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The Determinants of Investment in Petroleum Reserves and Their Implications for Public Policy

By JAMES C. COX AND ARTHUR W. WRIGHT*

Interest in the determinants of investment in crude oil and natural gas reserves derives from three sources. First, it is always interesting to find a satisfactory explanation of investment behavior in any industry. Second, an aspect of the current concern with the "energy crisis" is the domestic crude petroleum industry's productive capacity, which is an increasing function of the stock of proved oil and gas reserves. Third, there is a decades-old controversy over the special provisions of the federal corporation income tax law which apply to petroleum producers; those special provisions have traditionally been justified by an asserted need to increase investment in petroleum reserves in order to protect "national security."¹

In three previous papers,² we explored the running controversy over the special

petroleum tax provisions. In our 1973a paper, we outlined a framework for determining whether the special provisions were cost effective compared to alternative policies for increasing investment in petroleum reserves.³ We concluded that it was impossible to evaluate the policy because there were as yet no reliable estimates of the determinants of investment in petroleum reserves.

In this paper we present a model of investment in proved reserves in the *U.S.* crude petroleum producing industry, and empirical results for a subsector of that industry for 1959–71, using estimating equations derived from the model. The subsector consists of the five major petroleum producing states which practice "market-demand prorationing."⁴ The empirical results indicate that investment in petroleum reserves depended on three public policies: the special federal tax provisions, state market-demand prorationing, and the federal oil import quota. It is possible to draw some tentative policy conclusions from our empirical results, al-

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¹ The special federal tax provisions for crude petroleum producers are the option to claim "percentage" rather than "cost" depletion on producing wells, and the option to expense rather than depreciate so-called "intangible" drilling costs. Compared to uniform tax treatment of corporate income in all industries, the special provisions for petroleum are a subsidy administered through the revenue side of the budget. Other mineral industries may also claim percentage depletion. See Susan Agria for a detailed discussion of the special tax provisions for mineral industries.

² The authors (1973a, b), and Wright.

³ Even a finding that the tax-subsidy policy was cost-effective in increasing petroleum reserve investment would not, of course, necessarily imply that the policy is "in the public interest," since tradeoffs with other programs would not be considered. See the authors (1975a) for a preliminary application of the cost-effectiveness approach to evaluating the special tax provisions.

⁴ The five states are Kansas, Louisiana, New Mexico, Oklahoma, and Texas. According to American Petroleum Institute (*API*) et al. (1972), they contain about 75 percent of *U.S.* proved reserves outside Alaska. The operation of market-demand prorationing is discussed in detail in Sections I and IV below.

though a complete analysis of the three public policies will require additional empirical estimates.

The model is developed in Section I. The data sources and methodology used to outfit the model for empirical testing are discussed in Section II. The empirical results are reported in Section III. Finally, Section IV contains the conclusions, including the policy implications of our results.

I. A Model of the Crude Petroleum Producer⁵

We assume that crude petroleum producers maximize the present value of after-tax cash flow, subject to the constraints of a production function and an accounting identity. The production function is assumed to be *CES*. The accounting identity relates changes in petroleum reserve stocks to flows of gross investment in reserves and current output (“depreciation”).

The after-tax cash flow of a crude petroleum producer is conveniently represented as the difference between a revenue term and two cost terms, one for investment (reserve acquisition) costs and one for other input costs. Thus after-tax cash flow at time t can be written as

$$(1) \quad N(t) = N_1(t) - N_2(t) - N_3(t)$$

where N_1 is the revenue term and N_2 and N_3 are the investment and noninvestment cost terms, respectively. We discuss each of these cash-flow components in turn.

A crude petroleum producer must make royalty payments to the landowners from whom the drilling and production rights have been leased. These payments are customarily calculated as a percentage of

⁵ In constructing the model, we have benefitted from the earlier work on investment in manufacturing by Dale Jorgenson (1965, 1967) and by Robert Hall and Jorgenson. Throughout the present paper, “petroleum” refers to crude oil, natural gas, and natural gas liquids.

gross revenue.⁶ Let $(1-\pi)$ be the proportion of gross revenue which must be paid in royalty; then the proportion π of gross revenue accrues to the producer. If p is the price and Q the quantity of marketed output, the revenue of a crude petroleum producer before taxes is πpQ .

The after-tax revenue of a crude petroleum producer depends on several tax provisions. State and local governments assess production and severance taxes on both quantity of production and revenue; these are represented in the after-tax cash flow equation by the average production and severance tax rate y . These taxes are deductible from net income subject to the federal corporation income tax, which is assessed at rate u . Further deductions from federal tax are allowed for a proportion z of gross revenue through the percentage depletion allowance. Together, the royalty share and the tax provisions determine the after-tax revenue component of the cash flow equation at time t :

$$(2) \quad N_1(t) = \{1 - y(t) - u(t) \cdot [1 - y(t) - z(t)]\} \pi(t) p(t) Q(t)$$

Various categories of investment cost in the crude petroleum industry are treated differently under the federal corporation income tax. Define the following terms: $I(t)$ is total reserve acquisition cost at time t ; $q_1(I(t), t)$ is the proportion of $I(t)$ spent on drilling dry holes; $q_2(I(t), t)$ is the proportion of $I(t)$ spent on “intangible” costs of successful wells; $q_3(I(t), t)$ is the proportion of $I(t)$ spent on “tangible” costs of successful wells; and $D(t)$ is the discounted value at time t of the time stream of tax deductions from one dollar of depreciable outlays made at time t . The three proportions q_j sum to one at any time t .

