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# RESOURCE SCARCITY AND NEW TECHNOLOGY IN U.S. PETROLEUM DEVELOPMENT

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The United States petroleum extraction industry more than doubled production between 1939 and 1968. Throughout this period, the industry extended its activity to deeper depths, smaller deposits, and eventually into the ocean floor. Skeptics who have observed this process have argued that petroleum prices must increase substantially over time due to the nature of development costs and the depletion of scarce deposits. But the real price of crude oil at the wellhead rose only moderately during this period because the introduction of new technology and less costly inputs offset the effects of less accessible, lower quality petroleum deposits. But how significant have these opposing factors been? How much would petroleum development costs be if new technology and inputs had not been introduced? These are the specific questions to which this paper is directed.

There is a more general and more important objective as well. Ultimately, this paper is concerned with the long-standing, unsettled issue of natural resource scarcity. Anxieties stemming from the thoughts of Malthus are increasingly common among conventional worriers but are presently out of fashion among economists. It is difficult to reconcile natural resource scarcity doctrines with the past century of economic growth in western countries. But Malthus and his followers were correct as far as they went. For a given state of technology, resources are in limited supply. Technology, however, can change. Because of new technology, we have not experienced the resource scarcity and stagnation that might have occurred. The Resources for the Future studies attest to this. Unfortunately, the impact of new technology has been so phenomenal that economists have tended to reject rather than modify growth theories which include land quality as an explanatory variable. This study attempts to separate the effects of changes in natural resource quality and changes in technology in an important resource-extractive industry.[1]

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1. Since productivity studies are now commonplace, it is not surprising that this is not the first attempt to investigate technological change in the well drilling industry. Fisher analyzed drilling cost data collected by the industry during 1955, 1956, and 1959 and

Between 1939 and 1968, the number of dry holes increased from 16 percent to 43 percent of all wells drilled, the average depth of wells increased from 2,300 feet to 4,600 feet, and the industry increased its drilling activity in areas where sedimentary formations are less susceptible to the drill bit. The development of new knowledge and inputs offset the decline in prospect quality. Drilling rigs became larger and more powerful, yet simultaneously lighter and more mobile. New metallurgical knowledge improved the quality and reduced the cost of drilling bits, drill pipe, and casing materials. Through experience and controlled experiments, the transformation curves relating penetration rate, rock characteristic, drill-bit type, bit weight, rotary speed, type of drilling mud, mud pressure, and other factors have been determined. Overall, the decline in resource quality outweighed new technology, and the real cost of successful wells increased 64 percent. This study shows, however, that cost would have risen by 233 percent if there had been no improvement in knowledge and inputs.[2]

## THE GENERAL MODEL

The specific objectives of this paper are to determine the effects on petroleum development costs by changes in (1) the costs due to changes in the probability that a well would be successful, $\Delta S$; (2) the costs due to increases in the depth to which wells were drilled, $\Delta D$; and (3) the costs due to changes in the type of formation or

estimated the parameters of drilling cost functions by state and by type of well for each year. F. Fisher, Supply and Costs in the U.S. Petroleum Industry, Part II: Measuring the Effects of Depth and Technological Change on Drilling Costs (Resources for the Future, 1964).

To correct the changes in input costs over time, Fisher deflated them by a drilling-input cost index derived by the Independent Petroleum Association of America. This index, however, is not based on prices of constant quality inputs. Since the quality of inputs such as drill bits, drilling mud, well casing and cements, and some classes of labor has been improving as their costs increased, Fisher's use of the deflator tends to overestimate the change in technology. On the other hand, some components of this index, such as contractors' charges per foot of well drilled, are so directly related to output that technological change may have been underestimated. Nevertheless, he found that drilling costs fell and, though his period of analysis was short, concluded:

> . . . Technological change in the period 1955-1959 obviously more than kept pace in most areas with the tendency . . . to move toward more costly structures. Indeed, it is more than likely that average real drilling costs per well fell in most areas, as the increases in depth during the period were not enough to compensate for the technologically induced downward shifts in the cost function.

*Id.*, at 97.

2. The major histories of petroleum technology are: Executive Committee on Drilling and Production Practice, Div. of Production, Am. Petroleum Inst., History of Petroleum Engineering (1961); National Petroleum Council, Impact of New Technology on the U.S. Petroleum Industry: 1946-1965 (1967).

areas drilled, $\Delta A$. The total change in successful well cost, $\Delta C$, is the product of these separate cost factors adjusted for the effects of new technology and inputs. Thus, we have an accounting model based on the identity:

$$\Delta C = (1 + \Delta S)\ (1 + \Delta D)\ (1 + \Delta A)\ -\ (1 + \Delta T)$$

where $\Delta T$ indicates the effect of new technology within the well-drilling industry and the effect of changes in the prices of well-drilling inputs adjusted for quality. Over the long run, these latter changes can be presumed to be largely induced by new technology in the input-producing industries, or the reader can simply let $\Delta T$ be a nebulous residual. Well costs are deflated by the wholesale price index on the premise that this index is based on goods for which there have been fewer difficult-to-measure changes in quality.

