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Economic Incentives in the Exploration, Extraction and Refining of Crude Oil

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ECONOMIC INCENTIVES IN THE EXPLORATION, EXTRACTION AND REFINING OF CRUDE OIL

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Abstract

A simultaneous econometric model consisting of 37 stochastic equations and 3 identities which captures the decisions affecting the supply of new discoveries, the size of proven reserves, the production out of reserves, the demands and supplies of refined products and the imports of crude oil and refined products, is estimated. Simulation with the econometric model analyzed the effect of alternative pricing policies on domestic oil production, consumption and imports.

1. INTRODUCTION

An examination of the responsiveness to economic incentives of the U.S. petroleum industry is vital if the nation's oil supply is to be maintained or possibly increased. Government policy toward the petroleum industry might include price ceilings, import quotas, depletion allowances and other tax breaks, restrictions on gasoline consumption, and antitrust suits. Little is known with respect to how each of these government policies ultimately affect the prices and availability of oil and oil products to the consumer.

In this paper an econometric model designed to represent the economic relationships governing the petroleum industry is presented to provide some insight as to the impacts of alternative petroleum policies on the generation of reserves. Production out of reserves determines the flow of petroleum to the refineries. An examination of the responsiveness to economic incentives of petroleum exploration is vital if the nation's proven reserves are to be increased.

Imports of crude petroleum are explicitly taken into consideration. All liquids that go into the process used to produce refined petroleum products are modeled. Equations representing the supply of new discoveries to increase proven reserves and the production out of reserves are specified. Since crude petroleum is a nonrenewable asset special attention is paid to the issues of exhaustibility.

The price policies examined include: a) equalization of the domestic wellhead price of crude at the world price, b) constant wellhead prices for domestic crude, c) constant real wellhead prices and d) equalization of domestic wellhead prices with the world price in 1976 and an increase thereafter at the domestic wholesale price rate of increase.

2. THE STRUCTURE OF THE ECONOMETRIC MODEL

A number of econometric studies of the domestic petroleum supply have appeared recently. Fisher's

[9] was the first to estimate supply equations for the U.S. petroleum industry. The influence of Fisher's model is evident in subsequent empirical studies. Erickson, Millsaps and Spann [8], specified a model of crude oil reserves stocks. Khazzoom [11] dealt with the oil discovery problem. Epple's study [7] dealt with petroleum discoveries and the decisions of the oil exploring firms. Adams and Griffin [1] concentrated only on the petroleum refining industry. They estimated the supply of refined products with a linear programming model. The Federal Energy Administration's Project Independence Report is being revised to forecast oil and natural gas supply and energy demand. Haussman discussed potential biases identified with FEA's model [10]. MacAvoy and Pindyck are the first to have attempted an intergrated model of all aspects of the natural gas industry. They dealt with regulatory policies for the natural gas shortage [12].

A model explaining exploration, reserves determination, production out of reserves and total liquids to be refined has been developed and estimated.

Figure 1 presents a simplified causal arrow-diagram of the structure of the econometric model. Table 1 provides a list of the variables.*

2.1. Demand for refined petroleum products.

Crude petroleum is used in the refinery process, along with natural gas liquids, in order to produce refined products. The amounts of crude petroleum demanded can be derived from the estimation of the demands for refined products. Estimation of these demands becomes important also in determining the necessary mix of products to be refined at any given period of time. The following equation represents the technical relationships between crude and 10 major refined product categories:

$$\sum_{n=1}^{10} C_{nt} - F_t - G_t = D_t$$

where: C_t is the demand for each refined product category

F_t is the amount of natural gas liquids used in the refining process

G_t is the processing gain obtained from the expansion of fuels owing to such processes as reforming and cracking

D_t is the amount of crude petroleum demanded.

Each demand for refined products is specified as a function of per capita income, its own price, the price of coal chemicals and prices of other refined products. Miles flown are assumed to affect the demand for kerosene; the number of oil burners, the demand for distillate fuels; the miles of municipal and rural highways, the demand for coal oil and asphalt; the output of the chemical industry, the demand for liquified fuels; and the average number of gallons consumed per vehicle, the demand for gasoline.

The price, equations are assumed to be a function of the quantity supplied, specific concentration ratios, the price of U.S. crude oil at the well-head and the average price of imported crude oil. Import equations were specified for residual fuels and distillate fuels and they were assumed to be functions of domestic refining capacity, the domestic supply of those fuels and their stocks in the end of the year. Stocks were estimated for the residual fuels, kerosene, distillate fuels and distillates and they were assumed to be functions of their respective, prices, demand conditions and levels of imports.

