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A SYSTEMS APPROACH TO THE DESIGN OF A HYDROGEN ECONOMY

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ABSTRACT

A description of the organization and methods used to select and direct participants in the design of a hydrogen energy system; a hydrogen economy. The Systems Design concept was used throughout the task, including inputs from applied psychology. Task and time organization was such that the eighteen participants completed the task, including report writing, in eleven weeks (8000 man hours).

Projected costs of producing hydrogen from coal or from nuclear heat are in the range of \$1.00 to \$1.50 per million Btu. Transmission and distribution costs are estimated to be about half as much. Possibilities for large scale usage of hydrogen were explored, and recommendations were made.

INTRODUCTION

Through man's history he has moved from one energy "age" to another with relative ease. We have progressed from a widespread use of wood and farm wastes in the middle ages, to coal during the industrial revolution and beyond, to petroleum and natural gas today. In each instance we have changed from one "infinite" energy source to another primarily because of economics. It became cheaper to mine coal than to chop wood at the rates one wished to use it, for example.

The current energy problems present a different picture. In the not too distant future we will change from oil and natural gas to other sources of energy. But we will not make the change to an infinite source; at least not in the sense that a very large amount of cheap energy will become available. Rather, we will begin to tap those sources which become economically competitive as oil and gas become increasingly scarce and increasingly expensive. In the near future the United States will undoubtedly use more coal, a fuel which had been priced out of some segments of the marketplace in the recent past.

This phenomenon and others which have been brought to light by the energy shortage have caused engineers and scientists to reassess their ideas about energy systems. In particular, they are realizing that there is a lack of methodology to analyze and synthesize energy systems.

This paper concerns the design of a hydrogen energy system - a hydrogen economy. However, the basic concepts and methods used could apply to the design of any large scale change in the economic system. The Systems Design approach was used as a design philosophy and procedure. The design was carried out in the summer of 1973, at the NASA Johnson Space Center. It was one of a series of annual Systems Design Institutes sponsored by NASA, the American Society for Engineering Education (ASEE), and various universities. The universities involved in this one were the University of Houston and Rice University.

Why Hydrogen?

Petroleum and natural gas serve as both energy supplies and energy carriers. The only other widespread energy carrier in use today is electricity. As petroleum and natural gas supplies are depleted this country will undoubtedly turn increasingly to coal for its energy supply. Coal, however, is a relatively inefficient energy carrier. That is to say, it is hard to transport it from place to place. It would be more efficient to convert the coal to an easily transportable form of energy, then transport the energy for ultimate use. This is done today by those electric utility companies which use coal.

Other alternatives are to convert the coal to a liquid or gaseous form. One such form is hydrogen. There would be distinct long term advantages to choosing hydrogen; chief among them being that as coal resources are depleted, nuclear energy could be used to produce hydrogen from water. The economy could then make a transition from coal to nuclear energy as a supply of energy, without altering the transmission, distribution, and usage systems. In the longer time frame hydrogen could be produced from solar energy, again without altering systems downstream from the source.

DESCRIPTION OF DESIGN PROCESS

Advance Work

Work was initiated in October, 1972 with a proposal from the Power and Propulsion Division of NASA-JSC to design a hydrogen energy system. It was felt by NASA management that the topic would be timely, and that NASA would be a valuable source of information about hydrogen in general.

Following concurrence by the Institute directors, information was sent out through the normal channels open to ASEE. This was begun in December, 1972. Every member of ASEE receives such announcements, as do department chairmen and deans of engineering.

In March of 1973 a meeting was held at which most of the Institute Fellows were chosen. Six people formed a selection committee; one from NASA-JSC, two from the University of Houston, two from Texas A & M University, and one from Rice University. Judgments were made on the basis of written applications from each of the prospective Fellows. Each application was marked by each committee member with a 1, 2, or 3; 1 being the highest rank. Thus each applicant had a summed score from 6 to 18. In general, selection was made on the basis of these summed scores. Eighteen participants were finally chosen for the program. A list of participants and their diciplines can be found in the Appendix.