## THE DATA

The *Census of Mineral Industries* by the U.S. Bureau of the Census[3] is the primary source of data. In 1939, 1954, 1958, 1963, and 1967 the Bureau collected data from oil and gas well operators and companies engaged in contract services with operators. Information requested from operators and contractors included depth of wells; costs of drilling and completing wells; man-hours spent drilling and completing wells; and expenditures on materials, fuels, and electricity used in drilling and completing wells. This information was generally reported for 18 states and, during later census years, for subareas within the states.

In 1967 the Bureau attempted to report data on more variables; but due to disclosure restrictions, they ended up reporting less. Fortunately, data on well costs and depths by state have been published in the *Joint Association Survey of Industry Drilling Costs* (hereinafter referred to as JAS) since 1953.[4] This latter source was used to estimate changes in well costs between 1963 and 1968.

Average U.S. onshore well costs, deflated by the wholesale price index for the years 1939, 1954, 1958, 1963, and 1968, are shown in Table 1. The cost of oil wells increased about 17 percent between 1939 and 1954, decreased about 3 percent between 1954 and 1958, decreased about 9 percent between 1958 and 1963, and increased about 5 percent between 1963 and 1968. Over the entire period

3. Bureau of the Census, U.S. Dep't of Commerce, United States Census of Mineral Industries (1939, 1954, 1958, 1963, & 1967) (hereinafter cited as CMI).

4. American Petroleum Institute, Independent Petroleum Association of America, Mid-Continent Oil & Gas Association, Joint Association Survey of Industry Drilling Costs (1963 & 1968) (hereinafter cited as JAS).

TABLE 1

Number of Wells Drilled and Average Cost Per Well by Well Type

| | Oil wells | | Gas wells | | Dry holes | | All wells | | Successful wells | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Year* | *Number* | *Average cost* | *Number* | *Average cost* | *Number* | *Average cost* | *Number* | *Average cost* | *Number* | *Average cost* |
| | | *dollars*[a] | | *dollars*[a] | | *dollars*[a] | | *dollars*[a] | | *dollars*[a] |
| 1939 | 17,263 | 45,400 | 1,594 | 31,100 | 3,703 | 34,200 | 22,560 | 42,500 | 18,857 | 50,900 |
| 1954 | 28,695 | 53,000 | 3,857 | 68,900 | 16,386 | 36,200 | 48,938 | 48,600 | 32,552 | 73,100 |
| 1958 | 23,512 | 51,500 | 4,462 | 88,700 | 16,248 | 37,000 | 44,222 | 49,900 | 27,974 | 79,000 |
| 1963 | 19,134 | 47,700 | 4,484 | 79,500 | 14,534 | 35,300 | 38,152 | 46,700 | 23,618 | 75,500 |
| 1963 | 20,298 | 46,200 | 4,685 | 83,400 | 15,971 | 42,200 | 40,954 | 48,900 | 24,983 | 80,100 |
| 1968 | 13,010 | 49,400 | 3,145 | 113,300 | 12,099 | 49,800 | 28,254 | 56,700 | 16,155 | 99,200 |

[a]Current dollars deflated by wholesale price index with 1957-58 base.

Sources: CMI (1939, 1954, 1958 & 1963). JAS (1963 & 1968).

there was a net increase in costs of about 9 percent. The cost of gas wells, on the other hand, increased fairly regularly over the time period for a total of 265 percent. Since the technique and nonland inputs used to drill and complete oil and gas wells are nearly identical, we can expect that the difference in costs of these two types of wells will be explained largely by differences in land factors. Dry holes are typically less expensive than productive wells because dry holes are not completed for production. This saves expenditures on tubing and perforation of the well casing and wellhead equipment (among other items). Changes in dry hole costs over time reflect changes in the costs of drilling oil and gas wells and the change in relative emphasis toward drilling more gas wells. The average cost of successful wells (total well-drilling expenditures divided by the number of successful wells drilled) generally has increased more than the cost of any particular well type because the probability of drilling successful wells has continually declined.

## THE EFFECT OF DECLINING SUCCESS

In 1939, 84 percent of all wells drilled were successful oil or gas wells. This percentage decreased to 67 percent by 1954 and continued down to 57 percent by 1968. The success ratio was high in 1939 because large fields, such as East Texas, were still in their early stages of development. Wells drilled near the centers of large fields are almost always successful. By 1968, however, the known large fields had all been developed. Wells drilled in small fields or on the uncertain boundaries of the large older fields are less likely to be successful. The petroleum industry does not drill dry holes; it drills holes with some probability of success. For this reason, the cost of dry holes must be counted among the costs of successful wells. On the other hand, it is important to ask what the cost of successful wells would have been if large fields were still being developed and the success rate had remained the same.