Dry-hole costs $q_1 I$ and intangible costs

⁶ Stephen McDonald (1963, p. 18), explains how the royalty payment comes “off the top” before tax liability is calculated.

q_2I are fully deductible from gross income in the year in which they are incurred. Tangible costs q_3I must be capitalized and depreciated over a number of years; therefore the time t value of the tax deductions they provide is Dq_3I . Thus we have the after-tax investment cost component of the cash-flow equation at time t :

$$(3) \quad N_2(t) = \{ [1 - u(t)][q_1(I(t), t) + q_2(I(t), t)] + [1 - u(t)D(t)]q_3(I(t), t) \} I(t)$$

Other input cost categories are also treated differently under the federal corporation income tax. Define the following terms: L is an index of the quantities of nonreserve inputs into the production of crude petroleum; w_1 is the expensable cost per unit of L ; w_2 is the depreciable cost per unit of L ; and w_3 is the nondeductible cost per unit of L for producers taking percentage depletion rather than cost depletion. Then the noninvestment cost component of the cash-flow equation at time t is

$$(4) \quad N_3(t) = \{ [1 - u(t)]w_1(t) + [1 - u(t)D(t)]w_2(t) + w_3(t) \} L(t)$$

The quantity of output at time t is constrained by the differentiable implicit production function

$$(5) \quad F(Q(t), \Omega(t), L(t), t) = 0$$

The variable Ω is the full-time equivalent stock of proved reserves; we specify the proved reserves input that way instead of simply as the stock of proved reserves because of market-demand prorationing (*MDP*). *MDP* limits the use of the productive services of proved petroleum reserves. For example, the Texas Railroad Commission (*TRRC*) formerly imposed "shutdown days" on the operation of wells subject to its control.⁷ Thus if there had been fifteen

⁷ In 1963, the *TRRC* ceased using shutdown days and began setting "market demand factors" directly in percentage terms, as in statement (6). As the text indicates, the two regulatory procedures are equivalent.

shutdown days in a month of thirty days, the market-demand factor S would have been

$$(6) \quad S = 0.5 = \frac{30 - 15}{30}$$

If *MDP* were actually enforced as the name shutdown days suggests, by shutting wells down completely part of the time, the full-time equivalent of a stock of reserves R would be simply SR ; the flow of services from the stock of reserves could then be assumed proportional to SR . In fact, *MDP* is enforced differently; a controlled well is permitted to operate every day, so long as total output for the month does not exceed the quantity S times the "rated allowable" capacity of the well (which the *TRRC* also determines). Producers may therefore choose to obtain a given flow of productive services from fewer proved reserves than if they were forced to shut down part of the time; if so, they will utilize their reserves more intensively than they would under a literal shutdown days scheme. To include this possibility, we write Ω as the function

$$(7) \quad \Omega(t) = S(t)^\theta R(t), \quad 0 \leq S(t) \leq 1, \\ 0 < \theta$$

where θ is the elasticity of the full-time equivalent stock of reserves with respect to the market-demand factor S . A literal shutdown days scheme would be the special case of (7) where θ equals 1. If θ is less than 1, it would mean that prorated producers hold a smaller stock of reserves for any flow of productive services under actual *MDP* than under literal shutdown days. A value of θ greater than 1 would have the opposite implication; this case seems unlikely, but the actual value of θ is, of course, an empirical question.

Gross additions to proved reserves at time t are represented by the differentiable function $\phi(I(t), t)$. The function ϕ is as-

sumed to be increasing and strictly concave in I (expenditures on acquiring reserves) for all values of t . This representation assumes that at every point in time, as the size of the reserve acquisition program increases, the marginal addition to reserves per dollar spent decreases. This might occur, for example, if the proportion of "dry holes" increased or if the average quantity of proved reserves per successful well diminished.

Let $r(t)$ be the time-rate of change of the stock of proved reserves, $dR(t)/dt$. Then we have the accounting relation (capital stock equation of motion)

$$(8) \quad r(t) = \phi(I(t), t) - Q(t)$$

That is, the rate of change of the stock of proved reserves at time t must equal the rate of gross additions to reserves at time t less the rate of output from reserves at time t .

The assumed objective of a petroleum producer is maximization of the present value of after-tax cash flow,

$$(9) \quad V = \int_0^{\infty} N(t) e^{-\int_0^t i(s) ds} dt$$

where $i(s)$ is the after-tax rate of interest. The solution to the problem of maximizing (9), subject to (5), (7), and (8), can be found by maximizing the Lagrangian function

$$(10) \quad \int_0^{\infty} g(t) dt = \int_0^{\infty} \{N(t) + \lambda(t)F(Q(t), S(t)^\theta R(t), L(t), t) + \eta(t)[\phi(I(t), t) - Q(t) - r(t)]\} e^{-\int_0^t i(s) ds} dt$$

Substituting (1)-(4) into (10), we find the Euler necessary conditions to be equations (5) and (8), plus the following:

$$(11) \quad 0 = \frac{\partial g(t)}{\partial Q(t)} = \lambda(t) \frac{\partial F}{\partial Q(t)} + \{1 - y(t) - u(t) \cdot [1 - y(t) - z(t)]\} \pi(t) p(t) - \eta(t)$$

$$(12) \quad 0 = \frac{\partial g(t)}{\partial L(t)} = \lambda(t) \frac{\partial F}{\partial L(t)} - \{[1 - u(t)]w_1(t) + [1 - u(t)D(t)]w_2(t) + w_3(t)\}$$

$$(13) \quad 0 = \frac{\partial g(t)}{\partial I(t)} = \eta(t) \frac{\partial \phi}{\partial I(t)} - \{[1 - u(t)][q_1(I(t), t) + q_2(I(t), t)] + [1 - u(t)D(t)]q_3(I(t), t)\} - \left\{ [1 - u(t)] \left[\frac{\partial q_1}{\partial I(t)} + \frac{\partial q_2}{\partial I(t)} \right] + [1 - u(t)D(t)] \frac{\partial q_3}{\partial I(t)} \right\} I(t)$$

$$(14) \quad 0 = \frac{\partial g(t)}{\partial R(t)} - \frac{d}{dt} \left(\frac{\partial g(t)}{\partial r(t)} \right) = \lambda(t) S(t)^\theta \frac{\partial F}{\partial \Omega(t)} + \frac{d\eta(t)}{dt} - i(t)\eta(t)$$

The preceding necessary conditions can be used to derive the investment functions implicit in the model. We first derive and interpret one argument of those functions, namely, the output-input, after-tax relative price variable. Then we assume a specific form of the production function to derive the investment functions; their discrete approximations comprise the estimating equations used in the empirical work.

