refrigeration equipment accounts for 1/2 of 1% of the total food store investment over the life of the store. Consequently, up until the energy crisis of 1973, refrigeration equipment was not a real matter of concern to the people who used it, even though it was "the tool of their trade." However, once energy costs approached the rental charges, refrigeration energy requirements began to receive the attention of top management. Today, energy conservation is the most important single subject in food retailing.

In order to better understand the various areas of supermarket energy use, Hussmann has been conducting a series of in-store tests at Tom Tarpy's Market in Columbus, Ohio. This store has a completely integrated heating, air conditioning and refrigeration system. It is continually monitored at 130 strategic locations. Data points include number of customers, door openings, atmospheric conditions, store environmental changes, refrigeration requirements and recording watt hour meters in addition to the main watt hour meter provided by the local utility company. We have refrigerant flow meters measuring all liquid refrigerant flow to refrigeration and air conditioning, as well as devices to record continuously the pressure differential between the supermarket interior and exterior. Many of these tests have been designed in conjunction with the Mechanical Engineering Department of Ohio State University which has conducted extensive tests in other commercial buildings. Other tests at Tarpy's include a full weather station to record ambient weather conditions.

All the information gathered at Tarpy's is stored in a computer and sent to Hussmann for analyzing. We can change store conditions and study the effects on the rest of the store's environment.

Our long range goal for these tests is to develop a program whereby, using the test data, we can provide our customers with a total annual energy estimate for use in their store design process. Using this estimate, they can adjust store construction and equipment to create the lowest possible energy requirements. Based on what we have accomplished to date, we can predict consumption within 10% and we hope to get that figure down to 5%.

Now let's turn to some energy saving facts we have gathered. Reclaiming the heat of rejection from the refrigeration compressors to heat the store is the simplest money saver available to the supermarket operator. It is accomplished by diverting hot gas from the refrigeration compressors into a coil installed in the air conditioning system. In the test store, heat reclaim replaced electric resistance heat, saving \$6,197 during the winter of 73-74. The store owner realized a 12% savings on his annual power bill simply by using this otherwise discarded heat of rejection.

Another proven energy saver has been night setback. Turning the store temperature down at night not only saves on heating, but also lowers refrigeration costs. As the store cools down, the load on the refrigeration decreases. Heat reclaim is required to make night setback effective to warm the store in the morning. Night setback works in summer and winter.

Air conditioning properly designed can use the cooling that spills from the cases to reduce air conditioning requirements.

In order to equalize distribution of cold air throughout the store, we have designed a network of return air ducts beneath open multi-deck cases to capture the cold air spill over and return it into the air conditioning system. In some cases, this "free air conditioning" can provide all the required cold air for the store.

In any case, it creates a more even environment for the store, reduces cold aisles in frozen food departments and helps equipment because the returned air is already dehumidified.

The amount of "free air conditioning" depends upon the size of the store and the type of refrigerators used.

Another area of savings is in anti-sweat heaters. These heaters represent 6% of an annual power bill but are not really needed when the store dew point is below 50^{o} or equivalent to 40% relative humidity and 75^{o}. Controls to turn off heaters when these conditions are met are now available.

Insulated night covers would seem to be a possible energy saver in the future. At night when the store is closed, these covers keep refrigeration inside the case and reduce the load on the refrigerator. However, without the proper type of refrigeration system, it is possible that the reduction in load can cause mechanical failure through short cycling or loss of oil. A controlled test at Tarpy's Market showed a potential of 8% annual savings with insulated night covers.

We began by stating that supermarkets are different from other retail establishments. Environmental criteria for other stores simply will not work for supermarkets. There is very little literature available on the food store environment, so owners are having to make their own way through the maze. Hopefully, this presentation will start you in the right direction.

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EFFICIENCY IN THE USE OF ENERGY HAS BEEN EFFECTED THROUGH INDUSTRIAL USE OF SUBSURFACE SPACE

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Our Nation, with its high standard of living made possible by industrialization, draws heavily on energy producing natural resources. Self reliance mandates the use of every measure of conservation in order to extend the yet finite supply of energy to meet our national needs. Efficiency in the use of energy has been and can increasingly be effected through industrial use of subsurface space. The use of mined rooms for industry and warehousing utilizes the natural stable underground temperature and the low coefficient of heat transfer existing naturally in the lithosperic materials of the subsurface environment. The small amount of energy usage required to adapt and maintain an underground site at temperatures compatible to industrial use as compared to the energy usage required to maintain identical temperatures in a surface structure results in a considerable net savings in energy. Missouri leads the nation in the variety and number of uses being made of the subsurface mined areas and is contributing modestly but significantly to self-reliance in our nation's use of energy.

The further study of subsurface space usage as an energy saving measure is indicated.

The industrial use of subsurface space within the natural climate and physical properties of in situ rock material is significantly contributing to the efficient conservation of energy. This method of saving energy has an even greater potential if applied to a wider array of subsurface uses and extended to other areas having compatible geology and geographic market situations. This paper draws on the Kansas City leadership in this field where for two decades the use of subsurface space has been successfully practised. Though not as extensive in their range of uses of the subsurface, other localities have also made supporting contributions to subsurface uses. Among these are Carthage and Springfield, Missouri, Boyers, Butler, and Wampum, Pennsylvania, as well as sites in Norway and Sweden.

The Kansas City area is a model in good conservation practises in that once abandoned limestone mines have been converted to a secondary and continuing use. It is a natural laboratory in its conservation of energy through use of the mined rooms for refrigerated and dry storage, factories and offices. Some 2,000 people work daily from 50 to 200 feet below the surface. The subsurface rooms converted to these uses are a byproduct left from the room and pillar mining of limestone. These rooms are interspaced with supporting pillars of limestone which are 25-30 feet in diameter and spaced 50-65 feet apart on center (Figure 1). Floors are paved with asphalt or concrete and partition walls where desired are usually of building

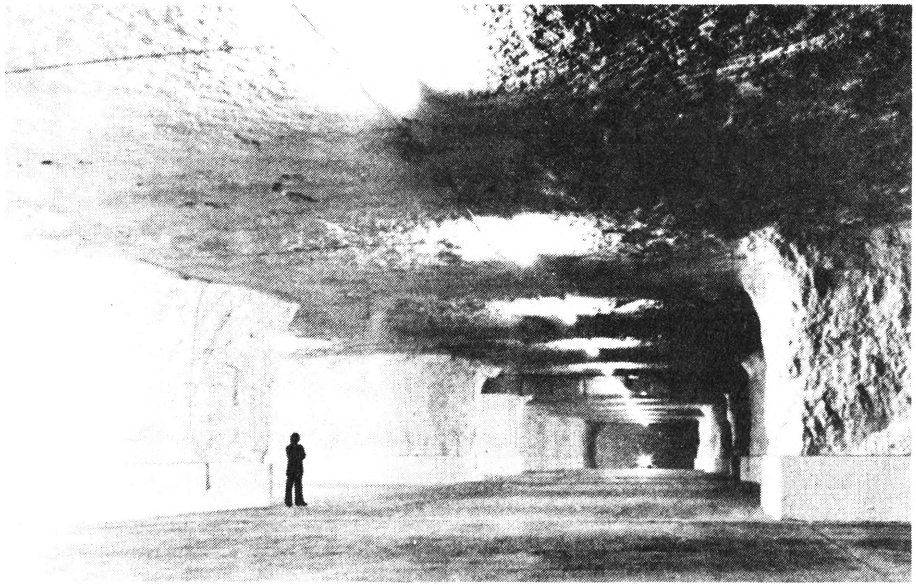

Figure 1. Mined Area Ready for Occupancy at Great Midwest Corporation in Kansas City

block construction. Large storage rooms, offices, and industrial space are easily arranged. The temperature and humidity is controlled by conventional heating and refrigeration methods.

Whereas the use of these underground rooms was motivated by the demand for economically attractive space, the economic benefits of low energy consumption was discovered as an added savings. The savings gained in low energy use are very important in our current national concern for independence during our energy crisis. Its greatest contribution may yet be achieved as it points the way for national acceptance of our underground space as a natural resource and its wise and careful use by compatible industries as an energy conserving factor on a national scale.

The rock strata commonly mined and later converted to space use in the Kansas City area is a Pennsylvanian limestone, about 24 feet thick, having a natural temperature in its mined rooms of 45 to 54^{o}F with less than 5^{o} variation between seasons. The surface temperatures, by comparison, dip below 0^{o}F and rise above 100^{o}F. One can quickly see the economy of energy consumption gained by the use of the subsurface. The natural untreated subsurface temperature is closer to the temperature desired for industrial use and therefore requires less modification, and hence, less energy consumption (Figure 2). The very low range of subsurface temperatures, their natural proximity to desirable temperatures, and their constant predictability allows less capital outlay for equipment as capacity to modify the wide range of surface temperature extremes is not necessary. The savings in reduced equipment installation also conserves the energy which would have been expended in its production.

Kansas City, largely because of its underground resources, has the largest storage capacity for frozen foods in the world and nearly all of this freezer space is underground. Its ability to effectively compete for a lion's share of the frozen food industry lies to a great extent in making optimal use of natural subsurface space temperatures and the insular qualities of the surrounding rock.

There are many variables operating in freezer storage such as the amount of unfrozen food brought in that must be initially frozen and stored, the turnover of products allowing cold loss through

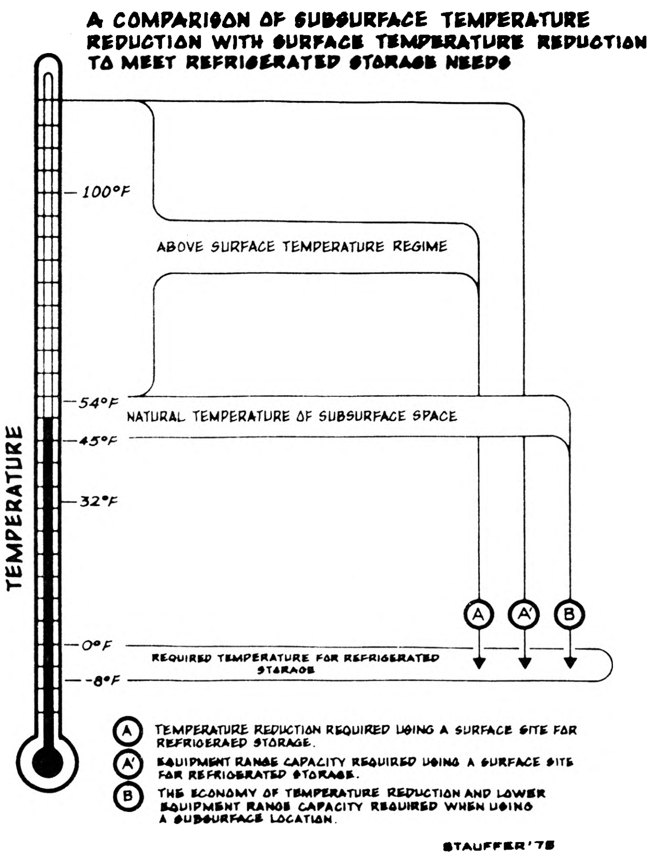

Figure 2.

opening of doors for loading, the character of the products, their dimensions, and mechanical and human activities within the storage area. All of these affect the efficient use of energy. For this study we will assume that the frequency and intensity of these variables happen to the same degree in both a surface and a subsurface freezer site or that they cancel each other. An example of such cancellation may be cited as the possible loss of space efficiency in the use of a mined site may be cancelled by its door traffic never admitting higher than 54°F air whereas the surface door may frequently admit air with very high temperatures. A monitored study with control of these variables is certainly indicated for greater accuracy.

The Kansas City experience, gained mainly by trial and error methods, has shown that the initial outlay for equipment in an underground refrigerated warehouse may successfully be reduced to 70% of that required for a conventional surface refrigerated warehouse. Research has shown that for a surface refrigerated warehouse of 1,600,000 cu. ft. to be kept at 0 to -8°F, 200 tons of refrigeration with 633 total connected horse power are required. For the same size plant located in a subsurface limestone mined area, the requirement for initial equipment is reduced to 448 horse power. To this initial reduction in energy use by virtue of smaller equipment may be added the additional savings gained by freezing down the rock walls.

Lorentzen (1959) reports on an underground freezer installation in Norway and cites definite advantages in using the natural rock for walls and freezing the rock walls, ceilings, floors, and pillars instead of using insulation. He found an initial savings by eliminating the cost of insulation and secondly, the cold stored deeply in the rocks could be tapped when large quantities of products to be frozen were brought in or in case of breakdown of machinery. These periods of peak loading, by the advent of fresh unfrozen commodities, tax the capacity of the conventional surface plant in that the compressor alone must compensate for increased cooling demand whereas the frozen rock of the underground serves in this capacity. The limestone rock of the Kansas City area has been found to be frozen to a depth of 22 feet and the pillars within the refrigerated rooms are solidly frozen. A temporary shutdown of the freezer within such a rock chamber will result in a temperature rise of about 1/2 of a degree per day whereas a breakdown in a surface location may raise 3-4 degrees daily. The risk of food quality loss is thus greatly reduced in the underground site.

Once the freezing of the rock surrounding the subsurface freezer plant has been achieved, the savings is even greater. The freezing of the rock walls to the optimum depth reportedly takes up to three years and gradual reduction of refrigeration may be achieved during this time so that eventual operation of refrigerator units in an underground site may be reduced to 40-50% of a comparable surface plant. Figure 3 shows the initial savings in

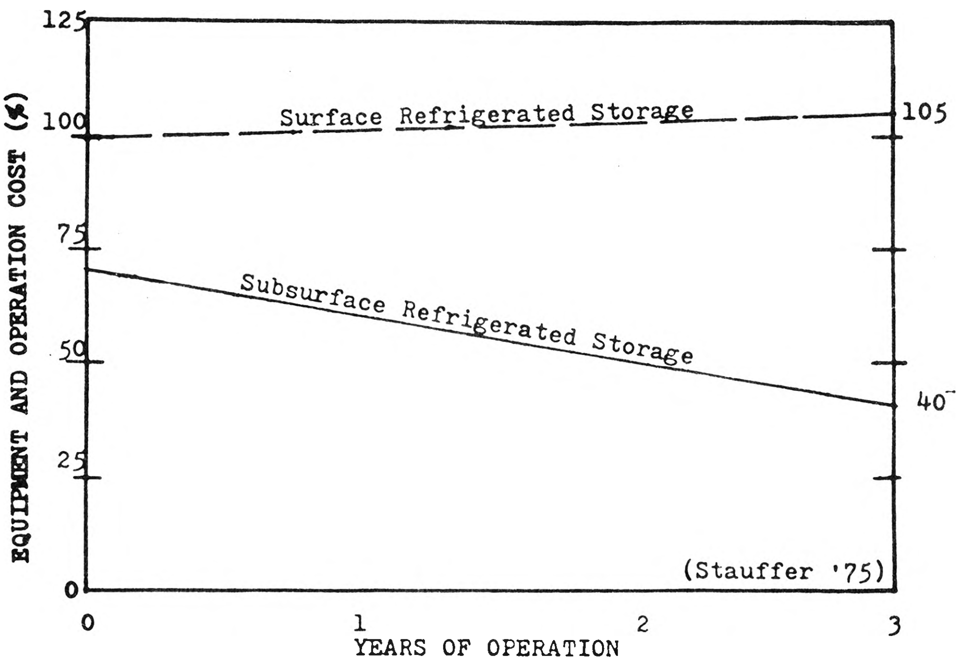

Figure 3. Comparison of energy savings effected by subsurface location based on equipment need and operation.

equipment outlay and the gradual reduction of equipment operation over time as compared to a surface operation which actually loses efficiency on a small scale.

Echo (April, 1975), an organ of Inland Storage Facilities, reports that their refrigeration equipment, by being underground, can cool twice as much as a comparable surface site. Muller (1975) also confirms the ability to withdraw up to 50% of the original equipment once the rock is frozen in depth but cites the problems of occasional low ceilings forcing short stacking of products, and pillars which spread outward toward the top prohibiting close storage, as taking a toll out of the savings. These areas which are not efficiently used have to be cooled regardless. His figure of net savings as compared to conventional freezer space approximates 30% which is yet a respectable savings in energy. One must also note that Muller is referring to an abandoned mine which has been converted to a freezer area. Current mining practises in the Kansas City area plan for the use of the mined space reducing if not eliminating low space use efficiency.

Warnock (1975) in his studies of initial equipment outlay found underground installation for refrigerated space to be only 50-60% of that required for a surface site and the heat loss in the underground installation in a full 24-hour day to be about equal to the heat loss above ground in a single hour.

Freezer storage in the Kansas City area ranges from sites which are in their initial months of operation to those sites with years of constant freezing wherein the rock has been frozen to its maximum. Assuming an average and conservative estimate of 40% in energy savings through use of the subsurface for refrigerated storage, as an attempt to evaluate the Kansas City experience, some interesting figures begin to emerge. In the Kansas City area alone the underground refrigerated warehouses are saving the electric energy used by 7,601 homes. When this is projected on a national scale the energy savings that could be realized if just one industry, the refrigerated warehousing industry, took advantage of the thermal qualities of the subsurface is quite impressive. A savings in energy could be achieved which would be sufficient to supply the electric energy needs of 110,019 homes or the residential needs for electric energy of a city of over a quarter million. The Kansas City figures are based on the 12,900 connected horse power currently installed in the Kansas City area for purposes of refrigerated storage being 60% of that required if the storage were on the surface and that in both cases the annual service use of the equipment is 75%. The rate of home use of electricity is based on the average non-business use of electricity in the Kansas City area. National projections are based on U. S. data of refrigerated warehousing.

Aside from the 3,320,000 square feet of refrigerated storage space located underground in the Kansas City area there is an additional 13,000,000 square feet which is currently used as space for cool and dry storage, factories, and offices. These uses require very minor modifications in the natural subsurface temperature. For most of these uses the heat gained by dehumidification is more than ample to make the adjacent office space comfortable. The ratio currently used for estimating the installation of equipment for these uses is .0825 of that for a comparable surface location. A five-ton unit of equipment is an accepted estimate of the needs for a home having 2,000 square feet. A five-ton unit underground efficiently serves 28,000-30,000 square feet in the Kansas City area. A few kinds of uses will require slightly more treatment, as in the case of tobacco storage, but to compensate for those requiring more treatment, there are other uses where no treatment whatsoever is required. On this basis, one can safely assume there is a 90% reduction in energy use when similar temperature and humidity conditions are attempted below the surface as compared to a conventional surface for such uses as general warehousing and factories. One cannot assume, however, that ideal temperatures and humidity are always maintained in warehouses on the surface. Subsurface space is easily maintained at the temperature and humidity desired whereas surface warehouse temperatures often go untreated and reflect the highs and lows of the existing weather. However, when and if similar conditions are attempted in both the surface and subsurface, the 90% savings in energy is conservatively realistic for a combination of non-freezer warehousing, factories, and offices.

It is my considerate opinion that the industries located underground in the Kansas City area have contributed significantly to the conservation of energy in both freezer and non-freezer uses and that a general figure of 70% reduction in energy usage for a combination of all subsurface uses in the Kansas City area is a conservative and reasonable estimate. Careful monitoring of controlled situations where all variables are compensated in both a surface and a subsurface experiment over a period of a minimum of three years is necessary to obtain absolute comparative data.

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PLANNED REDUCTION IN ELECTRICAL ENERGY USE IN NASHVILLE - DAVIDSON COUNTY, TENNESSEE: A PRELIMINARY ASSESSMENT

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Abstract

An assessment was carried out of the impacts of the various alternative strategies designed to reduce the rate of electrical energy use in the Nashville-Davidson County area, in the light of a potential crisis in supply. Seven strategies were identified among the major categories of voluntary reduction, price regulation, and mandatory reduction. Thirty-three sub-sectors were identified among residential, commercial and industrial users, and the consequences of imposing the strategies were assessed using a cross-impact matrix. The value of the methodology as an aid to public policy formulation lies in its possible extension to allow direct participation of various affected publics.

1. INTRODUCTION

As the demand for electrical energy continues to increase in the face of uncertain prospects for supply availability, the probability increases for a local or regional crisis requiring reduction of electrical energy use by consumers. Indeed, instances have arisen in which governmental agencies and utilities have been forced to stimulate conservation by various means of a more coercive nature than simple appeals to the voluntary spirit. As coal, petroleum, and nuclear energy sources continue to enjoy an uncertain future, we may again face such instances of forced reduction of usage.

Our purpose is to assess the impact of various alternative reduction strategies, one or more of which might be adopted in a crisis, upon various sectors of the consuming public, using supply and demand characteristics of Metropolitan Nashville-Davidson County, Tennessee as the unit of analysis.* These are the basic questions which must be addressed: What strategies are generally available to affect reduction in the residential, commercial and industrial sectors of the consuming public in this region? How effective is each strategy likely to be in each sector? What are the social, economic, political and technological impacts of each strategy upon individuals and institu-

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In addition to the authors of this paper, participants in the initial study were Professors Daniel M. Brown, Robert T. Nash, William Y. Smith, Francis M. Wells, and John W. Williamson. Other student participants were Jeffrey T. Delargy, Joseph H. Johnston, George A. Olive, Jr., John E. Pike, C. Vincent Schmidt, Alan B. Weatherly, and Cathy Wilson. The work of this group was assisted by an oversight committee involving representatives of business, industry, academia, and consumer organization.

The preliminary impact analysis of the task group, available from the Vanderbilt University Engineering School, Nashville, Tennessee, contains the material presented in this paper, as well as further explanation of the origins of the project and useful graphic presentation of some of the information contained herein. (See Reference 1.)

tions, both public and private? Finally, is it possible to facilitate public discussion of this issue that will contribute to formation of a broad consensus on the most desirable policy choice for planned reduction?

Answering these questions in any region or locale involves at least three principal tasks, which are addressed for the Metro Nashville area in the next three sections of this paper. First, the case histories of similar occurrences should be studied with a view to assessing the actual efficacy of the strategy selected, as well as identifying unique characteristics of that situation which may have increased or decreased the effectiveness of the effort - but which might not be present in a crisis situation in the Metro Nashville area. Such a review logically leads to specification of the unique characteristics of Metropolitan Nashville-Davidson County, including social, economic, legal-political, and technological data. Finally, selected strategies are assessed in terms of their impact upon these characteristics, and upon people and groups within the consuming public. Hopefully, this form of organization can be repeated by interested parties in any locality.

2. HISTORICAL REVIEW OF PLANNED REDUCTION EXPERIENCE

When considering planned reduction of electrical energy in Nashville, the experience of other areas which have had such reductions provides some insight into possible impacts. Drought, a coal-miner's strike, and the oil embargo necessitated planned reductions in the Pacific Northwest, United Kingdom (Great Britain), and Los Angeles, respectively. The remainder of this section describes the measures taken and some of the resultant impacts.

2.1 PACIFIC NORTHWEST[2]

The lowest rainfall level in 95 years left Washington and Oregon in 1973 with a 7.4% decrease in the absolute amount of electricity available. The shortage was projected to last at least until May, 1975. Various measures were taken. For example, there was a 68° F. heating limit for state agencies, and alternate street lights were turned out. Appeals to practice energy conservation measures (the Kill-a-Watt Program in Seattle) reduced overall demand by 8-9%. In Oregon aluminum plants laid off some 1000 of 4000 employees. A ban on outdoor advertising was put in force. Daily instead of nightly cleaning of buildings resulted in heating and lighting bills some 14% less than normal. Measures such as lower wattage bulbs in office buildings and lower hot water temperatures resulted in commercial electricity savings on the order of 10-20%.

In the Pacific Northwest, most power generation is hydroelectric; long-term shortages such as the one described are generally chronic problems and have only meteorological remedies, unlike the acute problems which can strike the Tennessee Valley region. Longer lead-time programs of consumer education and emphasis on volunteering have a better chance in such instances; also, the amount of load reduction needed is generally smaller.

2.2 UNITED KINGDOM[3]

A sharp fall in coal supplies to British power stations--nearly 40% below the expected level--led to the adoption of emergency measures in the electricity consumption sectors in December of 1973. Restrictions applied to the commercial and industrial classes were the following:

(1) no heating of commercial premises above 63° F.
(2) lighting cut 50% in shops, offices, and other premises
(3) electricity supplies limited for industrial and commercial users to three consecutive days per week according to a schedule drawn up in each area and no work beyond normal operating hours was permitted
(4) firms using non-interruptible processes were limited to 65% of their normal electricity consumption per week.

An S.O.S. (Switch Off Something) program in the residential sector resulted in about a 20% reduction. In spite of an electricity supply 40% below normal, industrial production as of February was reduced by less than 30%.[4] Employees in the production industries numbered 9.68 million in November and about 9.55 million the following February.[5]

As in the Pacific Northwest, British power plants are basically of one type; namely, in this case, fossil fuel steam turbines, with negligible hydroelectric and nuclear generation. Most British problems are attributable to shortages of petroleum or labor unrest amongst coal miners. Both supply problems, unlike the Pacific Northwest, are basically acute, and subject to alleviation by government policies.

2.3 LOS ANGELES

The greatest part of Los Angeles' electricity is produced by burning fuel oil. As of October, 1973, the city had contracts for 48% of its requirements from Middle Eastern sources. Because of the embargo, emergency action was necessary to curtail the use of electrical energy. Measures implemented resulted in a 17% reduction in electrical energy use. The specific legislative response(6) as well as the highlights of a report issued by the Los Angeles Energy Coordinator(7) are detailed in the remainder of this section.

The purpose of the "Emergency Energy Curtailment Plan" was to minimize the effect of a possible shortage of electrical energy on the residents of the city and to adopt provisions that would "significantly reduce the consumption of electricity over an extended period of time, while reducing the hardship on the city and the general public to the greatest extent possible."(6) In order to accomplish these goals, a variety of measures were undertaken; all, however, subject to the proviso that power necessary for public safety, security or essential government services was to be exempt. Major actions were the following:

(1) Residential users were to cut use by 10% in comparison with a year-ago base period. This did not apply to customers who were in the lowest third of residential users as determined by number of kilowatt hours (KWH) consumed in the base period.

(2) Commercial users were to reduce by 20%.

(3) Industrial users were to reduce by 10%.

Additional provisions were: a 25% reduction in street lighting; prohibition of outdoor advertising and decorative lighting; reduction of 50% in floodlighting of service stations, used car lots and similar establishments; temperature restrictions on heating to 68° F. and on air conditioning to 78° F.; and a 25% reduction in lighting of outdoor public exhibitions such as sporting events. Penalties were a 50% surcharge on the electric bill for the first violation, a 2-day interruption of service for the second, and a 5-day interruption for the third offense. Relief could be granted by the Department of Water and Power or by a system of appeal boards if curtailment would result in unemployment, if during the preceding year technological improvements had been made to the customers' premises, if occupancy changed, or for similar reasons.

Certainly the plan averted the spectre of rolling blackouts and a significantly reduced work week. As implemented, it did not appear to cause an "unacceptable level of economic dislocation or personal hardship."(7) This was, however, a curtailment and not a conservation program. There was a limited amount of electricity to sell and the aim was to keep use within certain limits, not merely to make use more expensive.

Although factors contributing to the success of the program (a 17% reduction in use) are not totally understood, it is believed that the mandatory nature of the ordinance contributed to some 10 of the percentage points of reduction. Voluntary curtailment programs in neighboring areas (such as Southern California Edison) and around the country average under 5%.

A recommendation was made to increase the "minimum exemption level" from the lower third of the residential customers to the lowest 60% (thus exempting all those who use less than 800 KWH per month). The remaining 40% of residential customers use some 70% of the residential total. This modification could also save considerable administrative time.

A new classification of "institutional" was suggested for schools, churches, hospitals, and government services with a 20% reduction requirement.

Rather than a flat penalty system, a graduated one was recommended. Moreover, it was felt that the average of two months' bills should be used for penalty purposes. This avoids problems with occasional meter estimation and other minor irregularities. The option of being able to "work off" a penalty by decreased use in the following month was suggested.

Despite the reduction in usage, citizens made it clear by a deluge of inquiries and complaints that they did not understand the adequacy of their efforts at compliance. The efficacy of various conservation strategies was unknown and people generally were unable to read their meters. It became evident that the administrative machinery for the task of informing the people, implementing the ordinance, equitably enforcing the penalty program and associated provisions did not exist. Thus, penalties were suspended on January 25 until after March 31, 1974 when adequate administrative mechanisms could be set up.

It is interesting to note that subsequent to the program, Los Angeles residents continued to conserve at a rate of about 12%. This created a difficult situation for the Department of Water and Power as lessened usage places upward pressure on rates.

In the Los Angeles experience, it is important to note that the municipal utility is a department of city government. As such, alternatives were available to the Mayor and City Council which would not be available to the Metropolitan Government of Nashville-Davidson County in a similar situation; the Nashville Electric Service (NES) - through the Electric Power Board - is insulated from direct political control by municipal government.[8]

3. METROPOLITAN NASHVILLE - DAVIDSON COUNTY

3.1 INTRODUCTION

The city of Nashville and Davidson County, united in 1963 under a mayor-council form of government, lie in the northern center of the state of Tennessee on the Cumberland River. In 1974, the Metropolitan area proper, the primary focus of this study, had an estimated population of 469,500. However, the SMSA estimate was 750,000, and the Retail Trade Zone contained approximately 1,271,400 people.

Metro Nashville is a focal point of Southern life. It is a regional center of industry, finance, education, recreation and product distribution - located at the intersection of Interstates 40, 24 and 65, as well as two railroads. Its industry is chiefly devoted to production of consumer goods, notably shoes, paper products, hosiery, stoves, food products, glass, appliances, synthetic fibers, barges, boats, tires and resins. Printing and music are also major contributors to the Nashville economy.

Nashville is a major retail-trade center, with a central-city shopping area and twenty-seven major retail-sales centers located elsewhere. There are an estimated 232,362 households in Metro, with a total personal income last year of $3,291,420,000 ($14,165/household). Of that total income, approximately $1,288,744,000 (39%) was expended in the retail-sales market.

Excepting perhaps iron and steel based manufacturing, Metro Nashville has a diversified economy, with substantial dependence on industry and commerce, in both goods and services, as well as transportation. Agriculture, as well, centers around Nashville. In the SMSA there are approximately 13,796 farms, which brought to the markets last year $19,667,000 in crops, and $61,576,000 in livestock. This sort of diversity makes Nashville an ideal laboratory in many respects for our purposes.

3.2 POLITICAL - LEGAL ASPECTS OF THE POWER SUPPLY SYSTEM

The power supply and distribution system for Metro has some unique characteristics, which must be taken into account.[8-10]

Nashville's electric power is generated by the Tennessee Valley Authority (TVA), the world's largest single producer of electricity. TVA, established by Congress in 1933, is a public corporation, governed by a three-man board of directors appointed for nine-year terms by the President, with the advice and consent of the Senate.[11] It receives Congressional appropriations each year for its non-power programs, but its power program must generate sufficient revenue to cover its costs and make in-lieu-of-tax payments back to the Treasury.

Thus, TVA differs from a private utility in that it serves a larger region, most of the area of which is non-urban agricultural land, and it is more directly subject to Congressional pressure (a factor somewhat mitigated by TVA's complete freedom from regulation by the Federal Power Commission and all state and local regulatory bodies). The General Accounting Office and the Environmental Protection Agency serve as significant controlling agencies, if indirectly. Essentially, TVA is indirectly affected by federal decision-making as though it were a private corporation of equivalent size and interests.

TVA sells its power to more than 160 private distributors, ranging in size from tiny rural electric cooperatives to large urban agencies in Memphis, Nashville, etc. The Nashville Electric Service (NES) is the TVA distributor throughout Metro, serving its customers through more than 170,000 meters. NES is a proprietary function of Metropolitan Government; as such it is a quasi-public agency, exempt from regulation by the Tennessee Public Service Commission, but liable to suit by private parties in much the same way as a private utility. The Mayor, subject to the approval of the Metro Council, appoints the five members of the Electric Power Board, who control the affairs of NES with virtual autonomy, a power authorized by the Metropolitan Charter.

In theory, consumer input into these agencies can be achieved through both the legal and political processes. In practice, local control has been minimal, although policies have recently been altered by both TVA and NES under threat of class-action suit, as well as through political pressure expressed through Congress. This situation affords certain advantages in terms of centralized regional policy-making and crisis management; however, from Metro Nashville's standpoint, it lessens the control which local political institutions and hence the public can exert - a different situation from Los Angeles, certainly.

3.3 DISTRIBUTION IN DEMAND FOR ELECTRIC POWER[12]

Table I indicates that the time of year at which a crisis occurs may make a significant difference in choosing a strategy for crisis management.

From analysis of this data several points can be made: 1) In the winter months there is a large shift from "base-load use" to higher average consumption* on the part of most residential users. In effect, it is as though 1/2 of the users increased their monthly consumption by 2000 KWH, which is compatible with the fact that 60% of the users have electric heating. In fact, the residential use essentially doubles while the commerical/industrial use is essentially unaffected. (This is further illustrated by Fig. 1.) 2) In the summer months there is an effective increase in monthly use of about 500 KWH on the part of all users.

This indicates that strategies which are designed to limit the maximum consumption of electric power would impact various segments of the user population in different ways, according to the season.

As an aid to designing effective strategies, the consumption is disaggregated into end-use (Figs. 2 & 3) averaged over the year.** It is important to realize that seasonal variations in this disaggregation must be taken into account. For example, strategies designed to reduce peak-load consumption must relate to winter-time usage (Fig. 1), while strategies reducing overall energy consumption must vary seasonally.

It is also interesting to note that because of the nature of use in Nashville-Davidson County (where 50% of the homes are all-electric) any effective strategy must deal with space-heating and air conditioning, which account roughly for 1/3 of the power consumed annually (Fig.3).

3.4 GROWTH OF DEMAND

The use of electric energy in the TVA region has grown rapidly over the past fifteen years. Assessing the potential for future power-supply crises must begin with an understanding of the total power demand, and of the types and generating capacities of the plants which provide their power.

Since 1960 the sale of TVA power has grown at the rate of about 4% per year, and of the total ($\sim 100 \times 10^9$ KWH in 1973) about one third is for residential use, and the remaining two thirds for commercial and industrial use. The mean residential use in the TVA region is about twice the national average of 8000 KWH/yr/dwelling. In the Nashville-Davidson County Metropolitan area, the average use per residential customer was

TABLE I Distribution of Residential Electrical Energy in the NES District for December, May, and August (1973-74)

User Group (KWH/Mo.)	per cent of Total Users	per cent of Resid. Energy	per cent of Total Energy
December (1973)			
A: 0-650	19	2.4	1.3
B: 651-1250	14	5.4	3.0
C: 1251-2000	13	8.2	4.5
D: 2000-4000	34	40	22
E: >4000	20	44	24
May (1974)			
A	30	10	3.8
B	35	32	12
C	26	38	14
D	8	19	7
E	0.3	1.6	0.6
August (1974)			
A	21	4.4	2.1
B	24	15	7.1
C	28	29	14
D	25	44	21
E	2.2	7.5	3.6

*Consumption in May, at which time heating and air conditioning should be minimal, is used as an indication of "base-load" use.

**Information on the disaggregation of this power by end-use is available for the residential sector in a TVA marketing analysis for Nashville,[10] but the commercial and industrial sector figures are national averages excerpted from a Federal Power Commission National Power Survey.[13]

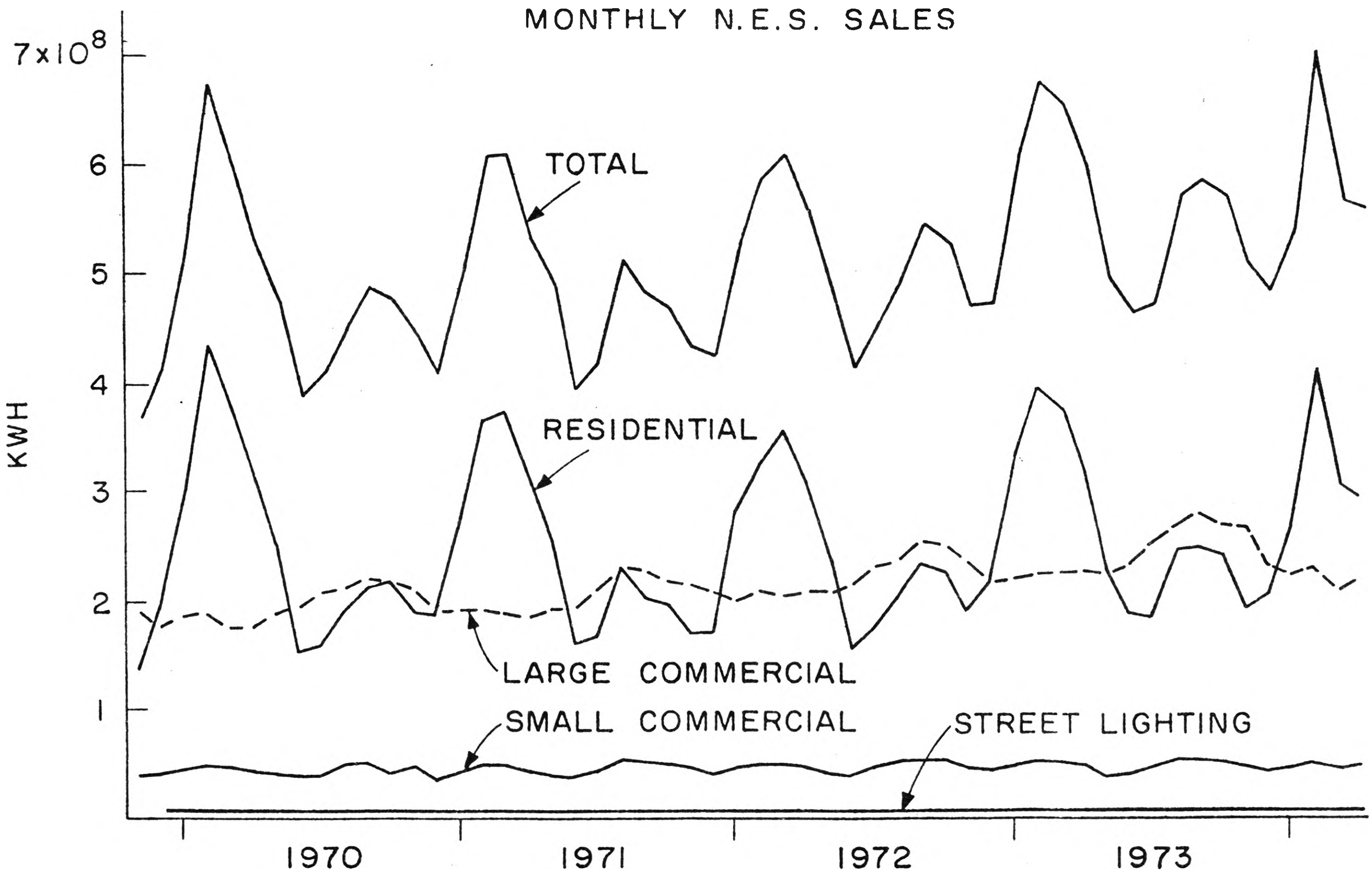


FIG. I MONTHLY SALES IN THE N.E.S. DISTRICT

more than twice the national average or approximately 20,000 KWH/yr. As noted previously, 50% of NES living units are all-electric.

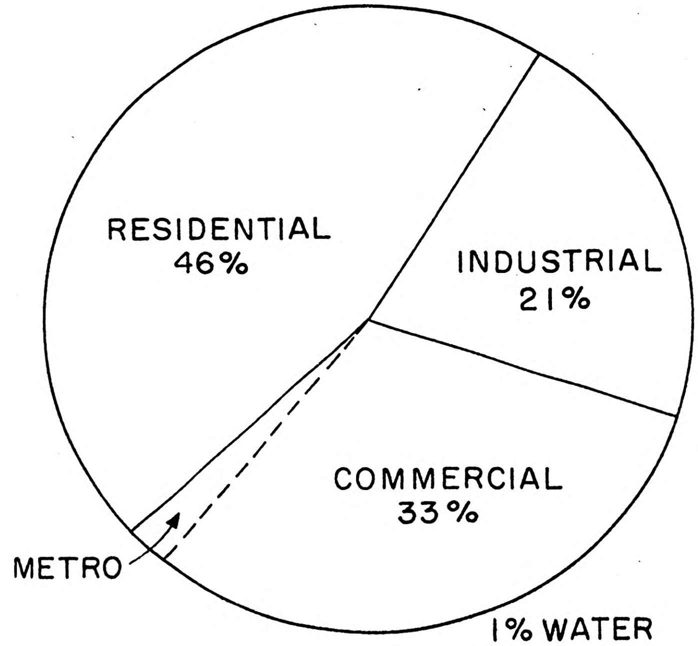
This rising demand is a consequence of two multiplicative factors: an increasing number of customers and an increase in their average use rate (KWH/yr). This demand is cyclic, with both daily and seasonal variations. Characteristically, during the day the demand starts rising above the average at 7:00 A.M. reaching a plateau at 8:00 A.M. which gradually peaks at about 6-9 P.M., depending upon the season, then dropping to the average two hours later, with correspondingly lower use during the night. The rise above the average is usually about 12%. This daily cycle is superimposed upon a seasonal variation (Fig. 1.) which reflects the heating and cooling demand of winter and summer. These seasonal variations for residential demand are very large, involving a 100% rise over the base-line use. For example, in October of 1973 the residential demand from NES was a little less than 200×10^6 KWH/month, while in January 1974, three months later, it was a little more than 400×10^6 KWH/month.

3.5 TECHNICAL ASPECTS OF THE POWER-SUPPLY SYSTEM[10,14]

In addition to providing power to Nashville, TVA supplies most of the Southeastern United States with power generated from a mix of hydroelectric generators (21%), coal-fired steam turbines (78%), and nuclear reactors (1%). Peaking power also is supplied by small gas-turbine units and some pumped-storage hydropower.

The capacity of the TVA system must be large enough to accommodate those peak loads accompanying high average demands, even though the daily average power demand is somewhat lower and the monthly and yearly average power demands are very much lower. In fact, the yearly peak demands (winter) in the TVA system exceed its dependable capacity (17×10^6 KW in 1973) by about 10%, but this is accommodated by exchange of

FIG. 2



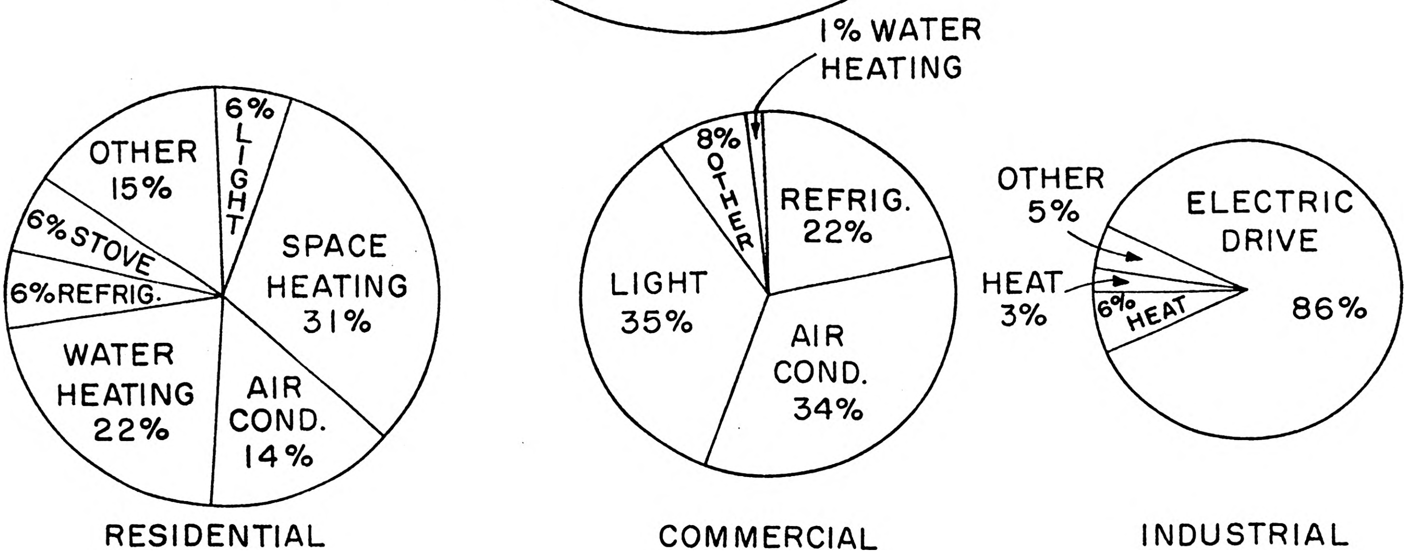
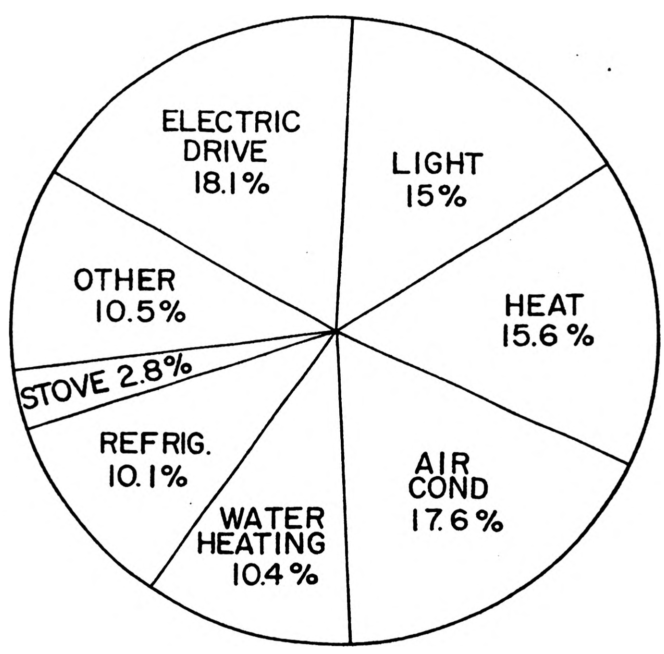


FIG. 3



FIGS. 2 & 3 DISTRIBUTION OF POWER BY-SECTORS AND END-USE IN THE NASHVILLE ELECTRIC SERVICE (AVERAGED OVER 1973-74) power with other systems to the south and west, who in turn draw on TVA capacity during their (summer) peak demands. The installed capacity is about 20% higher than its dependable capacity. This is to be expected, because hydrogenerators cannot be counted on for capacity generation at all times due to climatic conditions, some plants being on a stand-by basis, the occurrence of breakdowns, needed maintenance time, etc. Some improvement in efficiency can be obtained if the load factor (the ratio of average load over some representative interval of time to the peak load occurring in that interval) is maximized. Such "peak-smoothing" in the NES load would result in about a 10% saving since extra coal would not have to be used to provide for peaks.

Because hydrogenerators can be brought on and taken off line in minutes, the practice has been to use hydropower to supply the peak overloads while using the steam plants, which have more inertia, to provide the base loads. Since the possible future sites for hydroelectric dams are few, the growth in the demand for power is pushing the limits of flexibility offered by this approach. It is intended that nuclear power generators take over their function since they can respond more quickly to demand. When Browns Ferry units #1, 2, and 3 are fully operative, the complex will exceed in capacity the total output of all TVA hydrogenerators. In fact, projected nuclear capacity will increase the total TVA capacity by 50% some time after 1980.

3.6 PRESENT AND FUTURE NEED FOR REDUCTION

Because of potential coal supply shortfalls arising from the demands of organized labor and uncertainty over future strip-mining regulations (and also because of difficulties in increasing nuclear capacity on schedule) some pressure exists to decrease total power demand. If economy measures reduced the demand by 20%, this would be a one-step process, and the continuing growth in use and users would bring us back to the same level of demand in the TVA region in less than four years. This could only be prevented or delayed if the average demand (KWH/customer) were stabilized (likely) and if the growth in the number of customers were stabilized (unlikely).

Using NES as a representative sample, the demand of the residential sector seems to be growing at a rate of 1.3% per year, while that of the commercial-industrial sector is much higher at 6.5% per year, giving a growth in the total NES system of roughly 4%/yr. A contributory factor to the growth in residential demand for power, aside from the growing population, is the increase in the use of electric appliances. In 1973, 64% of the residential users had washing machines, 30% had freezers, 47% had clothes dryers, and 25 % had dishwashers. These units use about 6 % of the total energy consumed, and it is estimated that growth toward saturation (more users) would raise this to only 6.6% in 1983. A more likely cause for the growth in demand would involve refrigerators (99% saturation in 1973 but showing a 4%/yr rise in power requirements), air conditioning (82% saturation in 1973) and electric heating (58% saturation in 1973 expecting to rise less than 1%/yr), all of which use up over 50% of the power demanded by residents. Little change in this 50% factor is expected. However, the number of users is expected to increase 30% in ten years; this is the main cause for the expected increase in power demand.

In other use sectors, street lighting comprises less than 0.5% of the use, and strategies involving reduced street lighting would be essentially ineffective except for its psychological value, and the negative impacts on crime and safety could outweigh this. In the residential sector, lighting comprises only 6% of the total residential power used. On the other hand, lighting in the commercial and industrial sectors in some cases comprises the major fraction of their power demand. Since these sectors comprise 54% of the NES load and 75% of the TVA load, this provides for opportunities to effect a major reduction in power demand.

A voluntary reduction in lighting use by 50% and in heating by 30% (a ten-degree lowering of the thermostats and an approximate 3% reduction in heating power per degree lowered) would result in an overall reduction in the NES district by 12 percent. This assumes total compliance by the consumers and negligible chances of voluntary saving elsewhere. It appears unrealistic to expect 100% compliance; thus, the record of other regions (see Sections 2.1-2.3) which indicate a 6-10% reduction in power use by voluntary curtailment is likely to be repeated in the NES district.

If reductions greater than 6-10% in power use are required, other-than-voluntary strategies must be implemented, and their impacts on the various consumers should be considered.

4. THE IMPACTS AND EFFECTIVENESS OF SELECTED STRATEGIES*

Having briefly examined the history of electrical power supply crises and related it to the unique characteristics of the Nashville area, we are now able to draw upon that experience and additional current research to assess the effectiveness and potential impacts of some alternative strategies.

4.1 THE STRATEGIES

The case examples of electric power reduction strategies described in the previous section and in other literature available to the task group (e.g., drafts of TVA and NES power allocation plans) may be classed into three general categories:

I. Voluntary Conservation Appeal: designed to convince the consumers that they can and should reduce their electrical usage. There are no direct sanctions for noncompliance. The overall reduction to be expected from this approach ranges between 5% and 10%.

II. Price Regulation: designed to curb usage and effect a rationing by making the commodity (electrical energy) more expensive. Depending on the particular pricing regulation strategy employed, overall reductions in the range of 10% to 50% may be realized. Extreme pricing rapidly shifts this from a near-voluntary to a mandatory type of regulation.

III. Mandatory Regulation: designed to curtail the use of electrical energy through legislative enactment containing penalty provisions. This category will generally effect the greatest reduction in overall usage, but with a high probability of severe consumer impact.

The task group studied and debated a wide range of possible strategies that could be used to curtail electrical power usage. For the purposes of this preliminary investigation, similar strategies were grouped together and the number condensed until a list of seven separate strategies was identified.

Table II lists these strategies under their general category headings and describes some of the essential features of each. The numerical values shown in the Table for KWH base line usage, percentage rate increases, percentage surcharge, etc. were chosen as being reasonable for the particular residential user patterns, socio-economic data, and industrial manufacturing.

4.2 INTRODUCTION TO IMPACT ANALYSIS

The idea of a technology assessment on a problem of this type is to carefully and systematically look at the strategies that might be adopted to effect certain necessitated goals, and to see what their impact might be on the various groups and institutions within the region. The word "impact" is used here to mean those negative consequences which would be expected to accrue if a particular strategy were to be imposed - not the effectiveness of the particular strategy in reducing electrical-power usage. Once the probable impacts have been assessed, then the idea is, of course, to choose that strategy or combination of strategies which best meet the necessitated goals while placing as little hardship as possible on the people and institutions affected. Only by studying the probable effect of each strategy in turn on each subgroup of the consumer sector can we be sure of not overlooking a possible severe consequence in adopting a particular strategy. Even if we are forced into using a particular strategy, we will at least know beforehand who the most heavily impacted parties are likely to be, and we can begin to take steps to ameliorate the action of this strategy.

A simple method for making this systematic study is to set up a matrix with the strategies that might be adopted listed along one side and the parties (consumers) that might be affected along the other. (See Table VII, the master impact matrix for this study.) Each cell in this matrix represents the interaction of a particular strategy with a particular subgroup of the consumer sector. Then, after careful study, a notation representing the suspected magnitude or level of the impact can be

*In this section frequent reference is made to the activities of the "task group" in evaluating impacts of alternative strategies. The members of the task group are identified earlier in this paper in Section 1.

TABLE II Essential Features of Electrical Power Reduction Strategies

General Category	Strategy	Description
I. Voluntary Conservation Appeal	A. Media-Intensive Campaign	T.V. and radio spot advertising, newspaper advertising, billboards, pamphlets, and other mass-media efforts.
	B. Personnel-Intensive Campaign	Conservation advisory teams (staffed by TVA, NES, Metro, etc.) working with community groups, schools, churches, businesses, and industrial firms through workshops, seminars, public discussion groups, etc.
II. Price Regulation	A. Surcharge	A percentage of total monthly bill (eg., 50%) would be added to all KWH usage above a certain baseline level. Baseline could be a given monthly level (eg, 650 KWH/mo) or a percentage of previous year's usage by consumer (eg, 80%).
	B. Rate Increase	The cost per KWH would increase with the amount used above a certain baseline level. Prices would begin their progressive increase above a given monthly level (eg, 650 KWH/mo) or above a percentage of previous year's use.
III. Mandatory Regulations	A. Voltage Reduction	A voltage reduction of 5% to 8% would be made on all consumer sectors. Critical customers could petition for full line voltage.
	B. Mandatory Curtailment	1. Winter cut - all consumers would be required by law to use a certain percentage less (eg, 20%) than previous year. 2. Summer cut - same as above. Enforcement penalties: 1st violation - 50% surcharge; 2nd, etc. - 1 to 3 day interruptions.
	C. Power Rotation	Primary substations or distribution lines would be cycled on and off for specified time intervals (eg, 2 hrs). Certain critical loads would remain on.

entered in each cell of the matrix.* For the purposes of this preliminary investigation, the qualitative notations of H (= high impact), M (= medium impact) and L (= low impact) were used. With further investigation, this qualitative scale may be replaced with a quantitative scale of numeric values that will allow summation to show the total impact of a given strategy and better facilitate the ranking of strategies according to their expected impacts. Hopefully, this simple analysis will indicate which strategy or combination of strategies will best solve the problem with the least negative effect.

4.3 CONSUMER SECTOR BREAKDOWN

In order to carry out the exercise described in Section 4.2, the various consuming groups must be carefully identified. The consumer sector for electrical energy usage can logically be broken down into three major groups: residential users, commercial users, and industrial users. However, a study of this type would be of little value if the consumer sectors were left in such an aggregated form.** A

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*The task group divided into three smaller groups (of three or four members each) corresponding to the three categories of consumer usage: residential, commercial, and industrial. The groups continued to meet separately for several sessions to go through each cell in each sub-matrix for each strategy in turn. The process required considerable discussion and reference to collected data, until a suitable scenario was generated for each interaction and a rating notation agreed on by the group. The groups quite often kept notes during this process in order to make clear their rationale for choosing certain rating values. At the end of this process, the small groups came together again to discuss their work and record their rating notations on the master matrix form (See Table VII).

**It is desirable to further subdivide the three major user sectors (residential, commercial, and industrial) according to their social and economic characteristics. Within each sector there exist definable groups of users who will react differently to various strategies. Basic data is obtainable from U.S. Census compilations of population, housing, manufacturing, and business data, reports of the Metropolitan Planning Commission, data developed by the Mid-Cumberland Regional Development District staff, sample billing records of the Nashville Electric Service, and energy-use figures from both TVA and NES.

particular power reduction strategy could have widely different consequences in the residential sector, for instance, depending on the income level of the residential users. Another important factor would be the type of dwelling structure in which the user lived, since the electrical power needs of single dwelling units may vary considerably from multiple dwelling apartments. Therefore, if only these two factors are to be considered in the residential user case, we have already defined a sub-matrix of dwelling type *vs*. income level on top of which we are to consider the impact of each strategy we have designated. An example of the residential sector submatrix we have developed is shown in Table III. This residential submatrix was used to characterize eight user sub-sectors. Effects of all seven strategies were evaluated in turn on each sub-sector. Our analysis of NES residential usage patterns showed that single family dwellings and up to four-unit complexes were very similar; the real differences in usage were between the large apartment complexes and the small complexes of one to four units.

In like manner, the commercial sector was broken down into public and private institutions, with the main differentiation being between offices, stores, restaurants, educational, religious, medical, and government institutions. This commercial submatrix (Table IV) was used to characterize sixteen user subsectors, including stores, restaurants, offices, institutions (educational, religious, medical) and government services. Effects of all seven strategies were evaluated in turn on each subsector.

The industrial sector proved a little more difficult to disaggregate into its most important components. Since this study is concerned with the reduction of electrical energy usage, we felt it

TABLE IV Commercial Impact Areas

	PUBLIC	PRIVATE	
		Large	Small
I. Institutions			
A. Education/ Religion			
B. Medical			
C. Gov't. Services.			
II. Offices			
III. Stores			
A. Food			
B. Non-food			
IV. Restaurants			

desirable to have one classification factor that expressed electrical energy usage directly. Our data allowed us to classify industries in the NES region according to their electrical energy intensiveness: KWH per dollar of value added by their industrial processing operation. Table V is a partial list of area industries classified by S.I.C. code and energy intensiveness. The impact of a particular reduction strategy will be quite different for high energy intensive industries (SIC 22, 26,28,32) than for those which are not (SIC 25,34, 35,etc.). The other important factor for the industrial sector is the size of the firm, and we considered size from both the employment viewpoint and the economic (dollars-of-value-added) viewpoint. These industrial submatrices (Table VI) were used to characterize nine user subsectors according to (1) size of firm (based on value added and on number

TABLE III Residential Impact Areas

		INCOME LEVEL				
		Fixed	Low	Medium	High	Total Households
DWELLING TYPE	4 or more units	(15,000)	9,028	15,284	6,816	31,128
	1 to 4 units	(62,000)	36,112	61,136	27,264	124,512
	Total Households	(77,000)	45,140	76,420	34,080	155,640

TABLE V Energy Intensiveness of Area Industries (Manufacturing)

SIC CODE	INDUSTRY	ENERGY INTENSIVENESS (KWH/$ value added)
20	Food and Kindred Products	1.006
22	Textile Mill Products	2.550
23	Apparel and Other Fabric Products	.358
24	Lumber and Wood Products	1.603
25	Furniture and Fixtures	.606
26	Paper and Allied Products	5.029
27	Printing and Publishing	.405
28	Chemicals and Allied Products	4.960
30	Rubber and Plastic Products	1.583
32	Stone,Clay and Glass Products	2.497
34	Fabricated Metals	.710
35	Machinery (except electrical)	.619
36	Electrical Machinery and Supplies	.890
37	Transportation Equipment	.836

TABLE VI Industrial Impact Areas

Energy Intensiveness (KWH/$VA)

SIZE OF FIRM (SIC#)-(Value Added, $)

	Low (0-.75)	Medium (.75-2.00)	High (2.00-)
SMALL ($0-35M)	(SIC#34) $34M $34M	(SIC#24) $15M (SIC#36) $32M $47M	(SIC#22) $30M (SIC#26) $14M $44M
MEDIUM ($35-75M)	(SIC#23) $36M (SIC#25) $37M (SIC#35) $37M (SIC#35) $45M $118M	(SIC#30) $42M $42M	
LARGE ($75M+)	(SIC#27) $112M $112M	(SIC#20) $85M (SIC#37) $140M $225M	(SIC#28) $184M (SIC#32) $146M $330M

Energy Intensiveness (KWH/$VA)

SIZE OF FIRM (SIC#)-(Employees, 1000)

	Low (0-.75)	Medium (.75-2.00)	High (2.00-)
SMALL (0-2.0)	(SIC#34) 2.0 (SIC#35) 2.8 4.8	(SIC#24) 1.1 (SIC#30) 2.7 3.8	(SIC#26) 1.6 1.6
MEDIUM (3.0-5.0)	(SIC#25) 3.4 3.4	(SIC#36) 3.4 3.4	(SIC#22) 3.0 (SIC#32) 4.7 7.7
LARGE (5.0 +)	(SIC#23) 5.5 (SIC#27) 9.1 14.6	(SIC#20) 6.4 (SIC#37) 9.5 15.9	(SIC#28) 7.7 7.7

of employers) and according to (2) energy intensiveness (killowatt-hour of energy used per dollar value added to product).

4.4 MASTER IMPACT MATRIX

There are a number of ways that the matrix of impact values (Table VII) can be analyzed in an assessment study. Individual cells where major (H) and considerable (M) consequences are expected to occur should be noted. Then we should begin to integrate these individual instructions into patterns of high impacts within each sector. These clusters indicate whole regions that we would hope to avoid in selecting a strategy sequence to achieve our necessitated goal. In effect, we might visualize the matrix as a topographical map where the H's represent hills and the L's valleys. Our objective would be to traverse this map from one side to the other (i.e., across all sectors) by choosing the easy routes (low road) along certain strategy paths, changing routes (strategies) whenever the need dictates.

4.5 OBSERVATIONS

When viewed across all consumer sectors, the strategies can be ranked according to their expected severity of impact in the following order:

1. Power Rotation...........highly severe
2. Mandatory Curtailment....moderately severe
3. Price Regulation.........somewhat severe

The Voluntary Conservation Strategies remain low in expected impact because people and institutions will not apply them beyond a certain, low-level limit of discomfort and disruption. Likewise, Voltage Reduction will produce little in the way of disruption except in certain technical-machinery and industrial-processing cases.* It is also apparent that these two strategies (Voluntary Conservation and Voltage Reduction) are quite limited in their effectiveness and can produce at most a 10% savings in electrical power usage.

Within a particular strategy, the following observations can be made:

Power Rotation:

- Expected to impact the fixed and low income residences more severely than others because of lack of flexibility in their living style.
- Expected to place a greater burden on the small store and restaurant owners, on small business offices, and on medical institutions.
- Expected to disrupt the small industrial firms and the highly energy-intensive firms most severely.

Mandatory Curtailment:

- Expected to pose severe hardship on the fixed and low income residences because they have less margin for cutting back on electrical usage.
- Expected to produce a high impact on food stores, smaller offices, restaurants, and medical institutions and on government services such as water and sewage treatment, police, etc.
- Expected to disrupt the small and medium sized firms, especially those which are energy intensive.

Price Regulation**:

- With a proper exemption floor, these strategies should have only minor impact on fixed and low income residences.
- Expected to produce severe economic problems for small food stores, small restaurants, and for small, highly energy-intensive industrial firms.

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*Voltage reduction and power rotation strategies which may adversely effect certain machinery and/or processes can generate adverse feedback for utilities in the form of suits for damage caused by the selected strategy. In cases where insufficient warning has been given of such changes in the power supply, courts have held utilities liable for equipment damage and punitive damages.

**An important area for study is the question of the effect of price on electrical energy use. Recent studies at Oak Ridge National Laboratory(15) indicated the following "elasticity figures" (percent decrease in use for a one percent increase in price):

Residential:	0.4% decrease
Commercial:	1.1% decrease
Industrial:	1.2% decrease

Although these results are from relatively "short term" studies of the TVA region where price increases have been occuring over the past several years, there is considerable uncertainty as to the applicability of these numbers for the "very short term," such as would apply to a quasi-crisis situation. Such very short-term price elasticity data would be most useful in more precisely determining the effectiveness of price restructuring (in bringing about immediate reduction in electrical energy usage). Nevertheless, in the present assessment we are primarily concerned with impacts of alternative strategies on users, and therefore we have included evaluation of the consequences to users of such price restructuring strategies.

TABLE VII Master Impact Matrix

CONSUMER SECTORS

STRATEGIES	RESIDENTIAL								COMMERCIAL																INDUSTRIAL								
	1 to 4 Units				5 + Units				Stores				Res-tau-rants		Offices			Institutions							Large			Medium			Small		
									Food		Non-Food					Pri-vate		Educ./Relig.			Medical			Government Services									
	Fixed	Low	Medium	High	Fixed	Low	Medium	High	Small	Large	Small	Large	Small	Large	Public	Large	Small	Public	Large	Small	Public	Large	Small		Low	Medium	High	Low	Medium	High	Low	Medium	High
Media-Intensive Campaign	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Personnel-Intensive Camp.	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Surcharge	L	M	M	M	L	L	M	M	H	M	M	M	H	M	L	L	L	L	M	M	M	M	M	M	L	M	M	M	M	M	M	M	H
Rate Increase	L	M	M	M	L	L	M	M	H	M	M	M	H	M	L	L	L	L	M	M	M	M	M	M	L	M	M	M	M	M	M	M	H
Voltage Reduction	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Mandatory Curtailment (1)	H	H	M	M	H	H	M	M	H	H	M	M	H	M	M	M	H	M	M	H	M	M	H	H	M	M	H	M	H	H	H	H	H
Mandatory Curtailment (2)	M	M	M	M	H	H	M	M	H	H	M	M	H	M	L	M	M	M	M	M	M	M	H	H	M	M	H	M	H	H	H	H	H
Power Rotation	H	H	M	M	H	H	M	M	H	M	H	M	H	M	M	M	H	M	M	M	H	H	H	H	M	H	H	M	H	H	H	H	H

KEY: H = High Impact, M = Medium Impact, L = Low Impact

4.6 FACILITATING PUBLIC INVOLVEMENT

An important goal underlying the present study was to address the question of what constitutes the proper and necessary role of "the public" in deciding among alternative strategies for planned reduction of electrical energy. By implication, the broader question of public participation in technological decision-making is being raised as well. In the present study, the student-faculty team (the task group) joined by representatives of the oversight committee acted as surrogate for all publics in determining - with informed subjectivity - the relative impacts of the alternatives. Although certain kinds of expertise were present in the task group, and despite the obvious lack of representatives from many user subgroups, the "model" of the task group and oversight committee was more representative of a public equipping itself to make an important decision than of an insulated body of technical and bureaucratic expertise. The team gathered the information, consulted the experts when necessary, analyzed data and developed a methodology for choosing among alternatives. During this process, the group underwent a mutually self-educating experience as to the total problem perspective. This was as true for participating representatives from NES and TVA - functioning out of their customary environment of "institutional expertise" - as it was for students and faculty. That the information developed in this assessment was "useful" is attested to by the fact that several members of the task force served as advisors to the Mayor's office during the crisis period, previous to and during the UMW coal strike affecting TVA in November of 1974. The policy statement issued by the Mayor's office during this period utilized many of the results of this study.

One therefore wonders if this "model" of problem-oriented technology assessment may be extended to the community at large (or, what is more likely, to identifiable subgroups of the community) who can provide valuable input to the decision-making process. Furthermore, can the university with its multiplicity of resources (including students and faculty) serve as the convenor in such crisis-averting or crisis-moderating exercises? Traditionally the community entrusts the tasks of providing public technical services (utilities, communication, water supply, sanitation, refuse disposal) to a properly constituted, technical authority. The expectations are clearly that expertise will prevail, including planning for unusual and unexpected occurrences. As pointed out in Section 3.2, insulation from public involvement is assured by statute in the case of TVA/NES. In this and in similar cases, the law must be assumed to reflect the general public attitude of "let the expert do it." But that attitude is changing (Section 3.2) reflecting greater social complexity of technical decisions and the consequent demand for public involvement and accountability. It is within this context of increased public awareness and community need that the university is challenged to expand its traditional educational role of professional career preparation and/or liberal, general education. The details of organization and cost-effectiveness are well beyond the scope of this paper.

We would hardly suggest that such a proposed model is without ambiguity. The timing of such university-convened and community-participating assessments in relation to emerging or suspected "crises" is critical. How is it possible to sustain the interests of publics in the absence of the crisis? How can one deal with the problem of conflicting crises such as public concern with environmental issues undercut by concern with energy shortages? How can public inputs be effective when the crisis is fast upon us, and experts must make choices without delay? But "leaving it to the experts" is notwithstanding the more dangerous option as the following frequently-cited caveat attests:

> "It is one thing to urge the need for expert consultation at every stage in making policy; it is another thing, and a very different thing, to insist that the expert's judgment must be final. For special knowledge and the highly trained mind produce their own limitations which, in the realm of statesmanship, are of decisive importance. Expertise, it may be argued, sacrifices the insight of common sense to intensity of experience. It breeds an inability to accept new views from the very depth of its preoccupation with its own conclusions. It too often fails to see round its subject. It sees its results out of perspective by making them the centre of relevance to which all other results must be related. Too often, also, it lacks humility; and this breeds in its possessors a failure in proportion which makes them fail to see the obvious which is before their very noses. It has also a certain caste spirit about it, so that experts tend to neglect all evidence which does not come from those who belong to their own

ranks. Above all, perhaps, and this most urgently where human problems are concerned, the expert fails to see that every judgment he makes not purely factual in nature brings with it a scheme of values which has no special validity about it. He tends to confuse the importance of his facts with the importance of what he proposes to do about them."*

5. CONCLUSIONS AND RECOMMENDATIONS

This study sought systematically to pursue the consequences (technological, economic, social, and political) of strategies designed to reduce electrical energy consumption, given the need for such reduction. The study has succeeded in identifying subclasses of users and reduction strategies and has applied one particular assessment methodology in reaching the conclusions stated in the previous section. An important aid to public-policy formulation would result from the extension of the methodology to involve directly the various affected publics (identifiable groups of residential users in civic organizations, churches, neighborhood community organizations, etc.; Chamber of Commerce, businessmen's associations, trade associations, industrial managers, union representatives, etc.). This would require the development of packaged resource information, and the conducting of workshops to facilitate, to the maximum degree possible, public involvement in the decision-making process.

During the course of our study, (June-December, 1974), public-policy decisions regarding total energy use reduction were being formulated at various governmental and quasi-governmental levels in the TVA region: at the local (Metro-Nashville and the NES), the state (Governor's office of the State of Tennessee), and federal (the TVA itself). The threat of an impending coal strike in August and its brief realization in November of 1974 produced a "crisis" situation which enhanced the value of our effort in the eyes of local officials. Our preliminary assessment, undertaken, as it were, by an independent group, provided useful inputs for the decisions. These inputs were manifested by involvement of members of the task group in various community task forces, appearances on local public information programs, and through dissemination of a formal report.

Nevertheless, it is clear that despite the substantial accumulation and analysis of information there is a need for more data in order to avoid policy decisions which are unnecessarily socially destructive, or which in fact are "counterintuitive" in their effects.** In particular, in order to assess price restructuring or mandatory reduction strategies more completely, it is necessary to know the relationship between income, living standard, and energy consumption in the residential sector. A detailed analysis of billing data correlated with census-tract data is essential. Although we may presume a general correlation between income and electrical-energy use, the quantitative details have a number of implications for policy planning. Not the least of these are guidelines for setting threshholds or lower limits of energy use in price restructuring or mandatory strategies.[16]

Analysis of the political-legal aspects of the power supply system revealed the extent of insulation from direct public accountability which is afforded to the TVA and NES by existing statutes and their implementation. Further knowledge of the "micropolitical" details such as the relationships between decision-making groups, the identity of the key actors in the policy-setting and decision-making drama, the precedents of local customs, etc., all would be an important aid in allowing an optimal choice of strategy by an informed public.

Finally, there are additional technical aspects of the strategies associated with planned reduction which have been neglected in this preliminary analysis and which must be considered in further assessments. The need is clear for the development of methods for user control of equipment to bring about both reduction and redistribution (load leveling). In addition there is a need for new methods for direct utility control, whereby selective reduction (comfort heat but not food refrigeration, for example) could be affected. The need for careful assessment of impacts is obvious in these cases.

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*For example see Harvey Brooks in The Government of Science, M.I.T. Press, 1968, pp. 89,90. The original source of the quote is Harold Laski, "The Limitations of the Expert," Fabian Tract Number 235.

**An example of the latter would be voltage reductions (Strategy III A, of Table II) which although of low general impact would be virtually ineffective in reducing fuel consumption.

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7. BIOGRAPHIES

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THE DESIGN AND PERFORMANCE OF A DISTRIBUTED FLOW WATER-COOLED SOLAR COLLECTOR

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Abstract

Design of a flat plate collector which reduces the temperature differential between the absorber plate and the fluid is described. The reduced temperature differences are shown to yield increase collector performance. Flow characteristics of the collector are examined. Collector thermal performance is illustrated for typical operating and environmental conditions. A cost analysis is presented to demonstrate that material and assembly costs are substantially lower than for any collector presently on the market.

NOMENCLATURE

A_{flow}	cross-sectional flow area, m^2
A_i	tube area, m^2
c	specific heat, W-hr/kgm-°K
D	tube diameter, m
f	friction factor
g	gravitational acceleration, m/sec^2
h	tube wall to liquid heat transfer coefficient, W/m^2-°K
h_w	wind heat transfer coefficient, W/m^2-°K
HR	solar irradiation normal to collector, W/m^2
k	thermal conductivity of absorber plate, W/m-°K
L	collector length, m
m	$\sqrt{U_L/k\delta}$
$\dot{m}$	liquid mass flow rate, kgm/sec
n	number of tubes
N	number of glass covers
Nu	Nusselt number
q_ℓ	energy loss, W/m^2
q_u	useful energy, W/m^2
Q_{fin}	energy to fin, W
Q_{tube}	energy to tube, W
Q_u	useful energy to liquid, W
Re	Reynolds number
S	solar irradiation normal to plate, W/m^2
T_a	ambient temperature, °K
T_b	tube wall temperature, °K
T_i	entering liquid temperature, °K
T_o	leaving liquid temperature, °K
T_p	mean absorber plate temperature, °K
T_w	mean liquid temperature, °K
$\bar{T}$	mean temperature of region of plate between tubes, °K
U_L	collector loss coefficient, W/m^2-°K
V	mean velocity of liquid in tubes, m/sec
V_a	ambient wind speed, m/sec
W	center-to-center tube spacing, m
x	distance along plate (fin) measured from tube center, m
α	plate and tube solar absorptance
δ	thickness of absorber plate, m
ε_g	infrared emittance of glass (0.88)

ε_p infrared emittance of plate and tube

η fin efficiency

θ inclination of collector with respect to horizontal, deg

ν kinematic viscosity, m^2/sec

ρ liquid density, kgm/m^3

σ Stefan-Boltmann constant, $5.6697*10^{-8} W/m^2 - °K^4$

τ solar transmission of glass

1. INTRODUCTION

The losses from a flat plate collector increase with increasing temperature and, therefore, it is desirable that the collector absorber plate operate at as low a temperature as possible, consistent with the desired temperature of the collected thermal energy at the points of use. Temperature drops occur primarily in the various heat exchangers in the system, one of which is the absorber plate itself. This paper considers the temperature effect on the plate and presents a design which reduces the temperature differential between fluid and plate to the point where it is insignificant with respect to effect on collector performance. At the same time, the materials required and assembly costs would seem to be substantially lower than for any collector presently on the market.

The design is similar to flow between parallel plates. However, to reduce the tendency for excessive deflection for forced flow between parallel plates, flow is at negative gage pressure, and the flow channel is maintained by either of two possibilities: a) incorporating corrugations or other forms of surface indentations on one or both sheets or b) placing a porous spacer, such as screen wire, between the two sheets. The various layers are registered with each other, the ends inserted in slotted header tubes and sealed to the tubes and along the edges by appropriate means. Figures 1(a) and 1(b) show these two approaches to distributed flow.

The analytical approach to the problem for the sandwich construction shown in Figure 1(b) would logically be along the lines of flow through porous media, while that required for the flow path shown in Figure 1(a) would be the theory of flow through non-circular tubes. As for approximate approaches, both situations could probably be analyzed fairly accurately by assuming flow between parallel plates, while the flow path shown in Figure 1(a) could be represented by flow through circular tubes of individual cross-sectional area equal to that for the individual flow passage made by the corrugations.

The latter method was used in this paper. This is convenient, since one of the objectives of this work is to compare the performance of flat plate collectors which use the fin-tube absorber plate with that for collectors using distributed flow. The performance of the distributed flow design thus becomes that calculated for the fin-tube plate when the tubes are sufficiently close together. Figure 2 illustrates the general model.

In the analysis that follows, it will be assumed that the tubes are connected in parallel, and that the total cross-sectional tube flow area is 5.5 cm^2 per meter width of collector. The actual flow area for several commercially available collectors is very close to this value. As will be seen later, it is also the approximate value that is needed for the distributed flow design. In the temperature and heat transfer analysis, the calculations show that the maximum rate of collection of useful energy for high performance collectors at high values of irradiation seldom exceeds 600 $watts/m^2$. Accordingly, this value is chosen for purposes of calculation of a maximum design flow rate. A value for such a maximum flow rate is needed in order to determine the regime of flow, i.e., laminar or turbulent. For this latter determination, it is further assumed that at maximum flow rate, the liquid temperature increases 2.5°C per meter length. The analysis is carried out both for water and for anti-freeze solution consisting of half ethylene glycol and half water by mass.

2. THE FLOW PROBLEM

The maximum mass flow rate, per meter width of collector assuming liquid water is

$$\dot{m} = \frac{q_u L}{c(T_o - T_i)} = 0.057 \frac{Kgm}{sec\text{-}m}$$

This is approximately one gallon per minute-meter. Since the flow area is specified, the mean velocity of the fluid can be calculated:

$$V = \frac{\dot{m}}{\rho A_{flow}} = 0.9026 \frac{m}{sec}$$

The number of tubes per meter of width is $n = 1/W$ where W is the center-to-center spacing of the tubes. The area of each tube, multiplied by the number of tubes per meter, is 5.5×10^{-4} m^2.

$$\frac{\pi D^2}{4} \frac{1}{W} = 5.5 \times 10^{-4} \qquad \text{or}$$

$$D = (2.65) \times 10^{-2} \sqrt{W} \qquad (1)$$

The Reynolds number is

$$Re_{(anti-freeze)} = \frac{VD}{\nu} = 2460 \sqrt{W} \qquad (2)^*$$

$$Re_{(water)} = 11{,}500 \sqrt{W} \qquad (3)$$

For turbulent flows $2{,}460 \sqrt{W} > 2000$ (anti-freeze)
$11{,}500 \sqrt{W} > 2000$ (water).

Therefore, if flow is to be turbulent using anti-freeze,

$W > 0.667$ meters

and for water

$W > 0.174$ meters

A value of 15 cm is a realistic maximum value for tube spacing, both in terms of what is available commercially, and also from the point of view of performance. Therefore, flow can be assumed to be laminar in solar collectors that correspond to the assumptions as to flow area made here, and all calculations that follow are based on the assumption of laminar fully developed flow.

Both the Nusselt number and the friction factor can now be easily determined. The Nusselt number for constant heat flux, laminar flow is

$$Nu_D = 4.12 \quad . \qquad (4)$$

The friction factor for laminar flow is

$$f = \frac{64}{Re} \quad . \qquad (5)$$

In a later section, it is shown that when $W < 0.3$ cm the fin-tube plate is almost equivalent in thermal performance to that of a plate at the temperature of the liquid; i.e., losses due to plate-to-liquid temperature differences are practically zero. A logical question is, given $W \approx 0.3$ cm, and from Eq. (1), $D \approx 0.145$ cm, is it possible to have a flow rate of 0.057 Kgm/sec-m with the constraints on pressure that apply to distributed flow systems? The pressure of the flowing liquid must be below atmospheric pressure, but large negative values are unacceptable. The distributed flow system should be capable of generating liquid temperatures of 90°C, as required for air conditioning, and the saturation pressure is, of course, atmospheric at 100°C for water. In general, one would impose an upward flow direction on the plate to be assured of complete filling of all tubes. Upward suction in the case of distributed flow means that the fluid pressure at the top of the collector would be at least as much below atmospheric pressure as dictated by the principles of hydrostatic, i.e., for a collector in the vertical position 3 meters long, the pressure at the top would be approximately negative 0.3 atmospheres with zero flow, and perhaps considerably greater in the negative direction with an adequate flow rate. Therefore, downward flow is required for high temperature of collection, and an adequate system for purging of air during start-up must be provided.

Figure 3 shows the elements of such a flow loop. The float chamber d, and over-flow chamber e serve as pressure regulators so that the pressure at the inlet and exit are below atmospheric in amounts determined approximately by the values of h^u and h^L. During start-up, valve a is opened. The

*The value of ν for 50% by mass mixture of water and ethylene glycol was obtained by extrapolation to 60°C from the CRC Handbook ($\nu \approx 1.0 \times 10^{-6}$ m^2/sec).

air bleed is taken from the headers of the collector at the ends opposite the liquid inlet. The vacuum at a need only exceed the value of h^u by a small amount, so that when valve a is opened, liquid is drawn into the collector from reservoir d, and raised up somewhat from reservoir e. The air is purged out as the collector fills, with the system always at negative pressures. When the air is removed, flow proceeds from top to bottom automatically.