The difference, $\Delta S$, between what successful well costs would have been if the success rate had remained the same and actual costs can be estimated by an accounting procedure. The following formula uses beginning time-period weights:

$$\Delta S = \frac{\dfrac{\Sigma \eta_{i,t+1} \cdot C_{i,t}}{N^S_{t+1}} - C^S_t}{C^S_t}$$

where

$\eta_{i,\,t+1}$ = number of wells drilled of type i in year t + 1

$C_{i,t}$ = average cost of wells of type i in year t

$N^S_{t+1}$ = number of successful wells drilled in year t + 1

and

$C^S_t$ = average cost of successful wells in year t.

An analogous formula is used for end-point weights. The results of this analysis appear in Table 2. Given the lengths of the respective time periods, the impact of changing success on well cost is about the same between 1939 and 1954 and between 1954 and 1958. Increases in cost attributable to changing success decreased substantially between 1958 and 1963 and then increased again between 1963 and 1968.

TABLE 2

Effect of Changing Success Rate on Well Cost (ΔS)

| *Time period* | *Beginning-point weights* | *End-point weights* | *Average* |
|---|---|---|---|
| 1939-1954 | .197 | .160 | .179 |
| 1954-1958 | .048 | .057 | .052 |
| 1958-1963 | .029 | .029 | .024 |
| 1963-1968 | .061 | .060 | .061 |

THE EFFECT OF INCREASING DEPTH

There is a tendency to develop shallow petroleum deposits before deep deposits because shallow wells are less expensive to drill. The resulting trend to deeper deposits over time is apparent in the average well-depth data presented in Table 3. Though many new wells are still being drilled in older shallow fields, the average depth of oil wells has increased 23 percent since 1939. The average depths of gas wells and dry holes have increased 112 and 54 percent, respectively.

A relationship between well depth and cost has been estimated by regressing mean well cost and mean well depth across the 18 areas for which the U.S. Census of Mineral Industries and JAS provide this data. The standard deviation of well depth in each area (calculated from the JAS and earlier industry data) has also been included as an explanatory variable. The parameters of the following function are estimated for each well type and year:

$$\gamma_t = \alpha_t X_t^{\beta_t} (\sigma_x)_t^{\gamma_t}$$

where

$\gamma_t$ = mean well cost in year t

$X_t$ = mean well depth in year t

and

$(\sigma_x)_t$ = standard deviation of well depth in year t.

The Cobb-Douglas function was selected because it is convenient to use and because it is generally recognized that well costs increase geometrically with depth. The function fit the data reasonably well; $R^2$ (multiple correlation coefficient) ranged from 0.781 to 0.972 and averaged 0.909. The estimates of the depth-cost relationship are least successful using 1939 data, due partly, no doubt, to the fact that the estimate of the standard deviation of well depth was less reliable during that year but also possibly because the industry, then in its adolescence, had a greater variation in its performance. Table 4 presents the coefficients and statistics derived by regressing the total cost of wells against depth across states and illustrates how these coefficients have changed over time.[5]

TABLE 3

Average Depth of Wells
*(feet)*

| *Year* | *Oil wells* | *Gas wells* | *Dry holes* | *All wells* |
|---|---|---|---|---|
| 1939 | 3,234 | 2,785 | 3,218 | 2,300 |
| 1954 | 4,055 | 4,718 | 4,262 | 4,177 |
| 1958 | 3,850 | 5,346 | 4,414 | 4,208 |
| 1963 | 4,012 | 5,365 | 4,562 | 4,381 |
| 1963 | 3,812 | 5,252 | 4,435 | 4,232 |
| 1968 | 3,984 | 5,894 | 4,971 | 4,619 |

Sources: CMI (1939, 1954, 1958 & 1963).
JAS (1963 & 1968).