During the months of January through May, 1973 the directors organized the program and made arrangements for the Fellows' ancillary needs. This included such things as provision of working space, provision of literature search capability, provision of computer facilities, and information on housing. A seminar and short course program was also arranged. The aim of this activity was to make it possible for the Fellows to begin the design task with a minimum of preliminary work.

Orientation and Team Building

Approximately three days were spent on orientation. The first day was devoted to organizational sessions and a tour of the Johnson Space Center. During the second day the participants created a preliminary organizational structure, and by the third day had replied to the work statement. Such things as library orientation were also done by the third day.

The fourth and fifth days were spent in an activity which has been called team building[1]. Using an intensive series of lectures, tests, and role-playing "games", a professional counselor presented a philosophy of group interaction which has been found to be productive. The model used was the managerial grid model developed by Blake and Mouton[2]. The individual testing was administered with commercially available tests developed by Hall and Williams[3]. The results of the tests show where the testee stands relative to the managerial grid model, and the counselor recommends steps to move from this standing to the "ideal" position. For this activity to be effective it is imperative that it be conducted by a well trained counselor. Peter Diehl, staff consultant at Miami Dade Community College, was chosen for this team building session.

It is impossible to measure the effect of the team building sessions objectively. It was felt by both the Fellows and the directors, however, that it was an invaluable aid to group decision making.

Task Completion

Work on the task progressed as shown on the time-task chart of Figure 1. A detailed time-task flow diagram can be found in Reference (4). In Figure 1 Work Program Objectives refers to the creation of an organization structure and a reply to the original work statement. This was completed during the first week. The final organizational structure of the design team, with personnel assignments, is included in the Appendix. Also included in the Appendix is a list of the directors.

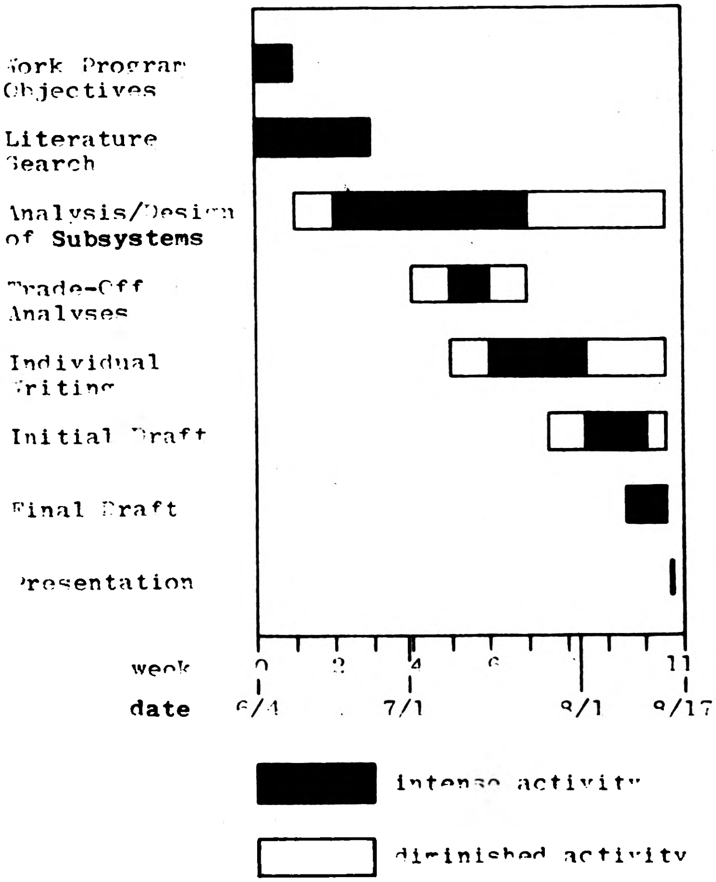

Fig. 1. Time-task chart.