The most desirable situation is probably for the pressure to be constant as the fluid flows downward through the collector. The head loss then becomes simply L sin θ, so in accordance with the Darcy equation

$$L \sin \theta = f \frac{L}{D} \frac{V^2}{2g} \quad .$$

Using Eqs. (1), (2), (3), and (5), one obtains the value for D for 0.057 Kgm/sec-m flow rate at constant pressure

$$D(\text{water flow}) = 2.55 \times 10^{-4}/\sqrt{\sin \theta}$$

$$D(\text{anti-freeze}) = 5.5 \times 10^{-4}/\sqrt{\sin \theta}$$

Or, for $\theta = 45°$

$$D(\text{water, p=const}) = 3.03 \times 10^{-4} \text{ m} = 0.0303 \text{ cm}$$

$$D(\text{anti-freeze, p=const}) = 6.54 \times 10^{-4} \text{ m} = 0.0654 \text{ cm}$$

These are minimum values, i.e., smaller values would reduce the flow rate below the choosen value of 0.057 Kgm/sec-m. The larger of the two values, that for anti-freeze, is somewhat smaller than required, according to the condition that $D \approx 0.145$ cm. Thus achieving adequate flow rate is not a problem, according to these calculations.

3. THE TEMPERATURE AND HEAT TRANSFER PROBLEM

The solar collector looses energy to the air and sky according to the equation

$$q_\ell = U_L (T_p - T_a) \qquad (6)$$

T_p is the mean plate temperature, including the tube portion, defined by the following equation

$$T_p = \frac{(W - D)\overline{T} + D\, T_b}{W} \qquad (7)$$

The value of $\overline{T}$ in Eq. (7), the mean value of the plate temperature in the region between tubes, is calculated using the usual extended surface theory. This problem has been adapted for solar absorber plates by Duffie and Beckman(1)*, and the fin temperature is given by the following equation

$$\frac{T - T_a - S/U_L}{T_b - T_a - S/U_L} = \frac{\cosh mx}{\cosh m(W - D)/2} \quad ,$$

or integrating T dx over the length of fin(W - D)/2, one obtains the mean temperature $\overline{T}$ of the fin portion of the plate:

$$\frac{\overline{T} - T_a - S/U_L}{T_b - T_a - S/U_L} = \frac{\tanh m(W - D)/2}{m(W - D)/2} = \eta \qquad (8)$$

where $m = \sqrt{U_L/k\delta}$. Heat conduction in the direction of fluid flow is neglected in the derivation of Eq. (8).

The value of T_b in Eq. (7), the tube wall temperature, is obtained as follows:

$$Q_u = h\, A_i (T_b - T_W) = h\, \pi\, D\, L (T_b - T_W) \qquad (9)$$

where Q_u is the useful energy collected over an area of width W and length L. From Eq. (4),

$$h = k\, Nu/D$$

so

$$h\, D_{(water)} = 2.73 \text{ W/°K} \qquad \text{and} \qquad (10)$$

$$h\, D_{(anti\text{-}freeze)} = 1.52 \text{ W/°K} \quad . \qquad (11)^{**}$$

*Bracketed numbers refer to entries in REFERENCES.

**A value of 0.415 watts/m-°C was used for 50% mixture of ethylene glycol and water (from the CRC Handbook).

Using the definition of fin efficiency, the thermal energy flowing to the tube from the fin is

$$Q_{fin} = (W - D)L\ [S - U_L(T_b - T_a)]\eta \quad . \tag{12}$$

The heat flow to the tube due to the solar radiation is

$$Q_{tube} = DL[S - U_L(T_b - T_a)] \quad . \tag{13}$$

The heat flow into the liquid is

$$Q_u = Q_{fin} + Q_{tube} \quad .$$

Combining Eqs. (9), (12) and (13) and solving for T_b, the result is

$$T_b = \frac{[(W - D)\eta + D](S + U_L T_a) + h\ D\ \pi\ T_w}{h\ D\ \pi + [(W - D)\eta + D]U_L} \quad . \tag{14}$$

The tube diameter D in Eq. (14) can be expressed in terms of W using Eq. (1). The loss coefficient U_L was evaluated using the emperical equation developed by Klein(2):

$$U_L = \left(\frac{N}{(344/T_p)[(T_p - T_a)/(N + f)]^{0.31}} + \frac{1}{h_w}\right)^{-1} + \frac{\sigma(T_p + T_a)(T_p^2 + T_a^2)}{[\varepsilon_p + 0.045N(1 - \varepsilon_p)]^{-1} + [(2N + f - 1)/\varepsilon_g] - N} \tag{15}$$

where

$$f = (1.0 - 0.04h_w + 5.0 \times 10^{-4}\ h_w^2)(1 + 0.058N); \tag{16}$$

and

$$h_w = 5.7 + 3.8\ V_a \tag{17}$$

All temperatures appearing in Eq. (15) should be in degree Kelvin. The procedure used to evaluate collector efficiency for various values of tube spacing is as follows:

(1) Assume values for the following parameters:

Liquid temperature, T_w

Solar irradiation normal to the collector plate, HR

Solar transmission and absorptance product, $\tau\alpha$; $\tau\alpha$ = 0.87, 0.80, 0.75 for N = 1, 2, 3, respectively

Wind speed, V_a

Air temperature, T_a

Infrared plate emittance, ε_p

Fin conductance, $k\delta$

Water or anti-freeze

(2) Determine the loss coefficient U_L based on an assumed plate mean temperature, T_p.

(3) Calculate the value of T_b using Eq. (14).

(4) Calculate mean plate temperature using Eq. (7). The calculated value of T_p is compared with the assumed value, and a corrected estimate for T_p is made and the process repeated. After a satisfactory value of T_p has been found, the useful energy collected per unit area is found from the following equation

$$q_u = S - U_L(T_p - T_a) \quad . \tag{18}$$

Calculations were made for the two values of liquid temperature of 60 and 90°C, and 60°C value being representative of building heating and water heating requirements, and the 90° being the approximate temperature needed for absorption air conditioning. In each of these cases, an air temperature must be assumed, and a nominal value of 10°C was chosen to correspond to the 60°C temperature of collection, and 35°C was chosen as a value appropriate for the 90°C collection temperature. For each of these pairs of values of air and liquid temperature, the value of infrared emittance, and choice of fluid (water or anti-freeze) were varied. The combinations are as follows:

Air Conditioning: T_w = 90°C, T_a = 35°C
- ε_p = 0.1, Working fluid water
- ε_p = 0.95, Working fluid water
- ε_p = 0.95, Working fluid anti-freeze

Heating: T_w = 60°C, T_a = 10°C
- ε_p = 0.95, Working fluid water
- ε_p = 0.10, Working fluid water

For all calculations, the wind speed was assumed to be 5m/sec, and the $\tau\alpha$ product 0.80 (two glass covers). In all cases, back and side losses were neglected.

Figures 4, 5, and 6 are the air conditioning cases. They show the efficiency versus tube spacing W for three values of solar irradiation normal to the plate, HR = 1000, 750 and 500 watts/m^2, and for four values of fin conductance, $k\delta$ = 0.001, 0.01, 0.1 and 10 watts/°K. For each value of solar irradiation normal to the plate, the horizontal line labeled $T_p = T_w$ corresponds to the efficiency for a plate which has a temperature equal to the water temperature. The various curves of efficiency versus W show that as the tube spacing decreases, the effect of fin conductance on efficiency decreases until at W = 0.3 cm, the efficiency is the same for all values of $k\delta$. Furthermore, at this same value of W(0.3 cm), the efficiency of the fin-tube design is within 1% of that for the case of $T_p = T_w$. Figures 5 and 6 show that use of anti-freeze results in a drop in performance as compared with that for water only for large $k\delta$ values. In any case, at W = 0.3 cm, the performance, even with anti-freeze as a working fluid, is essentially the same as that for distributed flow.

Figures 7 and 8 show similar results for the two cases of water heating, Figure 7 for an infrared plate emittance of 0.1, while Figure 8 is for $\varepsilon_p = 0.95$. The condition that

$$\eta_{\text{fin-tube}} \approx \eta_{\text{distributed flow}} \quad W \leq 0.3 \text{ cm}$$

applies for these conditions also.

In all the situations described above the effect of fin conductance vanishes at $k\delta$ = 10, or in other words, $k\delta = 10$ is equivalent to $k\delta = \infty$. Even at $k\delta$ = 0.1, most of the losses are associated with the tube wall-to-water temperature drop. The value of $k\delta$ = 0.1 is typical of several commercially available collectors.

The information shown in Figures 4 through 8 is shown in another way in Figures 9 and 10. These curves show the relative output increases when distributed flow is used instead of tube flow. This percent increase is plotted vs. W, for various cases previously described, and is 25% for $k\delta$=0.1, HR = 1000 W/m^2, W = 15 cm, ε_p = 0.95, T_w = 90°C, T_a = 35°C, as shown in Figure 9 for anti-freeze. When water is used instead of anti-freeze, the percent increase is about 18%.

The use of a selective black coating on the absorber plate allows the plate to operate at a high temperature without such a great loss, since the loss coefficient is low. The reduction in collection temperature, shown in Figure 10, also reduces the loss coefficient.

The percent increase for distributed flow vs. fin-tube flow for HR = 1000 W/m^2, W = 15 cm, ε_p = 0.1, T_w = 60°C, T_a = 10°C, anti-freeze, is only 12% while use of water instead of anti-freeze places the increase at 8%.

The curves in Figures 9 and 10 all merge at $W \approx 0.3$cm at essentially zero percent increase, showing again that for $W \leq 0.3$ cm, the losses associated with the plate-to-water temperature difference is negligible.

The above figure shows the effect of mean plate to water temperature difference without giving any direct indication of the actual value of this difference. Figures 11 and 12 show plots of plate temperature vs. W, for the various cases described above. Figure 11 is for the technically important case of $k\delta$ = 0.1 W/°K, and it shows, for example, that the plate operates at 24°C (mean value) above the water temperature when HR = 1000, ε_p = 0.95, anti-freeze, 2 covers, T_w = 60°C, T_a = 10°C.

Figure 12 is the same as Figure 11, except that the effect of $k\delta$ on $T_p - T_w$ is shown. This curve shows in a third manner that when $W \leq 0.3$ cm, $T_p \approx T_w$.

A comparison of the percent increase in energy gain using distributed flow with that for specific commercially available absorber plates is possible. However, the particular total design in which an absorber plate is marketed, in terms of infrared emittance, number of covers, etc., is not particularly relevant, since we are making no claims in connection with these variables. Accordingly, in the following discussion, the assumption is made that the absorber plate is used in arbitrarily assumed collector, with respect to cover transmittance, infrared emittance, number of covers, etc.

The values of W and kδ of 15 cm and 0.1 W/°K spectively are appropriate for the Revere Collector and the Sun-water collector. The tubes in the Revere Collector are bonded to the plate by means of copper-loaded epoxy, while in the case of the Sun-water collector, silicone rubber and aluminum foil is used for this purpose. We have assumed a perfect thermal bond in our calculations. Neglecting this and other design differences between these two collectors and our model, the percent gain in collected energy, distributed flow vs. the given fin-tube designs, would be between 8.5% (Fig. 10) and 25.5% (Fig. 9). The smaller value corresponds to T_w = 60°C, water, and a selectively coated surface, whereas the larger value corresponds to T_w = 90°C, non-selective surface, and anti-freeze. The lower value (8.5%) corresponds to a situation that is not presently available in these collectors (selective black) whereas the larger (25.5%) is a realistic number in terms of current usage.

The case of single-cover non-selective surface collectors has not been included in the results shown in our figures. However, a single-cover collector with a selective black absorber plate is a very good combination. Let us assume that the Revere or Sun-water collector is made available with this single cover-selective black combination, and is used for high temperature collection, say T_w = 90°C. A reasonable question is, what would be the comparative performance of these collectors and the distributed flow design, should the selective black degrade? Because of the high loss coefficient for such a situation, the distributed flow would produce a substantial improvement, 40% in this case if anti-freeze is used.

In general, the higher the loss coefficient, the better the distributed flow system will appear on a comparative plot such as Figures 9 and 10. The values in these figures are lower than the actual values should be, because the back and edge losses (as well as tube-to-plate bond) were neglected.

The Pittsburgh Plate Glass Collector uses an absorber plate that corresponds closely with the assumptions used in our calculations, with W ≈ 6.3 cm, and kδ ≈ 0.3 W/°K. For the situation of high fluid temperature, T_w = 90°, T_a = 35°, a non-selective surface, and HR = 1000 W/m^2, the relative percent increase using distributed flow would be between 4 and 7% depending on whether water or anti-freeze is used. The lower fluid temperature case (T_w = 60°C, T_a = 10°C), gives a similar relative percent increase of 3.7% and 6.5%.

4. DISCUSSION AND CONCLUSIONS

The experimental program using the distributed flow concept has not proceeded beyond the stage of flow experiments with certain sandwich and corrugated systems.

The flow rate has been found adequate for two experimental designs, one which represents the corrugated vs. plane surface system illustrated in Figure 1(a), and the other representing the sandwich construction shown in Figure 1(b). In the former case, the corrugated side of a 2' × 4' piece of "penticor," a commerically available decorative glass, was used with a plane sheet of 0.005" copper. The edges and headers were sealed with silicone rubber. The contour of the corrugations in the penticor are approximately sinusoidal. The peak-to-peak distance is 1/8", while the depth of the pattern is 0.027". This gives a flow area of 3.44 cm^2/m, a value somewhat below our assumed value of 5.5 cm^2/m. The flow rate, using water and for zero pressure differential (as per the discussion in the section on flow), was 0.114 Kgm/m-sec. This is for the vertical position. For θ = 45°, the flow rate should be 0.080 Kgm/m-sec for zero pressure differential. The values of W and D are 0.32 cm and 0.12 cm respectively, where D is the diameter of a circle of area equal to that of the individual flow passages in the penticor-copper sheet combination. The comparison is summarized for θ = 45°:

	Predicted Need	Penticor-Copper Sheet
Flow Rate	0.057 Kgm/m-sec	0.080 Kgm/m-sec
W	0.3 cm	0.32 cm
D	0.12 cm	0.14 cm

Experimental work is continuing with this system, since the flow area and shape are very close to what is needed. The values obtained as of this writing are approximate, and it is clear that the flow area, and therefore flow rate, is not independent of pressure level, since the pressure determines the closeness of fit of the copper sheet to the corrugations.

Flow experiments have also been made using wire mesh as a spacer. Ordinary screenwire presents too much resistance to flow, and a coarser mesh is required. Flow experiments were conducted using 1/8" × 1/8" mesh brass screen between plexiglass sheets. The mean flow area was 13 cm^2. The flow rate measured was 0.15 Kgm/m-sec. This is approximately twice the chosen maximum design value.

The ultimate criterion is cost of the collector per unit of energy collected. As indicated above, the distributed flow collector has the highest performance possible from the point of view of plate temperature distribution; but estimates of cost are difficult to make, since the anticipated useful life of the collector must be known. The PPG collector used an absorber panel made by the Olin Brass Co. In the literature describing their absorber panel, the statement is made that the panel is not guaranteed against corrosion damage, regardless of cause. On the other hand, the Sun-water and Revere collectors use copper tubes for flow passages. The distributed flow panel would probably be constructed of 0.005" copper sheet. This thickness gives adequate strength by a large margin of safety from the point of view of sustaining the compressive force due to the atmospheric-fluid pressure differential. The use of copper is required from the point of view of corrosion. A fair approach to a cost comparison would start with the dollar savings in material alone, taking into account probable life of the collector. Because of the stated no guarantee against corrosion "regardless of cause" in the Olin Brass literature, the materials used in the PPG collector will be weighted with a factor of 2. The following table gives the materials cost comparison. The cost is based on current prices 500 lb lots. The prices per 100 lbs used in the following calculation is:

0.005" copper	\$173.52
0.020" Al	174.00
0.010" copper	161.42

	Material	Wt/ft^2,lbs	Cost, \$/ft^2
Distributed Flow	Copper	0.5	0.87
PPG	Al	0.9 × 2 = 1.8	3.15
Revere	Copper	2.2	3.54
Sun-Water	Copper tubes	1.2	1.93
	Al plate	0.29	+ .50
			2.43

The rates for copper tubes were assumed equal per pound to that for 0.010 sheet copper. The cost of the 0.060" roll bond product was assumed equal to that of the 0.020 aluminum, per pound.

The table shows that a fair approximation to the dollar savings in materials is from \$2.67/ft^2 for the Revere collector to \$1.56 for the Sun-water, with the average material savings being about \$2/ft^2.

On the other hand, the collector efficiency for distributed flow will be about 44%, as compared to 38.4%, as shown for the HR = 750 W/m^2 in Figure 8. Thus, for example, if 800 square feet of collector is needed in a particular installation using fin-tube construction, area required to produce the same amount of energy using distributed flow would be

$$A(\text{dist. flow}) = 38.4/44 \times 800 = 700 \text{ ft}^2$$
(\$12/ft^2)

At current prices, this reduction in area required would represent a savings of \$1200. Furthermore, the 700 square feet of distributed flow collector would cost less by 700 × 2 = \$1400, with a total savings for the unit of \$2600.

$$\$1400 = (700 \text{ ft}^2 \times \$2/\text{ft}^2)$$

On a national scale, the savings on the 2000 units to be constructed as demonstration units would be \$5,200,000.

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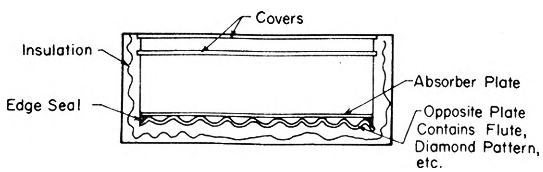

Fig. 1(a) Two plates, one or both being fluted or otherwise roughened to provide a uniform passage for flow of water.

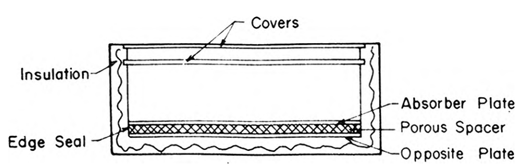

Fig. 1(b) The two parallel plates, with a porous spacer, such as screen wire, between.

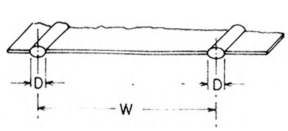

Fig. 2 Model for calculations, tube flow area $= 5.5\ cm^2/m$, $D = 2.65 \times 10^{-2} \sqrt{W}$ as W is varied.

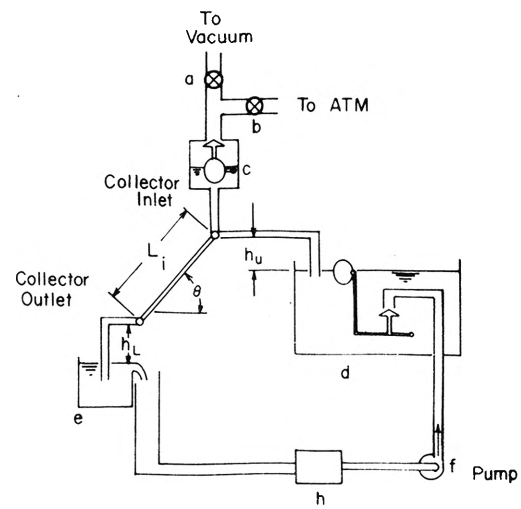

Fig. 3 Flow loop for flow downward through the collector.

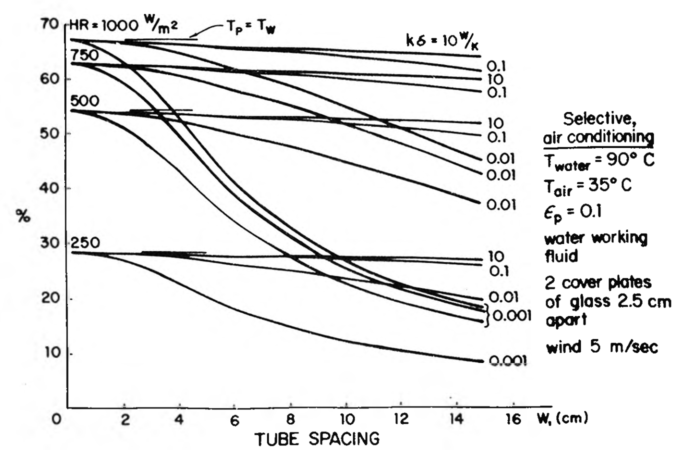

Fig. 4 Efficiency vs tube spacing for various fin conductance and irradiation.

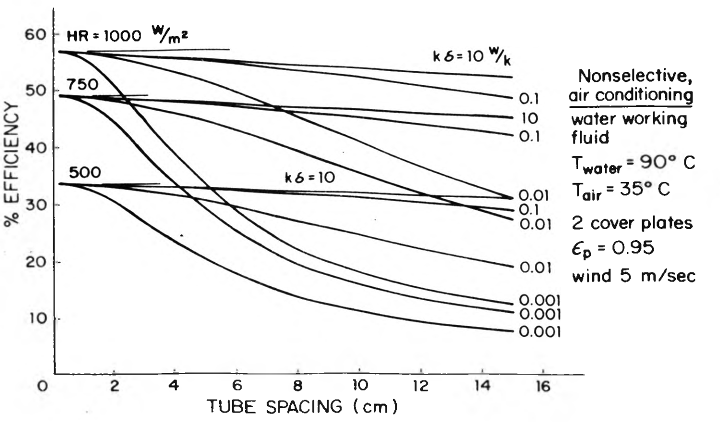

Fig. 5 Efficiency for various conductivities, solar input, and tube spacing.

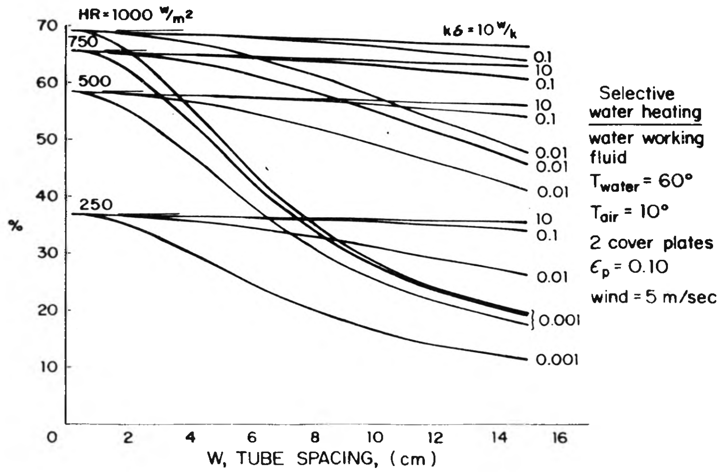

Fig. 7 Efficiency vs tube spacing for various values of conductance and irradiation.

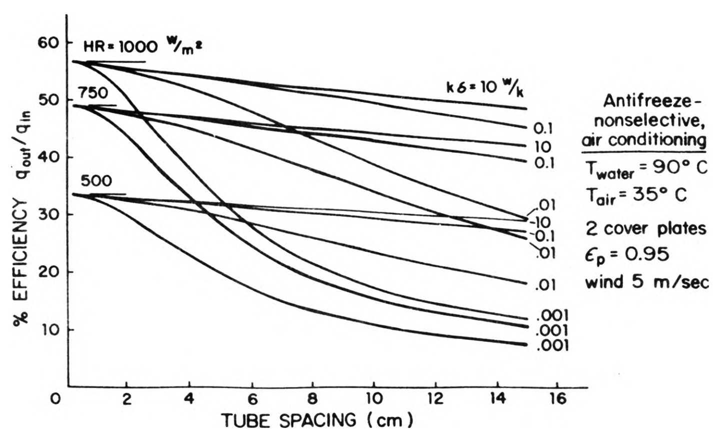

Fig.6 Efficiency for various conductivities, solar input, and tube spacing.

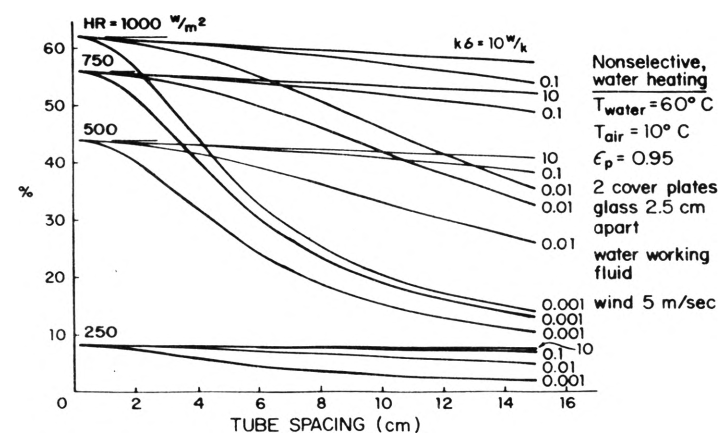

Fig. 8 Efficiency vs tube spacing for various values of kδ and HR.

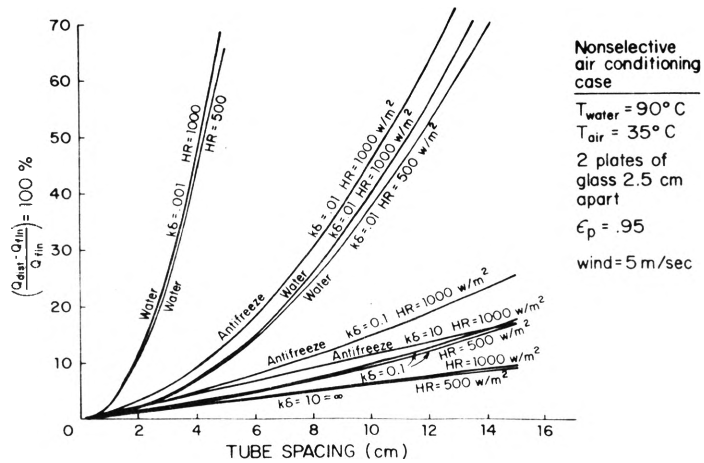

Fig. 9 Relative energy output increase using distributed flow instead of tube flow.

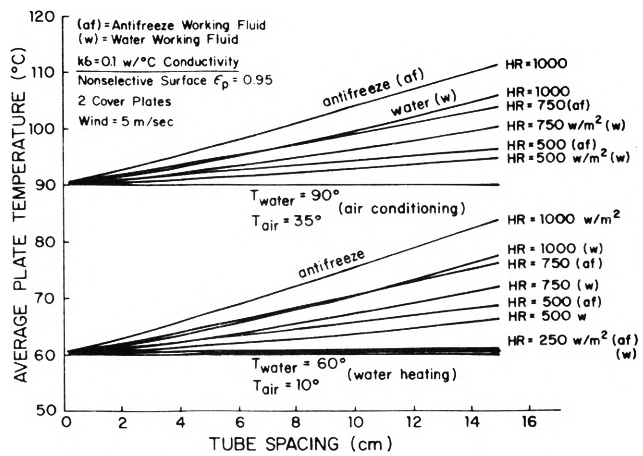

Fig. 11 Average plate temperature vs tube spacing, solar input, water vs antifreeze working fluid.

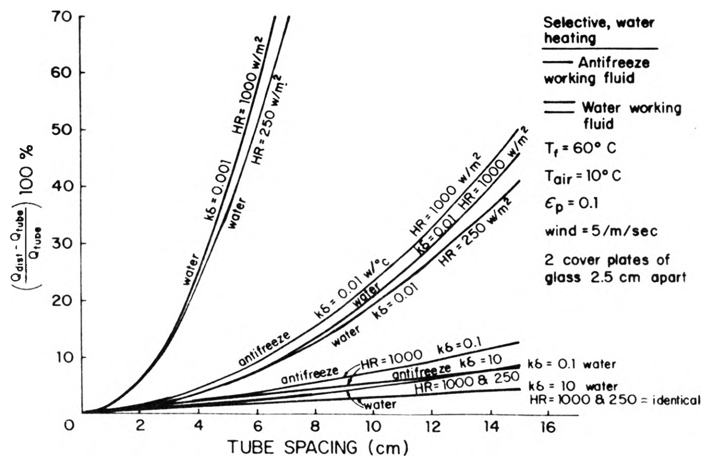

Fig. 10 Relative increase in energy output of distributed flow over tube flow.

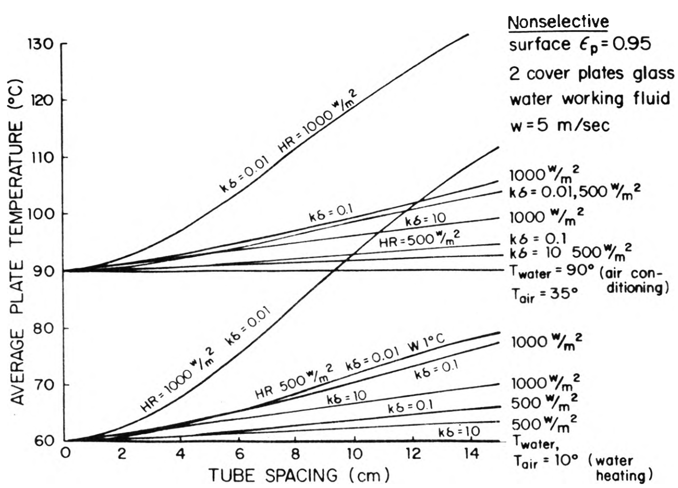

Fig. 12 Average plate temperature vs tube spacing, conductivity, and solar input.

A COMBINED DIGITAL-ANALOG TRACKER FOR TERRESTRIAL APPLICATIONS

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ABSTRACT

A combined Digital-Analog Tracker is suggested to allow maximum efficiency in a solar-electrical energy converter, utilizing a twelve-foot parabolic collector. The analog tracker compares solar beam radiation to ambient (diffuse) light to obtain optimum placement of the collector when the sun is visible. The digital portion of the tracker utilizes a wired program which derives information on solar position from a non-volatile random-access semiconductor memory. This arrangement allows accurate mapping of the sun even when the sun is obscured by atmospheric phenomena which would make mapping impossible.

INTRODUCTION

In order to optimize the collection of direct solar radiation, it is necessary to maintain the orientation of the collection surface normal to the sun's rays. The Solar-Kine[1] project at the University of Missouri - Rolla involves the collection and concentration of solar energy as a part of a solar energy conversion process. Studies[2,3] relating to the optimization of collector-absorber efficiency, collector concentration ratio and useful energy indicates the requirement for very precise tracking whenever the sun is visible. Reisbig[4] has shown that, for concentrating systems, the maximum allowable tracking error during normal operation is approximately 0.5 degrees in both azimuth and elevation.

This paper describes a combined digital-analog system which will maintain accurate tracking of a visible sun and limited tracking ($\pm 2^{\circ}$) of an obscured sun. The system is economical, reliable and simple to operate.

Analog Tracking System

The technique used to track the sun in normal operation of the system employs an analog comparator. The comparator consists of three major subsystems: a mechanical collimator; a photoresistive bridge, error detecting circuit and amplifier; and a hysteresis switch (Fig. 1).

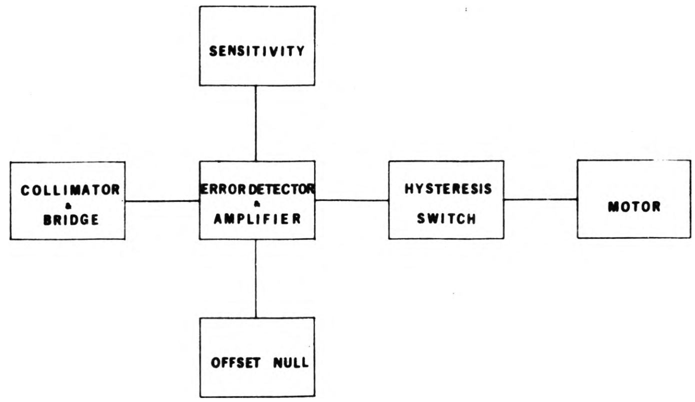

Fig. 1. Block Diagram of the Analog Tracking System

The mechanical collimators (Fig. 2) are constructed around a length of brass waveguide of rectangular cross-section. The end of the waveguide which is normally oriented toward the sun, is covered by a piece of clear plexiglass which has been taped to leave only a small (approx. 1/8")slit through which light may pass. The length of the waveguide has been experimentally determined to enhance the directional properties of the slit. The net "lock-on," or tracking range of the collimator system has been found to be very close to a $\pm 2.5^{\circ}$[5]. By restricting the lock-on range of the analog tracker (that is, the portion of the sky in which the sun must exist to cause tracking) to $\pm$ 2.5 degrees the selectivity of the tracker is greatly improved. Good selectivity minimizes the effects of extraneous light sources such as glare, reflected sunlight, and artificial light.

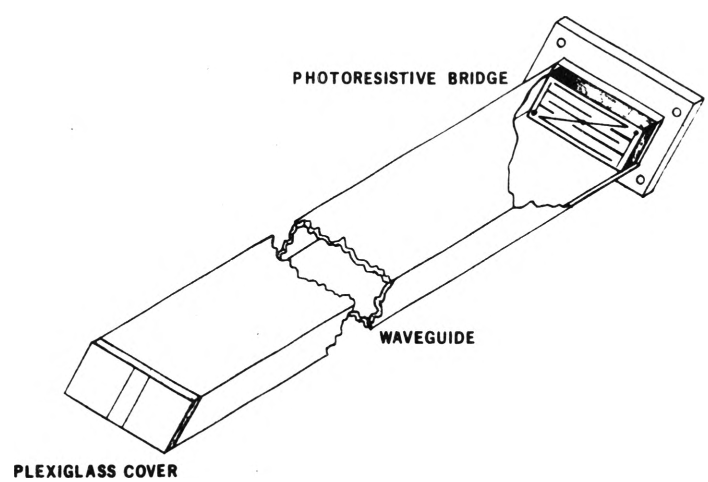

Fig. 2a. Collimator and Photobridge

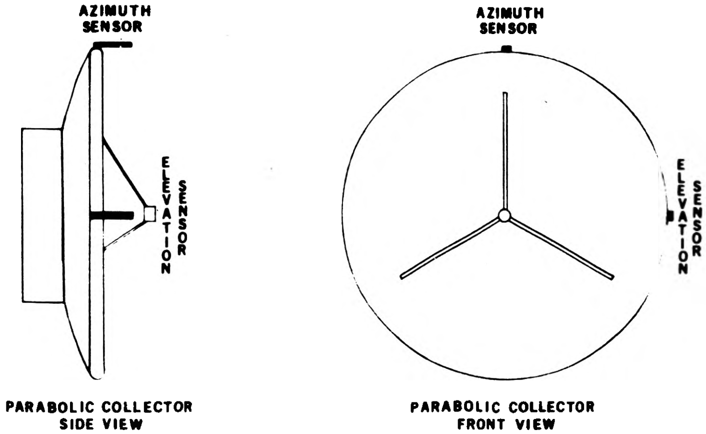

Fig. 2b. Location of Comparator Units on the Dish

The actual analog comparator is made up of a photoresistive bridge, and an error detector-amplifier connected, as shown in Fig. 3.

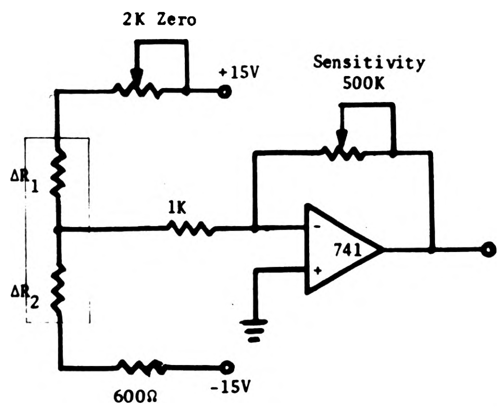

Fig. 3. Diagram of the Analog Comparator Unit

The photoresistive bridge sits snugly in the waveguide, at the end opposite the plexiglass lens. The three non-trivial conditions which describe the operation of the comparator are:

(1) Solar beam radiation equally incident upon both sides of the bridge.

(2) Solar beam radiation unequally distributed over the bridge.

(3) Diffuse radiation <u>only</u> present on bridge.

In the first case, the intensity of the light is equal on both sides of the bridge, making the resistance of both sides equal. With both resistances equal, the error voltage at the amplifier input is zero. Assuming that the output null is adjusted to yield zero output for zero input, the output voltage of the amplifier for equal beam irradience will be zero. In the second case, one side of the bridge is better illuminated, making the resistance of that side lower than the resistance of the other side. Hence, the error voltage will be driven either positive or negative as one side or the other receives more beam radiation. The polarity of the error voltage corresponds to the polarity of the poorly illuminated side, while the magnitude of the error voltage indicates the difference in areas illuminated. The error voltage is amplified and a portion of the output is fed back into the input through the gain control. Adjustment of the gain control determines the output voltage for a given error voltage or a given positional error, and hence determines the <u>sensitivity</u> of the error detecting circuit.

The third case to be considered occurs when the sun is outside the tracker's lock-on range and both sides are exposed to diffuse light. Since the diffuse light will be equally incident upon both sides of the bridge the error voltage, and hence the output voltage, will be zero. This result is important, as it insures that the analog tracker will not engage in a random search for the sun throughout the limits of the tracker's motion. If the sun is outside the lock-on range the analog tracker is essentially inoperative until some other system brings the sun within its tracking range of $\pm$ 2.5 degrees.

A final point of the error detector-amplifier which should be considered is the use of the offset null control. It became obvious early in the construction of the analog tracker that perfect mechanical alignment between the collimators (one each for azimuth and elevation) and the collector would not only be costly but unreliable, and would require handling that could not reasonably be expected in the devices' anticipated operating environment. The offset null provides, instead, an <u>electrical</u> means of obtaining precise alignment between the collimators and the collector. Fine adjustments may be made on a periodic basis, if necessary, in a matter of a few minutes by simply changing the setting of a potentiometer.

The Hysteresis Switch is a digital switch which employs hysteresis: that is, a certain value of voltage must be exceeded to cause switching to occur. The hysteresis switch employed in the analog tracker is bipolar; voltages exceeding the hysteresis level will trip one switch or the other, depending on the input polarity. For example, assuming a hysteresis of $\pm$ 0.8 volt, the output voltage of the error detector-amplifier must exceed 0.8 volt to activate one switch, or must exceed -0.8 volt to activate the other switch. Obviously the switches are mutually exclusive: one or the other may be on, or both may be off; however, both may not be on simultaneously. Each hysteresis switch drives a bi-directional motor and gear train. The two functions of the hysteresis switch are:

(1) to prevent oscillation of the collector around the point of zero tracking error, and
(2) to allow an "error zone" about the zero tracking error point, the zone width is determined by adjusting the sensitivity of the error detector-amplifier.

The hysteresis switches are connected to the motors in such a way that, when engaged, the motors tend to drive the collector towards zero tracking error. The motors used in the drive system, because of their internal gearing and, consequently, slow shaft speed, allow very accurate positioning of the collector and minimize the chances of overshoot. These advantages are obtained at the expense of a very slow slew rate, in both azimuth and elevation, of roughly 3^{o}/minute.

<u>Limitation of Analog Tracker</u>

The Analog Tracker, while boasting the advantages of simplicity and great accuracy, has one unavoidable limitation. To minimize tracking error and to prevent interference from extraneous light sources, only a comparatively small cross section of sky is seen by the photoresistive bridge. Should the sun be obscured by rain, dust, fog, or some other atmospheric phenomena for more than a very few minutes, the sun will have passed out of the lock-on range and analog tracking rendered impossible. The need for the accuracy mentioned in the introduction dictates the need for an auxiliary tracking system to maintain coarse positioning at all times during the solar day.

<u>Choice of Auxiliary Tracking System</u>

It became apparent that the narrow-range analog tracking system, described previously, required an additional coarse positioning scheme to keep the collector's attitude within lock-in range of the sun. The nature of the movement of the sun in azimuth and elevation, is described for 21 December, 21 March, and 21 June, in Figure 4.

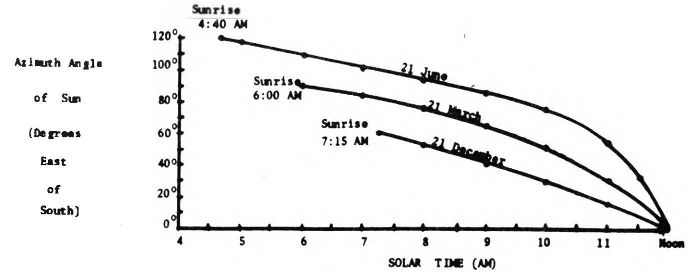

Fig. 4a. Sun Azimuth vs Time-of-day for Selected Days[6].

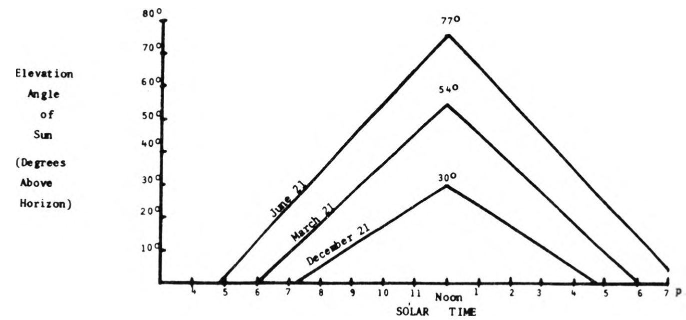

Fig. 4b. Sun Elevation vs. Time-of-day for Selected Days[6].

Note on Symmetry of Sun's Motion: Motion of sun in azimuth and elevation is symmetrical by day with respect to Solar Noon, and by year with respect to 21 Dec. All positional data for Rolla, Mo: 36^{o}N. Lat, 92^{o}W. Long.

To make the system as simple as possible, it was decided to make both auxiliary trackers (azimuth and elevation) identical in design and construction. The limits thus imposed on the system are a function of the motion of the sun. Since on any given day, the velocity of the sun in elevation with respect to a fixed point on earth is constant, no problem is encountered. The velocity of the sun is azimuth, however, is not constant for any day of the solar year. The apparent acceleration of the sun in azimuth is the limiting factor in the design of the auxiliary tracker. After careful consideration, possible solutions were studied: an analog wide-range tracker, a mechanical (motor-driven cam) system, an infrared sensitive tracker, an analog tracker using piecewise linear approx., and a digital tracking unit, using stored data. Of these alternatives, only the digital system satisfied all the requirements under all circumstances.

As may be seen from Fig. 4, the 21st of June has some unique qualities. June 21st is the longest solar day of the year, has the largest azimuth excursion and the sun reaches its maximum elevation all on this first day of Summer. By choosing this day as the worst-case design example, it was insured that the system would work on any other day in the solar year. In the description of the digital system, which follows, all data refers to the 21st of June.

The Digital Tracker

The entire operation of the digital tracker may be summed up in the following words: Stored positional data for the sun is periodically compared with the position of the collector, and if a difference exists, a motor-driven gear train is engaged to drive the error to zero. This description serves to illustrate the simplicity of the tracker's overall operation, but does not hint at the methods used to achieve its function. In considering the digital tracker, two principal topics will be covered in detail. The first of these topics will be the memory, or more importantly, the significance of the memory's concents, while the second topic will be the control sequence which describes in detail the operation of the digital tracker.

To sense the significance of the contents of the non-volatile semiconductor Random Access Memory (RAM) it is necessary to consider what information must be stored there. As shown previously, positional data for the sun is desired, and from the discussion of the analog tracker, the digital tracker is constrained to an accuracy of better than $\pm 2.5^{\circ}$. By considering the data in Figure 4, it becomes apparent that the maximum velocity of the sun is very nearly one degree/minute in azimuth (on June 21st) and 0.175 degrees/minute in elevation (also on June 21st). Since it is desired to make the azimuth and elevation systems identical, only the azimuth system, the limiting case, need be considered. Therefore, it is known that to meet worst case velocity conditions and accuracy restraints, the maximum sampling rate (rate at which positional data is compared and updated) is once every 2 minutes. In 2 minutes the sun can, at worst, have moved 2 degrees, 0.5 degree less than the maximum tolerable error; in general, the sun will have moved much less than 2 degrees, in 2 minutes. The graph of Azimuth Angle of the Sun vs. Solar Time (Fig. 4a) may be modified by enlarging it and breaking the Solar Time Axis up into 220 - 2-minute increments. (The time between sunrise at 4:40 AM and Solar Noon on June 21 is 7 hours and 20 minutes, or 440 minutes, or 220 - 2-minute increments.) Each of these 2-minute intervals is assigned a value, either a logical 1 or a logical 0. The presence of a logical 1 indicates that the sun has moved 2 degrees in azimuth since the last similar movement, while a logical 0 indicates that the sun has not yet moved 2 degrees. (The same procedure is applied to elevation, using Fig. 4b and will, from this point, be ignored.) Since it is known that the sun's excursion in azimuth on June 21st is 120° between sunrise and Noon, 60 logical 1's may be expected, corresponding to 60 - 2-degree increments. By the same reasoning, 160 logical 0's may be expected, making up the remainder of the 220 intervals. The next step requires that each of the 220 intervals be identified by a binary number, starting with sunrise as binary 0, 2 minutes later being binary 1, and so on, up to Solar Noon (219 in binary). Since the maximum value of an 8-bit binary number is 256, an 8-bit word will suffice to account for the 220 invervals. However, the 8-bit binary words corresponding to intervals, containing logical 0's convey no information -- they are 'no-action' words and may be neglected. On the other hand, the 60 binary words corresponding to logical 1's are 'action' words and must be stored. The necessary positional information is now ready to be stored in memory in the form of 8-bit binary words which indicate the times when the collector should have moved 2 degrees. The memory used was a 1 k bit oriented memory. It was rearranged artifically by use of counters and storage registers to appear electronically as a memory made up of 128 - 8-bit words. The positional data which has been gleaned from Fig. 5, may now be inserted in this memory after encoding, as described.

The control sequence (Fig. 5) may be divided, for purposes of explanation, into 3 main parts: (a) Memory Associated Logic; (b) Time Compare Logic; and (c) Position Compare and Control Logic. The main control signal in the sequence is 'scan.' Scan is generated once on every 2-minute decode of a solar time clock (a simple 24-hour digital clock set to local solar time). Upon generation of scan, each 8-bit word in memory is sequentially extracted and placed, one word at a time, into the Memory Information Register (MIR). This binary word is then digitally compared, bit by bit, with the Solar Time Counter(STC). The Solar Time Counter starts at count 0 at sunrise and is incremented by a count of 1 every scan pulse.

If the comparison fails, then another word is checked and so on, until every word has been checked or a comparison found. At the end of an unsuccessful comparison, the control sequence is terminated, as it is not time to check the position of the collector. On the other hand, if a comparison is successful, then the sun's position has moved 2 degrees and the position of the dish must be checked. A shaft angle encoder connected to the base of the collector increments a binary counter, called the Azimuth Position Register (APR), by a count of 1 for every 2 degrees of rotation. When a valid time comparison is made, the contents of the APR are compared to the contents of the Desired Azimuth Register, which contains the number of 2-degree movements the sun has made up to that time. If the DAR and APR compare, then the Analog Tracker is functioning normally and no action is taken - the control sequence terminates. Conversely, if the contents of the APR and DAR are not identical, then the motor is engaged and remains enable until the two position registers do agree. At that point the control sequence is terminated.

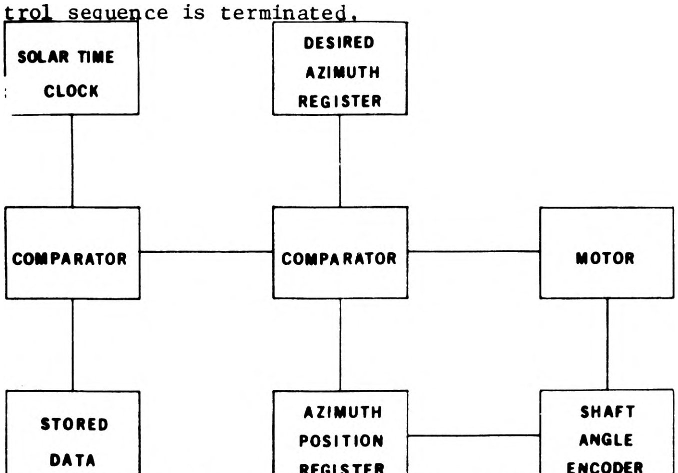

Fig. 5. Block Diagram of the Digital Tracking System

The digital control sequence which defines the operation of the Digital Tracking Unit was written originally in a computer language developed by Hill and Peterson[7], called 'A Hardware Programming Language,' AHPL. The language was intended for use in designing control sequences and simple instructional computers, and has as its chief advantage the fact that the AHPL program may be translated directly into hardware in the form of off-the-shelf TTL packages. No intermediate design phases were required, resulting not only in a great reduction in the number of engineering man hours required and savings in component costs, but most importantly, in making it possible to program the control sequence as a microprocess or unit using today's LST CMOS technology.

Conclusion

By using a combined Digital Analog Tracking Unit, the best advantages of both systems may be exploited. The Analog System results in superb accuracy during normal tracking of the visible sun, while the Digital System keeps the Analog Tracker within lock-on range of the sun at any time during which the sun may become obscured. The combination allows for maximum efficiency in extraction of electrical energy from sunlight even when using collectors with high (1000:1) concentration ratios and critical focusing.

The Analog Tracker is simple in design, requires a minimum of components and is inexpensive to construct. The Digital Tracker employs a straight forward control sequence which may be built with off-the shelf TTL components or, in volume applications, manufactured as a microprocessor on a single LSI CMOS chip.

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CHOOSING ALTERNATIVE ENERGY SYSTEMS UNDER CONDITIONS OF UNCERTAINTY

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Abstract

A methodology for simulating the decision process of an investor deciding between alternative energy systems is presented. The approach assumes the investor bases his decision on cost (or rate of return) and risk. Risk is treated directly in the model and not reduced to a certainty equivalent. The rate of return-risk characteristics of many system combinations allows them to be eliminated as viable choices to the investor without reference to his personal attitude toward risk.

1. INTRODUCTION

The future supply of energy in the United States has recently been receiving a great deal of political, scientific and public attention. Research organizations all over the country have been making projections of possible energy supply and demand conditions into the future as far as the year 2020. Almost all of these forecasts and accompanying models are at the macroeconomic level. They deal with the whole nation, large regions or, at best, states.

This paper deviates from the usual approach in that it deals with a single individual. It presents a microeconomic model of the energy investor's decision process. An energy investor is an individual in a position to decide which alternative type of energy system will be installed in a municipality, private utility or building to meet future demands for energy. Perhaps the best example of this individual is an executive of an investor-owned utility who is formulating plans for capacity expansion. The choices open to the decision maker include: coal-fired systems, gas-fired units, nuclear plants, possibly hydro plants, or some of the more exotic energy systems such as solar, wind or geothermal. It is the independent decisions of numerous energy investors which will dictate the nation's future mix of energy generation and, subsequently, the nation's derived demand for energy-related resources. Given the importance of these individuals, it is worthwhile to investigate their decision-making processes in more detail.

The two major factors entering the energy investor's decision are cost and risk. A large amount of research has been aimed at estimating the cost of alternative systems.* Very little work has been completed that deals with the latter subject. This study attempts to take an initial step in quantitatively evaluating uncertainty and its effect on the decision process. A methodology for dealing with uncertainty is presented. It is hoped that this framework will help stimulate additional research in this important area.

2. GENERAL APPROACH

The individual decision model utilized throughout the discussion is adapted from the Sharpe-Markowitz model of portfolio theory.** The original model was intended to simulate decisions concerning the optimal mix of stocks and bonds in a portfolio. A major advantage of the Sharpe-Markowitz approach over previous work is the explicit incorporation of uncertainty of return into the decision process. The model also eliminates most feasible alternative portfolio combinations without the necessity of evaluating interpersonal attitudes toward risk and rate of return trade-offs. Under some additional assumptions, a unique optimal combination of risky assets can be determined without the use of any subjective comparisons.

The model presented parallels the Sharpe-Markowitz approach very closely. The following discussion will,

* An article on evaluating the total cost of an energy system by J. Bradley and D. Costello appears in these proceedings.

** William F. Sharpe, Portfolio Theory and Capital Markets (McGraw Hill Co., 1970).

therefore, be limited to the adaptations of the model to the energy investment decision process.

Throughout the discussion, the term "energy system" will refer to an organized method of producing energy characterized by the type of fuel used as the major input. An "energy mix" is a combination of energy systems which together meet the entire demand facing the investor. For a utility, the "energy mix" represents the company's generation mix. When the cost of an energy system is mentioned, it refers to the total cost of the unit realized by the owner. The cost includes all generation, fuel handling, land and required pollution control equipment and any other costs incurred in meeting governmental safety, health and environmental regulations.

The energy investment decision model can be divided into three distinct phases.* The first step involves predicting the future return and risks associated with individual energy systems. This phase requires subjective evaluations of the future developments and trends in each of these systems. The interrelationship of these various systems must also be approximated in this phase. The second step is to compute all the possible energy mixes that can be derived by combining systems. The return and risk of each mix is then calculated and compared to other mixes. The final step involves selecting a mix based on the investor's preferences toward risk and return. These three phases will act as a guideline in the discussion that follows (Sections 3-5). Following that discussion, the incorporation of a riskless asset or system will be examined (Section 6). The last section contains a summary of the approach.

3. INDIVIDUAL ENERGY SYSTEMS ANALYSIS

The energy investor is assumed to make his decision based on the expected return of the investment and the uncertainty associated with that return. All relevant factors that affect the investor's decision are assumed to be summarized by these two parameters. The expected rate of return on conventional energy sources can be obtained from historical information. The rate of return on solar and other "new" forms of energy must be gathered by indirect means, including expert opinion and preliminary cost estimates.

The variance of the rate of return will be used to approximate the risk variable. The calculation is somewhat straightforward for conventional energy systems. Some modification in the risk variable may have to be made to incorporate future developments, such as fossil fuel availability, additional pollution control requirements, and/or safety regulations. The risk associated with nonconventional systems can be approximated by again using expert opinion, projected future trends in capital costs, consumer acceptance, storage capabilities and available practical experience with the systems.

The interrelationship of the rates of return for different systems is also required for the analysis. Measures of covariance will be used to estimate these interrelationships. The historical covariance between conventional energy systems can be used as a first approximation for some of the alternatives. Continued work will be necessary to approximate such relationships for unconventional systems. One possible solution involves the use of the expert opinion concerning expectations of returns on different systems. The covariance of each pair of systems could be calculated from this sample. These results would be used as a proxy for the required covariance terms.

4. ENERGY MIX ANALYSIS

Once the characteristics of each alternative energy system have been defined, the investor must choose one or a combination of systems to meet his total demand. The analysis that follows assumes that the investor prefers a larger rate of return to less and prefers less risk to more. In other words, return is considered desirable and risk is undesirable. Based on these assumptions, many combinations of assets can immediately be disregarded. Figure 1 illustrates this point.

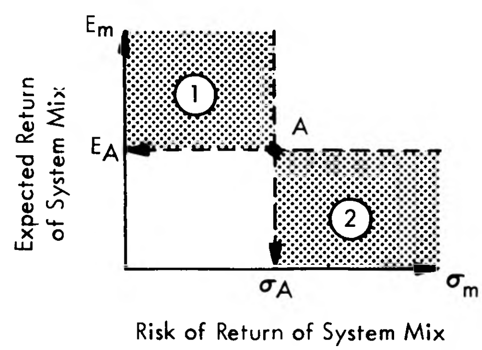

Figure 1 - Preferred and Undesirable Risk-Return Combinations

The combination of energy systems represented by point A in Figure 1 is characterized by an expected rate of return E_A and a risk (i.e., the standard deviation of return) of σ_A.** Combinations of systems which lie in area (1) are all preferred to A. Any combination in area (1) will either (a) yield a higher expected return than A with the same risk (σ_A) or (b) yield a lower risk than σ_A with the same return or (c) yield both a higher return and a lower risk than A. All combinations of systems which lie in area (2) are less preferred than A. Any combination in this area will either (a) yield a higher degree of risk with no increase in return or (b) yield a lower expected return with the same amount of risk or (c) result in a lower rate of return and a higher risk than A.

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* William F. Sharpe, Portfolio Theory and Capital Markets, p. 31 (McGraw-Hill Co., 1970).

** Standard deviation of return is merely the square root of the variance. It is portrayed in the figures for convenience of presentation.

4.1 ALGEBRAIC RELATIONSHIPS OF THE MIX ANALYSIS

The expected rate of return of the entire mix of energy systems represented by point A is comprised of the sum of returns in each component. That is, the expected return of the mix is a linear combination of the expected returns of each system that is part of the mix. Algebraically,

$$E_m = \sum_{i=1}^{n} E_i X_i \quad . \; . \; . \; . \qquad (1)$$

where E_m = the expected rate of return on the entire energy mix

E_i = the expected rate of return of energy system i

X_i = the percent of the total energy mix that is invested in system i (expressed as a decimal fraction of the total)

n = the number of systems in the energy mix

and $\sum_{i=1}^{n} X_i = 1$ and $0 \leq X_i \leq 1$ for all i

The expected return of the entire energy mix will usually be greater than the individual system with the lowest return and less than the return expected from the highest yielding system. If $X_i = 1$ for any one system, the expected return of the mix will equal the expected return of the one system that comprises the entire mix.

In analyzing the uncertainty associated with an energy mix, one must consider the risk associated with each component system and the interaction of these systems. The variance of expected returns of each system will be used to represent individual system risk. The covariance or correlation coefficient will be used as an approximation of the interaction between any two systems in the mix. The variance of system i is the squared deviation of each possible outcome from its expected value, weighted by its probability. Algebraically,

$$\sigma_i^2 = \sum_{k=1}^{\ell} P_k (R_k - E_i)^2 \quad . \; . \; . \; . \qquad (2)$$

where σ_i^2 = the variance of system i

P_k = the probability of outcome k

R_k = the rate of return of outcome k

E_i = the expected return of system i,

$$E_i = \sum_{k=1}^{\ell} P_k R_k$$

ℓ = the total number of possible outcomes.

The covariance between the return of system j and system k is the product of the deviations of the two systems from their respective expected returns, weighted by the joint probability of each set of outcomes. Algebraically,*

$$C_{jk} = \sum_{j,k} Pr\,(R_j R_k)\,(R_k - E_k)\,(R_j - E_j) \; . \; . \; . \qquad (3)$$

where C_{jk} = the covariance between system j and k

$Pr(R_j R_k)$ = the probability of outcome R_k and R_j occurring together

The correlation coefficient between energy systems j and k is given by:

$$\rho_{jk} = \frac{C_{jk}}{\sigma_j \sigma_k} \quad . \; . \; . \; . \qquad (4)$$

where ρ_{jk} = the correlation coefficient between system j and k

σ_j = the standard deviation of system j ($\sigma_j = \sqrt{\sigma_j^2}$)

σ_k = the standard deviation of system k ($\sigma_k = \sqrt{\sigma_k^2}$)

The uncertainty (variance) associated with the entire energy mix is related to the uncertainty of each system in the mix. However, unlike the expected return, this relationship is not linear. The variance of the mix is represented by the following general form:

$$\sigma_m^2 = \sum_{i=1}^{n} \sum_{j=1}^{n} X_i X_j \, \sigma_i \sigma_j \, \rho_{ij}$$

$$\sigma_m^2 = \sum_{i=1}^{n} \sum_{j=1}^{n} X_i X_j \, C_{ij} \quad . \; . \; . \; . \qquad (5)$$

where σ_m^2 = the variance of the energy mix m.

4.2 MIX ANALYSIS ASSUMING ONLY TWO CHOICES

To gain some insight into how the interaction of systems affect the risk of the entire mix, it is helpful to consider the special case of only two systems (i.e., n=2). In this case the expected return and variance of the mix simplify to:

* William F. Sharpe, Portfolio Theory and Capital Markets, p. 41 (McGraw Hill Co., 1970).

$$E_m = X_1E_1 + X_2E_2 \quad (6)$$

$$\sigma_m^2 = X_1^2\sigma_1^2 + X_2^2\sigma_2^2 + (2X_1X_2\,\sigma_1\sigma_2)\,\rho_{12} \quad (7)$$

where X_1 = the percentage of the total invested in system 1

E_1 = the rate of return of system 1

σ_1^2 = the variance of system 1

and $X_1 + X_2 = 1$

The expected return of the mix is a linear combination of the expected returns of the two systems. The variance of the mix depends on the variances of each system, the percentage invested in each system and the correlation of the systems. If X_1 equaled 1 (i.e., $X_2 = 0$), then σ_m^2 would equal σ_1^2. Other combinations of X_1 and X_2 will give a mix of risk that is a combination of σ_1^2 and σ_2^2. The uncertainty of the entire mix will then depend on how the risks of the two systems are correlated. To analyze these situations we will consider the effect of the alternative values of the correlation coefficient (ρ_{12}). Three cases will be examined: $\rho_{12} = +1$, $\rho_{12} = -1$ and $\rho_{12} = 0$.

4.2.1 Case 1; Correlation Coefficient Equal to + 1

If ρ_{12} equals + 1 the systems are perfectly correlated. In other words, whenever the return on one system changes the return on the other moves proportionally in the same direction. The advantage of diversifying your investment between these two systems is somewhat reduced because they both always move in the same direction. The variance of the energy mix can be expressed as: (assuming $\rho_{12} = +1$)

$$\sigma_m^2 = X_1^2\sigma_1^2 + X_2^2\sigma_2^2 + 2X_1X_2\sigma_1\sigma_2$$

$$\sigma_m^2 = (X_1\sigma_1 + X_2\sigma_2)^2$$

$$\sigma_m = X_1\sigma_1 + X_2\sigma_2 \quad . . . (8)$$

In other words, if $\rho_{12} = +1$ the standard deviation of the energy mix is a linear combination of the standard deviation of the two components.

This situation can be depicted graphically. The expected return of the entire energy mix is graphed vertically and the risk of standard deviation of the mix is on the horizontal axis in Figure 2. Point A in Figure 2 represents the mix made up entirely of system 1, while B represents a mix comprised entirely of system 2. The line AB represents the possible combinations of E_m and σ_m attainable by combining systems 1 and 2 in different amounts. That is, each point along the line AB represents different values of X_1 and therefore X_2, since $X_2 = 1 - X_1$.

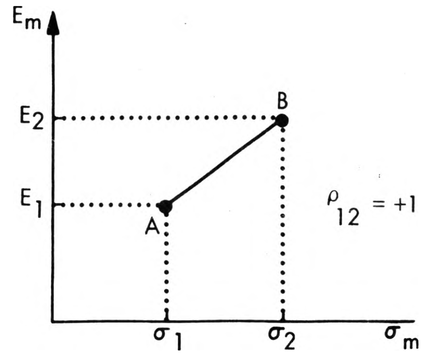

Figure 2 - Possible Combinations of Energy Mix and Return--Two Energy Systems, Perfect Positive Correlation

4.2.2 Case 2; Correlation Coefficient Equal to - 1

The second case we will consider assumes that the two systems are perfectly negatively correlated (i.e., $\rho_{12} = -1$). In this situation if the return on one system declines, the return on the other system will increase by a proportional amount. This makes diversification extremely appealing because investing in both of these systems will insure that the level of risk of the entire mix can be reduced below the risk of any one system. In fact, in the case of a correlation of - 1, risk can be totally eliminated. The following formulation will illustrate this point.

The variance of the mix under $\rho_{12} = -1$ is given by:

$$\sigma_m^2 = X_1^2\sigma_1^2 + X_2^2\sigma_2^2 - 2X_1X_2\sigma_1\sigma_2$$

$$\sigma_m^2 = (X_1\sigma_1 - X_2\sigma_2)^2$$

$$\sigma_m = X_1\sigma_1 - X_2\sigma_2 \quad . . . . (9)$$

The value of X_1 and therefore X_2 can be set so that σ_m equals 0. The relationship between E_m and σ_m in this case will be represented by the line segment ABC in Figure 3.

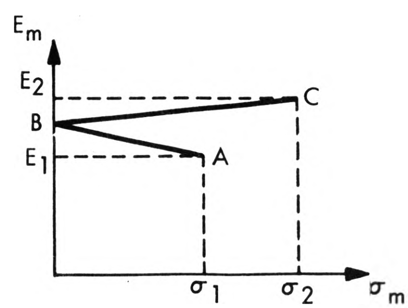

Figure 3 - Possible Combinations of Risk and Return--Two Energy Systems, Perfect Negative Correlation

Point B in Figure 3 represents a combination of systems 1 and 2 which yield no risk and an expected return greater than zero. It should be noted that the investor would never choose a point along line segment BA. Although any point along this segment is feasible, the investor can always find another combination of systems 1 and 2 that will yield a higher expected return for the same amount of risk. These combinations lie along line segment BC. The line segment BC dominates AB and an energy mix along AB would never be chosen. The line segment BC is therefore termed the "efficient frontier" of the feasible set. This concept is explained more fully later in the analysis.

4.2.3 Case 3; Correlation Coefficient Equal to Zero

The third alternative under investigation assumes a correlation coefficient equal to 0. In this case, the expected return of the mix takes on its characteristic form but, unlike cases I and II, the variance does not reduce to a perfect squared term. Algebraically, the mix is characterized by:

$$E_m = X_1E_1 + X_2E_2 \tag{10}$$

$$\sigma_m^2 = X_1^2\sigma_1^2 + X_2^2\sigma_2^2 \tag{11}$$

The feasible* (i.e., attainable) set of system mixes that can be obtained by varying X_i is graphed in Figure 4. Note that it is possible to reduce the risk of the mix below the risk of system 1. However, in this case it is not possible to reduce the energy mix uncertainty to zero. It should also be noted that the line segment AB is dominated by segment BC and can therefore be disregarded.

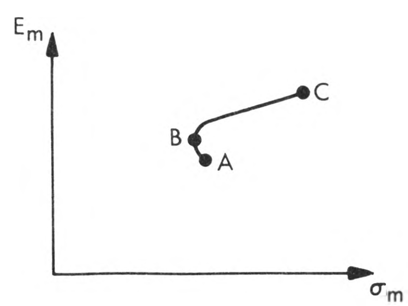

Figure 4 - Possible Combinations of Risk and Return--Two Energy Systems, Zero Correlation

In general, the correlation of the rates of return of the component energy systems will have an effect on the overall risk of the energy mix selected. The risk associated with the energy mix can usually be reduced by diversifying into more than one energy system.** In other words, real economic benefits can be derived from diversification.

4.3 GENERALIZING THE MIX ANALYSIS TO NUMEROUS CHOICES

Analyzing the energy mixes comprised of only two energy systems is useful for explanatory purposes and generalizing to more than two systems is straightforward. For example, if the energy mix only contained three possible systems one could first construct the feasible set for two of the three systems. The third system is incorporated by combining it with all possible combinations of the first two systems. Each point on the feasible set consisting of only two systems can be considered a new system. The new system is then combined with the third system. Figure 5 illustrates this approach.

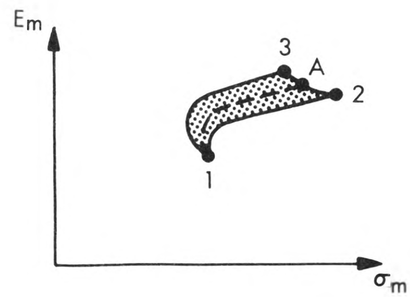

Figure 5 - Possible Combinations of Risk and Return--Three Energy Systems

Combinations of systems 1 and 2 in Figure 5 yield the feasible set designated by the line segment (1,2). Combinations of 1 and 3 yield segment (1,3). Combinations of systems 3 and 2 yield line segment (3,2). Point A represents some combination of systems 3 and 2. If those systems were combined with varying amounts of system 1, the feasible set would be given by the line (A,1). That is, energy mix A can be treated as a single system and combined with other systems. When all possible combinations are considered, the feasible set becomes an area rather than a line. This is the shaded area in Figure 5. The same approach is used to determine the feasible set for more than three systems.

4.4 THE EFFICIENT FRONTIER

Using the assumption that E_m is desirable and σ_m is not desirable, many of the feasible combinations can be eliminated from consideration. A combination of systems would be disregarded if another feasible

* The feasible set contains all possible combinations of rates of return and risk that can be obtained by combining the available systems in different ways.

** The risk associated with the mix will be less than the risk of the least risky system (if that risk is greater than 0) if $\rho_{12} < \sigma_1/\sigma_2$.

combination existed that had a higher rate of return with the same variance or a lower variance and the same rate of return. After this test is performed, each remaining energy mix will lie along a line that represents the north-west boundary of the feasible set. In other words, in order to get a larger rate of return one must take on additional risk. Similarly, in order to reduce risk one must accept a lower rate of return. This locus of remaining energy mixes is called the efficient frontier.* Figure 6 illustrates the relationship between the efficient frontier and the feasible set. The entire shaded area in the figure represents the feasible set. The line AECB represents the efficient frontier. Any point on the line AECB represents the highest return for each standard deviation or the lowest σ_m for each attainable level of expected return. For example, the mix D lies within the feasible set but energy mix C (on the frontier) yields a higher expected return and the same variance. Similarly, energy mix E yields a lower risk and the same return. Any point along the efficient frontier between E and C yields a higher return and a lower variance than D.

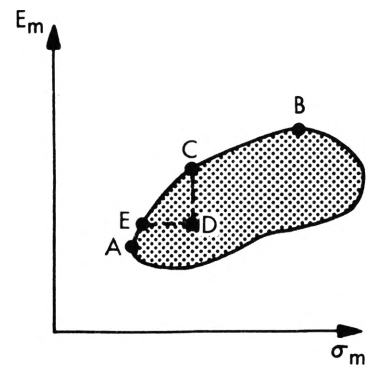

Figure 6 - The Feasible Set and Efficient Frontier

In general, the efficient frontier can be generated using a nonlinear programming approach. The problem can be stated in terms of a constrained maximization. The variables that can be manipulated to obtain this maximization are the percentage of the total invested in each system (X_i). Mathematically, the general problem can be stated as choosing X_i, X_2, $\ldots X_n$ to:**

$$\max\,[\lambda\, E_m - \sigma_m^2] \quad \text{for all} \quad \lambda \geq 0$$

$$= \max\left[\lambda\left(\sum_{i=1}^{n} X_i E_i\right) - \left(\sum_{i=1}^{n}\sum_{j=1}^{n} X_i X_j C_{ij}\right)\right], \quad \text{for all}$$

$$\lambda \geq 0$$

$$\text{subject to:} \quad \sum_{j=1}^{n} X_i = 1\ ,\ 0 \leq X_i \leq 1\ , \quad \text{for all} \quad X_i$$

and: any other constraints on X_i .... (12)

If every system under consideration had a variance greater than zero (i.e., some risk) then the efficient frontier, would be a set similar to line AB in Figure 7. The analysis of the energy mix would be complete. In other words, no energy mix along the efficient frontier can be eliminated on an objective basis. Along the efficient frontier, the only way to achieve a higher expected return is to accept more risk.

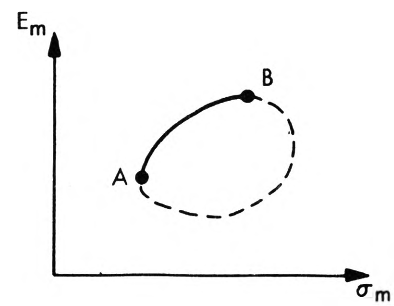

Figure 7 - The Efficient Frontier of Combinations of Hypothetical Energy Mixes

5. SELECTION OF ENERGY MIX BY THE INVESTOR

The final step in the methodology is to allow the investor to choose a mix that lies along the efficient frontier. The mix he chooses will depend on his attitudes toward risk and rate of return. He has to decide how much additional risk he is willing to take on to increase his expected return. If he is not too concerned with risk he will choose a point near mix B in Figure 7. If he is more averse to risk he will choose an energy mix near point A in the figure.

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* William F. Sharpe, Portfolio Theory and Capital Markets, p. 33 (McGraw Hill Co., 1970).

** William F. Sharpe, Portfolio Theory and Capital Markets, p. 58 (McGraw Hill Co., 1970).

6. ADDING A RISKLESS CHOICE TO THE ENERGY MIX

Additional energy mixes can be eliminated from consideration if a riskless asset is introduced. This new alternative can be interpreted as the choice of not investing in energy systems at all but rather in some government secured bond or Treasury bill. One could also conceive of this as an energy system that the government subsidizes in such a way as to insure some positive return. For a private individual considering energy for his residence, the riskless alternative could be construed as obtaining energy from the existing power grid.

The riskless alternatives available to an investor will depend on whether the investor is an individual, a corporation, or a public utility. If an investor has more than one riskless alternative before him it is relatively easy to reduce his alternatives to only one. Since more return is preferred to less and all these alternatives have no risk he will choose the alternative with the highest return and disregard the others. This is represented by point P in Figure 8.

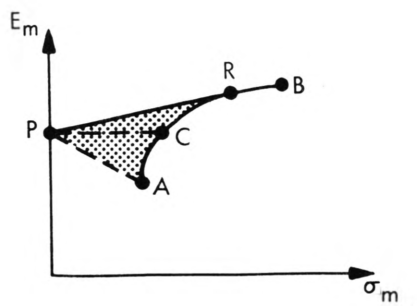

Figure 8 - Feasible Set of Energy Mixes with a Riskless Asset

As in the previous analysis, the investor is not restricted to putting all his investible funds in only one alternative. The new alternative can be combined with any energy mix along the efficient frontier. The result will be to increase his feasible set. One can consider any mix along the existing frontier just as the two systems were combined in the development of the two-system feasible set in Section 4.2. For example, alternative P can be combined with energy mix A in Figure 8 to yield a new set of possible combinations represented by the line PA . Similarly, alternative P can be combined with energy mix C to yield the new combinations along PC . In general, the new alternative can be combined with each energy mix along the efficient frontier. The total addition to the feasible set is represented by the shaded area in Figure 8.

The efficient frontier is also altered by the introduction of the riskless alternative. Using the assumption that E_m is a desired good and σ_m is not desired (i.e., a "bad") most of the new possible mixes can be eliminated. Even some of the energy mixes that were on the original efficient frontier are no longer desirable. For example, energy mix A is now dominated by all energy mixes on the ray PD in Figure 9.. In fact, all the energy mixes between A and R on the old frontier are now dominated by points along the ray PDR . The new efficient frontier is made of the line PDRB . All points between P and R are comprised of varying amounts of energy mix R and the riskless asset P . The line segment RB represents different mixes of energy systems and no funds in P .

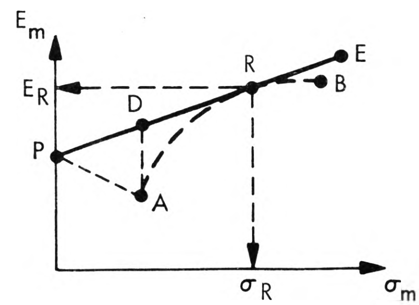

Figure 9 - Alterations in the Efficient Frontier with the Addition of a Riskless Asset

If the investor is allowed tc borrow at the riskless rate P the risky energy mixes beyond point R can also be eliminated. However, energy mix R does remain in the efficient frontier. If the investor were allowed to borrow at rate P he could invest the additional funds in energy mix R and lever his expected return (and risk) above E_R . Since combinations along the ray RE dominate energy mixes along RB , the efficient frontier becomes a straight line with intercept P tangent to the original efficient frontier ARB at point R .

The new efficient frontier contains only one point (R) that is made up entirely of a risky mix of energy systems. Points between P and R represent combinations of mix R and the riskless alternative and points between R and E represent combinations of mix R and borrowing at rate P . The energy mix R is the optimal mix of energy systems since it is the only energy mix remaining on the efficient frontier.*

* This terminology closely parallels Sharpe's concept of the optimal portfolio of risky assets (see Sharpe, p. 69).

The choice left to the investor is now reduced to choosing what combinations of the riskless and the optimal mix R he wishes to purchase. He does not have to choose between different risky energy mixes. The actual combination of the riskless alternative and mix R will be determined by the investor's subjective preference for risk relative to expected return (see Section 4).

7. SUMMARY

The energy investor is assumed to choose between competing energy systems based on two factors--expected rate of return and risk. The rate of return is equal to the difference between the expected revenue and the system's cost. This difference is then divided by the cost. Risk or uncertainty is represented by the variance of the return from its average value. The investor selects a combination of alternative systems, one of which may be riskless, to maximize the difference between the return of the mix and its risk. Using the Lagrange multipliers the problem can be stated algebraically. The investor chooses X_1, X_2, $\ldots X_n$ to:

$$\max_{X_i} [\lambda E_m - \sigma_m^2] \quad \text{for all} \quad \lambda \geq 0$$

$$= \max \left[\lambda \left(\sum_{j=1}^{n} X_i E_j \right) - \left(\sum_{i=1}^{n} \sum_{j=1}^{n} X_i X_j C_{ij} \right) \right], \quad \text{for all}$$

$$\lambda \geq 0$$

subject to the constraints:

$$\sum_{j=1}^{n} X_i = 1 \; , \; 0 \leq X_i \leq 1 \; , \quad \text{for all} \quad X_i$$

and: any other relevant constraints ... (13)

This general framework can be used to simulate the decision process of many diverse types of energy investors. The additional constraints facing each investor (such as regulation, availability of fuels or diversification requirements), should be incorporated when the model is exercised.

The methodology presented is only a small step in understanding the decision-making process of energy investors across the U.S. Additional research aimed at estimating the parameters outlined by the approach should add significant amounts to our understanding.

8. BIOGRAPHY

Mr. Costello is an energy economist at Midwest Research Institute, Kansas City, Missouri. He specializes in the application of micro and macro economic theory to the development and analysis of energy policy. Recently, he led the socioeconomic analysis tasks in a major study of the impacts of commercial development of solar energy for the U.S. Congress. Mr. Costello received the B.A. in Economics (1972) from the State University of New York where he graduated Magna Cum Laude and the M.A. in Economics (1973) from Ohio State University.

ENERGY, ENVIRONMENT AND INCREMENTAL DECISION MAKING

Jeff V. Conopask, USDA & Robert R. Reynolds, Jr., EPA

During the late 1960's and early 70's a variety of environmental/energy oriented legislation was enacted by the Congress. The most important of these acts, the National Environmental Protection Act (NEPA), required that environmental impact statements be filed when various private and public activities have a potential for impacting man and his environment. (17) Impact statement requirements go beyond the currently practiced cost/benefit analysis, which is often just a production (direct) impact assessment. Heretofore, indirect or second round economic and social effects of consequence affecting other national goals were seldom counted.

Impact analysis of the type specified in Sec. 102(c) is not required of legislation however. The NEPA does not require such analysis, yet often the legislation will have an impact on "man and his environment." The passage of the Clean Air Act of 1970 is an example. It initially triggered a low key demand for cleaner fuels and/or emission cleaners. Since the states were required to submit implementation plans to the Administrator of the Environmental Protection Agency, many states took the option of requiring stricter controls than the national standards. These individual state actions, however, may have national energy supply consequences. The aggregate requirements of states, each acting alone, could result in uncoordinated public and private sector activity.*

It is our intention in this paper to examine such manifestation of policy incrementalism in environmental/energy planning in the public sector. Incremental decision making presents problems because it does not focus attention on a clearly defined issues.

> ...There is no one decision and problems are not "solved"; rather there is a "never-ending series of attacks" on issues at hand through successive or serial analysis and policy making. The incremental approach is deliberately exploratory. Rather than attempting to foresee all the consequences of various alternative routes, one route is tried, and the unforeseen consequences are left to be discovered and treated by subsequent increments. Even the criteria by which increments are evaluated are developed and adapted in the course of action. (8)

Incremental decision making has led to property right (formal and informal) changes without consideration of impacts in the socio-economic sense.** Such considerations will be explored in this paper and an approach will be offered to explore the potential of policy action for disruptive change.

A CASE IN POINT: WESTERN COAL AND EASTERN CLEANER AIR

Under the Clean Air Act of 1970 (P.L. 91-604), air quality standards were established for the entire country. However, if a particular state has more stringent standards, the local regulation will take precedence.(4) Some of the energy supply planning implications of these statutory conditions are problematic.

One of the major emissions to be restricted and controlled are sulfur oxides (SO_x). It is estimated that by June 30, 1977, if P.L. 91-604 were not implemented, 64 percent of all SO_x emissions would be generated by steam electric facilities.(22) By 1977, it is additionally projected that total annual damage cost could be about $14 million for uncontrolled SO_x emissions. Over 90 percent of this damage would result from stationary sources, most of which are steam electric plants.

Control of these emissions, through P.L. 91-604 and the state implementation plans, is feasible by two modes: flue gas desulfurization or use of low sulfur fossil fuels. The latter approach can be used to illustrate the potential problems of incrementalism. Steam electric plants usually can burn either fuel oil or coal with a minimum of conversion effort. This "relative" mechanical ease of fuel switching may result in severe market disruption as utilities attempt to secure a fuel supply. Normally, purely economic decisions at the firm level will determine if low sulfur coal or oil is burned, but under the Federal Energy Supply and Environmental Coordination Act of 1974, utilities may be directed to burn either fuel (in fact, this occurred in June, 1975).(9,13)

Previously, during the 1973 Arab oil embargo, many utilities switched from oil to coal. In many cases, exemptions were given from state clean air standards. From November, 1974 to April, 1975 at least 13 coal burning plants in the Northeast were converted back to oil because of the loss of state-granted exemptions.(18) Concurrently the fuel adjustment charge to customers allowed the higher oil cost to be passed on to the consumer. Due to the Federal Energy Administration's (FEA) order to convert back to coal, new pressure on coal supplies (especially low sulfur) can be expected in the future.

The current status of domestic coal supplies appears to be in a state of flux. Large reserves of western coal appear to be the prime candidates for expanded production. In 1973, the Secretary of Interior stopped all further coal leasing on western lands pending completion of an environmental impact statement (EIS) on the Federal coal leasing policy.(27)

The EIS has become one of a number of opinions, briefly listed below, on the advisability of developing Federal western coal. This debate coupled with the history outlined above reflects the disadvantage of incrementalism in public sector energy decisions and environmental planning as well as the long term adverse impact potential of the current series of private incremental decisions. Of course both sectors often act in concert, either jointly or in reaction to one another. This supply debate appears to center on two major issues: (1) the advisability of large changes in coal supply sources, and (2) the socio-economic environmental impacts of developing new supplies.