5. The parameters in Table 4 are estimated from highly aggregated data. It seems unlikely that the relationship between depth and cost derived across state data would be representative of the relationship within states due to differences in sedimentary formations between states. Economic theory leads us to expect that data aggregation would lead to a negative bias in our estimates of the depth coefficients since the industry would tend to drill more

TABLE 4

Regression Coefficients and Statistics Relating Well Cost and Depth, 1939-1968[a]

| *Year* | *Log₁₀ α* | *β* | *γ* | *Adjusted $R^2$* | *Number of observations* |
|---|---|---|---|---|---|
| | | | *Oil wells* | | |
| 1939 | -0.207 | 2.269 | -0.547* | 0.817 | 15 |
| 1954 | 0.240 | 1.318 | 0.257 | 0.913 | 17 |
| 1958 | 0.110 | 1.469 | 0.171 | 0.949 | 17 |
| 1963 | 0.583 | 0.995 | 0.346 | 0.844 | 18 |
| 1963 | 0.529 | 1.021 | 0.363 | 0.899 | 18 |
| 1968 | 0.743 | 0.652 | 0.655 | 0.820 | 17 |
| | | | *Gas wells* | | |
| 1939 | 0.109 | 1.487 | 0.178* | 0.744 | 15 |
| 1954 | 0.660 | 0.842 | 0.558 | 0.962 | 16 |
| 1958 | -0.257 | 1.774 | 0.078* | 0.947 | 16 |
| 1963 | 0.151 | 1.626 | -0.080 | 0.967 | 16 |
| 1963 | 0.582 | 1.149 | 0.245 | 0.959 | 16 |
| 1968 | 0.294 | 0.962 | 0.690 | 0.944 | 15 |
| | | | *Dry holes* | | |
| 1939 | -0.453 | 1.988 | -0.074* | 0.817 | 15 |
| 1954 | -0.156 | 1.302 | 0.398 | 0.798 | 17 |
| 1958 | -0.462 | 1.356 | 0.541 | 0.905 | 17 |
| 1963 | 0.221 | 0.867 | 0.605 | 0.922 | 18 |
| 1963 | 0.256 | 0.965 | 0.539 | 0.933 | 18 |
| 1968 | 0.029 | 0.914 | 0.771 | 0.969 | 18 |

[a]All parameters are significant at the 0.95 level except those marked with an asterisk.

Sources: CMI (1939, 1954, 1958 & 1963). JAS (1963 & 1968).

The derived depth-cost relationship is utilized to estimate $\Delta D$ for each of the subperiods. The costs of drilling wells in year t to the depths they were drilled in year t - 1, ($Y_t^{t-1}$), and year t + 1, ($Y_t^{t+1}$), are estimated for each well type as follows:

$$Y_t^{t-1} = \sum_{i=1}^{18} \alpha_t \, X_{t-1,i}^{\beta_t} \, (\sigma_x)_{t-1,i}^{\gamma_t} \, \eta_{t,i}$$

deep wells in the areas where deep wells are least expensive. Several empirical tests on the less-aggregated recent JAS data, however, tend to refute this hypothesis. Given the combination of the strong theoretical supposition and the contradictory empirical evidence, no adjustment of the coefficients has been made on these grounds.

$$Y_t^{t+1} = \sum_{i=1}^{18} \alpha_t \, X_{t+1,i}^{\beta_t} \, (\sigma_x)_{t+1,i}^{\gamma_t} \, \eta_{t,i}$$

where $\eta_{t,i}$ is the number of wells drilled in area i in the year t.

The estimates of $\Delta D$ presented in Table 5 are consistent with the depth-of-well data in Table 3. The depth of oil wells decreased between 1954 and 1958 due to a decline in well drilling and a retrenchment to drilling in the older fields. $\Delta D$ for oil wells during this period was appropriately negative. Similarly, the large increase in the depths of gas wells between 1939 and 1954 resulted in a large $\Delta D$. The difference between the beginning- and end-point estimates, on the other hand, gives an indication of the reliability of our measure of $\Delta D$, the weighted average. Significant differences should be expected because of changes in the depth-cost relationship over time due to changing technology and input prices. The major part of the observed differences, however, is probably due to aggregate data problems and deficiencies in the estimates of the depth-cost function itself. For this reason, it is assumed that $\Delta D$ is actually within a

TABLE 5

Effect of Increasing Depth on Well Cost ($\Delta D$)

| *Time period and well type* | *Beginning-point estimates* | *End-point estimates* | *Weighted average* | *Probable range* |
|---|---|---|---|---|
| 1939-1954 | | | | |
| Oil | .093 | .165 | .125 | |
| Gas | .943 | .559 | .681 | |
| Dry holes | .636 | .415 | .492 | |
| All wells | | | .241 | .181–.301 |
| 1954-1958 | | | | |
| Oil | –.025 | .001 | –.013 | |
| Gas | .120 | .098 | .106 | |
| Dry holes | .011 | .027 | .019 | |
| All wells | | | .013 | .010–.016 |
| 1958-1963 | | | | |
| Oil | .053 | .133 | .092 | |
| Gas | .162 | .090 | .124 | |
| Dry holes | .003 | –.001 | .001 | |
| All wells | | | .073 | .055–.091 |
| 1963-1968 | | | | |
| Oil | .062 | –.001 | .033 | |
| Gas | .215 | .228 | .222 | |
| Dry holes | –.066 | .125 | .035 | |
| All wells | | | .073 | .055–.091 |

probable range of plus or minus 25 percent of the weighted average of the beginning- and end-point estimates. This estimate of the probable range is simply based on the author's judgment due to the lack of better criteria.