The Systems Design approach[5,6,7] was used throughout the task. In actual design the first task of each group was to find and categorize all systems and subsystems pertinent for group study. The production group, for example, produced the schematic diagram shown in Figure 2. In this figure energy sources are shown at the left, processes are located in the middle, and the product, hydrogen, is indicated at lower right. Each path from a source to hydrogen is a possible production method. Similar schematics were produced by the other groups.

In order to choose between the many alternatives available, a formal trade-off analysis was done for each system or subsystem within a group. A matrix including

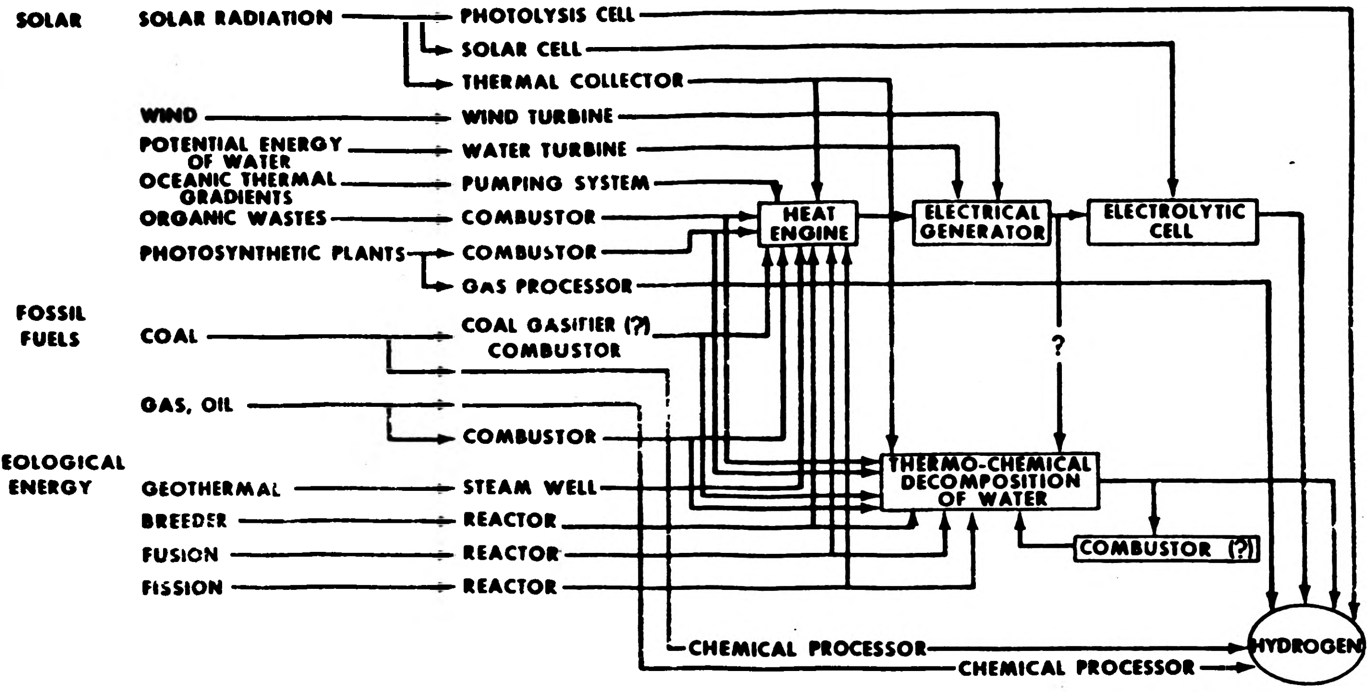

Fig. 2. Summary of methods for hydrogen production. From Reference (4).

24 factors, both technical and nontechnical, was developed for this purpose. Ratings were assigned on a scale from 1 (most favorable) to 5 (least favorable). For example, the use of hydrogen in catalytic burners for home heating might rate a "1" with respect to air pollution, but a "5" with respect to needed technology. Where known, dollar costs were used as rating figures. Each system was also rated for four specific time periods: (1) 1973-1975, (2) 1975-1985, (3) 1985-2000, and (4) 2000-2020.