The first step is to show that the necessary conditions imply that a petroleum producer should set the marginal product of its stock of reserves equal to the ratio of the marginal after-tax cost of holding reserves to the marginal after-tax net return from producing reserves. Using equations (5) and (7) and the implicit function theorem, we find

$$(15) \quad \frac{\partial Q(t)}{\partial R(t)} = -S(t)^\theta \frac{\lambda(t)\partial F/\partial \Omega(t)}{\lambda(t)\partial F/\partial Q(t)}$$

Equations (11) and (14) imply

$$(16) \quad -S(t)^\theta \frac{\lambda(t)\partial F/\partial \Omega(t)}{\lambda(t)\partial F/\partial Q(t)} = \frac{i(t)\eta(t) - d\eta(t)/dt}{\{1-y(t)-u(t)[1-y(t)-z(t)]\}\pi(t)p(t) - \eta(t)}$$

Equations (15) and (16) imply

$$(17) \quad \frac{\partial Q(t)}{\partial R(t)} = \left[\left\{ i(t) - \frac{1}{\eta(t)} \frac{d\eta(t)}{dt} \right\} \eta(t) \right] \div \left[\{1-y(t)-u(t)[1-y(t)-z(t)]\}\pi(t)p(t) - \eta(t) \right]$$

The left-hand side of (17) is obviously the marginal product of the stock of reserves. We now show that the right-hand side of (17) is the ratio of the marginal after-tax net cost of holding reserves to the marginal after-tax net return from producing reserves. Consider first the numerator. From (13), we see that $\eta(t)$ is the marginal after-tax cost of a unit of proved reserves;⁸ therefore $[1/\eta(t)][d\eta(t)/dt]$ is the own-rate of interest on reserves. Since $i(t)$ is the after-tax monetary rate of interest, the numerator of the right-hand side of (17) is the marginal after-tax net cost of holding a unit of reserves. Next consider the denominator. The first term $\{1-y(t)-u(t)[1-y(t)-z(t)]\}\pi(t)p(t)$ is the marginal after-tax revenue from selling a unit of output. The second term $\eta(t)$ is the marginal after-tax cost of a unit of reserves to replace that which is produced. The difference between the two terms is the marginal after-tax net return from producing a unit of reserves.

⁸ Let $\beta = [(1-u)(q_1+q_2) + (1-uD)q_3] + [(1-u)(\partial q_1/\partial I + \partial q_2/\partial I) + (1-uD)\partial q_3/\partial I]I$ in equation (13). Note that β is the marginal change in the time t value of after-tax cash flow with respect to investment expenditure. From (13), $\eta = \beta(\partial\phi/\partial I)^{-1}$. Since $\partial\phi/\partial I$ is the marginal increase in reserves from investment expenditure, $(\partial\phi/\partial I)^{-1}$ is the marginal *before-tax* cost of reserves; hence $\beta(\partial\phi/\partial I)^{-1}$ is the marginal *after-tax* cost of reserves at time t .

The right-hand side of (17) is the inverse of the output-input, after-tax relative price variable h , which is shown below to be an argument of the investment functions:

$$(18) \quad h(t) = \left[\{1-y(t)-u(t)[1-y(t)-z(t)]\}\pi(t)p(t) - \eta(t) \right] \div \left[\left\{ i(t) - \frac{1}{\eta(t)} \frac{d\eta(t)}{dt} \right\} \eta(t) \right]$$

We assume a CES production function,

$$(19) \quad Q(t) = Ae^{\gamma t} \{ a\Omega(t)^{-v} + (1-a)L(t)^{-v} \}^{-b/v}$$

where $A > 0$ is the scale parameter; $\gamma \geq 0$ is the rate of technological change; $a \in (0, 1)$ is the input-intensity parameter; $(1+v)^{-1} \in (0, 1]$ is the elasticity of factor substitution, restricted so that both inputs are necessary for positive production; and $b \in (0, 1]$ is the degree of homogeneity, restricted so that the production function is concave. Equations (7) and (19) imply that the marginal product of reserves is

$$(20) \quad \frac{\partial Q(t)}{\partial R(t)} = \frac{\partial Q(t)}{\partial \Omega(t)} \frac{\partial \Omega(t)}{\partial R(t)} = abA^{-v/b} [e^{\gamma t}]^{-v/b} [Q(t)]^{(1+v)/b} [R(t)]^{-(1+v)} [S(t)]^{-\theta v}$$

From equations (17), (18), and (20), we obtain the following expression for the optimal stock of proved reserves:

$$(21) \quad R(t) = [abA^{-v/b}]^{1/(1+v)} \cdot [h(t)]^{1/(1+v)} [Q(t)]^{(b+v)/b(1+v)} \cdot [S(t)]^{-\theta v/(1+v)} [e^{\gamma t}]^{-v/b(1+v)}$$

Taking a logarithmic transformation of (21) yields the optimal reserves stock equation

$$(22) \quad \ln R(t) = \alpha_0 + \alpha_1 \ln h(t) + \alpha_2 \ln Q(t) + \alpha_3 \ln S(t) + \alpha_4 t$$

where:

$$(23) \quad \alpha_0 = \frac{1}{1+v} [\ln a + \ln b] - \frac{v}{b(1+v)} \ln A$$

$$\alpha_1 = \frac{1}{1+v}$$

$$\alpha_2 = \frac{b+v}{b(1+v)}$$

$$\alpha_3 = -\frac{\theta v}{1+v}$$

$$\alpha_4 = -\frac{\gamma v}{b(1+v)}$$

Replacing continuous time by discrete time in (22), and adding the error term ϵ_t , we get the reserves stock estimating equation

$$(24) \quad \ln R_t = \alpha_0 + \alpha_1 \ln h_t + \alpha_2 \ln Q_t + \alpha_3 \ln S_t + \alpha_4 t + \epsilon_t$$