## THE EFFECT OF CHANGING AREAS

The petroleum industry has drilled less likely prospects and drilled to deeper depths in order to supply ever-increasing quantities of oil and gas. The industry has also shifted its operation to deposits underlying formations which are more difficult to drill due to physical characteristics and economic accessibility to drilling equipment. Table 6 indicates the share of all well drilling expenditures by year in the areas. The shares of Arkansas, California, Illinois, Indiana, Kansas, Michigan, and Texas declined from 73 percent of the total in 1939 to 35 percent in 1968. On the other hand, the shares of Alaska, Colorado and Wyoming, Louisiana and Mississippi, Montana, North Dakota, Oklahoma, and Utah increased from a total fo 20 percent in 1939 to 57 percent in 1968. Appalachia's share has fluctuated–it declined between 1939 and 1954 as the known oil fields became fully developed, increased during the late 1950's with the increased demand for natural gas, and then declined again possibly because field-gas price regulation discouraged continued expansion and development of more expensive gas deposits after 1963.

TABLE 6

Share of All Well Expenditures by Area and Year

| *Area* | *1939* | *1954* | *1958* | *1963* | *1968* |
|---|---|---|---|---|---|
| Alaska | .000 | .000 | .002 | .011 | .065 |
| Appalachia | .034 | .022 | .025 | .049 | .033 |
| Arkansas | .022 | .007 | .009 | .006 | .009 |
| California | .162 | .090 | .051 | .069 | .072 |
| Colorado and Wyoming | .013 | .057 | .036 | .035 | .060 |
| Illinois | .085 | .024 | .015 | .011 | .007 |
| Indiana | .005 | .004 | .004 | .002 | .001 |
| Kansas | .056 | .046 | .039 | .037 | .025 |
| Kentucky, Tennessee, and Alabama | .005 | .008 | .011 | .013 | .009 |
| Louisiana and Mississippi | .129 | .190 | .300 | .313 | .338 |
| Michigan | .020 | .006 | .004 | .006 | .004 |
| Montana | .004 | .010 | .011 | .011 | .017 |
| Nebraska, Missouri, and Iowa | .000 | .009 | .009 | .006 | .004 |
| New Mexico | .035 | .042 | .057 | .044 | .037 |
| North Dakota | .000 | .013 | .017 | .006 | .006 |
| Oklahoma | .056 | .105 | .082 | .083 | .073 |
| Texas | .375 | .363 | .314 | .306 | .235 |
| Utah and Nevada | .000 | .006 | .020 | .011 | .010 |

A simple accounting model is used to determine ΔA, the effect on well cost of shifting development to new areas. ΔA is the difference between what costs would have been in the year t if wells had been drilled where they were drilled in year t - 1 or t + 1 divided by the actual cost in year t.

$$\Delta A = \frac{\Sigma \eta_{t*,i} C_{t*,i} - \Sigma \eta_{t,i} C_{t,i}}{\Sigma \eta_{t,i} C_{t,i}}$$

where $\eta_{t*,i}$ is the number of wells drilled in area i in year t* and $C_{t,i}$ is the average cost of wells in area i in year t. These estimates appear in the first three columns of Table 7.

TABLE 7

Effect of Changing Areas on Well Cost (ΔA)

| *Time period and well type* | *Beginning-point estimates* | *End-point estimates* | *Weighted average* | *Adjusted estimates* | *Probable range* |
|---|---|---|---|---|---|
| | *1* | *2* | *3* | *4* | *5* |
| *1939-1954* | | | | | |
| Oil | .114 | .119 | .116 | .306 | |
| Gas | .292 | .325 | .314 | .590 | |
| Dry holes | –.167 | .064 | –.016 | .119 | |
| All wells | | | | .294 | .235–.382 |
| *1954-1958* | | | | | |
| Oil | –.012 | –.016 | –.014 | .044 | |
| Gas | –.008 | .174 | .104 | .207 | |
| Dry holes | .015 | .174 | .098 | .157 | |
| All wells | | | | .097 | .078–.126 |
| *1958-1963* | | | | | |
| Oil | .042 | .015 | .029 | .088 | |
| Gas | –.061 | .131 | .040 | .178 | |
| Dry holes | –.082 | .232 | .079 | .148 | |
| All wells | | | | .122 | .098–.159 |
| *1963-1968* | | | | | |
| Oil | .023 | .037 | .029 | .075 | |
| Gas | –.030 | –.052 | –.042 | .079 | |
| Dry holes | –.003 | –.015 | –.009 | .054 | |
| All wells | | | | .068 | .054–.088 |
| *1963-1968*[a] | | | | | |
| Oil | .079 | .071 | .075 | | |
| Gas | .057 | .099 | .079 | | |
| Dry holes | .067 | .043 | .054 | | |

[a]Using 28 areas.