With regard to developing new supply sources, the Department of Interior's Final Environmental Impact Statement for the Proposed Coal Leasing Program essentially concludes that renewed Federal coal leasing is necessary to meet the Nation's energy needs.(26) However, in the same report it is stated that "there is enough coal under lease to last 118 years at the rate

*Optimal public sector activity would be defined here as that which took cognizance of any designed policies for accounting of social and economic impacts, both short and long term.

**Property rights are defined as sets of order relationships among people which define their rights, exposure to the rights of others, privileges and responsibilities.

of production predicted for the year 2000".(26) In a separate document authored by the same agency, it is also argued that existing leases may not be adequate to meet the Nation's energy needs.(23)

Public critique of the Federal coal leasing may best be summed up by the following statement from the Ford Foundation Energy Policy Project: "...given the huge amounts of coal under lease, little of which is being mined, no apparent need exists for a major new thrust in coal leasing before 1980...".(7)

The Council on Economic Priorities echoed similar concerns in a report on coal leasing of Federally controlled lands.(1) The major points revolved around what needs to be done to improve currently practiced coal lease management.

The Environmental Impact Assessment Project of the Institute of Ecology, in its critique of the Department of Interior EIS, raises the issue of supply need in another form: What is the comparative need for new coal supplies in relation to existing or currently developing supplies east of the Mississippi?(6) Quoting a Bureau of Land Management study, they note that some 77 billion tons of less than 1 percent sulfur coal is centered on the eastern Kentucky, southern West Virginia and western Virginia area.(23) An industry publication cites a lower figure of some 55 billion tons existing as of January, 1974 for that area.(2)

The question of how much western, and particularly Federally leased, coal will be needed to meet national energy demands remains unresolved. In responding to technical criticism, the Department of the Interior indicated that it was not the purpose of a programmatically conceived EIS to consider the quantity of coal mined under the leasing program. Although effective research may require that problems be broken into manageable pieces and simplified, this process may preclude whole sets of policy issues and management options, and sets the stage for dependence on incremental planning.

Western coal development augurs tremendous socio-economic and environmental changes for areas such as the Northern Great Plains. Some of these would be short term resulting from the boom-town atmosphere of construction of coal related facilities, while others would be longer term. The latter would range from significant changes in the rural character of the social economy to a rehabilitation of land and water resources. The initial resource changes may become irreversible, however. The potential impacts include the following:

1. water shortages
2. aquifer disruption
3. reclamation impacts on the eco-system
4. regional climatic change
5. toxic and carcinogenic trace element release
6. air degradation
7. scientific and cultural resource destruction
8. potential permanent loss of agricultural production
9. social/economic problems of boom bust activity

The Department of the Interior's EIS final draft discusses these problems, but critics suggest additional research needs to be conducted. A major criticism relates to the availability and usage of water.

Water is as scarce a resource in the west as coal is abundant. Both surface and groundwater regimes are threatened from coal development. Mining, reclamation, dust control, and the associated coal resources which are exploited for western energy use, i.e., on-site coal conversion (generation, gasification, liquefaction), will require even more massive amounts of water.

The usage of surface water in this region has traditionally gone "to the one who is first in time of whether the water is used upon land contiguous to the source of supply or far removed from it".(12) However, the ownership rights of groundwater do not have the long and well defined legal history surrounding surface water rights. This will be critical since many western coal seams also act as aquifers. According to Davis, some western states have recently adopted codes for underground water which are essentially identical to those for surface water use. One appropriates the water and secures approval from a state authority. "A quantity used is determined by state authority, but the well may be shut down if it imperils a neighbor's supply or higher priority uses necessitate the water elsewhere".(5) On the latter, a case can be made for compensation. In any event the property right conflicts among coal and other water users need to be analyzed.

Another area of controversy is the reclamation of strip mined lands. According to the EIS critique, "successful reclamation of coal strip mines has occurred nowhere in the Southwest, Rocky Mountain or Northern Great Plains states".(6) However, a recent USDA/Forest Service study concludes:

> almost all the surfaced-mined lands of the Northern Great Plains can be rehabilitated successfully...a large amount of basic information needs to be collected, and numerous research problems require solutions before such rehabilitation can proceed expeditiously, effectively and economically.(21)

Another study by the National Academy of Science indicated that reclamation is not feasible where rainfall is less than 10 inches per year and the soils cannot retain moisture.(16) A number of areas in the Northern Great Plains region appear amenable to successful reclamation, but to what degree of success? These are still large unanswered questions.

All of these environmental impacts if the critics are correct, are negative enough by themselves but they are also the power train for direct and indirect, short and long term socioeconomic impacts of considerable magnitude. Although the EIS does provide descriptive data on the regional economics involved, critics argue that an extensive regional economic analysis demonstrating distributive effects is required as a critical link in beginning a valid social impact assessment. In turn the social impact questions would include land use, population patterns, public service provision/complexion, and human value conflicts.

To lend credence to the EIS critique's statement that "the social fabric would be altered in every respect by the incursion of coal development", a quick analysis of the regional economy of the Northern Great Plains coal leasing area is instructive. The following material is from the U.S. Water Resources Council OBERS estimates.(28) In four of the five water resources subareas (Tongue-Powder, Lower Yellowstone, Missouri-Little Missouri, Cheyenne, and Missouri-Oahe), over 30 percent of total earnings by employees in the primary or basic industries, accrued from agriculture. Some 65 percent of the Federal land in this area is used for livestock grazing. Non-agricultural activity is confined mainly to food processing, contract construction and wood using industry. In the case of the Wyoming area (major part of Tongue-Powder and one-third of Cheyenne), 28 percent of the State's cattle and calves and 42 percent of the sheep are raised in that area. About 20 percent of the State's wheat and oat crop is harvested in that region.(30) In essence then, if an incursion from massive coal development occurs in this area, it will result in a tremendous change in the complexion of the agrarian economy. This change into quick industrialization will include concomitant support industries and associated urbanization to accommodate an influx of workers and their families.

This is not to say this change in the economy is a good or a bad. Nevertheless, it is an exogenous change that is impacting the regional culture and its effects need to be evaluated. The short term consequences of this change may be mitigated through a compensation procedure for those who lose their agricultural livelihood, although neither the EIS nor its critique discussed this point. In the long run, this agricultural production may be lost forever. Although this region is not as productive as others, the possibility of an irreversible loss of agricultural production is a significant one for our future. This is not the only place where strip mining is affecting agriculture. In Illinois, where the land is much easier to reclaim, not all agricultural productivity has been reclaimed from strip mining.(11) Much of that former crop land has been reclaimed only to pasture land. By controlling the amount of strip mining today, we are preserving future options in an energy source/food source trade-off. New strip mining and reclamation technologies may be available then to better facilitate both needs.

Krutilla has an instructive statement on this very point of irreversibility and early consumption which is not conventionally met in resource economics.

> At any point in time characterized by a level of technology which is less advanced than at some future date, the conversion of the natural environment into industrially produced private goods has proceeded further than it would have with the more advanced technology. Moreover, with the apparent increasing appreciation of direct contact with natural environments, the conversion will have proceeded further, for this reason as well, than it would have were the future composition of tastes to have prevailed. Given the irreversibility of converted natural environments, however, it will not be possible to achieve a level of well-being in the future that would have been possible had the conversion of natural environments been retarded.(14)

To conclude this presentation of the controversy, one more broad socioeconomic impact needs to be addressed. If in fact low sulfur reserves are available in the east, and the western coal development occurs, the potential exists for large shifts in regional coal production from the east to the west. While some coal/utility companies may in fact be considering the possibility of a shift in coal supply source, others are planning to open 123 new mines over the next eight years, 78 of which are in the low sulfur region of eastern Kentucky and southern West Virginia.(2) Deep mines continue to open up, the industry is making training progress and it appears to be recovering from the trauma of the Federal Coal Mine Health and Safety Act of 1969.(3) In essence, while eastern and mid-western coal fields continue to expand, the prospect of apparently cheap western coal portends and excess supply situation. This would impact the established infra-structurer of eastern producing communities.

PROJECT INDEPENDENCE

No discussion such as this can ignore the need to consider other related policy options. The previous case in point is part of an even bigger energy/environment management problem. As alluded to earlier, the availability of fuel oil at various prices is of utmost importance to the coal supply/SO_x emissions problem. Of course, the new national goal of independence from foreign energy sources by 1980 (or security by 1985 as it now is envisioned) interjects a new facet to the dilemma.

One of the three options in the FEA's Project Independence report is to increase domestic supply. However, "accelerating domestic supply has the drawbacks that: (1) it will adversely affect environmentally clean areas, (2) it requires massive regional development in areas which may not benefit from or need increased supply, (3) it is a gamble on yet unproved reserves of oil and gas, and (4) it may well be constrained by key materials and equipment shortages".(19) The statement applies generally to all fossil fuels. An exemplary problem is suggested by examining the implications of the prospect of an increase in the mix of energy supply sources, with coal replacing fuel oil to a significant degree.

> To achieve even this kind of an energy future would require federal actions not yet taken. The most important of these are: modifying the Clean Air Act to permit more widespread use of high sulfur coals than the present statute allows....(19)

THE DECISION-MAKING PROCESS

The point of the above discussion is not to try to establish the truth or adequacy of any of the Federal policy statements or their criticisms. Rather, it is to point out that the energy issue is a broad problem with many facets and many decision makers. Further, none of these decision makers have all the facts they need, and in general only the Federal Government has sufficient authority to weigh all the effects of proposed changes.

The danger in such a situation is that incremental decision making--decisions over time by various private, state, and Federal agencies about small parts of the problem--will gradually preclude options for the long run, and even create crisis short run situations. In fact, the potential of irreversible consequences may emerge in an institutional as well as a physical environmental sense, where an accumulation of small decisions in period t become interlocked to form rigid irrevocable assumptions for policy decision in t+n periods.

Part of the problem is the result of specific institutional conditions in a multi-interest decision field. Each decision entity attempts to establish a distinctive domain* of responsibility in order to minimize outside interference with their operations. Thus, an executive agency will extend domain claims no farther than top level administrators perceive substantial constituency support to be available. In practice, this means an agency's decision makers will generally leave the agency a conservative margin of error, thereby,

*Domain refers to the "bundle" of responsibilities service organizations claim as their distinctive field of operation. Domain encompasses a specific target population (direct beneficiaries), a set of problems to be addressed, and specific services or intervention measures to be applied.(15)

interpreting the agency's legal mandate as narrowly as possible in order to minimize conflict with constituency elements and other agencies.

Narrowly defined public responsibility and literal adherence to the statutory mandates are characteristic behavior when an agency finds itself in "fringe areas". Traditional cost-benefit analysis has been regarded as an "objective tool" which permits decision independent of value judgments. In fact, we argue it is seldom value-free. The assumptions made in defining the very scope of the problem to be analyzed often, unintentionally, introduce value judgments.

Generally speaking, environmental/resource problems are so complex that, at a minimum, the analysis must be conducted at a comparative program level as well as an intra-program level before sufficient foresight for the contemplated intrusion into the private sector can be generated. Typically, evaluation is conducted only at one level, i.e., alternative classes of options that enhance "nontarget" benefits are seldom fully evaluated. Such narrow decision making conceived in the name of expedience and efficiency may bring the decision makers to an upper limit of intervention choices rather quickly, i.e., the point at which the next best option, (e.g., use of the land) will yield a zero or negative cost-benefit ratio*. When this threshold is reached, time is truly of the essence, because the decision to confine the focus to marginal decision making may preclude the possibility of a whole class (level) of beneficial decision options; e.g., development of socially suitable technologies. Where this mode is dominant in an agency, it may result in societal and environmental decisions with irreversible consequences.

TOWARD A SOLUTION

Solutions to this dilemma do not come easily. Decision tree analysis and similar decision aids will help one to systematize the levels of decision, information needs and options. However, the problem, we should emphasize, is not a technical/logistical one. A lasting solution to the problem is one that requires the generation of an institutional atmosphere for decision making and analysis that will permit proper integration of policy making and support activity, i.e., multi-level impact analysis. This is not a problem that can be wished away or easily side-stepped with a new analytic or methodological wrinkle. Solutions are available but they will not be achieved without adversary press..e.

The achievement of suitable decision conditions will not require major innovations of an analytic nature. Refinement of cost-benefit analysis to permit pricing of heretofore unpriced externalities and other secondary effects, plus extension of this analysis to a consideration of sociological and social psychological parameters are desirable innovations. Such extensions are under development and are commonly being subsumed under the rubric--social or socioeconomic impact analysis (SIA).(10,20,29)

*For a more detailed discussion of the origins and problems of incrementalism and the role of knowledge and analysis in policy making in advanced industrial society see (8). Etzioni distinguishes between rational decisions--marginal decision being a case in point--and incrementalism. The former involves consideration of appropriateness of the goal. Whereas the latter, incrementalism, represents a still more limited time of decision in that a full range of options are not considered.(8)

We do not mean to minimize the theoretical and methodolotical difficulties associated with the task of tracing the technological/natural resource related policy intrusions to changes in property rights and social arrangements (SIA). To the contrary, we merely wish to point out that this is not the major aspect of the problem. As we have suggested, the major hurdle to constructive social policy in this area is the institutional context in which analytic procedures for forecasting are employed. We hasten to note, however, that one cannot realistically expect change of the magnitude necessary to move away from incrementalism. It would be more reasonable to think in terms of legislative reforms that would explicitly require each Federal agency to periodically review their domain responsibilities at a program and project level (and ideally at an overall policy level) on the basis of systematic SIA.

The objective of the SIA procedure would be to evaluate progress in major goal areas. Multi-level SIA evaluation will provide the basis then for modifying agency actions where necessary in order to realign activities in accordance with mandated goals and/or to modify direction where subsequent change in the world indicates adjustments in agency goals (and/or domain definitions) are advisable. In the latter case, final decisions may pass out of the agency back to Congress, but there is little about this or other elements of this procedure that are not consistent with present modes of governmental operation. Our recommendation merely recognizes the inherent limitations of scope and temporal perspective (both retrospectively prospectively) associated with conventional analysis.

Multi-level SIA conducted on a periodic basis would be most efficiently accomplished by modifying and expanding existing monitoring and evaluation programs to attain an ongoing SIA capacity. This will provide a much needed flexibility and reality testing in public policy that is sorely needed in the resource/environment policy as well as other areas of social policy. Moreover, if Congressional appropriations were explicitly tied to the efficiency of these systems in terms of both long and short term savings of public funds and/or avoidance of public problems, executive agencies would have ample incentive to apply said evaluation judiciously.

CONCLUSION

The dangers of incrementalism in macro-planning are perhaps most pronounced in the long run as marginal decision-making becomes the basis for assumptions in the longer time frame. The energy-environment policy arena has experienced this situation in only six years. The prevailing decision making process has "evolved" from Congressional, Federal agency, state agency, plus strong firm level patterns of operation. We have not seriously challenged the supporting structure of this decision making process. In reality, it is a series of units making fragmented, non-interconnected policy analyses of energy and environmental problems. The dangers of marketplace disruption by ill-conceived public sector incursions are large without some overall planning mechanism for coordination. Multi-level socioeconomic impact assessment is one possible means to this end and short term planning costs appear to be insignificant when compared to longer term risk/costs of energy supply disruption, severe (perhaps irreversible) environmental degradation, and severe socioeconomic dislocation.

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BIOGRAPHIES

Jeff V. Conopask

The author received his graduate training from the University of Toledo (1971, M.A. in Economics) and Virginia Polytechnic Institute and State University (1975, Ph.D. in Agricultural Economics). In between, he spent almost two years (1974-75) with the Office of Pesticide Programs, U.S. Environmental Protection Agency. He is currently an economist with the Economic Development Division, Economic Research Service, U.S. Department of Agriculture.

Although his initial training was oriented toward natural resource/regional economics, his interests have expanded to include social impact, institutional arrangements and appropriate technology. He currently is doing research on coal energy development impacts in rural regions.

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The author received his Ph.D. in sociology from the University of Maryland in 1971. The major thrust of his educational preparation was in social psychology, and the sociology of complex organizations. His professional experience has ranged over a variety of interest areas in both academic and public policy research/analysis settings. He was staff member of the Social Science Research Center, Mississippi State University--1967-1969; an assistant professor at Old Dominion University in Norfolk, Virginia--1972-1974; and at present he is a senior staff sociologist with the Office of Pesticide Programs, Environmental Protection Agency..

Dr. Reynolds' research and policy analysis efforts have been primarily devoted to organizational problems affecting public service organizations in the social service and environmental/resource fields. More recent work has been directed at social impact questions related to technological innovations and resource management.

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NATURAL RESOURCE PRICING AND ECONOMIC DEVELOPMENT

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Abstract

In a competitive equilibrium the price of a natural resource will be increasing at a rate equal to the social time preference rate, but in a monopoly market, the price will be increasing at less than social time preference rate. If the producer countries utilise their monopoly of production and sale of a natural resource for the purpose of developing their economies, the price of the natural resource will be growing at the rate at which the producer countries' economies are growing, whether or not the sales proceeds are used to finance their investment programmes, fully or partly.

I. Introduction

The problem of analyzing the price-behavior of a non-renewable natural resource has, of late, attracted considerable attention. The quadrupling of petroleum prices has prompted the persistent question whether the countries having large and nearly exclusive reserves of a natural resource, can fix the price and limit the supply of their product at will. Since the petroleum exercise has apparently achieved considerable success from the producers' point of view, there seem to be some efforts in motion to create institutional structures aimed at achieving similar successes in other areas. The problem, however, is not a new one. It was analyzed from a conservationist point of view by Hotelling (1931). Scott (1965) discussed the problem of output regulation of a natural resource when shifts over time occurred in costs and prices, due to changes in technological and demand conditions. Gordon (1967) emphasized the influence of market conditions in the future on current output decisions. Little study, however, has been made of how the prices and quantities to be supplied are determined in a market which is nowhere near being perfectly competitive and in which the producers have the avowed aim of developing their national economies at a faster rate of growth.

Section II presents a simple model of a non-renewable natural resource being traded in a competitive market and discusses the conditions that affect the price-behavior. Section III presents a monopoly market situation and analyses how the changed market situation affects the prices. Section IV raises the problem of unequal geographical distribution of natural resources and discusses the issues implied in this discrepancy between production and consumption among nations. It analyses further what happens to the price behavior when the investment funds for the accelerated development of producer country come, fully or partly, from the sale proceeds of the natural resource. Section V summarizes the results.

II. The Simple Model

We start with a simple model of a resource which is non-renewable. The producer has complete knowledge of the total stock of the resource that could be extracted at zero costs almost fully and once it is extracted, it cannot ever be replaced. Let the total quantity of known and extractable resource be q and let q_t be the quantity produced in period t such that

$$\sum_{t=0}^{\infty} q_t \leq q \qquad (1)$$

Assume perfectly competitive market conditions, with a risk-free interest rate r, which could be used as a proxy for the *social time preference rate. Let the period-wise demand function for that particular natural resource be given by*

$$p_t = d_t\ (q_t) \qquad (2)$$

In these conditions the optimum course for the producers would be to maximise the present value of the discounted sum of the total revenue (= total profits) which is given by the quantity

$$P.V. = \sum_{t=0}^{\infty} (1+r)^{-t}\ d_t(q_t)\ q_t \qquad (3)$$

Subject to the supply constraint (1). Associated with the optimum solution would be an output stream given by the sequence $\{\bar{q}_t\}$. Setting a Lagrangean and differentiating it with respect to q_t, we get the solution

$$d_t(\bar{q}_t) = \lambda\ (1+r)^t\ (t = 0,1,2,\ldots) \qquad (4)$$

The value of λ, the shadow price of the natural resource, can be obtained by substituting t=0, in (4), which would be equal to $d_o(\bar{q}_o) = \bar{p}_o$, so that (4) can be written as

$$d_t(\bar{q}_t) = d_o(\bar{q}_o)\ (1+r)^t\ (t = 0,1,2,.) (5)$$

This shows that in a perfectly competitive market the price of the natural resource will be increasing at the rate r.

Given the demand function, the constraint condition (1) and the assumption t=T, the period in which the resource is completely exhausted, the initial and the maximum prices, $d_o(\bar{q}_o)$ and $d_T(q_T)$, can be easily obtained.

Let the demand be represented by the linear function

$$q_t = \alpha - \beta p_t \qquad (6)$$

At t=T, since q will be completely exhausted, $q_T = 0$. So $p_T = \alpha/\beta$, will be the maximum price that could be obtained in a competitive market.

Using (1) and (5), (6) can be summed up and written as

$$\Sigma q_t = q = \Sigma\alpha - \beta\Sigma p_o\ (1+r)^T$$

which gives the solution

$$d_o(\bar{q}_o) = \frac{n\alpha - q}{\beta r^T}$$

The two values represent the p intercept of the long-run demand function and the point of intersection of the demand function and the long-run perfectly inelastic supply function. If the demand function doesn't ever intersect the price axis, then the total stock of the natural resource will never be fully exhausted and the price will remain undetermined. The initial price could be zero when the total known reserves are large enough for the demand function to intersect the quantity axis and thus become a free good.

III. The Monopoly Behavior

The optimum course for a monopolist is to maximise the discounted sum of the total revenue stream (3) subject to the constraint (1). Associated with this maximum value for the monopolist would be an output stream represented by the sequence of quantities $\{\bar{q}\}$. The Lagrangean that is set up, when differentiated with respect to q_t, now gives a different solution, which is

$$d_t(q_t) + d_t'(q_t)q_t = \lambda\ (1+r)^t (t=0,1,2,..) (7)$$

Noting that the LHS of (7) is the marginal revenue in period t and by obtaining the value of λ by substituting t = 0, (7) can be written as

$$m_t = m_o\ (1+r)^t \qquad (8)$$

Where m_t is the marginal revenue in period t. This solution indicates the price behavior modification in a monopoly market relative to a competitive market. It is not the price, but the marginal revenue that increases at the rate r. Since for any given positive quantity marginal revenue is smaller than price, the price will increase at a rate less than r.

For the demand function (6)

$$q_t = \alpha - \beta p_t$$

the marginal revenue is given by

$$m_t = \frac{\alpha - 2q_t}{\beta}$$

and the price

$$p_t = (\frac{\alpha}{\beta} + m_t)\ /\ 2$$

The maximum price that the monopolist could charge would be equal to the price-intercept of the demand function (i.e. α/β and the minimum initial price would be the same as in the competitive conditions, unless the known reserves are large enough as not to effect the supply constraint (1). When the marginal revenue is zero, the monopolist will still be charging $\frac{1}{2} \cdot \frac{\alpha}{\beta}$ as the price.

IV. Less Developed Countries and the natural resources

The geographical distribution of natural resources, viewed at the present time, has given rise to a peculiar problem. At least in respect of some important natural resources, the consuming countries are endowed with little or no known reserves, while the producing countries, which have the most reserves, (and which are 'poor' otherwise), find that their reserves of natural resources are a sure source of investment funds, so badly needed to transform their economies. Realizing that the present prices are too low, they feel that they should price their product in such a way that they get the maximum amounts of investment funds, without having to exhaust the stock of the reserve too rapidly. This feeling stems from the thought that once they exhaust their known reserves they would be left with no source to fall back upon, and that their economies will continue to remain backward.

Let us assume a simple economy, growing at a steady-state rate, g. Let the investment funds required to sustain this rate of growth in period t be $p_t\, q_t$, the total revenue obtained by the sale of the natural resource, under the assumption that the sale of the natural resource output is the only source of investment. The quantity $p_t\, q_t$ will be growing at rate g, as in a steady state

$$p_t\, q_t = p_o q_o\, (1+g)^t \qquad (9)$$

It is obvious that the funds equalling $p_t q_t$ will make the same contribution to the process of growth in period t, as will do $p_t q_t\, (1+g)^{-t}$ in the initial period. Therefore, the producer countries will adopt an optimum course when they maximise the quantity

$$\sum_{t=0}^{\infty} p_t q_t\, (1+g)^{-t} \qquad (10)$$

under the constraint (1).

Associated with this maximisation course would be a sequence of quantities $\{\hat{q}_t\}$, which they will be selling in the market. The relevant Lagrangean will give the following solution.

$$\hat{p}_t = \lambda\, (1+g)^t \quad (t = 0,1,2,....)$$

Where λ could be interpreted as the shadow cost of development per unit of natural resource. The price, therefore, will be growing at the rate g. But by (4), we know that in competitive conditions $d_t(\bar{q}_t)$ grows at the rate r. If $g = r$, then both the quantities will be the same. In the event $g > r$, $\hat{p}_t > d_t\, (\bar{q}_t)$ and if $\hat{p}_t < d_t(\bar{q}_t)$ when $g<r$, an unlikely event. Similarly modified relationship we would observe in the behavior of marginal revenue in a monopoly market situation, where the price of the natural resource will be increasing at a rate less than g. Cartelization of oil trade could indeed be better for consuming countries.

Let us relax the assumption that all the investment funds are acquired through the sale of the natural resource. If they form only a part of the total requirements, the other part coming from the domestic savings, then the quantity to be maximised could be expressed as

$$\Sigma\, (p_t\, q_t - svp_t q_t)\, (1+g)^{-t} \qquad (11)$$

Where s is the savings propensity and v is the constant output capital ratio. Adjoining (11) and (1) and differentiating the Lagrangean with respect to q_t, we get.

$$\hat{p}_t\, (1-sv) = \lambda\, (1+g)^t \quad (t=0,1,2,...) \qquad (12)$$

or

$$\hat{p}_t = \frac{\lambda}{1-sv}\, (1+g)^t$$

Since sv is likely to be much less than unity, the initial price will be set at a higher level. The annual increase will however, take place at the same rate g.

V. Summary and Conclusions

In a competitive equilibrium the price of a natural resource will be increasing at a rate equal to the social time preference rate, r. In a monopoly situation the rise in prices will be *at a rate less than the social time preference rate, as it is the marginal revenue which will be increasing at the social time preference rate. If the producing countries have the aim of using the sales proceeds of their natural resource reserves to develop their economies at the rate of growth, g, then the price of the natural resource will also be growing at the rate g. g could be greater than r or equal to r, or less than r, in which case the price will be rising at the higher rate. If part of the funds for investment are however, provided by the domestic savings then the price-rise will take place at the rate, g, but the initial price will be set at a higher level.*

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OIL SHALE R & D - A BUREAU OF MINES PROGRAM

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Energy is one of our basic natural resources. Oil constitutes an important part of this resource but domestic production is dropping while imports are rising. Today, oil represents about one-half of the total energy consumed in this country, and demand is expected to grow at the rate of about 2 percent per year during the next 10 years. Increased reliance on imports can be reduced by synthetic fuels produced from the oil shale deposits of the Green River Formation in Colorado, Utah, and Wyoming. These deposits are so enormous (600 billion barrels in high-grade shale alone), that any limitations on production are set by economic, environmental, political, or technological constraints.

According to the Project Independence Blueprint, a shale oil production of 1,000,000 barrels per day could be attained by the year 1985. This would meet the goal established by President Ford in his recent State-of-the-Union Message.

This paper outlines the work that the Bureau of Mines is doing in oil shale mining research to further this goal. It describes the results of our first year's contract research program, and our plans for the future. Oil shale research is part of the Bureau's overall Advancing Mining Technology Program. The objectives of our program are to develop, test, and demonstrate improved low-cost mining and waste management methods and equipment that are capable of producing the large tonnages of oil shale and shale oil needed by the 1980's. Oil shale and associated minerals must be mined safely and economically, using methods that will allow maximum recovery of the mineral resource with acceptable environmental impact. The immediate objectives of the program are to assess the technical and economic feasibility of various surface and underground mining methods and of modified in situ extraction systems, evaluate the mineral resources, and determine the environmental impacts of an oil shale mining industry.

The Green River Formation, which covers some 25,000 square miles, is estimated to contain about 4 trillion barrels of oil equivalent. Oil shales with commercial potential are estimated to contain about 1.8 trillion barrels. Of this amount, some 600 billion barrels are contained in deposits classified as high-grade shale. Of this total, some 470 billion barrels are located in the Piceance Creek Basin of Colorado. This concentration of thick, high-grade shale beds and associated minerals of potential value make the Basin an attractive target for oil shale development.

It follows then that the major focus of our research program is directed to the Piceance Creek Basin. Because of the varied geology, hydrology, and topography of the oil shale region, no one mining method can be expected to suit all conditions. Rather, different mining methods and equipment will have to be developed to meet the specific requirements of a mine in a given locale. Hence, it is necessary to investigate a range of mining and waste management technologies.

Various modifications of the room-and-pillar mining method have been demonstrated for mining the thin, rich Mohogany Zone in the upper beds of the formation. Our attention has, therefore, been directed to the problems of mining the thick, deep beds of the lower Zone near the center of the Basin. This Zone contains the major portion of the resource. Since the program was planned primarily as a contract research program, contracts have been let for technical and economic feasibility studies of underground mining systems, integrated open pit mining, and modified in situ retorting systems. Results of the first year's work under these contracts is summarized below.

UNDERGROUND MINING

Low-cost, large-scale underground mining of the thick, deep beds of the central Piceance Creek Basin is technically feasible. Six mining systems were evaluated and ranked on the basis of technical feasbility, costs, resource recovery, reclamation, environmental impact, and health and safety. Four systems were selected as being the most promising: Chamber and Pillar, Sublevel Stoping with Backfill, Block Caving using LHD's, and Advance Entry and Pillar. The first two methods have the lowest production cost and environmental impact. Resource recovery is highest with Block Caving and lowest with Advance Entry and Pillar. Estimated mining costs ranged from $1.04 per ton for Chamber and Pillar to $1.31 for Block Caving with LHD's.

INTEGRATED OPEN PIT

Mining, backfilling, and reclaiming the oil shale resource of the Basin with one or more large integrated open pit mines offers several advantages. A preliminary mine site was selected and a method for opening a pit was planned. Production capacity was set at 1 1/4 million tons per day, and cutoff grade was 15 gallons per ton. Total material moved peaked at 2.5 million tons per day. The selected mining system used the largest mining equipment available. Mine development started with six mining units producing 360,000 tons per day, and production rose to 530,000 tons per day within a year. This production is larger than the largest open pit mine in the country. It might be possible to do this technically, but it would require a tremendous effort.

MODIFIED IN SITU RETORTING

Underground mining, rubblization, and in situ retorting is technically feasible, environmentally acceptable, and economically competitive. Ten conceptual systems were evaluated and ranked. The four best systems were then evaluated objectively. The two systems with the greatest potential were Room-and-Pillar Vertical Drill and Blast and Tunnel Boring-Horizontal Ring Drill and Blast. Operating costs ranged from $4.38 to $5.32 per barrel.

In addition to oil shale, the Lower Zone contains an estimated 32 billion tons of nahcolite, containing 65 percent by weight of soda ash and an estimated 19 billion tons of dawsonite, containing 35 percent by weight of alumina. Plans are underway to obtain bulk samples of these minerals for process development by the Metallurgy Group of the Bureau of Mines. Geologic and hydrologic investigations have been completed, a site selected, and a call for bids for core drilling issued. If successful, the drilling program will be followed by the boring of a large-diameter shaft for access to the Lower Zone. Two waste management studies, a geophysics study, a bit-and-cutter test for tunnel boring, and health and safety studies of dust and toxic gases are underway.

THE APPLICATION OF WATER JETS IN COAL MINING

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Abstract

Water is one of the natural erosion agents which through time has changed the face of the earth. Application of this principle to remove earth and rock by man is a long established technique. This paper briefly describes the changes in technology which have brought the application of water jets from the slow erosion of soil to the point where in Canada some 3,400 tons per shift are currently mined in a coal mine using high pressure water jet technology. The use of water jets has shown sufficient promise that there are several research programs currently being funded by the U.S. Bureau of Mines and other Federal agencies in the field of excavation technology. Three current areas of water jet mining are described. The first is the use of water at 10,000 psi as a modification of the cutting head of a longwall mining machine. The work which is being carried out at the University of Missouri is briefly described with the rationale for the jet parameters chosen for the experimentation. The second method of mining is a project currently under way in Canada where in a seam 50 ft thick and dipping at an angle of some 40 degrees, a low pressure, high volume flow rate up to 1,500 gallons per minute water jet system produced up to 3,400 tons per manshift. The third method of mining is an experimental program being carried out by Flow Research, Inc. in Washington state. With this method coal is mined from underground seams to boreholes driven from the surface, coal being reamed to the borehole by high pressure water jets and crushed in the bottom of the borehole prior to being pumped out of the borehole for external usage. This method does not, therefore, require access to the underground.

1. INTRODUCTION

The use of water as a means of extracting valuable minerals from the earth is something we learn from nature. The presence of gold in stream beds, the pulverizing of rock into valuable soil--these things indicate that my topic is as old as the Earth itself, and man has through the years learnt from nature and applied water to accomplish his own ends. We learn from ancient Egyptian stele that water was used in mining 4,000 years B.C. (1), and Pliny in his Natural History (2) talks of the Romans in Spain carrying water to reservoirs on hilltops, from which it was discharged onto ore veins, carrying the mineral down to the valleys where it was trapped on bushes, and one may conjecture sheepskins if one remembers the legend of the Golden Fleece. Agricola (3) talks of the use of water in "De Re Metallica" in the sixteenth century but it is not until about 100 years ago that hydraulic surface mining became of large interest. With the advent of pressure pumps, low pressure, high volume water was used to mine alluvial deposits of valuable material from California through Alaska, Siberia, Russia, and the Orient (4, 5). Around the turn of the century, the Prussians began to use water jets to mine peat, and the technique was also adopted in Russia. As equipment reliability increased, so jet pressure increased, and coal was mined in surface deposits. In 1935 Dr. Muchnik in the Soviet Union carried out experiments on mining coal underground in the Kuznetsk basin (6). These experiments were delayed by the war, and it was not until 1952 that the first underground hydraulic mine, the Tyrganskii-Uklony, was opened in the Kuznetsk coal basin (7). Output and costs per ton were much more favorable than with conventional mining and the methods were applied in many different mining conditions across the Soviet Union (8). As a result of these trials, experiments in hydraulic coal mining began in the United Kingdom (9), the United States (10), China (11), Japan (12), Poland (13), and Germany (14). Regretfully for the state of technology as methods of mining were being developed, two events occurred which put hydraulic mining temporarily out of the picture. The first of these was the introduction of the mechanized longwall face and the advent of the Anderton shearer loader, which promised very high productivity and fitted in with existing mining methods in a way that hydraulic techniques could not. The second was the collapse of the coal market. In more than one mine where hydraulic mining sections were established, although the hydraulic section remained profitable, the mine as a whole did not (15). The volume of coal mining research fell away, and hydraulic mining practice passed from the American scene. In Russia, however, the methods were being refined and hydraulic mining was also still being developed in China and Japan.

Then, in about 1969 interest in water jet technology began to increase again. Initially Dr. Maurer in his review of novel drilling techniques indicated many advantages to the use of high pressure water jets (16), and just prior to my arrival Dr. G.B. Clark had, at UMR, completed a review of the potential application of jets in excavation (17). Initially, in part because of funding availability, the research concentrated on the application of water jets for rock excavation. This program which has passed through several stages recently led to the addition of a set of water jets on a tunnel boring machine in Washington state (18) and is worthy of a paper itself. Unfortunately, in the author's opinion this research led to a misconstruction of results. In experiments at IIT Research Institute it had been found that the greater the jet pressure, the more effectively the jets cut rock. This conclusion was considered equally valid for coal, despite the many differences in structure between coal and the sandstones and granites used in most of the jet testwork. As a result of this misconception, initial development of water jets in coal mining in this "new era" of the 1970's was in the design of mining machines which operated at water jet pressures in excess of 50,000 psi (19, 20).

2. EXPERIMENTS AT UMR

Concurrently with other programs, the U.S. Bureau of Mines funded the University of Missouri - Rolla (21) to investigate the relationship between nozzle diameter, jet pressure, and cutting effectiveness in the design of a longwall water jet mining machine. The results of this study indicated that, for a given horsepower, coal would be mined more effectively with a lower pressure, larger diameter water jet than with an ultra high pressure, small diameter jet.

The results can be illustrated with reference to two curves which were derived from the results of the study. In the first curve (Figure 1) the effects of jet cutting are plotted against increase in pressure. It can be seen that as pressure increases so does the volume of coal mined; however, concurrently the energy contained in the jet also increases. Thus, if the energy of the jet required to remove unit volume of the coal, the specific energy, is plotted, there is only a slight decrease in required energy as pressure increases.

Conversely, when the curve is examined for the relative change in effect with increase in nozzle diameter (Figure 2), the volume of coal removed increases with diameter but, in this case, at a much greater rate than the energy contained in the jet. Thus, the specific energy of cutting drops with increase in nozzle diameter. This data can be expressed simplistically thus: If the jet energy is doubled by increasing the pressure, then approximately twice the volume of coal will be mined. Conversely, if the jet energy is doubled by increasing the diameter, then the volume of coal removed is quadrupled. Thus, for equivalent power it is better to put the jet energy into nozzle diameter rather than pressure, with one important proviso. Every rock has a certain threshold jet pressure below which the jet will not cut the rock, and this must first be substantially exceeded. For an example (Figure 3), UMR has a 75-hp pump which can be used to produce 10 gpm at 10,000 psi or 4 gpm at 30,000 psi. At 10,000 psi, 10 gpm will flow through four nozzles of 0.04-in. diameter, while at 30,000 psi only one nozzle of 0.02-in. diameter can be used. Thus, on a relative area basis, the lower pressure jet will cover 16 times the area of the higher pressure jet.

If the above derived relationships are considered, this will give a six times greater volume of coal removed by use of the lower pressure system. Because the jets can be used to exploit weakness planes in the coal and break to free surfaces, the lower pressure jet is more effective.

The current trend is, therefore, to water jet mining machines operating at between 2,000 and 10,000 psi at flow rates from 200 to 50 gpm at nozzle diameters from 1 mm to 1 in. in size. The method of application to a large extent governs the jet operating parameters, and three examples will serve to illustrate this.

3. CANADIAN MINING

The most dramatic application of water jets to mining is currently in the Sparwood Mine of Kaiser Resources in British Columbia (22). Entries are driven in the center of the 50-ft thick seam at intervals down the dip. Working from the top drift down a water jet monitor then mines out the overlying coal washing it down into the entry where it is collected and broken to a small enough size to be put into the flume and carried out of the mine with the spurt water from the operation. This system has produced 3,400 tons in a six hour shift

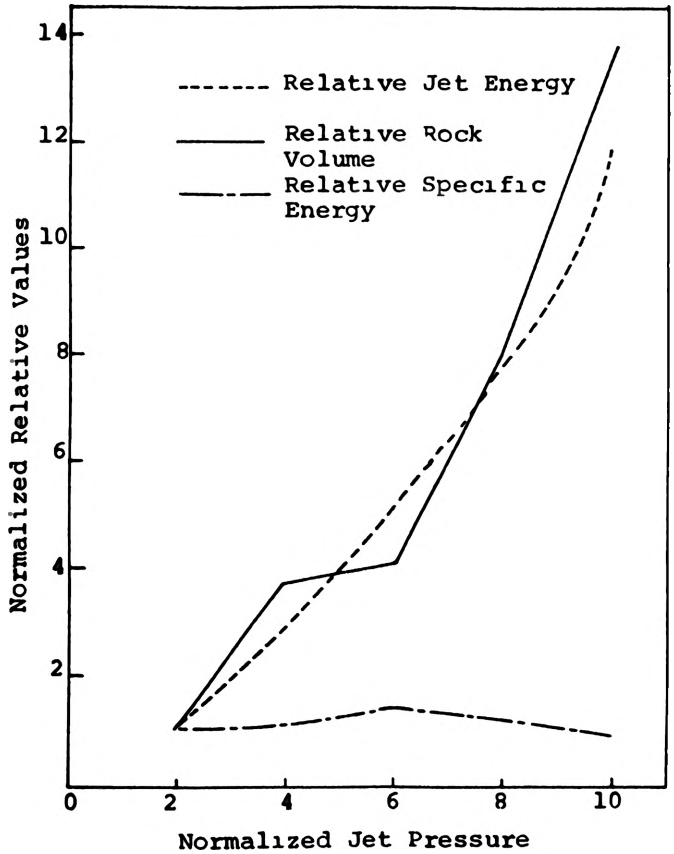

Figure 1. Relative variation in energy of the impacting jet, volume of rock removed and specific energy of cutting with relative change in jet pressure.

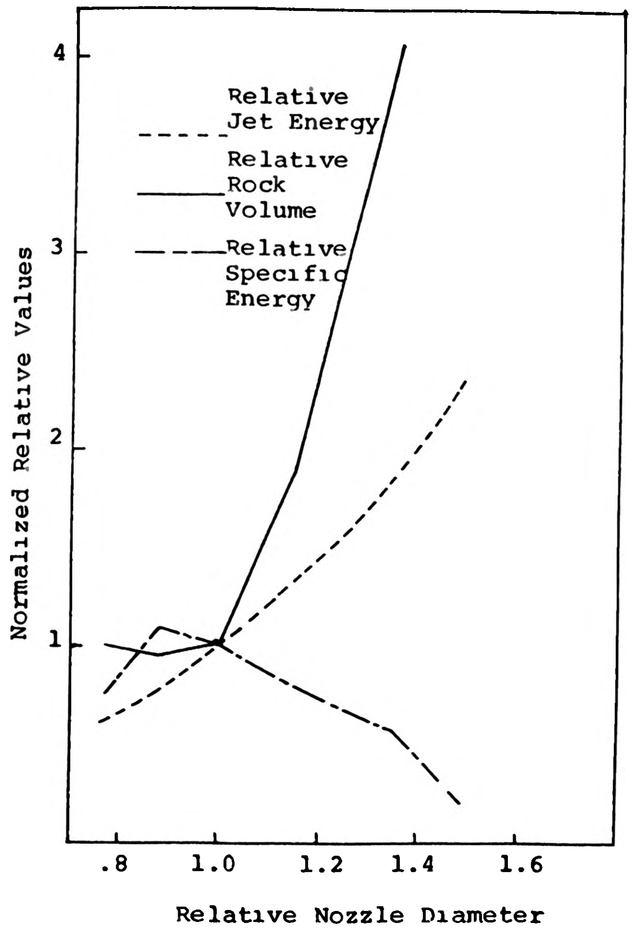

Figure 2. Relative variation in energy of the impacting jet, volume of rock removed and specific energy of cutting with relative change in nozzle diameter.

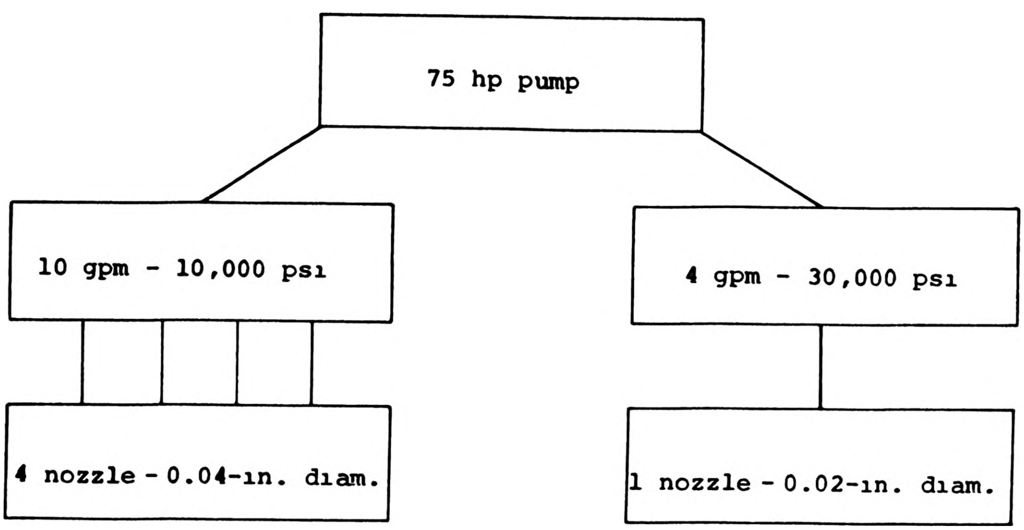

Figure 3. Options available with a 75-hp water pump.

with two men operating the unit; although because of other operations associated with the mining process, the overall output per man at the mine is only 60 tons per shift. Nevertheless, this compares well with the American average of 11 tons per manshift. There are plans for more mines of this type to be opened in the western coal seams where such operations will be feasible. Unfortunately, most of the coal seams being worked in this country are thinner and more horizontal than the Canadian case and a second method of mining must be developed.

This is the system being developed at the University of Missouri - Rolla.

4. PROJECT HYDROMINER

The vast majority of mines in this country use the room and pillar method of mining in which parallel tunnels are driven in the coal and periodically cross-connected to leave large pillars, required to hold the overlying ground in place (Figure 4).

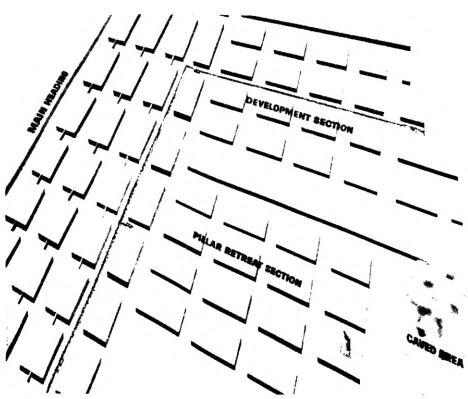

Figure 4. Room and pillar layout.

Unfortunately, these pillars may contain more than 50 percent of the available coal which has thus been "sterilized." In order to overcome this problem a method of mining called longwall has been introduced with which almost all the coal can be extracted. In this method access tunnels are driven to the boundary of the section, and then a crosscut is established. Within this crosscut steel supports are located which hold the roof up, and a conveyor is laid along the tunnel. A mining machine is then mounted on top of the conveyor so that it can travel the length of the tunnel (Figure 5).

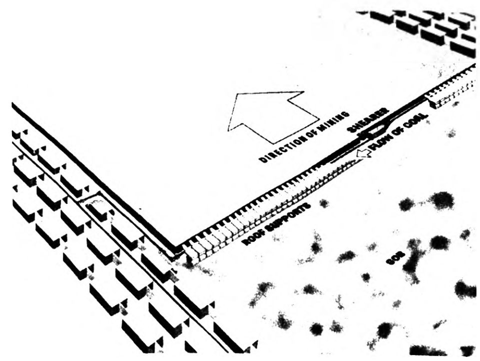

Figure 5. Longwall layout.

The machine then starts at one end of the tunnel and takes a slice of coal from the tunnel wall and loads it onto the conveyor. After the machine has passed the conveyor and roof supports move forward, and the unsupported roof behind the operation collapses. The machine is then moved back along the conveyor, taking a second slice of coal, and the cycle repeats. In this manner most of the coal is mined; the face workers are always protected from roof falls and by the time the subsidence of the ground reaches the surface it is so spread out over the ground as often to be unnoticeable.

However, a problem with this equipment lies in the amount of dust it generates and the environmental problems. In order to overcome these problems and demonstrate the use of water jets in this area, the University of Missouri - Rolla contracted with the Bureau of Mines to develop a design for this situation.

In the experimentation it was found that the use of water jets to mine the total seam by themselves would, in this case, require too much energy, and a combination water jet action with mechanical assistance system was proposed. In order to demonstrate the method as simply as possible it was determined that the best method would be to modify an existing mining machine. Accordingly, in the design the cutting heads of a shearer were removed and replaced by two high pressure pumps which together fed 50 gpm at 10,000 psi to the cutting head (Figure 6). The jets in the cutting head are then used to cut slots in the top, back, and bottom of the slice of coal being mined. This leaves a cantilever of coal which is readily broken off by the wedge shape of the cutting head. In the design experimentation it was found that a single jet would not cut a slot sufficiently wide to introduce the edge of the wedge into the slot (Figure 7). For this reason a dual orifice system was developed which produced (Figure 8) slots of sufficient width. This unit is now in construction under a Bureau of Mines contract. I am proud to announce that the initial design of this machine won this year's Student Design Award Competition run by the Lincoln Arc Welding Foundation.

5. BOREHOLE REAMING

A third application for water jets is also being considered and will shortly be tested by Flow Research at a Carbon River coal property in Washington state. Much expense is normally required to gain access to coal seams, and the process may take a number of years. In order to reduce both factors in the steeply dipping seams of that region a novel method of approach is being taken. Water jet drills will be used to drill from the surface down the dip of the seams. Once the required depth has been reached the nozzle system will be changed and the jets will be directed vertically outward widening the hole and washing the coal to the bottom or sump. Here it will be collected and pumped back up to the surface. The method, which is also being funded by the Bureau of Mines, is similar in some respects to earliest experiments in this technique carried out in the Gilsonite seams of the Green River basin in this country (23) and in Russia and Germany (24, 25).

6. ACKNOWLEDGMENT

This paper describes a project funded at the University of Missouri - Rolla under U.S. Bureau of Mines Contract USDI-H0252037 with Mr. J. Frank acting as technical project officer. The support of the Federal Government and the advice of Mr. Frank is gratefully acknowledged.

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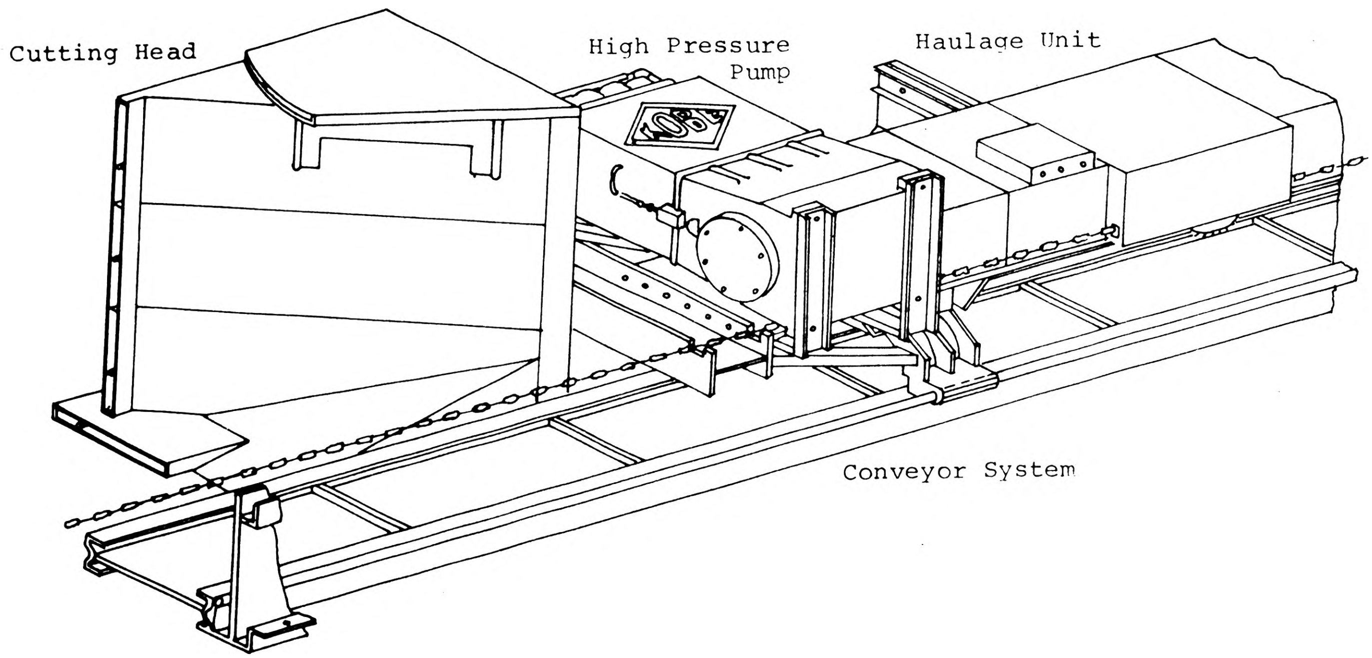

Figure 6. Artist concept of the Hydrominer unit.

Figure 7. Slot cut by single jet in coal.

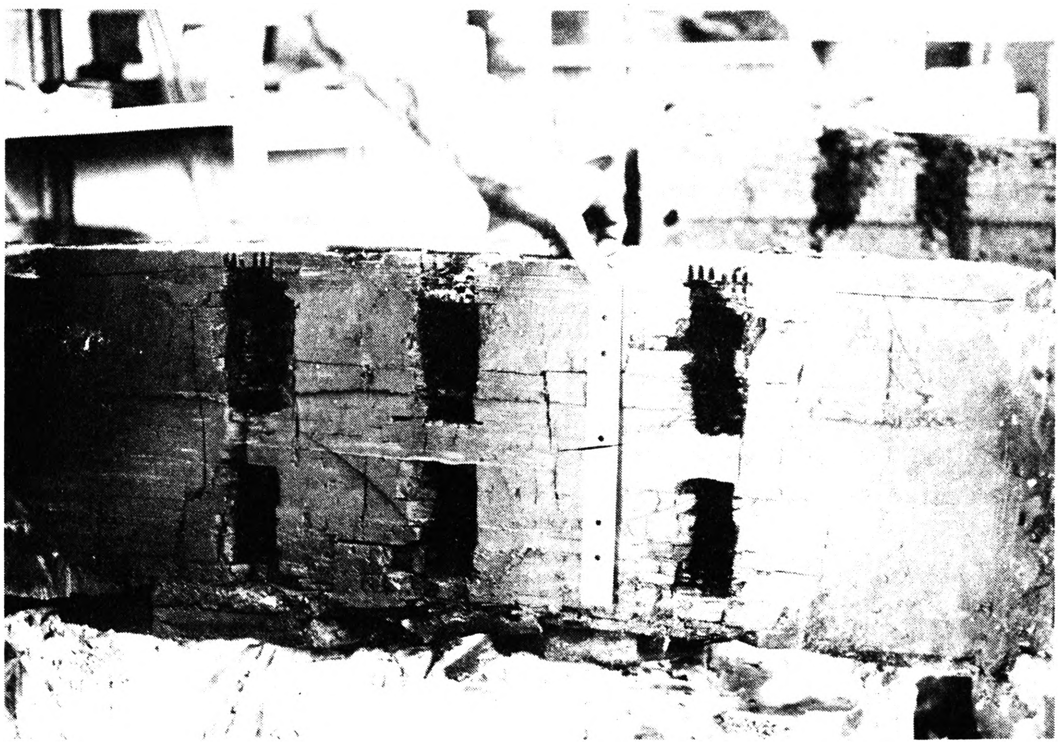

Figure 8. Slots cut by dual jets in coal.

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8. BIOGRAPHY

Dr. David A. Summers spent a year in the National Coal Board in the North of England prior to going to the University of Leeds, Yorkshire, England where he obtained a Bachelor of Science (Class I) in Mining Engineering in 1965 and a Ph.D. in Mining Engineering in 1968. His Ph.D. thesis dealt with water jet excavation of rock and since that time he has been on appointment at the University of Missouri - Rolla, Rock Mechanics & Explosives Research Center working in the field of applied jet cutting. He has produced over 30 papers dealing with this subject and is presently working on two research contracts developing a longwall water jet mining machine for the Bureau of Mines and a water jet drilling device for the Energy Research and Development Agency. He is currently Associate Professor of Mining Engineering and Senior Research Investigator at the Rock Mechanics & Explosives Research Center of the University of Missouri - Rolla, Rolla, Missouri.

DIRECT AC GENERATION FROM SOLAR CELL ARRAYS

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Abstract

Results of the investigation of the performance of solar cells when directly coupled to a conventional three-phase power network are presented. This approach dissociates the electricity production problem from the electric energy storage problem. Extensive studies of the required power inverter are performed. Preliminary simulation results indicate that ac power outputs of better than 90% of the optimum cell power output can be easily achieved by means of a suitably controlled inverter, thereby justifying the elimination of dc loads or local dc electric energy storage devices. It is also shown that the controlling policy for the inverter must depend on the operating conditions of the system, such as cell temperature, solar intensity and power system voltage variations, otherwise the performance of the inverter can deteriorate quite dramatically.

INTRODUCTION

It appears likely that the cost of solar cells will drop in the next few years; it is, therefore, pertinent to investigate the possibility of utilizing solar cells for bulk generation of electricity on earth-based facilities. Since solar cells are inherently dc devices, three alternatives appear feasible: direct utilization of the dc power, storage of dc electric energy and direct connection to the power network.

The direct utilization of the dc power through inverters requires the selection of a suitable useful dc load [1]. As the operating conditions vary, so do the optimal load characteristics. This method has other limitations, such as the location and type of load that can be used. Furthermore, the power available to the load is of an intermittent nature.

The storage of dc electric energy can be accomplished by a variety of means, such as electrochemical storage (batteries), or fuel cells. This eliminates the shortcomings due to the intermittent nature of the source. There are still limitations as to useful load location and type. Moreover, the overall efficiency of the system is reduced and its cost increased.

The third alternative, connection to the power network through inverters offers a great amount of flexibility and high efficiency at the expense of inverter circuit complexity. This approach places solar cells in the same category as "off the river" hydro plants to the extent that power is supplied to the network on an "as available" basis. The problem of energy storage is not eliminated, but it can be studied independently of the detailed study of solar generators/power inverters. A companion paper [9] studies the coincidence factor between solar insolation and electric demand for a specific region of the country. It is encouraging to notice that there is generally good correlation between peak electric demand and solar intensity.

MODELING SOLAR CELLS

Voltage-current relationships for solar cells are well-established from both theoretical and experimental considerations [2-6]. For the studies to be undertaken in this paper the following mathematical model has been chosen, based primarily on [5]:

$$E = K_e \; T \; \ell n[1 + (I_s - I)/I_o] \quad (1)$$

$$I_o = K_o \; T^4 \; A \; \exp[-E_g/(K_e T)] \quad (2)$$

$$I_s = K_s \; A \; G \quad (3)$$

$$V = E - I \; R_i \quad (4)$$

where

- E - internal light-induced cell voltage (V)
- I - cell current (A)
- T - temperature (°K)
- I_s - ideal ($R_i = 0$) cell short-circuit current (A)
- I_o - maximum reverse-current (A)
- V - cell terminal voltage (V)
- R_i - internal series resistance (Ω)
- A - cell area (m^2)
- G - energy density (W/m^2)
- E_g - energy gap of material (eV)
- K_e, K_o and K_s - proportionality constants (K_o and K_s depend also on material properties).

The incident radiation is characterized in this model by the total solar energy density G. For this reason the "constant" K_s depends on the shape of the solar spectrum density, since I_s depends actually on n_{ph}, the photon rate of flow per unit area for photons with an energy content greater than the energy gap E_g in the semiconductor junction. Larger values of n_{ph} (like those achieved by means of concentrators) tend to increase the importance of the losses in the internal cell resistance R_i [3,4,7]. Important dynamic effects appear if temperature variations are considered. The present paper neglects thermal dynamics and assumes constant temperature. Higher temperatures (often the result of larger G) result in reduced voltages and powers.

To illustrate the typical relationships obtained from (1) to (4) a silicon solar cell with the following parameters was chosen [6]:

$$K_e = 8.617 \times 10^{-5} \qquad E_g = 1.11 \text{ eV}$$

$$K_o = 275 \qquad A = 2 \times 10^{-4} \text{ m}^2$$

$$K_s = 4.28 \times 10^{-2} \qquad R_i = .4 \text{ ohm}$$

(Note: Under the solar conditions and energy gap chosen $G = 1$ W/m^2 corresponds to $n_{ph} = 7.20 \times 10^{17}$ photons/m^2.)

The E-I curves for this cell were obtained for a variety of incident radiation levels G and cell temperature T combinations. The results are illustrated in Figure 1.

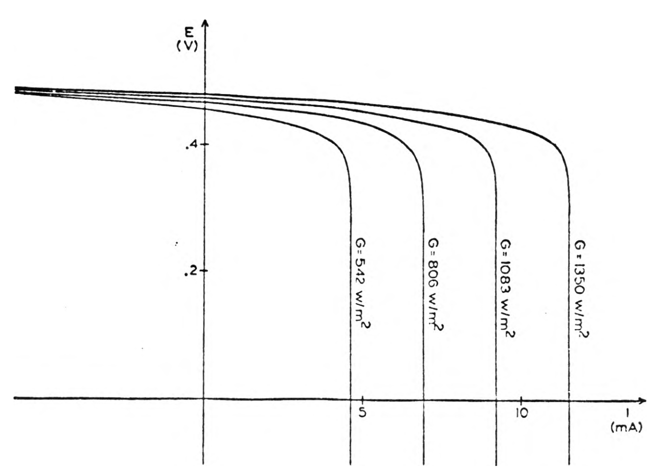


Fig. 1a. Voltage-current characteristics of cells. Variations in G with $T = 300°K$.

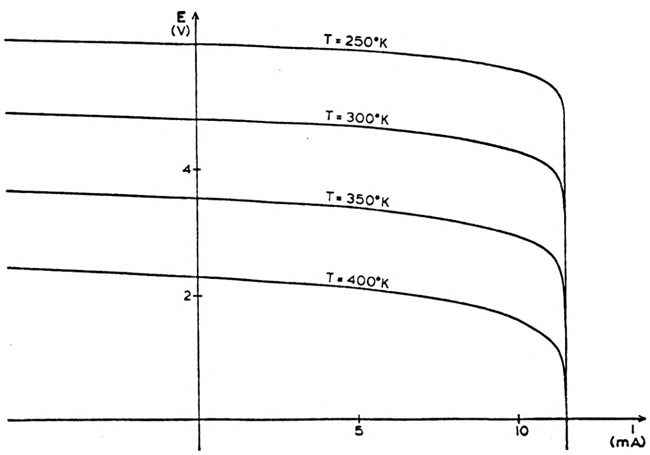


Fig. 1b. Voltage-current characteristics of cells. Variations in T with G = 1350 w/m^2.

THE INVERTER

This paper considers the use of controlled rectifiers to convert from ac power to dc power. This technology has been extensively studied and developed in connection with dc power transmission lines [8]. The specific configuration used in this report is the one for a three-phase full-wave rectifier/inverter using six controlled rectifiers as illustrated in Figure 2. Ideal controlled rectifiers are considered. The ideal controlled rectifier is a memory binary element with two states: "on" (g = 1) and "off" (g = 0). The "on" state is reached under the presence of an appropriate control pulse p = 1; the "off" state is reached by attempting to circulate a negative current. For simulation purposes an ideal controlled rectifier can be mathematically modeled as follows:

$$g(t+dt) = \begin{cases} 0 \text{ if } g(t) = 0 \text{ and } v(t) \leq 0 \\ 1 \text{ if } g(t) = 1 \text{ and } i(t) \leq 0 \end{cases} \quad (5)$$

$$\begin{cases} g(t) = 0 \Rightarrow i(t) = 0 \\ g(t) = 1 \Rightarrow v(t) = 0 \end{cases} \quad (6)$$

The model for the active component within the dc source (the solar cell) has been described in the previous section. It is assumed that a low-pass filter in the form of a simple series inductor is used. The series of resistance of the cells is combined with the inductor resistance into an overall series resistance R_d. The model for the dc source is also illustrated in Figure 2. The presence of L_d introduces a dynamic equation for I_d and (4) must be replaced by

$$\dot{I}_d = (E_d - V_d - R_d I_d)/L_d \quad (7)$$

The three-phase ac system is modeled by inductive impedances in series with ideal sinusoidal voltage sources. The model for this system is illustrated in Figure 2 and it can be described mathematically as:

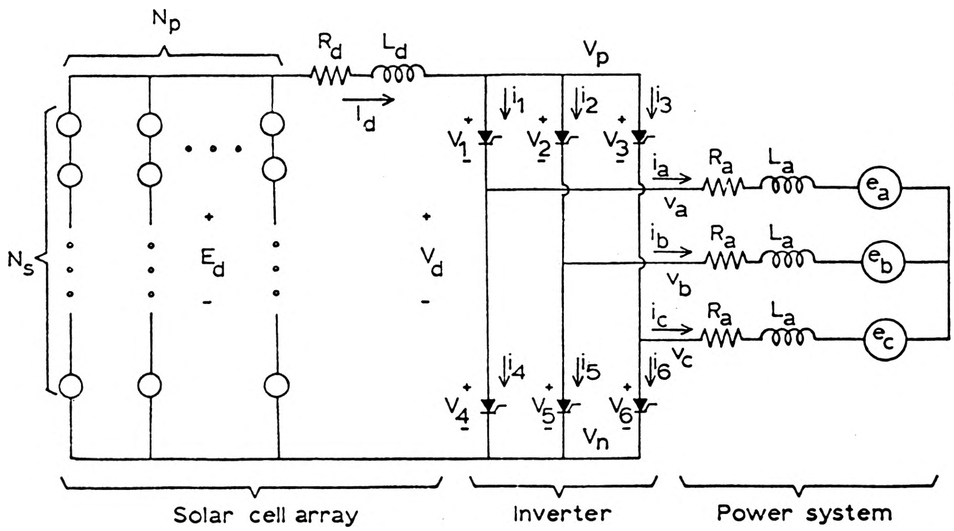


Fig. 2. The cell/inverter/power system equivalent circuit. Voltages V_p, V_n, V_a, V_b and V_c are defined with respect to power system neutral.

$$\dot{i}_a = (v_a - e_a - R_a i_a)/L_a$$
$$\dot{i}_b = (v_b - e_b - R_a i_b)/L_a \qquad (8)$$
$$\dot{i}_c = (v_c - e_c - R_a i_c(/L_a$$

$$e_a = E_a \sqrt{2} \sin (\omega t - \Theta_a)$$
$$e_b = E_a \sqrt{2} \sin (\omega t - \Theta_a - 120°) \qquad (9)$$
$$e_c = E_a \sqrt{2} \sin (\omega t - \Theta_a - 240°)$$

where

E_a - effective line to neutral voltage

Θ_a - phase angle

THE SIMULATION STUDY: GENERAL

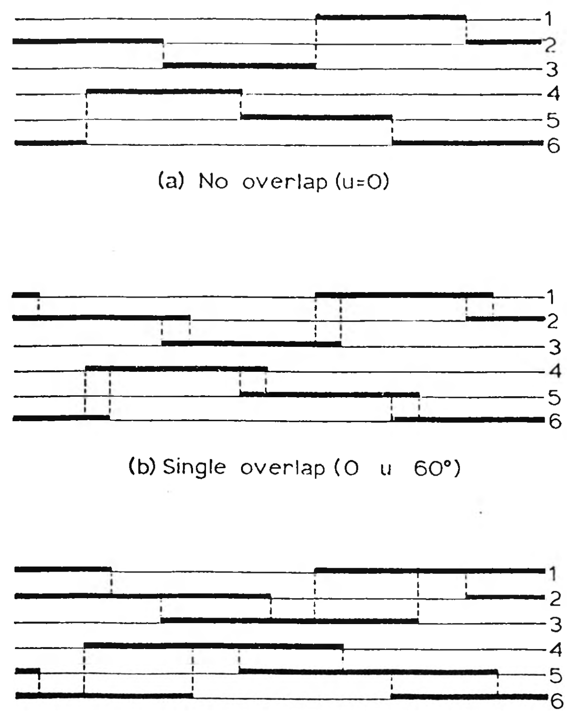
The successful design and operation of the solar electric generator described in the previous sections involves such considerations as the adequate design, orientation and location of solar cells, the design of adequate concentrators, the selection of circuit parameters (inductors, etc.) and the selection of the number of series cells and parallel paths within an array. One of the most fundamental considerations, however, is the appropriate timing of the control pulses p to the controlled rectifiers. The remainder of this paper is devoted primarily to the study of controlled rectifier control policies. The following notation is adopted for all further discussions:

α - ignition delay in electrical degrees (e.g., delay between the time when conduction would start in an uncontrolled rectifier, $v > 0$ and the time when the corresponding pulse p is applied to the rectifier).

u - overlap angle (time in electrical degrees between the beginning of conduction of a given controlled rectifier and the termination of conduction of another rectifier directly in parallel with it).

$\delta = \alpha + u$ - extinction angle.

Kimbark [8] has performed detailed analytical studies of these three-phase inverters. One of the limitations of these analytical studies is that for mathematical convenience the dc source is modeled as a constant current source for all commutation studies, although slow long term variations are allowed.



(a) No overlap (u=0)

(b) Single overlap (0 u 60°)

(c) Double overlap (u 60°)

Fig. 3. Rectifier conduction sequence (solid line denotes "on" state of rectifier).

Under ideal conditions conduction in one rectifier ceases when one in parallel with it is fired. This situation arises when $L_a = 0$ and implies $u = 0$ [8]. Figure 3a illustrates the typical conduction sequence under these circumstances. The voltage V_d waveforms for various ignition delay angles α for the same case are illustrated in Figure 4. It can be observed that the average value of V_d positive is positive only when $\alpha > 90°$. This means that if $\alpha \leq 90°$ power cannot be delivered by the dc source but is instead absorbed by it, an obviously undesirable situation. Also, α is further restricted

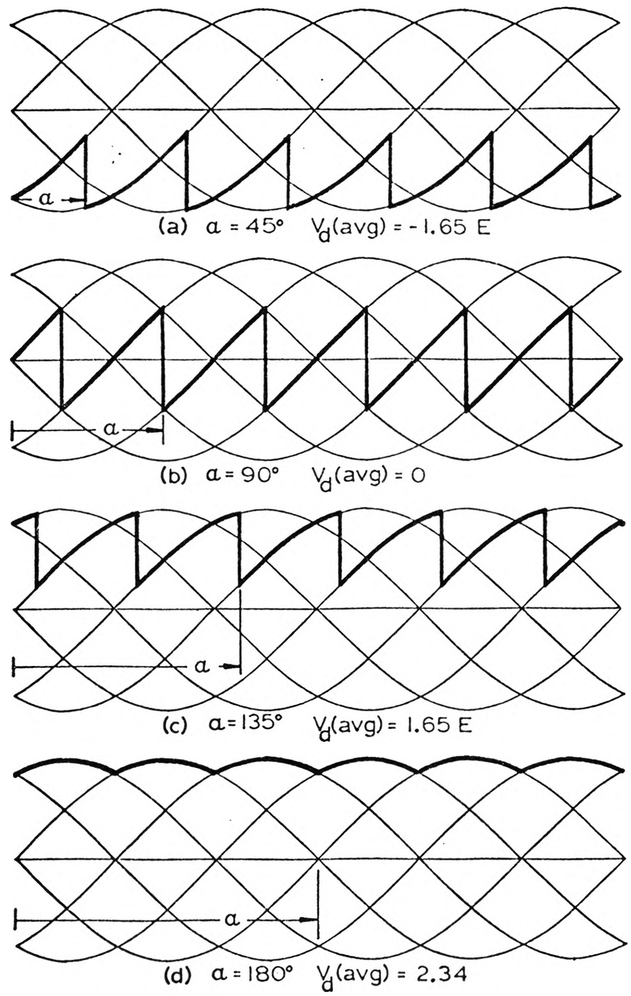


Fig. 4. V_d waveforms, no overlap.

to less than 180°, otherwise conduction in the previous valve cannot cease naturally.

The presence of an inductance in the ac system alters the commutation sequence so that three rectifiers can be conducting at once, as illustrated in Figure 3b. This situation occurs when $L_a > 0$ and results in $u = \cos^{-1}(\cos\alpha - I_d/I_{s2}) - \alpha$, where $I_{s2} = \sqrt{3}E_a/\sqrt{2}\omega L_a$. In fact, if either L_a or I_d become sufficiently large or E_a sufficiently small, an abnormal condition in which four rectifiers conduct at once can develop, as illustrated in Figure 4c. This abnormal situation is not discussed herein. A further effect due to the presence of L_a is a resistive drop in the average value of V_d, even if R_a is zero. Also, δ must be restricted to less than 180° for proper operation.

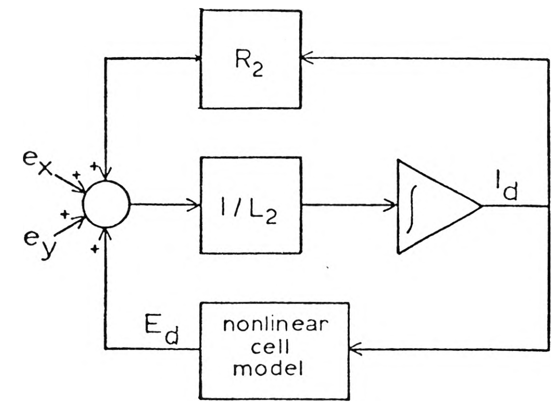
Three modes of control for controlled rectifiers are traditionally recognized: constant ignition angle α control (CIA), constant current I_d control (CCC), and constant extinction angle δ control (CEA). In the absence of L_a, CIA and CEA are equivalent. Adjusting α or δ under these conditions results in a change in V_d with a corresponding change in I_d according to (1) and (4). The presence of an inductance L_a affects the CIA to the extent that V_d will become somewhat current dependent. More important, however, is its effect on CEA, when a nonzero u means that the rectifier must be triggered in advance of the desired extinction, and this angle must be based on computed predicted values of the current; this problem becomes more critical when values of δ close to 180° must be chosen, since δ should never exceed 180°. CCC is based on adjustments of the ignition angle α based on deviations of the actual current I_d from a desired value of current. Proper design of gains and time constants in the feedback loop should be made to prevent possible control loop instabilities.

Rectifier/inverter systems are generally controlled by setting the rectifier in a CCC mode (current approximately constant); or alternately, the rectifier in a CCC mode and the inverter in a CEA mode. The choice is usually dependent on the operating conditions. It is, hence, interesting to notice that the solar cell characteristics under fixed operating conditions as illustrated in Figure 1 closely resemble the characteristics of three-phase rectifiers with one approximately constant current segment and one approximately constant voltage segment.

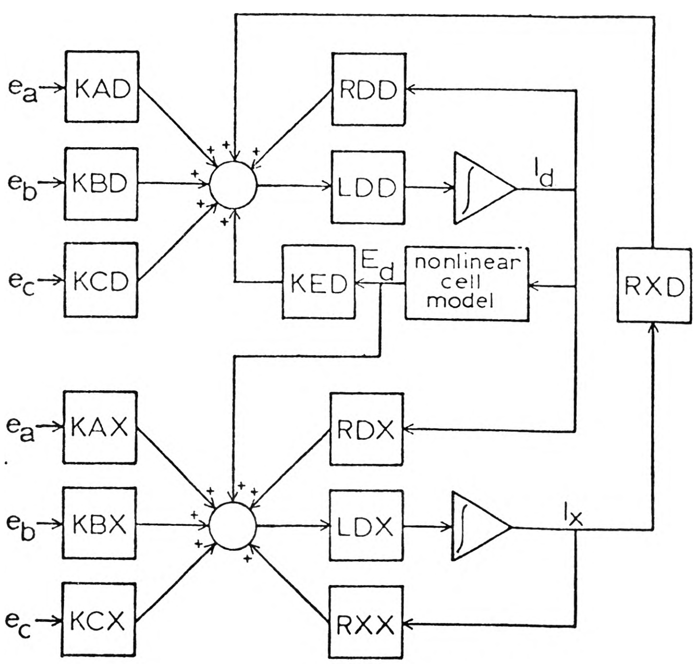
The simulated experimental setup used in connection with the present research was implemented in a digital computer using a continuous system modeling program.

Equations (1) - (3) and (5) - (9) were used in addition to all the necessary binary logic for the control of the rectifiers. A block diagram for each of the two possible operating configurations (two rectifiers conducting or three rectifiers conducting) was implemented as illustrated in Figure 5.

Other portions of the model, not illustrated in Figure 5, are used to control the transition between model configurations and to re-evaluate model parameters at the appropriate intervals. The ignition



(a) When two rectifiers conduct.



(b) When three rectifiers conduct.

Fig. 5. Block diagram of model. Parameter values depend on which rectifiers are conducting.

pulses can be controlled by either one of the three control modes already described, or by a fourth mode, constant ratio control (CRC). Another portion of the model is used to simulate the behavior of the ignition timing controller. Only simple integral-error feedback controllers were considered in this study, although some nonlinear gains were used in an attempt to linearize the effect of control signal errors. The equations that describe the dynamics of the ignition delay angle α each of the four control modes are:

Constant Ignition Angle:

$$\alpha = \alpha_{set} \tag{10}$$

Constant Extinction Angle:

$$\alpha = \cos^{-1} (\cos \delta_{set} + I_d/I_{s2}) \tag{11}$$

Constant Current Control:

$$\dot{\alpha} = \begin{cases} 0 \text{ if } I_d > I_{set} \text{ and } \\ \cos\alpha \geq I_d/I_{s2} - 1 \\ K_c \; (I_d - I_{set})/\sin\alpha \\ \text{otherwise} \end{cases} \tag{12}$$

Constant Ratio Control:

$$\alpha = \begin{cases} 0 \text{ if } R_{set} > V_d/I_d \text{ and } \\ \cos\alpha \geq I_d/I_{s2} - 1 \\ \\ K_r \; (R_{set} - V_d/I_d)/\sin\alpha \end{cases} \tag{13}$$

where

$$I_{s2} = \sqrt{3}\; E_a/\sqrt{2} \cos L_a$$

$$V_o = 3\sqrt{6}\; E_a/\pi$$

The purpose of the Constant Ratio Control mode is to provide an easily implemented control mode such that the inverter efficiency is less sensitive to errors in the determination of the operating conditions, as illustrated in this next section.

A possible modification to CEA control that could be of practical interest involves the use of a feedback error signal from the desired δ to adjust α rather than the predictive formula (13). The error signal, however, could be determined only at discrete intervals. Other likely straightforward modifications include the use of a predictive term $\dot{I}_d$ in (11) and of more complex dynamic characteristics in (12) and (13).

Another feature of the simulated model is its capability of measuring efficiencies. Three different efficiencies are defined and evaluated:

$$\eta^*_{cell} = \frac{P^*}{GA} \qquad (14)$$

$$\eta_{cell} = \frac{V_d I_d}{GA} \qquad (15)$$

$$\eta_{inv} - \frac{\eta_{cell}}{\eta^*_{cell}} \qquad (16)$$

where:

P^* is the maximum power that the solar cell array can deliver under the given conditions of temperature and incident radiation. This number is calculated by the model via Newton iterations

GA represents the total incident power

η^*_{cell} represents the maximum efficiency that the solar cell array is capable of operating at.

η_{cell} represents the actual efficiency under the conditions and control policies used

η_{inv} represents the efficiency due to performance deviation from the optimal by the presence of the inverter circuitry. This is the number that measures the effectiveness of the inverter.

THE SIMULATION STUDY: AN EXAMPLE

The digital model described in the previous section can be used to answer a variety of questions about the performance of any particular solar cell array under various operating conditions and control modes. This section outlines some of the most important experiments that have been performed with this model or with some variations of it, and presents the results of a few of these experiments as performed for a specific solar cell array. These experiments include: the determination of the steady state waveforms for the various currents and voltages for specific sets of parameters, operating conditions and control modes; the determination of the instantaneous and average inverter efficiencies under steady state conditions; the determination of the effect of variations of the inverter control parameter (α_{set}, δ_{set}, I_{set} or R_{set}) as well as variations of the operating conditions (G, E and T) on the inverter efficiency. These studies can be useful in selecting optimal control parameter settings and predicting the performance degradation in case of erroneous determination of the operating conditions for the various control modes. The determination of the effect of parameter variations (L_d, L_a, N_p, N_s) on the performance of the system under CRC mode was also undertaken, as well as the study of the ransient behavior of the system under sudden variations of the operating conditions.

An array of the same cells described earlier in this paper was used. The following additional system parameters were chosen for the simulation.

System Parameters:

R_d = 26.1 ohm $\quad$ R_a = .3 ohm

L_d = 1 henry $\quad$ L_a = .3 henry

N_p = 4 $\quad$ N_s = 260

(ω) = 377 rad/sec (60 Hz)

Control Parameters:

α_{set} = 137° $\quad$ I_{set} = 45.5 mA

δ_{set} = 144° $\quad$ R_{set} = 3000 ohm

Operating Conditions (basic study):

T = 300 K $\quad$ G = 1350 w/m^2 $\quad$ E = 49 volts

Figure 6 illustrates some of the steady-state waveforms obtained. The comparatively large variations in E_d for small

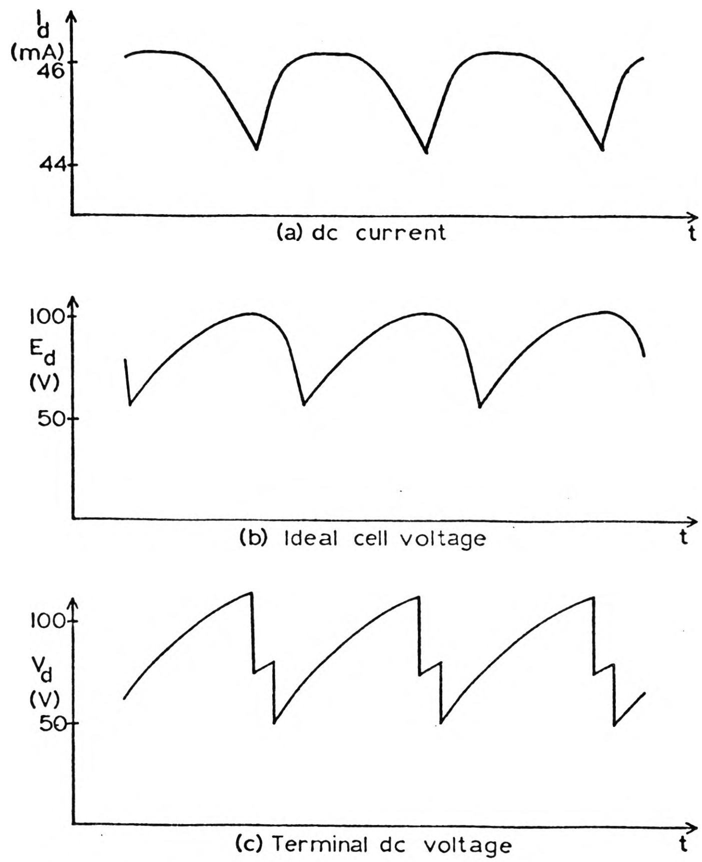


Fig. 6. Approximate steady state waveforms under CIA control, $\alpha = 137°$.

variations in I_d when attempting to operate at high inverter efficiency (89% in this case) can be observed. Also, the abrupt variations in V_d (Figure 6c) at the switching instants can be observed. This waveform can be compared with Figure 4c. The short "transition intervals" visible in Figure 6b are due to the nonzero commutation angle.

