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# An Experiment To Evaluate Methods For Estimating Fossil Fuel Resources

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ABSTRACT

Estimates of petroleum and natural gas resources vary substantially, both over time and across estimation methods. This paper develops a simulation model of global oil resources to evaluate different resource estimation techniques. Protocols for the Hubbert life cycle and USGS geologic analogy methods are developed and applied to synthetic data generated by the model. It is shown that the Hubbert method can generate an accurate estimate as early as twenty years before the peak of global production, but the geologic analogy approach overestimates the true resource base over the life cycle of the resource. The results show the applicability of simulation and the synthetic data approach to the problem of evaluating forecasting methods.

> "Oil is a finite commodity...once it has gone, it cannot be replaced."
>
> "It just isn't going to happen...The more you use, the more there is."
>
> (Christian Science Monitor, 11 March 1983, 1)

The estimation of petroleum resources is perhaps one of the most controversial and important of all forecasting activities. As illustrated by the quotations from oil market analysts cited above, there are fundamentally divergent views on the nature of petroleum resources, the role of technology, and the appropriate sources of information for estimating the resource base. The uncertainty, combined with the importance of oil, have spawned a minor industry which since 1973 has witnessed a proliferation of forecasts, models, and estimation procedures (for surveys and reviews see Mathtech 1978, MIT 1982, Grenon 1975, and Meyer 1977). The effort devoted to resource estimation, however, has not reduced the uncertainty or settled the debate. Estimates of ultimate

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recoverable petroleum resources vary substantially, both across estimation methods and over time (Meyer 1977, Odell and Rosing 1980). Worse, the traditional approach to evaluating forecasting methods, repeated comparison of forecasts to actual outcomes, is of little use because the true resource base will not be known for decades.
The research reported here contributes to the development of methods for evaluating forecasting techniques before actual outcomes are known. The approach is based on the use of synthetic data generated by a model of the processes being forecasted (Richardson 1982).

A wide variety of estimation techniques currently exist, including life cycle (Hubbert 1956, 1962, 1982; Ryan 1966; Wiorkowski 1981), geologic analogy (Zapp 1962, Hendricks 1965, USGS 1975, Jones 1975, Energy, Mines, and Resources Bureau (Canada) 1977, Semenovich et al. 1977), rate of effort (Hubbert 1974) econometric (Khazzoom 1971, MacAvoy and Pindyck 1973), and discovery process methods (Arps and Roberts 1958, Ryan 1973, Barouch and Kaufman 1977). The techniques range from the basin and play level to continental and global aggregation, from detailed structural and process models to curve-fitting. Despite the differences, all estimation procedures can be thought of as information processing schemes which take certain data as input and produce an estimate of the resource base as the output. Previous appreciations of estimation methods (e.g. Mathtech 1978, MIT 1982) have focused on the logical structure, parameter estimation, and data requirements of the methods. But to compare the various methods it is necessary to apply them to a consistent set of data. This is done by generating data through a simulation model of global oil discovery, development, and production.

To demonstrate the approach, we have chosen to evaluate the Hubbert life-cycle method and the geologic analogy method. First, the estimation methods are formalized. The resulting protocols specify in an exact and reproducible manner the way in which information is processed to yield an estimate. Second, the protocols are applied to synthetic data generated by the model, and a dynamic path of the estimates is generated. The evolution of resource estimates over time is then compared to the resource base assumed in the model, and the accuracy of the estimation protocols is evaluated. But will a good estimation method perform well on the synthetic data? And will a flawed method perform poorly? The answer to both questions is yes, if the data-generating model corresponds closely enough to the real petroleum system. "Closely enough" in this context means that the behavior of the information inputs to each estimation method must be broadly consistent with history. More important than historical fit, however, the resource development scenarios generated by the model must be both feasible and internally consistent. To insure feasibility and consistency, the data-generating model should portray the physical structure of the resource system and the decisionmaking procedures used by the actors. As described below, the model portrays technical, geologic, economic, and other factors which interact to endogenously produce the lifecycle of world petroleum. If the model appropriately mimics the real system, then the synthetic data will constitute a fair test of the estimation methods.