Within each group this procedure aided system selection. Then the selections were matched between groups to ensure compatability. This method was found to be an effective way to aid decision making in a problem of this complexity. A detailed account of the trade-off study and the matrix can be found in Reference (4).

RESULTS

The results of the study are given in great detail in Reference (4), and in summary form in Reference (8). The most important of them will be presented here, in group format.

Production Group

The Production Group generated Figure 2 as described, then proceeded to subject all paths in Figure 2 to trade-off analyses. The results are indicated in Figure 3. This figure shows cost projections for the five most promising system alternatives for producing hydrogen, covering the 50 year time span from 1970 to 2020. All projected costs are within an order of magnitude. Thus it is unlikely that one process would completely dominate the hydrogen market, except that coal gasification and nuclear heat-thermal decomposition would be clear choices for the near future. It is expected that these two processes could produce gaseous hydrogen in the range of $1.00 to $1.50 per million Btu.

Transmission and Storage Group

All economically competitive methods of production will yield hydrogen in a gaseous form. Transmission and storage considerations have thus focused on the gaseous state. A hydrogen gas pipeline system seems to be the most practical solution. In addition it would be possible to use depleted natural gas fields and aquifers for large scale underground storage. Small scale but more costly storage could be furnished by high pressure gas tanks, cryogenic liquid tanks, and mined caverns.

It would be most advantageous and economical to use the existing natural gas pipeline system, which consists of over 900,000 miles of pipe. The possibility of this is uncertain at present, however. When certain metals are plastically deformed in the presence of hydrogen gas, cracking can occur at the metal surface. This is known as hydrogen environment embrittlement. This is a new phenomenon, and relatively little research has been done on it, in particular no research relative to hydrogen environment embrittlement has been done on in-service natural gas pipeline steels.

The factors which seem to influence hydrogen environment embrittlement in steels are the susceptibility of the steel, the stress level of the steel, and the purity of the hydrogen. An impurity of 200 parts per