The effect that variations of the control parameters (α_{set}, I_{set}, δ_{set} and R_{set}) under their respective control modes (CIA, CCC, CEA and CRC) have on the inverter efficiency can be observed in Table I. (Due to numerical errors and finite settling times all efficiencies subject to about 2% errors.) It can be observed from this table that, under the proper circumstances, all control modes can result in a commutation failure or at least a change in mode to prevent one. The relatively wide range of settings that result in acceptable operation in the CRC mode can be observed, as well as the range of settings acceptable in the CCC mode under similar conditions.

Tables II through IV illustrate the effect of variations in the system voltage E, temperature T and solar intensity G in each of the control modes under the basic parameter settings (shown underlined in

Table I. Inverter efficiency vs. control parameter setting (fixed operating conditions).

Mode		Parameter Setting/Efficiency					
CIA	α_{set} (deg)	108	130	<u>137</u>	144	151	156
	η_{inv} (%)	< 40	77	89	96	99	*
CCC	I_{set} (mA)	44	44.5	45	<u>45.5</u>	46	47
	η_{inv} (%)	*	99	95	93	85	< 40
CEA	δ_{set} (deg)	108	136	<u>144</u>	151	158	180
	η_{inv}	< 40	80	88	94	99	*
CRC	R_{set} (Ω)	1000	1500	<u>2000</u>	2360	2560	3000
	η_{inv} (%)	55	75	94	98	99	*

*Commutation failure results (unless mode can be changed).

Table II. Change in inverter efficiency vs. system voltage level

Mode	Voltage Level E (Volts) 45	49	53
CIA	-8	0	+6
CCC	-5	0	-4
CEA	-9	0	+7
CRC	-6	0	-1

Table III. Change in inverter efficiency vs. temperature

Mode	Temperature (°K) 300	330
CIA	0	+11
CCC	0	-12
CEA	0	+13
CRC	0	+ 5

Table IV. Inverter efficiency vs. solar intensity

Mode	1200	1350	1500
CIA	-10	0	-1
CCC	< -50	0	*
CEA	0	0	-1
CRC	-12	0	-1

*Commutation failure results

Table I). The overall observation from these tables is that (at least under the conditions given) the CCC mode is far too sensitive to variations in solar intensity to be of practical importance. The CIA and CEA mode are simple, yet they offer a somewhat wider range with acceptable performance; CEA is generally preferable for its reduced likelihood of misoperation. It may be observed that both these modes were somewhat sensitive to variations in E and T. The CRC mode resulted in the best overall steady state operation due to its relative insensitivity to errors. Both the CCC and CRC modes, however, require careful selection of the feedback gains to prevent feedback loop instabilities and provide adequate settling times.

SUMMARY

This paper has demonstrated by means of a digital model that high inverter efficiencies can be achieved by direct three phase inversion of power from solar cell arrays. This suggests that this approach could become the primary utilization mode for solar cells should they become competitive with the ever-increasing costs of other forms of electric generation. This study has also emphazized the importance of adequate design and control of the inverter and related hardware. The controlling policy for the inverter must be dependent on the operating conditions, and the characteristics of four different controlling policies have been evaluated under a variety of conditions. Additional questions that deserve further investigation are the feasibility of real-time self-optimizing inverter controllers, the study of inverter failure modes, the analysis of filtering requirements, and the evaluation of the impact of large amounts of intermittent power generators on the power system.

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THE IMPACT OF DIRECT COUPLING OF SOLAR CELL ARRAYS TO ELECTRIC POWER NETWORKS

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ABSTRACT

This paper has to do with a preliminary investigation of the economic impact of solar cells when directly coupled to a conventional three-phase power network in the Toledo area.

A correlation is established between power system demand curves and solar insolation data in the Toledo area using computer simulation. The correlation studies determine how successfully solar cell/inverter systems can alleviate the power system demand during peak hours. They also show how much solar cell area will be needed to cause a significant impact on the power generating system.

Using computer simulation the initial cost of the solar cell/inverter is compared to the economic gains, i.e., money saved from reduced demands on the power network. The time value of money is considered in order to determine how long such a system will have to operate in order to pay for itself.

INTRODUCTION

One of the anticipated consequences of the shifting availability of natural energy resources is a trend toward more all-electric buildings. This shift will tend to increase the peak demands on the power system, thereby forcing the least desirable units in the system to be operated. Electrical energy utilization can be enhanced if an intermittent clean source of electric energy is available such as solar cells to supplement the main source.

The NSF/NASA Solar Energy Panel on photovoltaic programs projected that at least 20 percent of the nation's energy needs could be derived from solar energy after the turn of the century [1]. The Panel projected that photovoltaic conversion of solar energy could provide at least 1 percent of the electric power demand by the year 2000, which is equivalent to 5 percent of the present electrical power demand.

Three modes of utility-related use of solar cells are recognized: (a) the direct use of solar cells for generation of power by utilities in a bulk manner, (b) the encouragement of users to install utility-owned roof-top solar cells, (c) the indirect use of power from solar cells by utilities in the form of privately owned solar cell arrays. The wide spread use of these systems could provide a significant amount of the peak energy load which is now mainly supplied by fossil fuel burning power plants.

SYSTEM DESCRIPTION

Figure 1 represents the block diagram of a solar cell array system coupled to the electric power network as proposed in [2]. The system receives energy from two sources. It receives electric energy from the power network, which is considered as a controlled input variable. It also receives solar energy through the solar cell array and that is considered as an uncontrolled system input. Solar energy will be converted to d.c. electric energy through the solar cell array. The proposed inverter [2] converts this d.c. energy to a.c. energy, and delivers it to the power network. The controller determines the present state of the solar cells and the load then applies the proper control signals to obtain maximum power transfer.

WEATHER DATA

Winter weather in the Toledo area can reach subfreezing temperatures with high winds and snow. Summers are best described as warm and reasonably dry with mild breezes. Springs are cool and wet with moderate breezes. Falls are cool and dry with virtually no wind.

The statistical average of solar insolation available (in the Toledo area) is expected to be one of the dominant factors in the solar energy economic feasibility equation. Raw data has been recorded continuously for the past 15 years by the Libbey-Owens-Ford Company in Toledo, for the purpose of testing glass, and was made available for this study.

A data processing system to perform a statistical analysis of the raw solar insolation data has been designed using a Data General Computer at The University of Toledo Solar House Experiment. This system is shown in Figure 2.

Preliminary results have been obtained for the annual, seasonal and monthly expected insolation values and variances in the Toledo area. Some of these results are shown in Tables 1 through 3 and Figure 3. It is observed from these tables that the highest solar insolation obtained in the Toledo area is in the month of September with a percentage of 74.3 of the maximum possible. June is the lowest with 56.6%. In general, the fall delivers the highest, spring the lowest.

POWER LOAD DATA

The load of an electric utility may be divided into two major components, the base load and the weather-sensitive load. The base load of the Toledo Edison, being the fixed components of the system load, has a known expected value at any particular hour of each day of the week; it may be reflecting the business cycle of the territory served. The weather-sensitive load in the Toledo area is determined by the heating load in the winter and by the cooling load in the summer. Figure 4 illustrates a typical Toledo Edison demand curve for a typical winter day. The demand curve for Toledo Edison may be roughly divided into three regions A, B, and C. The fuel used in region A is primarily coal at a cost of αdollars/KWH. The fuel used in B is oil at a cost of βdollars/KWH. The fuel used in C is natural gas at a cost of δdollars/KWH. It is assumed that $\alpha < \beta < \delta$.

COINCIDENCE FACTOR

This section defines an index to be used as an indicator of how well electricity generated from solar cells can be used to alleviate the demand on the power system. This index is named the coincidence factor and is defined as follows: Coincidence Factor = (Normalized Solar Insolation) x (Normalized Power System Load).

When the coincidence factor is high the solar cell arrays can be used more efficiently to alleviate the demand on the power network. However, when the correlation function is low, the power generated by the solar cell arrays is not as efficient in alleviating the power system load for a given array area.

Four sample days and four ideal days were selected for the study representing the four seasons. Sample days: January 6,1972, April 16, 1972, July 6, 1970, and October 16, 1972. Ideal days: January 21, April 21, July 21, and October 21. Recordings of solar insolation and demand curves versus time of these days were obtained.

The solar insolation curves were normalized with respect to the maximum value of that day. The demand curves were also normalized with respect to the maximum value of power for the day. Similarly, a normalized generation cost curve was established. A computer program was written in order to calculate the coincidence factor as defined above for those days. Results of this program are shown in Figures 5 through 8.

It is apparent that the high demand period on the power system in the Toledo area is from 7:00 a.m. to 9:00 p.m. with slight seasonal variations. For a sunny day in the month of January or October, it is observed that the coincidence factor is above 0.4 for the period approximately between 9:00 a.m. and 4:00 p.m. indicating a good degree of alleviating the demand on the power network.

A sunny day in the month of April offers reasonable relief to the power network in the period between 8:30 a.m. to 4:30 p.m. Similarly, for a sunny day in the month of July is the period between 9:00 a.m. to 4:30 p.m. All of these figures are for a 45° orientation.

ECONOMIC ANALYSIS

The effective cost of a solar cell/inverter system is the initial cost of the solar cell array and inverter minus the economic gain created by reducing the amount of electrical power required from the power network. The time value of money is also considered. Therefore, the effective cost C(n) can be represented as:

$$C(n) = I(1+i)^n - \sum_{k=1}^{k=n} \eta_1 \eta_2\, G(k)\, A_s\, R\, F(k) H(k) U(k)$$

C(n) is the effective cost in dollars at the end of the nth interval. Each interval corresponds to one season (e.g. one full year n = 4). I is the initial cost of the solar cell array and inverter. The projected cost of solar cell arrays as determined by [1] is used for this study. Such projected data is shown in Figure 9. Unlike the solar cell arrays, little information is available about the cost of inverters suitable for direct coupling with the power system. In order to obtain approximate figures regarding the cost of such inverters, a brief survey of commercially available inverters was made. The results are given in Figure 10. i denotes the quarterly interest rate in %. η_1 denotes the efficiency of the solar cells, i.e. $\eta_1 = \frac{\text{electrical power out}}{\text{solar insolation}} \times 100\%$. Silicon solar cells are assumed with efficiencies of approximately 10% [3,4]. η_2 is the efficiency of the inverter, i.e., $\frac{\text{electrical power out}}{\text{electrical power in}} \times 100\%$. For this study, it has been assumed that an inverter with efficiency of 95% can be built [2]. G(n) is the maximum solar insolation of the nth interval expressed in watts/m^2. A_s is the solar cell array area in m^2. It should be noted that this is the actual cell area and does not include any reflector area if they are used. R is a dimensionless orientation factor which takes into account the mounting angle of the solar cell array. This factor is unity if the solar cell array is mounted on the same altitude angle as the solar insolation data. F(n) is a dimensionless cloud cover factor which takes into account variations in solar insolation throughout the day. The product of G(n) and F(n) is the time average solar insolation for day. H(n) is the number of sunlit hours in the nth interval, i.e., the nth season.

$$H(n) = \frac{365 \text{ days/yr}}{4 \text{ seasons/yr}} \times \frac{\text{no. of sunlit hrs.}}{\text{day}}$$

U(n) is the utility rate for the nth interval in dollar/watt hour. Two kinds of utility rates are studied, one is a simple linearly increasing model, i.e., constant dollars/KWH regardless of the demand. This kind of utility rate used is shown in Figure 11. The other model takes into account the fuel being used at the time and the relative cost of that fuel (demand pricing). In addition, yearly cost increases are considered as shown in Figure 12.

Figure 13 shows the effective cost C(n) in dollars versus the time in years, with the percentage interest rate i as a parameter, the initial investment I fixed at $6,000 per KW, solar insolation being ideal, and with a linearly increasing model for utility rate of 11% every five years starting at 3.3 cents/KWH. Such system is obviously not economically feasible, and will never pay for itself.

Figure 14 shows C(n) versus time in years with i as a parameter. Ideal solar insolation is also used with a utility rate of 3.3 cents/KWH increasing linearly by 100% over the first five years. An initial investment of $1,000 per KW was used. It can be seen that the system becomes more economically feasible as the interest rate goes down. With an interest rate of 6%, the system pays for itself in 13 years.

The next step is to investigate the effective cost C(n) with a utility rate model that takes into account the fuel being used at the time, the relative cost of that fuel (demand pricing), and yearly increases. Therefore, it is necessary to study the variations in the demand curves (in the Toledo area) resulting from coupling solar cell arrays directly to the power network so that new generation cost curves can be constructed. Four typical days in January, April, July and October were selected. Figures 15 through 18 indicate the effects of coupling different areas of solar cell arrays ranging from 500,000 m^2 to 3,000,000 m^2 to the power network.

Figures 19 and 20 indicate the effect cost C(n) as a function of time for two initial investments of $6,000 per KW and $1,000 per KW respectively taking into consideration the fuel being used and yearly increases (as shown in Figure 12) starting at 3.3

cent/KWH. Figure 19 does show an improvement over its corresponding case when using a linearly increasing model for the utility rate but still economically not feasible. Figure 20 indicates that a system with an initial investment of $1,000 per KW and an interest rate of 8% will pay for itself in about 15.5 years. If the interest rate is 6% it would pay for itself in about 9.5 years.

CONCLUSION

A preliminary investigation of the economic impact of coupling solar cell arrays to a conventional three-phase power network in the Toledo area has been performed.

Results obtained indicate that direct coupling of solar cells to the power network will give a good degree of alleviating the demand. Considerable reduction of the demand happens between 8:00 a.m. and 7:00 p.m. for at least 7 hours period within these hours depending on the season.

Results also show that with a solar cell array/inverter system of $1,000 per KW, the system would pay for itself in 13 years when using a linearly increasing model for utility rate, and in 9.5 years when using a demand pricing model, and with an interest rate of 6%.

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Table 1: Average Monthly Solar Insolation at 45°

Mo.	watthr/m^2/day	Mo.	watthr/m^2/day
Jan.	3804	July	3978
Feb.	4252	Aug.	4558
Mar.	4785	Sept.	5163
Apr.	4063	Oct.	4772
May	3861	Nov.	3641
June	3748	Dec.	3502

Table 2: Average Maximum Monthly Solar Insolation at 45°

Mo.	watthr/m^2/day	Mo.	watthr/m^2/day
Jan.	5831	July	6676
Feb.	6878	Aug.	6875
Mar.	7272	Sept.	6950
Apr.	7073	Oct.	6553
May	6783	Nov.	5749
June	6616	Dec.	5317

Table 3: Average Monthly Percentage of Maximum Solar Insolation at 45°

Month	Percent	Month	Percent
Jan.	65.2	July	59.6
Feb.	61.9	Aug.	66.3
Mar.	65.8	Sept.	74.3
Apr.	57.4	Oct.	72.8
May	56.9	Nov.	63.3
June	56.6	Dec.	65.9

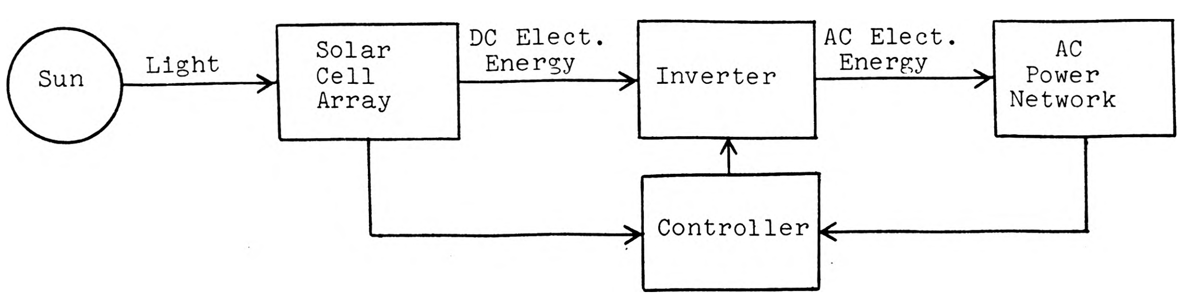

Figure 1. A Solar Cell Array System Coupled to the Power Network

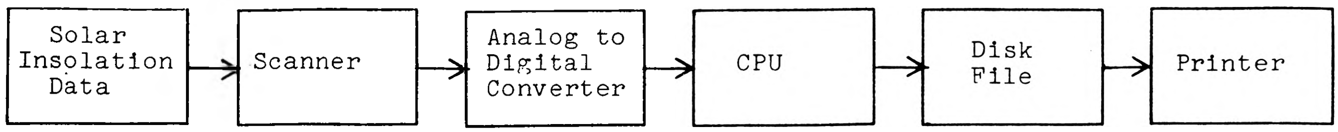

Figure 2. Solar Insolation Data Processing System

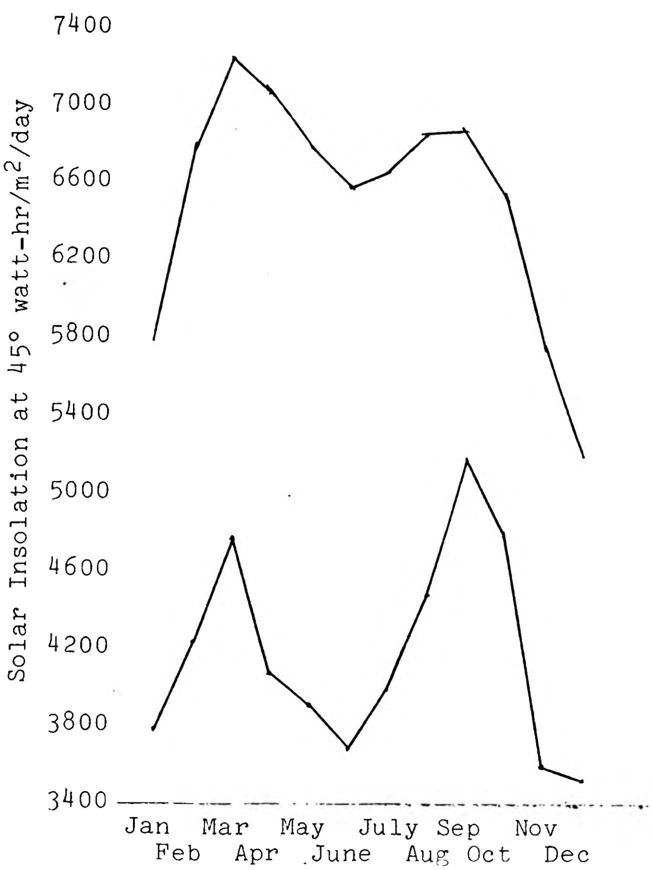

Figure 3. Monthly Solar Insolation in the Toledo Area

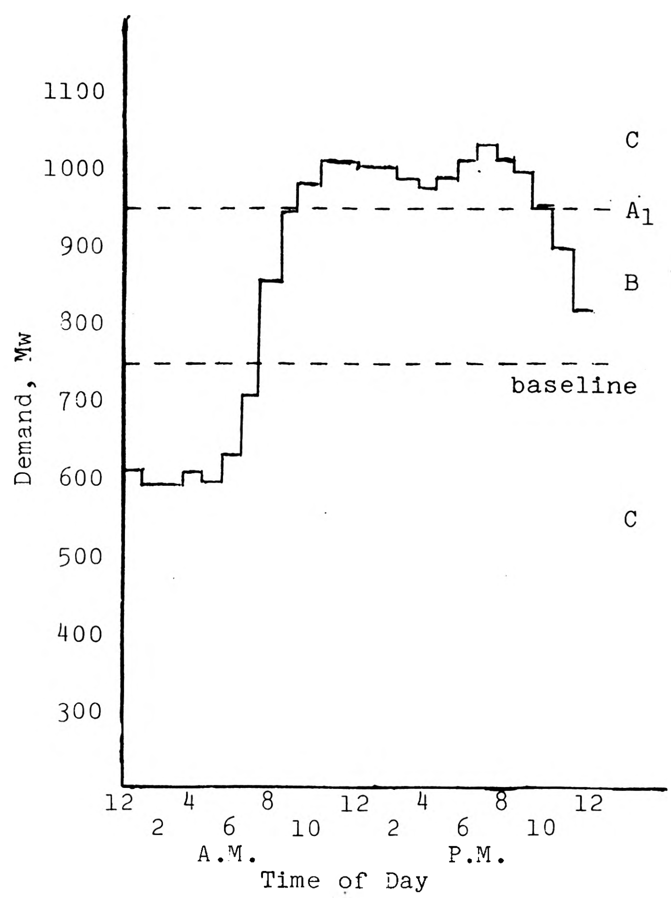

Figure 4. A Typical Toledo Edison Load Curve

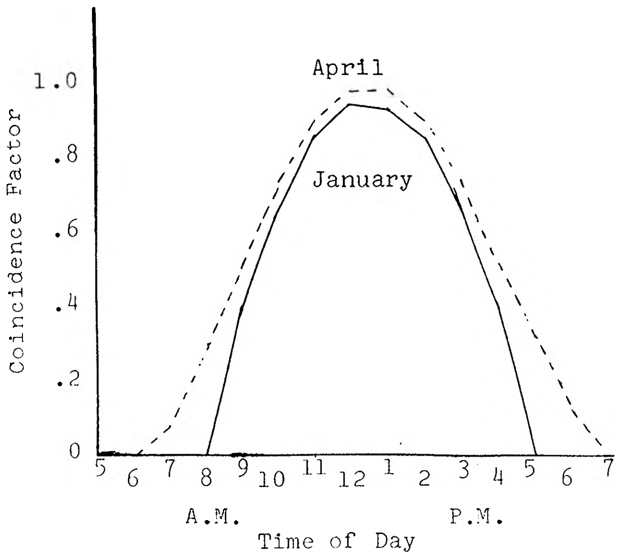

Figure 5. Coincidence Factor for Sunny Days in January and April

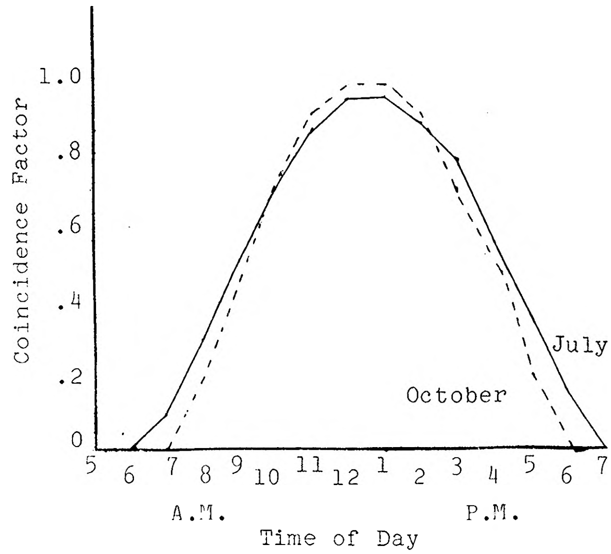

Figure 6. Coincidence Factor for Sunny Days in July and October

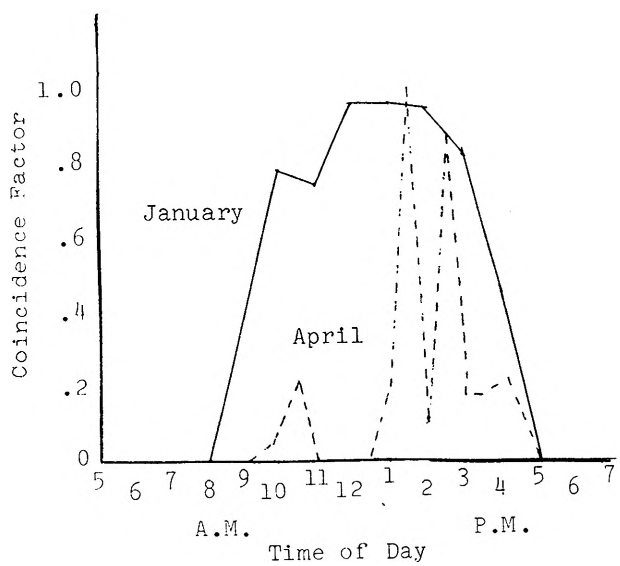

Figure 7. Coincidence Factor for Sample Days in January and April

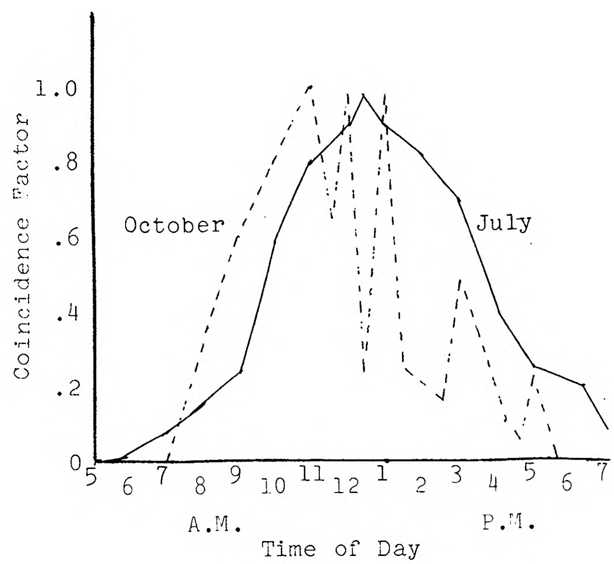

Figure 8. Coincidence Factor for Sample Days in July and October

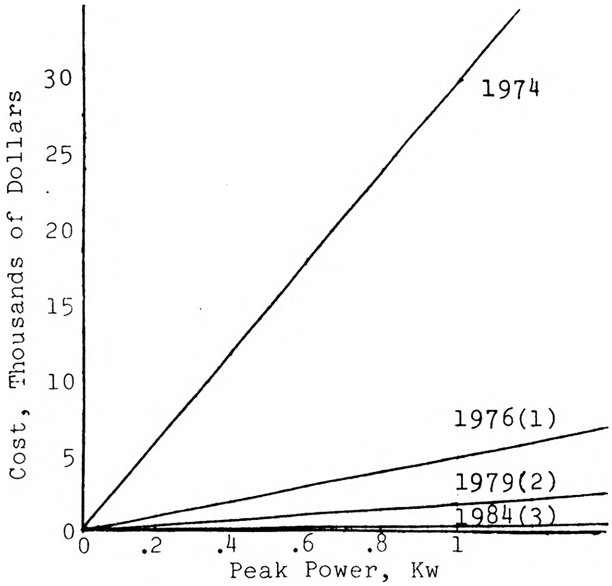

Figure 9. Projected Cost of Photovoltaic Semiconductor Devices, Ref. (1)

(1) Establish \$5,000/peak Kw market price for solar photovoltaic arrays.
(2) Establish \$2,000/peak Kw market price for solar photovoltaic arrays.
(3) Establish \$500/peak Kw market price for solar photovoltaic arrays.

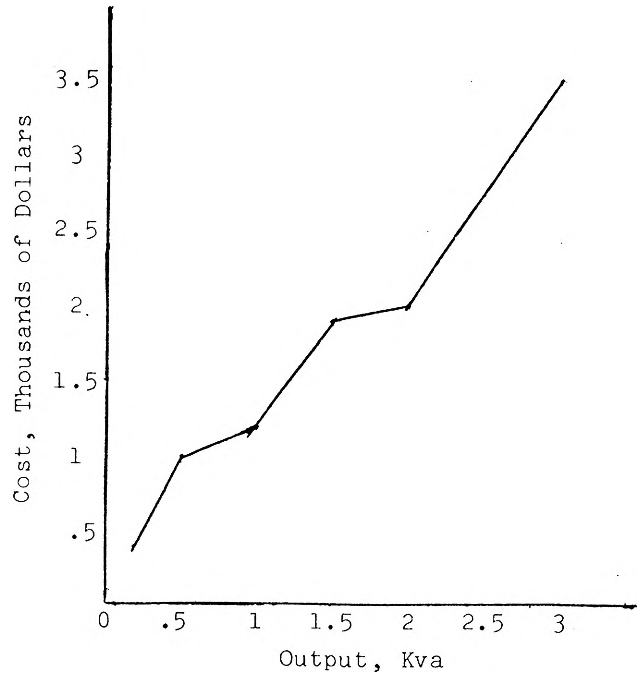

Figure 10. Present Cost of Inverters, Ref. (6), η = 75%, 1ϕ, 60 hz.

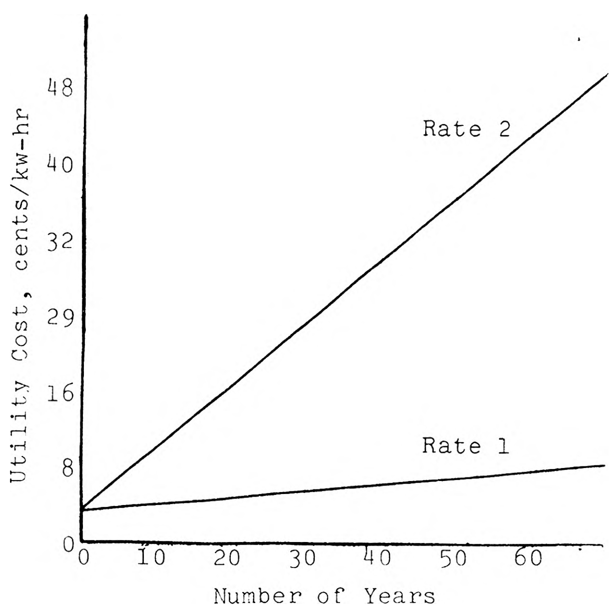

Figure 11. A Linearly Increasing Model Utility Rate

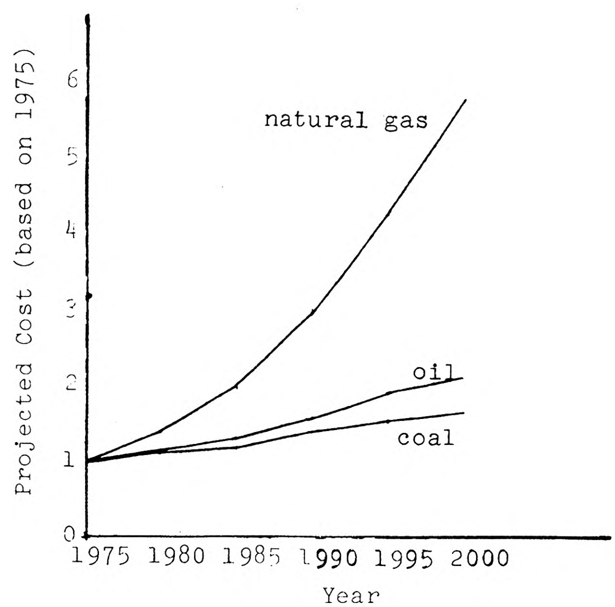

Figure 12. Projected Cost for Great Lakes Area, Ref. (5)

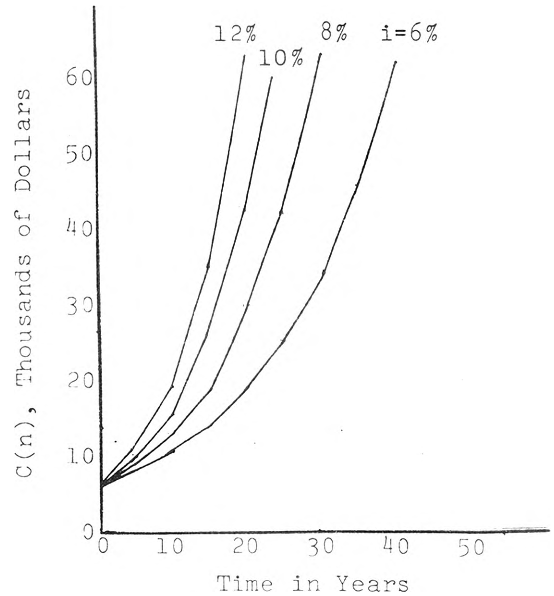

Figure 13. C(n) versus time (I=$6,000)

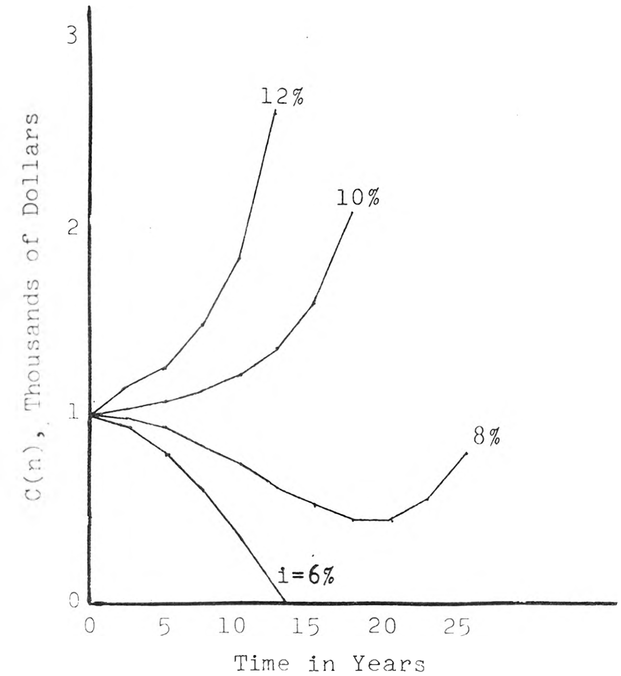

Figure 14. C(n) versus time (I=$1,000)

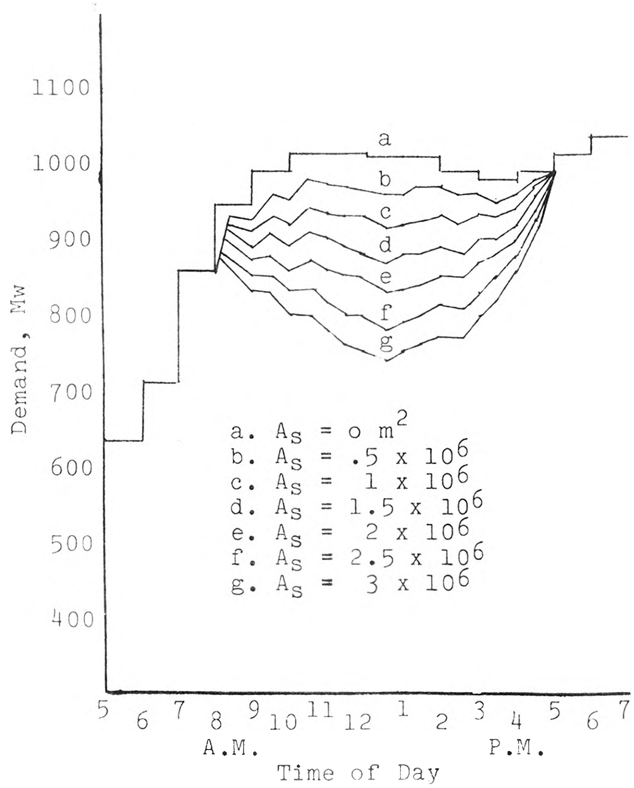

Figure 15. Demand Curves for a Sunny Day in January Showing Effect of Solar Cell Array

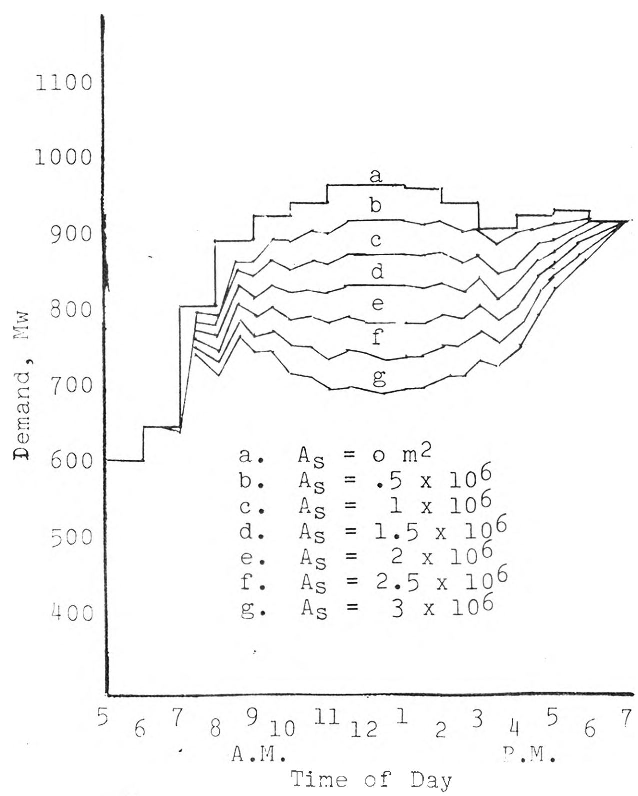

Figure 16. Demand Curves for a Sunny Day in April Showing Effect of Solar Cell Array

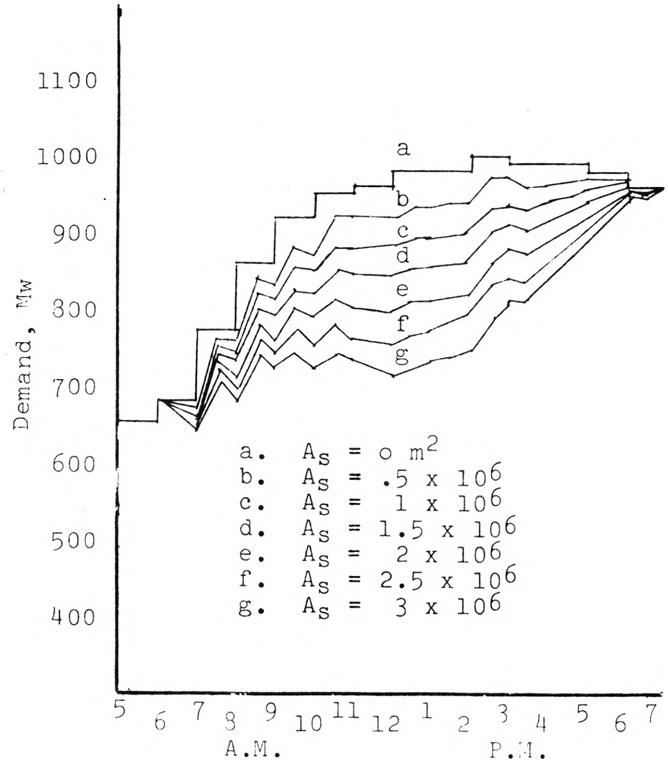

Figure 17. Demand Curves for a Sunny Day in July Showing Effect of Solar Cell Array

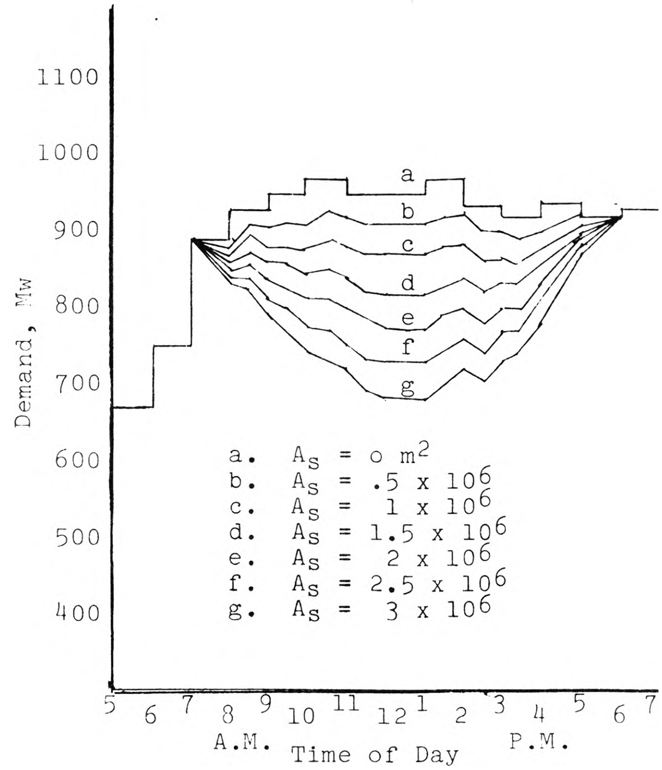

Figure 18. Demand Curves for a Sunny Day in October Showing Effects of Solar Cell Array

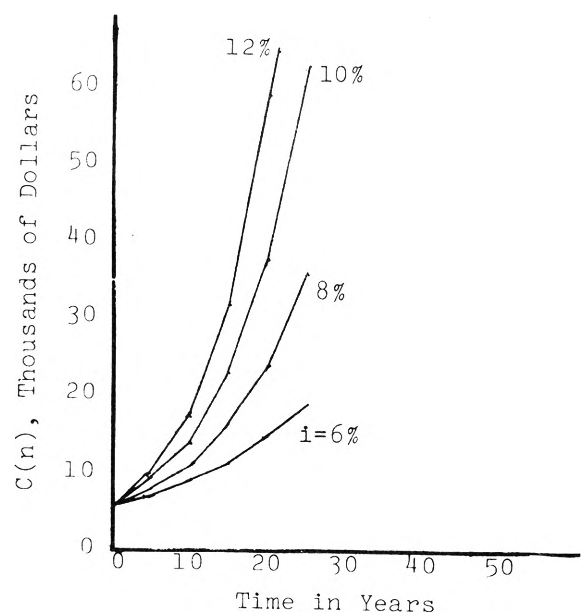

Figure 19. C(n) versus time (I=$6,000, using demand pricing)

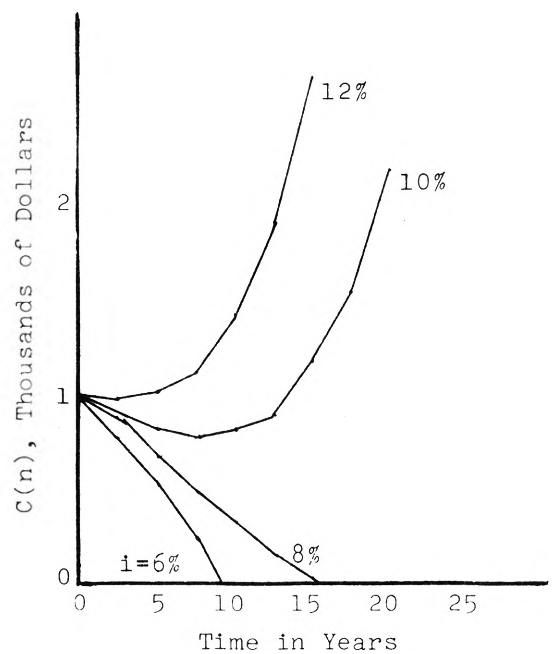

Figure 20. C(n) versus time (I=$1,000, using demand pricing)

INEXPENSIVE INERTIAL ENERGY STORAGE UTILIZING HOMOPOLAR MOTOR-GENERATORS

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Abstract

The pulsed power demands of the current generation of controlled thermonuclear fusion experiments have prompted a great interest in reliable, low cost, pulsed power systems. The Energy Storage Group at the University of Texas at Austin was created in response to this need and has worked for the past three years in developing inertial energy storage systems. 0.5 and 5 megajoule homopolar motor-generators have been designed, built and tested at the University of Texas and design studies have been completed for several systems ranging in size up to 63 gigajoules. The performance of the two laboratory machines and the potential applications which have been investigated are discussed.

INTRODUCTION

Many processes in the scientific, industrial and military communities require relatively large magnitude short duration pulses of electrical energy. Some such processes utilize pulsed power because it is not feasible or practical to produce the extremely high power levels continously, others because the pulsed power consuming process is only one of a sequence of operations resulting in "dead" time between pulses, and still others because they are inherently pulsed phenomena. Controlled thermonuclear fusion experiments, lasers, resistance welding, electrochemical processing, heat treating and forming of metals, seismic wave generation, down-hole formation fracturing, shock tunnel experiments, and X-ray simulation experiments are all examples of processes utilizing pulsed power.
The periodic nature of most pulsed power requirements, that is regular pulses followed by "dead" times, makes energy storage systems attractive for these applications. Such systems can store energy at a continuous, relatively low power rate during the dead time and then deliver a high power, short duration pulse on demand.

COMPARISON OF PULSED POWER SUPPLIES

A survey of pulsed power supplies in use in different areas reveals a surprising diversity. Functionally all such power supplies have two features: the method for storing energy and the mechanism for energy conversion and transfer. Due to the magnitude of the power requirements for such systems, the cost per unit of stored energy and the efficiency at which the energy is delivered to the load are of prime importance. The discharge time (relative power level) required of the power supply is also an important factor both in determining the proper system to use and the cost of the system.
Typical pulse power supplies include:

(a) Capacitive Energy Storage
(b) Inductive Energy Storage
(c) Inertial Energy Storage (rotating elec-

trical machinery)

(d) Chemical Energy Storage (batteries)

(e) Chemical Explosives

Item (e) is included only as a matter of interest since it does not comply with the general notion of energy storage and is difficult to harness except in unusual applications such as liner implosions to generate extremely high magnetic fields. Table 1 shows a detailed comparison of these various pulsed power supplies.

From Table 1 it becomes apparent that, especially in large sizes and for pulses of more than 1 msec. duration, inertial energy storage utilizing homopolar conversion, that is: systems in which the flywheel is also the motor-generator armature, and very attractive in terms of size, cost, discharge efficiency, and simplicity. In comparison, batteries are inefficient, discharge slowly, and generate explosive gases; inductive energy stores are inefficient unless superconducting windings are used, in which case they become more expensive and of questionable reliability. Capacitors are capable of very rapid discharges, but their cost is high and because of their low energy density, 10 to 20 Mj per installation is a practical limit.

HISTORICAL APPLICATIONS OF HOMOPOLAR MACHINES

Although they may recently have been hailed as a new device to solve the problems associated with providing pulsed power for fusion experiments, homopolar generators have, in fact, been in use for some time. The following incomplete list serves to illustrate this point.

1831 - Farady, M., first homopolar generator.

1906 - Westinghouse Elect. Co., 2000 KW, 260 volt, 7.7 KA, 1200 RPM continuous duty power supply for cement plant, used until conversion to purchased power in 1925.[2]

1934 - Westinghouse Elect. Co., 1125 KW, 7½ volt, 150 KA, 514 RPM resistance welding supply for pipe manufacture for Youngstown Sheet and Tube Co. later supplied currents up to 270 KA, still in use in 1956.[2]

1948 - Progressive Welder Co., 7.0 volt, 50 KA flash/spot welder.[3]

1949 - Electric Products Co., 400 KW, 18.7 volt, 21 KA, homopolar power supply for Carnegie Institute of Technology Syncro-Cyclotron magnet.[4]

1952 - Allis Chalmers Mfg. Co., 100 KW, 4 volt, 250 KA homopolar generator to power electromagnetic pumps for liquid metals.[5]

1956 - Atomic Energy Research Establishment, 10 KW, 1.0 volt, 10 KA homopolar generator.[6]

1958 - General Elect. Co., 4 EA, 45 volt, 550 KA homopolar generators for arc discharge wind tunnel at USAF Arnold Engr. Dev. Center.[7]

1960 - Henschel Werke (Austria), 14 volt, 20 KA homopolar machine built for Technische Hochschüle.[8]

1961 - N.A.S.A. Lewis Research Center, 4.5 MW, 37 volt, 300 KA homopolar supply for pulsed high field magnet.[10]

1962 - Australian National University, 500 Mj, 800 volt, 1.6 MA, pulsed homopolar power supply for air cored magnet.[10]

1964 - University of Paris at Orsay, 1.5 Mj, 1.1 MA, 7000 RPM, pulsed homopolar power supply.[11]

1969 - International Research and Development Co., 3250 hp. continuous duty homopolar motor for power plant pumping.[12]

1973 - University of Texas at Austin, 0.5 Mj, 17 volt, 14 KA, 6000 RPM pulsed homopolar motor-generator.[13]

1974 - University of Texas at Austin, 5 Mj, 42 volt, 560 KA, 5680 RPM, pulsed homopolar motor-generator.[13]

CURRENT PROGRAMS HOMOPOLAR MACHINES

Although homopolar machines have been used as continuous duty devices in the past, all major programs involve their use as pulsed power supplies with the exception of naval programs developing homopolar ship and submarine motors.

The 500 Mj machine at the Australian National

Source	Energy Density (Joule/cm^3)	Largest Existing Installation (megajoules)	Potential Discharge Times (milliseconds)	System Efficiency (%)	System Cost ($/Joule)
Inductive Energy Storage	10	100 (Frascatti)	0.1 - 10	50 - 70	0.25 - 0.3
Capacitive Energy Storage	10^{-2} - 10^{-1}	10 (Los Alamos) (Fast Bank) 25 (Lawrence Livermore) (Slow Bank)	10^{-6} - 10	80	0.25 - 1.0
Inertial Energy Storage (Motor-Flywheel-Alternator)	25	1400 (Garching)	10^3 +	40	0.015 - 0.04
Inertial Energy Storage (Homopolar)	100	500 (Canberra)	1 - 10^3 +	50 - 95	.001 - .01
Chemical Energy Storage (Batteries)	500	100 (Frascatti)	10^3 +	.5 - 10	.03 - 3.0
Chemical Explosives	10^4	100 (Los Alamos)	10^{-3} - 10^{-1}	2	*

Table 1

Comparison of Pulsed Power Supplies[1]

*See Text

University in Canberra is still in use and has recently been used to power rail gun experiments and intermediate inductive stores which in turn drive laser flash lamps.[14] The 5 Mj machine at Orsay, France has been superseded by a similar 100 Mj unit which is still under development. Dr. A. E. Robson at the Naval Research Laboratories is developing a self excited 10 Mj homopolar generator in which the field coil acts as an intermediate inductive store, for use in liner implosion experiments.[15]

In 1972 the Energy Storage Group (ESG) was formed at the University of Texas at Austin for the purpose of developing low cost pulsed power supplies primarily for use in controlled thermonuclear fusion experiments. Inertial energy storage with homopolar conversion, in which the flywheel acts as both the motor and generator armatures, was identified as the most promising candidate for this application. The accomplishments and current programs of the Energy Storage Group are described in more detail in the following section.

THE ESG PROGRAM

In the winter of 1972-73 a 0.5 Mj homopolar motor-generator was built using a 38 cm. diameter, 18 cm. thick ferromagnetic steel rotor shrunk fit on a nonmagnetic stainless steel shaft. A water cooled, room temperature, field coil produced a uniform axial magnetic field of 16 kilogauss across the face of the rotor. Unlike many homopolar devices, this machine used solid (sintered copper-graphite) brushes to collect the current from the rotor surface. This can be accomplished at much higher current densities than in conventional D.C. machines since there is no commutation loss in a homopolar machine. Also, the added friction due to solid brushes is not of serious consequence in pulsed operation where the brushes are in contact with the rotor for only a short period of time. The machine initially used rolling element bearings for both axial and radial location of the rotor, but the radial bearings were later changed to hydrostatic units and the axial bearings were placed on an extended shaft to eliminate problems of very high, erratic, operating torques experienced with the rolling element bearings in the high magnetic field (See Fig. 1).

The 0.5 Mj machine self-motored to 6000 RPM in approximately 150 seconds with an armature supply current of 1000 amperes and produced a 7 second discharge pulse with a peak current in excess of 14,000 amperes. This represents a current density of 723 amps/sq. cm. (4667 amps/sq. in.) under the brushes. Based on the success of the 0.5 Mj program, a 5 Mj single rotor homopolar motor-generator was designed using the same basic concepts. Concurrent with this effort a brush testing program was established to determine the brush materials most suitable for use in pulsed homopolar motor generators. Figure 2 shows a cutaway view of the 5 Mj homopolar motor-generator which was designed and built at the University of Texas in a six month period during the spring and summer of 1974.

The 5 Mj machine has a 61 cm. diameter, 28 cm. thick steel rotor supported by hydrostatic radial and axial bearings in a 1.6 Tesla magnetic field created by a room temperature, water cooled field coil. It, too, uses solid, metallic brushes, each being 2.5 cm. square, with 108 brushes on the rotor and 36 on the shafts (shaft brushes were later increased to 64). The individual brush interface pressure can be externally controlled. The rotor bearings were made extremely stiff to allow detailed study of rotor dynamics during discharge.

The 5 Mj machine motors to 5680 RPM in approximately 15 minutes with an armature supply current of 1200 amperes or in approximately 3 minutes with a supply of 3000 amperes. It has been discharged from half speed (2800 RPM) into a short circuit (total circuit resistance of 34 microhms) producing a 0.7 second pulse with a maximum current of over 560,000 amperes. This represents a peak current of over 2300 amps/sq. cm. (15,000 amps/sq. in.) under the shaft brushes. This generator has now undergone a year of extensive testing and will soon be operating in a repetitive discharging mode using a room temperature load inductor to demonstrate the machine's durability.

The testing of the 5 Mj machine required the design and development of a 500,000 ampere making switch which was also accomplished by the Energy Storage Group of the University of Texas at Austin. Additionally the group has conducted or participated in design studies for several pulsed homopolar systems ranging in size up to 63 gigajoules. The ESG is presently involved in the design of three new homopolar systems: a 200 Mj, 400 volt homopolar power supply for a new Texas Tokamak, a 0.5 Mj, 200 volt machine intended to explore the fundamental limits to discharge times of homopolar machines, and the reversible 22 KV, 63 Gj compression power supply for Los Alamos Scientific Laboratories' Reference Theta Pinch Reactor.

These last two machines are expected to open an entirely new area of performance for pulsed homopolar generators; that of discharge times in the 1 to 100 millisecond range. In the spring of 1974 a theoretical program was established within the ESG to determine the fundamental limitations to discharge times of homopolar machines. For a properly designed machine this limit has been identified as the time required for the electromagnetic wave to diffuse into the rotor and stator conductors. For practical sized machines this limit is around 1 millisecond. This problem has been treated in detail analytically[16] and detailed engineering designs are now underway for machines to operate in this regiem.

In conclusion, our studies and experiments to date indicate that inertial energy storage using homopolar conversion is a practical, low cost alternative for meeting the pulsed power needs of fusion experiments. Initial studies indicate that the same technology can be applied to meeting the pulsed power requirements of industry and the military. Units as large as 63 Gj, discharging in 30 msec. with 95% efficiency, do appear practical and for special applications, units discharging in less than 1 msec. can be built. Of course such units require very high magnetic fields which can be most economically produced with superconducting coils. New brush materials and techniques must be developed to allow operation at very high speeds and current densities for long periods of time. To date very little work has been done on increasing the energy to weight ratio of homopolar devices, but improvements of an order of magnitude or more do not appear unreasonable. This improvement, of course, would be necessary for some mobile applications.

The work was supported by the U.S. Energy Research and Development Administration, the Electric Power Research Institute, and the Texas Atomic Energy Research Foundation. The authors and personnel of the Energy Storage Group wish to express their gratitude to those agencies for making this work possible.

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BIOGRAPHIES

Herbert H. Woodson received his Sc.D. degree in Electrical Engineering at MIT in 1956. Dr. Woodson taught at MIT from 1954 to 1971 where he was also Philip Sporn Professor of Energy Processing, 1967-71, and Director, Electrical Power Systems Engineering Laboratory, 1968-71. Since 1971 he has been associated with the University of Texas at Austin as Chairman of the Department of Electrical Engineering, Alcoa Foundation Professor, 1971-75, Director, Center for Energy Studies, and Associate Director, Fusion Research Center. He presently serves on the board of directors of 3 firms and has acted as consultant to over 20 other major firms. He is a member of the National Academy of Engineering, and Eta Kappa Nu, Tau Beta Pi, Sigma Xi, and Phi Kappa Phi honorary fraternities and is listed in Who's Who in America and American Men of Science.

Henry Grady Rylander received his Ph.D. in 1965 from Georgia Institute of Technology. Dr. Rylander has been a professor in Mechanical Engineering at the University of Texas at Austin since 1947. He has taught over twenty different courses in the mechanical systems group as well as supervising 24 master's theses and 6 doctoral dissertations. He has been honored by membership in Tau Beta Pi, Pi Tau Sigma, Sigma Xi, and Phi Kappa Phi. He received the Teacher's Excellence Fund Grant in 1960, the Mobil Oil Foundation Grant in 1968, 1969, 1970, and 1973, and the Engineering Foundation Faculty Award in 1970 and 1973. He is listed in American Men of Science and Who's Who in Engineering.

Dr. Rylander has been involved in research and consulting assignments with more than 20 major corporations and has 35 technical publications. He is a registered professional engineer in the state of Texas.

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STORAGE OF SPENT FUEL FROM LIGHT WATER REACTORS

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Abstract

The effects of possible inadequate nuclear fuel reprocessing capability upon a public utility, Washington Public Power Supply System, are studied. The possible alternatives for storing spent fuel are reviewed.

1. INTRODUCTION

At present, there are no operating commercial nuclear fuel reprocessing plants in the U.S. Two plants are under construction and/or modification. According to present schedules, they would apparently be operating in time to receive spent fuel in the late 1970's. However, the owners of these plants are reluctant to contract for new business until such time as they better understand their costs, regulatory constraints, and construction schedules. Thus, it becomes necessary to examine the possible alternatives for storing spent fuel until reprocessing capability is available to nuclear electric utilities.

In this paper, the problem is examined from the standpoint of the Washington Public Power Supply System (WPPSS) nuclear plant construction and operation schedule. However, the analysis should be applicable to other possible utility systems. Some general conclusions are drawn which can be used to develop a general strategy leading to solutions to this problem.

2. DIMENSIONS OF THE PROBLEM

By examining the fuel management plans and proposed operating schedules for the WPPSS nuclear power plants, it is possible to project the nominal rate of discharge of spent fuel from the WPPSS reactors. The incremental and integral fuel discharge for each of the reactors is given in Table 1 for the decade of the 1980's. In addition, accumulated totals are given by year for the tandem units (i.e. WNP-3 & 5 and WNP-1 & 4).

In addition to the discharge schedule, the spent fuel storage capacity of the plants is needed in the analysis. WNP-2 has a nominal storage capacity of 1000 elements. WNP-1 and WNP-4 have storage capabilities of 288 elements each. WNP-3 and WNP-5 have spent fuel storage capabilities of 323 elements each. Typically, each spent fuel pool is designed to accommodate one full core plus an additional refueling batch, more or less. In the situation where refueling (and thus storage) is imperative, the requirement to be able to unload a full core at any time could be waived with the acceptance of some risk of forced shutdown.

Using the full capability of the spent fuel pool, the WNP-2 spent fuel pool as designed is filled to capacity in 1984. (Specifically, May 1 if present plans hold.) Similarly, the spent fuel pool of WNP-1 becomes full in 1984. The spent fuel of WNP-3 is full in 1985. The WNP-4 spent fuel pool becomes full in 1986 and the WNP-5 fuel pool becomes full in 1987. If the spent fuel pools of WNP-1 and WNP-4 are taken together, the pool of the combined facility is full in 1985. If WNP-3 and WNP-5 are taken together, their combined storage capacity is exhausted by 1986 (i.e., September 1, 1986). The actual date for mandatory shutdown for each plant extends one cycle beyond the above dates.

Storage of fuel from WNP-2 in the storage pits of the other reactors and vice versa could not be accomplished without radical redesign of the spent fuel racks of the other reactors because of dimensional differences between BWR and PWR fuel. Fuel storage between twin units is possible only if a fuel cask is available for the transfer and at some incremental risk of damage to the transported fuel assemblies.

The dimensions of the problem are clear. Assuming that spent fuel storage racks are incompatible for different fuel design types, and assuming that no reprocessing contract becomes available to the system, the capability to store WNP-2 fuel will be exhausted on May 1, 1984 and the total capability of the system as planned will be exhausted on September 1, 1986. Shutdown of WNP-2 would be mandatory on May 1, 1985 and the five planned reactors would be shut down on September 1, 1987.

In addition, the above dates assume that full core storage will not be required for maintenance and repair to the plant. There is a finite probability that shutdown could come much earlier. If WNP-2 were operated for its first two cycles and then be required to shut down during the third cycle for major maintenance requiring core removal, a stalemate situation would be reached in that the reactor could neither be unloaded or operated. Thus, any time after August 1, 1981, the potential for WNP-2 shutdown exists in the absence of either a reprocessing contract or expanded storage capability.

This review summarizes the situation with regard to the WPPSS nuclear power plants. Most probably, a similar situation exists for most electrical generating utilities with nuclear power plants. Clearly, a substantial amount of nuclear fuel will be available for reprocessing in the 1980's.

3. THE EFFECT OF THE NATIONAL SITUATION

One of the factors in determining the viable options available to a nuclear utility in the event it cannot obtain a fuel reprocessing contract is the probable situation with regards to the rest of the nuclear power industry during the next 20 years.

The national situation does not necessarily dictate the action that a utility might take. Even in a time of reprocessing capacity shortage, some organizations will obtain a reprocessing contract (probably at premium rates). However, the more dismal the national situation, the smaller the chance becomes that a given utility will obtain a reprocessing contract. Therefore, this discussion is intended to give some context to and set the stage for a discussion of alternatives in the event that a utility does not obtain a reprocessing contract.

A number of predictions have been made of

TABLE 1

Accumulation of Spent Fuel
From WPPSS Nuclear Power Plants

Nuc. Pow. Plant / Year	WNP-2 Fuel Ele. Disch.	WNP-1 Fuel Ele. Disch.	WNP-3 Fuel Ele. Disch.	WNP-4 Fuel Ele. Disch.	WNP-5 Fuel Ele. Disch.	WNP-2 Acc. Disch.	WNP-1 Acc. Disch.	WNP-3 Acc. Disch.	WNP-4 Acc. Disch.	WNP-5 Acc. Disch.	WNP-1 WNP-4 Acc. Disch.	WNP-3 WNP-5 Acc. Disch.
1980	168					168						
1981	164	69				332	69				69	
1982	184	68	72			516	137	72			137	72
1983	184	68	80	69		700	205	152	69		274	152
1984	208	69	81	68	72	908	274	233	137	72	411	205
1985	216	68	80	68	80	1124	342	313	205	152	547	465
1986	212	68	84	69	81	1336	410	397	274	223	684	630
1987	212	69	85	68	80	1548	479	482	342	313	821	795
1988	212	68	84	68	84	1760	547	566	410	397	957	963
1989	212	68	84	69	85	1972	615	650	479	482	1094	1132
1990	212	69	85	68	84	2184	684	735	547	566	1231	1301

the rate at which nuclear power will be introduced in this country.[1] In federal reports, these predictions are labeled A through D, ranging from C being the highest rate of introduction, then B, then D, and finally A as the lowest rate. These rates can be translated on a yearly basis into projected reprocessing loads. In this analysis, rates B (high intermediate) and D (low intermediate) are considered.

The national reprocessing load, in metric tons per year (MT/Y) for rates B and D is shown in Table 2. Additionally, there are a number of possible scenarios which can be defined which specify the rate at which reprocessing capability might be added in this country. A number of scenarios (labeled B through H) are defined during the course of this analysis. The specific scenarios used are listed in Table 3.

In table 3, scenario B is the currently anticipated rate at which reprocessing capacity will be added to the system. In the other scenarios, delays and cancellations of Plants #2 (AGNS), #3 (NFS), and #4 (EXXON) are envisioned. Changes in the schedule (i.e., delays or cancellations) of Plants #5 and beyond are not of interest to this analysis as we wish to assess the situation in the 1980's. Additionally, adding capacity beyond that now planned seems unrealistic for the time period 1975-1983, as it apparently takes about as long to build and license a reprocessing contract as it does a reactor.

Considering first the nuclear plant start-up Schedule D (assumes some delays from the 1974 nominal), Figure 1 displays the quantity of spent fuel which must be stored in any given year from 1974 to 1994 for the present planned situation (scenario B), delay of Plant #3 (NFS) by two years (scenario D), and cancellation of Plant #3 (scenario C). If the nominal situation comes true, a utility with plants coming on line in the 1980's will not be affected materially as the problem is solved by 1983. If the NFS Plant is delayed two years, a national storage problem exists until 1987 and if the NFS Plant is cancelled, a national problem exists until 1994.

Figure 2 displays the impact of delay or cancellation of Plant #2 (AGNS). Delay of AGNS for two years results in extension of the storage problem to 1987, just as in delay of the NFS plant, but the fuel storage requirements are somewhat larger (i.e., a peak of 4650 MT vs. 3450 MT). Cancellation of AGNS creates a major national storage problem of up to 14100 MT of spent fuel until the year 1997.

Figure 3 shows the effect of delay or loss of Plant #4 (scheduled to start up in 1983) on the requirement for storage of spent fuel. Because this plant comes into the system later, its impact is felt later. A delay of two years results in a requirement for storage out to the year 1990 with a storage peak of 5200 MT in 1984. Loss of the 1983 plant results in a requirement for storage until the year 2000 with a required storage peak of 21600 MT in 1992.

In order to estimate the effect of delays or speedup of nuclear power plant construction on the nominal spent fuel storage requirements, the storage requirements for scenario B (nominal) are shown in Figure 4 for two nuclear power plant construction schedules (B - high intermediate and D - low intermediate). The major effect of changing the initial nuclear power plant construction schedule on spent fuel storage requirements, given the present planned reprocessing plant construction schedule, seems to vary the peak requirements for storage (i.e., 3300 MT for Schedule B vs. 2500 MT for Schedule

TABLE 2

SPENT FUEL REPROCESSING LOAD FOR NATION

Year	Schedule B MT/Y	Schedule D MT/Y
1970	51	
1971	85	
1972	147	
1973	229	4
1974	367	0
1975	567	250
1976	814	930
1977	1080	1310
1978	1300	1710
1979	1500	1660
1980	1730	1740
1981	2050	2300
1982	2550	3000
1983	3190	3700
1984	3820	4300
1985	4490	4800
1986	5270	5600
1987	6090	6200
1988	6950	7000
1989	7870	8100
1990	8860	8900
1991	9910	9900
1992	11000	11000
1993	12100	11900
1994	13100	13000
1995	14400	14000
1996	15500	14900
1997	16500	15800
1998	17500	16800
1999	18400	17500
2000	19400	18300

TABLE 3

REPROCESSING PLANT ADDITIONS

Plant No.	Owner	Capacity (MT/Y)
1	General Electric (GE)	300
2	Allied General Nuclear Services (AGNS)	1500
3	Nuclear Fuel Services (NFS)	750
4	EXXON*	3000
5	-	3000
6	-	3000
7	-	6000
8	-	6000
9	-	6000

EXPLANATION OF SCENARIOS

Plant No.	B	C	D	E	F	G	H
1 (GE)	----	----	----	----	----	----	----
2 (AGNS)	1978	1978	1978	1978	1978	1980	----
3 (NFS)	1978	----	1980	1978	1978	1978	1978
4 (EXXON)	1983	1983	1983	1985	----	1983	1983
5	1987	1987	1987	1987	1987	1987	1987
6	1990	1990	1990	1990	1990	1990	1990
7	1993	1993	1993	1993	1993	1993	1993
8	1997	1997	1997	1997	1997	1997	1997
9	2000	2000	2000	2000	2000	2000	2000

* Most Propable Owner (Not Announced)

---- Plant Cancelled

——— Change from Nominal

FIGURE 1 EFFECT OF LOSS OR DELAY OF UFS PLANT

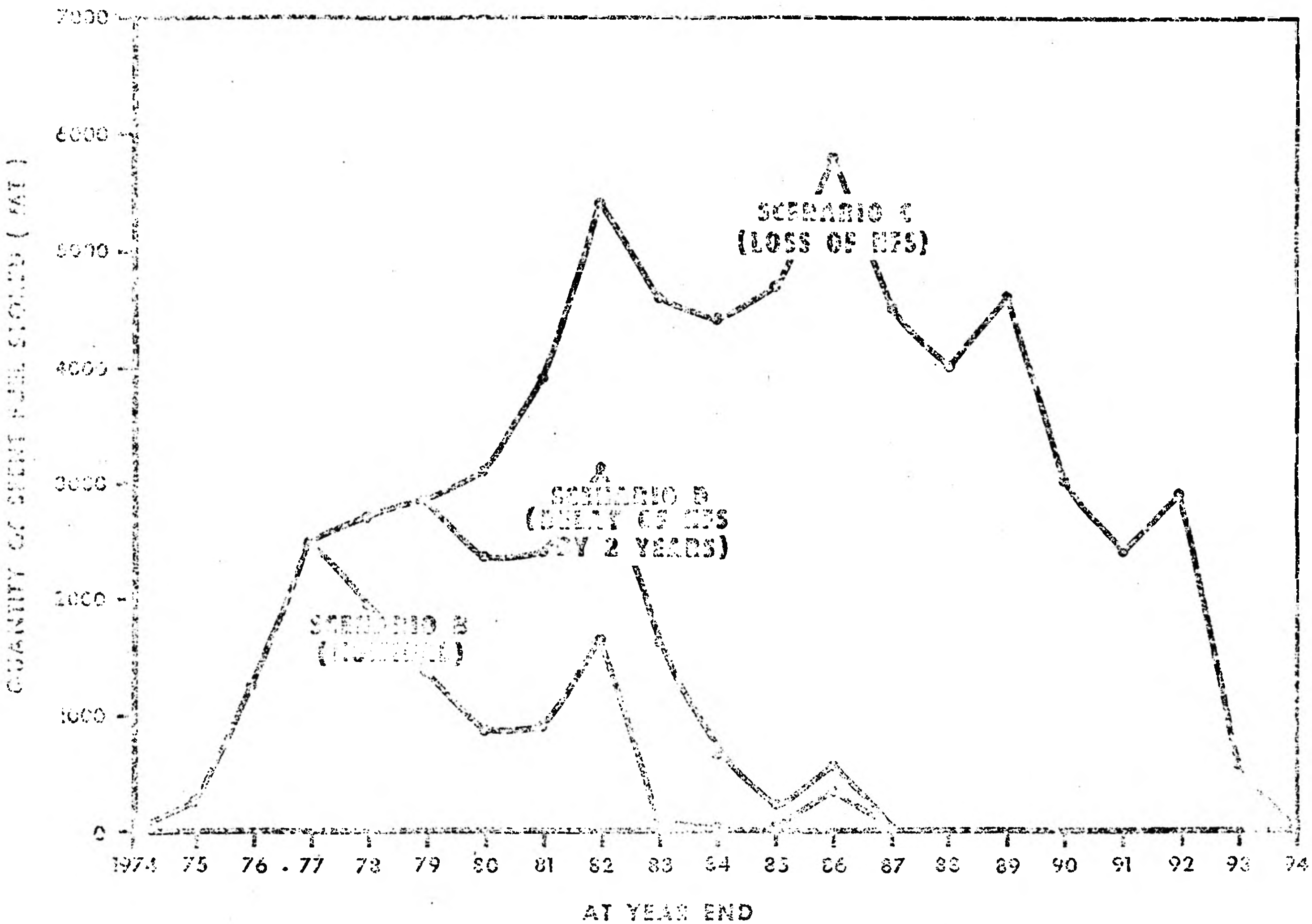
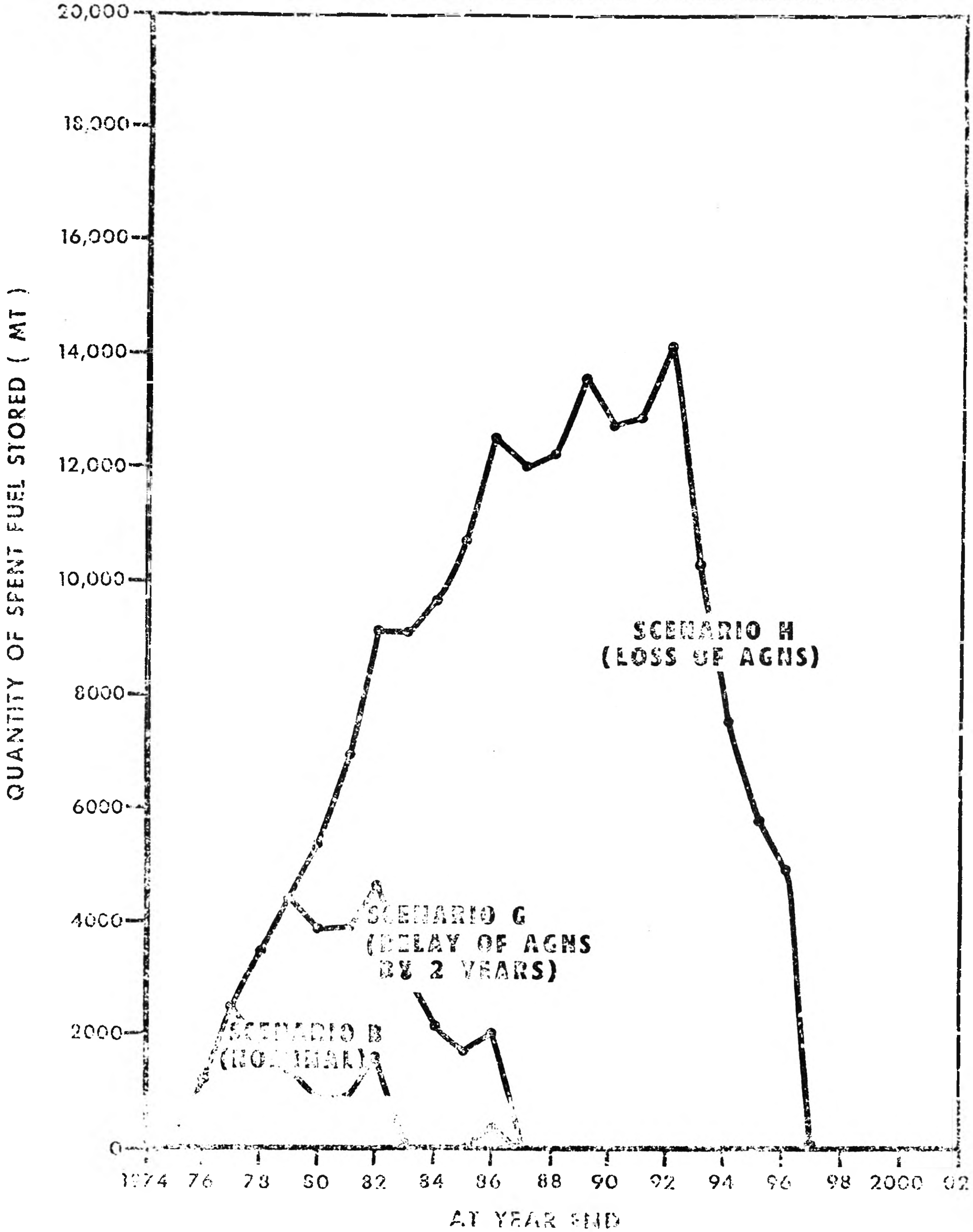


FIGURE 2 EFFECT OF LOSS OR DELAY OF AGNS



C). The peak year is still 1977 and the problem persists to some extent through 1983 independent of the nuclear power plant construction schedule.

A number of conclusions can be drawn from this analysis of the national situation. They are:

(1) If the nominal schedule for future reprocessing capacity additions holds, there will be sufficient reprocessing capability for the nation beyond 1983.

(2) Any deviation from the nominal schedule could result in the need for a utility to expand, build or lease storage space for several years, starting in 1983. Certainly, the likelihood of a utility obtaining a contract for reprocessing services would be greatly decreased.

(3) Changes in the construction schedule for nuclear power plants are not likely to affect the above conclusions.

(4) The spent fuel surplus in the 1980's cannot be materially changed by adding an additional reprocessing plant unless it can be built before 1983 (which is extremely unlikely).

(5) If storage facilities are built, a minimum payoff period of five years seems justified, based on the length of likely periods of a national deficit in reprocessing capability.

In addition to the above conclusions, a key question that must be considered is the likelihood that Plant #4 (Exxon) will be available in 1983. This plant has not as yet been announced. A review of Figure 3 shows that a nominal delay of this plant would assure a captive reprocessing market whereas introduction in 1983 results in a slight industry surplus of reprocessing capacity. Conversely, a captive market could result in utilities building storage facilities. Once built, they would be integrated into fuel management plans so that utilities might tend to delay reprocessing in order to achieve (hopefully) cheaper reprocessing rates.

To analyze this question, Figure 5 displays the results of the nominal schedule (scenario B) with and without Plant #1 (G.E.). The latter curve represents the situation which existed when the present plants were committed. This curve shows that cancellation of Plant #1 did not materially affect the present situation. Additionally, it shows that the reprocessing industry was slow in planning additions compared to demand. This could be attributed to lack of anticipation in the 1960's of nuclear growth in the 1970's, or it could be construed as delay in order to be assured of a market. In any case, based on the present and past conditions, delay of the 1983 plant for business reasons does not seem unrealistic.

In summary, the present situation is not catastrophic with regard to nuclear utilities. However, a utility should be reviewing its options in the event of delays of Plants #2 (AGNS), #3 (NFS) and #4 (1983) and should exercise one or more of these options if any delays seem likely.

4. CONSTRUCTION OF SEPARATE SPENT FUEL STORAGE FACILITIES

With regard to construction of separate spent fuel storage facilities, the USAEC apparently considers this a probable short-term reality. The USAEC has recently issued Regulatory Guide 3.24, "Guidance on the License Application, Siting, Design and Plant Protection for an Independent Spent Fuel Storage Installation" (December 1974). The licensing procedure is similar to that for a nuclear power plant. The installation is conceived of having a minimum capacity of 1000 metric tons (MT) of spent fuel (3200 BWR elements). A typical nuclear power plant discharges about 30 MT of spent fuel per year.