## The History of Petroleum Estimates: Excelsior!

Serious estimates of world ultimate recoverable petroleum resources date from at least the 1940s, and show a clearly rising trend over time (exhibit 1). A similar pattern exists for estimates of the ultimate recoverable resource (URR) in the United States (exhibit 2). The rising trend reflects increasing knowledge of geology, improvements (actual and anticipated) in recovery technology, and, of course, increases in discoveries and recoverable reserves.

In general, there are two polar responses to the rising pattern of estimates.[1] The more conservative response is typified by Warman (1972, 292) who states

> It is interesting to note that estimates have increased with time and it is fair to ask whether we are still underestimating. There are some good reasons for believing that during the time span of these estimates our knowledge has increased to a point where future continued expansion on the same scale seems unlikely.

Warman concludes that the URR is likely to be 1,800 billion barrels. In contrast, some see in the rising trend of estimates justification for assuming the ultimate recoverable amount is much greater. Peter Odell (1973, 454) extrapolated the past estimates and concludes

> ...the resource base,...given the extrapolation of the calculated trend, would reach almost $4,000 \times 10^9$ barrels...by the year 2000. In brief, the oil resource base in relation to reasonable expectations of demand gives very little apparent cause for concern, not only for the remainder of this century, but also thereafter well into the twenty-first century at rates of consumption which will then be five or more times their present level.

Because the endowment of nature-made petroleum (oil-in-place) is finite, estimates of URR should eventually level off. Given that it takes time to develop the knowledge and experience that permit accurate estimates to be made, the ideal pattern would be a gradual approach to the (correct) URR. Alternatively, estimates might overshoot the URR, gradually approaching the true resource base from above as more knowledge is gained (exhibit 3). Close examination of the estimates for the United States (exhibit 2) reveals an apparent peak in the early 1960s at a level of 500 to 600 billion barrels, compared to more recent estimates in the range of 160 to 300 billion barrels.

The consequences of overestimation are potentially serious. Overestimation may lead to inefficient allocation of exploration effort, overvalued lease tracts, and complacency in the development of oil substitutes. It is important, therefore, to identify possible sources of overshoot in the estimation methods currently in use.

## Modeling The Estimation Process

The model described below is but one of many that could conceivably be used to generate the synthetic data for the experiment. Not all models of the oil supply process are appropriate, however. In addition to the obvious constraint that the model must generate data at an appropriate level of aggregation for the estimation protocols, the model should have the following characteristics.

First, it should be a structural model. It should attempt to represent the physical and causal structure of the processes modeled, as opposed to a model based on historical correlations. Nonlinearities and constraints may alter historical correlations in the future. Physical delays, such as the time required to develop an oil field or build a synfuel plant, should be represented explicitly.

Second, it should be a behavioral model, portraying the information available to actors and the procedures they use to process it and arrive at decisions. The petroleum system is characterized by imperfect information, uncertainty, and distributed decisionmaking. If the model is to respond to changes in the environment in the same way the real actors do, this bounded rationality should be incorporated (Simon 1979, Hogarth 1980, Morecroft 1983).

Third, the model should generate its behavior endogenously. The discovery and production process is tightly interconnected with energy price, demand, substitution, and technology. A change in one part of the system may have ramifications throughout. A model that relies on exogenous variables is likely to produce inconsistent results as the feedback effects are ignored. A model that generates the petroleum life cycle endogenously constitutes an internally consistent theory that is subject to analysis, refutation, and revision (Bell and Senge 1980).