2.2. Production out of reserves

The supply of domestic production [5] is determined by the marginal cost of developing existing reserves because of the desire to balance annual flows with reserve levels. Marginal production costs will, therefore, depend on reserve levels relative to domestic production, and as the reserve to production ratio declines, we would expect marginal costs to rise sharply. This is

*The estimated equations can be found in [14] [15].

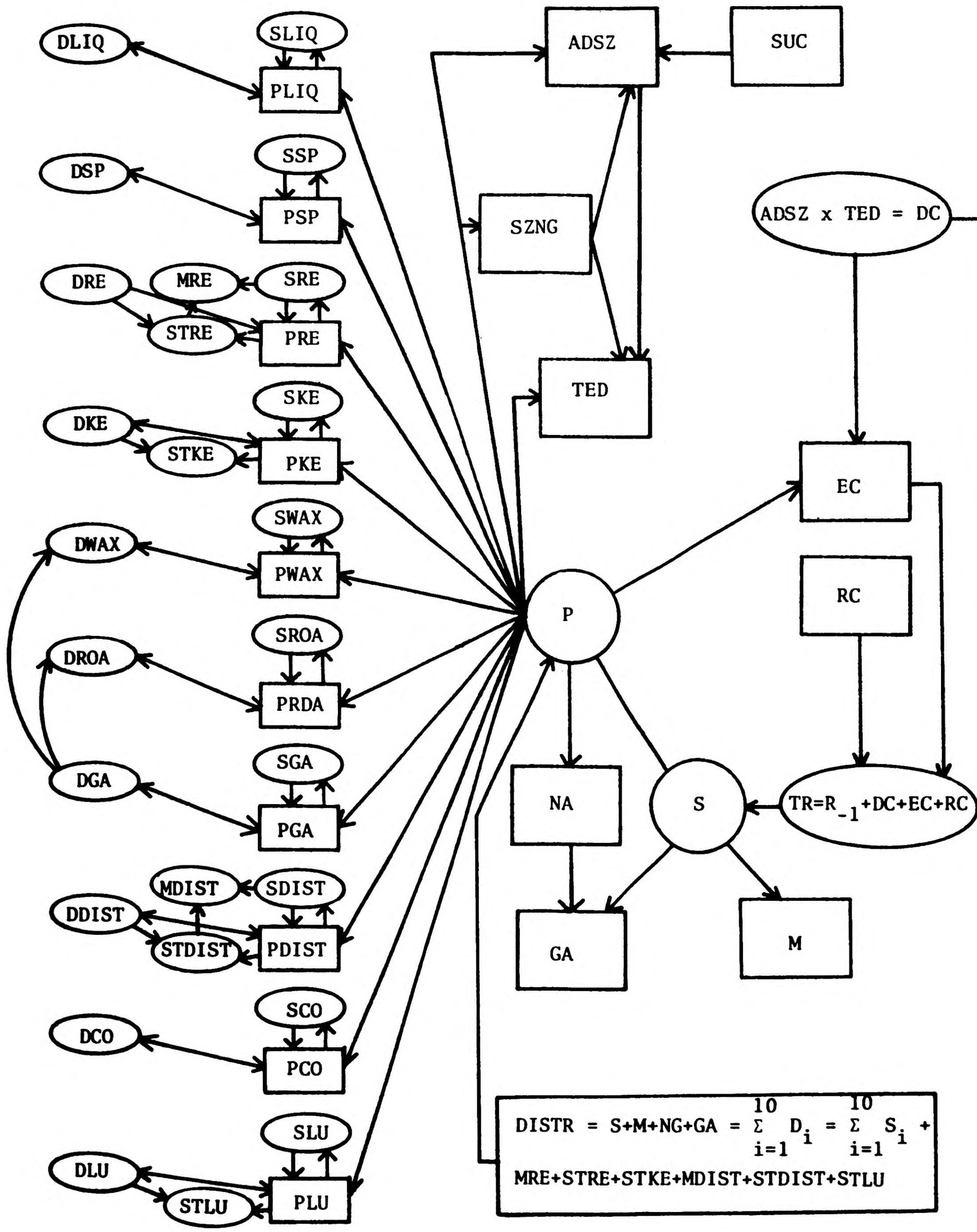

Figure 1.--Simplified causal diagram of the model.