DELAY OF 1983

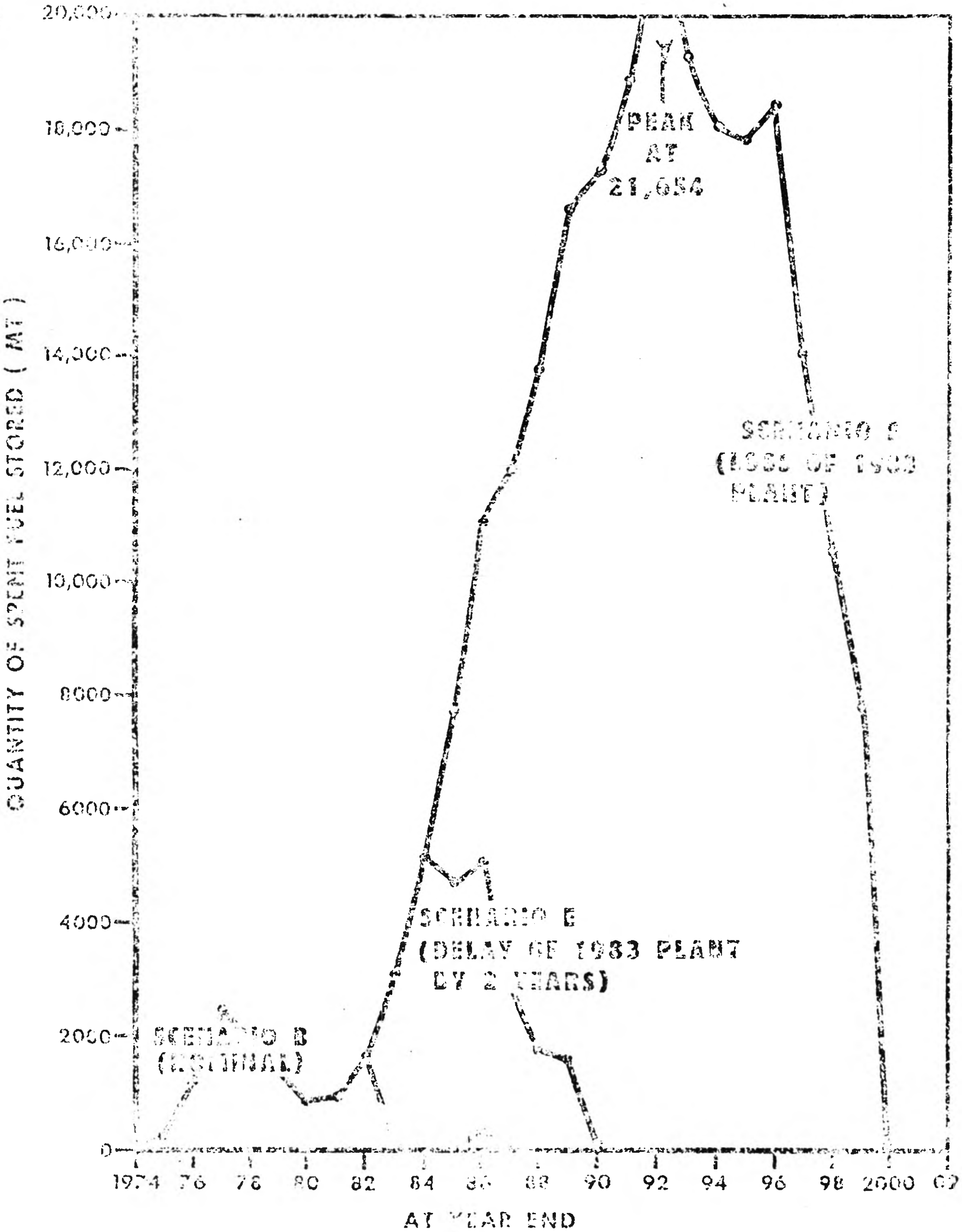


FIGURE 4 EFFECT OF DELAY OF [illegible] PLANT STARTUP

SCENARIO C (NOMINAL)

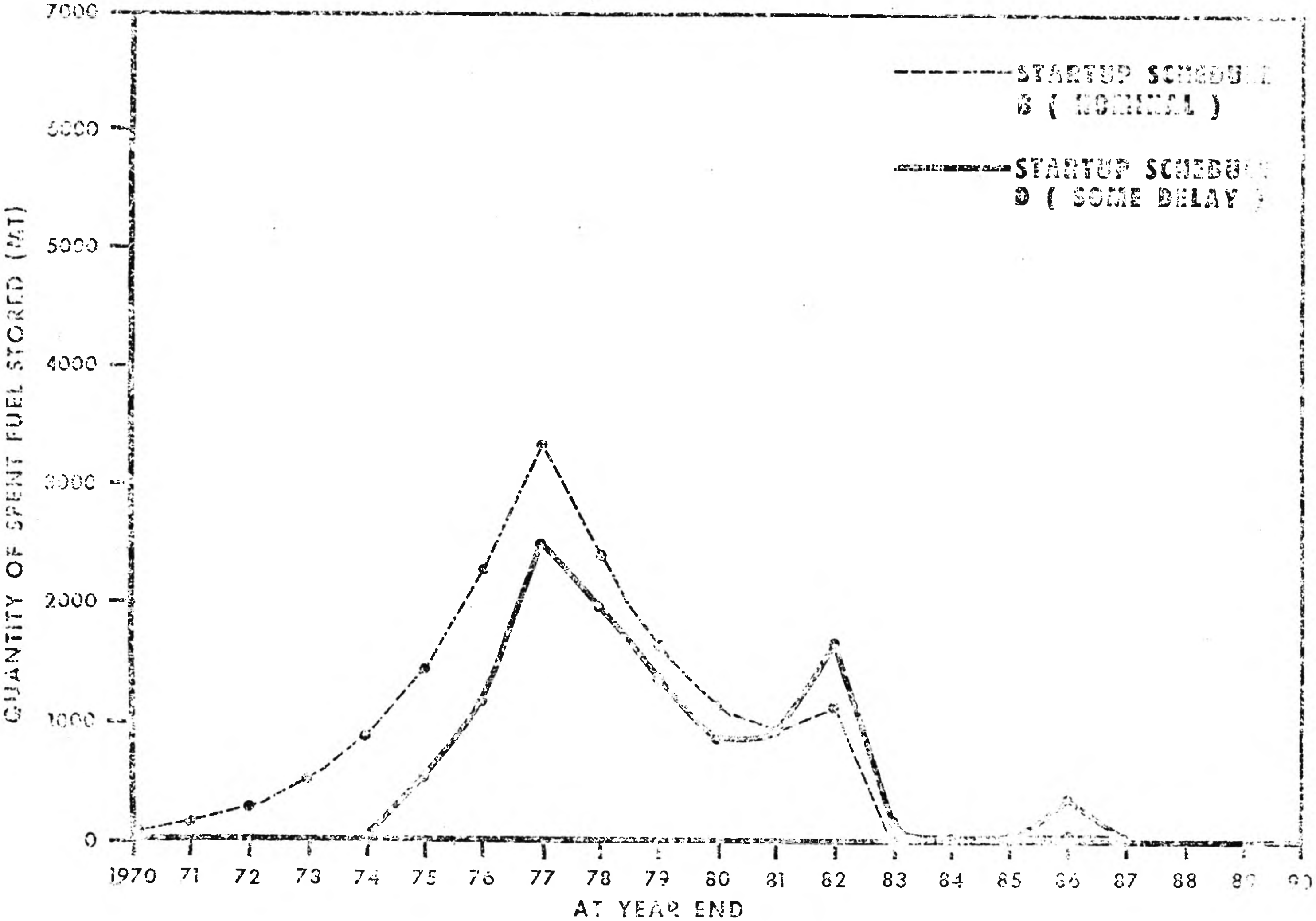
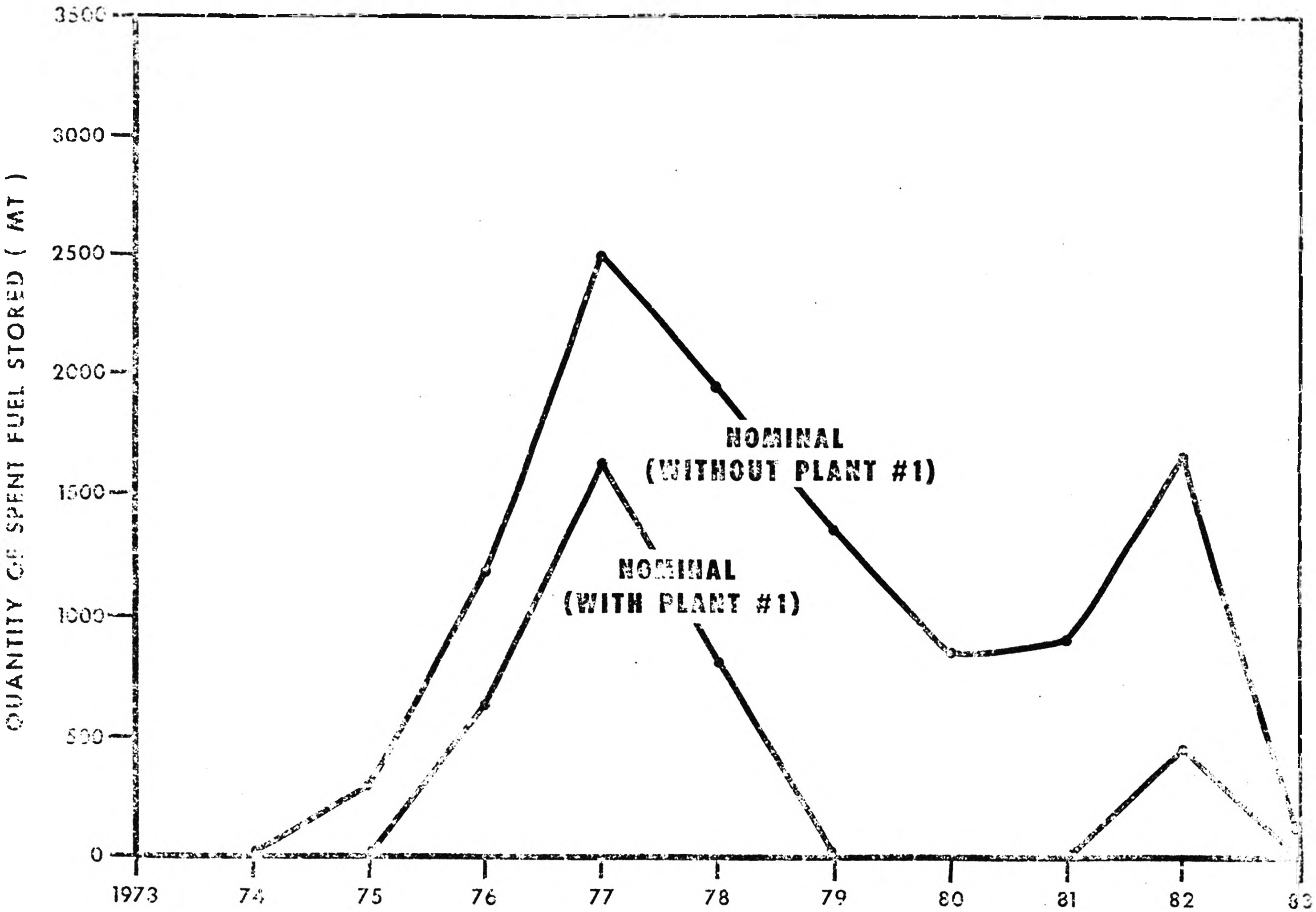


FIGURE 5 STORAGE REQUIREMENTS FOR NOMINAL REPROCESSING PLANT CONSTRUCTION SCHEDULE WITH AND WITHOUT PLANT # 1 (G.E.)



A 1000 MT storage facility with a 15-year payoff has been estimated to cost 20 million dollars. Assuming linearity, a 3000 MT storage facility would then cost 60 million dollars. Assuming an interest rate of 6%, this would result in an average storage charge based on capital return of $4,500 per MT per year. The cost would be lower if it were filled faster. This rate reflects the fact that the facility is partially empty for most of its life. At an interest rate of 14%, the average storage charge based on capital return would be $7,500 per MT per year. I arbitrarily assume a value of $1,000 per MT per year for facility operating costs. If this is the case, at an interest rate of 6%, the storage charge would be $5,500 per MT per year and at an interest rate of 14%, the storage charge would be $8,500 per MT per year. In addition to the above storage charges, there would be a transportation charge per metric ton of fuel which accrue to that fuel which must be shipped to the storage facility. I estimate this cost to be $8,800 per MT with no escalation for at least one typical situation. The average cost with escalation would be $12,300 per metric ton. Considering the total storage bill for the 15-year time period, the transportation charge is small in comparison.

5. LEASE/STORAGE

Renting of storage space for spent fuel may prove to be attractive. Factors which need to be evaluated include possible high incremental transportation costs, possible high rental charges due to incentives for early cost recovery on the part of entrepreneurs, and questions of ultimate responsibility.

General Electric Company has proposed construction of a separate $25,000,000 storage facility in addition to expansion of the storage capacity of its Morris, Illinois, installation. In addition, E. R. Johnson Company, in collaboration with Merrill, Lynch, Pierce, Fenner, and Smith, Inc., has proposed construction of a 1000 MT storage facility. This facility is estimated to cost 20 million dollars. Space would rent in this facility at the rate of $10,000 per MT per year. The location of the facility is unspecified.[2]

The sponsors justify this charge by asserting that the equivalent cost of storing the plutonium contained in a MT of spent LWR fuel would amount to $20,000 per MT of spent fuel if the plutonium were separated during reprocessing and not recycled but stored.

There are approximately 10 reactors which could utilize this facility immediately. Assuming a discharge of 30 MT per reactor per year means that 10 reactors would fill this facility in three years. Assuming a design life of 15 years for the facility and assuming that it fills at the above rate, the rental charge amounts to a return on capital excess of 35%, if the operating cost is taken as $1,000 per MT per year. Viewed another way, assuming an interest charge of 14%, this facility would be paid for in less than five years with the storage charge of $10,000 per ton per year. If the facility were filled as soon as completed, the facility would be paid for in about three years with this storage charge. Assuming that this facility could be built by 1980 but not before, a five-year payoff period is generally consistent with the present situation (Figure 1-Scenario B). Any delays would result in substantial profit to the owners.

As with owned storage space, there would be a transportation charge associated with shipment of the fuel to the storage facility. I assume that the transportation distance would be 2,000 miles and therefore I assign a transportation charge of $50,000 per metric ton to the fuel. If the storage facility were located near an eventual fuel reprocessing facility, this transportation charge could then be pro-rated, on some basis, to both storage and reprocessing.

6. IMPACT OF DELAYED REPROCESSING ON NUCLEAR FUEL COSTS

The calculations in this analysis were performed with the Hanford Fuel Cost (HFC) code developed by Omberg.[3] The calculations were performed using the WNP-2 reactor characteristics as input. A twenty-four cycle calculation was performed in order to assure that the reactor was on an equilibrium fuel cycle. In general, unless noted otherwise, a 6% interest rate was used in the analysis.

During the course of performing the analysis, two significant changes were made to the code by D. H. Thomsen. One change delayed reprocessing until a date which is specified as input. At this date, all fuel which has been delayed is reprocessed and credited to the appropriate batch (weighted by a present worth factor). Fuel discharged after this date is reprocessed in the normal manner. The second change allowed for input of a fuel storage charge (in $/Kg U) for the fuel which was delayed.

The first step in the analysis was to calculate the impact of the reprocessing delay alone on fuel cycle costs without computing the accompanying cost of fuel storage. The major costs of delaying reprocessing are the costs of additional fuel and storage of the spent fuel. By separating these costs, it is possible to identify the important cost parameters in the problem.

Figure 6 shows the levelized fuel cost for WNP-2 as a function of reprocessing delay. The costs reflect the additional fuel which must be purchased but do not, in this figure, reflect the storage costs.

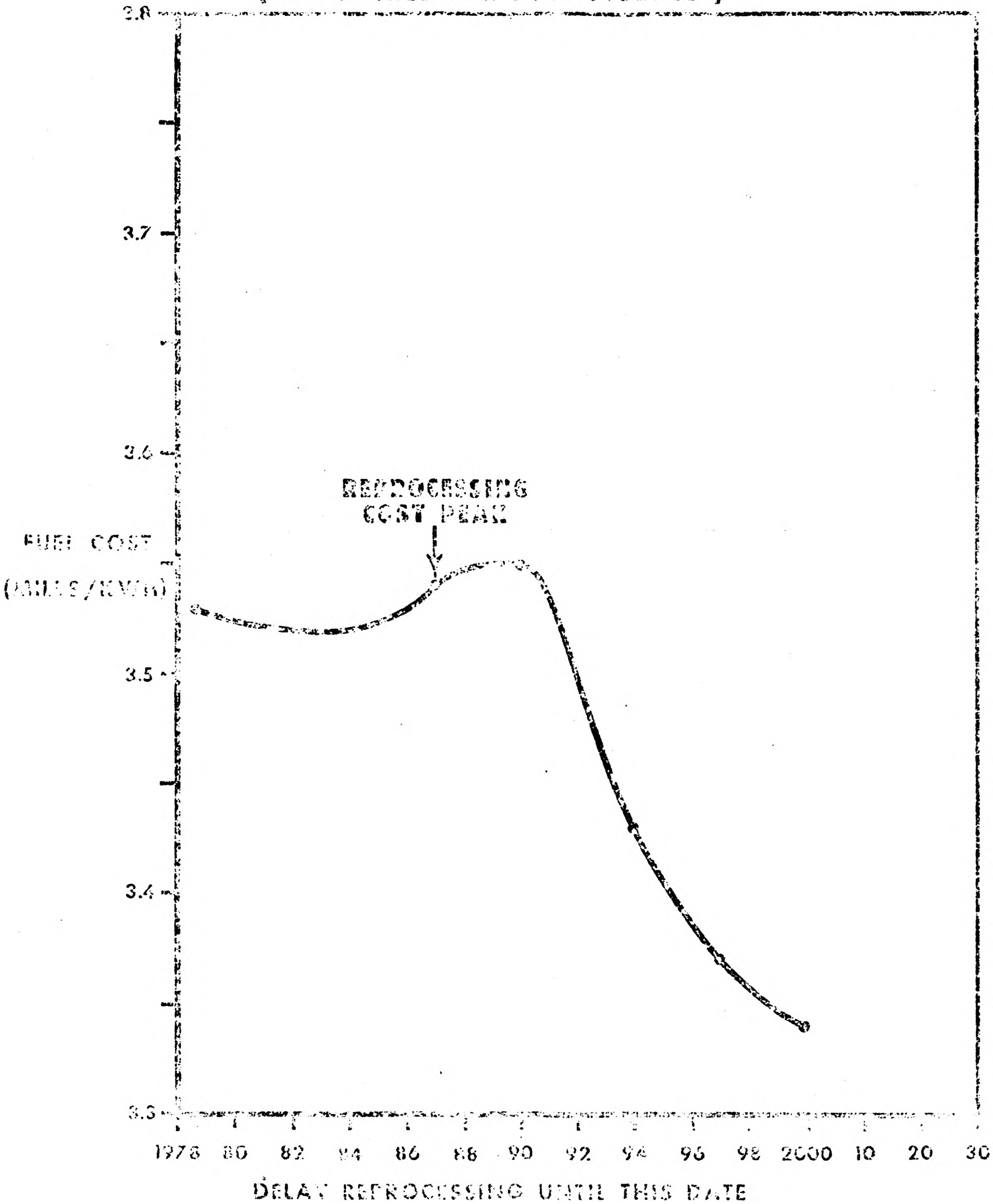
Figure 6 starts with a base case (no reprocessing delay) fuel cost of 3.53 mills/kwh. The fuel cost drops slightly before rising to a maximum of 3.55 mills/kwh in 1990. From 1990 until 2000, the fuel cost drops rapidly to 3.34 mills/kwh. No analysis was performed for the years beyond 2000. The relatively rapid drop in fuel costs beyond 1990 is attributed to the predicted cost structure used in this analysis. As noted on Figure 6, the cost of enrichment used in this analysis peaks in 1987 and then drops substantially over the period of interest. Fuel fabrication and uranium costs continue to rise over the total period. The plutonium price escalates until the year 2000 and is assumed stable beyond 2000. Thus, this curve shows that, for the price and particularly the enrichment price structure shown, it is cheaper to store fuel and buy extra enrichment than it is to reprocess the fuel if the price of storage is zero.

It has been shown that the drop in fuel cost curve caused by a reprocessing delay is temporary. Delaying reprocessing essentially forever results in a fuel cost of 4.32 mills/kwh.

To obtain perspective, the base case was run at 12% interest rather than 6% interest. The resulting levelized fuel cost was 3.76 mills/kwh. Thus, changes in interest rate overshadow all the fuel cost changes shown in Figure 6.

In this portion of the analysis, the previous calculations were performed with the addition of a cost for storage of the fuel. Costs were used which reflect the cost, both in WPPSS-owned facilities and rental of storage space in facilities owned by others. Specifically, a charge of $5,500 per metric of fuel ton per year of fuel

FIGURE 6 FUEL COST VS. DELAY IN REPROCESSING
(NO CHARGE FOR FUEL STORAGE)



was used for WPPSS-owned facilities and a charge of $10,000 per metric ton of fuel per year was used for rented facilities.

Figure 7 shows the levelized fuel cost for 24 cyçles for WNP-2 as a function of reprocessing delay assuming a storage charge of $5,500 per metric ton of fuel per year.

Comparing Figure 7 to Figure 6 shows that the cost of storing the spent fuel is the major cost item in delaying reprocessing. In Figure 7, the fuel cost peak at 1990 is located at the same time point as in Figure 6, but the peak is higher (3.61 mills/kwh as 3.55 mills/kwh) and the minimum in the year 2000 is 3.49 mills/kwh rather than 3.34 mills/kwh as in Figure 6. A study of Figure 7 also indicates that if fuel is to be stored, it is advantageous to store it for a considerable length of time (i.e., beyond 1990). This is probably due mostly to the enrichment price structure described previously. Another conclusion that can be tentatively drawn from Figure 7 is that the decision on whether or not to store fuel will probably be made on the basis of other parameters than fuel costs as the variations shown in Figure 7 are probably within current calculational uncertainties and, in any case, are considerably overshadowed by such parameters as the interest rate.

7. SUMMARY

It has been shown that there is a strong possibility that utilities will be forced to delay reprocessing of spent fuel from their nuclear power plants due to a shortfall in reprocessing industry capacity which is likely to exist well into the 1980's. In this analysis, some preliminary calculations have been done to assess the impact of this delay on nuclear fuel costs. The specific calculations were performed on the WNP-2 nuclear power plant but the conclusions drawn from the results are expected to be generally applicable to other nuclear power plants.

On the basis of this analysis, a number of conclusions have been drawn. They are:

(1) The major change in the fuel cost which results from delay in reprocessing spent nuclear fuel is the cost of storing the spent fuel.

(2) The cost of additional uranium and enrichment requirements is not substantial.

(3) For the specific reactor analyzed, the levelized fuel costs rise if a short storage period is used, but ultimately decrease with long-term (i.e., 10 years) storage. Therefore, if reprocessing is delayed, storage of spent fuel for time periods greater than 10 years is preferred.

(4) The changes in levelized fuel costs due to storage are small compared to other uncertainties. Under certain conditions, a small decrease in levelized fuel costs can be realized by temporary storage of spent nuclear fuel.

8. BIOGRAPHY

Mr. W. C. Wolkenhauer is a nuclear engineer with the Washington Public Power System. Prior to that he worked at Battelle-Northwest Laboratory and at the LaCrosse Boiling Water Reactor.

He received his B.S. from Carroll College in 1961 and his M.S. from Missouri School of Mines in 1962.

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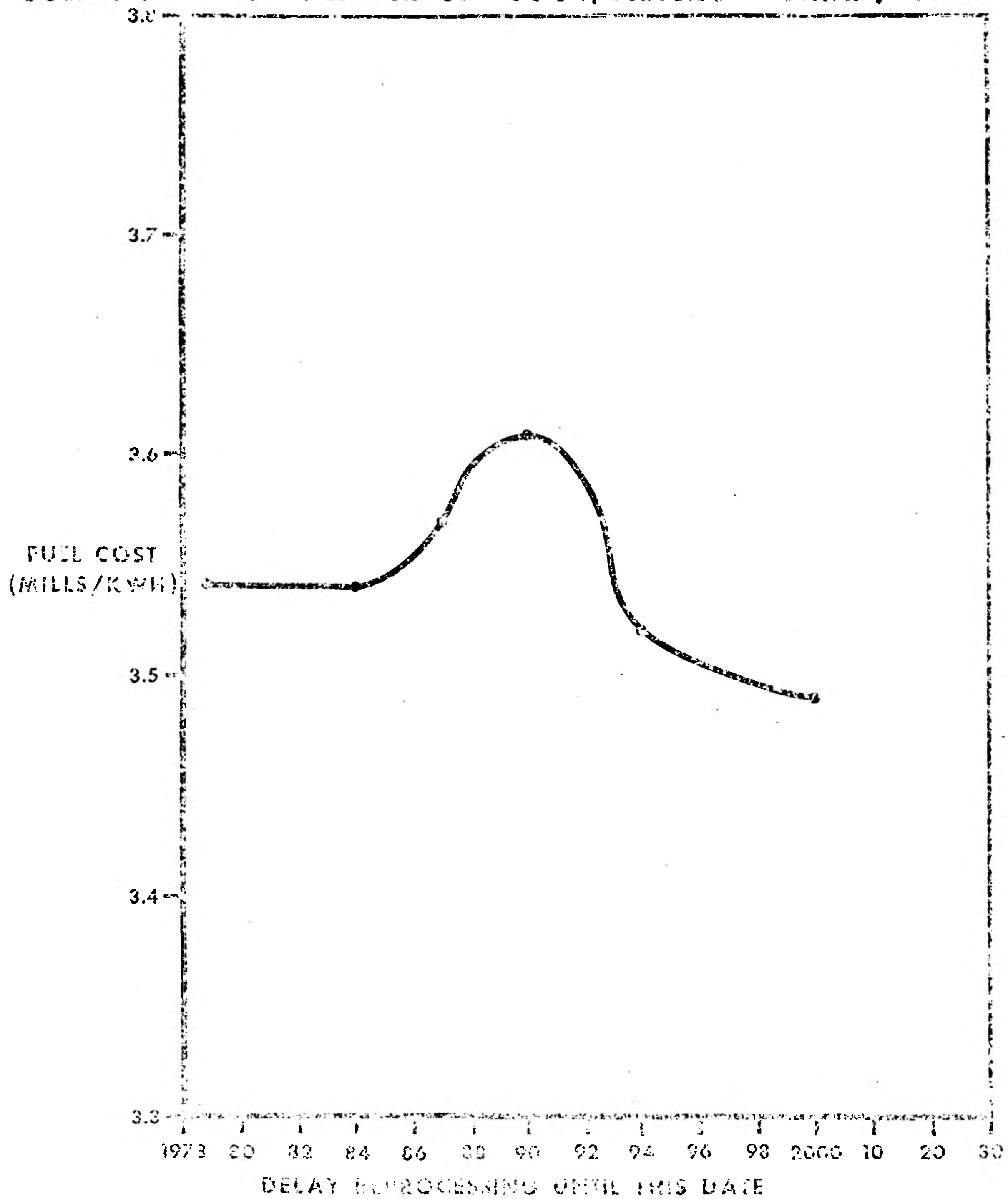
3. R.P. Omberg, "A Model for Calculating the Incremental Fuel Cost of Reactor Operating Strategies," Hanford Engineering Development Laboratory, September 17, 1974, Richland, Washington.

FIGURE 7 FUEL COST VS. DELAY OF REPROCESSING
FOR A STORAGE CHARGE OF [illegible] / YEAR



STATUS REPORT ON THE CALLAWAY NUCLEAR POWER PLANT

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Abstract

The progress to date of the first nuclear-powered, electric generating plant proposed to be constructed in the state of Missouri is described.

1. INTRODUCTION

The Callaway Plant will be the first nuclear-powered, electric generating plant in the state of Missouri. It is being built by Union Electric Company which provides electrical power to St. Louis and the northeastern portion of the state.

This paper will describe the progress on the project to date with regard to the site selection, the plant design, the licensing process, expected environmental effects, and construction schedule.

2. SITE SELECTION

In July of 1973 Union Electric announced the selection of a site in central Missouri for the proposed nuclear plant. The site is located in Callaway County, 10 miles southeast of Fulton, 25 miles northeast of Jefferson City and 100 miles west of St. Louis. The site consists of about 6,600 acres, and is 4-1/2 miles north of the Missouri River. The site is on a plateau well above the flood plain (about 300 feet higher than the mean river level).

The selection of the site was made following an extensive 18-month study conducted by Union Electric and Dames & Moore, a consulting firm which specializes in environmental and applied earth sciences. More than 70 sites in four states (Missouri, Iowa, Illinois and Arkansas) were investigated before the Callaway site was selected. The site is outside areas subject to high seismic activity. Numerous base-line studies have been conducted at the site in order to confirm its suitability for a nuclear power plant and to determine the environmental effects of construction and operation.

3. PLANT DESIGN

The plant will consist of two units each of 1.15 million kilowatt electrical generating capacity. The two nuclear steam supply systems (reactors) will be manufactured by Westinghouse and the turbine-generators by General Electric.

Five utilities (Union Electric, Northern States Power Company, Rochester Gas & Electric Company, Kansas City Power & Light Company, and Kansas Gas & Electric Company) have formed an organization called SNUPPS (for Standardized Nuclear Unit Power Plant System) to build five identical nuclear generating units, including the two for Union Electric. The other three units will be built in Kansas, Wisconsin and New York.

Bechtel Power Corporation, of Gaithersburg, Maryland, is the architect-engineering firm responsible for developing the design of the standardized plants for SNUPPS. Sverdrup & Parcel and Associates, of St. Louis, is the architectural-engineering consultant for the development of the Callaway site for Union Electric. Daniel International Corporation, of Greenville, South Carolina, has been selected as contractor for construction of the Callaway Plant.

The Callaway Plant is projected to cost about $1.75 billion. As was indicated in the testimony presented to the Missouri Public Service Commission, the two-unit plant has been projected to cost $765/kW compared with $685/kW for equivalent coal plant capacity. Although the capital costs of building a nuclear plant are greater than for a coal plant, when the other costs such as for fuel, operation and maintenance, and annual investment charges are taken into account the electricity generated by the nuclear plant will be about 30 per cent less than that from a coal plant. This corresponds to approximately $145 million annual savings to the customers. (The cost figures are in 1982 dollars.)

The standardization of the plant design and multiple unit equipment purchase is expected to result in savings of both time and money. Included in the standardized design is the concept of "slide-along", duplicate units for multi-unit plants such as Callaway. There are no shared operating systems or facilities from one unit to the next, except for the switchyard and ultimate heat sink. Another design feature is that the turbine building is of a penisular arrangement, thus the likelihood of a turbine generated missile being of consequence to the reactor is less than for a tangential arrangement.

An access corridor from the Missouri River to the site will contain an intake pipeline to supply the plant's water requirements. The plant will utilize two hyperbolic, natural draft cooling towers for waste heat disposal, thereby minimizing the effect of returning heated water to the river.

There are about 56 nuclear power plants licensed to operate in the U.S. These present plants have the capacity to produce 8 per cent of the nation's electricity. An additional 63 units are under construction, and 103, including Union Electric's two units, have been announced or are on order. (These figures are the official figures as of June 1, 1975.)

4. LICENSING PROCESS

The Union Electric nuclear facility will meet all applicable design, operational, safety and environmental requirements as directed by the U.S. Nuclear Regulatory Commission (formerly the U.S. Atomic Energy Commission) and other regulatory bodies.

The licensing of a nuclear power plant is a complex process and this has been the major effort by Union Electric to date. During the same time Bechtel Power has been involved with the overall plant design. Before an electric utility can build a nuclear power plant it must obtain the approval of the U.S. Nuclear Regulatory Commission. The licensing process is a two-stage procedure. The first stage consists of the filing and processing of an application for a construction permit. The second stage consists of the filing and processing of an application for an operating license at the time the plant is nearly complete. The main documents which are used to support the application for a construction permit are the Preliminary Safety Analysis Report (PSAR) and the Environmental Report (ER). These two documents for the Callaway Plant were filed in April and May of 1974, respectively. Following the so-called "mini-review" for completeness of the documents, the NRC formally docketed the application on June 21, 1974.

Numerous other approvals are required by various regulatory agencies; however, the NRC has the primary responsibility for assessing the environmental and safety effects of the proposed plant. For instance, application was made to the Missouri Public Service Commission in June of 1974 for a certificate of convenience and necessity. Public hearings were held before the MPSC in the fall of 1974 and their approval was granted in March.

The regulatory staff of the NRC conducted their review of the Environmental Report from May 1974 to October of that year when they issued their Draft Environmental Statement to the other concerned agencies for comment.

The Final Environmental Statement which incorporated the comments of other agencies was prepared by the NRC and published March 1975. A summary of the expected environmental effects of plant construction and operation is given in that report. After weighing the environmental, economic, and technical benefits of the Callaway Plant against environmental and social costs resulting from the facility, and considering the available alternatives, the Nuclear Regulatory Commission concluded that a construction permit should be granted for the Callaway Plant. Special actions would have to be taken to avoid unnecessary adverse environmental impacts due to construction, and monitoring programs would be conducted to assure that negative environmental impacts are minimized during construction and operation.

Public hearings were then conducted in April of 1975 by a three-member Atomic Safety and Licensing Board (ASLB) on the environmental effects and other site-related matters. Also in April a Limited Work Authorization was requested by Union Electric. Eleven days of public hearings were held between April 8 and July 2. On August 8 the ASLB recommended that the NRC grant the request for Limited Work authorization and on August 14 the NRC gave official notice that they would grant the request for Limited Work Authorization. The activities which could be done under the LWA include site preparation consisting of relocation of an existing transmission line, removal of houses and other buildings, clearing, grubbing and grading of the construction area, and excavation for the foundations. Also allowed are the construction of support facilities, consisting of a limestone processing facility and mine and the drilling of a well for construction water. Certain roads will be relocated and the railroad spur subgrade prepared, as well as the necessary construction buildings will be erected.

An independent review of the safety aspects has been conducted by the Advisory Committee on Reactor Safeguards (ACRS) and their approval for the project was given September 17.

Another round of public hearings will be conducted this fall in about November by the ASLB regarding the radiological safety of the proposed plant design. These hearings must be completed and the ASLB must give its final approval before actual plant construction can begin.

5. CONSTRUCTION SCHEDULE

Activity under the Limited Work Authorization began near the first of September 1975 and issuance of the Construction Permit is anticipated in March or April of 1976 at which time major construction will begin. The construction work force is projected to peak at 3000 in 1980. The operating staff for the plant will be approximately 150 people.

In approximately 1980 an application will be submitted for an Operating License.

Unit one is planned to be in operation in October of 1981 and unit two in April of 1983.

6. BIOGRAPHIES

Dr. A. E. Bolon is an Associate Professor of Nuclear Engineering and Metallurgical Engineering at the University of Missouri-Rolla. He also is a consultant to Union Electric Company. He has worked with the company the past four summers and the 1972-73 academic year while on sabbatical leave.

Dr. Bolon received his Ph.D. in nuclear engineering from Iowa State University and his B.S. and M.S. from Missouri School of Mines and Metallurgy.

Mr. D. F. Schnell is Manager, Nuclear Engineering at Union Electric Company. He is responsible for plant site studies, equipment procurement, coordination of design with the architect-engineer and licensing of the Callaway Plant.

Mr. Schnell has been with Union Electric Company for 19 years. He received both his B.S. and M.S. degrees in Mechanical Engineering from Washington University.

EVALUATING THE TOTAL COST OF AN ON-SITE SOLAR ENERGY SYSTEM

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Abstract

A methodology for evaluating the total or life-cycle cost of an on-site solar energy system is presented. The costs represent after-tax or effective costs realized by the owner of the energy system. The methodology addresses: (1) capital costs; (2) fuel costs; (3) maintenance and operating costs; (4) property taxes; (5) the tax benefits of depreciation; and (6) the investment tax credit. The model was developed for evaluating solar energy systems located at the point where the energy is demanded. However, the methodology also has applicability to many other types of energy systems.

1. INTRODUCTION

The 1973 Arab oil embargo and subsequent increases in the price of all types of energy have dramatically highlighted the United States' dependence on energy, and especially energy imports. Among other things, the current energy situation has led to a resurgence of interest in solar energy. The utilization of solar energy can take a variety of forms. They include (1) domestic hot water heating, (2) space heating, (3) air conditioning, and (4) the generation of electricity. Each of these applications faces numerous technical and economic barriers to their commercial development.

Midwest Research Institute has recently undertaken a study for the U.S. Congress to evaluate the use of solar energy to generate electricity.* The study dealt with the generation of electricity at the point of use (i.e., on-site) and the utilization, where economical, of the resulting waste heat to provide heating and cooling energy.

Among the many findings of the study was the conclusion that economic factors were of major significance in the commercial viability of the technology. On-site solar electric systems exhibit many economic differences from their conventional energy system rivals. The solar energy systems are more capital intensive than conventional systems and therefore have a higher initial cost. Secondly, they require very little fossil fuel (used only as backup) and will exhibit lower operating costs than conventional units. These two major differences lead to subsequent discrepancies in taxes and other cost considerations. To evaluate the extent of these discrepancies a methodology has been developed to evaluate the total or life-cycle cost of on-site energy systems.

The methodology presented is designed to evaluate on-site solar energy systems. However, the approach is general enough to be used in a wide variety of other applications. For example, in the technology assessment mentioned above, the methodology was used to estimate the total cost of a conventional fossil energy system and a fossil "total-energy" system. The "total energy" system produces electricity using fossil fuels and utilizes the waste heat for space heating and cooling. Many other types of energy systems can also be investigated with this methodology.

2. TOTAL COST CALCULATION METHODOLOGY

Evaluating the total cost of an energy system requires that all expenses incurred in construction and operation to be taken into account. These costs include the cost of capital equipment, financing costs, maintenance and operating costs, taxes, depreciation and tax credits. Alternative energy systems can be compared on a cost basis if they produce the same quantity

* "Technology Assessment of On-Site Solar Electricity," conducted by Midwest Research Institute for the Office of Technology Assessment, U.S. Congress. The final report is to be released in early 1976.

and quality of energy at the same point in time. Since construction time varies for different systems and expenses are incurred at different times, the present value concept is utilized.

The cost function consists of six basic components. They are: (1) capital costs; (2) fuel costs; (3) maintenance and operation costs; (4) property taxes; (5) depreciation; and (6) the investment tax credit. The present values (PV) of these six components are then added to obtain the total cost estimate.

2.1 CAPITAL COSTS

The capital cost component consists of cash outlays to purchase and install the necessary equipment plus the cost of financing those expenditures over the life of the system. If the system is a solar energy system, the capital outlays would consist of items such as:

(1) (amount of collector area in ft^2) x (price/ft^2)

(2) (amount of prime cycle heat storage capacity in KWH) x (price/KWH)

(3) (amount of space conditioning heat storage in BTU's) x (price/BTU)

(4) (amount of solar electric equipment capacity in KW) x (price/KW)

(5) (amount of fossil fuel electric equipment capacity in KW) x (price/KW)

(6) (amount of fossil fuel space conditioning equipment capacity in BTU/hr) x (price/BTU per year)

(7) (amount of solar space conditioning equipment capacity in BTU/hr) x (price/BTU/hr)

(8) (amount of battery storage capacity) x (price/unit)

If these capital goods were all purchased and erected in the present period the installed cost of capital equipment would simply be the summation of the eight components above (denoted as K). No discount factor would be necessary.

However, a more realistic approach to the problem takes the time of construction into consideration. Let t_o equal the present time period. (In this analysis, each time period represents one year). An accurate comparison of the cost of systems that take varying lengths of time to construct requires that all systems begin operation in the same year. Let m equal the number of years necessary to build the system with the longest construction period. Let α equal the number of years required to build the system being considered. Therefore, by definition, α is less than or equal to m. All systems will begin operation m years in the future. Construction of the longest system will begin at t_o ($t_o = 0$). Construction of any other system will begin at $m - \alpha$. Figure 1 illustrates this formulation.

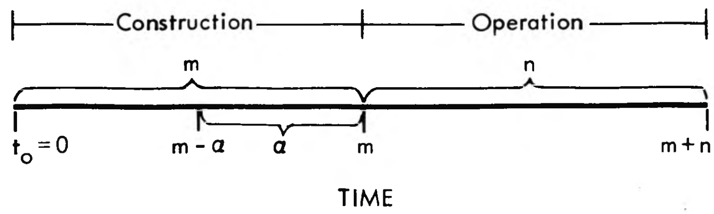

Figure 1 - Timing Sequence of Construction and Operation of Energy Systems.

Letting k_t denote the capital expenditures in period t , we can express the necessary cash outlays, in general, as:

$$K = \sum_{t=m-\alpha}^{m} k_t$$

The present value of the capital outlays (K_p) is given by:

$$K_p = \sum_{t=m-\alpha}^{m} \frac{k_t}{(1 + c_k)^t} \qquad \ldots \quad (1)$$

where: c_k = the owner's weighted cost of capital. (explained below)

The distribution of capital expenditures (k_t) over the construction period affect the present value of the capital costs (K_p). In order to determine the direction and magnitude of these effects, a series of four distinct capital outlay distributions were compared. The first distribution or cash flow pattern considered flows of equal size during each year of construction (see figure 2).

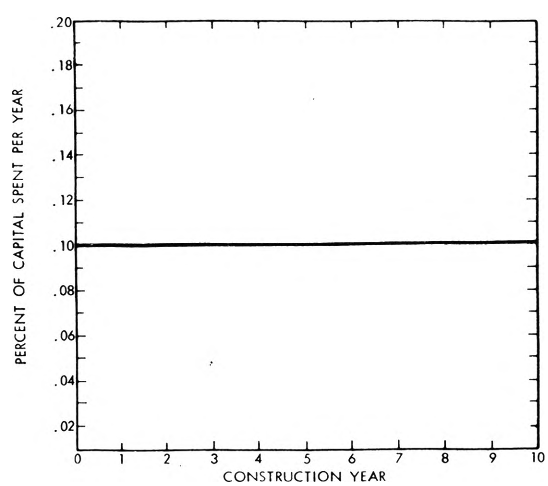

Figure 2 - Hypothetical Construction Outlay Pattern, Case I: Constant Outlay Pattern

The present value of this cash flow pattern is given by the expression:

$$K_F = \frac{K}{\alpha} \sum_{t=(m-\alpha)}^{m} \frac{1}{(1+c_k)^t} \qquad \ldots \quad (2)$$

where: K_F = the dollar amount that will have to be financed.

The second case considered cash flows that increase each year. That is, the capital expenditures in each period would exceed those of the preceeding period. The largest yearly outlays would occur in the last year of construction. Figure 3 approximates this situation using a step function.

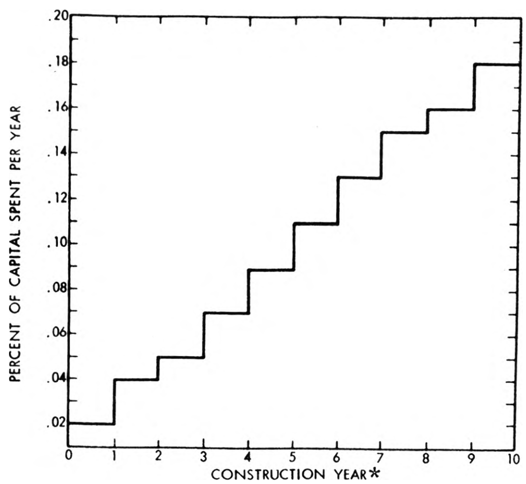

Figure 3 - Hypothetical Construction Outlay Pattern, Case II, Increasing Outlays

The third case represents a cash flow pattern which is just opposite the situation in Case II. Capital expenditures are the highest in the first year of construction and decline throughout the rest of the construction period. The last period of construction therefore contains the smallest amount of capital outlays. Figure 4 illustrates this situation.

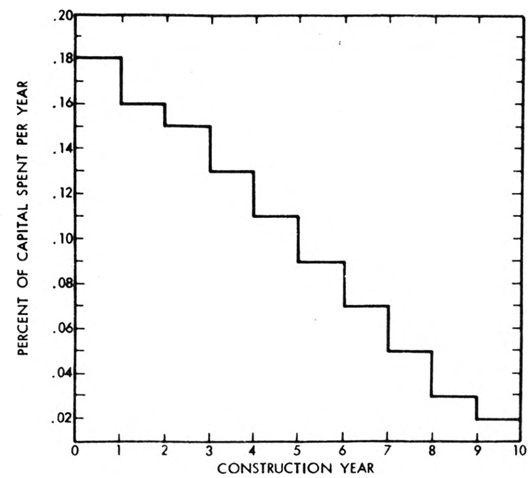

Figure 4 - Hypothetical Construction Outlay Pattern, Case III: Decreasing Outlays

The final example considered is a peaked distribution of outlays. In the early years of construction, cash outlays are relatively small. As the project continues, outlays per period increase. As the project nears completion, the outlays taper off (see Figure 5).

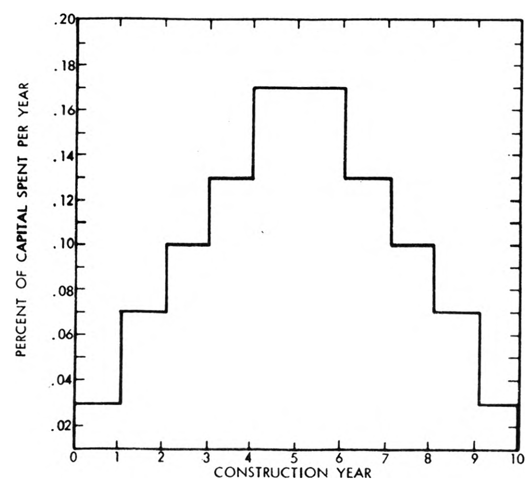

Figure 5 - Hypothetical Construction Outlay Pattern, Case IV: Peaked Outlays

A comparison of the present value of each of these four example cases was accomplished by setting the discount rate (c_k) equal to 5% and the construction period at 10 years. The present value of each case is then calculated as a percentage of the total construction costs. Table I summarizes the calculations.

* Construction time refers to the number of years required to build the system. Year 1 on the axis is the year construction begins. It is equivalent to period ($m-\alpha$) in the previous discussion. A 10 year construction time is assumed in the discussion that follows.

TABLE I

SUMMARY CALCULATIONS FOR ALTERNATIVE CONSTRUCTION OUTLAY PATTERNS

	Year									
Case I (Equal Outlays)	1	2	3	4	5	6	7	8	9	10
Percent of capital spent each year	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
Discount factor	.95	.91	.86	.82	.78	.74	.71	.68	.64	.61
Present value (Percent of capital in each year	.09	.09	.09	.08	.08	.07	.07	.07	.06	.06
Total present value of capital	= .77 (Total capital outlays)									
Case II (Increasing Outlays)										
Percent of capital spent each year	.02	.04	.05	.07	.09	.11	.13	.15	.16	.18
Discount factor (r = .05)	.95	.91	.86	.82	.78	.74	.71	.68	.64	.61
Present value (Percent of capital in each year)	.02	.04	.04	.06	.07	.08	.09	.10	.10	.11
Total present value of capital	= .71 (Total capital outlays)									
Case III (Decreasing Outlays)										
Percent of capital spent each year	.18	.16	.15	.13	.11	.09	.07	.05	.04	.02
Discount factor (r = .05)	.95	.91	.86	.82	.78	.74	.71	.68	.64	.61
Present value (Percent of total capital in each year)	.17	.15	.13	.11	.09	.07	.05	.03	.03	.01
Total present value of capital	= .84 (Total capital outlays)									
Case IV (Peaked Outlays)										
Percent of capital spent each year	.03	.07	.10	.13	.17	.17	.13	.10	.07	.03
Discount factor (r= .05)	.95	.91	.86	.82	.78	.74	.71	.68	.64	.61
Present value (Percent of total capital in each year)	.03	.06	.09	.11	.13	.13	.09	.07	.04	.02
Total present value of capital	= .77 (Total capital outlays)									

Table I shows that the greatest difference in the total present values occur between Case II and III. This is expected since these cases represent opposite extremes of cash flows. Cases I and IV lie within these extreme values and, in this example, are identical. These latter two cases could be expected to be similar because outlays in the peaked distribution exceed the constant outlays in the middle of construction but are less in the beginning and end of the period.

This analysis gives some evidence that a constant cash outlay assumption over the construction period is not an unreasonable approximation of the more realistic peaked outlay pattern. The present value of a constant outlay pattern also lies within the extremes of the more radical patterns. Its use therefore minimizes the error created by choosing an incorrect pattern of either of the extreme cases. It is realized that the cases just described are only one set of possible examples. Alternatives using other discount rates, construction periods and outlay patterns may yield different results. However, to protect the analysis from becoming so full of detail it becomes impossible to solve, we have chosen a simplified outlay pattern. The pattern used in our analysis is expressed by $k_t = \frac{K_P}{\alpha}$ for all t.

2.1.1 Financing the Capital Investment

The options available for financing depend on the ownership and size of the energy system. For example, an on-site solar or fossil fuel energy system geared to service a community of 100,000 could be an investor-owned corporation. The corporation would buy long-term debt and issue equity in the form of common and/or preferred stock. If the same size energy system was publicly owned, the financing would probably be generated by means of long-term debt. An on-site energy system designed for a single family dwelling would probably finance construction costs only by buying long-term debt in the form of a mortgage.

A weighted cost of capital approach will be used to overcome these differences. This approach also explicity considers differences in debt-equity mix and differentials in competing interest rates.

The weighted cost of capital approach multiplies the percentage of the corporation's capital account in each instrument times the appropriate interest rate. Let P_s equal the percentage of capital in common and preferred stocks and P_D equal the percentage in the debt instrument. The interest rate and required rate of return are given by r_D and r_s, respectively. Therefore, the weighted cost of capital is given by the expression:

$$c_k = P_D(r_D) + P_s(r_s) \qquad \ldots \quad (3)$$

where: c_k = the weighted cost of capital expressed as a decimal fraction.

The weighted cost of capital (c_k) is then used as an approximation of the discount factor in the organization's present value calculations. Its major purpose is to represent the opportunity cost of money.

2.1.1.1 Corporate financing. The corporate owned firm can borrow and/or issue stocks. The mix of debt and equity actually used will depend on the size of the project in relation to the corporation, as well as the financial status of the firm. Let q_D be the percentage of the project financed with debt and let q_s be the percentage financed in equity. The present value (PV) of the interest costs for each instrument is given by:

$$\text{PV of interest cost} = r_D(q_D)(K_F) \sum_{t=m-\alpha}^{m+n} \frac{1}{(1+c_k)^t} + r_s(q_s)(K_F) \sum_{t=m-\alpha}^{m+n} \frac{1}{(1+c_k)^t} = [r_D(q_D) + r_s(q_s)]\left[K_F \sum_{t=m-\alpha}^{m+n} \frac{1}{(1+c_k)}\right] \qquad \ldots \quad (4)$$

where: q_D = the percent of the system's capital cost financed by debt.

q_s = the percent of the system's capital cost financed by issuing equity.

Interest paid on debt is a deductible expense for corporate income taxes. The effective cost of debt interest is therefore reduced by the factor $1 - T_c$ where T_c is the corporate income tax rate. The debt principal must also be repaid at the end of the financing period. The funds raised by issuing stocks do not have to be repaid in a lump sum at the end of the project. However, in order to sell the stock the buyer must be expecting a positive return. The present value of the principal repayment plus the funds that will continue to be paid as dividends can be approximated by the expression:

$$\frac{K_F}{(1 + c_k)^{(m-\alpha)+n}}$$

The present value of the total cost of capital to the firm can be expressed as:

$$C_c = [(1-T_c)(q_D)(r_D) + r_s(q_s)]\left[K_F \sum_{t=m-\alpha}^{m+n} \frac{1}{(1+c_k)^t}\right] + \frac{K_F}{(1+c_k)^{(m-\alpha)+n}} \qquad \ldots \quad (5)$$

2.1.1.2 Mortgage debt. If the owner of the energy system is not a corporation, his financing alternatives are reduced to buying debt or saving in advance. For this analysis we will consider the debt alternative only. We also assume this debt would probably be in the form of a mortgage. The cost of a mortgage includes interest expense and the repayment of the principal. These two costs must be separated because only the interest can be used as a tax deduction.

Repayment of a mortgage is accomplished by periodic payments of a specific amount for a predetermined number of time periods. Each payment consists of interest due on the remaining principal and repayment of a portion of the principal. Let X equal the amount of the periodic payment. Let K_p equal the amount originally financed. The percentage of the payment which is interest is I_t and the remainder represents a principal payment (P_t). Therefore, I_t plus P_t equals 1.

The first payment will be almost all interest ($I_0 \approx 1$). The percentage of X which is interest in the second payment is given by:

$$I_1 = \frac{rK_p}{X}$$

where: r = rate of interest on the mortgage.

similarly, $$I_2 = \frac{r(K_p - P_1X)}{X}$$

$$I_3 = \frac{r(K_p - P_1X - P_2X)}{X}$$

Therefore, in general:

$$I_t = \frac{r\left[K_p - \sum_{j=1}^{t} (P_{j-1}\ X)\right]}{X} \quad . . . \quad (6)$$

where: $(K_p - X \sum_{j=1}^{t} P_{j-1})$ represents the remaining principal at time t.

Substituting $(1 - I_t)$ for P_t in equation (6) yields:

$$I_t = \frac{r}{X}(K_F \quad X \sum_{j=1}^{t} (1 - I_{j-1})$$

$$I_t = \frac{rK_F}{X} - r \sum_{j=1}^{t} (1 - I_{j-1}) \quad . . . \quad (7)$$

The standard method for determining the size of a mortgage payment is given by the capital recovery formula.* Algebraically;

$$\frac{r}{1 - (1+r)^{-(N+\alpha)}} = \text{capital recovery factor}$$

where: $(N + \alpha)$ = the length of the mortgage

In other words, the expression represents the decimal fraction of the intial mortgaged amount which, paid in equal amounts, will repay interest and principal over the life of the mortgage ($(N + \alpha)$ years). Therefore, we can redefine X as:

$$X = \frac{K_F r}{1-(1+r)^{-(N+\alpha)}}$$

substituting in equation (7) yields

$$I_t = 1 - (1+r)^{-(N+\alpha)} - r \sum_{j=1}^{t} (1 - I_{j-1}) \quad . . . \quad (8)$$

The present value (PV) of equation (8) is expressed as:

$$\bar{I}_t = \text{PV of } I_t = \sum_{t=m-\alpha}^{m+n} \left[1 - (1+r)^{-(N+\alpha)} - r \sum_{j=m-\alpha}^{m+n} (1 - I_{j-1})\right] (1+c_k)^{-t} \quad . . . \quad (9)$$

Since mortgage interest is a deductible expense for income tax purposes, the effective cost of the interest payment (as a decimal fraction of X) can be expressed as:

$$\left[1 - T_I\right] \bar{I}_t \quad . . . \quad (10)$$

where: T_I is the individual income tax rate.

Multiplying equation (10) by X (the amount of the payment) expresses the effective interest cost in present dollars.

$$\text{Effective PV Cost of Interest} = \left[1-T_I\right] \bar{I}_t X \quad . . . \quad (11)$$

The cost of the principal each period can be expressed as:

$$P_t X = (1 - \bar{I}_t)X \quad . . . \quad (12)$$

Combining equations (11) and (12) yields the total cost of buying a mortgage.

$$\begin{aligned}\text{(PV) of total cost} &= \left[1 - T_I\right] \bar{I}_t X + (1 - \bar{I}_t)X \\ &= X\left[\bar{I}_t (1 - T_I) + (1 - \bar{I}_t)\right] \\ &= X\left[\bar{I}_t - T_I\bar{I}_t + 1 - \bar{I}_t\right]\end{aligned}$$

* The Engineers Companion, Mott Souders, John Wiley and Sons, 1966, p. 270.

$$(PV) \text{ of Total Cost} = X\left[1 - T_I \bar{I}_t\right] \quad \ldots \quad (13)$$

Equation (13) is then entered into the cost function if the system is privately owned and financed with a mortgage. If it is corporate owned, equation (3) should enter the cost equation.

2.2 FOSSIL FUEL COSTS

The present value of future fuel expenses is handled using a straight forward present value approach. The quantity of fossil fuel needed is determined by the technical requirements of the system and its geographical location. The price is forecast for each period. The present value of the total cost of fossil fuel (C_p) is expressed as:

$$C_p = \sum_{t=m}^{m+n} \frac{C_t}{(1+c_k)^t} \quad \ldots \quad (14)$$

where: C_t = the total cost (quantity times price) of fossil fuel used in the period t.

Fuel costs are considered an operating expense for income tax calculations. This is a federal subsidy to fossil fuel consumption since the tax reduces the effective cost by a factor of $[1 - T_c]$. Equation (14) can then be rewritten as:

$$C_p = [1 - T_c] \sum_{t=m}^{m+n} \frac{C_t}{(1+c_k)^t} \quad \ldots \quad (15)$$

Forecasting the price of fossil fuel in each of the n periods is the crucial, as well as the most difficult, component of this cost estimation. Price forecasts differ widely. Therefore, different estimates should be entered into the model and tested for cost sensitivity. In the case of on-site solar energy systems fuel costs refer to fossil fuels used in both electricity generation and space conditioning energy.

2.3 MAINTENANCE AND OPERATION COSTS

Maintenance and operating costs, excluding fuel expenses, are estimated using the same approach as fuel costs. The present value of maintenance and operating costs (C_{o+m}) is given by:

$$C_{o+m} = \sum_{t=m}^{m+n} \frac{C_o^t + C_m^t}{(1 + c_k)^t} \quad \ldots \quad (16)$$

where: C_o^t = the total operating cost incurred in the period t. (The superscript t does not represent a power function)

C_o^t = the total maintenance cost incurred in time period t.

These operating costs are also tax deductible expenses. The effective cost of maintenance and operation is given by:

$$[1 - T_c]\, C_{o+m} = [1 - T_c] \sum_{t=m}^{m+n} \frac{C_o^t + C_m^t}{(1 + c_k)^t} \quad \ldots \quad (17)$$

2.4 PROPERTY TAXES

To this point, the analysis has only considered the effect of the corporate and individual income tax on costs. Some energy systems,may result in higher property taxes. It will be assumed that property tax is a relatively small expense for a corporation. Therefore, only the effect of property tax on individually owned systems will be considered.

The property tax pertinent to this study is the additional tax paid as a direct result of adding an energy system. Usually, property taxes are compiled on the basis of assessed valuation. The assessed value is some fraction of the market value of the property. The actual tax is then calculated as a percentage of the assessed valuation. The wide variation in property taxes was demonstrated in a recent study prepared for the National Commission on Urban Problems.* According to the study, approximately 70,000 local government units are authorized to levy property taxes. In addition, each state (and the District of Columbia) has a different legal system. As a result, according to the author, "there are really 70,000 or so different property taxes in the United States, grouped into 51 systems with common legal settings."*

Despite the complicated nature of the property tax system, some averages of the tax rates and assessed value ratios have been compiled. If the exact location of the system is known, the appropriate local tax rate can be used.

The market value of an energy system can be approximated by the book value of the capital cost. In this analysis it is approximated by K. The present value of the additional property tax can then be expressed as:

$$T_p = \sum_{t=m}^{m+n} \frac{(p)\ (a)\ (K)}{(1 + c_k)^t} \quad \ldots \quad (18)$$

where: T_p = the present value of property tax attributible to a new energy system

a = assessed value expressed as a percent of market value

p = property tax rate

K = book value of the capital goods, (an approximation of the system's market value)

* Impact of the Property Tax by Dick Netzer for the National Commission on Urban Problems, 1968, p. 5.

Since property taxes are a deductible expense for individual income taxes, the effective cost is reduced $[1 - T_I]$ where T_I is the individual income tax rate. Equation (18) is then expressed as:

$$[1 - T_I]T_p = (1 - T_I) \sum_{t=m}^{m+n} \frac{(p)\ (a)K}{(1+c_k)^t} \quad . . . \quad (19)$$

2.5 THE TAX BENEFITS OF DEPRECIATION

The depreciation of capital assets reduces the effective cost of an energy system because it lowers the corporation's income tax. The first step in calculating the cost reduction is to determine the depreciation each time period. The two methods for calculating depreciation which will be considered are straight line and double declining balance.

For both methods, it will be assumed that at the end of m+n years the energy system does not have enough salvage value to be worth considering. Let D_t equal the amount of depreciation deducted in period t. The present value of the depreciation, using a straight line (SL) method is given by:

$$\frac{K}{n} \sum_{t=m}^{m+n} \frac{1}{(1+c_k)^t}$$

Incorporating the tax benefit feature of the depreciation this column yields:

$$\text{Tax Benefits of SL Depreciation} = -T_c \frac{K}{n} \sum_{t=m}^{m+n} \frac{1}{(1+c_k)^t} \quad . . . \quad (20)$$

The expression is negative because it reduces the total cost of the energy system.

The double declining balance method is given by the following general form:*

$$D_t = K\left(\frac{2}{n}\right)\left(1 - \frac{2}{n}\right)^{(t-1)}$$

However, most corporations only use a double declining balance (DDB) until the time period when a straight line method would yield a larger amount to depreciate. This process can be expressed by:**

$$D_t = \begin{cases} K\left(\frac{2}{n}\right)\left(1 - \frac{2}{n}\right)^{t-1} & \text{if } t < \left(\frac{n}{2}\right)+1 \\ \dfrac{K\left(1 - \frac{2}{n}\right)^{t_c-1}}{n + 1 - t_c} & \text{if } t \geq \left(\frac{n}{2}\right) + 1 \end{cases}$$

where: t_c is the first t greater than or equal to $\frac{n}{2} + 1$.

The present value of this method is then:

$$\sum_{t=m}^{m+n} \frac{D_t}{(1+c_k)^t}$$

Incorporating the tax effect yields the final equation:

Tax benefits of DDB and SL Depreciation =

$$-T_c \sum_{t=m}^{m+n} \frac{D_t}{(1+ck)^t} \quad . . . \quad (21)$$

2.5 THE INVESTMENT TAX CREDIT

In addition to depreciation allowances, the cost of an investment to a corporation can also be reduced by utilizing investment tax credits. An investment tax credit allows a certain percentage of new investment to be deducted from the firm's tax liability. The credit can only be claimed in one time period and it does not reduce the basis for depreciation.

The law also states that the credit cannot be more than the first $25,000 of tax liability plus one-half of the liability in excess of $25,000.*** For the purpose of this analysis, however, we will assume the tax credit does not exceed the allowance maximum. Given this assumption, the cost reduction attributable to an investment tax credit can be expressed as:

$$-(\beta) \cdot (K)$$

where: β = the investment tax credit (expressed as a decimal fraction)

We will assume the tax credit is claimed when construction of the project is started (time $m-\alpha$). The present values of the credit is given by:

* The Capital Budgeting Decision by Harold Bierman and Seymour Smidt, MacMillan Company, New York, 3rd Edition, p. 246.

** "Public Utility Investment Analysis" by J. Hass, National Technical Information Service, Department of Commerce, January 1971.

*** 1974 Federal Tax Course, Prentice-Hall, Englewood Cliffs, New Jersey, 1973, p. 2050.

$$I_t = -\beta(K)(1+c_k)^{-(m-\alpha)} \quad \ldots \quad (22)$$

3. SUMMARY

The components of the total cost function applicable to any energy system will depend on the ownership of the system. The function can be divided into two general cases. The first is corporate owned, with minor modifications for publicly owned corporations, and the second is privately owned. The corporate owned system finances using equity and debt, uses depreciation to reduce cost and is assumed to ignore the effect of property tax. The corporate cost curve is the summation of equations (5), (15), (17), (21), and (22).

Algebraically,

$$\text{P.V. of Total Cost}_{\text{Corporate}} = \left\{ \left[(1-T_c)q_D r_D + r_s q_s\right] \left[K_F \sum_{t=m-\alpha}^{m+n} \frac{1}{(1+c_k)^t} \right] + \frac{K_F}{(1+c_k)^{(m-\alpha)+n}} \right\} + \left\{ \left[1-T_c\right] \sum_{t=m}^{m+n} \frac{C_t}{(1+c_k)^t} \right\} + \left[1-T_c\right] \sum_{t=m}^{m+n} \frac{C_o{}^t + C_m{}^t}{(1+c_k)^t} - T_c \sum_{t=m}^{m+n} \frac{D_t}{(1+c_k)^t} - \frac{\beta(K)}{(1+c_k)^{m-\alpha}} \quad \ldots \quad (23)$$

The individually owned energy system is financed with mortgage debt, incurs additional property tax, and does not receive the tax benefits of depreciating the asset. The individually owned system is represented by the summation of equations (13), (14), (16), (19), and (22).

Algebraically:

$$\text{P.V. of Total Cost}_{\text{Individual}} = X\left[1 - T_I \bar{I}_t\right] + \left\{ \sum_{t=m}^{m+n} \frac{C_p{}^t}{(1+c_k)^t} \right\} + \left\{ \sum_{t=m}^{m+n} \frac{C_o{}^t + C_m{}^t}{(1+c_k)^t} \right\} + \left[1 - T_I\right] \sum_{t=m}^{m+n} \frac{p(a)K}{(1+c_k)^t} - \left\{ \frac{\beta(K)}{(1+c_k)^{m-\alpha}} \right\} \quad \ldots \quad (24)$$

Equations (23) and (24) represent the total life-cycle cost of an on-site solar energy system to a corporation and an individual, respectively. As mentioned previously, the equation also offers a convenient method for calculating the life-cycle cost of other types of energy systems.

4. BIOGRAPHIES

Mr. Costello is an energy economist at Midwest Research Institute, Kansas City, Missouri. He specializes in the development and analysis of energy policy.

Recently, he led the socioeconomic analysis tasks in a major study of the impacts of commercial development of solar energy for the U.S. Congress.

Mr. Costello received the B.A. in Economics (1972) from the State University of New York where he graduated Magna Cum Laude and the M.A. in Economics (1973) from Ohio State University.

Mr. Bradley is an Associate Engineer at Midwest Research Institute and specializes in the technical and economic analysis of solar energy systems.

He is currently responsible for the technoeconomic analysis phases of MRI's on-going studies of solar electric systems.

Mr. Bradley is a member and former officer of the Kansas City chapter of the Society of Manufacturing Engineers and is a member of the International Solar Energy Society. He received the B.S. in Mechanical Engineering (1968) and the M.B.A. in Finance (1973) from the University of Kansas.

SELF-CONSISTENCY IN ESTIMATING FUTURE ELECTRICAL ENERGY CONSUMPTION*

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Abstract

A socio economic computer simulation model for the State of Oregon is described. The Oregon State Simulation Model (OSSIM) includes a thirty-seven sector model of electrical energy consumption. Coupling between this model and the OSSIM ensures self-consistent scenarios of socio economic phenomena which underlie energy consumption. One of the purposes of this effort is to help state-level decision makers understand the determinants of electricity consumption within a context of changing economic conditions.

1. INTRODUCTION

Until recently, examples of personal inconvenience or attenuation of economic growth caused by increasing prices or local shortages of electricity have been rare. Now, however, the local environmental, economic, and social impacts of electrical energy production and consumption are major concerns. To deal with these concerns, various policies--both exogenous and endogenous to individual states--have been developed or are proposed and many of them carry serious implications for electricity costs and availability. Possible implementation of such policies, combined with definite changes in energy prices and even shortages of some energy forms, makes the estimation of future electrical energy consumption for individual states a challenging problem.

Techniques which have been used in the past to attack this problem have been remarkably accurate. This does not necessarily mean, however, that comparable techniques employed today will yield equally good results. Until recent years, energy demand projections have been performed in the context of: seemingly endless, steady growth in

* This research is supported by the Rockefeller Foundation and the Pacific Northwest Regional Commission.

population and economic activity; surplus or at least adequate energy supplies; and real energy prices which were low and in many cases steadily declining. Few and perhaps none of these conditions exist today, nor are they likely to exist in the forseeable future.

The present authors contend that future electrical energy consumption should be viewed as arising from elements of a complex socioeconomic system and that these elements can only be correctly addressed in concert with one another. It is vital that this viewpoint be appreciated by state level decision makers, whose actions can influence not only the electricity supply system but the general economic condition of the state. For example, in the latter half of 1974 the United States electric utility industry cancelled or postponed the construction of large numbers of generating stations, particularly nuclear power plants. Analysis by L. J. Perl* indicates that these cancellations are principally a result of capital shortages, and places the blame on state regulatory agencies for failure to grant required rate increases. Thus the regulatory commission, having the capability of directly influencing both electricity prices and supplies, is itself an important element in a state's energy system. Clearly, it is imperative that key inputs to the complex, dynamic energy system be manipulated with maximum understanding of the potential consequences, both direct and indirect, and short-term and long-term.

The methodology presented in this paper is casual in structure and relies only to a limited extent upon correlation and extrapolation. Electrical energy consumption is determined, in concert with economic and demographic activity, in the Energy Component of a socioeconomic simulation model of the State of Oregon (described in Section 2). A major strength of this approach is that self consistent scenarios of underlying economic and demographic activity are ensured. That is, most variables that are exogenous to econometric models, and thus whose self-consistency cannot be demonstrated mathematically are endogenous to this model. M.F. Searl**, in a recent review of contemporary energy modeling efforts lends support to the importance of this feature:

> "Historically, most energy models have not been coupled to comprehensive economic models. Instead, the economic input to the energy model was in terms of individual demographic and economic projections presumed to be consistent but rarely derived from a comprehensive economic model."

Self-consistency is particularly important when models are used to assess possible impacts on future energy consumption of proposed policies which are not at first perceived to be directly related to energy.

2. OREGON STATE SIMULATION MODEL (OSSIM)

In late 1972, the Rockefeller Foundation awarded a grant to Oregon State University with the goal of enhancing the University's capability to address the complex problems of economic growth and environmental quality in Oregon. One specific objective of the project has been the development of the Oregon State Simulation Model (OSSIM). A brief description of the model is contained in the latter part of this section. However, because some confusion can arise concerning the objectives, the capabilities and the limitations of computer

* Perl, L.J. "The Future of Nuclear Power in the Electric Utility Industry." Nuclear News, 17, No. 15 (1974), pp. 60-63.

**Searl, M.F. "Introduction." Energy Modeling. Ed. by M.F. Searl. Washington, DC: Resources for the Future, Inc., March 1973.

simulation models such as OSSIM, the following summary is provided.

The principal objective of the OSSIM is to provide a mechanism for making research results available to state level decision makers that hopefully will:

(1) Heighten their appreciation for the complexity and dynamic interrelatedness of economic growth, energy consumption, land use, and environmental quality, and

(2) Provide them with one more means of estimating the likely consequences or outcomes associated with various policies and/or scenarios.

It should be emphasized that the OSSIM is not intended to replace any of the sources of information already available to and used by decision makers. Simulation models do not yield decisions, but rather generate additional information that can facilitate decision making. (The specific role of the decision maker is indicated in Section 4.)

The computer simulation methodology is just one of a large and growing number of "systems approaches" which, though they differ considerably from one another in purpose, conceptual framework and technique, have one attribute in common; they all differ from classic analytical procedures in that:

(1) The interactions between the parts of a true "system" cannot always be neglected when describing the behavior of any isolated part, and,

(2) The sum of the behavior of the parts does not, in general, represent the behavior of the "system".

The system, the model, and the simulation are related to each other in the manner illustrated in Figure 1.

There are several important characteristics of the simulation process that should be kept in mind when evaluating the simulation results. First, simulation really consists of two translations "in series," and the degree to which the simulation replicates the observed behavior of the real world system depends on the validity and accuracy of both translations. The success of the first translation really depends on how much is known and understood about the system being modeled. The success of the second translation depends on the selection and correct application of appropriate computational techniques.

Second, it should be stressed that each translation is a "one-to-many" relationship. That is, for every real world system there are many models which could be devised, and the choice will (or should) depend on the objectives of the modeler. Once a model has been devised, there are then alternative ways of translating it into a simulation. There is usually less latitude in this choice, which will depend largely on the nature of the model and on the availability of computing equipment.

Finally, the broken arrow indicates the role the simulation plays (hopefully) in the real world. Studying the behavior of the model improves our understanding of how the real world functions, and this knowledge is "translated" into better real world decisions. In other words, the simulation model is simply a way of structuring one's thinking which forces methodical, meticulous, and simultaneous consideration of all important factors and interrelationships in the real world. The simulation output is one more piece of information that can be available to decision makers, and information plus judgment yields decisions.

OSSIM is a dynamic, nonlinear continuous

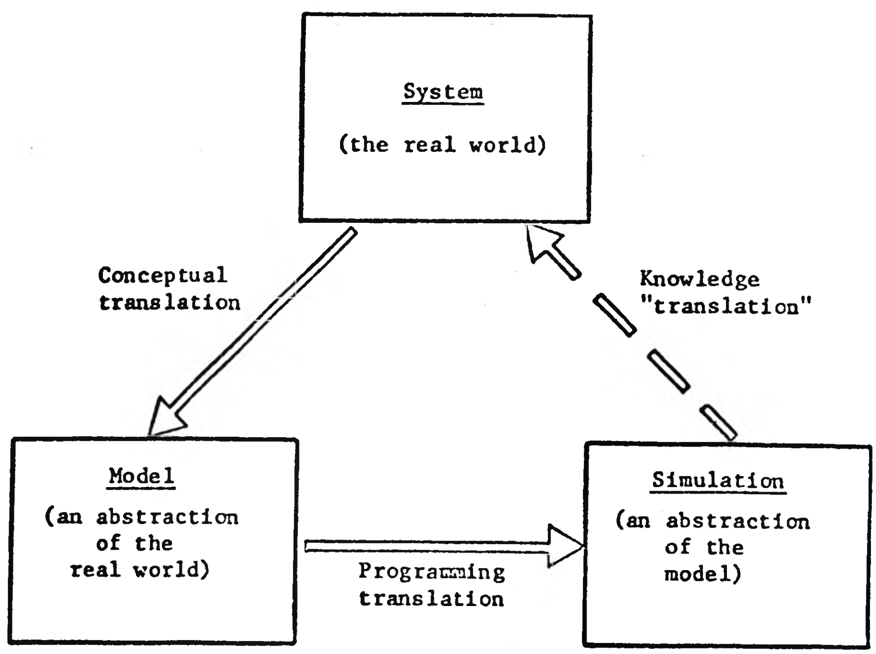

Figure 1. RELATIONSHIP BETWEEN THE SYSTEM, MODEL AND SIMULATION

simulation model of man's activities in the State of Oregon. It was built utilizing the well-known systems approach alluded to earlier--with the general procedure being an iterative process of problem definition, mathematical modeling and simulation, model refinement and testing and model application.

As many of the questions raised in the problem formulation stage centered on differences between the Willamette Valley and the rest of Oregon, the state was divided into three geographic regions as illustrated in Figure 2. While the general boundaries of these regions are primarily related to the physical geography of the state, it was clear that they also differed from one another in many other respects (e.g. climate, economic base, population density, etc.). Hence, the OSSIM consists of three interdependent "parallel" models which are structurally identical but numerically different.

The maximum time horizon for the model is fifty years (1970-2020). A much shorter time horizon (one to five years) was not considered appropriate since the questions raised in the problem definition phase involved long run projections. A time horizon in excess of fifty years was also considered inappropriate since the accumulation of technological and institutional changes occurring over that time span could make the model totally invalid.

There are seven components in the model structure: Demographic, Economic, Land Use, Transportation, Energy, Pollution and Government Revenue. These components are dynamically connected to one another in the manner illustrated in Figure 3. The "labels" on the arrows are representative samples of the nature of the interactions between components.

It should be noted that the internal structure of each component reflects the present modelers' conceptual views of the State of Oregon. While the methodology employed is general and could be used to model regions other than Oregon, the specific structure and dynamic behavior of

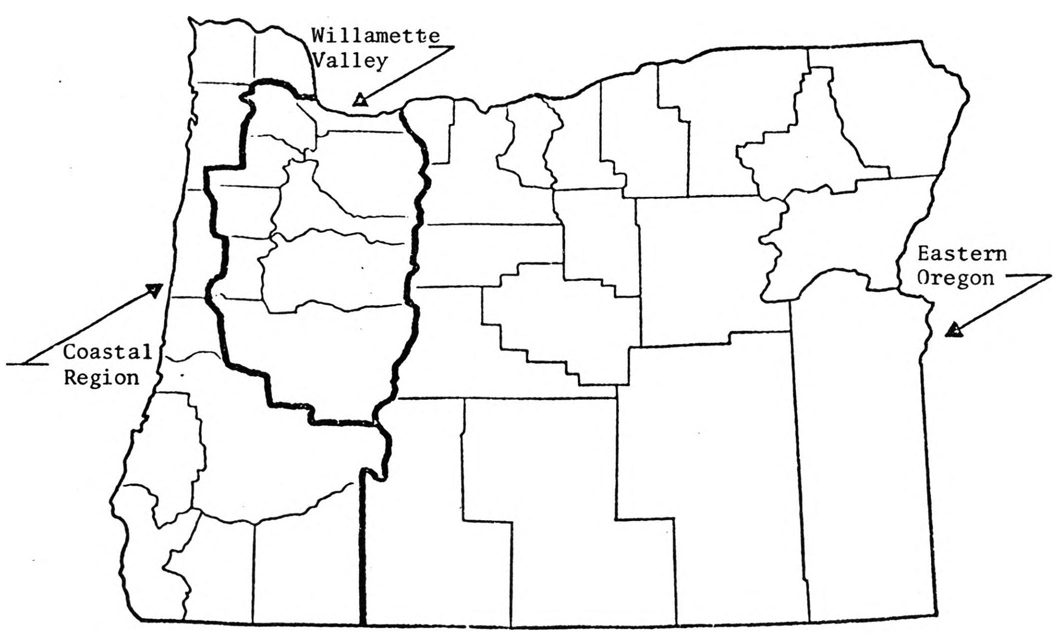

Figure 2. THE THREE REGIONS OF THE STATE OF OREGON

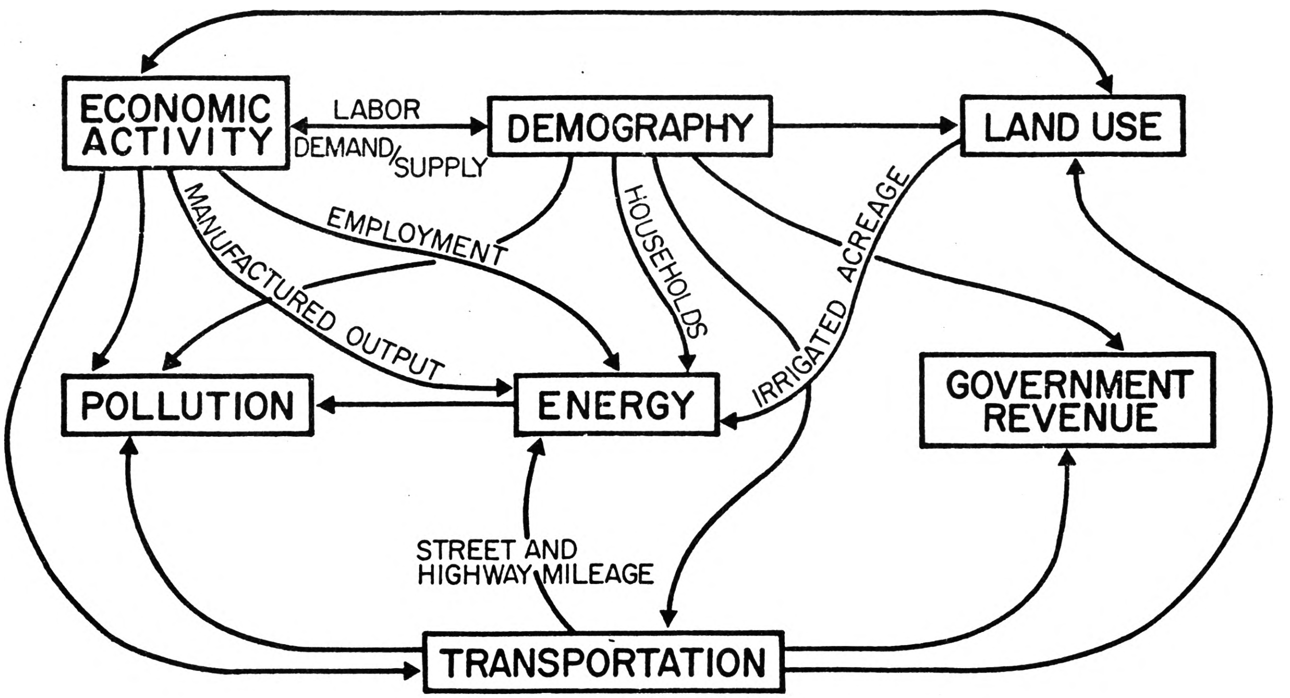

Figure 3. OREGON STATE SIMULATION MODEL (OSSIM)

any or all components could differ considerably from those presented here. Six of the seven components are discussed in the remainder of this section. The Energy Component is described in Section 3.

2.1 DEMOGRAPHIC COMPONENT

The Demographic Component contains a detailed accounting of the population of each region of Oregon, resolved into nine household size classes, two fertility classes, and two socio economic strata. The choice has been made to use numbers of households, rather than of individuals, as the principal variables since the household seems to be the more significant unit for economic and social considerations. This choice is a major departure from previous simulation models, which typically have used a standard age-cohort type of demographic analysis and projection.

In dynamic terms, the component traces the "life cycle" of households from formation to extinction. The major driving forces are the class-specific birth rates, which implicitly determine the age distributions within households and hence the fecundity and rates of maturation. These birth rates are modeled as being dependent on economic expectations through the regional unemployment rate, and on socio economic stratum as determining effectiveness of family planning. The dynamics of socio-economic stratification are modeled as processes of upward and downward diffusion between "marginal" and "mainstream" household classes, with spontaneous rates that are augmented on the upward side by subsidized job training as a typical "war-on poverty" policy variable.

A second driving force which affects Oregon's demographic characteristics is migration, which is modeled with two different types of relationships for three different age groups (age of head of household). Net migration in the age groups 15-29 and 30-44 is assumed to be sensitive to employment opportunity in the region, as measured by the unemployment rate, and to the social size of the region, as measured by its population. Only the parameters are different for these two age groups. The age group 45+ is assumed to continue a net inmigration to Oregon at a rate which depends on the number of such households already in Oregon. In addition, a joint distribution of households by income and family size is generated using wage income information supplied by the economic component.

The principal output from the Demography Component to the Energy Component is the number of residential utility customers, which is computed as a function of the household size and income distribution.

2.2 ECONOMIC COMPONENT

The Economic Component is viewed as having four basic sectors which operate in each of the three subregions: logging and wood products, agriculture and food products, manufacturing, and services. These have been modeled and programmed as subroutines which are called in sequence by a calling program. This calling program is itself a subroutine of the overall model, and also performs the "bookkeeping" tasks of summing up total labor demands by occupational category, comparing this demand with the labor force supplied from the Demographic Component, and computing unemployment rates and resulting wage rates. The Economic Component avoids reliance on exogenous variables by incorporating the assumption that there are fundamental natural and human resource bases that both support and limit regional production. The four sectors are discussed below, in order of their importance to Oregon's economy as a whole.

2.2.1 Logging and Wood Products Sector

The level of logging activity is viewed as depending, over the long run, entirely on the resource base of mature and growing timber and its management. Projections of the annual sawtimber yields over the next one hundred years have been made by the U.S. Forest Service, and these projections are provided as exogenous information.

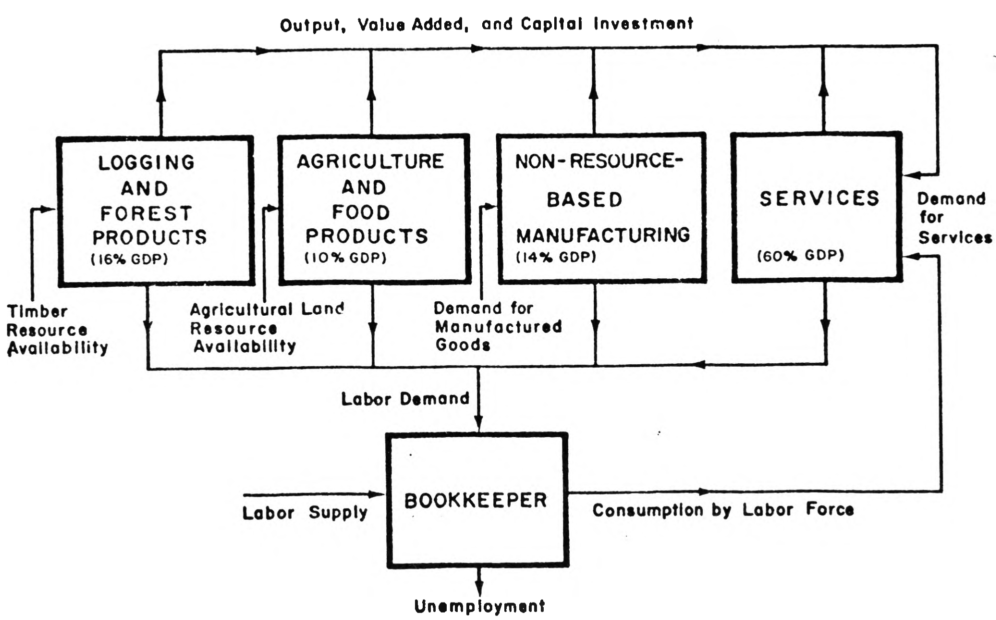

Figure 4. STRUCTURE OF THE ECONOMIC COMPONENT

Different projections can be supplied for each subregion, depending on the policy choices of rotation period and management intensity. While the actual annual cuts will vary from the projected yield because of the short-run cyclical nature of the sector, these variances are thought to have little long-run effect.