In addition to these general considerations, a model of petroleum resources to be used in forecast evaluation should include the following specific features as endogenous components:

1. Technology: The ultimate recoverable resource depends heavily on the recovery factor. Only 30 to 40 percent of oil-in-place can be recovered economically with current technology, but the fraction recoverable has been rising and may rise substantially in the future.

2. Economic incentives: Economic incentives (primarily determined by the price of oil) play a large role in determining proved reserves, exploration, and production. Oil that is subeconomic at $10 per barrel may be highly profitable at $30 per barrel. Regions that were not even considered for exploration may be prime candidates for test wells at a higher price.

3. Price: Because the price has a strong influence on the incentives for exploration and development, it must be modeled explicitly. The effects of production costs, supply and demand, and market imperfections should be incorporated.

4. Demand and Substitution: Petroleum demand is sensitive to price. As prices rise, the demand for oil will be depressed, and the production of substitutes ("backstops" [Nordhaus 1973]) such as synfuels will be stimulated. The pattern of demand and substitution will have a strong influence on production and investment in exploration. Delays in the response of demand and in the development of the backstop industry should be explicit.

5. Depletion: The total initial quantity of oil-in-place is finite. As it is consumed, the quantity remaining inevitably declines, and the marginal cost increases, *ceteris paribus*. Though improving technology may offset depletion and cause the real price of oil to decline, the limited nature of the resource base and its depletion must be treated explicitly.

## The Data-Generating Model

The criteria proposed above impose strong constraints. The model described below should be thought of as a step towards an endogenous, structural theory of petroleum geology, economics, and technology.

The system dynamics approach to simulation is used (Forrester 1961, Richardson and Pugh 1981). Application of system dynamics to energy include Naill (1973, 1977), Backus et al. (1979), Choucri (1981), and Sterman (1983). A documented listing of the model is available from the authors and has been lodged with the editors. The model is divided into five basic sectors: (1) exploration; (2) production; (3) technology; (4) revenue and investment; and (5) demand and substitution (exhibit 4).

1. Exploration: The model divides the total quantity of oil-in-place into three basic categories: as yet undiscovered oil, identified resources, and cumulative production. Within these broad categories, several finer divisions are portrayed. The disaggregation of the resource base follows standard resource classification shown in the McKelvey box format (USGS 1976) in exhibit 5. The McKelvey box is a useful but static characterization of the resource base. Over time, exploration and production activity shift the boundaries in the McKelvey box. Successful exploration shifts the boundary between identified and undiscovered resources to the right; improvements in technology or increases in the real price of oil shift the boundary between economic and subeconomic resources towards the bottom. Production shrinks the reserve base.

As an example, the determinants of the exploration rate are shown in exhibit 6. The rate at which undiscovered resources are identified is determined by investment in exploration and the productivity or yield of that investment. Note that additions to the identified resource include all oil-in-place identified through exploration and not just the economic, proven part that is immediately producible, which is often mis-labeled "discoveries" (MIT 1982, part II). Additions to the identified resource depend on investment expenditure and the desired discovery rate. To represent the time required to identify and explore a prospective oil-bearing region, the potential discovery rate is given by lagged investment expenditure. The rate of investment, in turn, depends on the desired discovery rate, modified by profitability. If the expected revenues from exploration activity do not justify the cost, or if the cost of developing new reserves exceeds the expected cost of oil substitutes, exploration is curtailed. Conversely, higher than normal return induces entry and expansion of exploration efforts. The desired discovery rate is the rate at which resources need to be identified to meet anticipated production and expected growth in production, and to provide the reserve levels required to meet anticipated production.

The cost of exploration activity is determined directly by the yield or productivity, which depends on technological and geological factors. At the dawn of the oil era, only a small fraction of oil-in-place was discoverable. As the ability to drill deeper wells was developed, a larger fraction of oil-in-place in a given region could be identified. As the ability to drill offshore and in increasingly hostile environments was developed, a larger fraction of the potential oil-bearing area of the globe could be economically explored. And as the sophistication of seismic detection technology grew, smaller and smaller oil deposits, for example, in stratigraphic traps, could be identified.