Column 3 of Table 7 gives estimates of the cost of changing drilling emphasis among 18 areas of the United States. If the sedimentary structures in each of these areas were homogeneous throughout the area, then these estimates would accurately measure $\Delta A$. But clearly this is not the case. Formations change considerably across areas as large as Texas or as diverse as California. The estimates of $\Delta A$ indicate that costs have increased considerably due to shifting drilling emphasis among the 18 areas. But one would expect that there has also been a shift to more expensive formations within each of the 18 areas. This hypothesis is confirmed when $\Delta A$ is estimated on the JAS data available for 28 areas in 1963 and 1968. These estimates appear at the bottom of Table 7.

The difference in the estimates of $\Delta A$ using 18 and 28 areas is large. For oil wells, $\Delta A$ calculated from the 28-area data is more than 2.5 times as large as that calculated from the 18-area data. The JAS does not report data for randomly selected areas. To some extent area boundaries are determined by geologic characteristics. Thus, there probably would not be a similar increase in $\Delta A$ if it were estimated from data reported for 40 areas, for example. Since the number of significantly different formations from an economic standpoint is undoubtedly less than 100, the estimate of $\Delta A$ using the 28 areas may be reasonably close to the real $\Delta A$. Though economic considerations lead us to presume that less-aggregated data would result in larger rather than smaller estimates of $\Delta A$, it is possible that, if data were available for more than 28 areas, it would indicate that there had been shifts to less expensive formations within the 28 areas even though there had been shifts to more expensive formations within the 18 areas. For this reason, the probable range of $\Delta A$ is assumed to be within -20 percent and +30 percent of the estimate derived from the 28-area data.

The estimates of $\Delta A$ for the earlier time periods are adjusted by assuming that the difference between the 18- and 28-area estimates was proportional to the number of years in the time period and the number of wells drilled; thus, for each well type and time period,

$$\Delta A' = \Delta A + B \cdot \frac{t_{i+1} - t_i}{5} \cdot \frac{\eta_0 + \eta_1}{\eta_{63} + \eta_{68}}$$

where

$\Delta A$ = initial estimate on 18-area data

B = difference between the 18- and 28-area data estimates of $\Delta A$ during 1963-1968 and

$\eta$ = number of wells drilled.

The adjusted estimates appear in column 4 of Table 7.

Given the techniques used to calculate $\Delta D$ and $\Delta A$, there may have been some double counting. $\Delta A$ may have been overestimated because part of what was counted as a shift to more expensive formations in another area is in fact a shift to deeper wells in another area. The significance of double counting can be determined from the correlation between $\Delta F_i$ (the change in the fraction of wells drilled) and $\Delta X_i$ (the change in mean well depth) for each well type during each time period. For all well types between 1939 and 1968, the correlation between $\Delta F_i$ and $\Delta X_i$ is small and negative. R equals $-0.036$. This indicates that $\Delta A$ may have been slightly underestimated due to a tendency to decrease the number of wells drilled in those areas where the depth of wells is increasing faster than average. The correlation between $\Delta F_i$ and $\Delta X_i$ was also tested for three particular well types and time periods. These tests do not support the double-counting argument.

The identity, $\Delta C = (1 + \Delta S)(1 + \Delta D)(1 + \Delta A) - (1 + \Delta T)$, is our accounting model. Table 8 presents $\Delta C$, $\Delta D$, and $\Delta A$ for each well type and time period. It was hypothesized earlier that the greater $\Delta C$ for gas wells would largely be explained by deposit factors since the inputs and technology used on the different well types are very similar. The data in Table 8 tend to confirm this hypothesis. The variation in $\Delta T$ between well types is less than the variation in $\Delta C$ for each time period. There is, nevertheless, considerable variation in $\Delta T$ between well types.

Table 9 summarizes the information of Tables 2, 5, and 7 for all wells. It is interesting to note that changing to higher cost formations has been the most significant deposit factor except between 1963 and 1968 when drilling to deeper depths increased costs somewhat more. The total effect on successful well cost of changing deposit quality has been considerable. Table 9 indicates, however, that changes in the price of inputs and the introduction of new technology have offset between 52 percent and 68 percent of the increased costs due to changing deposit factors.