The annual sawtimber yield is then distributed among three wood products industry activities: production of lumber, plywood, and pulp and paper. The raw material inputs to each of these are calculated from the annual sawtimber projection by applying factors which apportion the board feet of sawtimber to lumber and veneer, and which give the volume of residues and small roundwood available for pulp and paper.

Value added by each wood product industry is then calculated, and supplied to the Energy Component as a dynamic input.

2.2.2 Agriculture and Food Products Sector

The agriculture and food products sector, like the logging and wood products sector, is viewed as depending on a natural resource base. Agricultural land and the capital stock associated with that land are assumed to be the key factors of agricultural production. Operating expenses, labor costs, taxes and interest are deducted from the calculated value of gross production to determine net returns. A deferred annual capital gain, based on the increase in speculative value of agricultural land, is added to net returns and the sum forms the basis for capital formation in agriculture.

Value added by primary processing of farm products is also calculated and supplied to the Energy Component as a dynamic input.

2.2.3 Manufacturing Sector

The manufacturing sector sums the demand for durable and non-durable goods from the other sectors, including exports. Required inputs of these goods are taken as being equal to current output minus total current demand (the excess demand). Required investment in new capital is determined by the smoothed excess demand and a subsequent delay called the excess demand closure time. Environmental standards and availability of labor influence the length of the excess demand closure time. A capital installation delay allows for the time delay between ordering and installing capital.

Value added by the manufacturing sector, which is determined by the level of installed capital, is then supplied to the Energy Component as another dynamic input.

2.2.4 Service Sector

The service sector accounts for all business and household services, including wholesale and retail trade, utilities, construction and financial, health care, educational and government services. The regional inter-industry demand is computed from the output of the other three sectors using technical input/output coefficients. Final demand is calculated as a function of household incomes, tourism, investment in the basic sectors, and government revenues. Inter-industry and final demands are summed to provide the total regional demand for services. A "regional shift matrix" is then employed to determine the regional breakdown of the supply of services, with some services being imported from outside Oregon.

Unlike the other sectors, regional employment in services is used as the surrogate for economic activity, which is supplied to the Energy Component as a dynamic input.

2.3 LAND USE COMPONENT

The Land Use Component maintains a current inventory of the land (by region) in each of eight use categories, and simulates the dynamic processes which results in transitions between categories.

The demand for residential land in three density classes is driven by the Demographic Component. The housing demand is a function of household size and income, the price of land and housing, the cost of providing services to the land, and the residential density. Changes in the housing stock required to meet the changing demand are calculated, with appropriate adjustments for replacement and vacancies.

Agricultural land is the principal source of land entering the residental use category. Transfers of land to or from the forest land, "open space," or unused categories is permitted as a user-supplied scenario. The number of acres of land available for agricultural production is supplied to the agricultural sector of the Economic Component, where it is a factor of production. In addition, the number of acres currently undergoing irrigation is supplied to the Energy Component as a dynamic input.

The forest land use category accounts for all land upon which commercially harvestable timber is growing. The industrial/commercial land use category responds to demands generated by the level of activity in the industrial and service sectors of the Economic Component, with agricultural and high density residential land acting as the sources. The Open Space/Wilderness use category enables the model user to set aside agricultural/forest land in a preservation status. Unused land is that area of each region which does not qualify for one of the other seven use categories (a residual).

2.4 TRANSPORTATION COMPONENT

The Transportation Component analyzes transport demand, provides measures of effectiveness of Oregon's transport service and determines the consequences of providing that service. Transportation demand between and within fifteen urban areas, the five largest in each region, is analyzed.

The Transportation Component allocates to each of the urban areas increments of regional population growth provided by the Demography Component. Models of urban travel, intercity passenger travel, and intercity cargo transport estimate the total passenger vehicle miles and cargo ton miles of transport by significant modes. One output of the Transportation Component is the number of illuminated highway miles, which is supplied to the Energy Component as a dynamic input.

2.5 POLLUTION COMPONENT

The Pollution Component translates levels of polluting activities (e.g. transportation, manufacturing, space heating) furnished by other components of the model into rate of discharge of air pollutants (presently fine particulates and SO_x).

The level and emission intensity of various polluting activities in conjunction with the control strategy for that category of sources (as reflected in the emissions intensity ratio) determine rate of pollutant emissions in that source category. When the emissions by each source category are added together, the impact of a particular emission control strategy on the aggregate emissions can be assessed.

2.6 GOVERNMENT REVENUE COMPONENT

The function of the Government Revenue Component is to translate certain output variables of the Demographic, Economic, and Transportation Components into the common language of tax dollars, with reference to three important taxes collected at the state level in Oregon. The joint distribution of households by size and family income, generated in the Demographic Component, provides the basis for the state personal income tax revenue calculation. Corporate income tax revenue is projected on the basis of value added in each sector of the Economic Component. Finally, the level of transportation activity, determined in the Transportation Component, is utilized to project motor vehicle tax revenue.

3. ENERGY COMPONENT

The Energy Component provides estimates of electrical energy consumption by means of a detailed consideration of energy use in thirty-seven consumer categories. Appropriate groups of these categories compose the four traditional sectors of industrial, commercial, transportation, and residential users. The Industrial Sector consists of three resource-based manufacturing industries, sixteen non-resource-based manufacturing industries, and three irrigation regions. These nineteen industries constitute the Commercial Sector, which is highly aggregated due to data limitations, while the Residential Sector is based upon far more extensive data which allows consideration of thirteen specific household appliances.

The consumption of electrical energy in each consumer category is written as the product of two time-dependent functions, here designated Ue and Y.

$$DE = Ue(p,t) \cdot Y(p,t)$$

Ue represents the intensiveness of electricity use in each category or subsector and is called "electrical energy intensiveness." Y is a surrogate for the level of economic or demographic activity of that subsector. Since Ue and Y are simulated separately, it can be readily determined whether changes in the rate of economic growth, or to both and in what proportion. Note that, in general prices (represented by p) of electricity, gas and petroleum products may affect both intensiveness and economic activity.

It is further asserted that electrical energy intensiveness functions can be unfolded into two additional functions, one of which is independent of energy prices:

$$Ue + Ue_o(t) \cdot Fe(p)$$

The utility of this effort lies in the isolation of two components which will, in all probability, behave quite differently from one another in the future. That is, Ue_o (which is called "base energy intensiveness") depends upon fundamental phenomena such as technical progress and can reasonably be expected to follow past trends. Fe(p), on the other hand, depends upon the history of energy price changes and will most likely deviate considerably from pre-1970 patterns.

In principle there exists an economic demand function for each subsector, which indicates the degree to which demand for electrical energy is elastic.* However energy is an intermediate good, and adjustment of patterns of energy consumption to changing energy prices cannot occur instantaneously. Studies have also shown that the response of energy demand to a change in price can be approximated by the response of a first-order, linear system with some characteristic time constant. Figure 5 illustrates an economic demand curve for electrical energy with demand as a function of time shown in Figure 6.

We have written demand as the product of intensiveness and activity; however, we

*Note that the word "demand" is used in the sense of the economist rather than in that of the electrical engineer.

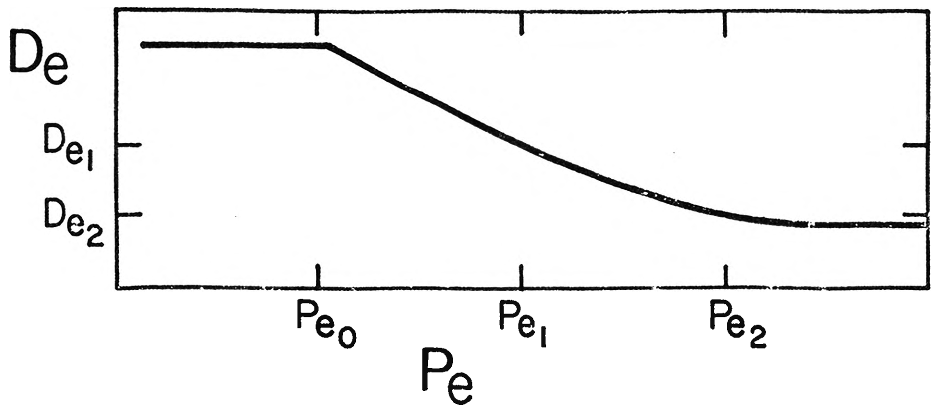

Figure 5. HYPOTHETICAL ECONOMIC DEMAND CURVE FOR ELECTRICAL ENERGY

are really interested in the individual response of each of these factors. We thus define a new quantity--price elasticity of intensiveness--which is completely analogous to price elasticity of demand. We also recognize that the own-elasticity of intensiveness ξ_e, can have three components: one pertaining to electricity conservation; one which accounts for interfuel substitution; and one reflecting locational decisions of industries. Interfuel substitution, of course, can occur from electricity to gas or to petroleum products (ξ_{e_s}), and also from each of the fossil fuels to electricity (represented by ξ_g and ξ_p).

$\frac{\partial Ue}{\partial Pe} \frac{Pe}{Ue} = \xi_e$, the own-elasticity of intensiveness of electricity;

$\frac{\partial Ue}{\partial Pg} \frac{Pg}{Ue} = \xi_g$, the elasticity of substitution to electricity for gas;

$\frac{\partial Ue}{\partial Pp} \frac{Pp}{Ue} = \xi_p$, the elasticity of substitution of electricity for petroleum.

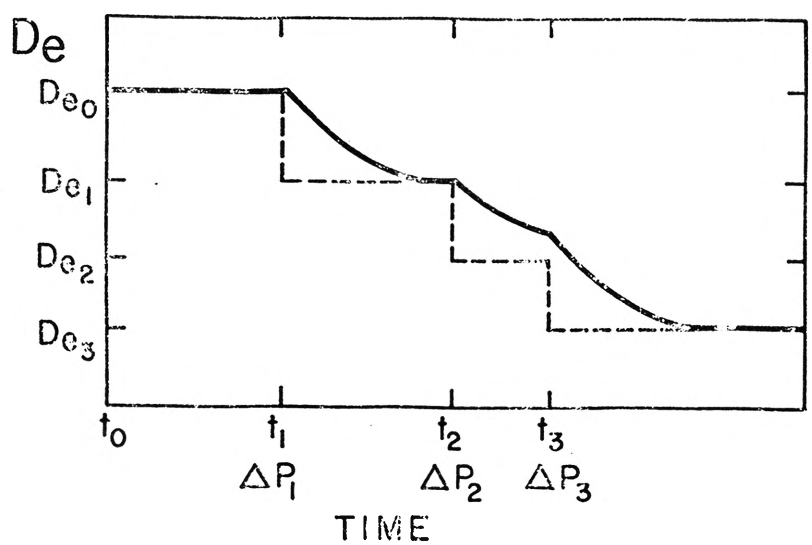

Figure 6. DEMAND IN TIME DOMAIN

$\xi_e = \xi_{e_c}$ (conservation) + ξ_{e_s} (substitution) + ξ_{e_ℓ} (location)

$$\xi_{e_s} = \xi_{e_{e \rightarrow g}} + \xi_{e_{e \rightarrow p}}$$

Finally, we associate time constants with these various kinds of consumer responses. These time constants are related to the time required for a given subsector to alter its average pattern of energy use--or energy intensiveness--in response to energy price changes. For example, in the Industrial Sector conservation would be the initial response to a significant increase in electricity price, perhaps being felt in 1-3 years. On the other hand, interfuel substitution is a longer-run effect, due to the relatively long lifetime of much process equipment.

In summary, then, the following concepts are taken into account in the electrical energy demand model:

- consumers respond to energy price increases by conservation, interfuel substitution, and alteration of habits of appliance acquisition and industrial location.
- these responses may not occur until some threshold price is exceeded.
- changes in patterns of energy consumption take time.
- technical limits to conservation and interfuel substitution exist.

4. IMPLEMENTATION

For many years Oregon has been known as a leader in the area of environmental management. Recent legislation has asserted a similar leadership role in the area of land use planning and energy management. The creation of a Department of Energy, with broad energy planning responsibilities, has increased the potential for and actual interaction between modelers and decision-makers. With a statutory requirement to produce "independent" energy forecasts which "identify and account for all major components of demand and anticipated increase in demand, including but not limited to population, commercial, agricultural, and industrial growth," the need for employment of coupled socioeconomic models becomes more clear. The proper interpretation of model results requires a close working relationship between the modeler and the decision maker as illustrated in Figure 7.

Project personnel have been provided office space in the Department of Energy and are working on a regular basis with agency staff in the necessary interactive stages

CONSUMER RESPONSES TO ENERGY PRICE CHANGES

	Appliance Saturation	Appliance Consumption (Conservation)	Interfuel Substitution	Industrial Location
Response Time:	Quite Short	Short	Medium	Long
Sector of Importance:				
Industrial		X	X	X
Commercial	X	X	X	
Residential	X	X	X	

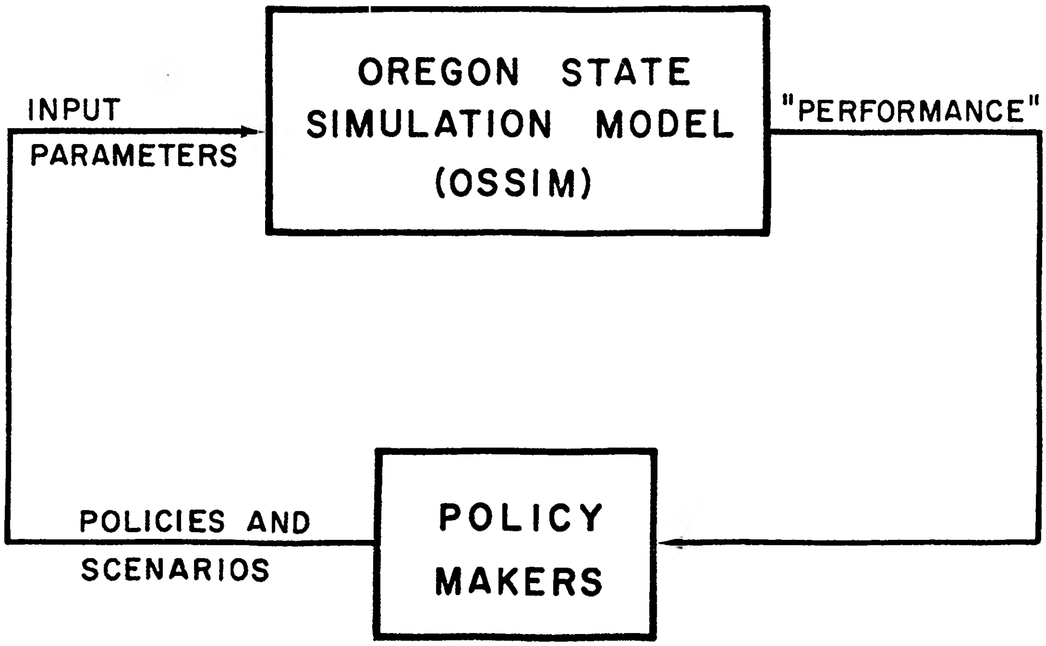

Figure 7. THE ROLE OF THE DECISION MAKER IN THE SIMULATION PROCESS

of problem identification, model refinement, and data analysis. Through this process the project is attempting to meet its objective of providing research results which will be useful to the people of Oregon as they make choices relative to environmental quality and economic growth.

THE DESIGN AND APPLICATION OF INDUCTION MOTORS FOR

EFFICIENT ENERGY UTILIZATION

By
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ABSTRACT

The various means for increasing electric motor efficiency and power factor are presented from the design and application points of view. Various design options are explored using computer aided design procedures. Motor characteristics are reviewed with the intent of maximizing efficiency through proper application. A thorough study of the economics of higher efficiency motors is presented showing payback to the user in terms of energy cost savings and payback of the increased energy required to produce the higher efficiency motors.

Today energy conservation is a vital national concern. The reasons are numerous. Our resources for energy are diminishing and are becoming more difficult to obtain. We are becoming more dependent upon foreign sources. It appears that if conservation measures are not taken, the possibility exists for a shortage of energy within the next ive years. Perhaps the greatest impact of energy conservation measures that can be felt immediately is the savings that can result. These potential savings have been the object of various energy management programs carried on by private consulting firms as well as large corporations involved in processing and manufacturing. In addition, the consumer and the homeowner are becoming more aware of the increasing costs of energy and the savings available with the proper selection of equipment.

The costs of energy have skyrocketed in recent months. A recent survey by National Utility Service Incorporated reveals that the average increase among the nation's fifteen largest investor-owned utilities during the 18 month period from June, 1973 to December, 1974 was 61.3%. Similar increases in publicly owned utilities have occurred. Electricity rates in the U.S. may soon be the highest in the world. Future predictions conclude that increases in the 12-15% range can be expected in the next five years. As alternate sources of energy are developed and the costs of capital come down, the cost increase may level off to the 4% range after 1980. It is a very dynamic situation and leads to the conclusion that energy management is a very important issue for all of us.

As the energy issue becomes more clearly focused, the federal and state governments are taking active roles in establishing voluntary and regulatory energy standards. A recent count shows that 1250 different pieces of legislation have been proposed before Congress relating to energy. At the state level 29 states already have the authority granted by legislation to regulate energy in construction or are in the process of passing legislation this year. There are several energy conservation activities related directly to electric motors. These are (1) the establishment of energy efficiency goals for appliances by the National Bureau of Standards, (2) the Federal Energy Administration survey on motor and generator efficiency, (3) GSA purchases of high efficiency appliances, (4) energy conservation in existing buildings by the General Services Administration, and (5) the ASHRAE Standard 90-75, Design and Evaluation Criteria for Energy Conservation in New Buildings.

Due to the increased pressure from federal agencies the Motor and Generator Section of the National Electrical Manufacturers Association (NEMA) established an Energy Management Committee which has already met to act upon the energy and efficiency issues as related to electric motors and their applications.

Electric motors are major consumers of electrical energy. Figures* released by the Federal Energy Administration indicates that 35 percent of all electricity generated in the United States is used to drive electric motors and in the industrial sector, the figure is 50 percent.

*From *Patterns of Energy Consumption in the United States*, Stanford Research Institute report prepared for Office of Science and Technology, Washington, D.C., 1972

REVIEW OF DEFINITIONS

Before discussing motor characteristics it would be well to review the following definitions:

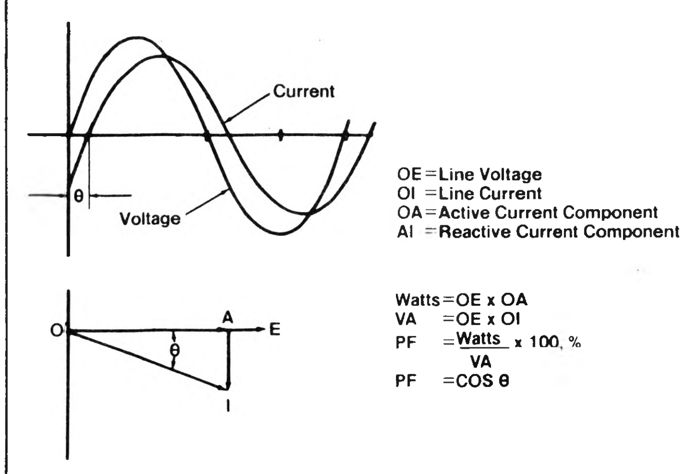
$$\text{Efficiency, \%} = \frac{\text{output}}{\text{input}} \times 100$$

$$\text{or Efficiency, \%} = \frac{\text{input} - \text{losses}}{\text{input}} \times 100$$

$$\text{Power Factor, \%} = \frac{\text{watts}}{\text{volts} \times \text{amps} \times \sqrt{3}} \times 100$$

In order to understand power factor one must understand that the impressed sinusoidal voltage when applied to an inductive device such as an induction motor will result in the current through that device lagging by an angle, θ (Ref. to Figure 1). Another way to represent this lag is shown in the phasor diagram in Figure 1. Here the vector OI is displaced θ degrees from the voltage vector OE. In this situation the generator at the power station supplying this motor must produce voltage OE and current OI and hence is rated in volt amperes or the product of OE x OI. However, the motor only consumes watts OE x OA. Thus the ratio of watts to volt amperes is known as the power factor. Some utilities in various parts of the country charge varing rates depending upon the power factor. If the power factor is low the utility must provide more current than it is charging for as indicated by an ordinary watt meter, therefore it is not unusual for a penalty to be assessed. High power factors are consistent with the efficient utilization of electric energy because they also require smaller feeder conductors to service the equipment, smaller rated service entrance equipment and result in lower line losses. Hence the ASHRAE Standard 90-75 has recommended a minimum power factor of 85% for all equipment rated at 1000 watts or higher.

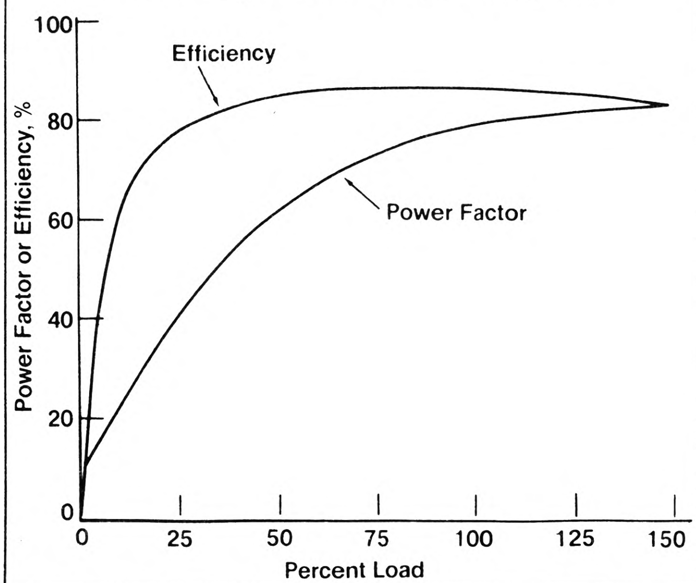
Figure 1 -- Power Factor Definition



MOTOR CHARACTERISTICS

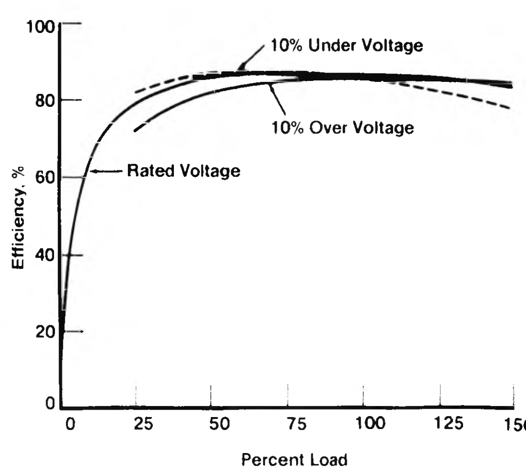
The variation of power factor and efficiency with motor load is shown in Figure 2. Notice that the efficiency is essentially constant over a range from 50-125% of full load. The power factor is more severely effected by underloading the motor and therefore it is important to size the motor to the load as closely as possible to the full load point. Most dripproof integral horsepower motors have a 15% service factor which means that the motor has a 15% reserve over its full load point. Therefore, it is recommended that motors be operated as close to full load as possible.

Figure 2 -- Typical 3-Phase Motor Characteristics



NEMA Standards* allow a 10% voltage variation from rated voltage for all machines. Figure 3 shows the effect of 10% under voltage and 10% over voltage on the efficiency. At the rated horsepower, there is less than 1% variation in efficiency due to voltage variation. However, if the motor is over-loaded the under voltage condition will result in a drop of efficiency. Conversely, if the motor is quite under loaded the over voltage condition will result in a drop in efficiency. Again, it is important to maintain the motor load as close to the full load point as possible.

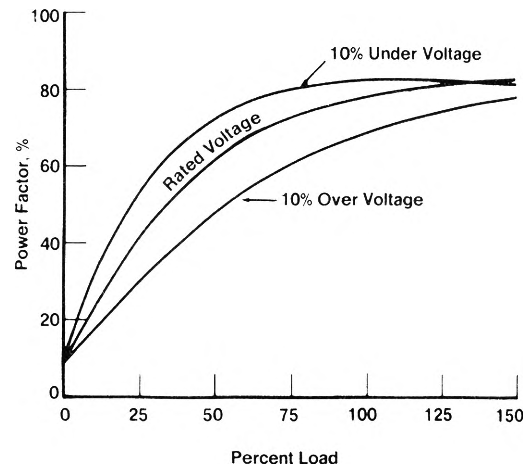
Figure 3 -- Typical 3-Phase Motor Characteristics Efficiency Sensitivity



*NEMA Standards for Motors and Generators, Publication MG-1, National Electrical Manufacturers Association, New York, N.Y.

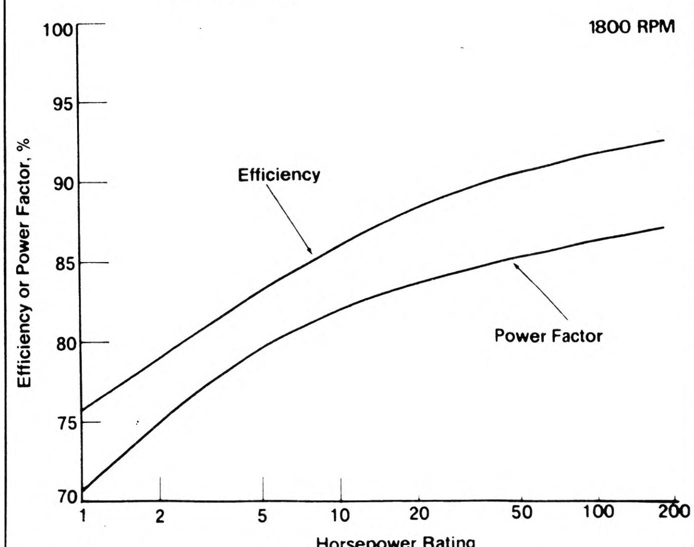
The effect of line voltage on power factor is much more dramatic as can be seen in Figure 4. The under voltage condition actually improves the power factor by a few points and the over voltage condition has an even greater effect in the opposite direction. This effect is due to the high magnetization current required to magnetize the core of the modern day electric motor. This is true in both integral and fractional horsepower sizes. If the motor is under loaded the drop in power factor is quite dramatic particularly in the over voltage condition.

Figure 4 -- Typical 3-Phase Motor Characteristics Power Factor Sensitivity



The trend of efficiency and power factor for various horsepower ratings from 1 to 200 is shown in Figure 5. Both efficiency and power factor are greater for the larger machines than they are for the smaller machines. It can also be said that two pole (3600 RPM at 60 Hz) motors have higher efficiencies and power factors than 4 pole (1800 RPM at 60 Hz) machines. This trend continues with higher numbers of poles.

Figure 5 -- Efficiency and Power Factor vs. Horsepower Rating (Current Designs)



MOTOR APPLICATION

No electric motor is operated alone. Every electric motor is a component in a system which converts electric energy into some other form of useful work, such as air moving, compressing of air or gas, moving a conveyor, operating a washing machine, etc. In every case, the efficiency at which this energy conversion takes place is the product of the individual efficiencies of all the components in the system. Hence, the efficiency at which clothes are washed is a complex function of the motor efficiency in combination with the efficiencies of the transmission, belts, pump, and the manner in which the various functions are controlled by the timer or other sensor mechanisms. Therefore, the efficiency of a motor is only a part of the total system's efficiency.

Some devices do not impose a smooth steady load on the motor, but instead, cause wide fluctuations in motor load due to the nature of the driven mechanism. Examples of these types of load are punch presses, oil well pumps, and various types of compressors. These loads require special motors with high slip rotors that will allow the speed to vary widely with the load. The inertia in the load can then supply the stored energy on each half cycle. The steady state "full load efficiency" of such a motor will be considerably less than a standard motor, but under operating conditions, the overall system efficiency with the high slip motor will be considerably higher. Therefore, with cycling loads, the operating efficiency of the entire system is the important factor and not the individual components operating separately.

Other types of uneven loads are possible also, such as those found in machine tools, crane and hoists, and traction drives in lift trucks. Motors for these devices seldom operate at a single "full load" point. The amount of energy consumed is again a function of the total system efficiency including the efficiency of the electric motor to provide its energy conversion functions over the range of speeds and torques required. Therefore a comparison of one unit to another, or one motor to another must be done with a common duty cycle and an assessment made of the total energy consumed to complete the mission required.

METHODS FOR INCREASING EFFICIENCY

From looking at the equation for efficiency it is obvious that a reduction in the losses will result in an increase in efficiency. The losses in an electric motor are found in several basic components. The core losses are the watts dissipated in the magnetic steel due to hysteresis effects and eddy currents. These losses can be reduced by using thinner gauge laminations to reduce eddy current losses and by using steel with improved core loss properties. A steel with improved core loss properties that is currently available is known as silicon steel. This material presents other problems such as reduced permeability at high inductions and shorter die life due to increased punching difficulties. The magnitude of the core loss in the various portions of the magnetic circuit are a non-linear function of the flux density in that portion of the circuit. A reduction in the density by means of increasing the area for the flux to permeate, or a reduction in the strength of the machine or the flux itself will reduce the core loss significantly. This translates into adding more material in the magnetic core structure.

The copper losses are a result of the line current pasing through the copper (or aluminum) windings in the stator and are known as I^2R losses. These losses can be reduced by reducing the R which means using a higher conductivity materal (copper is about the best available) or increasing the cross sectional area of the conductor to drop its resistance. This again translates into the addition of winding conductor material in the stator circuit. A reduction in the current (I) can be attained most easily by reducing the magnetizing portion of the current. The magnetizing current can be reduced by shortening the air gap or reducing the flux density in the magnetic portions of the motor. The air gap length is generally chosen based on a number of compromises involving mechanical considerations, noise and air gap density levels. Adding more magnetic material will reduce the flux densities.

Among the other losses which can be considered are the I^2R losses in the rotor which is a function of the rotor conductor (usually die cast aluminum) and the slip of the machine or the difference between operating speed and synchronous speed. The lower slip machines have lower rotor I^2R losses. Friction and windage are other components which are usually small but can be considered in the design of the ventilating fans and the bearing and lubrication configuration. Additional losses which are more difficult to analyze, but which can be significant are the fundamental and high frequency stray load losses.

Thus, it can be seen that the design of an electric motor with respect to its losses is a compromise involving the performance of the machine, the economics of the material to be used and in many cases the ability of the ventilating fans or radiating surfaces of the motor to remove heat losses generated by the machine itself.

METHODS TO INCREASE POWER FACTOR

In studying the equation for power factor one has several choices, the first of which is to increase the watts loss. This is contrary to what we have been discussing on efficiency; however, if power factor is the only consideration the watts can be increased and a higher power factor will result.

Perhaps the best approach is to decrease the line current. As this is done the watts will also decrease. There are ways, though, to decrease the line current at a faster rate than the watts will decrease. These methods are related to the non-linearity of the magnetic circuit. As discussed above, the line current can be reduced by decreasing the air gap, decreasing the magnetizing portion of the current by decreasing the flux densities or the magnetic loading and also by decreasing the leakage reactance which is a function of the geometry of the stator and rotor slots. All of the compromises discussed above apply here and the same conclusion can be drawn that an increase in amount of material will be the most direct way to increase the power factor and efficiency.

In both cases the design of the machine must be optimized for the best utilization of the active materials. This process of optimization has been greatly enhanced in recent years with the use of the digital computer. Most motor manufacturing companies today have computer aided design procedures which aid the designer in making many of the complex calculations required to design an electric motor in a matter of just a few minutes. Prior to this time such calculations would take several hours.

THE TWO LEVEL DESIGN APPROACH FOR INCREASED EFFICIENCY

The first approach to be investigated is the brute force method of adding material to a group of selected ratings, observing the increases in efficiency and power factor and then making an economic study of their impact. In our analysis we chose two levels of material increase as follows:

Level 1, add 15% more core length which results in approximately 11% increase in material cost, and

Level 2, add 30% more core length which results in a 23% increase in material costs.

In both cases, copper magnet wire was added to maintain the same strength machine with the same winding slot fill.

The material costs are based on active material only, i.e. the wound core and rotor core. No consideration of mechanical construction changes are included.

Figure 6 displays the results of the increased material designs on efficiency for the ratings investigated from 1 to 200 HP. It is apparent from the curve that the first increase in material has a greater impact on the current design than the second level of material increase. Also, the effect on smaller horsepower ratings is more significant than on the larger horsepower ratings. The same trend analysis is shown in Figure 7 for the power factor.

Figure 6 -- Efficiency vs. Horsepower Rating Level 1 and Level 2 Designs

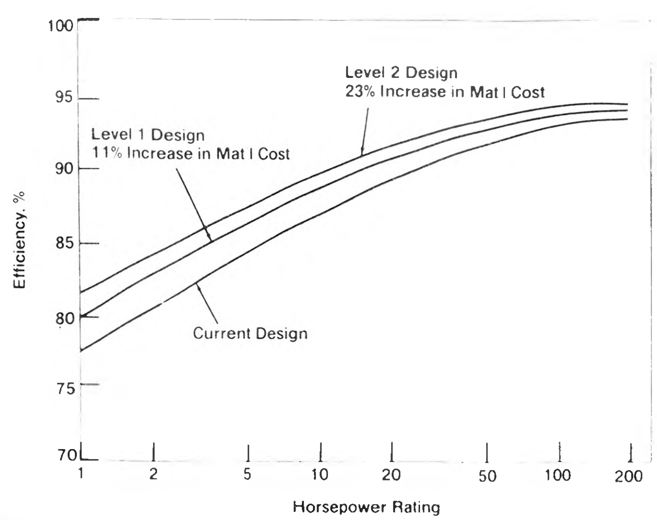
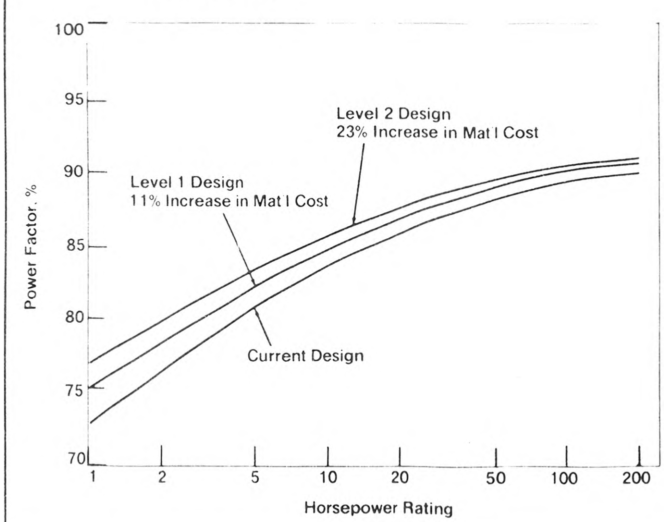


Figure 7 -- Power Factor vs. Horsepower Rating Level 1 and Level 2 Designs



In order to quantify the economics of the addition of active material the payback period was selected as one possible measure. The payback may be defined as follows:

$$\text{Payback (years)} = \frac{\text{Price increase}}{\text{KW saved x running time x energy costs}}$$

where the price increase is in dollars, KW saved are in kilowatts, running time in hours per year and energy costs in dollars per kilowatt hour. Other considerations which are not quantified are the savings in power factor penalties, the copper in the distribution system and the savings in the distribution transformer due to the smaller KVA rating required.

If we assume a running time of 4000 hours per year based on 2 shifts per day or 16 hours, 5 days per week and 50 weeks per year we can plot payback in terms of the years to payback at 4000 hours per year running and energy costs in cents per kilowatt hours. (Note that one year = 8760 hours.) Figure 8 shows a plot of payback directly in years vs. energy costs in cents per kilowatt hour for several ratings of the Level 1 design. Note that at 3¢ per kilowatt hour the payback for the 5 HP rating is only 6/10 of a year and that for the 100 HP rating the payback period is just over one year.

Figure 8 -- Payback vs. Energy Cost for Various Level 1 Designs

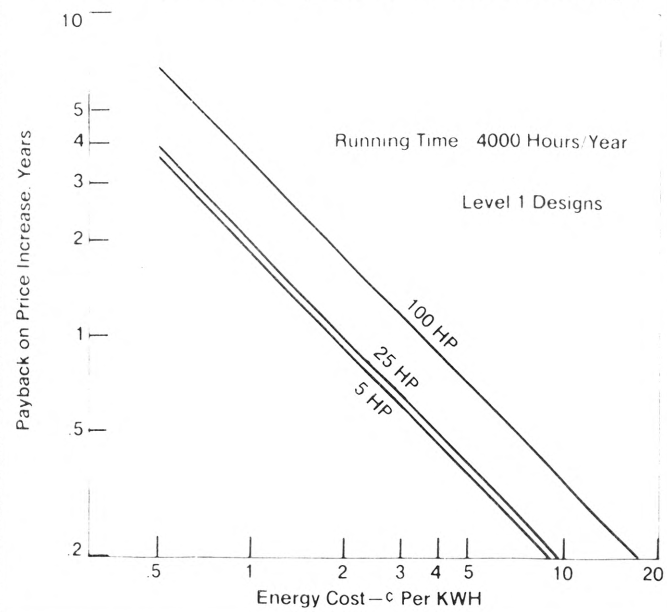
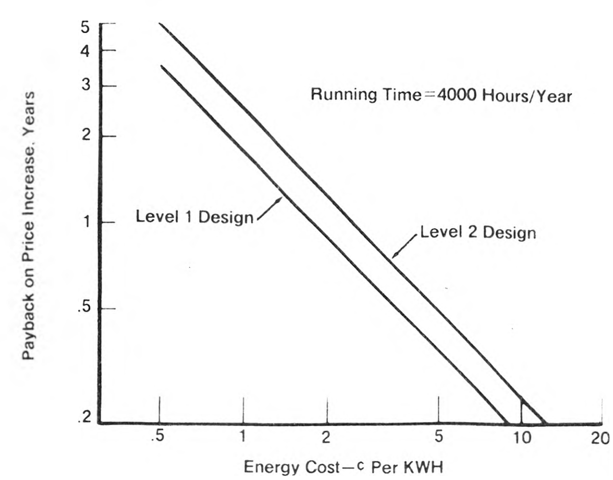


Figure 9 shows the same data for the 5 HP motor for both Level 1 and Level 2 designs. Note the faster payback for the Level 1 design. Considerably more work must be done to optimize these designs. However, these data shows the basic feasibility of economically adding material to conserve energy.

Figure 9 -- Payback vs. Energy Cost for 5 Hp Motor



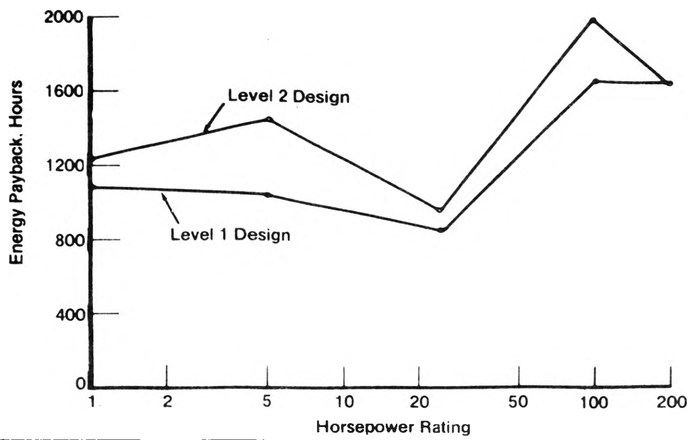
ENERGY PAYBACK

While the economics of the higher material content motors appears to be justified it is important to assess whether the increased energy required to produce the higher efficiency machines is justified. Therefore energy payback is defined as the hours of running time to save the quantity of energy required to produce the additional material in the higher efficiency machine. The energy requirements to produce the 3 major materials in the active portions of the electric motor as follows:

Steel	=	5.45 KWH/pound
Copper	=	15.15 KWH/pound
Aluminum	=	36.6 KWH/pound

These figures * include all the energy required from the mining operation, transportation, and all the processing until it is put into the electric motor itself. The results are shown in Figure 10 and indicate that the energy payback generally lies in the range of 800-2000 hours of running.

Figure 10 -- Energy Payback vs. Horsepower Rating



The above analysis using the Level 1 and Level 2 design approach indicates that in every respect higher efficiency machines are possible and that in general the economics appear to justify the more expensive machine. This was certainly not true five years ago when energy costs were much less significant than they are today. The foregoing study has justified also the refinement of our approach to develop a line of motors discussed in the next portion of this paper.

THE GOULD APPROACH TO HIGH EFFICIENCY AND POWER FACTOR MOTOR DESIGN

Because of impending legislation and the ASHRAE Standard 90-75 which imposes the 85% power factor level on all utilization equipment rated at 1000 watts and higher, the 85% power factor level was chosen as a design parameter. In addition, efficiency improvement was deemed necessary in order to help justify the power factor improvement from an economic standpoint. In developing this line various methods were used to optimize the designs in addition to simply adding material. These included air gap adjustments, changes in slot configuration, a change in steel, changes in winding design etc. Mechanical considerations were made and their associated costs assessed. NEMA frame assignments were established and Marketing established preliminary pricing so that realistic figures could be used for the payback analysis. These motors are currently being marketed under the name E-PLUS.

Figure 11 shows the result of the improvement from the current design to the new design for power factor and Figure 12 shows the efficiency improvement. This development was limited to the ratings from 1 to 25 HP polyphase, 1750 rpm.

*Technology Review, February, 1975, Pp. 39-43, Massachusetts Institute of Technology, Cambridge, Mass.

Figure 11 -- Efficiency vs. Horsepower Rating Dripproof Motors

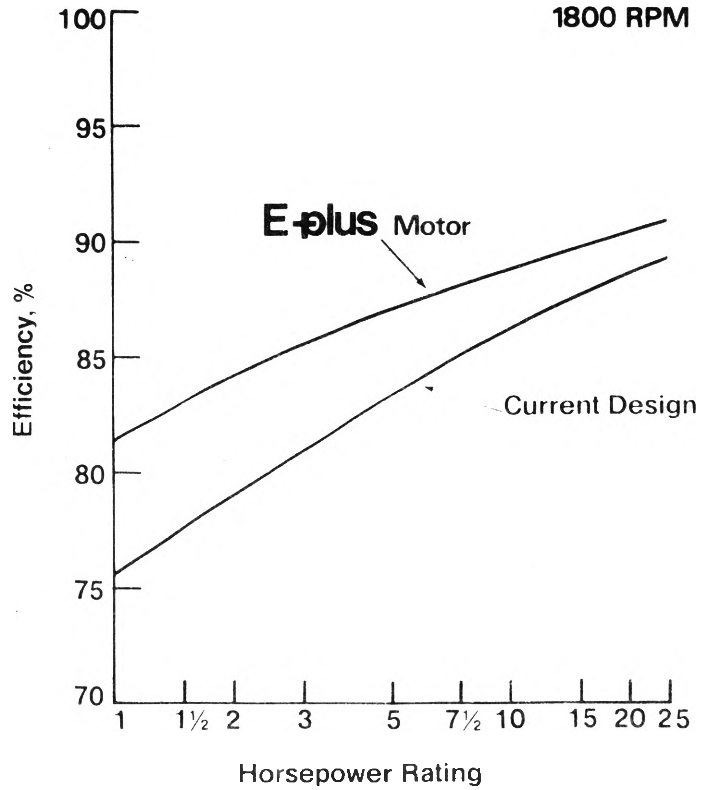
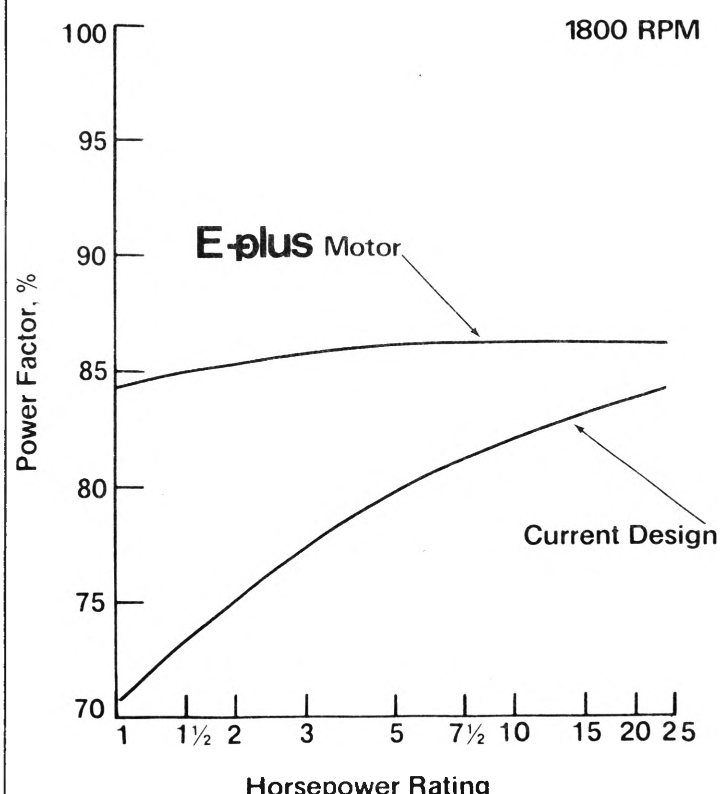
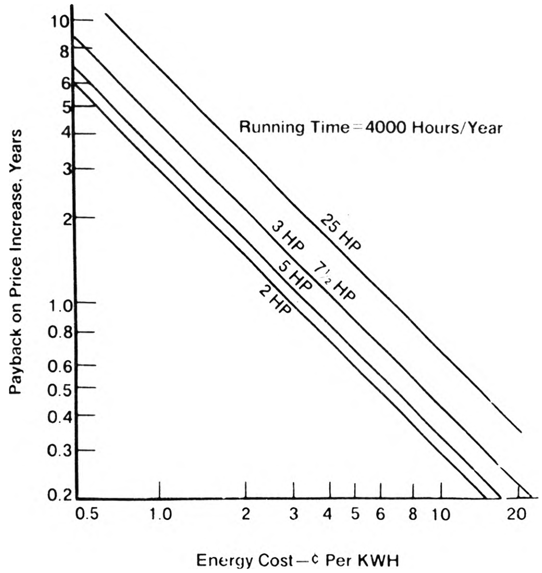


Figure 12 -- Power Factor vs. Horsepower Rating Dripproof Motors



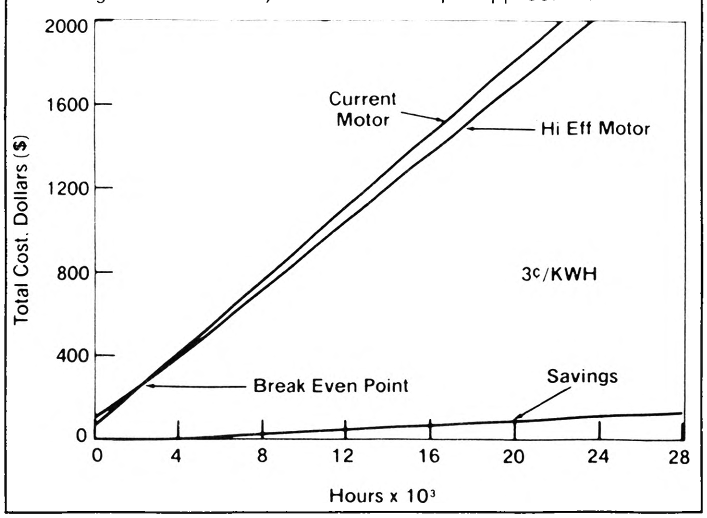
Again, the actual payback on price increase in years is plotted against energy costs in ¢ per kilowatt hour for several ratings (Figure 13) and they show very reasonable numbers. The 2, 3, 5 and 7½ Hp ratings all fall within a band which has a payback period of less than 2 years at the 2-3¢ energy cost level. Even the 25 HP rating has a payback of less than 2½ years at today's energy costs.

Figure 13 -- Payback vs. Energy Costs for Various Horsepower Ratings



An additional method of analyzing economic justification is life cycle costing. Taking the initial cost and the operating cost of the two designs and plotting them against operating hours, yields a relationship as displayed in Figure 14. The breakeven point is shown where the total costs of the two designs are equal. After this point the higher efficiency motor generates savings for the rest of its life. This curve is quite conservative, assuming no energy cost increases.

Figure 14 -- Life Cycle Costs for 3 Hp Dripproof Motors



A similar study has been completed for a line of TEFC (totally-enclosed fan-cooled) motors, commonly used in the chemical and processing industries. Efficiency and power factor improvements are equivalent to the dripproof line and payback values are equally attractive.

ADVANTAGES TO THE HIGHER EFFICIENCY DESIGNS

In addition to the obvious economic advantage of the higher efficiency and power factor motors, there are a number of other benefits that result. Because the motors are built with lower magnetic densities, the magnetic noise is much reduced. These motors are dissipating considerably lower losses, the motors are running cooler and therefore the insulation life is extended. It would not be unusual to find a 10°C lower temperature rise which will result in a doubling of insulation life. Because the motors are dissipating less watts, the fan noise could be reduced through the use of smaller and quieter ventilating fans.

The sensitivity of the new motors to line voltage variations is much reduced. Figures 15 and 16 show the effect of 10% over and under voltage on efficiency and power factor for a typical rating. A comparison of the power factor variation with the older design is shown in Figure 17, and reveals the new design to be far less sensitive to fluctuations in voltage. The improvement is even more dramatic at loads under full load.

Figure 15 -- E-plus Motor Characteristics Effect of Line Voltage on Efficiency

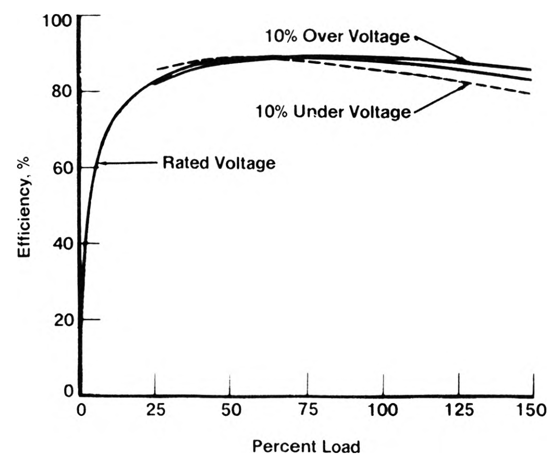


Figure 16 -- E-plus Motor Characteristics Effect of Line Voltage on Power Factor

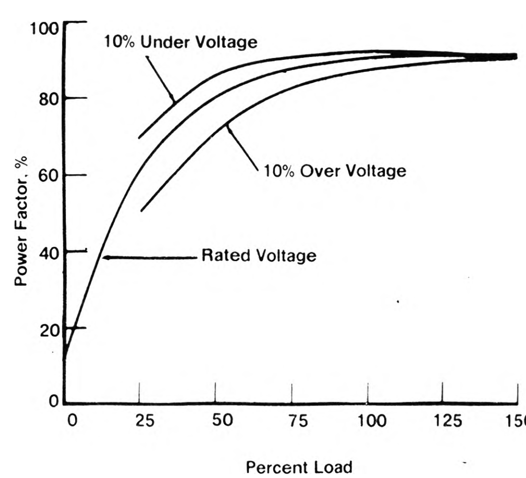
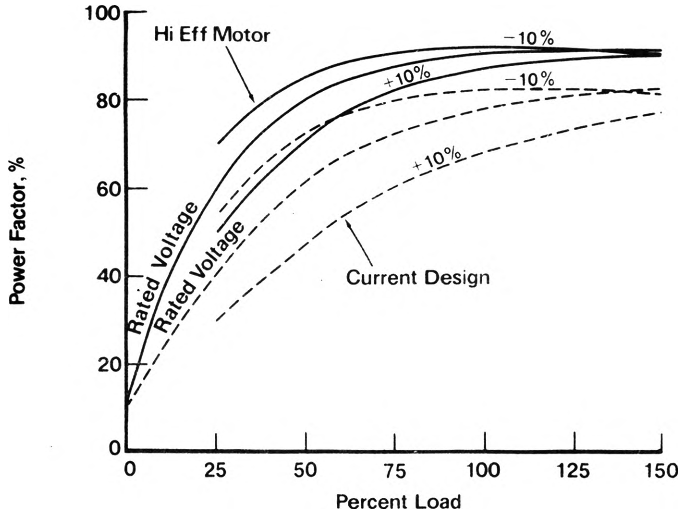


Figure 17 -- Motor Characteristics Power Factor Sensitivity Comparisons



SUMMARY

Increasing costs of energy have practically dictated a line of higher efficiency and power factor motors. Increased product costs of these motors can be justified by the energy saved in their operation. Correct application of the proper motor is essential for a successful, energy efficient conversion of electrical to mechanical energy.

BIOGRAPHY

Paul K. Lindhorst was born in St. Louis, Missouri on February 25, 1942. He received his B.S.E.E. degree from the University of Cincinnati and the M.S.E.E. degree from St. Louis University in 1965 and 1970, respectively.

He is presently Manager of Advanced Design in the Product Development Department at the Century Electric Division of Gould, Inc. His responsibilities include development of new design concepts, new product development, and administration of the various product development activities in the corporation related to motors and associated products. Prior to his current position, he was Chief Engineer of Fractional Horsepower Motors for 4 years where he had complete design responsibility for small motors. He has, also, held design engineering positions in the Integral Horsepower Motor Department.

Mr. Lindhorst is a Registered Professional Engineer in the State of Ohio, a member of the Institute of Electrical and Electronics Engineers, and Eta Kappa Nu, the Electrical Engineering honorary.

INDUSTRIAL INNOVATIONS AND MANAGEMENT TOWARD MORE EFFICIENT USAGE OF ELECTRICAL ENERGY

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Fulton, Mo.

Abstract

This paper deals with some of the industrial accomplishments in alleviating energy supply and demand problems. A survey is presented on how electrical energy in America is generated, resources used and kilowatt usage for the years 1970 to and including 1974. Conservation of electrical energy is the main theme in which three primary areas of innovation and utilization of industrial equipment are discussed; induction, lighting, heating and air conditioning. An awareness of natural gas shortages and the trend toward an "electric economy" are reviewed. The real challenge to energy management is apparent in order to handle the greatest expansion in energy technology since the mid-1800's.

INTRODUCTION

It has been 18 months since the 1st UMR-MEC Conference. We saw charts and figures which were understood but the magnanimity of the numbers, sizes and shapes left us awed and concerned. It was informative and effective; the proceedings were a manmouth undertaking and the task was well done. We finally got a grasp or handle of what the overall energy situation is evolving to in this country. Questions were asked, statements were made, ideas of varying opinions were expressed and exchanged. We were told that there is no solution to our energy supply/demand problem for the next 25 years unless federal regulatory overbearance subsided and technical innovative forces were put into motion immediately, preferably in the same direction. (1)

Today I can report to you that such forces for technical innovation are in motion. From the commercial and industrial sectors of our society, the clamor of invention is moving outward in many technical areas. R & D energy expenditures by private enterprise are up to 15% this year. (2) A comprehensive marshalling of talents is beginning to produce the answers we need to have.

First to emerge on the energy market are the results of intensive work and efforts of TEM (Total Energy Management groups or teams) within industry aimed at conserving energy. The scope of this presentation is directed at the conservation of electrical energy. Voluntary energy conservation programs within industry are generating an energy usage philosophy which will eventually reach and effect every stratification of the American life/work style. Because of our base energy supply problems we are finding better ways to accomplish production goals at equal costs and expanding our energy developments with more efficient alternative possibilities.

A SURVEY OF ELECTRICAL ENERGY USAGE IN AMERICA

How do we presently use electrical energy in America? It has been reported that 80.1 million customers use electricity according to the following percentages of distribution:

88.6%	are residential
10.6%	are commercial
0.5%	are industrial
0.3%	are municipal
100.0%	

But the electric power required breaks down as:

32.6%	residential
23.1%	commercial
40.5%	industrial
3.8%	municipal
100.0%	(3)

In 1974 we went through 1.8717 trillion kilowatt hours and using the above percentages: 71 million customers (residential) used 0.610174 T-kw-hrs; 8.5 million customers (commercial) used 0.432363 T-kw-hrs; 0.4 million customers (industrial) used 0.758038 T-kw-hrs; 0.2 million customers (municipal) used 0.071125 T-kw-hrs

Expanding the above data with a little arithmetic, an approximate average use per customer can be determined so that in 1974 the: average residential customer used 8,594 kw-hrs; average commercial customer used 50,866.2 kw-hrs; average industrial customer used 1,895,095 kw-hrs; average municipal customer used 355,625 kw-hrs

The real challenge of a TEM group is to cut these non-residential values without the loss of production or jobs in an environment which is acceptable to the common good.

Figure 1 illustrates the electrical energy usage on a national scale.

There are two organizations in the U.S. which are monitoring the use of electricity. They are the FPC (Federal Power Commission) and the EEI (Edison Electric Institute in New York). U.S.A. Electricity Production (Trillion KW-HRS):

	FPC*	EEI**	
1970	1.531609	1.536400	
1971	1.613936	1.617100	
1972	1.747323	1.752200	
1973	1.856216	1.868800	
1974	1.864961	1.871700	(4)

*Total electric utility industry electricity production per FPC based on a 12 month year.

**1970-1974 output per EEI electric power survey committee based upon a 52 week year. "Yellow Sheets" published by EEI Statistical Section are released to the Wall Street Journal and appear every week.

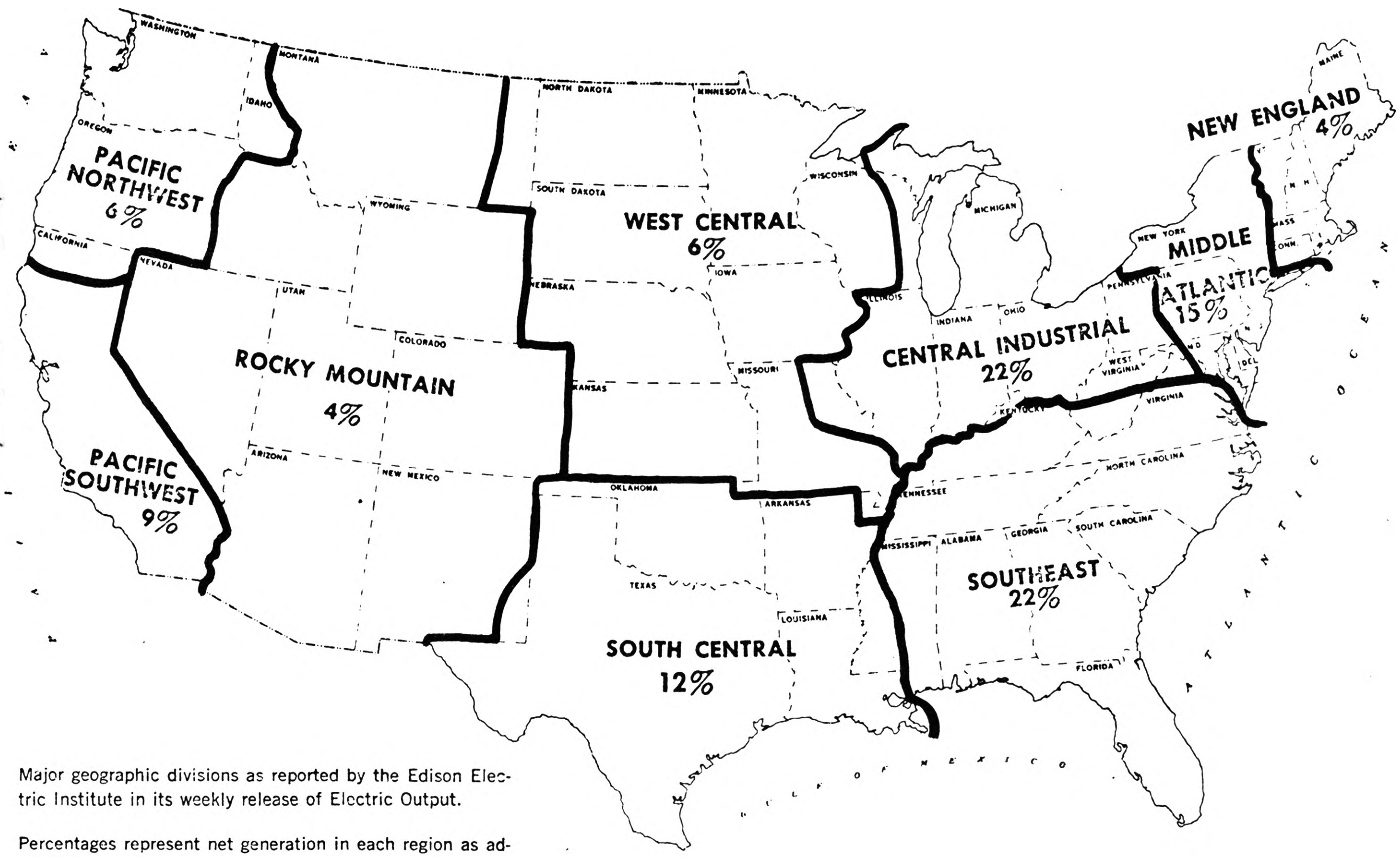
Electricity, as we presently know it, is a source-dependent form of energy. Most of it is a by-product of torque, time and temperature within a power plant/distribution system. When discussing the aspects of an electric economy, we should keep in mind that movements of inter-related energy forms will always be based upon availability of supply and cost of supply. Thus, all fossil fuels and petrochemicals are resource-dependent; a simple deduction all too often overlooked by forecasters.

Corresponding energy forms to produce the electricity are as follows: (%)

	OIL	COAL	NG	NUCLEAR	HYDRO
1970	12.7	45.6	22.4	1.4	15.9
1971	14.8	42.6	23.9	2.3	16.4
1972	16.9	42.2	22.1	3.1	15.7
1973	18.4	43.5	18.6	4.5	15.0
1974	17.6	44.1	16.9	6.0	15.4

Source: U.S. Bureau of Mines (5)

The generation and maintenance of our electricity depends upon another source of energy, usually coal, to produce the BTU's



Major geographic divisions as reported by the Edison Electric Institute in its weekly release of Electric Output.

Percentages represent net generation in each region as adjusted for net imports.

January 1, 1973

FIGURE 1

to generate the steam, that turns the turbine, that motors the generator that produces the electricity on a continuous basis.

POWER PATTERN OF ELECTRICITY

GENERATION — DISTRIBUTION — APPLICATION

BTU — WATT

BTU's/WATT → → KW-HR

10,000 BTU's → 1 kw-hr → 3413 BTU's

→ Lumens - Lighting
→ BTU Heat - Heating
→ BTU Cool - Cooling
→ HP - Processing

With the present day technology, the overall efficiency is between 30% and 40% depending upon hardware and policy so that to have this single kilowatt hour in workable form it requires:

0.8 lbs. of coal
or
0.00175 barrels of oil (6)
or
10.5 cu. ft. of natural gas
or
1.25×10^{-5} gm. E. Uranium (7)

Advancements are being made in various generation areas with heat recovery cycling techniques, fuel combination, and new hardware to improve these overall efficiency values, thus reducing the number of BTU's required per watt. But we are talking about time and a great deal of capital investments to make all the necessary physical changes. In the meantime, these base energy resources are not as plentiful as we first thought nor are the sources secure at stable prices.

To parallel these efforts, alternate sources and development work are on the way. This we can see in much of the work which is being presented to us this week.

This also brings us right back to where we were --- conservation; conservation for two reasons: Economics and Time.

ECONOMICS

From the standpoint of economics, the power you save may be your own. Not only is the industrial rate in cost per kilowatt hour going up but the demand rates and fuel adjustment costs are going up as well.

Cost of base kilowatt hour
Cost per kilowatt on demand
Cost for fuel adjustment
Local taxes

All of which contribute to the overall price per kilowatt hour which we will be paying. Peak power penalties, fuel adjustment charges and taxes are compelling business leaders to look in the direction of on-premise energy systems as a competitive hedge against incrementing utility costs. If such energy systems use fossil fuels as a basis of prime movement, the competitive hedge will not be realized in most cases. And for this reason, the cost of power is no longer considered a fixed cost item.

From June 1973 to December 1974, a survey of 24 utilities was conducted and electric rates paid by industrial and large commercial customers rose an average 63.1%. (8)

TIME

By reducing the load on the feeder system with careful conservative measures on a consistent schedule, the demand is more easily met at the point of generation, thus reducing the amount of capitalization required to meet and maintain the demand. This in effect will buy needed time in order for the production technology to catch up with the application technology; the improved systems of greater efficiency to come on stream.

In the beginning stages, electrical energy conservation within the home or office or industry are not the result of procuring expensive modifications or hardware, but rather a well-planned system or survey of many small alterations which are compatible with work/life sytle patterns, schedules and safety guidelines.

The ultimate indicator of progress from efforts in conserving electrical energy is the familiar kilowatt meter, and with the aid of a stopwatch and a simple formula, many interesting and revealing studies can be conducted on the effect of various

$$\frac{\left(\frac{3600}{t}\right) \times K_h}{1000} = \text{kw-hr usage for (t) at observed load}$$

whereby: t = seconds required for a single revolution of the meter rotor

K_h = factor of the meter

pieces of cycling equipment in relationship to total load characteristics. In industry, 6 to 8% of the electrical energy can be saved by the mere simple reduction of nonproductive lighting and equipment usage. An additional 3 to 18% savings have been realized with power factor corrections and periodic power auditing of load distribution centers. With proper management and enthusiasm, electrical energy conservation is beginning in earnest with the American industries and is yielding the largest percent of savings change with the least amount of capital required, in the shortest length of time. The lessons on how to do it are about to come forward. Soon to be available from the Electric Power Research Institute in Palo Alto, California is a needed handbook entitled, "Handbook of Electricity Conservation Technology", which will present the state of the art of technology and procedures for electrical energy conservation by users. It will not have all the answers, but it will perhaps for the first time, allow a company or industry to draft its own program to handle its internal energy requirements in a more efficient manner. Specific hardware markets are developing which offer consistent and unique innovations toward solving the multi-faceted energy conservation dilemma which we find ourselves groping with.

There are three primary areas of innovation and utilization of industrial equipment for electrical energy conservation.

1. Induction Equipment
2. Lighting Equipment
3. Heating and A/C Equipment

INDUCTIVE EQUIPMENT

a. Gains in electronics have produced low cost solid state relay control systems which offer several benefits to the user. The control side of using industrial equipment has long been an area in need of updating. AC loads of up to 45 amps can now be controlled more efficiency with less mechanical effort, thus less energy.

b. Brushless DC motor drive systems are now available because of innovations of magnetic solid state switches, thus improving the conversion efficiencies of the total drive system.

c. Load monitoring and shedding. Motor control centers can now be monitored with an array of advanced equipment which generate to large computer type of programmable load controllers and phase balance simulators.

LIGHTING EQUIPMENT

To develop a practical light source from electricity which can provide the most lumens per watt at the least cost is the continuing goal of people involved in this particular energy conservation market. At present, the HPS (High Pressure Sodium) light and ballast system provide this result.

LAMP	WATTS	LUMENS PER WATT
Incandescent	150	19
Fluorescent	40	78

LAMP	WATTS	LUMENS PER WATT
Mercury Vapor	100	42
	175	49
	250	48
	400	56
Metal Halide	175	86
	400	100
High Pressure Na	100	95
	150	107
	250	120
	400	125 (9)

The HPS can be easily adapted to the office as well as these outside lighting needs with normal outlet voltages. The relative high initial cost of the HPS is quickly offset by the advantages of having fewer fixtures per area, the longevity of the HPS bulb and the power savings of 8 to 10% over past systems.

HEATING AND AIR CONDITIONING

In process heating, the predecessor of the "heat pump" is the temperature amplifier. (10)

Target heating for forced air heating systems is being considered by microwave, dielectric and induction. Steam can also be produced from water using microwave target heating and a less expensive system with induction target heating technique. (11)

Compressor stages via turbine compressor is coming forth as an efficient step forward in air conditioning equipment. This is coupled with the developments of more efficient electric drive systems.

WORKING WITHOUT NATURAL GAS

This is a 66 bed, acute care hospital located in Callaway County. It is the Callaway County Memorial Hospital. Their supply of natural gas is not guaranteed for this winter, forcing its administration to consider converting back to fuel oil for heating purposes. Two other hospitals in adjoining counties have had to make the transition. These energy tradeoffs are more expensive and less efficient, throwing dependency upon an energy base which we are supposed to be getting away from on a national scale. The Natural Gas shortage is real and the FPC priority level system has reached hospitals in several regions of Missouri. Consequently, the "electric economy" is here whether we are ready for it or not. You either go all electric or you don't build; there simply is no present alternative.

Under construction is this 28,000 sq. ft. manufacturing area with an all electric 1800A service. Here evaluations will be conducted on conservation techniques and equipment. Here electrical energy will be in the center of Total Energy Management and the EUI (Energy Use Index) will be used to formulate a power philosophy of practical adaptation.

THE PRESS

There simply isn't time here to discuss the problems which the press is having in this struggle to present the facts. The rate at which events are moving on a numerical scale makes it difficult to evaluate before the variables move. There simply is no other source of contemporary information available to go by. I believe the following slides best depict the problems.

THE ADVENT OF ANOTHER INDUSTRIAL REVOLUTION?

What I have presented here today is but a small portion of the overall efforts and results in innovations concerning electrical energy conservation. The social and economic conditions are ripe, the need is definite and the potential is present --- for the greatest expansion in energy technology since the mid-1800's.

In conclusion, unless efforts are unified, technical goals moving in the same direction, and incentives of freedom and accomplishment are present, then all other social problems and causes accompanying the real physical shortages of base resources and capital (and indirectly, food supplies) will be secondary to this one --- securing independent base energy alternatives and know-how for the future generations to come. The worst mistake that we can make here today is to assume that our federal government is going to solve this problem with its present machinery. The ERDA (Energy Research and Development Administration) inspite of 90 or so committees and sub-committees which regulate it, is a bright spot in the confidence flap which exists between a government and its people. The very least that we can do is to begin, first by encouraging our youth to participate and get involved in the many fronts which make up our energy dilemma.

Where we are headed with these energy systems and technology, I simply do not know --- I do know that we are most certainly on our way.

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RE: 1 "Today's Energy Sources - Their Projected Life", presented at 1st UMR-MEC Conference by Dr. John McKetta, Department of Chemical Engineering, University of Texas, Austin.

RE: 2 St. Louis Post-Dispatch, September 2, 1975, p. 7B.

RE: 3, 4 and 5 (See 1st acknowledgement).

RE: 6 Taken from a conversion table prepared by General Electric Corporation (LB4 back cover).

RE: 7 The Ubiquitous Atom, G. and L. Spruch. Taken from a conversion of 2000 lbs. of uranium = 3 million tons of coal or 12 million barrels of oil of potential fuel value.

RE: 8 Wall Street Journal, May 14, 1975, p. 11.

RE: 9 Taken from literature provided by Guth Lighting, a Division of Sola Basic.

RE: 10 "The Templifier for Process Heat", Westinghouse Corporation, report #PSP 5/30/75, R. L. Dunning.

RE: 11 Studies by Central Electric Company.

ACKNOWLEDGEMENTS

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35mm SLIDES

1. Kilowatt meter and stop watch
2. Optrol, Inc., Solid state relays DC control of AC loads to 45A
3. Optrol, Inc. Test Board
4. Siemens Corporation Brushless DC Motors

5. Pacific Technology, Inc., Model 410 Power Demand Monitor and limiter
6. Pacific Technology, Inc., Model 410 Power Demand on line
7. Pacific Technology, Inc., Model 410 Power Demand on line
8. Pacific Technology, Inc., Proportional Load Control Systems
9. Pacific Technology, Inc., Programmable Load Control Systems
10. Pacific Technology, Inc., Model 414 Power Demand Controller
11. Pacific Technology, Inc., Incremental Load Control System
12. Pacific Technology, Inc., Load Simulator and Proportional Controller with power factor monitor
13. Pacific Technology, Inc., Automatic Load Control System
14. Reduced diameter of stator with PMs
15. General Electric Supply HPS Intersection
16. General Electric Supply Lighted Factors with HPS
17. General Electric Supply Office Interior HPS
18. General Electric Supply Lighted Swimming Pool HPS
19. General Electric Supply Auditorium HPS
20. Central Electric Company, Lake Wappapello, Mo. HPS System
21. Central Electric Company, Lake Wappapello, Mo. HPS System
22. Central Electric Company, Callaway Memorial Hospital
23. Central Electric Company, South Plant, All Electric Service
24. Central Electric Company, South Plant, All Electric Service
25. Central Electric Company, Our Energy Crisis and the Press
26. Cartoon - Cat and Mice
27. Cartoon - Our Knight in Shining Armor
28. Cartoon - President Ford and Congress on Energy Police Compromise
29. Cartoon - Democratic Energy Policy
30. Rural America 1914 - "Electricity on the Farm for 14¢ per week"

DYNAMIC SIMULATION FOR REGIONAL ENERGY STUDIES

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Abstract

A series of models has been developed for regional studies of energy supply-demand systems. The models are based on dynamic simulation of components of the system using equations derived from the technical details of the system. The models contain sufficient detail to make in-depth studies and specific recommendations. The final goal is to include all aspects of regional energy systems from native supplies of energy resources to the economic activities of the region.

To develop a comprehensive model, the system has been partitioned into subsystems, so that a detailed model can be made for each subsystem. The detailed model of the electrical energy subsystem is complete and has proven to be a valuable model in itself. It is to be used for studying the effects of both local and national governmental regulations and controls, and to study electric utility policies.

INTRODUCTION

A study has been undertaken at Oklahoma State University to develop simulation models which can be used to assist in a wide range of energy forecasting studies and policy decisions in government agencies and private companies. The final goal is to develop and validate a model or group of models which can simultaneously simulate the major parts of the energy supply/demand system of a particular geographical region. It was felt such a total system approach was preferable to a group of separate models each independently considering a certain aspect of the energy system. Since the energy supply/demand system is highly interactive, an action taken at one point can have significant effects at seemingly unrelated points. Thus, it is desirable to be able to evaluate the effects of an action on all parts of the system. Also, as the effects of an action taken at one point spread throughout the system, the resulting perturbations may reflect back to the original point resulting in a feedback effect. These feedback effects can be a dominating feature in the response of the energy system to changes, and result in much of the basic behavior of the energy system.

The feedback paths often pass through several parts of the energy system. Thus, models considering only one aspect of the system at a time lose much of the feedback behavior of the system. This is not to say that for a model to be useful it must consider all parts of the energy system in detail; it only means that important advantages can be gained by using models which consider a total energy picture. It also means that whenever a model is used which deals only with part of the system, the user should be aware of what limitations are encountered by arbitrarily severing feedback paths. The use of such incomplete models should be restricted to studies where the lost feedback will not significantly affect the results.

The interaction and feedback effects in the energy system can result in complex dynamic behavior such as overshoot, oscillation, and instability. Thus, it was considered necessary to use dynamic modelling techniques rather than the more traditional equilibrium methods. It was also desired to be able to consider a wide range of policy options under a wide range of conditions. For these reasons we chose to use the Forrester (1), or dynamic system simulation, modelling technique based on system structure and real entities in the system rather than methods based on more abstract econometric variables and linear relationships. Also, this type of a model provides for a better understanding of what is actually going on in the energy system and why certain things happen the way they do. This can lead to a better understanding of counter-intuitive and apparently perverse behavior.

A major part of the energy system structure involves technical relationships and constraints, and the decisions of the companies and individuals. Thus, an important part of the model must be the simulation of the actual decision processes in the system. The simulation of these decision processes should also be able to explicitly reflect government policy and regulation.

It was felt that a more useful model could be developed by considering a regional energy system as opposed to national and world systems. It is at the regional level where a large number of the decisions are made. World and national models often cannot address the precise policy questions required to assist in these decisions; nor can they make detailed policy recommendations. On the other hand, it is desirable to make regional assessments of decision options relating to world and national energy systems. Thus, a regional model can serve as a complement to models which consider larger geographic areas. Also, a regional model is more accurate, as much of the geographic variability seen in national and world energy systems is eliminated, and more useful information concerning decision processes, technical relationships and constraints is available.

This model has been termed the DRESA (dynamic regional energy system analysis) model. This paper reports our results to date in developing the DRESA model.

PRELIMINARY STUDIES

The DRESA modelling effort started out quite simple. Before starting on a completely detailed model, a simple qualitative model was developed (2). The purpose of this model was to describe the basic behavior of the energy system and to serve as a conceptual framework for later, more detailed models. Figure 1 shows a Forrester diagram of this initial model.

Since the model was quite simple and contained no quantitative information it could not be used for detailed energy studies. However, it could show the overall interaction and feedback effects which could be expected in the energy system.

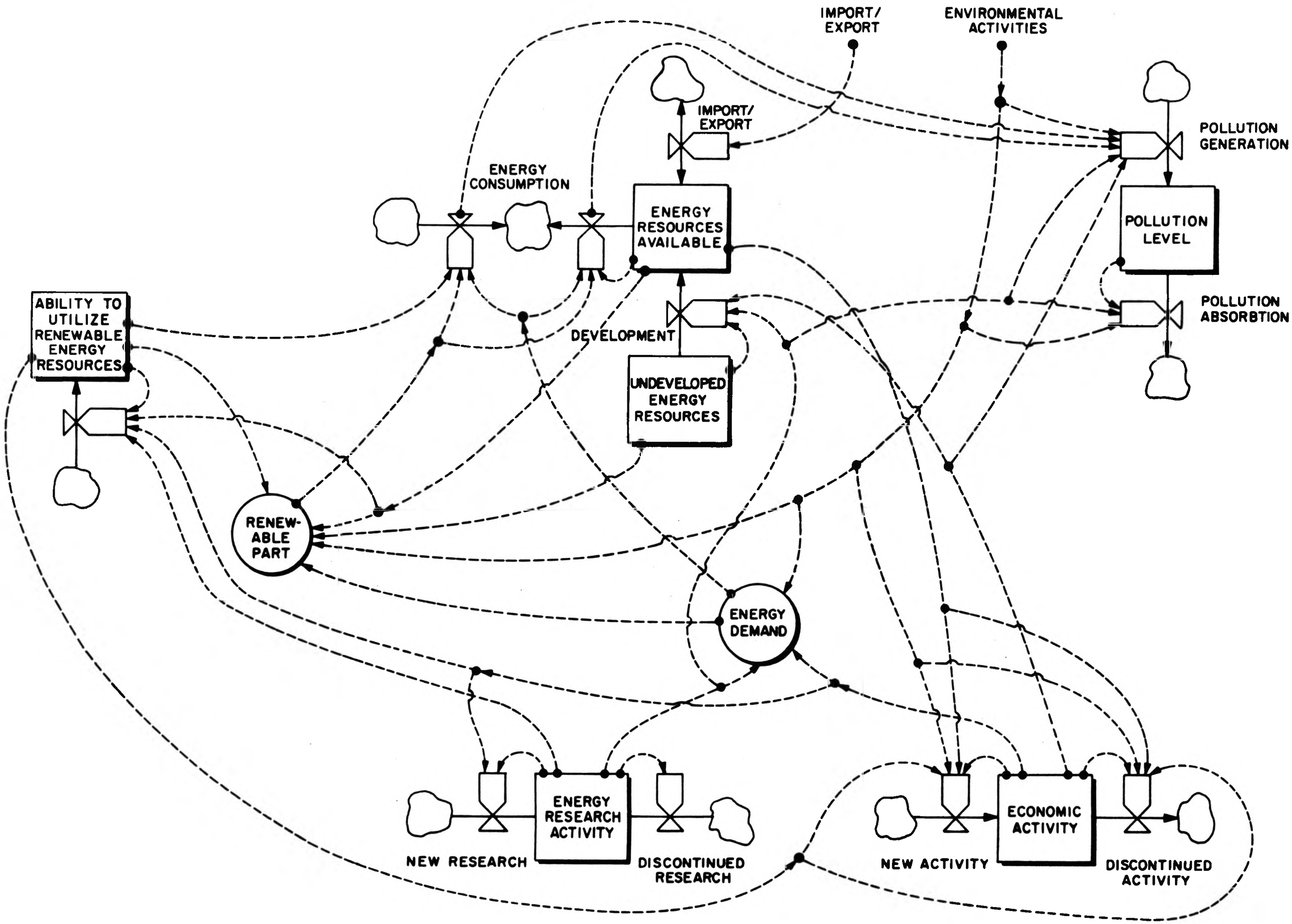


Figure 1. Forrester diagram of initial qualitative model.

Figure 2 shows a sample of this by showing the effect of pollution controls required to maintain a high level of environmental protection.