Table 1.--List of variables and data sources

TED = number of new exploratory wells drilled (total productive and dry holes drilled each year). Source: [4].

SUC = success ratio (ratio of productive to total new wells drilled).

ADSZ = average size of new oil discoveries (ratio of new discoveries to total productive and dry holes).

SZNG = average size of new natural gas discoveries (ratio of new discoveries to total productive and dry holes). Source: [4].

DC = new oil discoveries, measured in 42-gallon barrels. Source: [4].

EC = extensions of oil reserves, in 42-gallon barrels. Source: [4].

TR = total reserves, beginning of year (in 42-gallon barrels). Source: [5].

P = price of crude oil at the well head (dollars per barrel). Source: [20].

S = production of crude oil (thousands of 42-gallon barrels). Source: [4].

M = imports of crude petroleum (S.I.T.C.: 331.01). Figures converted to thousands of 42-gallon barrels from metric tons. Source: [19].

NG = natural gas liquids added (thousands of 42-gallon barrels). Source: [4].

GA = processing gain (thousands of 42-gallon barrels). Source: [4].

DISTR = sum of domestically supplied refined products, net of imports, exports and change in petroleum stocks (42-gallon barrels). Source: [20].

RC = revisions of established reserves (42-gallon barrels). Source: [4].

DGA = gasoline demanded (in thousands of 42-gallon barrels). Source: [20].

SGA = gasoline supplied (in thousands of 42-gallon barrels). Source: [20].

PGA = price of gasoline (is the average price of regular grade gasoline, in cents per gallon at the service station including tax). Source: [13].

DCO = coke demanded (in thousands of 42-gallon barrels). Source: [20].

SCO = coke supplied (in thousands of 42-gallon barrels). Source: [20].

PCO = price of heavy fuel used as a proxy for the price of coke (a wholesale price in cents per gallon). Source: [13].

DRE = fuel demanded (in thousands of 42-gallon barrels). Source: [20].

SRE = residual fuel supplied (in thousands of 42-gallon barrels). Source: [20].

PRE = the price of residual fuel (in dollars per barrel) reported. Source: [13].

STRE = stocks at the end of the year (in thousands of 42-gallon barrels). Source: [19].

MRE = imports (in thousands of 42-gallon barrels). Source: [18].

DWAX = wax demanded (in thousands of 42-gallon barrels). Source: [20].

SWAX = wax supplied (in thousands of 42-gallon barrels). Source: [20].

PWAX = price of retail No. 2 oil used as a proxy for the price of wax (in dollars per barrel). Source [13].

DDIST = distillate oils demanded (in thousands of 42-gallon barrels). Source [20].

SDIST = distillate oils supplied (in thousands of 42 gallon barrels). Source: [20].

PDIST = price of light fuels used as a proxy for the price of distillate oils (is a wholesale price in cents per gallon). Source:]13].

STDIST = stocks at the end of the year (in thousands of 42-gallon barrels). Source: [20].

MDIST = imports (in thousands of 42-gallon barrels). Source: [19].

DROA = road oil and asphalt demanded (in thousands of 42-gallon barrels). Source: [20].

SROA = road oil and asphalt supplied (in thousands of 42-gallon barrels). Source: [20].

PROA = price of road oil and asphalt (in dollars per barrel). Source: [13].

DLIQ = liquified fuels demanded (in thousands of 42 gallon barrels). Source: [20].

Table 1.--Continued

SLIQ =	liquified fuels supplied (in thousands of 42 gallon barrels). Source: [20].
PLIQ =	price of liquified fuels (in cents per gallon and refers to charges in New York Harbor/Philadelphia). Source: [20].
DSP =	still gas and petrochemical feedstock demanded (in thousands of 42-gallon barrels). Source: [20].
SSP =	still gas and petrochemical feedstock supplied (in thousands of 42-gallon barrels). Source: [19].
PSP =	price of petrochemical feedstock (in dollars per barrel). Source: [20].
DKE =	Kerosine demanded (in thousands of 42-gallon barrels). Source: [20].
SKE =	Kerosine supplied (in thousands of 42-gallon barrels). Source: [20].
PKE =	average of four prices used as a proxy for the price of Kerosine (is the average of motor gasoline, aviation fuel, light fuel and heavy fuel and is expressed in dollars per barrel).
STKE =	stocks at the end of the year (in thousands of 42-gallon barrels). Source: [20].
DLU =	lubricants demanded (in thousands of 42-gallon barrels). Source: [20].
SLU =	lubricants supplied (in thousands of 42-gallon barrels). Source: [20].
PLU =	price of lubricants (with 200 viscosity at 100, 0-10 pour test, 96 V.I. at East Coast expressed in cents per gallon). Source: [20].
STLU =	stocks at the end of the year (in thousands of 42-gallon barrels). Source: [20].

because the greater the output, the more oil must be drawn from high cost, distant, low-quality sources.