Differentiation of (22) yields the proportional net investment equation

$$(25) \quad \frac{dR(t)/dt}{R(t)} = \alpha_1 + \alpha_1 \frac{dh(t)/dt}{h(t)} + \alpha_2 \frac{dQ(t)/dt}{Q(t)} + \alpha_3 \frac{dS(t)/dt}{S(t)}$$

Replacing continuous time by discrete time in (25), and adding the error term ϵ'_t , we get the proportional net investment estimating equation

$$(26) \quad \frac{\Delta R_t}{R_t} = \alpha_1 + \alpha_1 \frac{\Delta h_t}{h_t} + \alpha_2 \frac{\Delta Q_t}{Q_t} + \alpha_3 \frac{\Delta S_t}{S_t} + \epsilon'_t$$

The net investment estimating equation with error term ϵ'_t is

$$(27) \quad \Delta \ln R_t = \alpha_4 + \alpha_1 \Delta \ln h_t + \alpha_2 \Delta \ln Q_t + \alpha_3 \Delta \ln S_t + \epsilon'_t$$

Equation (27) can be derived either by taking a first-order Taylor series approximation of (22), or by taking first differences in (24).

II. Data Sources

In this section, we discuss the selection and use of empirical measures of the cost of acquiring proved reserves and of the output and price of crude petroleum. We also briefly describe the other data used in the estimations.

A. Cost of Acquiring Petroleum Reserves

The only suitable data on reserve acquisition costs which are broken down by state are those published by the Joint Association Survey (*JAS*) for "costs of drilling and equipping wells" (hereafter *D&E* costs). These data are available separately for successful oil wells, successful gas wells, and total dry holes; they appear to cover the vast bulk of "proving up" outlays. The *JAS* series on *D&E* costs is only available continuously for the years 1959–71, restricting the empirical estimations to thirteen observations.⁹

B. Current Petroleum Output and Price

For the output variable Q , U.S. Bureau

⁹ American Petroleum Institute (*API*) et al., Section I. The *D&E* costs include only the "Christmas tree" on wells to be used in production. The procedures underlying the *JAS* data have been criticized by Franklin Fisher; we have not evaluated the data published since Fisher wrote (i.e., those for 1961–71), but the methodology appears to have been substantially improved (see, e.g., Morris Adelman, p. 121). *JAS* published *D&E* costs for 1953, 1955, and 1956, but not for 1954 or 1957 and 1958; the early data are of much lower quality than those for 1959–71. The Chase Manhattan Bank (*CMB*) and the *JAS* (*API* et al., Section II) publish series on exploration and development outlays but only for the entire United States. The *CMB* series would not be suitable for econometric work because it is intended as information for investors, not as a consistently defined time-series. Moreover, it includes production facilities beyond the "Christmas tree."

of Mines (*USBM*) data were used in constructing a Divisia quantity index¹⁰ of current outputs of oil, natural gas (nonassociated and associated-dissolved), and natural gas liquids—i.e., all petroleum production from which revenue was received.¹¹ The *USBM* natural gas figure used in the output Divisia index was “marketed output,” which is equal to “gross” output from oil and gas wells, less “repressuring” and “losses.”

For the price variable p , a Divisia price index of oil, natural gas, and natural gas liquids was constructed. For oil and natural gas liquids, *USBM* data on values realized “at the well” (oil) and “at plants” (natural gas liquids), divided by the appropriate *USBM* output figure, were used. For natural gas, the relevant price for decisions on new reserves in year t is the price obtained on new contracts made in that year, not average realized prices which include sales under long-term contracts made in years past; accordingly, a series for “new contract” prices prepared by Foster Associates for the Energy Policy Project was used.

C. Other Data Sources

1) The stock of proved reserves R . Annual data on end-of-year proved reserves of oil and natural gas, in American Petroleum Institute, American Gas Association, and Canadian Petroleum Association, were used in a Divisia index of reserves.

2) Market-demand factor S . The values of this variable were those set by the *TRRC*; the annual market-demand factor was calculated as a percentage equal to the average of the twelve monthly figures.

3) U.S. corporate income tax rate u . Data for 1959–69 were obtained from

¹⁰ On Divisia quantity and price indexes, see Herman Wold and Lars Jureén, and Jorgenson and Griliches.

¹¹ The *USBM* data are given in convenient form through 1969 in *API*. For 1970 and 1971, the *USBM*'s *Mineral Industry Surveys* were used.

Joseph Pechman, p. 118; the rates for 1970 and 1971 were taken from the U.S. Internal Revenue Code.

4) Percentage depletion rate z . The statutory percentage depletion rate was used for want of a time-series of the effective rate; the latter rate would be less than the former because of the net income limitation.

5) Average production and severance tax rate y . This rate was calculated from data in *API* et al., Section II, on state and local taxes paid on oil and gas production, divided by the total value of petroleum production.

6) Discounted value at time t of \$1 of depreciable cost incurred at time t , D . Iterations from 0.4 to 0.8 in increments of 0.1 showed very little variation in the results. We used the conservatively high value of $D=0.8$, which is the approximate value of \$1 of depreciable cost over five years at 12 percent by the sum-of-years-digits depreciation method (see Hall and Jorgenson).

7) Interest rate i . Two alternative time-series for the after-tax rate of interest were used. (a) The quantity $(1-u)$ times Moody's index of all “industrial” bond yields, for thirty-six bonds, referred to as the “debt” interest rate. (b) The quantity $(1-u)$ times the inverse of Standard and Poor's composite “price-earnings ratio,” referred to as the “equity” interest rate.

8) Royalty share $(1-\pi)$. Based on information in McDonald (1971, p. 14, and 1963, p. 103, n. 132), we iterated over values from 0.10 to 0.20. Since the empirical results varied little between iterations, we follow *API* et al., Section II, and report the results for a royalty share of 15 percent.