At the same time, however, depletion reduces the productivity of exploration efforts. Producers naturally follow a Ricardian resource exploitation strategy, exploring those areas they believe most likely to yield oil first, drilling shallow wells and tapping giant oilfields when possible before moving on to less accessible and more expensive regions. To the extent producers are able to identify oil at a better than random rate, the productivity of future exploration activity is necessarily reduced (ceteris paribus), as future additions to the identified resource will involve more dry holes, deeper wells, and increasingly, drilling offshore or in distant and hostile locations. The evidence suggests exploration activity in the United States historically has been 2.75 times more effective than chance drilling (McCray 1975, 229). Hubbert and others (Hall and Clevelend 1981) have documented a significant decline in yield per foot drilled both as a function of time and as a function of cumulative exploratory effort for the United States:

> In fact, 'finding rates' had fallen sharply since the late 1930's as oilmen skimmed the cream off the prospects in Texas, Oklahoma, and California. From a high of 276 barrels per foot of exploratory drilling, discoveries have fallen to about 35 barrels per foot by 1965 and to 30 in 1972 (Gillette 1974, 129).

Though depletion causes yield to decline, close examination of the U.S. data show actual yields increased in the 1920s and again in recent years, illustrating the shifting dominance of technical, economic, and geological factors. These factors are represented in the model and, as shown below, the simulated yield to exploration first rises with technology and then falls with depletion.

2. Production: Production in the model is determined by three major factors: the quantity of identified resource remaining, recovery technology, and investment in production facilities. Investment in production facilities depends on anticipated demand for natural pretroleum, modified by profitability. As in the exploration decision, higher than

normal returns cause expansion of production. An insufficient return causes a cutback in production as existing wells are shut down and plans for new wells cancelled. Investment in production capacity is also constrained by the technically recoverable quantity of oil. Limitations on the rate of flow and on the density of producing wells constrain useful investment in producing wells, though it is assumed in the model that production/reserve ratios can be increased somewhat above normal levels in a situation of high demand or profit.

3. Technology: Technology in the model is endogenously generated. As shown in exhibit 7, the model distinguishes between the fraction of oil-in-place that is discoverable with current technology and the fraction of the identified resource recoverable with current technology. The fraction discoverable represents the feasible depth of wells, the ability to drill offshore and in hostile environments, and the effectiveness of geologic survey and identification technology. The fraction recoverable represents the effectiveness of secondary and tertiary recovery techniques.

Each type of technology improves as the result of research effort. Improvements in technology take time, and an average delay of six years is assumed between an increase in expenditures on research and development and the resulting improvement in technology. Expenditures on R&D are assumed to be a fixed fraction of industry revenues. The effectiveness of investment in technology is variable. As the level of technology improves, the marginal improvement in technology per dollar of research effort declines. The total R&D effort is allocated between discovery and recovery technology on the basis of the perceived marginal benefit to each. Initially, the majority of research is devoted to improved exploration technology designed to increase the fraction discoverable. As the fraction discoverable rises, research effort gradually shifts to improving the recovery factors from developed fields.

4. Revenues and Price: Revenues are given by the price and production of natural petroleum. The price of natural petroleum is determined by production and exploration costs and by relative supply and demand. When supply and demand are in balance, the price equilibrates at a level sufficient to cover exploration and production costs and to provide the required return on investment. Investment expenditures are allocated among exploration, production, and R&D on the basis of the relative need for funds.

5. Demand and Substitution: The demand for petroleum is endogenously portrayed in the model (exhibit 8). The total demand for oil is determined by the stock of capital in the economy and the oil intensity of that capital. Capital is assumed to grow at an exogenous rate. The oil intensity of the capital stock is determined by the average price of oil. The average price is given by the prices and market shares of natural and synthetic petroleum. An average lag of fifteen years is assumed between a change in the price of oil and its full effect on demand. The fifteen year lag is somewhat shorter than the twenty year average life of energy consuming capital (Coen 1975, Sterman 1981), to represent the potential for retrofitting existing capital.