Development of new production sites will be undertaken only if the expected price of oil covers all costs including a normal return on investment and a risk allowance. Price expectations are represented in the model by a distributed lag of past prices and the opportunity cost of investing in petroleum production (opportunity cost of extracting the exhaustible stock resource) is expressed as a distributed lag of the difference between net price and the rate of interest. The marginal production (development) cost is an exponential function of the supply of production [5] which is also a function of the reserves at the beginning of the year.

2.3. Imports, natural gas liquids, processing gain and price

Imports of crude petroleum (M) are assumed to respond to domestic economic policy as well as the price of imported crude oil [2, 3, 6]. Current imports (M), viewed as demand for foreign crude oil, are a function of imported oil in the previous time period, the price of imports, the domestic supply of crude (S) since import quotas were set on the basis of domestic output, and the utilization of domestic refining capacity which acts as a capacity constraint.

The amount of natural gas liquids added, because of economic and technological factors, has been steadily increasing over time. The quantity of natural gas liquids (NG) is positively related to the price of crude relative to the price of natural gas liquids and a nonlinear time trend.

The quantity of processing gain (GA) increases in direct proportion to the amount of crude oil and lease condensate run through stills, and declines in proportion to the amount of natural gas liquids added for refining (NG). A curvilinear time trend has also been added to the estimating equation.

The price of crude oil (P) is positively related to the sales of refined products, the price of crude oil imports, and the price of natural gas (PNG), and negatively related to the extent of refinery capacity utilization (REF). A distributed lag of the sales of refined products (DDISTR) rather than actual sales are used, because a sustained increased in sales of refined products must occur if the price of crude petroleum is to increase.

2.4. Supply of new reserves

For any time period t, total proven reserves of crude oil (R) are given by the identity:

$$R_t = R_{t-1} + DC_t + EC_t + RC_t - S_t$$

where extensions (EC), revisions (RC) and new discoveries (DC) during the year are combined to form additions to reserves.* The amounts of crude oil extracted (S) are the only major subtraction from reserves.

Crude oil reserve extensions (EC) vary positively with expected prices and inversely to the amounts of crude previously discovered through exploratory drilling. Economic incentives account for the use of either new technologies or making present secondary and tertiary recovery methods economical. Furthermore, if discoveries (DC) at any point in time are small, an incentive exists for the recovery of oil from already existing reservoirs by recovery from greater depths. Revisions of established reserve levels (RC) are assumed to be proportional to changes in reserve levels.

The supply of additional proven reserves (DC) is generated by determining the number of exploratory wells drilled (TED) and average discovery size per well (ADSZ). The amount of new discoveries is then the product of discovery size and wells drilled:

$$DC_t = ADSZ_t \times TED_t$$

The decision concerning the number of new exploratory wells drilled (TED) depends upon the inter-relationships between expected returns from oil and gas, costs of production and risk.

The search for oil and gas is carried out jointly. Because of their common occurrence, new oil discoveries (ADSZ) are associated with discoveries (SZNG) of natural gas. The higher the ratio of past gas discoveries to past oil discoveries the higher will be the probability of finding oil. The success ratio (SUC) defined is the ratio of productive to total new wells drilled. The success ratio (SUC) at any time period is a function of the success ratio in the previous time period, the average size of discovery for crude petroleum (ADSZ) in the previous period, the average size of discovery of natural gas (SZNG) in the previous period and the depth at which exploration is taking place.

3. MODEL VALIDATION AND PREDICTION

The econometric model consisted of 37 stochastic equations and 3 identities and the parameters of the structural relationships were simultaneously determined. The model is block recursive with 2 blocks. The first block, the supply and demand for refined products was estimated with two-stage least squares and the second block, the discovery and extraction of crude oil with three-stage least squares.