III. Empirical Estimations

In this section, we first discuss the construction of the relative price variable h from the data discussed in Section II. We

then report ordinary least squares estimates of the reserves investment equations derived in Section I.

The first step in constructing the time-series of h was to calculate an average-cost proxy for the marginal after-tax cost of reserves η defined by (13). To separate *D&E* costs on successful wells into intangible (expensable) and tangible (depreciable) components, we regressed intangibles on total *D&E* costs for successful oil wells and for successful gas wells, using *JAS* data for 1959–64. The total figure for each type of well was then multiplied by the fitted slope coefficient and by one minus the coefficient to obtain intangible and tangible costs, respectively.¹²

The time-series of average costs of acquiring reserves by type of tax treatment were then obtained by dividing dry-hole, intangible, and tangible *D&E* costs by gross additions to petroleum reserves. Let Λ_t be a Divisia quantity index of $(R_t - R_{t-1} + Q_t)$ for crude oil and nonassociated natural gas in year t . Also let X_{dt} , X_{ct} , and X_{gt} be *D&E* costs in year t on dry holes, successful crude oil wells, and successful gas wells, respectively. Finally, let β_c and β_g be the estimated proportions of intangibles in *D&E* costs in year t for successful oil wells and successful gas wells, respectively. Then for year t the average dry-hole cost of new reserves was calculated as X_{dt}/Λ_t ; the average intangible cost of new reserves was $(\beta_c X_{ct} + \beta_g X_{gt})/\Lambda_t$; and the average tangible cost of new reserves was $[(1 - \beta_c)X_{ct} + (1 - \beta_g)X_{gt}]/\Lambda_t$.

The last step in calculating the average-cost proxy for the time-series of η was to multiply the above dry-hole and intangible

costs by $(1 - u)$ and to multiply the above tangible costs by $(1 - uD)$. The time-series of η in turn was combined with the production-tax rate y , the percentage depletion rate z , the royalty share π , the price index of petroleum production p , and the rate of interest i , to calculate the time-series of the output-input, after-tax relative price variable h , given by (18). There is no time trend in the time-series of η ; the ratio of the variance to the mean of the series is less than 0.2 percent. This allowed us to assume that over the time period covered by our data, the own-rate of interest on proved reserves was zero. Consequently, the term $[1/\eta(t)][d\eta(t)/dt]$ was set equal to zero in calculating the time-series of h .

Market price p is a component of h , and the quantity of output Q enters the estimating equations as another explanatory variable. During the period covered by our data, authorities in the five prorationing states effectively controlled the price of crude oil through the policy of *MDP* (under the protective cover of the import quota). By varying the market-demand factor, the state authorities in effect selected price-quantity pairs from the domestic demand curve. It is therefore appropriate in the following regressions to assume that market price and output were both exogenously determined variables over the period studied.¹³

The results of least squares regressions for the estimating equations derived in Section I, using the data described in Section II and the procedures detailed above, are reported in Table 1 (debt interest rate) and Table 2 (equity interest rate). Given the small number of degrees of freedom, the results of the least-squares regressions are encouraging. All estimated coefficients of explanatory variables are highly

¹² The *JAS* definitions of intangibles and tangibles correspond closely to those in the federal tax law (e.g., *API* et al., 1964, section I, pp. 7–8). Scatter diagrams of intangibles against total *D&E* costs for successful wells indicated very tight linear fits for both oil and gas wells. Least squares regressions gave $R^2 > 0.999$; the constant terms were not significant.

¹³ For further explanation of this point, see fn. 17 and the accompanying discussion in Section IV below.

TABLE 1—REGRESSION RESULTS: DEBT INTEREST RATE

	Coefficients					\bar{R}^2	DW	F
	h_t	Q_t	S_t	t				
	α_0	α_1	α_2	α_3	α_4			
(24) $\ln R_t$	4.3423 (2.99)	.0335 (4.18)	.8667 (9.40)	-.1719 (16.92)	-.0275 (7.17)	.9734	2.0823	110.7915
(26) $\Delta R_t/R_t$	—	.0443 (5.11)	.9081 (7.12)	-.1877 (8.62)	-.0292 (6.06)	.8919	2.1853	31.2575
(27) $\Delta \ln R_t$	—	.0379 (4.16)	.8488 (5.96)	-.1699 (7.17)	-.0266 (4.84)	.8507	2.1009	21.8947

Note: Absolute values of t -ratios in parentheses. \bar{R}^2 = coefficient of determination adjusted for degrees of freedom. DW = Durbin-Watson statistic; null hypothesis of no serial correlation, $DW = 2.0$. $F = F$ -statistic; $F(4, 8)$ for equation (24) and $F(3, 8)$ for equations (26) and (27).

TABLE 2—REGRESSION RESULTS: EQUITY INTEREST RATE

	Coefficients					\bar{R}^2	DW	F
	h_t	Q_t	S_t	t				
	α_0	α_1	α_2	α_3	α_4			
(24) $\ln R_t$	3.6807 (2.55)	.0332 (4.06)	.9078 (9.93)	-.1893 (18.42)	-.0295 (7.89)	.9723	2.4401	106.1457
(26) $\Delta R_t/R_t$	—	.0299 (3.91)	.9644 (6.30)	-.1898 (7.10)	-.0338 (6.04)	.8417	2.3299	20.5016
(27) $\Delta \ln R_t$	—	.0297 (3.58)	.9176 (5.91)	-.1789 (6.60)	-.0308 (5.32)	.8185	2.5032	17.5367

Note: See Table 1 for explanation of terms.

significant; moreover, they are quite stable between the stock and the flow estimating equations. The \bar{R}^2 are relatively high; indeed, we expected worse fits for the first-difference equations, (26) and (27). The Durbin-Watson statistics evidence virtually no serial correlation of the residuals for the debt interest rate and only a weak tendency towards negative serial correlation with the equity interest rate.¹⁴ The F -statistics for all six equations estimated exceed the confidence values at the 1 per cent level of significance.