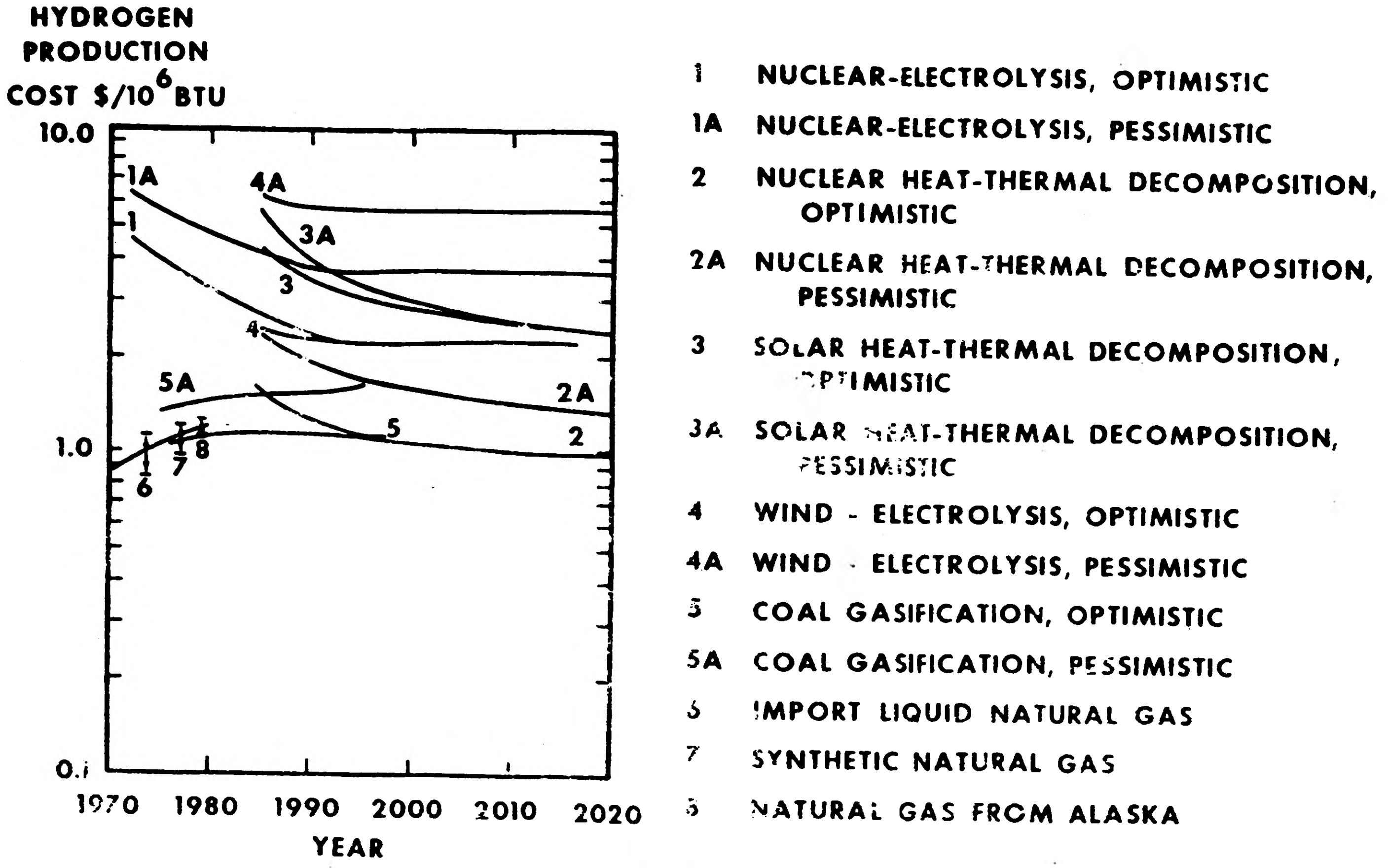

Fig. 3. Hydrogen production cost for various path alternatives. From Reference (4).

million of oxygen, for example, can inhibit this type of embrittlement[4].

Given the characteristics of the present natural gas pipeline system and proposed hydrogen production methods, the use of the present system seems favored. Before this course is taken, however, much research must be done in order to answer the questions about hydrogen environment embrittlement.

The economics of gaseous pipeline transmission per se are quite favorable. The use of existing natural gas pipelines would require four times the present compressor capacity and five times the present compressor power, to deliver energy at the same rate. Hydrogen gas transmission would thus cost about double natural gas transmission costs. These costs would still be significantly less, however, than overhead electrical transmission costs. In general, transmission and distribution costs for hydrogen would be approximately half as much as production cost.

Usage Group

The usage group was able to identify five areas into which total United States energy usage could be divided. These are residential and commercial, industrial fuel, transportation, electric power generation, and industrial chemical. The term "electric power generation" refers to the net energy consumed by the electric power industry, and is normally equated with energy rejected in the form of heat.

In assessing which usage areas could or should convert to hydrogen the emphasis was on optimum use of all fuels, as opposed to maximum use of hydrogen. Thus, for example, even though hydrogen fueled internal combustion engines work very well, it was decided that hydrogen should not be used as a transportation fuel because of its poor volume energy density.

Table 1 summarizes the pertinent conclusions relative to usage area. The transportation area is the only one for which conversion to hydrogen is advised against. Even here hydrogen might find a small direct rule and a large indirect role to play. Although liquid hydrogen has a low volume energy density (0.31 that of gasoline), it has a high mass energy density (2.58 that of gasoline). Thus fuel mass limited transportation systems could use liquid hydrogen to advantage. Commercial and military aviation both fit this category.

The indirect role concerns the use of hydrogen to produce synthetic fuels. Hydrogen can be combined with nitrogen to produce ammonia, and it can be combined with coal to form synthetic gasoline and lubricating oils. In addition, the usage of hydrogen in other

Table 1. Summary of Usage Group results.