The market share of natural petroleum is determined by its price relative to the price of synthetic substitutes. The share responds to changes in the relative prices of natural and synthetic oil with an average lag of ten years, representing the time required to develop a synthetic fuel industry. The real price of synthetic substitutes is assumed to be constant.

## Model Calibration

The model used in these experiments has been calibrated to represent the global petroleum system. The major quantitative assumptions are listed in exhibit 9. The simulation results reproduce the global experience fairly accurately. However, the key aspect of the simulations is not the specific values of parameters or variables. The evolution of the petroleum system to date is but one draw from a large number of possibilities: the world's endowment of petroleum could have been different, discoveries could have occurred earlier or later, recovery technology could have developed at a different pace, and so on. A good estimation procedure should be able to produce accurate estimates for any consistent resource development scenario, and must not depend on the realization of a particular scenario. Thus, the results presented here are not contingent on the precision with which the model reproduces the past history of oil discovery and use. The purpose of the model is not to estimate the resource base. Our focus is the relationship between estimates of the resource base and the assumed resource base, not the absolute magnitude of the resource base or other parameters.

The total quantity of oil-in-place in 1900 is assumed to be slightly greater than 5000 billion barrels. It is assumed technology can improve so that all oil-in-place is potentially discoverable and that the recovery factor can rise to as high as 60 percent. The maximum ultimate recoverable resource is therefore about 3000 billion barrels, consistent with contemporary estimates. Note that the actual values of the discovery and recovery factors are endogenous and may not attain their maxima; likewise, the ultimate quantity produced may be less than the potential due to the substitution of backstop technologies before exhaustion of the resource.

## Results

Simulation results are shown in exhibit 10. The simulation starts in 1900 and runs until 2100. With the sole exception of the exogenous growth rate of energy consuming capital, the behavior is endogenously generated over the two hundred year life cycle of the resource.

In the early years of the century, simulated demand and production grow rapidly (exhibit 10a). Growth of the industry stimulates R&D, and the fraction discoverable rises rapidly (exhibit 10c). Between 1900 and 1940, improving technology causes the yield to exploration effort to rise from an initial value of about 60 barrels per foot to nearly 200 barrels per foot exhibit 10c). As a result, the rate at which resources are identified greatly exceeds production (exhibit 10a), causing recoverable resources and the reserve-production ratio to rise, especially after 1940 (exhibit 10b).

The improvement in technology and yield causes the real price of oil to decline by over sixty percent between 1900 and 1950 (exhibit 10d). The reduction in the real price of oil causes demand to grow faster than capital stock, and the average oil intensity rises.

After 1940, simulated yield begins to drop: though discovery technology is still improving rapidly, the very effectiveness of exploration in locating oil implies future efforts will be less successful. As the giant oilfields and shallow deposits are found, additional exploration yields more dry holes and smaller finds. By the mid-1960s, the rate of addition to identified resources reaches its maximum. But though new finds are declining, they remain well above production, and reserves continue to grow.

Initially, R&D activity was focused on discovery technology, and the fraction recoverable grows only slightly (exhibit 10c). But as discovery technology becomes more effective, R&D effort is shifted to enhancing recovery factors. After 1940, the fraction recoverable begins to rise rapidly, reflecting the development of secondary and tertiary recovery techniques.

By the 1980s, the industry has reached a turning point. Declining yield has caused real prices to begin to rise, and the higher price begins to suppress demand and stimulate the development of substitutes, though natural petroleum still dominates the market. Over two-thirds of the total oil-in-place has been identified, and additions to identified resources are falling. But because recovery technology is improving rapidly, reaching 35 percent in 1980, recoverable reserves continue to grow, and the reserve-production ratio reaches a peak of more than 34 years in 1985.