¹⁴ Our colleague, Ronald Ehrenberg, has pointed out that regardless of the calculated values of the Durbin-Watson statistics for the equations estimated, the apparent absence of serially correlated residuals can be true for only the stock equation or the flow equations but not for both simultaneously.

The signs of the estimated coefficients reported in Tables 1 and 2 can be interpreted as follows. For the stock equation (24), producers held a larger stock of proved reserves during the period studied, *ceteris paribus*, (a) the higher was the output-input relative price variable ($\alpha_1 > 0$); (b) the higher was the rate of current petroleum output ($\alpha_2 > 0$); (c) the smaller was the market-demand factor ($\alpha_3 < 0$);¹⁵

¹⁵ One might be tempted to think that a more stringent (smaller) value of the market-demand factor would have reduced the stock of reserves by raising the price of the effective flow of reserve services into the production of crude petroleum (e.g., Adelman, p. 106). In fact, producers were forced by the policy of *MDP* to increase the reserve/output ratio for any given level of output. Hence the negative relationship which we find is the one to be expected.

TABLE 3—IMPLIED PARAMETER VALUES:
DEBT INTEREST RATE

Equations	Parameters			
	$1/(1+v)$	b	θ	γ
(24) $\ln R_t$	.0335	1.1599	.1779	.0330
(26) $\Delta R_t/R_t$	.0443	1.1064	.1964	.0338
(27) $\Delta \ln R_t$	.0379	1.1865	.1766	.0327

Note: We lack information to solve explicitly for A (scale parameter) and a (input-intensity parameter); see (23).

and (d) the lower was the rate of technological change ($\alpha_4 < 0$). For analogous interpretations of the two flow equations (26) and (27), add a modifying phrase, "proportional change in" or "change in," where appropriate in the above interpretation of the stock equation.

We report in Tables 3 and 4 the values of the production function parameters $1/(1+v)$, b , θ , and γ which from (23) are implied by the estimated coefficients reported in Tables 1 and 2. The estimates of $1/(1+v)$, which is the elasticity of substitution between reserves and nonreserve inputs and is equal to the coefficient α_1 , are contained in $(0, 1]$ as required by our specification of the production function. In addition, the values of the elasticity of substitution are quite small, plausibly suggesting that it is difficult to substitute non-reserve inputs for proved reserves in producing crude petroleum. The estimates of b , θ , and γ are biased because they are non-linear functions of the α_j . The estimates of b , which is the homogeneity parameter and is equal to $(\alpha_1 - 1)/(\alpha_1 - \alpha_2)$, are not contained in $(0, 1]$ as required by our specification of the production function. The estimates of θ , which is the elasticity of the full-time equivalent stock of reserves with respect to the market-demand factor and is equal to $\alpha_3/(\alpha_1 - 1)$, are positive as required by (7); they are also much smaller than unity, suggesting that crude petroleum producers in the prora-

TABLE 4—IMPLIED PARAMETER VALUES:
EQUITY INTEREST RATE

Equations	Parameters			
	$1/(1+v)$	b	θ	γ
(24) $\ln R_t$	.0332	1.1054	.1958	.0337
(26) $\Delta R_t/R_t$	.0299	1.0381	.1957	.0362
(27) $\Delta \ln R_t$	.0297	1.0928	.1844	.0347

Note: See Table 3 for explanation.

tioning sector did indeed respond to *MDP* by utilizing their proved reserves more intensively than they would have under literal "shutdown days" prorationing. Finally, the estimates of γ , which can be interpreted as the rate of technological change and is equal to $\alpha_4/(\alpha_1 - \alpha_2)$, are nonnegative as required by our specification of the production function; furthermore, the implied values of 3.3 to 3.6 percent per annum are reasonable.

IV. Conclusions and Policy Implications

Our empirical estimates of the determinants of investment in crude petroleum reserves in the prorationing sector of the *U.S.* petroleum industry for 1959–71 are consistent with the model of investment in crude petroleum reserves presented in Section I. The results indicate that several public policies have significantly affected investment in reserves in the prorationing sector. Three of the four explanatory variables depend on instruments of government control. The relative price variable is a function of the special federal corporation income tax provisions for petroleum. The market-demand factor is under the direct control of state prorationing authorities. In addition, both those authorities and the federal government exercised control over crude oil price and quantity during the period studied, through the policies of *MDP* and the oil import quota, respectively.

Two of the three policies had direct par-

tial effects on investment in petroleum reserves which can be inferred from our estimates. In addition, all three policies had indirect partial effects through induced changes in equilibrium price and quantity, which can also be inferred from our estimates. The total effects can be determined from our results if both the direct and the indirect effects have the same sign; otherwise, further information is required. We consider first the direct and then the indirect policy effects on petroleum reserves.

The special federal tax provisions for petroleum corporation income increase the value of the relative price variable h , given the price of petroleum output.¹⁶ Thus the significantly positive estimates of α_1 imply that those provisions increased investment in reserves compared to uniform tax treatment. Similarly, the significant positive estimates of α_3 imply that setting the market-demand factor S at less than unity increased investment in reserves compared to the absence of effective MDP ($S=1$).

The oil import quota indirectly affected investment in prorationing-sector petroleum reserves by restricting the quantity of imports. Given the market-demand factor and the special tax provisions, reduced imports would lead to a higher price in the U.S. market; the higher price in turn would induce an increase in quantity supplied in the prorationing sector. Therefore, the significantly positive estimates of α_1 and α_2 , the coefficients on relative price and output, imply that the oil import quota increased investment in petroleum reserves.