Usage Area	Feasible Systems	Impact Evaluation	Estimated Convertability to Hydrogen
Residential and Commercial (23% of total energy use in 1970)	Converted vented combustors Unvented H_2-air combustor Catalytic burner Absorption refrigeration system Fuel cell	Unfavorable-Cost of changeover; System upgrading to ensure safety Favorable-Ecologically desirable	About 85%; that percentage presently used for purposes other than lighting
Industrial Fuel (30% of total energy use in 1970)	Conversion of existing furnaces Aphodid burner-Rankine cycle H_2-air furnace designed specifically for H_2 IC engine Gas turbine	Unfavorable-Cost of changeover Favorable-Reduction of air pollution	100%
Transportation (24% of total energy use in 1970)	Many systems operate well on H_2, but low volume energy density limits range considerably	Increased availability of fossil fuels as H_2 is used in other areas	Nil, except for possibilities in commercial and military aviation
Electric Power Generation (17% of total energy use in 1970)	Conversion of existing furnaces Aphodid burner-Rankine cycle H_2-air furnace designed specifically for H_2 IC engine Gas turbine	Aphodid burner or H_2-air furnace would be of considerably smaller size than present furnaces Improved air quality	100%
Industrial Chemical (6% of total energy use in 1970)	Hydrogenation of coal for gasoline and lubricating oils Ammonia manufacture Hydrogenation of natural oils Hydrogenation of benzene to hexane, for nylon Reduction of iron ore Methyl Alcohol	Release of fossil fuels for use in other areas	About 50%; that percentage presently using H_2 from hydrocarbons

areas would free existing hydrocarbons for use in transportation.

Figure 4 shows the forecast for convertability to hydrogen from 1970 to 2020. In this figure "Total Conservation Demand" refers to the result of a study done by two participants[9]. It is a projection of U.S. energy demand, assuming strict but realistic conservation measures for the years indicated. The portion not convertible to hydrogen reflects the judgment that hydrogen would make a poor fuel for transportation purposes.

SLEEPS (Safety, Legal, Environmental, Economic, Political, and Social) Group

The SLEEPS group was composed of a Political Scientist, an attorney, and one representative from each of the other three groups. They did not generate designs or recommendations *per se*. Rather, their task was to gauge analyses and designs relative to the six coordinates comprising their title. As such, their effort is diffused throughout the resultant design. The chief instrument for accomplishing this diffusion was the trade-off study done for each system. The primary responsibility for writing and administering it was given to this group.

Safety aspects were investigated primarily by this group. This was a high priority item, since hydrogen has a popular reputation as an extremely dangerous substance. Compared to natural gas its safety deficits are that it is much more prone to leak, its ignition energy is much lower, and it is flammable over a much wider range of fuel-air mixtures. In addition, it burns

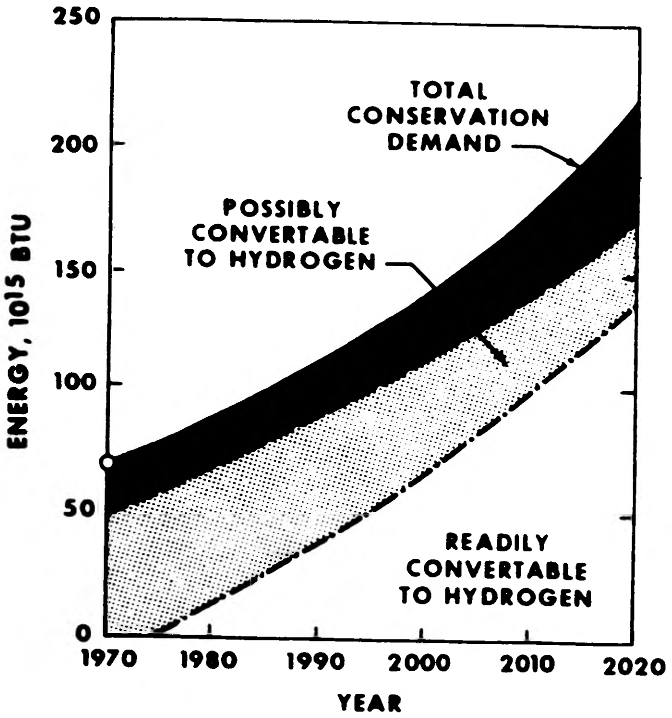

Fig. 4. Forecast of hydrogen convertability, 1970-2020. From Reference (4).

with an almost invisible flame.