The comparatively low Root Mean Square Errors, for all equations suggest that the model could reproduce sample data with a high degree of accuracy. Both the original Theil coefficient and the new Theil coefficient were calculated with similar results [17, 18]. The Theil coefficients were near zero for all equations further substantiating the efficacy of the model within the sample period. Regression coefficients of actual on predicted values were also near one. The correlations between actual and predicted values

*About 50 percent of the oil from the reservoirs discovered to date is still in the ground [16].

were high for most equations of the model. For most equations the model predicts a high proportion of the turning points over the period 1959-1976.

Demand for crude petroleum is expected to increase at the rate of 2.2 per annum under world prices.*

The important exogenous determinants of supply of reserves and production include the price of crude at the wellhead, the average drilling costs and the lagged success ratios for oil and gas together. It is expected that natural gas prices will increase at a rate of 9 percent per annum in current dollar terms and that the average drilling costs will increase at 7 percent per annum in keeping with the trend of costs increases over the 1960's and early 1970's.**

These values of the exogenous variables, together with an assumed decreasing success ratio at the historic rate (over the period 1959-72) can be inserted into the econometric model to produce simulated values of additions to reserves, production out of reserves and average wholesale prices for crude oil at the wellhead.***

The crude oil price at the wellhead was regulated by the Federal Government in 1975 (Energy Policy and Conservation Act) which fixed the price of "old" oil to a "ceiling" price of $5.25 dollars per barrel. "Old" oil constituted about two thirds of the 1975 production and refers to the output produced in excess of the output in the same month of 1972. "New" oil and oil from wells that produce less than ten barrels per day are subject to a ceiling price of $11.28.

4. ALTERNATIVE PRICE POLICIES FOR DOMESTIC CRUDE OIL

4.1 Domestic production and reserves under world prices

The impact of the price increases on new discoveries of reserves would spread over the period 1978 to 1982. This is partly due to the assumption of a decreasing success ratio and partly to the lagged response of exploration to economic incentives. New discoveries are expected to increase by 25 percent in 1978 over 1977 and surpass 3 billion barrels in 1982. Total additions to reserves do not necessarily track closely the new discoveries due to the increased production levels over the period.****

From 1983 on, when the full impact of price increases is felt, with total additions to reserves being more then the supply out of reserves (Table 2). Total additions to reserves, levels off at 7 billion barrels a year which is an amount approximately 5.5 billion barrels greater than the new additions to reserves realized in 1977, before this series of price increases.

The new crude oil prices at the wellhead would make it more profitable to increase production very quickly (an increase of more than 2 billion barrels during the period 1978 to 1985). The increased production out of reserves reduces the reserve-production ratio from 9:1 to less than 6:1 at the lowest point since price increases

*The Energy Policy and Conservation Act provides for a Strategic Petroleum Reserve in order to reduce the impacts of disruptions in supplies of petroleum products. The Act requires storage of at least 150 million barrels of petroleum products and crude oil by December 22, 1978, and authorizes the storage of up to 1 billion barrels by December 22, 1982. These amounts of crude oil will have to be added in our calculations of demand.

**See MacAvoy and Pindyck for the expected natural gas price increases [12].

***The assumption of a decreasing success ratio is conservative in that despite the past trend, future offshore leasing may stimulate larger average discovery sizes per well drilled.

****The figures include the 9.6 billion barrels located in Prudhoe Bay, Alaska, in 1968.

TABLE 2

WORLD PRICES FOR DOMESTIC PRODUCTION AND CONSUMPTION

Year	Total additions to Reserves	Total Reserves	Supply of Production	Excess Demand	Reserve Production Ratio
1977	1,497	32,797	3,450	1.3	9.0
1978	1,876	30,974	3,890	1.0	8.0
1979	2,103	29,378	4,317	0.6	7.0
1980	2,530	28,208	4,435	0.6	6.4
1981	2,922	28,931	4,590	0.4	6.3
1982	3,100	29,131	5,018	0.1	5.8
1983	5,256	30,487	5,447	-0.2	5.6
1984	6,370	33,657	5,965	-0.7	5.6
1985	7,106	33,857	6,028	-0.7	5.6

provide incentives to take out a larger proportion of reserves.

The result of a deregulated price which reaches the world price levels, is to increase substantially domestic production and therefore reduce greatly the magnitude of the crude oil shortage. The domestic production shortage is eliminated by 1983 at which time an excess supply results. These excess supplies registering after 1983 would probably lead to rebuilding of the reserves base and to some price softening on new field contracts.