The next major step in the DRESA modelling effort was to develop a model which contained quantitative relationships. This resulted in a single fuel model for a regional energy system (3). A Forrester diagram of the model is shown in Figure 3. The relationships in this model were based on technical information and historical data wherever possible. Two energy forms were considered - primary and secondary. Electricity was considered the only secondary energy form and all primary energy was assumed to be natural gas. These assumptions are quite limiting, but for electrical energy generation in Oklahoma, natural gas has been almost the only fuel in the past. Although all results from the model must be viewed in the light of these limitations, it was able to simulate past behavior surprisingly well as shown in Figure 4. The forecasts it gives for the future could also be considered what would happen to the Oklahoma economy and energy system if it were to continue to rely heavily upon natural gas. By basing the model on quantitative relationships more precise policy questions could be addressed. Figure 5 shows the effect on the economy of a intra-state price ceiling of 40¢/MCF. This price ceiling initially results in a slight improvement in the economy but later is offset by a larger slowing due to the unavailability of gas at that price.

CURRENT STUDIES

Although the preceeding model contains quantitative relationships and could be used to address certain

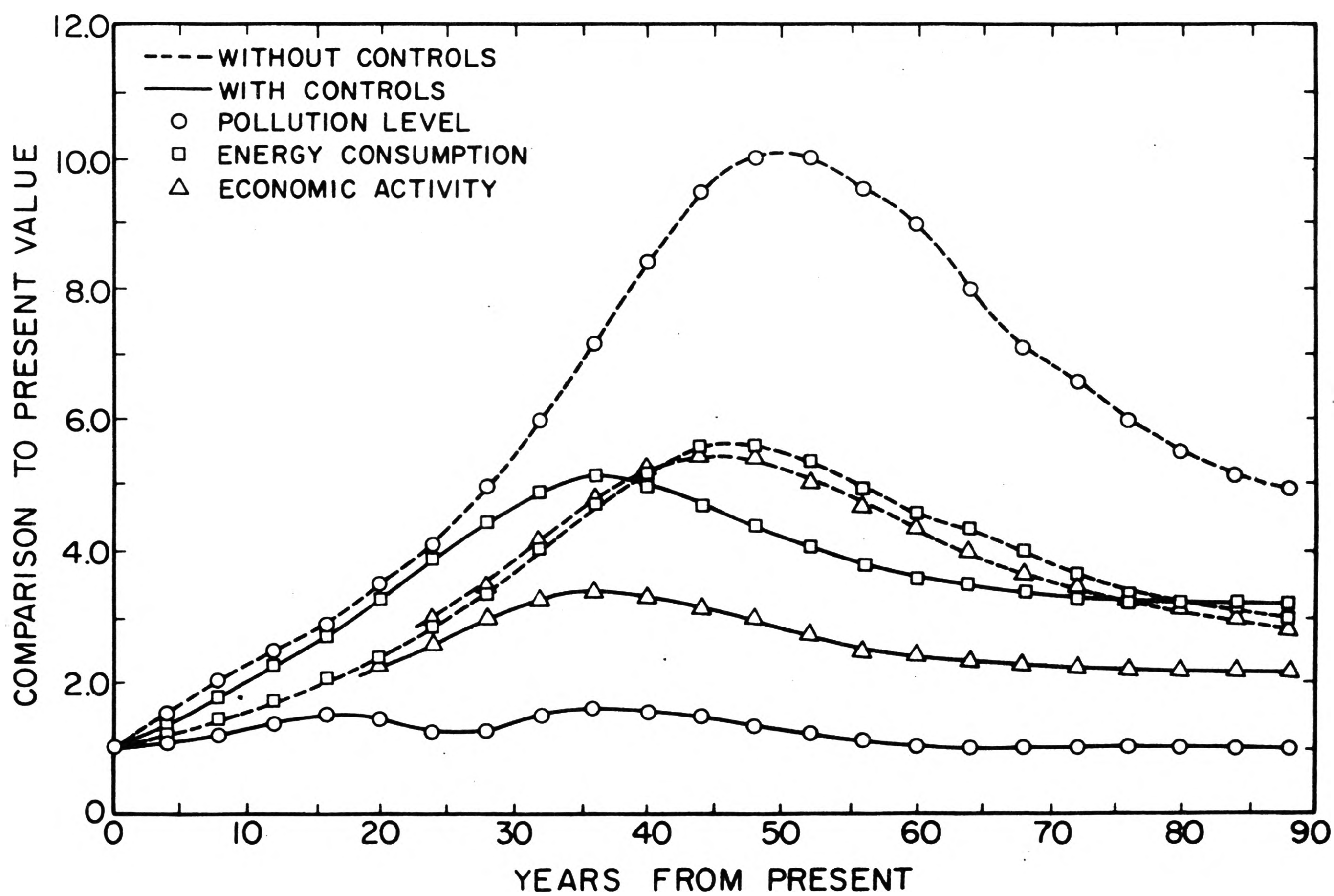


Figure 2. Demonstration of the effect of pollution controls with qualitative model.

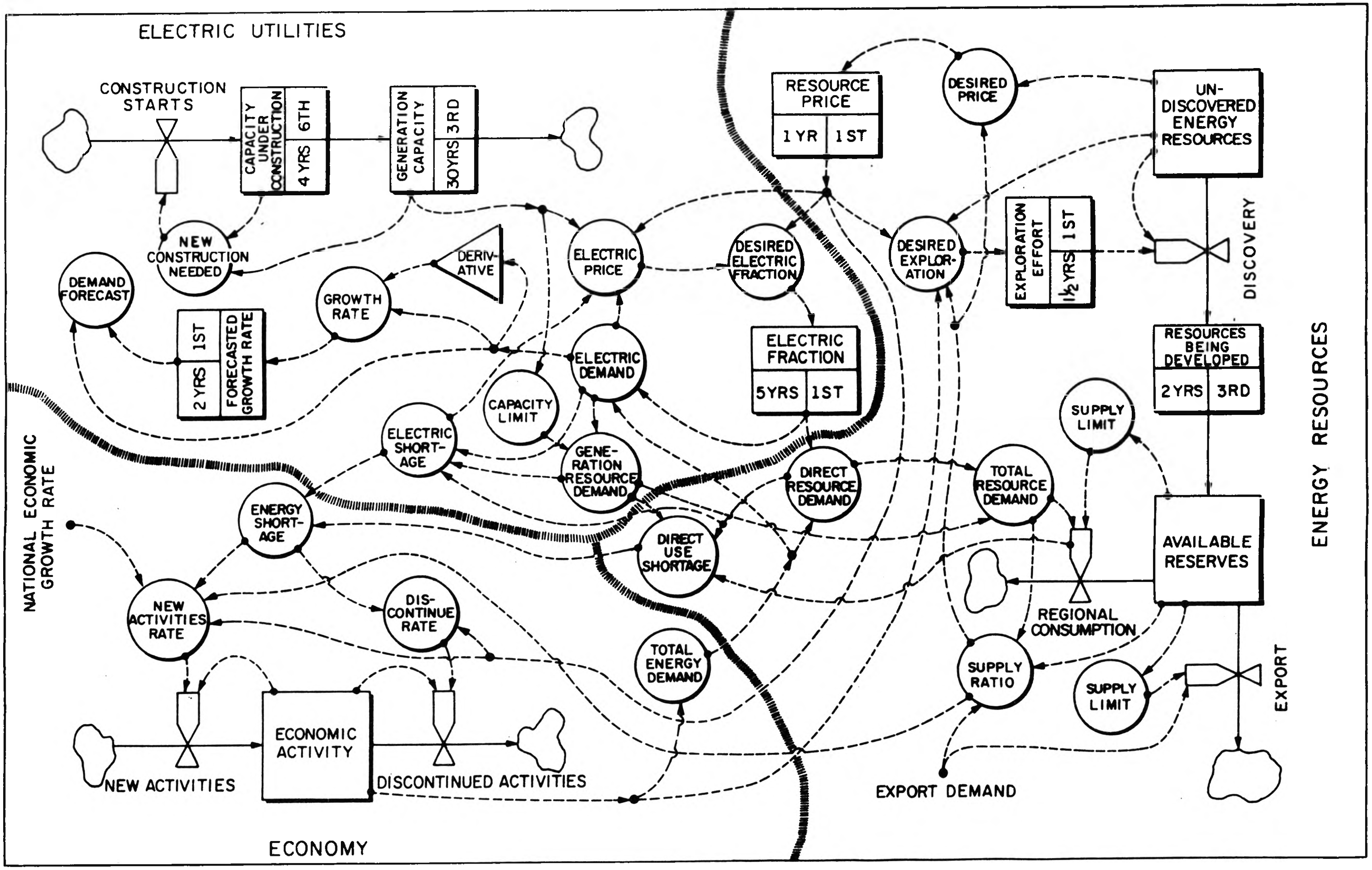


Figure 3. Forrester diagram of single fuel model.

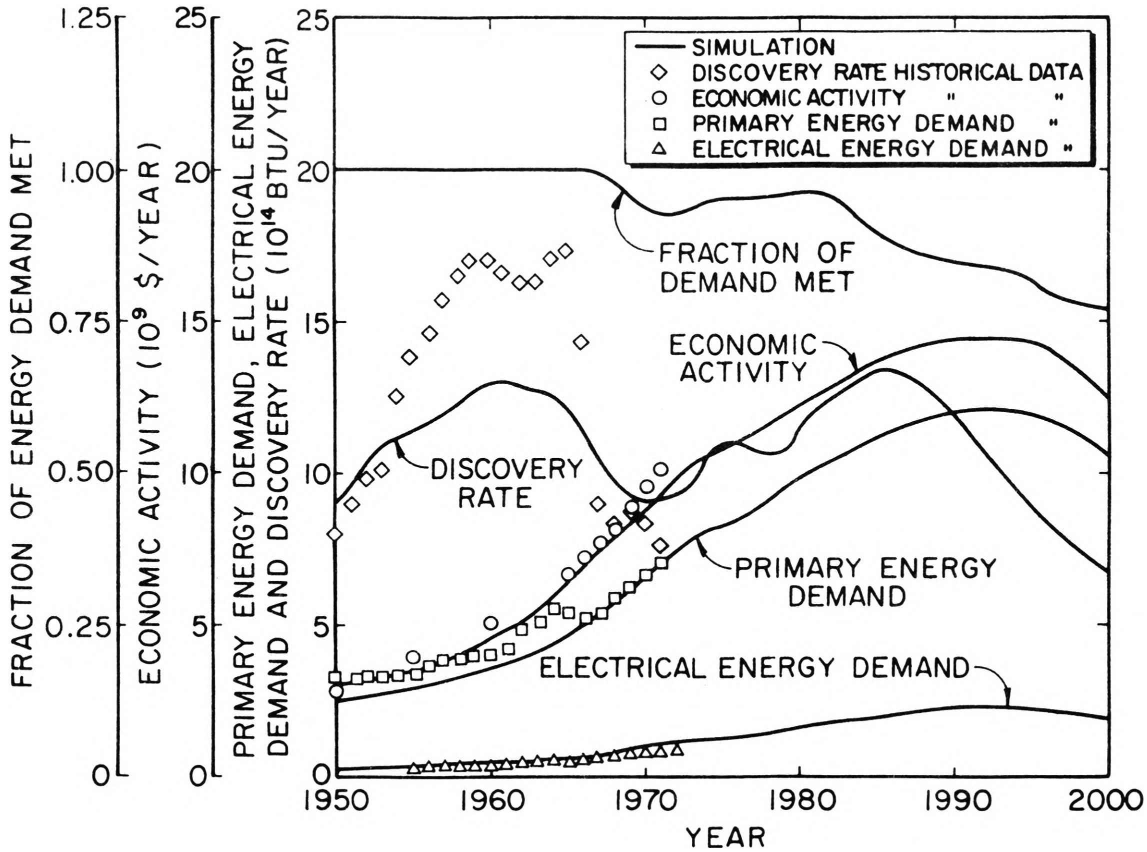


Figure 4. Selected variables from base case simulation run for single fuel model.

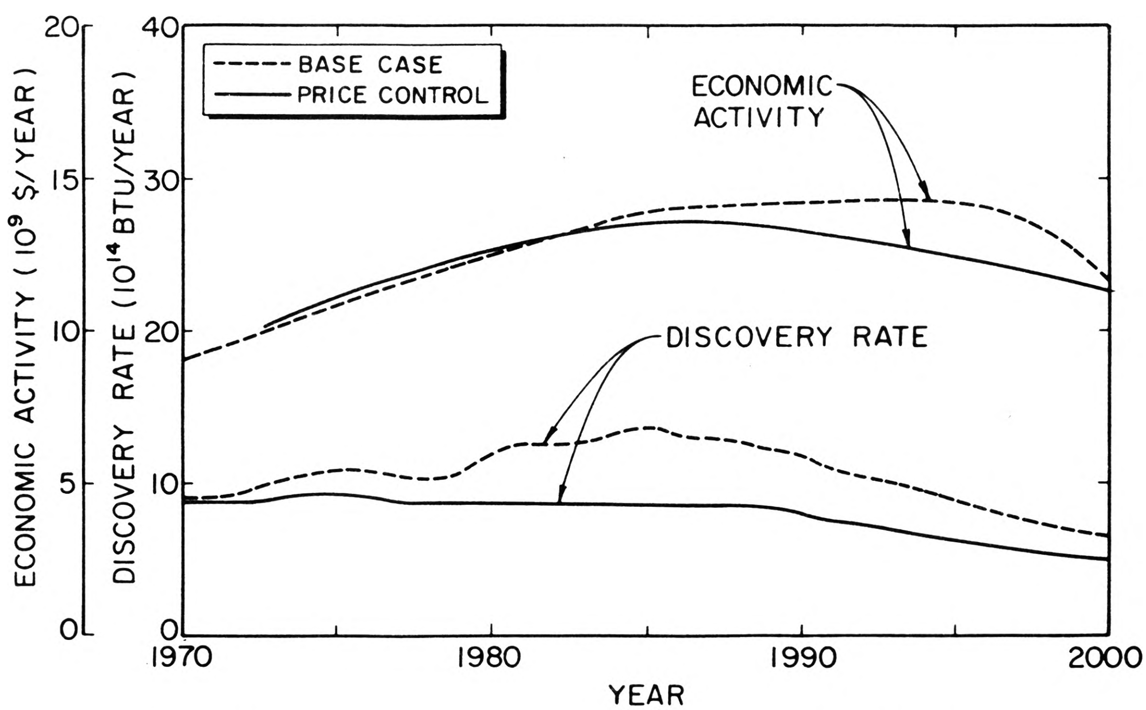


Figure 5. The effect of a price ceiling on intra-state natural gas.

policy questions, it was still very limited in scope and possible applications. It was mainly built as a demonstration of incorporating technical information into a model. We are now in the process of developing and testing a fully detailed model which will consider the technical constraints and relationships as well as the decision processes involved in the energy supply/demand system. This model has the following features:

(1) Both the supply, demand, and environmental aspects of a regional energy system are considered simultaneously.
(2) The feedback paths which travel through different parts of the system are included.
(3) It is flexible enough to consider a wide range of policy questions of concern to national and regional governmental agencies and private companies.
(4) It is based on relationships that can account for the behavior of the energy system under a wide range of future possibilities.

It would be difficult to build such a model all at once. Our approach has been to divide the energy system into a number of subsystems which are then modelled separately. These subsystems are modelled in the context of the total energy system and must receive inputs from and supply output to other subsystems. Thus, the subsystems must all be selected so they do not overlap and have consistent inputs and outputs. In this way, when the models for all of the subsystems are complete, they form the comprehensive DRESA model. Also, the subsystems are selected and modelled so that each model can be used independently for separate studies. However, these studies must observe the limitations encountered by arbitrarily cutting some of the feedback paths in the system.

THE ELECTRIC UTILITY COMPONENT OF THE ENERGY SYSTEM

Our choice for a starting point for this modelling effort was the electric utility industry (4). This part of the energy system was chosen for a number of reasons:

(1) The electric utility industry is at a uniquely strategic location in the energy system. Through conversion to electricity, nearly every energy resource can be reduced to a common product. Thus, at this point in the energy system the energy resources are direct substitutes for each other and are highly competitive. Also, energy in the form of electricity is one of the most easily used forms we have.
(2) The electric utility industry is probably the most regulated industry in the energy system. This poses the need for a thorough understanding of the response of the electric utility industry to regulation policy in order to make wise decisions. A poor understanding of this response can lead to unexpected and harmful side effects from poor decisions. On the other hand, a good understanding can indicate policy options which can alleviate problems in this critical part of the energy system.
(3) The demand for electricity has been growing rapidly in the past, more rapidly than the demand for most other forms of energy. There is considerable uncertainty as to whether this rapid growth will continue. The long construction period required to build some generation facilities and the nonstorable nature of electricity makes accurate planning essential if electric utilities are to meet demands efficiently. It is difficult to plan in face of uncertainties. Thus, various planning policies need to be

tested to determine whether they are adaptable to unexpected changes in the future.

(4) A considerable amount of cooperation in this effort was available from the local electric utility companies. Since our modelling method emphasizes technical relationships and decision processes, this cooperation was considered to be very valuable.

In simulating the electric utility industry there were several features which we felt the model should include if it was going to be able to provide useful information.

(1) The demand for electricity in a region varies considerably from hour to hour, from day to day, and from season to season. The nonstorable nature of electrical energy makes it necessary to account for these variations if an accurate simulation of the ability of the electric utilities to meet demand is to be made. The computation time to simulate the hour by hour operation of the system would be prohibitive. However, a yearly load duration curve as shown in Figure 6 can represent most of the characteristics of the demand variations with a simple function. It provides a viable form of communication as it is widely used in the electric utility industry. It also provides a means whereby changes in demand characteristics can

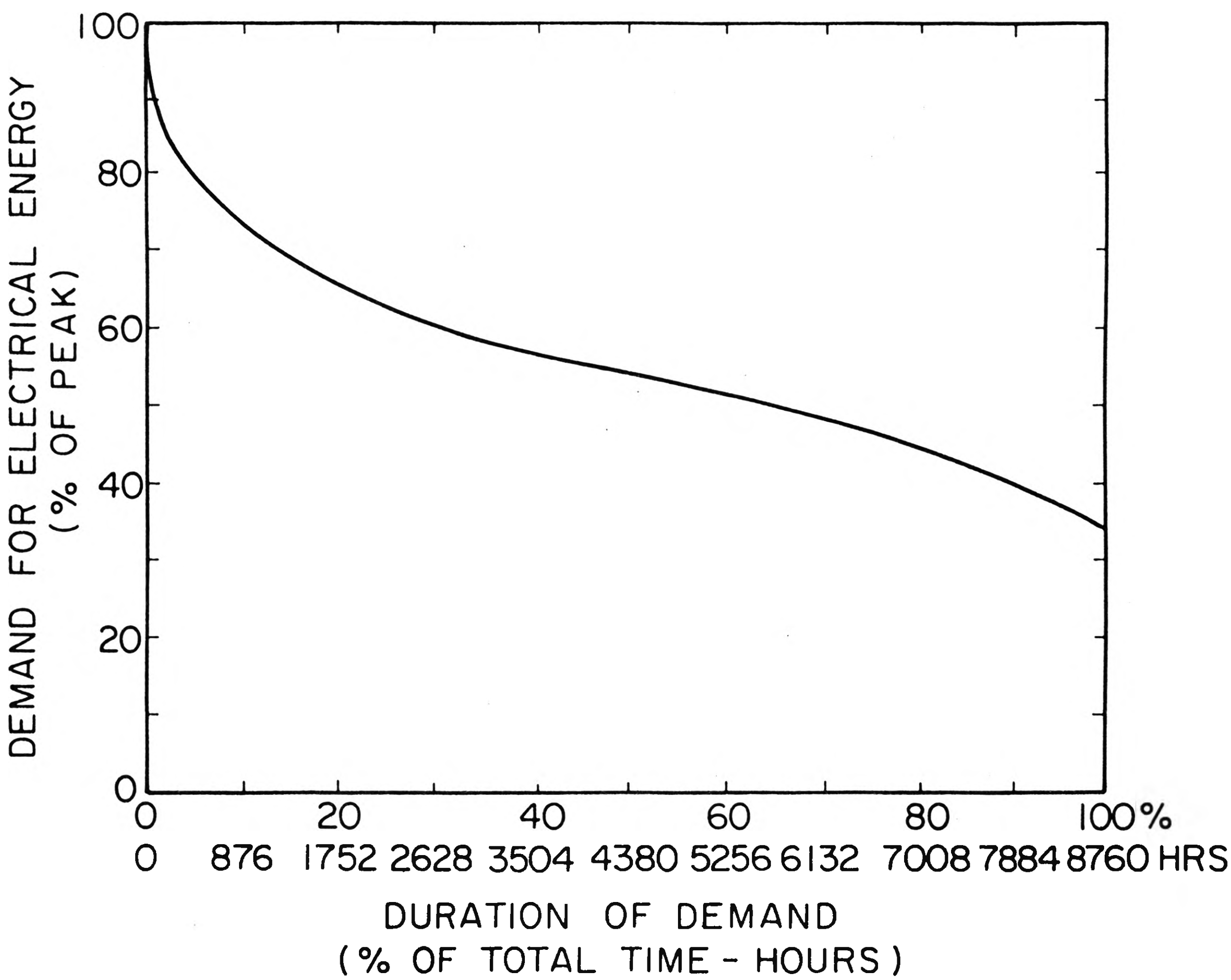


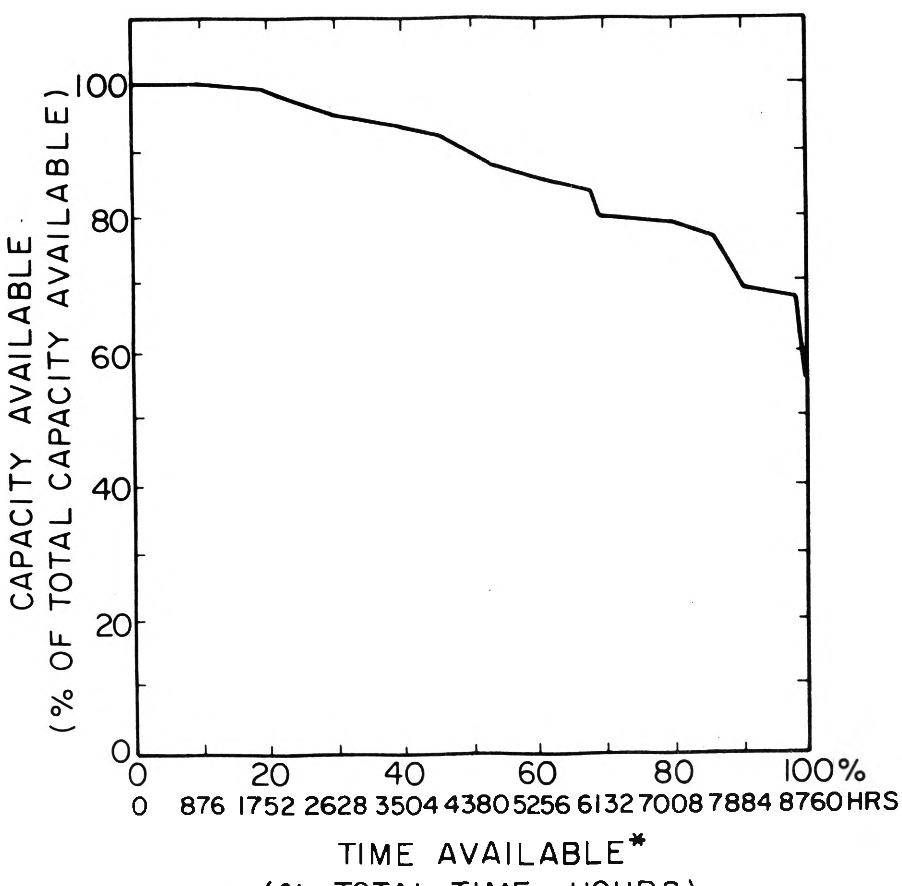
Figure 6. A typical load duration curve for electrical energy demand in a region.

be studied. In addition, the time axis of the load duration curve can provide a basis for converting other variables which fluctuate during the year to a common reduced form.

(2) Various types of power plants have different costs and performance capabilities. These costs should be fully accounted for and broken down into their various sources - capital, operation and maintenance, and fuel. Some means must also be provided to account for the performance capability of various types of generation facilities. This can be done using a curve similar to the load duration which describes how the availability for a particular type of facility varies throughout the year. If this generation availability curve is derived using the same time axis as the load duration curve, then it can be compared directly to the demand. A typical generation availability curve is shown in Figure 7.

(3) Since an important aspect of the electric utility component of the energy system is its ability to utilize many different forms of energy to make a common product, all commonly used energy resources should be considered in the simulation. This should include explicit consideration of their prices and availabilities. In addition, the model should allow for the possibility of considering new or novel energy resources.

(4) Transactions with electric utilities in other regions should be considered in detail. The



*The time axis for the load duration curve is not used in this plot.

Figure 7. A typical generation availability curve for a group of natural gas fired boiler power plants.

flows of electrical energy to and from the region throughout the year should be described on the same time basis as demand in the load duration curve. The transactions should be broken into the different classes which describe their function - emergency, economy, firm and long-term capacity lease.

By meeting these criteria, we feel our model has a unique capability to make useful studies of questions concerning the electrical energy system at the local, regional, and national levels and to make detailed policy recommendations.

THE ELECTRIC UTILITIES MODEL

The activities of electric utility companies can be broken into two fairly distinct categories - planning and operation. Planning activities deal with forecasting future conditions and preparing for them. In general, they are the activities which are responsible for putting the system into a certain "state". The operation activities deal with the use of the generation facilities to supply demands and much of the buying and selling of electricity with other utility companies. In general, they are the activities which the state of the system requires in response to the conditions that actually arise.

PLANNING ACTIVITIES

The planning activities are broken into three areas for the purpose of simulation. These are forecasting, capacity expansion, and energy resource planning.

The exact forecasting method used varies from company to company and also depends upon the variable being forecast. They typically involve an extrapolation of averaged historical data (5). This is simulated in the model by averaging the percentage rate of change for past years with a first order exponential smoothing function. This function weights the recent years more heavily than the earlier ones. The electric utilities are then simulated as forecasting this growth rate to be constant for planning purposes. Where necessary this scheme was modified by forecasting the variable to decay exponentially towards an asymptotic value. The model simulates the forecasting of regional demand and energy resource prices. It also combines separate forecasts of energy resources available and the electric utilities share of energy resources available to derive a forecast of the amount of each energy resource the electric utilities expect to have available to them. Although individual companies may use somewhat different and more sophisticated forecasting methods, the model captures the essential considerations of traditional forecasts. Also, if desired the model could be used to test other forecasting methods.

Using these forecasts, the electric utilities must make plans to provide the necessary generation capacity. Most companies attempt some form of optimization in this area. There are sophisticated computer programs which are used for this purpose (6, 7). The cost of simulating an optimizing process would be prohibitive. Also, it is difficult to exactly define an optimum under conditions of uncertainty and rapid change even if the optimum value can be calculated mathematically. In view of these problems a somewhat more simple process is used to simulate capacity expansion planning.

For given fixed and variable costs the cheapest capacity for different loads can be calculated as shown in Figure 8. If this information is adjusted for limits to capacity availability, energy resources available, on line and committed capacity, and the maximum rates at which capacity can be constructed, the mix of facilities which would be

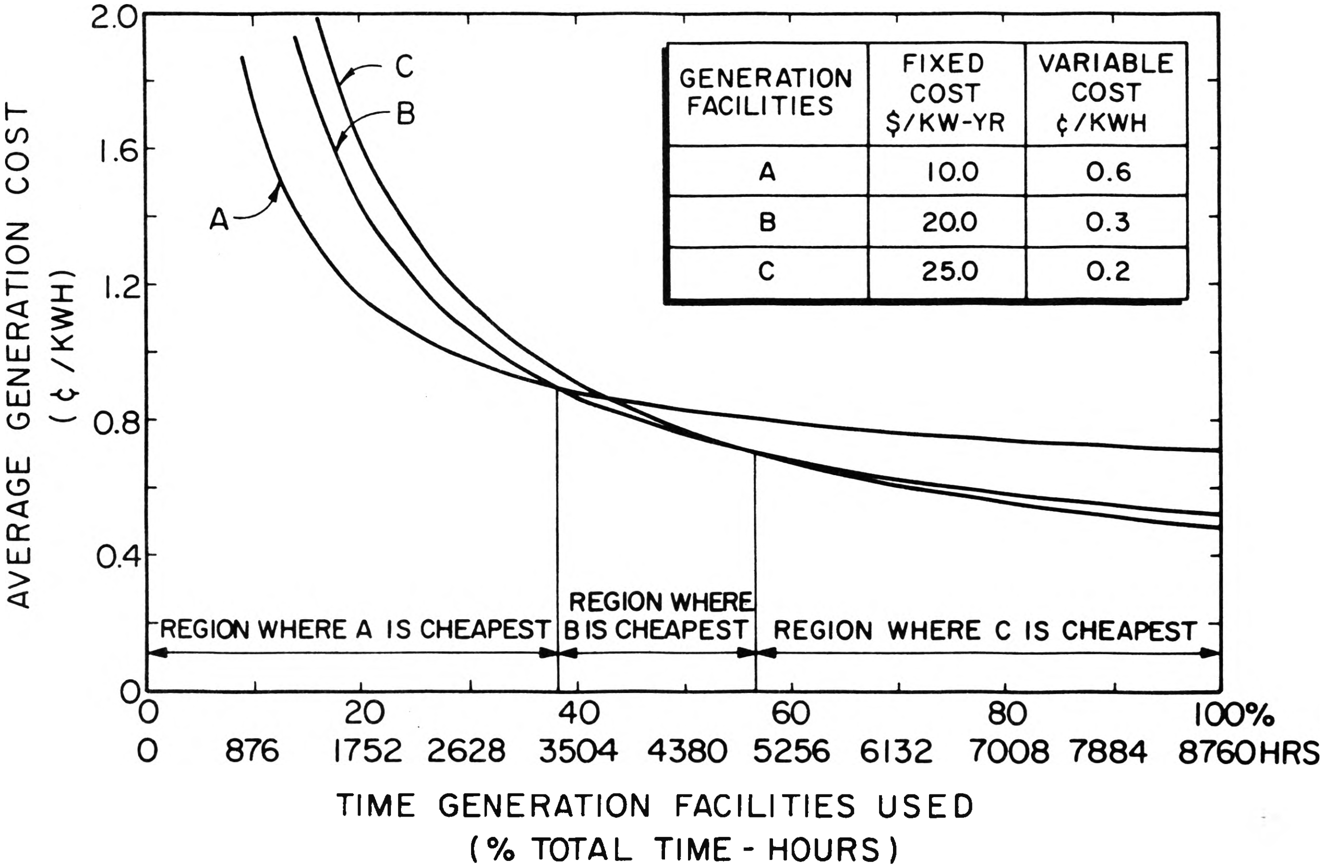


Figure 8. Total generation cost vs. time used for several cost combinations.

desired in the long run at the given costs can be determined. The electric utilities can be expected to build new facilities with the goal of achieving this long-run mix but, subject to the immediate requirement of meeting demand. The model simulates the determination of this mix by using forecasts for an arbitrarily chosen "planning year" to calculate the mix. The planning year is assumed to be the final year of the "planning period" which, by necessity, must be longer than the longest construction time for any of the generation facilities considered.

In the short-run the electric utilities are constrained by the facilities on line, the facilities under construction, the time required to build new facilities, and the necessity of meeting current demands. Also, it may be uneconomical and technically difficult if not impossible to convert existing facilities to alternate fuels. Thus, they cannot immediately move to the desired mix of facilities but must do it gradually over a number of years. This movement toward the mix is simulated by assuming that, within the above constraints, the electric utilities will add capacity consistent with the forecasted demand for each year in a manner such that the types of capacity that are furthest from their desired mix will be built first. Again, this may not be the exact method used by an individual company but it does capture the essential factors involved in making the decisions which result in capacity additions.

Once the plans are made as to what generation facilities are intended to be built, arrangements must be made for an energy resource supply for the fuel burning power plants. This usually involves contracts for anticipated future needs. Such energy resource planning cannot be a haphazard process. If the electric utilities do not have sufficient supplies they will be unable to meet demand. On the other hand, most contracts require certain minimum usage rates. These two restrictions can leave a narrow margin for operation; thus, making accurate energy resource planning essential. Also, as forecasts change, plans change, requiring a continued updating of amount of contracts needed.

This process is simulated by first assuming an arbitrary number of years of each energy resource is desired. Then for each year in the planning period the anticipated usage of each fuel is calculated by "stacking" the generation facilities according to their variable cost as shown in Figure 9. The energy to be supplied from each type is then simply the area under the load duration curve. Using this information, the contracts desired for each energy resource are calculated. This quantity is compared to the actual contracts existing. If more are desired, the process of seeking out new contracts begins. This process normally takes some time, thus a delay is included in the simulation. Once this delay is overcome new contracts are made according to the quantity being sought, but within the limits of the energy resources available. As in the other planning activites, this energy planning simulation may not follow exactly the activities of an individual utility company, but should provide a reasonable simulation of the process.

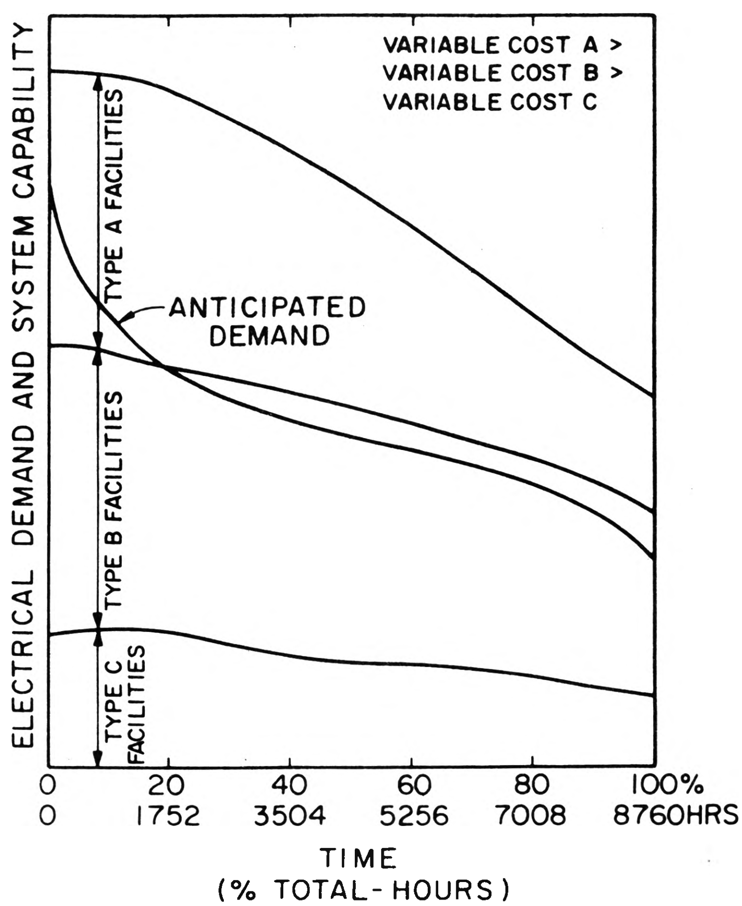


Figure 9. Use of generation facilities to fill demand in energy resource planning.

OPERATION ACTIVITIES

The operation activities can be broken into four areas. The first three deal with the flow of electricity to and from other regions. They are firm capacity, emergency energy, and economy energy purchases and sales. The fourth area deals with supplying the regional demand and the demand created by firm capacity sales.

There are two considerations involved in buying or selling firm capacity; (1) the ability to meet demand and (2) economics. Also, since firm capacity decisions must be made ahead of time, there is some uncertainty as to what the demand will most likely be. Thus, decisions made regarding ability to meet demand will consider the maximum probable demand. On the other hand, the economic decisions are made on the basis of what demands are most likely to occur or the most probable demands. In the model, firm capacity is bought if it appears that the utilities will be unable to meet the maximum probable demand and maintain reserves. Additional capacity will be bought if it can be utilized to the extent that it is cheaper than existing capacity. Similarly, maintaining sufficient capacity and reserves for the maximum probable demand sets a limit on the maximum firm capacity which can be sold. Within this limit, capacity will be sold if the total expected revenue from the sales will exceed the cost of operation.

The simulation of puchases and sales of emergency energy is fairly straightforward. If, because of unforeseen circumstances, the electric utilities in other regions are unable to meet their demands and request emergency energy it is supplied if possible. Likewise, if the electric utilities in the region are unable to meet demands they will purchase emergency energy if it is available. The price associated with emergency energy is normally quite high as it reflects all of the production costs.

The concept behind purchases and sales of economy energy is also quite simple. If, at a given point in time, another region has a lower incremental cost for generation, energy is purchased from that region. Likewise, if another region has a higher incremental cost, it purchases energy. Before this process can be simulated, the supply of and demand for economy energy in other regions must be defined. This can be done using quantity vs. price curves based on the same time axis used for the load duration curves as shown in Figure 10. However, it should be noted that the determination of these curves is quite difficult and represents a major area of uncertainty in the use of the model. Using these curves, the simulation assumes economy energy is bought and sold until the supply price, the demand price, and the incremental cost of production are all the same or some limiting factor is encountered. These limits include available capacity and transmission limits.

Once all of the transactions with other regions are made the model simulates the use of the available capacity for supplying the remaining demands. This is done in exactly the same manner as in the energy resource planning simulation except that energy resource limits must be accounted for.

In reality the decisions concerning emergency energy, economy energy, and the use of generation facilities are carried out simultaneously. This is also done in the simulation. The separation made here is strictly for the sake of clarity.

Figure 11 shows a modified Forrester diagram of the entire model. Double lines indicate indexed variables.

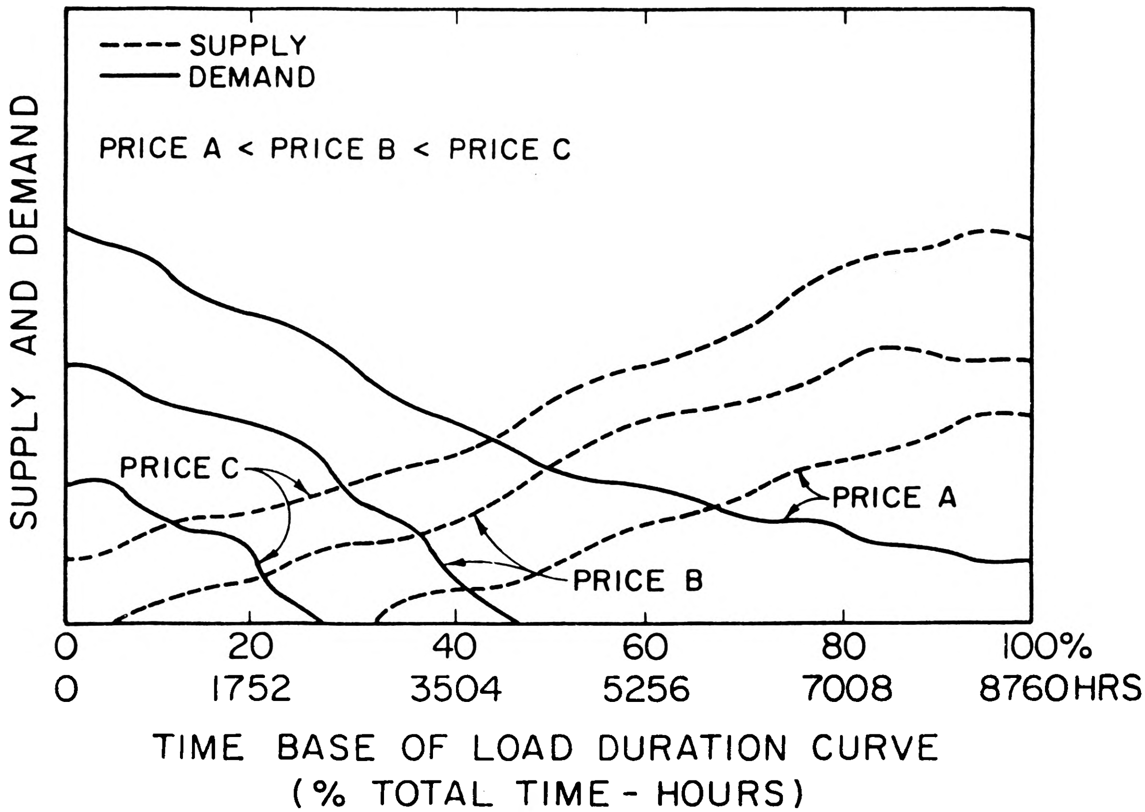


Figure 10. Representation of economy energy supply and demand for neighboring regions.

STUDIES WITH THE ELECTRIC UTILITIES MODEL

As stated earlier, the primary purpose of the electric utilities model is to be a component of the comprehensive DRESA model. However, it also has the purpose of being a useful independent model. In this, it is of course limited by the cut feedback paths. In view of this limitation, the most useful area of study for the model is seen in the analysis of the electric utility industry's response to changes in input variables. These changing variables include demand, energy resource prices, energy resource availability, and a wide range of regulation policies. This response can be measured in a number of ways, such as, types of capacity built, electricity and cash flows to and from other regions, energy resources consumed, etc. These are all included in the model. However, probably the most important measures are the ability of the electric utilities to meet the electrical energy demands in the region and the cost of generating the electricity to meet this demand.

The model is currently being used in a study of the response of the electric utility industry in Oklahoma to changes in these variables. One of the first important observations made in this study resulted during the validation of the model. The model was able to show that small changes in the demand growth rate have caused the utility companies to over-react resulting in sporadic construction of new generation facilities as shown in Figure 12. The model was also able to show that this sporadic construction had some important secondary consequences. In the past in

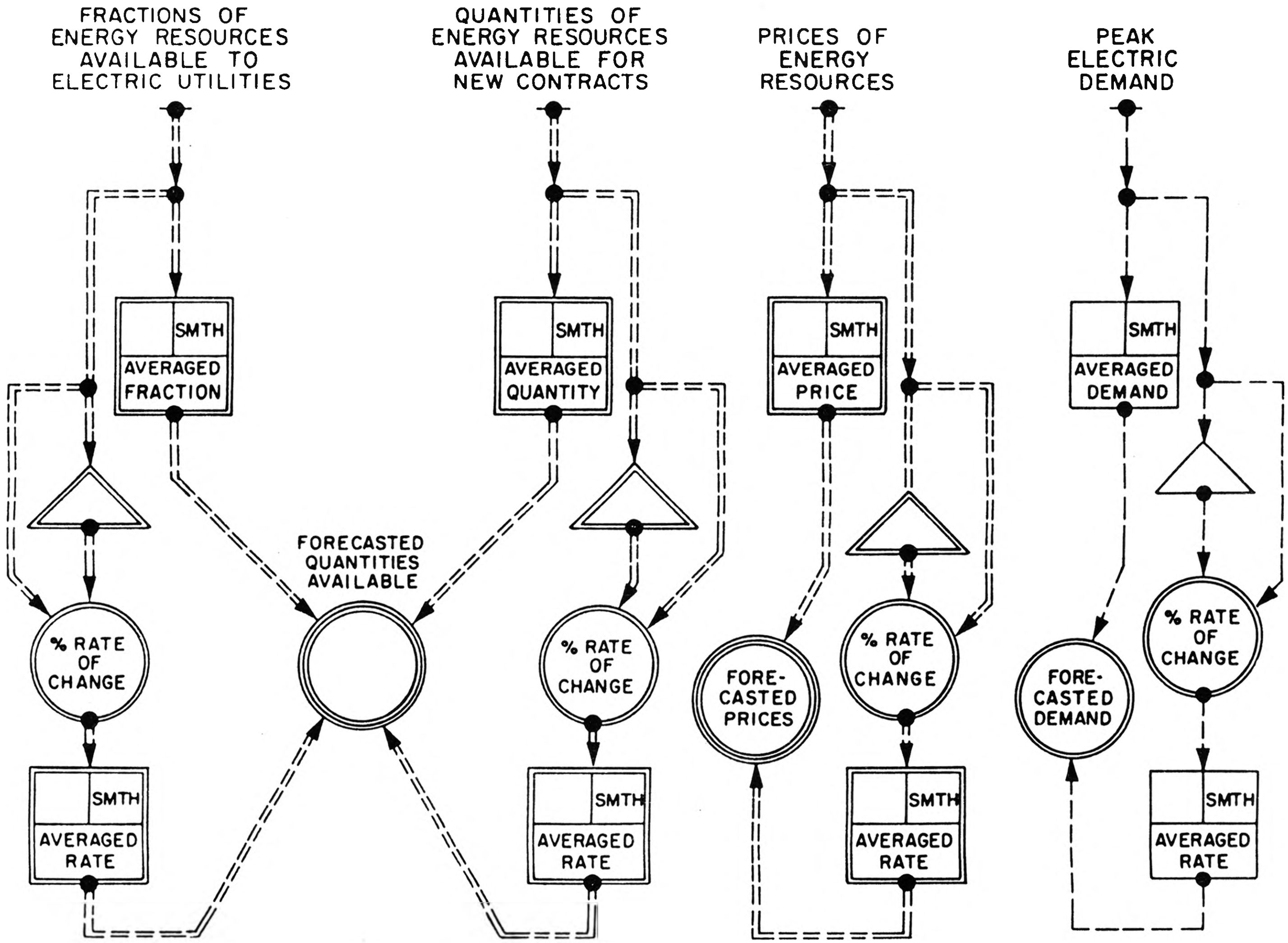
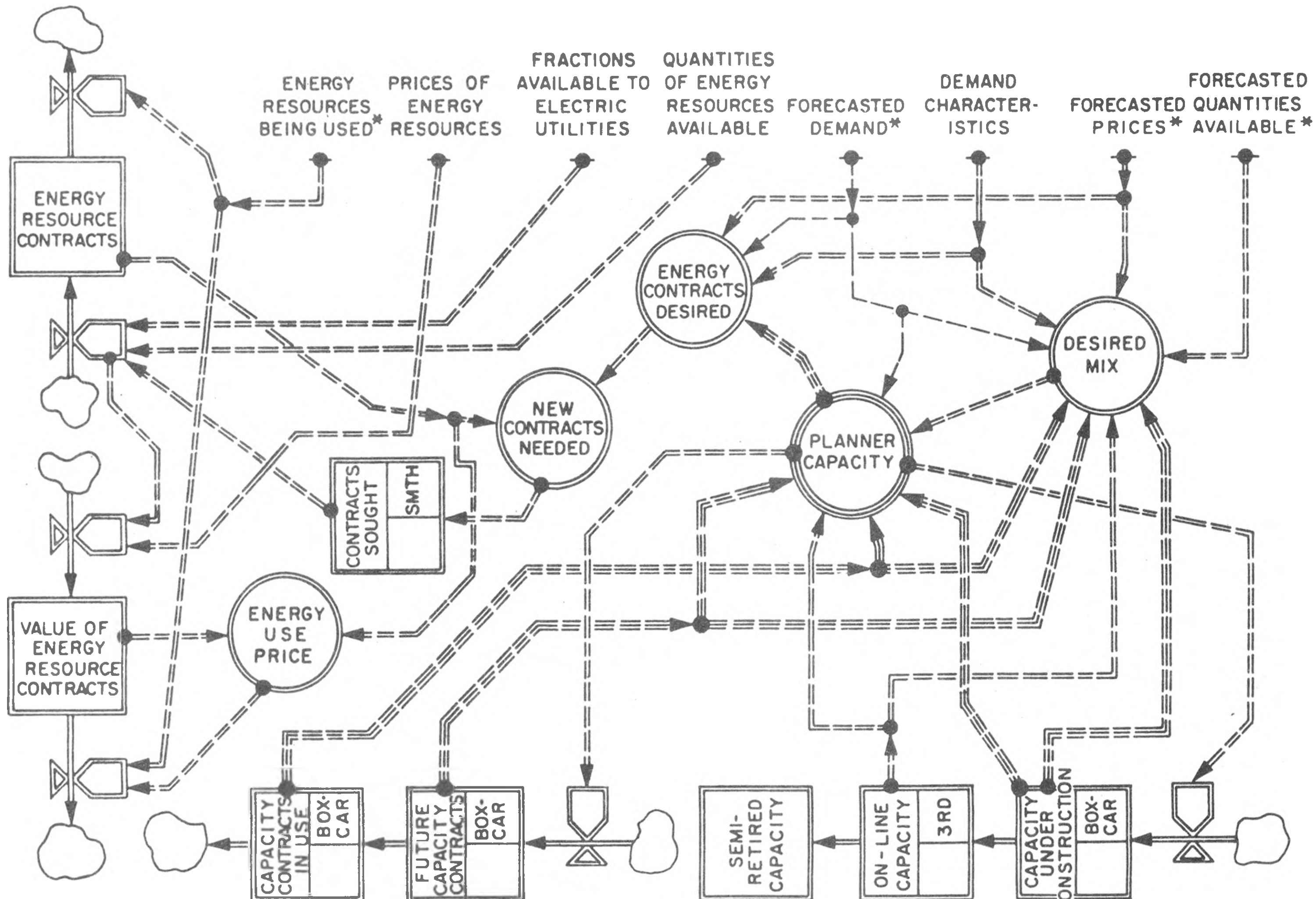


Figure 11a. Forrester diagram of forecasting part of electric utilities model.



*Variables determined in other parts of the model.

Figure 11b. Forrester diagram of generation capacity and energy resource contracts parts of the electric utilities model.

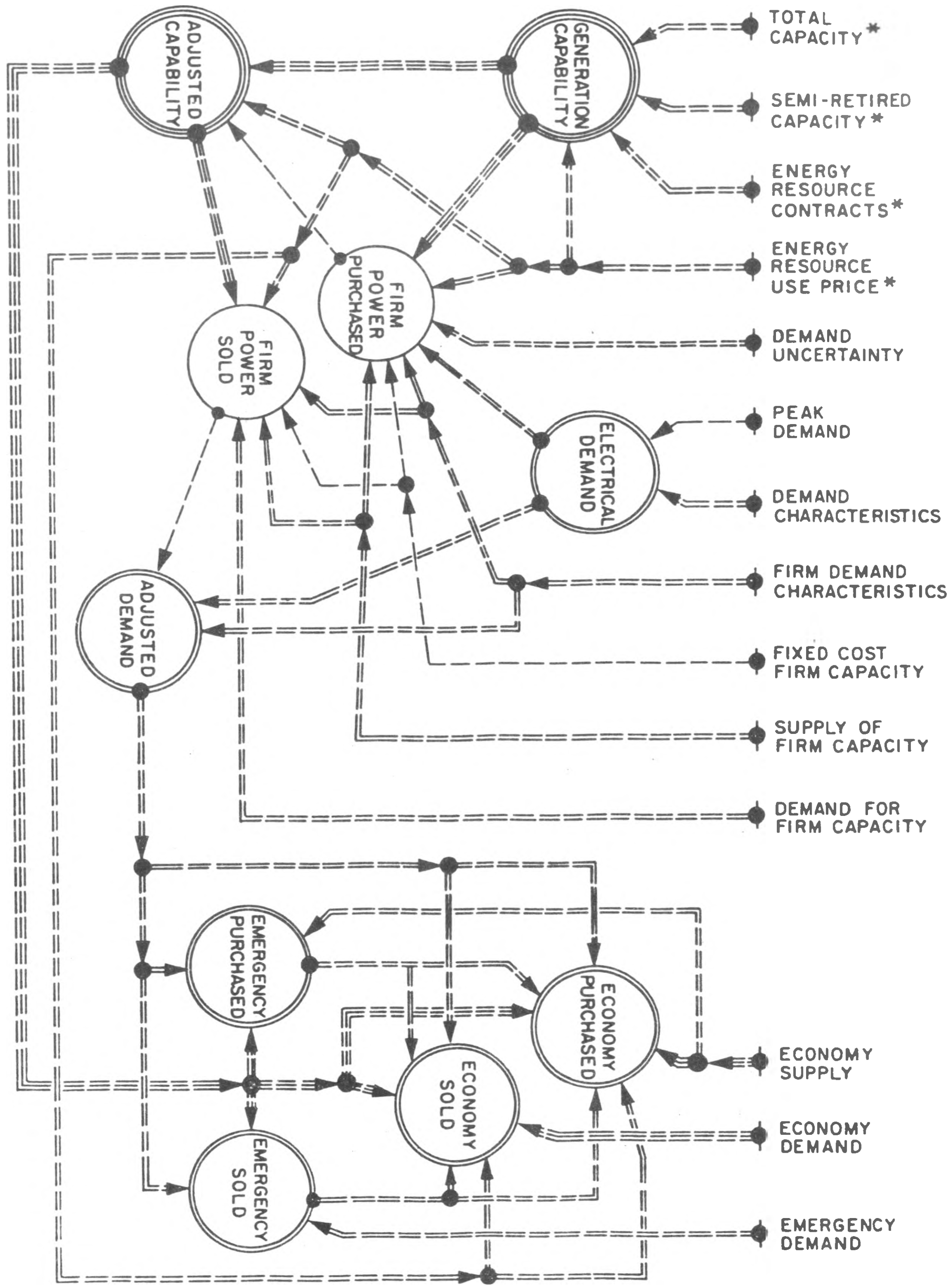


Figure 11c. Forrester diagram of inter-regional transactions part of the electric utilities model.

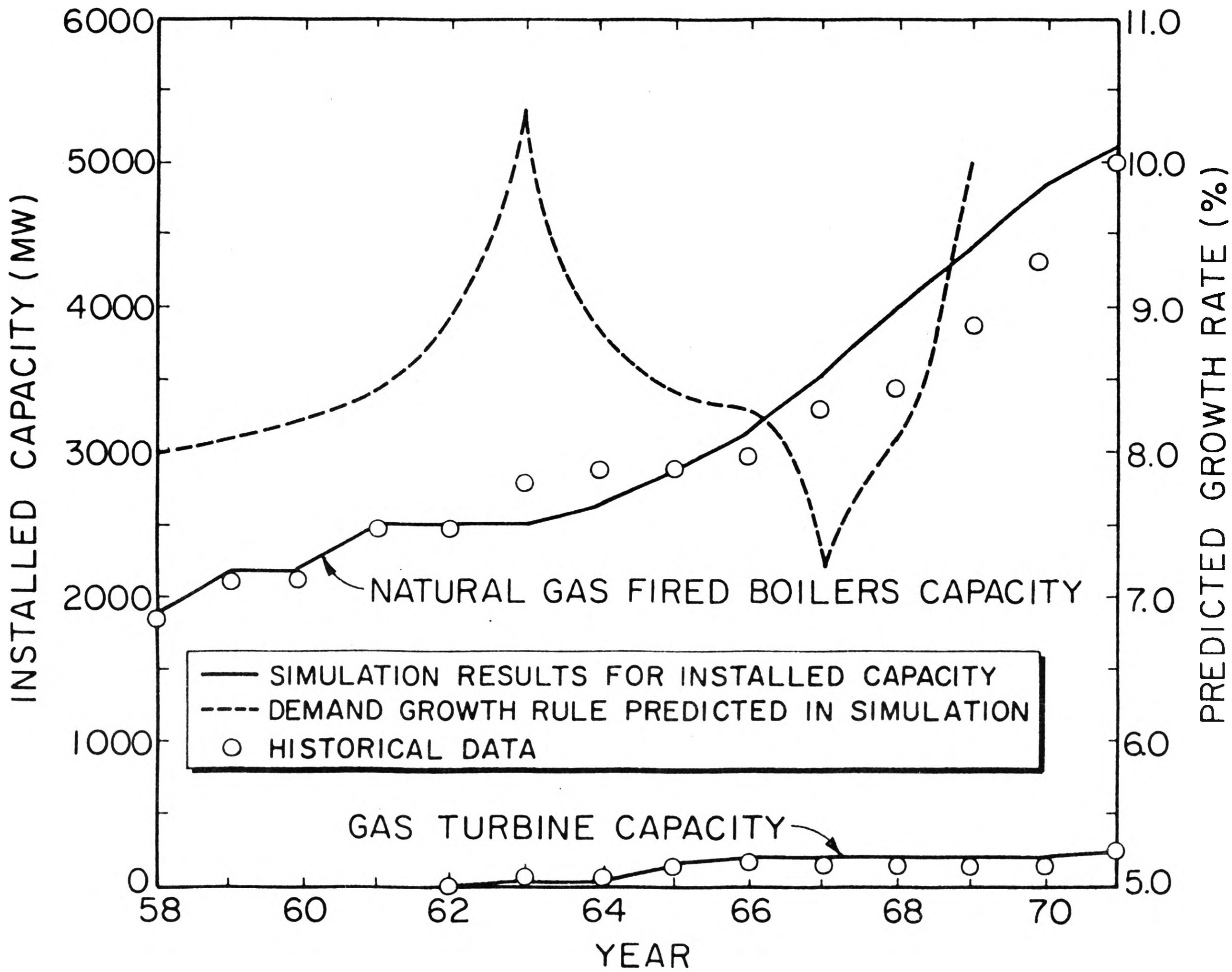


Figure 12. Comparison of simulation results and historical data for installed generating capacity.

Oklahoma, natural gas fired boilers have proven to be very economical. Thus, very small amounts of other types of capacity have been desired. However, in reacting to increasing growth rates the construction period for gas boilers becomes too long. This led to the construction of gas turbines, which have a much shorter construction period, to make up for the anticipated shortage of capacity. Thus, the response to demand dynamics was shown to be a larger factor in the historical capacity mix than were economic considerations.

This study is now centering on determining the ability of the electric utility industry in Oklahoma to respond to changing prices and availabilities. This includes the short-term fluctuations that may result from unsettled market conditions and major long-term price trends. Also, the possibility of price trends not reflecting energy resource availability must be considered. This possibility is very likely where natural gas is a major energy resource. The study has not been completed at this time so no final results can be presented. A sample of one of the preliminary simulation runs is shown in Figure 13. In this run a shift from dependence on natural gas to coal and nuclear fuels is shown for one scenario of future resource prices. A number of such scenarios will be considered to obtain a profile of

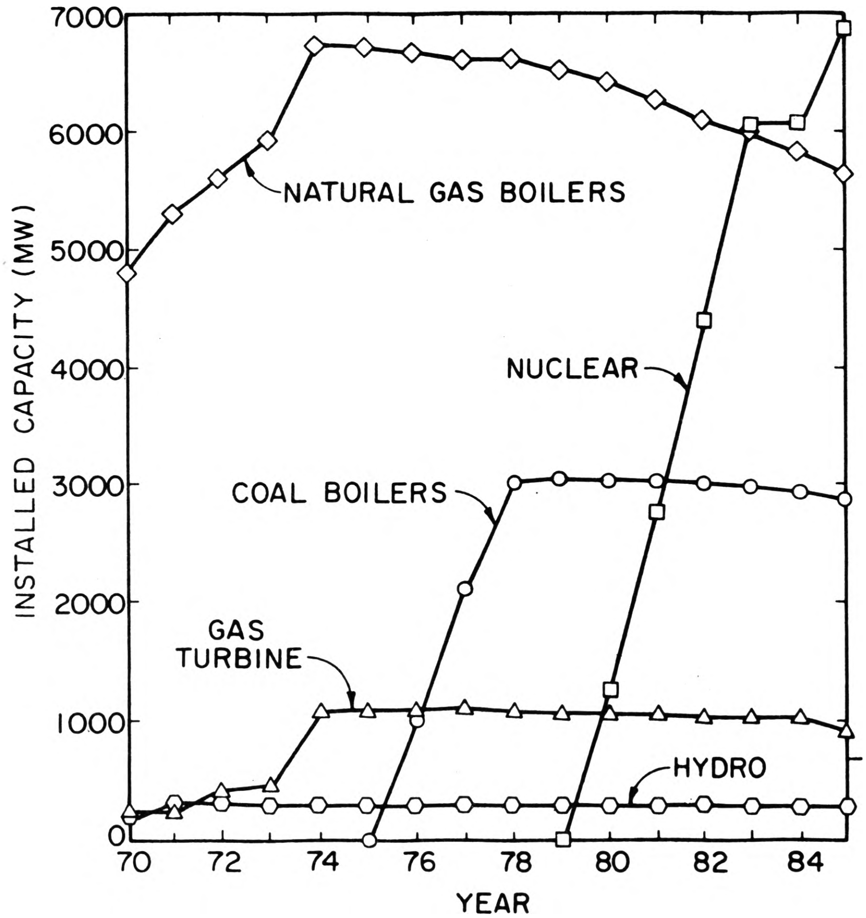


Figure 13. Preliminary simulation run for a scenario which results in a switch to coal and nuclear power plants.

the expected response to the different changes. As a part of this study, the utility companies' response to government regulation and the effects of different government and company policies on the ability to respond to changes are being studied. Specific test policies will include:

(1) Increasing restrictions on one or more fuels to gradually reduce their use;

(2) A sudden ban on the use of a particular fuel;

(3) Restrictions on the types of power plants which can be built;

(4) Basing utility cost calculations on replacement costs of energy resources; and

(5) Allocating the use of fuel in power plants on the basis of availability rather than cost.

With this study we will attempt to detect possible problem areas in regard to the utility industry response to an uncertain and changing future. In this way, specific measures can be employed to avoid the problems or to lessen their impact. Also, we will attempt to show what government and utility company policies will aggrevate and which ones will lessen the problems. Also, we hope to show what policies are best suited to achieve a desired goal with the minimum of harmful side effects.

CONCLUSION AND FUTURE STUDIES

The electric utilities model is proving to be a useful independent model. However, it is desired to be able to undertake a much wider range of studies than is possible with the model of the electric utility industry. It is hoped that in the future studies can be made of questions dealing with other parts of the energy supply/demand system. To move one step closer to achieving this capability, a modelling effort is soon to be initiated to develop models of other parts of the supply side of the energy system. It is anticipated that this will include models of the petroleum and natural gas industry, the coal industry, and the nuclear fuel industry. These models, combined with the model of the electric utility industry, should provide a fairly comprehensive model of the traditional supply side of the energy system. It is planned to develop similar models for the demand side of the system at a later date.

The development of these models will follow along the same line as the development of the electric utility model. They will continue the approach of dynamic simulation with the structure of the models emphasizing technical realities and the decision processes in the energy system. The primary function of each model will be to serve as a component of the comprehensive DRESA model. However, each model should be useful in making independent studies. When finished, it is planned for the DRESA model to be used in making studies using any number of the component models. In this way, only the parts of the energy system which need to be simulated for a particular computer run will need to be included. But, as many parts as necessary to account for the interaction and feedback in the system can be included.

We believe the DRESA model and the component models from which it will be made will provide a tool to improve the quality of decisions at every level by demonstrating more of the good and bad consequences of various options than had been rigorously possible before.

ACKNOWLEDGEMENTS

This work was aided by advice and financial support from Public Service Company of Oklahoma and Oklahoma Gas and Electric Company. It was also supported by the National Science Foundation through the Center for Systems Science at Oklahoma State University.

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BIOGRAPHIES

Byron W. Jones received his B. S. in Mechanical Engineering from Kansas State University in 1971, his M. S. in Mechanical Engineering from Oklahoma State University in 1973, and completed requirements for the Ph. D. at Oklahoma State University in December 1975. He is currently an Instructor at the School of Mechanical and Aerospace Engineering, Oklahoma State University, and has been selected for a post-doctoral Fellowship by the National Science Founcation.

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OPTIMUM CONTROL OF

HEATING, VENTILATING, AND AIR CONDITIONING SYSTEMS

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Abstract

The control of HVAC systems has traditionally been performed by relatively simple field hardware. The industry appears, however, to be ready for the use of more sophisticated measures. The paper presents several approaches to the conservation of energy in this area with the use of closed-loop computer control and optimization.

1. INTRODUCTION

Anthropologists cite the discovery of fire as a hallmark event in the development of the human race. Truly the ability to control and convert energy is still the backbone of our continuing technological progress. Is it not interesting, though, that the first use of this energy by the cave man is still the primary use of our energy sources - that of keeping man comfortable! Even more astonishing must be the fact that we are nearly as inefficient in our use of energy as was the cave man. He was forced to build a fire at the mouth of his cave in order to keep the smoke outside, and was able to utilize only a portion of the heat generated by his fire to keep his family warm. This couldn't be considered any more primitive than using energy to extract heat from the interior core of an office building and discharge it to the atmosphere while simultaneously using energy to heat the perimeter offices.

What, then, must be done to improve our use of energy sources in the conditioning of modern buildings on the drawing board or in existence? There are basically two areas deserving of attention. The first is the primary equipment itself. This would include fan systems, pump systems, chillers, boilers, etc. This equipment is being continuously improved and evaluated, along with developments in new equipment to accomplish schemes that have been tried by HVAC designers and found to be effective. Heat recovery wheels are one good example of this development. The traditional once-through systems used in hospitals or laboratory buildings were prime users of both heating and cooling energy on such buildings until the use of a non-contaminating heat transfer method became practical. Likewise, variable air volume systems have replaced the less efficient terminal reheat systems previously used to maintain interior comfort. By using only the required amount of cold air, instead of reheating an excessive amount, energy has been successfully conserved without great sacrifice in comfort.

There are, though, problems associated with the implementation of such schemes. As noted above, the use of the Variable Air Volume system poses a more difficult problem to the control designer if traditional comfort levels are to be maintained. This brings up the second area of effort in energy conservation in HVAC systems, the control of their operation.

Traditional automatic temperature controls have always contributed to the conservation of energy in HVAC systems. The use of a smiple two-position thermostat has prevented over-heating and over-cooling of spaces for decades. The modulating thermostat further refined such techniques. Rising energy costs have, however, made more sophisticated control schemes cost effective in their use as energy conservation measures. The traditional automatic temperature control system has now been expanded into a Building Automation System with a digital computer and digital multiplexed transmission system as its "heart". The following are examples of the use of such a computer to optimize control of several parts of a typical HVAC system, along with comparison to traditional control methods in each case.

2. OPTIMAL SEQUENCES

2.1 MIXED AIR CONTROL

Traditional methods of mixed air control involve the choice of a "design temperature" for the mixture of outdoor and return air. This temperature is generally that which satisfies any cooling requirements of the system. The intent is to provide "Free Cooling" as opposed to the use of mechanical cooling for such requirements. The theory works, and has been termed the "economizer" cycle.

There is a problem, however, in the application of such a cycle. During the seasons of the year in which the outside air temperature is in excess of the desired mixed air temperature, it has been customary to use an "economizer" thermostat to override the mixed air controller and close the outdoor air intake to a minimum ventilation position. The traditional temperature for such a switchover has become 55°F - 60°F dry bulb in the Missouri area. This seems to have become the standard due to the use of a 55°F - 60°F dry bulb discharge temperature from the system's cooling coil as a design parameter.

A more reasonable approach is the use of a more sophisticated means of selecting this switchover point. The intent of an economizer cycle is to provide a mixed air stream with the lowest possible total heat content such that as little mechanical cooling as possible is used. Thus, a more effective method would be to compare the enthalpy of return and outdoor air streams and to select, via a logic network or a Building Automation Computer, the most economical mixture of air to utilize in system operation. The following description of such a system's operation refers to the pyschrometric chart, figure I:

2.1.1 Region I

When outside air dry bulb temperature is below the desired supply air set point both are mixed to obtain the desired supply air temperature without the use of mechanical cooling. Dampers are controlled by a direct acting mixed air temperature controller.

2.1.2 Region II

This region is defined as that portion of the psychrometric chart in which the outdoor air enthalpy is below the enthalpy of the return air and the dry bulb temperature is between the desired leaving coil temperature and the return air dry bulb temperature. Outdoor air in this region has less total heat than return air and should be used for maximum economy.

2.1.3 Region III

This region is that part of the psychrometric chart where the outdoor air enthalpy is higher than the enthalpy of the return air. In this region only a mixture of outdoor air should be used.

2.1.4 Region IV

This region is that part of the psychrometric chart where outdoor enthalpy is lower than the return air enthalpy and the dry bulb temperature is above the return air dry bulb, to avoid latent cooling the program shall choose minimum outdoor air if return dew point is below supply air temperature and 100% outdoor air if both outdoor and return air dew points are above the supply air temperature.

Such a control system can save between 6% and 10% over the traditional economizer cycle depending on the present dry bulb switchover temperature. The computer inputs required are outside and return air dry bulb temperature and humidities. The computer's output positions the dampers as required.

2.2 SUPPLY AIR CONTROL

Traditional methods of HVAC design have included the sizing of equipment to maintain a fixed cooling coil discharge temperature, calculated to maintain temperature in the space at worst-case heat loads or humidity conditions. This usually results in excessive mechanical cooling and reheating of air streams in all but worst-case load situations.

This scheme can be replaced by a Supply Air Reset Program in the Building Automation Computer which will compare space conditions and demand to cooling coil discharge temperature and select the optiminum discharge temperature. The program has as its inputs the load conditions of each of the zones served by the air handling system. This would include valve positions of reheat coil valves or damper positions in doubleduct mixing boxes.

The position of these control devices are direct feedback of the demand of each zone for cooling. The computer will periodically increase the discharge temperature until one of the zones is demanding maximum cooling. At this point, the computer will lower the discharge temperature by 1°F thereby bringing the high-demand zone back into control. This will result in a minimum of excessive mechanical heating and cooling commonly found in double-duct and terminal reheat systems. The only other consideration in the Missouri Area is the use of the cooling coil for dehumidification purposes. Thus, an additional computer input, return air humidity, is used to override the program should excessive return air humidity be present, and it will cause the computer to lower the discharge temperature until the humidity falls within acceptable limits.

The savings available by the use of such a program vary with the type of fan system, but generally show favorable payback. The cost of implementation is dependent upon building construction and ease of obtaining zone demand signals at a central point for their entrance into a computer multiplexing panel.

2.3 OPTIMUM START TIME

Most HVAC equipment is presently started each morning in time to properly condition the space before occupants arrive and turned off each evening after they have departed. Generally this is accomplished by a simple time clock mechanism. A typical building's operating cycle includes a warm-up time based on each season's requirements. A building engineer may start three hours early in winter, one hour early in spring and fall, and two or three hours early in summer. These warm-up and cool-down times are usually established by experience and typically reflect the worst-case conditions expected during each particular season. Thus, an unusually cold night may cause the start-up to be set earlier, and probably not reset for several weeks or months. Also, it is not uncommon to several units serving spaces with different characteristics to be started by one common clock.

The Optimum Start Program for a Building Automation Computer is designed to allow for all factors affecting the required length of time for warming up or cooling down the space, and then use this information to control the start-time of each unit each morning. These factors include infiltration, U factor, mass temperature, and indoor temperature of the space along with a comparison of outdoor temperature. The measured variables (indoor, outdoor, and mass temperatures) are plotted by the computer on a stored U factor curve and compared with the heating or cooling capacity of the unit to be controlled. The computer then projects the required start time and updates its projections as the projected time draws near. Thus the unit is started at the time necessary to provide comfort in the space at the desired time of occupancy. The secondary function of this program is to provide a control signal to close the unit's ventilation dampers so that only the return air is conditioned. The dampers are allowed to open their minimum position a few minutes before occupancy in order to purge the space of stale air, and any exhaust fans normally in use would then be started by the computer.

This program can save several hours of fan run time per day, which will produce obvious savings in utility cost. The secondary effect, though, is to shorten the period that the building will be maintained at a temperature other than that of an unconditioned building, with a corresponding savings in heat gain or loss. Its implementation is not difficult or expensive when compared with the savings available through its use.

2.4 CHILLER OPTIMIZATION

The control of chilled water machines has become somewhat standard as witnessed by the proliferation of standardized unit-mounted control packages. Chilled water is usually maintained at a selected set point by control of refrigerant flow through the machine, while condenser water temperature is usually controlled by a step controller cycling a group of cooling tower fans. While this method is relatively effective in controlling a single chiller and a few fans, it is not especially efficient in the control of several chillers in a large chilled water plant serving a complex of buildings such as a campus, shopping center, or high rise project.

For this purpose, a computerized optimization program can be employed within the Building Automation Computer to reduce the energy required to produce cooling for the complex. The inputs to program include all the pertinent variables in the chilled water system. These variables would include KW usage of each chiller motor, pump, and tower fan in the system, as well as flow and temperature information required to measure chilled water output of each machine in the system. Thus the efficiency of each machine can be measured by varying load levels and the computer is able to select the combination of machines that should be employed to satisfy each chilled water demand situation presented to the plant as a whole.

In addition, the computer can control the cooling tower fans to produce the most efficient entering condenser water temperature. Most modern centifugal machines are capable to accepting condenser water temperatures as low as 75°F, resulting in a 1 to 1-1/2% increase in chiller efficiency for each degree of reduction in condenser water temperature. This will, of course, necessitate the use of additional power to operate the tower fans required to maintain such a temperature. The computer can analyze these alternatives and select the proper operating combination of equipment. It is also assuming that a sufficiently low outdoor wet bulb temperature is available to cool the tower water. Therefore, the computer compares the total efficiency of the chiller plant along with present outdoor conditions in selecting the optimum quantity of tower fans to be used. Should the outdoor wet bulb temperature be so high that additional fan horsepower is useless, the computer will shut down fans to conserve energy.

It is obvious that such a program requires a multitude of inputs and a considerably flexible piece of software to be effective. However, in a chiller plant of 2500 tons or greater capacity it can become extremely cost effective.

2.5 LOAD SHEDDING

The concept of load shedding has recently been developed as a hedge against the spiraling demand charges levied on users by the electric utility companies. Demand charges are meant to compensate the utility company for the peaks in a user's consumption of energy, which requires higher capacity generation and transmission equipment than would otherwise be needed.

Several different schemes are used to establish the peak level and to apply it to a billing formula. A common method is to measure total KW consumption for each 15-minute interval during a billing period, and declare the largest total the peak demand. Then, this determines the rate schedule for the entire month's billing. This increase in rate is rarely linear with an increase in demand. Thus a 10% decrease in demand could produce a 12-15% decrease in billing service. A more convincing method is to project any demand peak over the next 11 months billings and raise all the rate schedules for that period in accord with the new peak.

Therefore, the concept of controlling peaks in electrical usage is, in the right application, a considerable savings in the energy dollar but could not be considered as an energy savings. This is due to the fact that the basic theory of demand control is to defer a peak in usage over several 15-minute intervals thus reducing the peak but allowing the same net usage at a lower cost.

One method for doing this is to establish an "Ideal Rate" of consumption for each 15-minute period. When the actual rate begins to exceed the ideal rate, which predict that the demand level would exceed that previously reached, a group of loads is turned off. This "shedding" of loads continues until consumption falls back within the limits of the "Ideal Rate" curve. Then, when the end of the 15-minute interval has passed the loads may be restored and a new projection begun.

Although publicized as an energy conservation measure, load shedding has to be regarded as a method of saving money, with little or no net energy saving effect.

3. IMPLEMENTATION

The important fact for the HVAC industry to face is that energy cannot be considered without some additional "first cost" if traditional comfort levels are to be maintained. The measures outlined are all effective in reducing either energy consumption or energy cost, but such savings can only be attained if capital expenditures are made to allow their installation. Studies on the application of such measures in the St. Louis Area have shown payback periods on such investments between three and five years. These payback periods are being shortened drastically by spiraling energy rates. This type of cost justification has proven, through that computerized monitoring and control of building has indeed come of age.

4. BIOGRAPHY

Mr. Weaver is a 1973 BSEE graduate of Kansas State University. While in attendance there, he was elected to Eta Kappa Nu and Sigma Tau Scholastic honoraries. He is presently employed as a System Sales Engineer with the St. Louis Branch of Johnson Controls, Inc., a worldwide manufacturer of automatic temperature controls. His experience in computerized automation includes the design and commissioning of several systems as herein described.

AN ENGINEERING, GEOLOGICAL AND HYDROLOGICAL ENVIRONMENTAL ASSESSMENT OF A 250 MMSCFD DRY ASH LURGI COAL GASIFICATION FACILITY

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Abstract

A preliminary engineering, geological, and hydrological environmental assessment of a proposed 250 MMSCFD dry ash Lurgi coal gasification facility is discussed.

The facility's emission spectrum is examined on the basis of the proposed design and empirical data. This system utilizes approximately 13 million tons of lignite and 17,000 acre feet of water per year and consumes 6500 tons of oxygen per day. The results of the study indicate that the major gaseous effluent is CO_2, that the federal limits on SO_2 effluent may be met, and that the atmospheric degradation criterion will be the most difficult one to meet.

The fate of trace elements during the gasification process is discussed. Available preliminary data indicate that the majority of the trace elements will be concentrated in and leave the system with the ash.

The probable hydrological and geological impacts pertinent to ash and sludge disposal and water table depression are discussed. The results of the study indicate that the water table will be depressed during mine operations and that some groundwater pollution will occur due to waste disposal.

1. INTRODUCTION

Coal gasification is but one of several avenues that are being followed by the gas industry in an attempt to alleviate the growing discrepancy between gas supply and gas reserves as shown in Table 1. (1) This discrepancy has been identified and recognized by virtually everyone associated with the industry, including government officials, university personnel and private citizens.

The cost associated with the building of one of the coal gasification facilities proposed for North Dakota is very high, on the order of three quarters of a billion dollars. (2) The funding of a 250 MMSCFD (million standard cubic feet per day) plant is a serious problem for private industry. This investment usually represents 25 to 50 percent of a pipeline company's net capital worth. A single such facility would ordinarily supply approximately one-twelfth of a pipeline company's gas. (3) Superimposed upon the funding problem are serious material supply problems; for example, delivery times of four years for draglines and three years on much of the plant equipment. Permit acquisition problems are also present; permits are required for land, water, plant construction, the mine, plant startup and plant operation. Political pressures are also being generated by the fact that significant coal development can be expected to cause a shift in the balance of political and economic power in the state. Ninety-nine percent of the state's gross product is currently agricultural. (4) Examples of the environmental problems present are: impacts associated with strip mining, socioeconomic impact, and air and water pollution.

This paper deals specifically with the environmental impacts associated with a proposed 250 MMSCFD Lurgi dry ash coal gasification facility to be located in western North Dakota as shown in Figure 1.

The operation, maintenance, and size of a 250 MMSCFD mine-mouth coal gasification facility are all large in scope. The mining operation will be about five times larger than any mine currently operating in the state of North Dakota. The proposed mine will produce approximately 13 million tons of coal per year. About 87 percent of this coal will be converted to substitute natural gas (SNG) by the gasification plant. The facility consists of four main process

Table 1

United States Natural Gas Supply*
1946-1973
(All Volumes in Trillions of Cubic Feet @ 14.73 Psia and 60°F.)

Year	Production	Reserve Additions	Proved Reserves	R/P Ratio** (4) ÷ (2)	F/P Ratio** (3) ÷ (2)
(1)	(2)	(3)	(4)	(5)	(6)
1946	4.9	17.6	159.7	32.5	3.6
1947	5.6	10.9	165.0	29.5	1.9
1948	6.0	13.8	172.9	28.9	2.3
1949	6.2	12.6	179.4	28.9	2.0
1950	6.9	12.0	184.6	26.9	1.7
1951	7.9	16.0	192.8	24.3	2.0
1952	8.6	14.3	198.6	23.1	1.7
1953	9.2	20.3	210.3	22.9	2.2
1954	9.4	9.6	210.6	22.5	1.0
1955	10.1	21.9	222.5	22.1	2.2
1956	10.9	24.7	236.5	21.8	2.3
1957	11.4	20.0	245.2	21.4	1.7
1958	11.4	18.9	252.8	22.1	1.7
1959	12.4	20.6	261.2	21.1	1.7
1960	13.0	13.9	262.3	20.1	1.1
1961	13.5	17.2	266.3	19.9	1.3
1962	13.6	19.5	272.3	20.0	1.4
1963	14.5	18.2	276.2	19.0	1.3
1964	15.3	20.3	281.3	18.3	1.3
1965	16.3	21.3	286.5	17.6	1.3
1966	17.5	20.2	289.3	16.5	1.2
1967	18.4	21.8	292.9	15.9	1.2
1968	19.4	13.7	287.4	14.8	0.7
1969	20.7	8.4	275.1	13.3	0.4
1970	22.0	37.2	290.7	13.2	1.7
1971	22.1	9.8	278.8	12.6	0.4
1972	22.5	9.6	266.1	11.8	0.4
1973	22.6	6.8	250.0	11.1	0.3

* Includes gas in underground storage.
** Computed prior to rounding.

Source: A.G.A.

streams, a small power plant (40 to 60 megawatts), a boiler plant (about 1.5 million lbs/hr of steam, at 600 psig, 900°F), and a sewage treatment facility. This facility generates solid, liquid and gaseous discharges. The major solid discharge is ash which, following quenching, is transported back to the mine area and covered with overburden. The water transported with the ash represents a major liquid effluent stream (500 gallons per minute (gpm)). The major (by weight) gaseous effluent is CO_2 from the Rectisol part of the process stream and flue gas from the steam plant.

This facility would utilize approximately 13 million tons of lignite per year from the Fort Union reserve in western North Dakota and would consume approximately 10,500 gpm of water from Lake Sakakawea. (5) Approximately 350 acres of land are required for the facility. In addition, the mine produces the lignite from about 500 acres per year with 1500 to 2500 acres being out of agricultural production at any one time.