The indirect effects on petroleum reserves of the special tax provisions and MDP involve shifts in the petroleum sup-

ply curve. It can be shown that the model developed in Section I leads to a prorationing-sector supply function relating quantity supplied to the market-demand factor, time, and two output-input relative price variables, our h and another relative price, which we have not explicitly defined, for the nonreserve input. In order to represent the supply function as a family of supply curves in price-quantity space, we define the following variable:

$$(28) \quad c(t) = \frac{i(t)\eta(t)}{\pi(t)\{1-y(t)-u(t)[1-y(t)-z(t)]\}}$$

Given the assumption of a zero own-rate of interest on reserves (see Section III), statements (18) and (28) imply

$$(29) \quad h(t) = \frac{p(t)}{c(t)} - \frac{1}{i(t)}$$

Then holding constant the price of the non-reserve input and the rate of interest, quantity supplied in the prorationing sector at time t is an increasing function of p and S and a decreasing function of c . A similar argument leads to a supply function for the nonprorationing sector which is increasing in p and decreasing in c ; the market-demand factor S does not, of course, appear in the nonprorationing-sector supply function. Since total domestic supply is the sum of the quantities supplied by the two sectors, the total supply function can be represented by the family of supply curves $Q(\cdot)$ in the price-quantity space of Figure 1.

Let $D(p)$ in Figure 1 be the demand curve for petroleum in the domestic market. Then suppose that the special tax provisions were made more generous, so that c decreased from (say) c'' to c' ; as a result, the supply curve would shift from $Q(p, c'', S')$ to $Q(p, c', S')$. Given $D(p)$, the shift in supply would in turn reduce equilibrium price from p^b to p^a and increase the

¹⁶ From (18), h is seen to be an increasing function of the rate of percentage depletion z . It can be seen from (13) that the expensing of intangible drilling costs transfers marginal acquisition costs in the amount $[q_2 + I(\partial q_2 / \partial I)]$ from a term with weight $[1-uD]$ to a term with the smaller weight $[1-u]$.

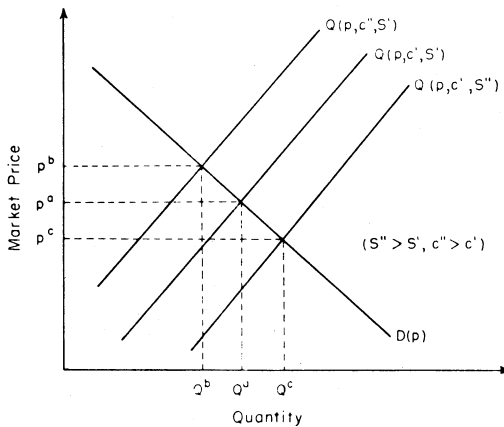


FIGURE 1

quantity supplied from Q^b to Q^a . Part of the increase in quantity supplied would come from the prorationing sector. Thus making the special tax provisions more generous would (*ceteris paribus*) reduce market price and increase the quantity supplied (and vice versa for making the provisions less generous).

To isolate the indirect effects of varying the special tax provisions, we take the differential of (22), set dS_t and dt equal to zero, and use (29) to obtain

$$(30) \quad dR_t = - \frac{\alpha_1 p_t R_t}{(c_t)^2 h_t} dc_t + \frac{\alpha_2 R_t}{p_t} \left[\frac{\alpha_1 p_t}{\alpha_2 c_t h_t} - E_t \right] dp_t$$

where E_t is the price elasticity of demand for petroleum at time t . The first term on the right-hand side of (30) is the direct effect on reserves of changes in the special tax provisions; since dc_t is negative, the sign of this term is positive, which is consistent with our earlier finding that the direct effect of the special tax provisions was to increase reserves.

The second expression on the right-hand side of (30) is the indirect effect on reserves of changing the special tax provisions. As noted above in discussing Figure 1, making

those provisions more generous reduces the market price. Therefore dp_t is negative and, since α_2 is positive, the sign of the indirect effect is the opposite of the sign of the term in brackets. The latter sign is analytically indeterminate, depending on whether $\alpha_1 p_t / \alpha_2 c_t h_t$ is greater or less than E_t . To place limits on the sign of the bracketed term, we calculated the values of $\alpha_1 p_t / \alpha_2 c_t h_t$, using the estimates of α_1 and α_2 (see Tables 1 and 2) plus the observed figures for p_t , h_t , and c_t for 1959–71; these values vary from 0.0366 to 0.0659. Therefore the bracketed expression in (30) was negative in each year between 1959 and 1971 in which the price elasticity of demand for crude petroleum exceeded 0.0659. If the bracketed expression was negative, the indirect effect as a whole would have been positive, thereby reinforcing the direct effect. On the assumption that E_t was larger throughout the period than the very low value of 0.0659, we tentatively conclude that both the direct and the indirect effects of the special tax provisions increased the stock of proved reserves of petroleum.

To examine the indirect effect of market-demand prorationing on reserves, let us begin with the supply curve $Q(p, c', S'')$ in Figure 1. Now suppose *MDP* is made more stringent by a reduction in the market-demand factor from S'' to S' . We showed above that this reduction would directly increase the stock of petroleum reserves. There would also be an indirect effect, however, since moving from S'' to S' would shift the supply curve in Figure 1 from $Q(p, c', S'')$ to $Q(p, c', S')$.¹⁷ As a result, equilibrium price would increase from p^c to p^a and total quantity supplied would decrease from Q^c to Q^a . By reasoning

¹⁷ The ability to shift the supply curve in market price-output space is the reason why effective *MDP* enables the prorationing boards to pick points on the demand curve. Thus, so long as prorationing is effective, market price and output are exogenous to the prorationing sector producer.

analogous to that above for the special tax provisions, the indirect effect of *MDP* would be a decrease in reserves, provided that the price elasticity of demand for crude petroleum was greater than 0.0659. Because the direct and indirect effects have opposite signs in this case, the direction of the total effect of *MDP* on petroleum reserves cannot be determined from our estimates alone. Additional information on the supply and demand functions is required to determine the net total effect.