## NEW TECHNOLOGY AND THE WELL COST-DEPTH RELATIONSHIP

The nature of new technology can also be determined by statistical analysis. Existing data provide an insufficient base for answering

TABLE 8

Effect of Changing Resource Quality

| *Time period and well type* | $\Delta C$ | $\Delta D$ | $\Delta A$ | $\Delta T$ |
|---|---|---|---|---|
| *1939-1954* | | | | |
| Oil | .154 | .125 | .306 | .315 |
| Gas | .756 | .681 | .590 | .917 |
| Dry holes | .057 | .492 | .119 | .613 |
| *1954-1958* | | | | |
| Oil | -.029 | -.013 | .044 | .059 |
| Gas | .251 | .106 | .207 | .084 |
| Dry holes | .022 | .019 | .157 | .158 |
| *1958-1963* | | | | |
| Oil | -.077 | .092 | .088 | .265 |
| Gas | .109 | .124 | .178 | .433 |
| Dry holes | -.050 | .001 | .148 | .199 |
| *1963-1968* | | | | |
| Oil | .067 | .033 | .075 | .043 |
| Gas | .304 | .222 | .079 | -.015 |
| Dry holes | .165 | .035 | .054 | -.074 |

many interesting questions. But the effect of new technology and cheaper inputs on the well cost-depth relationship can be roughly determined. The question whether new technology and cheaper inputs reduced costs at deeper depths more than at shallow depths can be answered.

The production function is assumed to be:

$$Y = \alpha X^{\beta} \sigma_{x}^{\gamma}$$

Changes in the depth-cost relationship over time will be observed as changes in $\beta$ and $\gamma$.

$$\frac{dY}{dt} = \frac{d\alpha}{dt} X^{\beta} \sigma_{x}^{\gamma} + \frac{d\beta}{dt} \log_e x \left(\alpha X^{\beta} \sigma_{x}^{\gamma}\right)$$

$$+ \frac{d\gamma}{dt} = \log_e \sigma_x \left(\alpha X^{\beta} \sigma_{x}^{\gamma}\right)$$

$$\frac{1}{Y} \frac{dY}{dt} = \frac{1}{\alpha} \frac{d\alpha}{dt} + \frac{d\beta}{dt} \log_e x + \frac{d\gamma}{dt} \log_e \sigma_x .$$

TABLE 9

Effect of ΔS, ΔD, and ΔA on Successful Well Cost
By Time Period

| | *Estimate* | *Range* | *ΔC* | *ΔT* |
|---|---|---|---|---|
| *1939-1954* | | | | |
| ΔS | .179 | .179– .179 | | |
| ΔD | .241 | .181– .301 | | |
| ΔA | .294 | .235– .382 | | |
| Total | .893 | .720–1.120 | .358 | .362–.762 |
| *1954-1958* | | | | |
| ΔS | .052 | .052– .052 | | |
| ΔD | .013 | .010– .016 | | |
| ΔA | .097 | .078– .126 | | |
| Total | .169 | .145– .204 | .078 | .067–.134 |
| *1958-1963* | | | | |
| ΔS | .024 | .024– .024 | | |
| ΔD | .073 | .055– .091 | | |
| ΔA | .122 | .098– .159 | | |
| Total | .232 | .186– .295 | –.058 | .244–.353 |
| *1963-1968* | | | | |
| ΔS | .061 | .061– .061 | | |
| ΔD | .073 | .055– .091 | | |
| ΔA | .068 | .054– .088 | | |
| Total | .216 | .180– .259 | .214 | .034–.045 |

Thus, if $d\beta/dt$ and $d\gamma/dt$ weighted by $\log_e x$ and $\log_e \alpha_x$, respectively, are positive, then new technology and cheaper inputs have decreased the cost of shallow more than deep wells (shallowness-favoring). If the weighted average of $d\beta/dt$ and $d\gamma/dt$ is negative, then the cost of deep wells has decreased more than the cost of shallow wells (depth-favoring). The results of this analysis appear in Table 10. The coefficients indicate that new technology and cheaper inputs have been depth-favoring for oil wells. This conclusion is true both for oil well drilling and completion between 1939 and 1963. New technology was depth-favoring for gas well and dry hole drilling but shallowness-favoring for completion between 1939 and 1963. Over the entire study period and all well types, it appears that new technology was depth-favoring.

The conclusion that new technology and cheaper inputs would be depth-favoring is not unexpected. The industry has been drilling to deeper depths over time. There were only a few opportunities to acquire an understanding of the production frontier at 10,000 feet in 1939 and only a few 10,000-foot wells for which to develop special