4.2. Increasing wellhead prices at 5 percent a year

Continuation of present regulations is envisioned as a maintenance of "ceiling" prices on "old" oil but at a higher level and continued deregulation of "new" oil. Overall the increase in the price of crude oil at the wellhead is hypothesized to be increasing at a rate of 5 percent per annum.

The increments of total additions to reserves are shown in Table 3; total additions each year fall short of those for Table 2. The supply of production out of reserves is steadily decreasing after 1978 with a doubling of the excess demand by the year 1985. Not only, the lower wellhead price, does not provide enough incentive for exploration and production out of reserves but it stimulates a higher level of demand in the economy. Because of the relatively lower profitability the reserve-production ratio remains higher than before with proven reserves decreasing to 14.8 billion barrels and production out of reserves to 2 billion barrels in 1985.

4.3. Constant wellhead prices

Under the assumption of constant wellhead prices, additions to reserves decline very fast with no new oil being discovered after a 5 year period (1977-1982). The supply out of reserves also decreases, due to the lack of economic incentives. Excess demand reaches 5.5 billion barrels in the year 1985. As expected, the reserve production-ratio increases as more oil is kept in the ground (Table 4).

4.4. Extended price controls

Under this plan, price controls on the price of crude petroleum at the wellhead are to change as follows: a) the price of newly discovered oil will be allowed to rise over a 3 year period to the 1976 world price, adjusted thereafter for domestic price increases, b) the current $5.25 and $11.28 price ceilings for previously discovered oil will be allowed to rise at the rate of domestic price increases; c) incremental tertiary recovery from old fields would receive the world price. Domestic oil to the consumer will be priced at the world price through a crude oil equalization tax equal to the difference between its controlled domestic price and the world price.

This scheme of pricing domestic oil at the well-

TABLE 3

INCREASING WELLHEAD PRICES AT 5 PERCENT PER YEAR

Year	Total additions to Reserves	Total Reserves	Supply of Production	Excess Demand	Reserve Production Ratio
1977	1,195	31,996	3,050	1.7	10.5
1978	1,365	29,662	3,103	1.7	9.6
1979	1,238	27,200	3,023	1.9	9.0
1980	1,303	24,803	2,899	2.2	8.5
1981	1,372	22,476	2,787	2.4	8.1
1982	1,475	20,251	2,637	2.6	7.7
1983	1,692	18,243	2,483	2.8	7.3
1984	1,853	16,397	2,186	3.2	7.5
1985	2,065	14,835	2,056	3.5	7.2

TABLE 4

CONSTANT WELLHEAD PRICES

Year	Total additions to Reserves	Total Reserves	Supply of Production	Excess Demand	Reserve Production Ratio
1977	1,229	31,300	3,013	1.7	10.4
1978	1,077	28,330	2,865	2.0	10.1
1979	933	26,507	2,607	2.3	10.1
1980	809	23,941	2,278	2.7	10.5
1981	703	21,051	1,879	3.4	11.2
1982	--	18,054	1,419	3.8	12.7
1983	--	14,854	--	5.3	--
1984	--	11,654	--	5.4	--
1985	--	8,454	--	5.5	--

head seems to provide adequate economic incentives for increased efforts in exploration and extraction of crude oil (Table 5). Total additions to reserves about double within a five year period (1977-1981) and supply out of reserves increases by about 40 percent over the same period. Excess demand reduces to zero by 1983 (within a 6 year period) and reserve-production ratios are fairly low. Although the reserve-production ratios are higher than the ratios under world prices for domestic producers, the incentives for extracting oil are substantial.

TABLE 5

EXTENDED PRICE CONTROLS

Year	Total additions to Reserves	Total Reserves	Supply of Production	Excess Demand	Reserve Production Ratio
1977	1,385	31,996	3,050	1.7	10.4
1978	1,650	30,102	3,490	1.5	8.6
1979	1,890	28,106	3,995	0.9	7.1
1980	2,410	28,501	4,183	0.9	6.8
1981	2,708	28,789	4,364	0.6	6.6
1982	2,887	29,001	4,679	0.4	6.2
1983	4,950	30,202	5,170	0	5.8
1984	5,700	33,168	5,635	-0.3	5.8
1985	6,780	33,500	5,650	-0.3	5.9

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