The gas produced is to be supplied to a pipeline and will be blended with the lower cost natural gas. The Emission Spectrum, Geology, and Groundwater Hydrology for this facility are discussed below. The data reported below are a summary of the results of a project completed by the Engineering Experiment Station in August, 1974. (5)

2. FACILITY REQUIREMENTS AND EMISSION SPECTRUM

The proposed facility contains 30 to 35 dry ash Lurgi gasifier units which produce approximately 40 percent of the methane in the plant's end product, SNG. A single unit, which is shown in Figure 2, is approximately 3.5 meters in diameter and 20 meters in height. The gasifiers supply four main line process streams shown in Figure 3. Each process stream consists of a shift conversion step, several cooling steps, two gas purification steps, a methanation step, and a compression step. When combined, these four process streams will produce 250 MMSCFD of SNG from 28,330 tons per day (tpd) of North Dakota lignite. The gas produced is expected to be 96 percent by volume methane and have a heating value of 975 Btu/scf. The hydrogen required for gasification is derived from the process water supplied by the lake (approximately 10,500 gpm) and water brought in with the coal. The oxygen required by the facility (5500 tpd) will be supplied by a cryogenic oxygen plant. Approximately 35,000 tons of lignite will have to be mined to obtain the sized gasifier input (2 in. x 1/8 in.). The balance of the lignite will be used to support the energy needs of the facility (approximately 5500 tpd) or sold.

Table 2 provides the average analysis data for the coal that will be used in the proposed facility. The moisture content of the lignite is high enough to provide the hydrogen required for the gasification step. This amount is approximately 10 percent of the water requirement for the facility. The gas stream exiting the gasifiers passes through crude scrubbers and coolers which separate the condensate into tar and gas liquor and produces a partially cleaned raw gas stream. The liquor is processed offline while the gas stream continues on to the shift conversion step. At the shift conversion step, the gas stream is split into two streams one of which undergoes the following reaction:

$$CO + H_2O \xrightarrow[\text{Catalyst}]{\text{Heat}} CO_2 + H_2 + 16538 \text{ Btu/lb mol at reaction temp.}$$

The gas streams, when recombined following this step, result in a 3.5 H_2/CO mol ratio. The gas is then cooled, resulting in additional gas liquor streams, and enters a "Rectisol" plant for further purification. This unit utilizes a low temperature methanol wash and removes hydrogen sulfide, carbon dioxide and carbonyl sulfide by physical absorption. The methanation feed gas (3.5 H_2/CO mol ratio) is essentially sulfur free (less than 0.2 ppm). The H_2S stream is sent to a sulfur plant for sulfur recovery. The CO_2 is either used as lock gas for the gasifier units or is vented. The purified H_2, CO, and CO_2 stream is methanated using a catalyst and is then processed in a second Rectisol unit where the remaining CO_2 and H_2O generated during methanation is removed. Approximately 60 percent of the end product methane is produced in the methanation step. Following the second rectisol unit, the process gas stream is compressed and sent to sales as SNG.

The gas liquors, collected at multiple points in the main process stream, are processed in tar and oil gravity separators. The gaseous stream from the separators is recompressed and sent back to the main stream for further processing. The tar and oils are marketed. The remaining gas liquor is sent to a phenolic recovery unit. The Lurgi Phenosolvan Process, using isopropyl ether, is used to extract the phenols from the liquor stream. The CO_2, H_2S, and NH_3 are removed from the liquor stream by heating and stripping, and the remaining stream is routed to biological treatment.

All the acid gas streams within the facility are routed to a sulfur-recovery plant where 99 percent of the sulfur is to be removed. The residual gas stream is incinerated in the boiler and processed along with the boiler plant flue gas for sulfur removal.

The energy balance of this facility is summarized in Table 3. The complete material

Table 2. Analysis of Dunn County, N. Dak., Lignite, Average of four Dunn Center bed composites.

Proximate analysis, percent by wt.	As received	Moisture free	Moisture and ash free
Moisture	38.56	-----	-----
Volatile matter	27.03	44.00	49.51
Fixed carbon	27.57	44.87	50.49
Ash	6.84	11.13	-----
Ultimate analysis, percent by wt.			
Hydrogen	6.97	4.38	4.93
Carbon	39.05	63.56	71.52
Nitrogen	.40	.65	.73
Oxygen	45.90	18.92	21.28
Sulfur	.80	1.30	1.47
Chlorine	.04	.06	.07
Ash	6.84	11.13	-----
Heating value, BTU/lb	6456	10508	11824
Ash analysis, percent by wt.			
Silicon dioxide		21.17	
Aluminum oxide		11.37	
Ferric oxide		9.27	
Titanium oxide		.46	
Phosphorus pentoxide		.27	
Calcium oxide		20.25	
Magnesium oxide		7.51	
Sodium oxide		2.90	
Potassium oxide		.50	
Sulfur trioxide		25.54	
Undetermined		.76	

Ash fusibility, ^{o}F	Reducing	Oxidizing
Initial Deformation	2240	2310
Softening	2360	2410
Fluid	2480	2530

balance can be obtained. (5) The total energy content produced by the facility (2.95×10^{11} Btu/day) is approximately equivalent to 3600 megawatts (thermal). In terms of energy consumed, the total energy content of the facility is equivalent to a 2100 megawatt power plant. The water use of the facility is summarized in Figure 4.

Good design practice requires that cooling towers be used due to the large variance in local environmental conditions (95°F, 90% RH to -40°F, 40% RH). In essence, all of the incoming lake water is evaporated while the process water is provided by the coal. The major portion (71 percent) of the evaporation occurs in the cooling towers. The total water use rate (16,800 acre-feet/year) is approximately twice that of the gasification plants being built in the Southwest. (6)

The sulfur flow diagram (Figure 5) shows that the expected sulfur emissions from the facility can be as low as 0.1 pounds/million Btu of total production and approximately 0.25 pounds/million Btu for the direct fired boilers. In both cases, the sulfur emitted is well below the limit of 1.2 pounds/million Btu. (7) The NO_x effluents are expected to be less than the limit of 0.7 pounds/million Btu. (7) The particulates have been estimated to be 0.09 lbs/million Btu which is slightly less than the limit of 0.1 lbs/million Btu. (7) Thermal emissions from the facility account for approximately 33 percent of the energy input. The major thermal emissions are from

Table 3. Energy Balance

Input		Tons per day	Heat of combustion BTU x 10^9 per day
Lignite to Gasifier Train		28331	365.8
Lignite Fines to Steam Plant		5500	71.0
	TOTAL	33831	436.8
Output			
Substitute Natural Gas		5519	243.8
Sulfur		126	1.0
Tar		908	29.1
Oils		300	10.3
Naptha		152	5.5
Crude Phenols		116	3.6
NH_3		123	2.4
			295.7

Thermal Efficiency Gasifier Train $\frac{295.7}{365.8} \times 100 = 80.8$ percent

Overall plant [1,2] $\frac{295.7}{436.8} \times 100 = 67.7$ percent

[1] This does not take into account the use of an auxiliary steam superheater nor the effect of additional heat usage to dry lignite.

[2] The thermal efficiency based on the fuel products: substitute natural gas, tar, and oils would be 64.8%.

the cooling towers with minor contributions being made in the areas of the stack and vent gases and the evaporation ponds. Solid wastes are to be disposed of in the mine area prior to reclamation and will consist of 2500 tons of ash per day as well as sludges from raw water treatment, biological treatment, and other settling ponds.

The question of trace element availability was addressed during this study but only partially answered. The available data (8), (9), (10), (11), (12) indicate that some of the trace elements will probably be concentrated in the ash. The more volatile trace elements will enter the process stream and be removed in one of several gas liquor streams. Table 4 portrays the possible disposition of trace elements within the facility. A study to determine which trace elements are present in the Dunn Center Bed coal was completed, and the results are given in Table 5. There is significant variability between the two samples. These samples were physically located within a few miles of each other. This work is continuing on a considerably expanded scope which includes an attempt to form a trace element balance around the facility based upon analysis of samples of effluents from the gasification facility at Sasolburg, South Africa.

Table 4. Possible Disposition of Trace Elements in Ash, Liquid, Gaseous and Unknown Streams

Element		Ash	Liquid	Gaseous	Unknown
Silver	Ag		X(?)		X
Arsenic	As		X(?)	X	X
Boron	B	X			
Barium	Ba	X			
Beryllium	Be	X			
Bismuth	Bi	X			
Cobalt	Co	X			
Chromium	Cr	X			
Copper	Cu	X			
Gallium	Ga		X(?)		X
Germanium	Ge	X(?)			X
Mercury	Hg			X	
Lithium	Li	X			
Manganese	Mn	X(?)			X
Molybdenum	Mo	X(?)			X
Nickel	Ni	X			
Lead	Pb		X(?)	X	
Tin	Sn		X(?)		X
Strontium	Sr	X			
Uranium	U	X			
Vanadium	V	X			X
Ytterbium	Yb	X(?)			X
Yttrium	Y	X(?)			X
Zinc	Zn		X(?)		X
Zirconium	Zr	X			

Table 5. Computer Calculated Concentration of Elements Detected by Instrumental Neutron Activation Analysis (Precision ± 20%) in PPM, Dry Coal

		Composite Sample Identification	
Element		C-9AA	C-13-1
Argon	Ar	10.8	11.4
Arsenic	As	.73	3.05
Barium	Ba	107	57
Bromine	Br	12.7	12.9
Cesium	Cs	ND	.042
Cobalt	Co	2.39	.93
Iron	Fe	5990	4210
Hafnium	Hf	.415	.525
Potassium	K	ND	245
Lanthanum	La	4.24	3.84
Sodium	Na	790	1120
Antimony	Sb	.384	.220
Scandium	Sc	.914	1.11
Selenium	Se	ND	.604
Strontium	Sr	184	329
Tantalum	Ta	.062	.076
Thorium	Th	.932	1.03
Uranium	U	2.41	.545
Manganese	Mn	96.49	ND
Tellurium	Te	2.22	ND
Gold	Au	.00166	ND

ND - Not Detected

3. GEOLOGY AND SUBSURFACE HYDROLOGY

The Dunn Center project area straddles the valley of Spring Creek, a tributary of the Knife River. The valley is about 15 miles wide and 250 feet deep. North of the project border is the Little Missouri arm of Lake Sakakawea, which is approximately 600 feet below the Knife River uplands. The project area is generally undulating and has an integrated drainage pattern typical of the Great Plains. The area is located to the southeast of the center of the Williston Basin and has been structurally stable for about 50 million years.

The generalized stratigraphy of the Dunn Center project area is shown in Figure 6, and a detailed description of the uppermost units is given in Figure 7. The Pierre Formation, consisting of a dark grey clayey shale, is about 1500 feet thick and is judged to be the base of significant groundwater flow. Above the Pierre at an elevation of 750 feet is the Fox Hills Formation. It is 250 feet thick and consists of alternating layers of sand, silt and clay. Above the Fox Hills is the Hell Creek Formation at an elevation of 1200 feet. It is 300 feet thick and consists of alternating lenses of clay, silt and poorly-sorted sand. The Cannonball Formation, at a depth of 900 feet, is 300 feet thick and is comprised of alternating sand, silt and clay. The Tongue River Formation is encountered at a depth of about 400 feet, is 500 feet thick, and is comprised of about 80 percent silt and clay layers, 15 percent sand layers and 4 percent lignite layers. The Sentinel Butte Formation ranges in thickness from 300 feet, below Spring Creek, to 550 feet thick in the northern and southern parts of the Dunn Center area. The Sentinel Butte Formation consists of about 60 percent alternating clay and silt, 30 percent silty fine to medium sand and 10 percent lignite. The Sentinel Butte Formation is the one that will be mined.

The sand layers in the Cannonball, Tongue River and Sentinel Butte Formations form important aquifers in the area and must be considered in evaluating the scope of groundwater pollution. A conservative estimate is that there is sufficient lignite within the project area to support four 250 MMSCFD coal gasification facilities over a 30 year plant life. (In all likelihood the plant life will be longer than this.) The Knife River Flint quarries are known to exist within the project area and are of archaeological interest. (13),(14) The project area climate has been arid to subhumid since the last glacial period. The area appears to be well-suited for a gasification facility.

Little data currently exist (5),(15) that deal directly with the subsurface hydrology in the Dunn Center area. The adjacent counties of Mercer and Oliver have experienced some work (16) which can be reasonably extrapolated to Dunn County.

Many water wells in the Dunn Center area top the lignite beds of Sentinel Butte and, to a lesser extent, the Tongue River Formation. The yield of these wells is typically 10 to 20 gpm (or less), suggesting a permeability of 10^{-5} to 10^{-4} feet per second, probably caused by fractures in the coal beds. (A drilling program taking place as this is written seems to be bearing out this judgment.) These permeability data are consistent with Croft's data. (16) Many of the clay beds in the Pierre and perhaps in the Cannonball Formation are expected to have permeability that is four to seven orders of magnitude less than the clay beds in the Sentinel Butte and Tongue River Formations. Thus, at least the Pierre and perhaps the Cannonball Formation may form an effective base of the regional flow system. A model of the regional flow system is being built as part of a continuing study to assess the impact of mining and waste disposal.

Unfortunately, the available data base at present permits only a qualitative assessment of the mining and waste disposal impact upon the groundwater system.

Wells within about two miles of an active mine are expected to be disturbed by the mining activities. In addition, available data indicate that water levels in wells will be affected by the mining activities even after reclamation. In some wells, the water level will be restored to its original level, in others it will be lower, and in some it will be higher. A significant amount of water chemistry data is currently available. (5, p. 123)

A possibility of groundwater pollution exists from several sources within the facility. Some of the more notable potential pollutants to be disposed of in the mine are the wetted gasifier ash, the sludge from the biotreating (phenols) ponds, the wastewater from the water-treatment plant, and the sludge from the scrubbers on the boilers. Studies of waste disposal streams in North Dakota oil fields (17) indicate that migration of waste fluids is possible and should be considered in the design of the facility and mine.

At this writing, a significant geological and groundwater hydrology study is being carried out which will considerably expand the data base for the project area. This program includes 60 stratigraphic test holes with geophysical logs, 60 piezometers installed in the test holes and a transient analytical groundwater-flow model of the project area.

4. SUMMARY AND CONCLUSIONS

A 250 MMSCFD dry ash Lurgi coal gasification facility has been proposed for the Dunn Center area. The facility will annually use about 13 million tons of lignite, 16,800 acre-feet of water and 2.4 million tons of oxygen. The sulfur emissions are expected to be about a tenth of the federal limits for the total facility and a quarter of the limits for the coal-fired boilers. The major gaseous effluent (by weight) is CO_2. Most (70 percent) of the water is evaporated from cooling towers. The trace elements in the coal have been established. Preliminary data indicate that most of the elements will be concentrated in the ash. The facility will be designed to satisfy or exceed all federal and state effluent limits.

The geology of the area was discussed. The area is seismically very stable. The coal resource, sufficient to support four facilities assuming a 30-year facility life, will be obtained from the Sentinel Butte Formation. The major aquifers in the area are located in the Sentinel Butte, Tongue River and Cannonball Formations. Some of these aquifers will be disturbed by mining activities. The water table within two miles of the mine will be lowered during mining. Water levels in wells within two miles of the mine following reclamation cannot be predicted at this time; however, it is expected that some will be raised, others lowered, and some returned to their original levels. The potential for groundwater pollution exists from any of several waste streams, both liquid and solid. Too few data are available at this time to predict the extent of groundwater pollution, but it is expected that some will occur.

An extended and continuing experimental and analytical program is being carried out in all of the above areas. This program includes analysis of chemical effluents from a gasification facility in South Africa, an extensive geological and subsurface hydrology program, and a continuing emission spectrum study.

5. RECOMMENDATIONS

The gasification industry, assuming one develops, should work to create and improve the effluent guidelines, particularly for the trace elements and common gaseous effluents. Current effluent guidelines are very limited for trace elements (mercury and beryllium) and may not be directly applicable for SO_2 and NO_x. (7),(18) The industry should develop a wider data base to determine the fate of trace elements during coal gasification. There is significant trace element concentration variability in coals which must be considered in determining the fate of trace elements during gasification. Government and industry should consider the geological and groundwater impact in designing a reclamation plan. Original contour and topsoil reclamation requirements do not necessarily protect groundwater sources.

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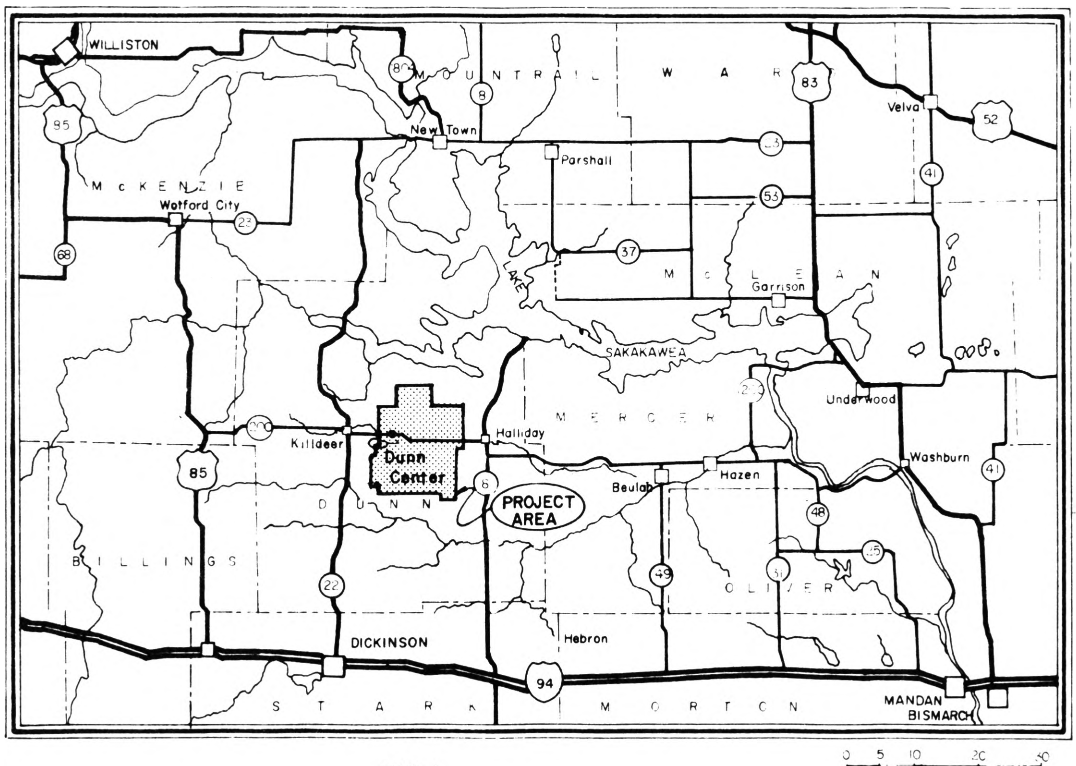

FIG. I

PROJECT AREA IN WESTERN NORTH DAKOTA

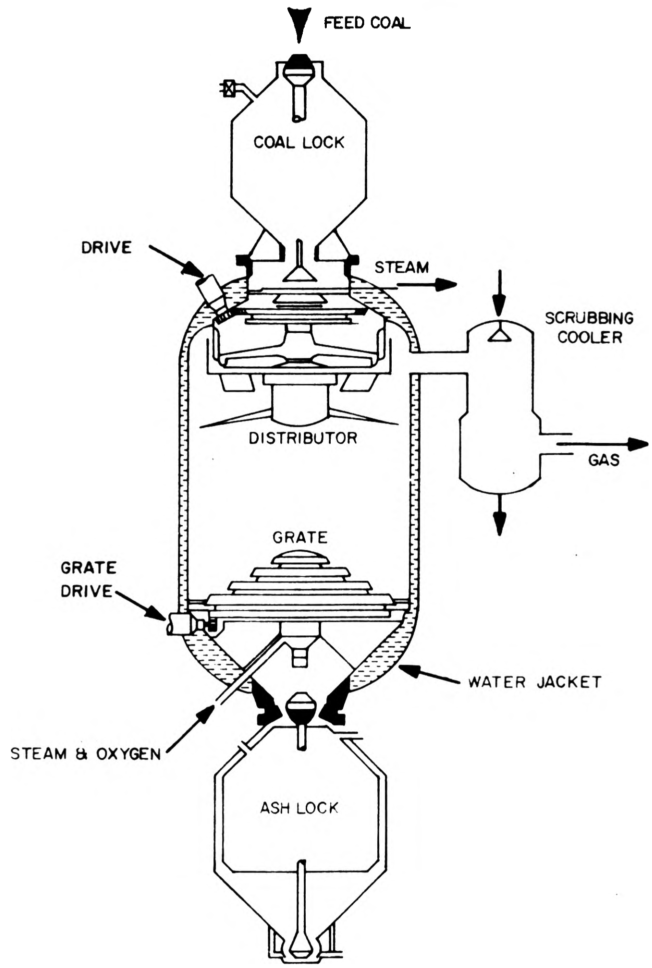

FIG.2
LURGI GASIFIER

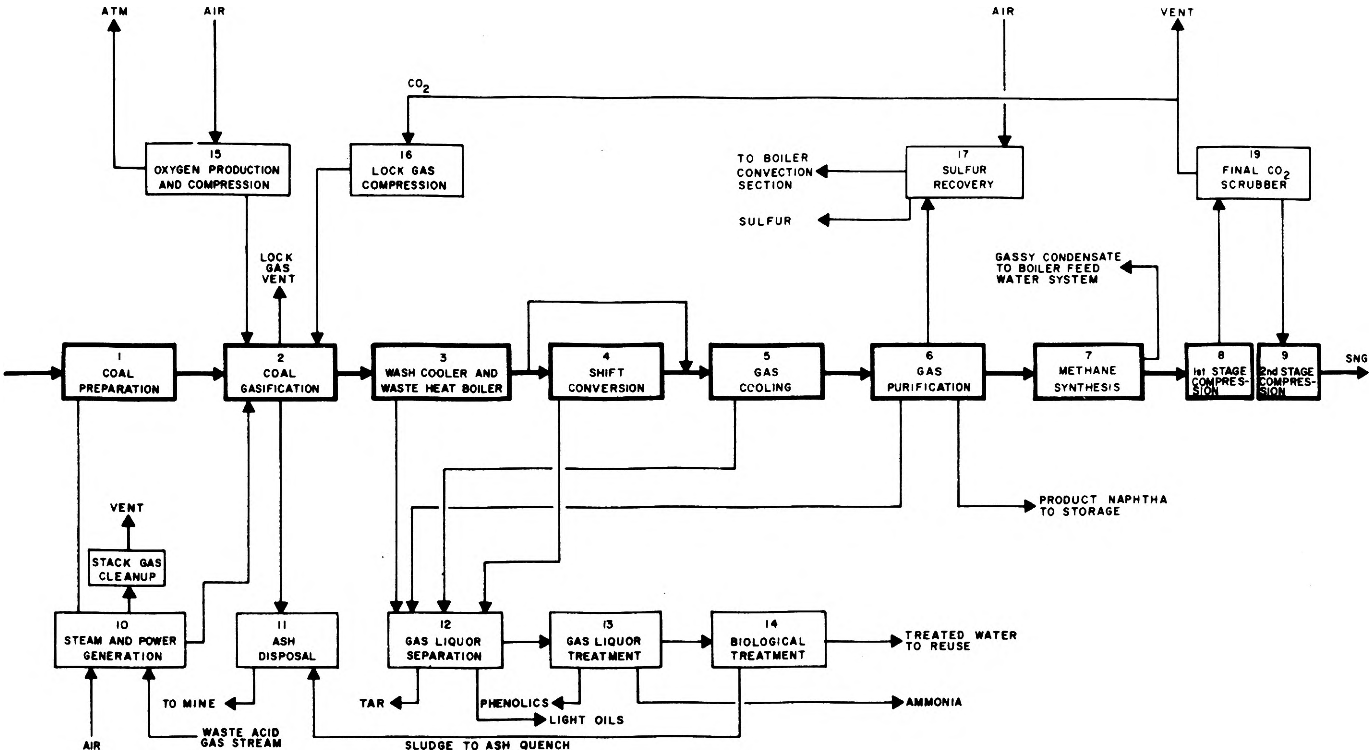

FIG. 3
TYPICAL LURGI PLANT PROCESS FLOW DIAGRAM

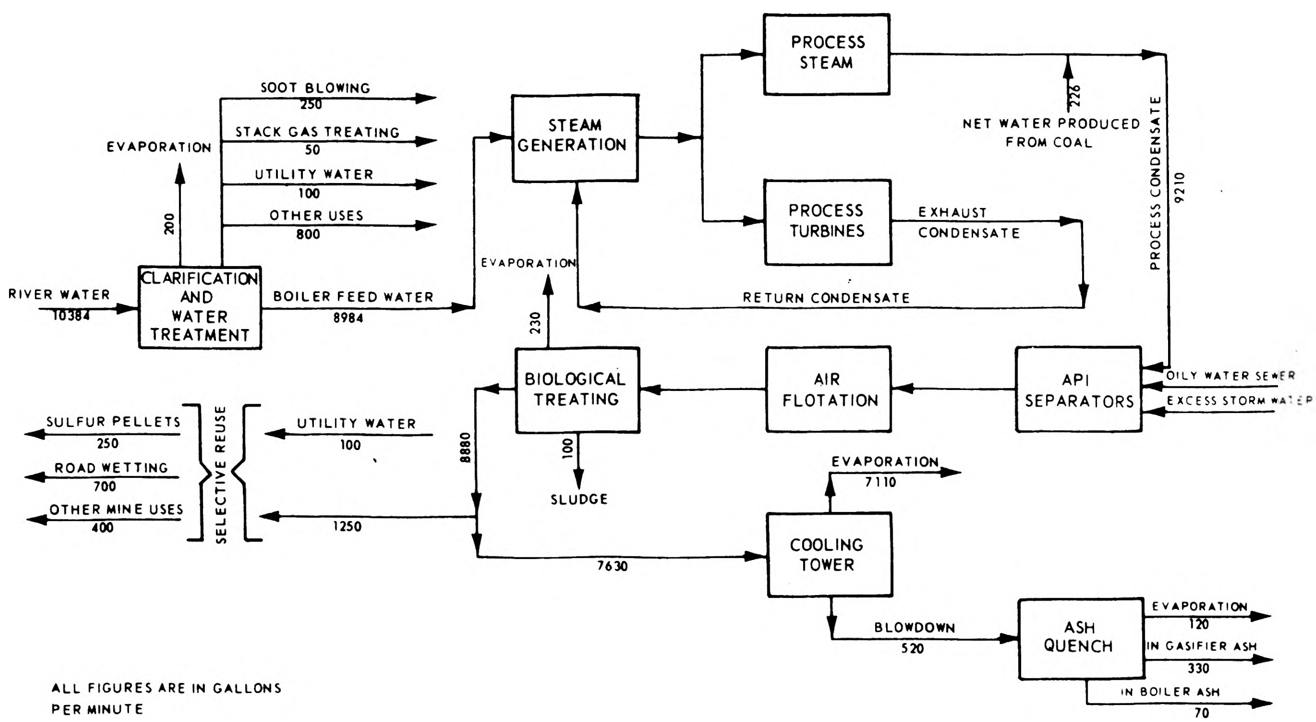

FIG. 4
WATER USE DIAGRAM

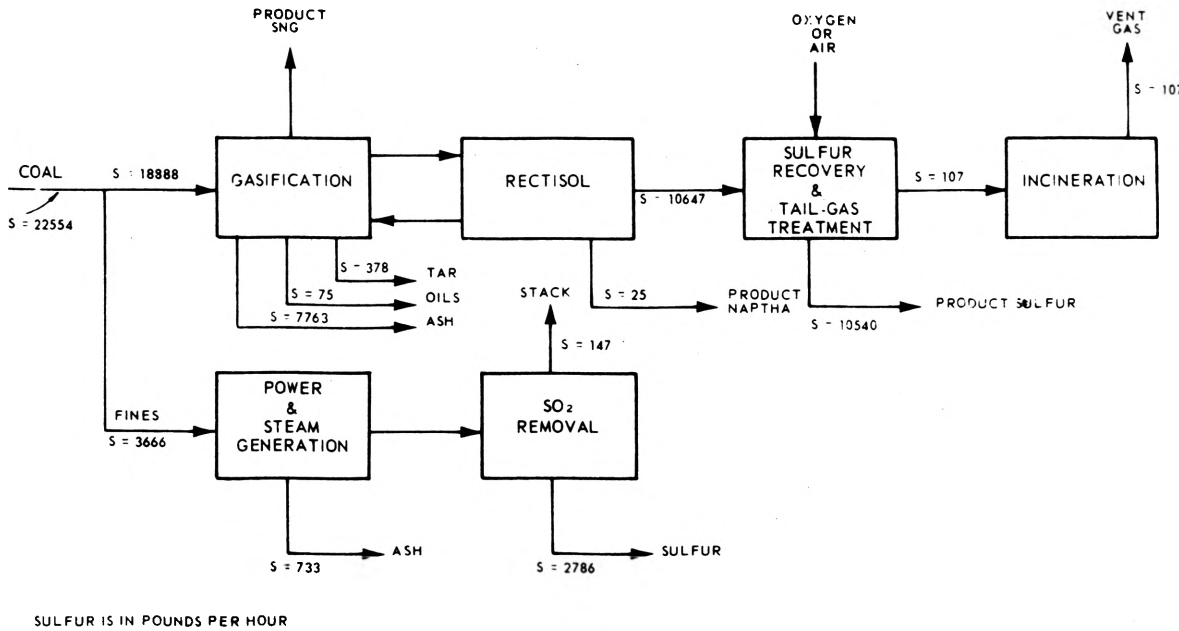

FIG. 5
SULFUR FLOW DIAGRAM

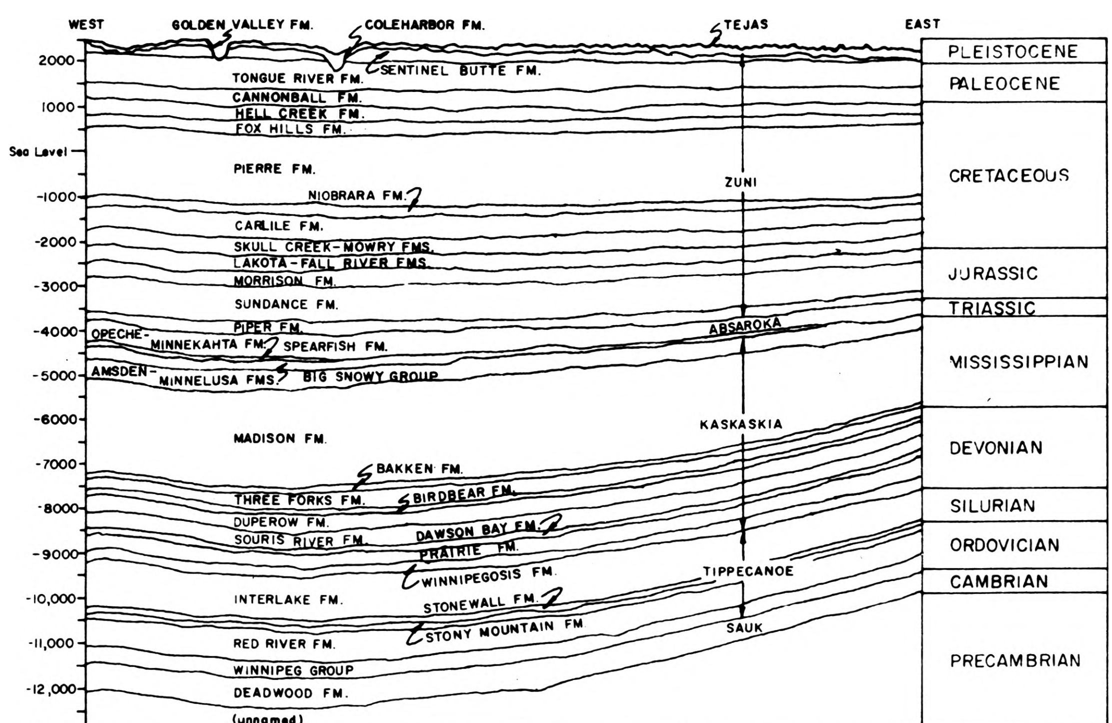

FIG. 6
GENERALIZED STRATIGRAPHY OF THE UPPERMOST 14,000 FEET IN DUNN CENTER AREA

FIG. 7

DESCRIPTION OF THE UPPERMOST STRATIGRAPHIC UNITS IN THE DUNN CENTER AREA

AGE	UNIT NAME					DESCRIPTION	
EOCENE	ZUNI SEQUENCE		GOLDEN VALLEY FORMATION	UPPER MEMBER		YELLOWISH, MICACOUS, CROSSBEDDED SANDSTONE, MORTMORILLONITIC SHALE, SILTSTONE, AND MINOR LIGNITE (FLUVIAL AND LACUSTRINE)	
				LOWER MEMBER		LIGNITE OR SILICIFIED SILTSTONE	(LACUSTRINE OR FLUVIAL)
PALEOCENE		FORT UNION GROUP	SENTINEL BUTTE FORMATION			LAVENDER CLAY	
						WHITE OR ORANGE, KAOLINITIC CLAY	
						GRAY CLAY	
						CROSSBEDDED SAND (PART OF GOLDEN VALLEY FM ?) (FLUVIAL)	
						UPPER YELLOW BED	
						LOWER YELLOW BED	
						"BIG BLUE" CLAY BED	
						SOMBER BROWNISH GRAY, 60% SILT AND CLAY (FLUVIAL OVERBANK, FLOODBASIN, AND OFFSHORE LACUSTRINE); 35% SAND (FLUVIAL AND SHORELINE); 3% LIGNITE (SWAMP); SOME SANDSTONE, SCORIA, AND LIMESTONE; PETRIFIED STUMP ZONE BELOW "BIG BLUE", STEEP, RILLED SLOPES	
						BASAL SAND BED	
			TONGUE RIVER FORMATION			HT LIGNITE BED	
						YELLOWISH, 75 % SILT AND CLAY (FLUVIAL OVERBANK, FLOODBASIN, AND OFFSHORE LACUSTRINE); 10% SAND (FLUVIAL AND SHORELINE); 3% LIGNITE (SWAMP); SOME LIMESTONE, SCORIA, AND SANDSTONE; GENTLE, ROUNDED SLOPES	
						BASAL SAND BED	
			LUDLOW FM / CANNON BALL FM	LEBO MEMBER		LEBO: DARK-GRAY CLAY WITH FLUFFY SLOPES.	CANNONBALL DARK SHALE (OFFSHORE MARINE) AND SAND (SHORELINE)
						SIMILAR TO TONGUE RIVER (YELLOWISH)	
						SIMILAR TO SENTINEL BUTTE (GRAY)	
				TULLOCK MEMBER		TULLOCK SIMILAR TO SENTINEL BUTTE, BUT THINNER BEDDED, YELLOWISH BED AT TOP	
LATE CRETACEOUS			HELL CREEK FM	PRETTY BUTTE MBR		DARK-GRAY CLAY, FLUFFY, ROUNDED, BARE SLOPES (LACUSTRINE)	
						SOMBER-GRAY, LIGNITE SHALE AND DIRTY CROSSBEDDED SAND, DARK-PURPLE CONCRETIONS (FLUVIAL, SOME MARINE)	
				COLGATE MBR		WHITE, CROSSBEDDED SAND (FLUVIAL)	
			FOX HILLS FM	BULLHEAD MBR		THINLY INTERBEDDED, BROWNISH-GRAY SILT AND CLAY	(MARINE COASTAL SEDIMENT)
				TIMBER L MBR		YELLOWISH, GLAUCONITIC, DIRTY, FINE SAND	
				TRAIL CITY MBR		GRAYISH-BROWN SILT AND CLAYEY SAND	
			PIERRE FORMATION	VIRGIN CR MBR		SOFT, DARK-GRAY, FLAKEY, NONCALCAREOUS SHALE	(MARINE OFFSHORE SEDIMENT)
				ODONAH MEMBER		HARD, SILICEOUS, NONCALCAREOUS, GRAY SHALE, REDDISH-BROWN STAINS ON JOINTS, A FOOT-THICK BED OF LIGHT-YELLOW WAXEY CLAY AT BASE, FORMS STEEP SLOPES	
				DEGRAY MBR		SIMILAR TO ODONAH MEMBER	
						SOFT SHALE THAT LACKS TREES IN WOODED AREAS	
				GREGORY MBR		THINLY-BEDDED, CALCAREOUS, GRAY TO YELLOWISH SHALE WITH FLUFFY SURFACE, COMMONLY SLUMPS	
				PEMBINA MEMBER		SLIGHTLY ORGANIC	SOFT, NONCALCAREOUS, BLACK SHALE WITH YELLOW STAINS, POORLY EXPOSED
						HIGHLY ORGANIC (FISH SCALES)	
						WITH WHITE, WAXEY, CLAY BEDS	
			NIOBRARA FORMATION			TAN TO ORANGE, CALCAREOUS SHALE, FORMS STEEP SLOPES	
						GRAY, CALCAREOUS SHALE WITH WHITE SPECKS	
			CARLILE FORMATION			SOFT, BLACK, NONCALCAREOUS SHALE WITH LARGE ELLIPSOIDAL CONCRETIONS, FINE SAND AT TOP	

THE CONSERVATION OF HUMAN RESOURCES IN ENERGY SYSTEMS

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Abstract

The operation of an energy system often requires that its personnel engage in manual and technical activities that involve exposure to health and safety hazards. A typical electric utility is used as a model for studying the operation of safety and health programs for energy systems. Specific criteria regarding standards and management are presented and discussed. These criteria are general enough so that they may be applied in the management of future energy systems.

1. INTRODUCTION

Annually, in American industries, more than 14,000 employees are killed and approximately 2,500,000 suffer disabling injuries. The National Safety Council estimates that the total cost to industry is 14 billion dollars, and some believe that the cost is even higher. (1)

This problem is dealt with herein with regard to the efforts that have been expended by the electrical utility industry to reduce this annual loss of human resources. In particular the impact of the Occupational Safety and Health Act of 1970 (OSHA) and its relationship to the present safety and health posture of the energy industry as well as future energy systems is examined.

Systems that generate and deliver energy usually have a working environment that exposes employees to many safety and health hazards. This has been true of the many operating utilities in the United States since their inception; however, several of them, such as the gas and electric utilities, have recognized the situation and have instigated safety and health programs which have made their places of employment relatively safe and healthful. This can be demonstrated by comparing the current data from various industries for the frequency of accidents (Table I).

The injury frequency rates shown in Table I are the number of disabling injuries per million man-hours of work. A tabulation of the severity rates would show that the electric utilities rank well below the industrial average. The severity rate is the time charges per million man-hours worked. This is due to the nature of the injuries sustained by electrical utility workers.

TABLE I

COMPARATIVE FIGURES FOR INJURY FREQUENCY RATES FOR 1973*

Industry	Frequency Rate
Communications	5.00
Electric Utilities	6.93
Gas	8.17
All Industry	10.55
Water	28.60
Sewer Systems	45.41
Streets & Highways	49.87
Refuse Disposal	71.86
Refuse Collection	104.53

*Courtesy National Safety Council and American Water Works Association

Because of their interest and past experience in the establishment of safety and health programs, the gas and electric utilities responded well and were very instrumental in formulating the standards for OSHA. The principal effort in this respect was expended by the investor-owned utilities, although the Rural Electric Cooperatives and some governmental agencies participated.

The enactment of OSHA was an event of some note for American industry. The Act states that "Each employer - (1) shall furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees; (2) shall comply with occupational safety and health standards promulgated under this Act." In other words, by law, the Act requires the employer to provide a safe and healthful workplace for his employees and to comply with certain standards. (2)

The first of these requirements, as stated previously, has been practiced by most of the electric utilities for many years as shown by the following discussion of a typical utility's approach to the establishment of a safety and health program.

2. A TYPICAL SYSTEM

The Union Electric Company, which has its general offices in St. Louis, Missouri, is a medium-sized utility, which serves the urban and industrial center of St. Louis and parts of the rural areas in Missouri, Iowa, and Illinois. Because of the diversity of its operations, this company is considered to be a good example of an energy system.

2.1 ELEMENTS OF THE SAFETY PROGRAM

The basic elements of the Union Electric's Safety Program are: (1) management responsibility, (2) assignment of responsibility, (3) maintenance of safe working conditions, (4) an accident record system, (5) a medical and first aid system, (6) training, and (7) employee responsibility.

Management's responsibility is assumed and demonstrated by written policy which is promulgated by the top management. The president of the company has delegated the proper authority throughout all management levels to provide for safe operation.

Personnel, such as the staff safety personnel, are assigned to the program and provided with authority to perform their duties. Adequate financing is budgeted to carry out the program. The safety organization is recognized and established as a decentralized operation with adequate safety personnel from the staff who are appointed to administer policy, to provide technical information and program materials, and to assist in the training programs. The heads for the different functions interpret and support safety policies. Managers and superintendents carry out the program. Foremen, who are the key persons in the program, inspect for compliance with safety rules and standards, train their workers in safety procedures, supervise the safe operations of their crews, maintain a safe work environment, and carry out the details of the safety program with respect to first aid, accident reporting, and accident investigation. The staff safety personnel carry out their assignments by advising, assisting, evaluating, and promoting the safety program within all of the departments of the company.

Safe working conditions are maintained by proper planning and control. Planning is accomplished by including or providing for safety in the design of new systems and in normal operations. Safety rules, standards, and work procedures are established and followed. The company has a safety suggestion system. Control is maintained by means of regular safety inspections, accident investigations, and accident analysis.

The accident record system is well established and is utilized by the company to provide a basis for identifying safety problems and causes of accidents as well as for evaluating the program.

The medical and first aid system provides information for the proper placement of newly hired personnel. It assures adequate care and rehabilitation of the occupationally injured. It also protects employees against health hazards in the work environment. This last provision is accomplished by a staff industrial hygienist whose duties are to recognize and evaluate the environmental factors of the work place.

Staff safety personnel direct the safety training and provide a central source for information and support. The basis for all training is the foreman who trains his workers. He is assisted in informal training by the safety supervisors who coordinate such activities.

The last element of the program is the responsibility of the employee. This is set forth very well in the Occupational Safety and Health Act under "Duties", Section 5(b) "Each employee shall comply with occupational safety and health standards and all rules, regulations and orders issued pursuant to this Act which are applicable to his own actions and conduct." This has been interpreted to mean that the employee follows his employer's rules as well as the OSHA standards. (3) This is especially appropriate for the utility worker, because in many instances there are no applicable OSHA standards, and the worker must follow the rules of the company in order to work safely. This may be even more true in energy systems of the future when relatively new processes and procedures will be involved. Where no specific OSHA standard applies, the administrators of the OSHA law have relied on the above general duty clause for enforcement of the Act. If a compliance officer observes an employee working in an unsafe manner, his employer is held responsible and is subject to possible citation and fines. This has been a very controversial part of the OSHA law for some, but it merely follows the practices of good management.

2.2 STANDARDS

The second requirement of the Act, for both the employer and the employee, requires that certain standards be followed. This has caused considerable confusion especially when the OSHA standards are involved.

There are more than 22,000 OSHA standards. These cannot be expected to cover all possible hazards in all industries. This has been found to be true in the utility industry, which always has been exempted from provisions of the National Electric Code for construction activities and has used the National Electric Safety Code instead. There are two OSHA standards that apply to utilities: the General Industrial Standards (1910) and the Construction Standards (1926). The numbers refer to that portion of the Federal Register where the standards are found, and these numbers are used by industry to indicate the specific standards. Because a large percentage of the work done by utilities is construction, the 1926 Standards are usually applied. If a specific standard cannot be found in the 1926 Standards or they do not apply, the 1910 Standards are tried. If this fails, then the utility finds another standard or devises its own standards or rules.

The 1910 Industrial Standards do not specify specific electrical standards, instead Subpart S of that standard adopts as a national concensus standard the National Electric Code, NFPA 70-1971. This standard specifically exempts two industries: communications and electric utilities. (4) There are some exceptions in the electric utility industries where the 1910 Standards must be used for facilities in offices, warehouses, garages, and shops. Those facilities directly used for transmission and distribution of electrical energy are excluded. Standards for transmission and distribution are found in the 1926 Construction Standards under Subpart V. (5) These standards create a unique situation for the electric utilities by setting up a separate set of vertical standards for the transmission and distribution of electric energy. Vertical standards are those which apply specifically to one industry as opposed to horizontal standards which might apply to any industry; however, the standards that are found in Subpart V do not apply to the generation of power. The operation of generating stations is governed by the 1910 Standards for General Industry unless there is a period of construction when the 1926 Standards apply.

Thus, it can be seen that the application of standards for the operations within an electric utility are quite complex; however, they do provide a legal basis for the safe operation of such an energy system and in this respect can be extended to energy systems in the future.

3. CONCLUSION

It has been shown that safety and health problems do exist for energy systems, and an examination of an electric utility illustrates how one company copes with these problems by using a well-organized and structured program. The following are some general rules which may be used to establish a safety and health program for energy systems:

(1) Cultivate a positive attitude.

(2) Procure and maintain a good reference library.

(3) Put policies, rules and regulations in writing.

(4) Ensure top management's responsibility.

(5) Determine the objectives of the program.

(6) Establish priorities for accomplishment.
(7) Integrate into line management.
(8) Provide a staff organization.
(9) Set up a training program.
(10) Establish a means for evaluation and control.

The above rules could be called "the ten positive rules for a safe and healthful energy system". If properly applied, they will do much to help conserve America's most valuable resource for now and in the future.

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5. BIOGRAPHIES

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HOW MIGHT SYNTHETIC FUELS FROM COAL AFFECT NATURAL RESOURCES AND ENVIRONMENT?

by

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Abstract

Energy self-sufficiency for the U. S. requires substantially increased use of coal. Direct combustion of coal without adequate environmental controls, as would occur if coal were used as a fuel for homes and offices throughout the country, would result in severe air pollution problems. Synthetic fuels from coal such as methane, low BTU gas, or hydrogen, when utilized by the homes and businesses as gas or as electricity from gas, will contribute a much smaller amount of air pollution. However, to make these synthetic fuels available, it is necessary to mine more coal than would have to be mined for direct combustion, as the conversion processes all have energy losses. It is also necessary to make more extraction equipment, more fuels processing equipment and more distribution equipment which places a heavier burden on mineral resources, with associated added requirements for energy to make the equipment.

This paper explores the effects on energy resources, and the environment by carefully taking account of extra coal needed, extra equipment required, and the associated environmental costs due to all forms of pollution resulting from the mining operation, conversion of coal to synthetic fuels, and the combustion of the synthetic fuels. Resource depletion and environmental impact are compared for the present system and a synthetic gas system which provides all of our electric power.

1. INTRODUCTION

It is well known that the material standard of living in an industrialized society such as ours is roughly proportional to the amount of energy resources converted by industry into beneficial goods and services (1)*. The recent oil embargo with its painful economic consequences has forced our society to examine carefully the problems concerning our energy resources. Energy self-sufficiency would certainly be preferred to reliance on imported resources with undesirable associated political and economic pressures.

Of our domestic energy resources, only coal is abundant enough to provide the hoped for self-sufficiency. Petroleum and natural gas, and to a lesser extent uranium, are in more advanced stages of their respective life cycles (2). The disadvantages of coal are well known. Coal is a solid substance, making it much less convenient as a fuel than gas or oil. From an environmental standpoint, coal is a dirtier fuel (3). Whether strip mined or deep mined, coal is responsible for some very serious and costly land and water degradation problems. When coal is burned without adequate environmental controls, it contributes to serious air pollution problems. With careful controls, much of this coal-generated pollution can be eliminated, but at a rather substantial cost (4).

A very promising alternative for coal which would provide convenient and clean fuel for a wider range of energy users is synthetic gas from coal. Two types of gas are possible, depending on the process. Low BTU gas, requiring a simpler gasification process is useful as a gas turbine fuel, and has been considered as a promising fuel for the topping cycle of combined cycle power plants. Pipeline gas, essentially pure methane, is also a possible product of coal gasification; requiring more complex manufacturing processes. The gasification processes and the

* Numbers in parentheses indicate references cited at the end of the paper.

various uses for the gases are discussed in References (5) and (6).

Synthetic gas from coal, though clean and convenient, is not totally free from problems. The processes which can be used to convert coal to gas have efficiencies between 70 and 80% (coal Btu's to gas Btu's). This means that for a given fuel energy content, more coal is required for gas than if the coal were utilized directly as a fuel. For either type of synthetic gas, rather large quantities of water must be used in their manufacture (7). Water is used to supply the steam for the heat processes and to supply the hydrogen for the gases, molecular hydrogen and methane in low Btu gas, and methane in pipeline gas. In many regions where coal is plentiful and near the surface for convenient stripping, water is scarce and is also in demand by agriculture and other industries. If synthetic gas is the principal coal product, then more coal must be mined, resulting in an increase of the environmental damage resulting from the mining activity. Also, additional apparatus (gasifiers) must be built and maintained, which requires added energy resources. The most damaging pollutants when coal is burned directly are sulfur, particulate matter and ash. In a properly functioning gasifier, most of these are trapped. The sulfur is a useful commercial by-product; the particulates and ash are disposed of as solid waste, frequently by returning them to the worked portion of the mine and buried. All these process steps require equipment and trained personnel and therefore, add substantially to the cost of gaseous fuel (8).

This paper examines the effects on energy resources and the environment of one possible alternative, that of converting the portion of the electric power industry now based on fossil fuel (petroleum, gas, and coal) to synthetic gas from coal using combined cycle generation systems. Results are compared with the present mixed fuel system. Comparisons are made on the basis of a simplified mathematical equilibrium model of the U. S. energy-economic system, developed in another paper by the author (9). Parts of this paper are included, for completeness, in the next section. The important quantities obtainable from the model are energy flows into the various sectors (Btu/yr.), dollar flows into and out of the sectors ($/yr.), labor (person-hr./yr.), devoted to resource extraction and production, and environmental costs ($/yr.) to our society as a result of the considered activity.

2. THE U. S. ENERGY-ECONOMIC SYSTEM MODEL

Statistical information about energy consumption, dollar flows and labor potential are available in various documents (refs. 10, 11, 12, 13). It is customary to account for the energy resources (all forms) extracted from the earth by splitting the energy economy into four main sectors, namely industry, electric power, home and commerce, and transportation. Energy flows for 1975, projected from data of previous years assuming normal growth rates and full employment not now enjoyed, are displayed in flow chart form in Figure 1. Using this chart and other pertinent data in the references cited above, it is possible to develop a simplified energy-economic system model which is based on three sectors, namely the extraction sector which provides the basic fuel resources, a production sector which provides goods and services to the consumer and uses some of the fuels provided by extraction, and a consumption sector which utilizes the goods and services of production and some of the fuels from extraction. The consumption sector (all of us!) provides the labor for extraction and production. Dollars flow from sector to sector in the opposite direction to flows of fuel, goods and services and labor. The total labor force is assumed to have an income equal to half of the gross national product, and the quantities of labor assigned to extraction and production are assumed proportional to the dollar values for each sector. Numerical data for energy, dollars and labor are obtained from Ref. (10). The results are displayed in the form of a flow chart in Figure 2. All dollar values are given in 1971 dollars.

The mathematical model to be used for comparison of various alternatives is constructed from Figure 2. The variables of interest are:

F = total fuel from energy resources, Btu/yr.

F_P = fuel to production sector, Btu/yr.

F_C = fuel to consumption sector, Btu/yr.

F_E = fuel used by extraction sector, Btu/yr.

L_P = production labor, person-hr/yr.

L_E = extraction labor, person-hr./yr.

GS_C = goods and services to consumption sector, \$/yr.

The following relations among the variables are assumed:

$$F_P + F_C + F_E = \beta_E L_E \quad (1)$$

$$F_E = f_E L_E \quad (2)$$

where β_E and f_E are constants for the economy in any particular year. On eliminating F_E, we get

$$F_P + F_C = (\beta_E - f_E)\, L_E \quad (3)$$

Also it is assumed that

$$GS_C = \ell L_P + \frac{\ell}{\beta_E - f_E} F_P \quad (4)$$

$$L_P + L_E = L, \text{ the total labor available} \quad (5)$$

$$F_P = (\beta_P/\eta_P)\, L_P \quad (6)$$

$$F_C = (k_C/\eta_C)\, GS_C \quad (7)$$

where ℓ = average hourly wage, \$/person-hr.

β_P = production fuel - labor constant, Btu/person-hr.

k_C = consumption fuel - dollar constant, Btu/\$

η_P = production efficiency, $\dfrac{\text{useful energy output}}{\text{energy input}}$

η_C = consumption efficiency, $\dfrac{\text{useful energy output}}{\text{energy input}}$

For 1975, from Ref. (10) the following values of the system constants defined above, are obtained.

TABLE I

β	= 5.159 x 10^6 Btu/person-hr.
f_E	= 0.423 x 10^6 Btu/person-hr.
η_P	= 0.524
η_C	= 0.441
(β_P/η_P)	= 0.158 x 10^6 Btu/person-hr.
(k_C/η_P)	= 0.0684 x 10^6 Btu/person-hr.
ℓ	= 4.173 \$/person-hr.
L	= 173 x 10^9 person-hr./yr.

Note that the quantity $\frac{\ell}{\beta_E - f_E}$ in Equation (4) is the price of fuel.

The solutions to Equations (1) through (7) are

$$F_C = \frac{L}{\left[\frac{1}{\beta_E - f_E} + \frac{1}{\ell\,(k_C/\eta_C)}\right]} \quad (8)$$

$$GS_C = \frac{F_C}{(k_C/\eta_C)} \quad (9)$$

$$L_P = \frac{GS_C}{\ell\left[1 + \frac{(\beta_P/\eta_P)}{\beta_E - f_E}\right]} \quad (10)$$

$$L_E = L - L_P \quad (11)$$

$$F_P = (\beta_P/\eta_P)\, L_P \quad (12)$$

$$F_E = f_E L_E \quad (13)$$

$$F = \beta_E L_E \quad (14)$$

3. MODELING OF ENVIRONMENTAL EFFECTS

Portions of the labor assigned to extraction and production in Figure 2 are used to combat undesirable environmental effects. For example, in the extraction sector some effort must be expended in controlling water pollution from acid mine drainage and in restoring strip mined land after coal has been removed. In the production sector effort is expended on such activities as sulfur and ash removal from coal, disposal of solid wastes, control of effluents from power plants and industries, and in the development and manufacture of devices to reduce damaging effluents which come from transportation vehicles.

Suppose, for the time being, that environmental effects are of no concern. Then the portions of labor assigned to environmental controls can be diverted totally to extraction and production. In this (unrealizable) case, β_E, η_P, and η_E would each be greater than the values given previously. For coal mining approximately 4% of the cost of the fuel is attributable to environmental controls (3). For other energy resources, the costs are not as high. As a conservative estimate, we shall assume that 2% of the cost of fuel is for environmental control. Thus, β_E for an uncontrolled economy would be

$$\beta_E^* = (1.02)\ (5.159 \times 10^6) = 5.262 \times 10^6 \text{ Btu/person-hr.}$$

The production sector consists of that portion of electric power supplied to industry, and the various industrial processes using energy to supply the manufacturer with various refined raw materials such as steel, aluminum, cement, etc., and in the manufacture of consumer products. For coal fired power plants, the following cost increases are attributable to pollution control (4):

6% for sulfur removal

3% for particulates removal

1% for waste heat control

10% Total

We shall assume that the overall percentage cost increase for the production sector due to pollution control is 7%. This is less than the 10% total for electric power from coal since not all industrial processes use coal. Then the production efficiency for an economy without environmental controls would be

$$\eta_P^* = (1.07)\ (0.524) = 0.561$$

For the consumption sector only its share of electric power and its transportation are the primary contributors to environmental damage. We shall assume that transportation and electric power have the same cost increases due to pollution control as electric power, and that home and commerce have none. Using the energy flow values of Figure 1, it can be shown that the approximate overall cost increase due to environmental controls in the consumption sector is 6.4%.

The values of production and consumption sector efficiencies, without environmental controls, would therefore be

$$\eta_P^* = 1.07(0.524) = 0.561$$

$$\eta_C^* = 1.064(0.441) = 0.470$$

Now consider a fictitious modification of the 1975 energy-economic system of Figure 2 for which β_E^*, η_P^*, and η_C^* are used instead of β_E, η_P and η_C. We also assume that the 2% increase in β_E results in a 2% increase in GNP, which in turn results in a 2% increase in ℓ, the average hourly wage. That is

$$\ell^* = 1.02(4.173) = 4.257 \text{ \$/person-hr.}$$

The results of using Equations (1) - (7) with the above modified constants are shown in Figure 3. On comparing Figure 2 with Figure 3 it is seen that if pollution damage could be ignored (which of course it can't!) less total energy would be consumed, and the dollar value of goods and services would be greater for the same labor input.

Now consider the alterations in the previous unrealizable economy by including the actual costs to society of pollutants which would enter our land, water and air if no environmental controls were employed. The effects of these pollutants are essentially of two types:

(1) reduction in productivity in the production sector due to decreased agricultural production and reduced worker performance

(2) unwanted conditions detracting from

the qualify of life, such as dirty air and water, eye and lung irritation, health hazards, all of which require some form of combative effort to reduce or avoid.

Using data from Ref. (3) in which various environmental costs of types (1) and (2) are stated, one can deduce that the uncontrolled environmental costs of a coal-fired (2% sulfur coal) power plant are three times as great as the costs of adequate environmental controls. Here it will be assumed, conservatively, that the environmental damage resulting from the production sector, with no environmental controls, is twice the cost of adequate pollution control in this sector (industry plus power generation).

The effect of loss in worker productivity is accounted for in the analysis which follows by modifying the values of β_E^*, f_E^*, and β_P^*, the fuel-labor constants. In each instance a 4% reduction in fuel Btu flow per person-hour of labor is assumed. This is twice the value for worker performance reduction due to the presence of carbon monoxide alone in city air (3). It seems reasonable to assume that the combined effects of sulfur and particulates are equally as damaging to human health and performance as those of carbon monoxide. A 4% decrease in GNP is assumed to result from the decline in productivity, with an associated 4% decrease in hourly wage. Here we use ℓ = 4.093 \$/person-hr. This means that the actual beneficial goods and services are reduced by 8% as a result of environmental damage when no environmental controls are employed (2 x 2% for the production sector plus 4% for loss in productivity).

The value to society of environmental controls is most evident in rough economic terms. The "cost" to society in lost goods and services due to pollution control is approximately 2.4% (compare Figures 3 and 2), while the cost to society in the absence of controls is 8%.

The effect of unwanted dirt and irritation is accounted for by reducing the efficiencies for production and consumption, η_P^* and η_C^* obtained previously by 14% and 13% respectively (twice the costs of controls). The results for such an uncontrolled system, including environmental damage, are given in Figure 4.

On comparing Figure 4 with Figure 3, it is seen that neglect of environmental effects results in 8% more total fuel used, and a 4.5% reduction in the dollar value of goods and services to consumers. It should be remembered that a portion of the dollar flow for goods and services is to combat unwanted effects such as dirt and irritation by paying for cleaning, painting, extra lighting, transportation required to escape the dirty environment, extra taxes, etc. Thus the actual beneficial goods and services is somewhat less than that shown in Figure 4. Data given in Ref. (3) indicate that roughly 3.5% of the dollars spent for goods and services is used to combat unwanted effects. Thus it is seen that the total % reduction in beneficial goods and services is 8%, as assumed.

4. POLLUTION DAMAGE

In the last section it was shown that the social cost of pollution control is a 2.4% reduction in beneficial goods and services, while in the absence of controls the cost is an 8% reduction.

It will be assumed that the pollution damage varies as the square of the amount of effluent in the environment and that the cost of control varies as the square of the amount of effluent removed (see Figure 7).

The first assumption is based on the idea that the more rapidly waste is inserted into the environment, the slower will the natural process of dissipation become. Similarly the cost to remove pollutants increases more rapidly than the amount to be removed because of the increasing technical difficulties in locating and separating unwanted substances from larger and larger volumes.

Let P_E = percent of effluent removed

C_C = cost of pollution control, in % reduction in goods and services

C_P = pollution cost, or environmental damage, in % reduction in goods and services

Then

$$C_C = \frac{2.4}{10^4} P_E^{\,2}$$

$$C_P = \frac{8}{10^4} (100 - P_E)^2$$

The optimum percentage of effluent removed is that for which the social cost $C = C_C + C_P$ is a minimum.

$$C = C_C + C_P = \frac{2.4}{10^4} P_E^{\,2} + \frac{8.0}{10^4} (100 - P_E)^2$$

For a minimum,

$$\frac{dC}{dP_E} = \frac{4.8}{10^4} P_E - \frac{16.0}{10^4} (100 - P_E) = 0$$

or

$$\frac{20.8}{10^4} P_E - \frac{1600}{10^4} = 0$$

The optimum value of P_E, for the minimum social cost is

$$(P_E)_{opt} = \frac{1600}{20.8} = 77\%$$

The social cost C for this amount of effluent removed is

$$C_{opt} = \frac{2.4}{10^4} (77)^2 + \frac{8.0}{10^4} (23)^2$$

or

$$C_{opt} = 1.85\%$$

As a rough measure of cost to society for removal of effluents to the optimum condition, we shall use 2% of the dollar value of all goods and services, including the electrical energy sent to the consumption sector.

Modeling of System with Electric Power from Coal via Synthetic Gas

Consider the case in which all electric power, which in 1975 consumes approximately 27% of the total fuel for the whole system, is obtained by using synthetic gas from coal. This alternative is realizable, and if it is done, would enable the U. S. to be self sufficient in energy resources. It will be assumed that the gas is used to operate combined cycle plants such as the one diagrammed in Figure 5.

Coal, after being mined and processed, is transported to the gasification plant. Here it is converted to low Btu gas at an efficiency of 77%. Then the gas is used as a fuel in a combined cycle power plant consisting of a gas turbine first stage and a steam plant second stage. The combined cycle plant is assumed to have overall efficiency,

$\frac{\text{Electrical energy out}}{\text{Gas energy in}}$, of 45%. See Ref. (4) for discussion of such systems.

To analyze the effect on energy resources and the environment of this coal-based synthetic gas electric power sector,* it is necessary to modify Figure 2 including the electric power generation and gas producing sectors as separate items apart from the production sector as shown in Figure 6. In this arrangement, the production sector consists of the industrial sector only. It is necessary to know some additional facts such as the amounts of labor required to gasify the coal and to operate the power plants, the dollar values ($/yr.) for maintenance and capitalization of coal gasification and power generation equipment, the cost of coal to the gasification plant and of gas to the power plant, the amounts of electrical energy used by the production and consumption sector, and the unit cost of the electricity.

Electricity generated in this manner will be more expensive than that generated by present (mostly petroleum based) steam plants because of the extra stage (the gasifier) in the process. This added cost may influence industry, home users and businesses to use less electricity than now. However, to make the analysis as simple as possible, it will be assumed that industry and the consumption sector use the same amounts of electricity as shown in Figure 1.

An estimate of the labor required for the

* For simplicity in analysis the portions of electric power from nuclear and hydroelectric sources are also assumed to be replaced by coal-gas systems.

power generation sector will now be made. On the average, in 1971, power plants spent 50% of their income for capital recovery, taxes and fair return (14). Assuming that the average cost of electricity in 1975 was 3.2¢/Kwhr, it is possible to show that the 6.8×10^{15} Btu/yr of electrical energy, shown in Figure 1, yields a total income of 63.74×10^9 \$/yr. The fuel cost, using the fuel price of 0.8813×10^{-6} \$/Btu given in Figure 2, is 18.60×10^9 \$/yr. The amount used for capital, taxes and investor return is 50% of total income, or 31.87×10^9 \$/yr. Thus, the cost of labor is what remains of the total income, or 13.27×10^9 \$/yr. Using the hourly rate of 4.173 \$/pers-hr. obtained from Figure 2, the total power plant labor is found to be:

$$L_{EP} = 3.18 \times 10^9 \text{ pers-hr./yr.}$$

Next an estimate of the labor required for coal gasification will be made. According to Perry (8), the cost to gasify strip mined coal is 0.7×10^{-6} \$/Btu. If the combined cycle power plant has an efficiency of 45%, and if transmission lines have an efficiency of 85% (5), then the gas energy required to supply 6.8×10^{15} Btu/yr. to customers is 17.78×10^{15} Btu/yr. The cost of gasification is therefore $0.7 \times 10^{-6} \times 17.78 \times 10^{15} = 12.45 \times 10^9$ \$/yr. for labor, equipment, capitalization, etc.

Assume now that the cost of capital, taxes and fair return for the gasifiers is 1/6 of that for the power plant or 5.31×10^9 \$/yr. Therefore the cost of labor for gasification is 7.14×10^9 \$/yr., and the amount of labor can be shown to be:

$$L_{CG} = 1.71 \times 10^9 \text{ pers-hr/yr.}$$

The unit cost of coal to the gasifier is 0.9 $\times 10^{-6}$ \$/Btu (8) and the amount of coal used at 77% gasifier efficiency is 23.09×10^{15} Btu/yr. Therefore the total coal cost for the entire industry is 20.78×10^9 \$/yr. Thus the cost to the gasification industry for maintenance and operation is the cost of gasification minus the labor cost, or 5.31×10^9 \$/yr., which flows from CG to P in Figure 6.

The unit cost of electricity to customers in industry and the consumption sector is obtained as follows. The cost of gas to power plants is the sum of the cost of coal and the cost of gasification, or 33.23×10^9 \$/yr. The unit cost of electricity is the sum of the above gas cost, the cost of power plant labor (3.18×10^9 pers-hr/yr. @ 4.173 \$/pers. hr., or 13.27×10^9 \$/yr.), and the cost of capital taxes and investor return (31.87×10^9 \$/yr.) divided by 6.8×10^{15} Btu/yr. The result of this computation is 11.53×10^{-6} \$/Btu of generated electricity (or approximately 3.9¢/Kwhr.).

Figure 6 shows the results of dollar, labor and energy flow analyses for the economy in which all electrical energy is supplied by synthetic gas from coal. These results were obtained by solving the following set of equations for L_E, L_P, GS_C, P_F, F, F_E, F_P, and F_C:

$$L_E + L_P = (173 - \underbrace{3.18}_{L_{EP}} - \underbrace{1.71}_{L_{CG}}) \times 10^9 \quad (15)$$

$$GS_C + P_F F_C + \underbrace{39.78 \times 10^9}_{\substack{\text{cost of}\\ \text{elect. to}\\ \text{consump.}\\ \text{sector}}} = \underbrace{4.173(173 \times 10^9)}_{\substack{\text{cost of total}\\ \text{labor force}}} \quad (16)$$

$$GS_C = \underbrace{38.63 \times 10^9}_{\substack{\text{cost of elect.}\\ \text{to prod.}}} + 4.173\, L_P + P_F F_P - \underbrace{31.87 \times 10^9 - 5.31 \times 10^9}_{\substack{\text{Cap. \& taxes in gasif.}\\ \text{\& elect. ind.}}} \quad (17)$$

$$F_P = (\bar{\beta}_P / \bar{\eta}_P) L_P - \underbrace{5.027 \times 10^{15}}_{\substack{\text{electricity to}\\ \text{prod.} \div \bar{\eta}_P}} \quad (18)$$

$$F_E = f_E L_E \quad (19)$$

$$F = \beta_E L_E \quad (20)$$

$$P_F = \frac{4.173}{\beta_E - f_E} \quad (21)$$

$$F_C = (\bar{k}_C / \bar{\eta}_C)\,(GS_C) - \underbrace{5.789 \times 10^{15}}_{\substack{\text{electricity to}\\ \text{consump.} \div \bar{\eta}_C}} \quad (22)$$

where, in the above equations the constants

β_E, f_E, etc. are:

TABLE II

β_E = 5.1587 x 10^6 Btu/pers-hr.

f_E = 0.4233 x 10^6 Btu/pers-hr.

$\overline{\eta}_P$ = 0.666

$\overline{\eta}_C$ = 0.477

$\overline{\beta}_P/\overline{\eta}_P$ = 0.1318 x 10^6 Btu/pers-hr.

$k_C/\overline{\eta}_C$ = 0.0632 x 10^6 Btu/\$

Note: $\overline{\eta}_P$ is different from the value of η_P in Table I because η_P is obtained from data in which electric power is included in the production sector. Here we have separated the power sector from production. Similarly $\overline{\eta}_C$ is different from η_C because $\overline{\eta}_C$ is computed for non-electric energy to consumers only. Details of these computations are omitted here.

5. CONCLUSIONS

Some important conclusions obtainable by comparing Figure 6 and Figure 2 are:

(1) The total amount of energy resources used increases by approximately 2%.

(2) The dollar value of goods and services to consumers, including electrical energy, increases by 1.5%.

(3) The dollar value of goods and services, exclusive of electrical energy increases by 0.15%
Note: The present dollar value of electrical energy to consumers is 30.33 x 10^9 \$/yr.

(4) The total cost to society for environmental effects (environmental damage plus control costs for optimum conditions) increases by 17%. For the present system it was shown previously that the environmental cost for optimum conditions was 2% of the dollar value of goods and services. The corresponding cost in percentage of goods and services for the substitute system, in which all electric power is generated by using synthetic gas from coal, will be slightly higher since coal is a dirtier fuel. It is found from the following:

$$\frac{(3\%) \times \overbrace{(23.09 \times 10^{15})}^{\text{Coal Btu}} + (2\%) \times \overbrace{(56.45 \times 10^{15})}^{\text{Other fuel Btu}}}{\underbrace{79.54 \times 10^{15}}_{\text{Total fuel Btu}}} = 2.3\%$$

Thus in calculating the environmental cost for the system with the coal-synthetic gas-electric economy we use 2.3% of the dollar value of goods and services, including the dollar value of consumer electricity.

Table III summarizes the resource and environmental costs to the U. S. society, at 1975 levels of energy resource use and at full employment, for the present mixed resource system (with domestic petroleum prices) and for a substitute system in which synthetic gas from coal is used as fuel for the entire electric power generation industry.

The indicated increases in total energy resources consumed and in environmental cost for the synthetic gas economy are small compared to the increases in fuel cost when large amounts of petroleum must be imported at high prices. Thus it seems advantageous to proceed with such a plan.

One item not considered in this paper is the effect of the large amounts of water needed to produce the synthetic gas. Since much coal to be mined is on Western lands, the water required would be scarce and expensive, particularly if it had to be piped over long distances. This may cause an increase in the cost of synthetic gas over that assumed in the paper with accompanying increases in the cost of electric power. There would also be political conflicts over the use of the water, particularly if the water to agriculture in the region near the coal gasification plant is reduced.

This problem, and the effects of disturbing large areas due to strip mining, are not included in the estimated environmental costs. A rough estimate of the land degradation cost is the dollar value of the biomass production lost during the years when the area is being mined. This would vary considerably for different situations, depending upon whether the land produced trees, grasses, or food crops prior to mining.

TABLE III

	1975 Mixed Energy-Economic System (increases in cost of imported oil and in unemployment are ignored)	Substitute System where electrical energy is derived from synthetic gas from coal
Total Energy Consumed	78.0×10^{15} Btu/yr	79.54×10^{15} Btu/yr
Dollar value (1971 dollars) of goods and services, including electrical energy	680.94×10^{9} $/yr	691.37×10^{9} $/yr
Dollar value (1971 dollars) of goods and services, excluding electrical energy	650.61×10^{9} $/yr	651.59×10^{9} $/yr
Cost to society from pollution control and environmental damage	13.62×10^{9} $yr	15.90×10^{9} $/yr

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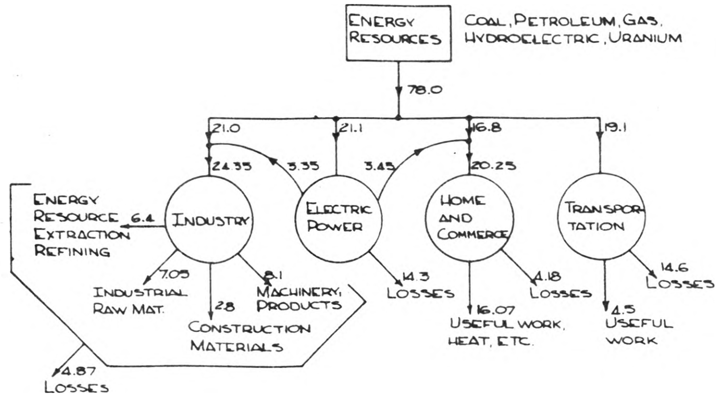

ALL NUMBERS ARE IN QUADRILLION (10^{15}) BTU

FIG. 1 U.S. ENERGY FLOW FOR 1975

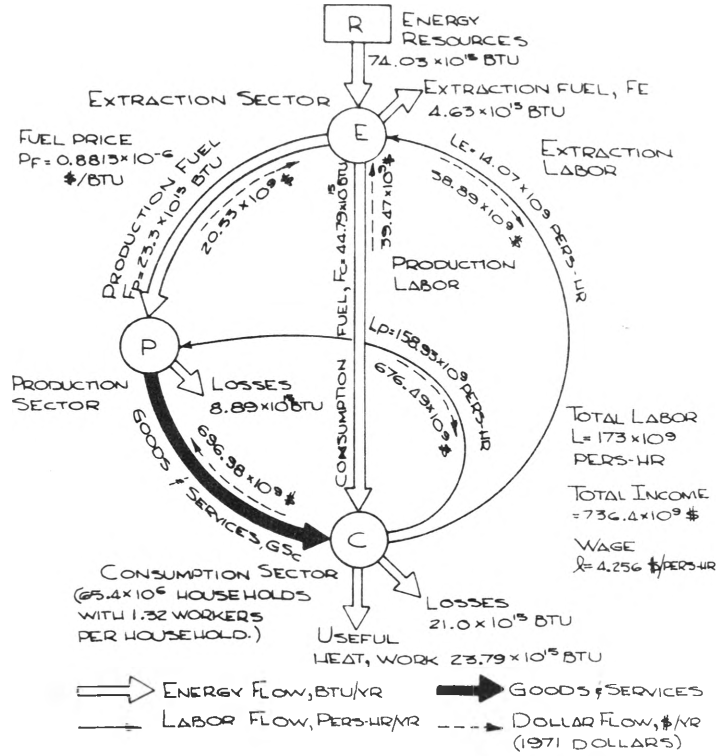

FIG. 3 FLOW CHART FOR ENERGY, LABOR AND DOLLARS FOR 1975, ASSUMING NO POLLUTION CONTROL EFFORT AND NO ENVIROMENTAL DAMAGE

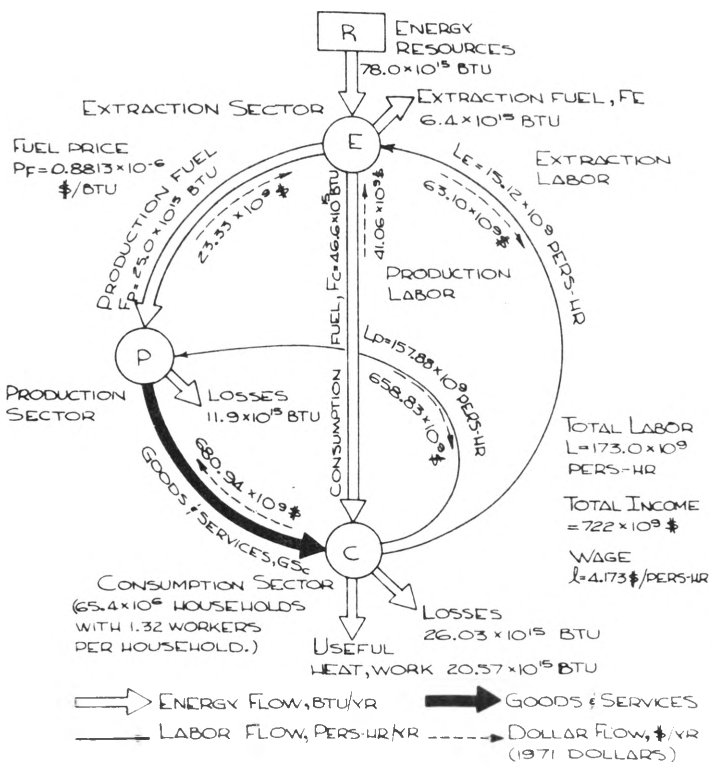

FIG. 2 FLOW CHART SHOWING ENERGY, LABOR AND DOLLAR FLOWS FOR 1975 (1971 DOLLARS)

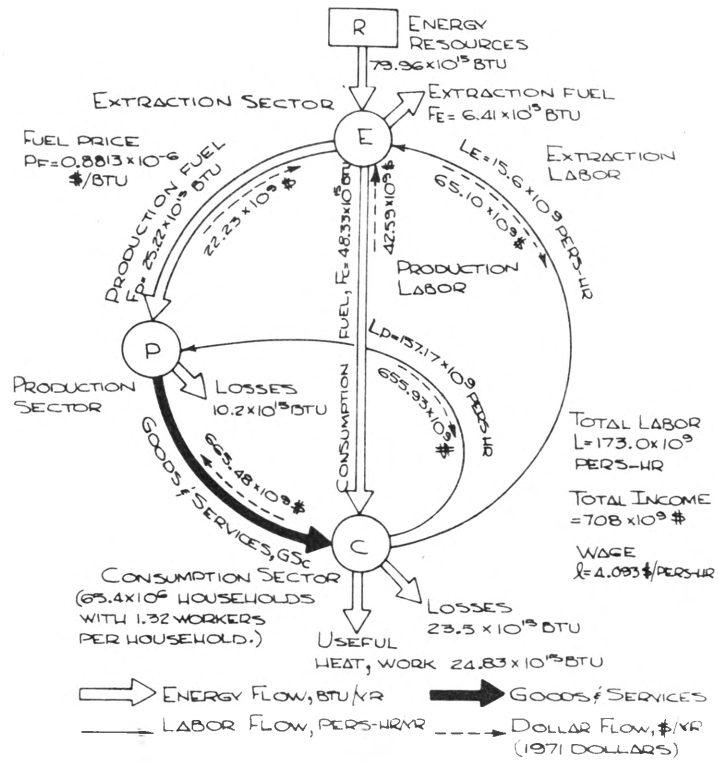

FIG. 4 ENERGY LABOR AND DOLLAR FLOWS FOR 1975 (1971 DOLLARS) ASSUMING NO POLLUTION CONTROL AND TAKING ACCOUNT OF FULL ENVIROMENTAL DAMAGE

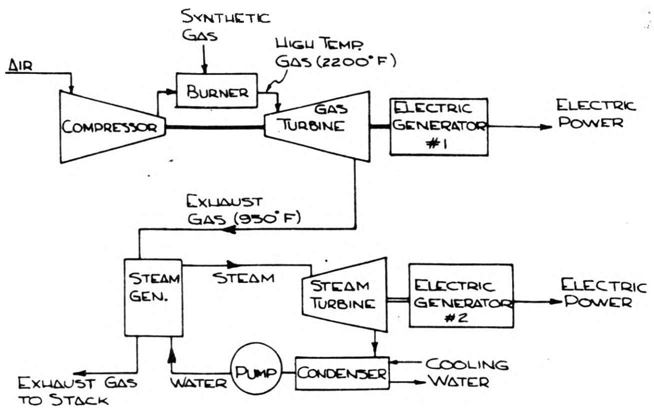

FIG. 5 SCHEMATIC DIAGRAM OF COMBINED CYCLE POWER PLANT

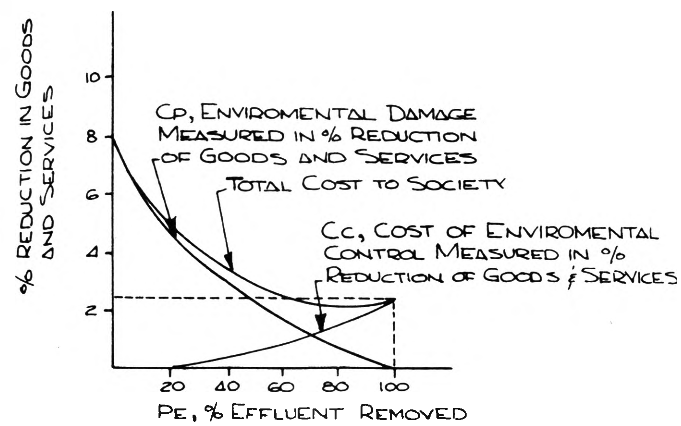

FIG. 7 COST CURVES FOR ENVIROMENTAL DAMAGE AND ENVIROMENTAL CONTROL vs. % EFFLUENT REMOVED FROM THE ENVIROMENT

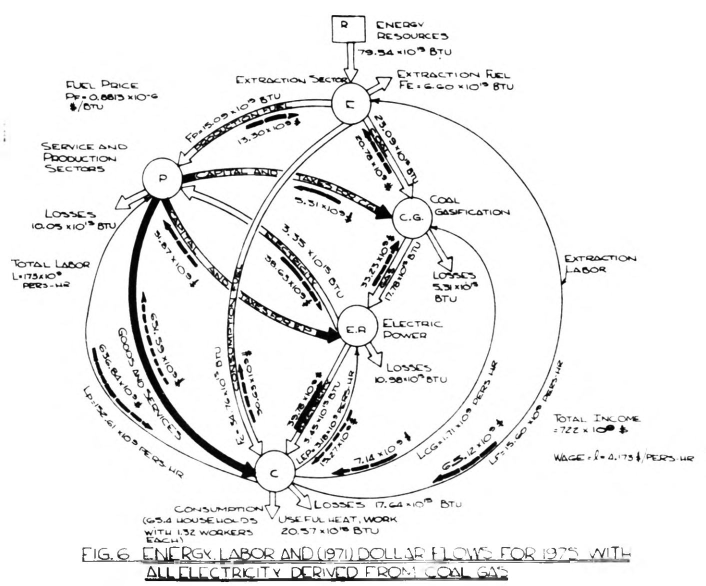

FIG. 6 ENERGY, LABOR AND (1971) DOLLAR FLOWS FOR 1975 WITH ALL ELECTRICITY DERIVED FROM COAL GAS