TABLE 10

Effect of New Technology and Cheaper Inputs on the Depth-Cost Relationship

| Period | Area-weight year | Weighted change in β and γ: Drilling cost | Completion cost | Total cost |
|---|---|---|---|---|
| *Oil wells* | | | | |
| 1939-1963 | 1939 | −2.54 | −3.26 | −2.28 |
| | 1963 | −1.90 | −1.06 | −1.68 |
| | Average | −2.22 | −2.16 | −1.98 |
| 1963-1968 | 1963 | | | −0.27 |
| | 1968 | | | −0.50 |
| | Average | | | −0.39 |
| *Gas wells* | | | | |
| 1939-1963 | 1939 | −0.90 | 1.79 | 0.07 |
| | 1963 | −1.46 | 1.17 | −0.01 |
| | Average | −1.18 | 1.48 | 0.03 |
| 1963-1968 | 1963 | | | 0.84 |
| | 1968 | | | 0.66 |
| | Average | | | 0.70 |
| *Dry holes* | | | | |
| 1939-1963 | 1939 | −2.05 | 2.84 | −1.16 |
| | 1968 | −1.28 | 0.35 | −1.02 |
| | Average | −1.66 | 1.60 | −1.09 |
| 1963-1968 | 1963 | | | 0.56 |
| | 1968 | | | 0.45 |
| | Average | | | 0.51 |

inputs. By 1968 there had been many. Simplistic theories, such as "learning by doing," and economies of scale combined with the trend to deeper wells, suggest that new technology and inputs would be depth-favoring.

## CONCLUSIONS

Large increases in the cost of petroleum development between 1939 and 1968 have been offset by new technology. Without new technology, well costs would have increased by about 70 percent due to shifts in drilling activity to more difficult formations, by about 45 percent due to drilling to deeper depths, by about 35 percent due to the decline in the rate of success, and by about 233 percent due to the combination of these three factors. New technology and cheaper inputs significantly reduced the effect on well cost of changes in deposit quality, and well costs increased only 64 percent. Holding deposit factors constant, the real price of wells decreased between 53 and 87 percent. New technology and inputs have consistently been depth-favoring for well drilling and depth-favoring on the average for all expenditures.

If petroleum-deposit quality had not been considered in this study, the 64 percent increase in the real cost of successful wells (uncorrected for changes in deposit quality) between 1939 and 1968 would have led to the conclusion that productivity in the well drilling industry had declined substantially. The well drilling industry is, of course, a unique example. Nevertheless, the general implications of the findings of this study to the approach used and conclusions reached in earlier studies of productivity in the mining industries, as well as the entire United States economy, should be discussed. Previous studies did not consider the effect on productivity of changes in land quality.[6] Changes in land inputs are difficult to measure, and previous researchers presumed that the effects of these changes were small. Barger and Schurr, for example, argued that the petroleum resources had probably increased slightly in quality:

> One of the outstanding characteristics of the history of oil and gas exploitation in this country has been the continual migration to new flush production areas. . . . The data indicate not only that these new fields have replaced fields of declining productivity, but that successive shifts in production have also been accompanied by higher levels of productivity per well than obtained in older fields.
>
> Although migration to new fields is thus seen to have favorably affected resource conditions in the industry, we must also note one negative factor in the situation. The oil and gas formations exploited in the newer fields of the West and South generally lie at greater depth than the producing formations of an earlier day.[7]

Kendrick avoids discussion of the issues of changes in land quality and merely notes, "Land [in mining industries] is not included owing to the difficulties of deflating the book values into meaningful real terms. . . ."[8] Denison argues in his study of the sources of productivity change in the United States economy that "some adjustment for changes in the quality of land would be desirable but I have

6. In a study of coal mining productivity, G. S. Maddala considered the differences between strip and underground mining but did not consider other land quality variables. *See* Maddala, *Productivity and Technological Change in the Bituminous Coal Industry, 1919-54*, 73 J. Pol. Econ. 352 (1965).

7. H. Barger & S. Schurr, The Mining Industries, 1899-1939: A Study of Output, Employment and Productivity 197, 199 (Nat'l Bur. of Econ. Research, 1944).

8. J. Kendrick, Productivity Trends in the United States 393 (Nat'l Bur. of Econ. Research, 1961).

not found it to be feasible. This is not a large source of error not only because the weight of land is small but also because there could hardly have been an important change in average quality."[9]

Well drilling accounts for about 25 percent of all petroleum extraction expenditures and 15 percent of all mining expenditures. If deposit quality with respect to well drilling changed about the same during Barger and Schurr's period of analysis as it did between 1939 and 1968, then Barger and Schurr significantly underestimated the rate of productivity change in the petroleum extraction industry. Even though changes in deposit quality were not accounted for, Kendrick found that total factor productivity increased faster in the mining industries and considerably faster in oil and gas extraction in particular than for the private economy as a whole. If Kendrick had considered changes in quality, the differences between the rates of productivity change in mining and other sectors would have been considerably greater. Denison's argument that changes in land quality probably have little effect on the average for the economy as a whole may be correct, but there is insufficient evidence to support this belief. More research is needed.

9. E. Denison, The Sources of Economic Growth in the United States and the Alternatives Before Us 91 (Comm. for Econ. Development, 1962).