On the positive side, its diffusion rate is much higher. Thus it will leave the scene of a leak much faster, diminishing the time and volume in which a flammable mixture occurs. The nearly invisible flame means that radiant heat is much less in hydrogen fires. This helps diminish injury, and offers less resistance to fire fighting and salvage efforts.

On balance, hydrogen is no more or less inherently unsafe than fuels in common use. Thus the usage areas of industrial fuel, electric power generation, and industrial chemical, all of which consider safety precautions a normal part of their operations, should be able to accept hydrogen in stride. The residential and commercial sector is less safety conscious in general. Here special efforts should be taken to make designs tamper-proof and to upgrade systems to make them less susceptible to leakage. This will represent an investment cost of large magnitude, and thus it is cited as an unfavorable impact in Table 1.

The two non-engineers in this group performed another vital function. Since they had no preconceived ideas about the hydrogen economy, nor about engineering concepts and practices in general, they were able to see others' efforts from a different perspective. Using techniques taught in the team building sessions they were able to share their observations with the engineers. It is felt that this, and the reciprocal interaction, contributed substantially to overall design excellence.

DISCUSSION

This has been a description of a process, the process being the design of a major new energy system. Although the particular result is a hydrogen economy, the concepts and methods used could be applied to the design of any large scale new system which must fit into the United States socio-economic pattern. Uniqueness was present only in the particular disciplines of the participating Fellows.

The methods of systems design and cost-benefit analysis used by this team are by no means the only methods available. There are several highly developed techniques for technology assessment[10,11] and complex decision making[12] which should be employed in any such task in the future.

It is not possible to gauge objectively the worth of this design effort. However, some observations of a subjective nature can be made. The Institute has two objectives: education of the participants in Systems Design techniques, and performance of a design task. To meet both objectives, participant selection is intentionally slanted toward those with limited experience. This forces them to simultaneously acquire experience and generate results. The final report is evidence that this was done successfully.

The time allotted was nominally 8000 man-hours. This is 200 man-weeks, or about a five month effort for a 10 man engineering-social science team. This would be a fairly small scale project for either industry or government. If one assumes that ten times the effort should be expended to yield a working system design, one realizes that reasonably sized crash efforts might yield some solutions to United States energy problems in the near future.

APPENDIX

Program Directorate

Co-Directors
Dr. C. J. Huang, University of Houston
Ms. B. H. Landi, NASA-JSC
Associate Director
Dr. J. R. Howell, University of Houston
Technical Director
Dr. W. R. Downs, NASA-JSC
Assistant Director
Dr. T. J. Hebert, Rice University

Design Team

Team Leader
Dr. Robert Savage, Chemical Engineer

Production Group
Dr. Kenneth Cox, Leader, Chemical Engineer
Dr. Saul Chao, Chemical Engineer
Dr. Melvin Eisenstadt, Mechanical Engineer
Dr. Stamatis Paleocrassas, Nuclear Engineer
Dr. Richard Williams, Chemical Engineer
Dr. Jeffrey Witwer, Mechanical Engineer

Transmission and Storage Group
Dr. Harold Koelling, Leader, Materials Engineer
Dr. Samuel Lee, Mechanical Engineer
Dr. Leonard Traina, Civil Engineer
Dr. Albert Wilson, Nuclear Engineer

Usage Group
Dr. Richard Murray, Leader, Mechanical Engineer
Dr. Leland Blank, Industrial Engineer
Dr. Richard Johnson, Mechanical Engineer
Prof. Samuel Powers, Mechanical Engineer
Dr. Richard Riley, Mechanical Engineer

SLEEPS Group
Prof. Thomas Cady, Leader, Attorney
Dr. Jack Salmon, Political Scientist
Dr. Leland Blank
Dr. Albert Wilson
Dr. Jeffrey Witwer

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