The Arab embargo of October 1973 has prompted interest in the question of national "independence" in oil. Independence can be defined as having the capacity for self-sufficiency—that is, the capability of being independent of foreign suppliers if the need arises. It can be promoted through actual self-sufficiency in production or through holding excess domestic capacity which can be used in the event that foreign supplies are disrupted. For a depletable resource such as petroleum, increasing domestic output in order to pursue self-sufficiency in production in one period will make it more expensive to be self-sufficient or to hold excess capacity in later periods. In contrast, a policy which promotes independence by inducing domestic producers to hold excess capacity need not mortgage future independence by increasing the present rate of depletion of the resource.¹⁸

An interesting question is whether past public policies have contributed to or detracted from national independence in oil. Proponents of those policies have claimed that they promoted a "strong petroleum industry" and thus increased "national security." Our empirical estimates permit us to shed some light on this question. In what follows, we analyze the effects of past policies on self-sufficiency as measured by the quantity of imports; discussion of

policy effects on alternative measures of self-sufficiency is relegated to footnotes. We also analyze the effects of past policies on independence as measured by the ratio of imports to domestic proved reserves; because reserves are a measure of productive capacity, this ratio is one index of the capability of the domestic petroleum industry to replace imports.

We saw above that, *ceteris paribus*,¹⁹ the indirect effects of the special petroleum tax provisions were transmitted in part through an increase in domestic quantity supplied. Given that the oil import quota was administered by limiting imports to a fixed percentage of domestic production,²⁰ the increase in domestic production led to an increase in the quantity of imports. Thus the special tax provisions tended to reduce self-sufficiency in oil during the period 1959–71.²¹ In addition, the increased domestic production caused the faster depletion of domestic petroleum resources; hence the existence of the special tax provisions in the past has made the present pursuit of independence more costly. Finally, we saw above that the total effect of the special tax provisions was probably to increase investment in proved reserves. Since those provisions also increased imports, we cannot determine their net effect on past independence in oil as

¹⁹ All changes and effects discussed below are partial ones.

²⁰ James Burrows and Thomas Domencich, p. 12; Cabinet Task Force, p. 10. There was a gradual accumulation of exceptions to this policy criterion but they are irrelevant to an analysis of partial effects.

²¹ Other measures of self-sufficiency are the ratio of imports to domestic production Q_m/Q_d , and the ratio of imports to total domestic quantity demanded Q_m/D . Given the way the import quota was administered, the first measure Q_m/Q_d could not be changed by any other petroleum policy. Because the special tax provisions increased both Q_m and D , the second measure Q_m/D would have varied with tax policy; unfortunately, our estimates do not enable us to calculate the relative magnitudes of the two increases. Note that a different administration of the oil import quota would have led to other conclusions about tax policy effects on the several measures of self-sufficiency and independence.

¹⁸ These points are fully explained in the authors' paper, 1975b.

measured by the ratio of imports to proved reserves.

As we showed above, the policy of market-demand prorationing (*MDP*) reduced domestic petroleum production. Given the way the import quota was enforced, *MDP* therefore reduced oil imports and thereby increased past energy self-sufficiency.²² Because the direct effect of *MDP* on reserves was positive but the indirect effect was negative between 1959 and 1971, we cannot determine the net effect of *MDP* on past independence in oil as measured by the ratio of imports to reserves. We can say, however, that past *MDP* made the present pursuit of independence less costly because the lower rate of petroleum production reduced the rate of depletion of domestic petroleum resources.²³

The oil import quota, of course, reduced the quantity of imports compared to a policy of free trade in oil; thus it increased past self-sufficiency in oil.²⁴ In addition, we found that the quota indirectly increased investment in proved reserves by raising the market price of petroleum. The combination of lower imports and greater reserves means that the quota increased past independence in oil as measured by the ratio of imports to reserves. The increased market price, however, led to larger domestic production and hence faster depletion of domestic petroleum resources. The oil import quota of the past

²² Using the alternative measure Q_m/D , the effect of prorationing on self-sufficiency is qualitatively indeterminate, since both components of the ratio would be reduced.

²³ We abstract here from the considerable inefficiencies, due largely to overdrilling and favoritism towards "stripper" wells, introduced by *MDP* when it was an effective policy; see Adelman.

²⁴ The quota unambiguously increased self-sufficiency according to the alternative measure Q_m/Q_d , since the numerator was reduced and the denominator was increased. According to the measure Q_m/D , however, the effect is ambiguous, since both components were reduced (domestic quantity demanded was reduced by the higher market price caused by the quota).

therefore made the pursuit of present independence more expensive.

A lesson in the importance of evaluating related public policies simultaneously rather than in isolation from one another is provided by the interaction between the import quota and the special petroleum tax provisions. The quota was ostensibly intended to promote self-sufficiency in oil. We saw above, however, that the special tax provisions in the presence of the quota tended to reduce self-sufficiency in oil during the period 1959–71 by increasing the quantity of imports. Ironically, had there been no import quota, the special tax provisions would have *reduced* oil imports,²⁵ thereby increasing self-sufficiency. Furthermore, without the quota the special tax provisions would have increased past independence in oil, in that the increase in reserves coupled with the reduction in imports would have decreased the import-reserve ratio. With the quota, in contrast, both the numerator and the denominator of the ratio were increased, leaving the effect on independence indeterminate.

In conclusion, we wish to stress two implications of the preceding discussion of independence in oil. First, in evaluating a particular petroleum policy, one must take into account possible interactions with other policies; we found, for example, that the effects of the special tax provisions on self-sufficiency would have been reversed, had the oil import quota not existed. Second, our analysis reveals that past policies, contrary to assertions by their proponents, did not unambiguously promote national

²⁵ If the supply curve of imports was horizontal and (in the absence of an import quota) constituted the controlling marginal supply price in the domestic market, the increase in domestic supply resulting from more generous federal tax treatment would mean larger domestic production and hence fewer imports, since the total quantity demanded would not change. For an upward-sloping import supply curve, the increase in domestic supply would reduce the market price and hence also reduce the quantity of imports supplied in the market.

independence in oil. In designing future petroleum policies, then, attention should be paid to achieving consistency among different policies. Moreover, public officials would do well to explore alternative sets of policies which may dominate the past set in the sense of offering (say) a lower-cost time path for national independence in oil (see, for example, the authors, 1975b).

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