In the next twenty years, newly identified resources drop below production, proved reserves peak and begin to decline, and the reserve-production ratio falls. Production, though still rising, grows at a diminishing rate. Improving technology boosts the fraction discoverable to over 85 percent and the fraction recoverable to over 50 percent. Nevertheless, the real price continues to rise reaching nearly $20 per barrel by 2000, though transitory periods of glut cause temporary plateaus. Significant investment in substitutes is undertaken, but due to the long construction lags, natural petroleum loses market share only slowly.

After 2000 the transition to substitutes accelerates. The market share of synthetics rises to 25 percent by 2016 and exceeds 75 percent by 2045. Production of natural petroleum peaks about 2020 near 40 billion barrels per year and falls rapidly. Additions to identified resources are stimulated somewhat by higher prices, but as substitutes begin to be competitive, investment is curtailed, and exploration activity is virtually zero after 2050. The reserve-production ratio falls to 20 years by 2020 and to 16 years by 2050 as falling reserves force production down.

The real price of natural petroleum continues to rise, exceeding the assumed substitute price of $30 per barrel by 2020, and rising to $60 per barrel before stabilizing after 2060. The average price of oil (both natural and synthetic) grows less rapidly than that of natural petroleum as substitutes come on stream. But because of the development delays, the average price of oil overshoots the cost of the substitutes, remaining over $33 per barrel for nearly thirty years. The overshoot of energy prices as a consequence of delays in substitution is consistent with the results of several other models of the energy transition (Sterman 1983, Energy Modeling Forum 1981, DOE 1979).

By 2060 the petroleum era in the model is largely over. Production is about six billion barrels per year and falling. Substitutes account for 90 percent of the market, and the remaining petroleum demand is for premium uses only. Reviewing the entire life cycle highlights the following points:

1. The life cycle of production follows a roughly bell-shaped path, though it is definitely asymmetrical, with production falling off faster than it grew (exhibit 10a).

2. Consistent with the United States experience, the yield to exploration first rises, as a consequence of improving technology, and then falls as a consequence of depletion (exhibit 10c).

3. Likewise, improvements in technology first cause the real price to decline, but eventually depletion dominates technology and the real price rises (exhibit 10d).

4. Substitution to backstop technologies limits the average price of oil, but substitution delays cause an extended period of price overshoot in which the economy must continue to depend on natural petroleum even though it is more expensive than the substitutes (exhibit 10d).

5. Though the ultimate recoverable resource could have reached as high as 3000 billion barrels, the actual resource recovered by 2100 is approximately 2700 billion barrels. Substitution to the backstop causes production and investment in technology to stop before the ultimate limits are reached (exhibit 10b).

## The Estimation Protocols

We have evaluated two estimation procedures, the Hubbert life cycle approach and the geologic analogy approach used by the USGS and others. Each of these techniques can be applied to the aggregate data generated by the model.

The Hubbert Method: Hubbert has actually developed two methods to estimate ultimate recoverable resources, the original life cycle approach and a later rate-of-effort approach. We consider here the life cycle approach. It was the first method he developed, the most controversial, and also the most accurate to date in projecting production and reserves in the United States.

Hubbert's method has been extensively described, criticized, and analyzed elsewhere (MIT 1982, Mathtech 1978). To apply the method to the model-generated data, we developed the following protocol:

1. Define cumulative proved discoveries as cumulative production plus technically recoverable reserves.

2. Assume cumulative proved discoveries follow a logistic path given by:

$$Q_t = \frac{Q^*}{1 + a*\exp(b(t-t_o))} \qquad \text{(H1)}$$

where

$Q^*$ = ultimate recoverable resource

$Q_t$ = cumulative proved discoveries at time t

a, b = parameters to be estimated

$t_o$ = an arbitrary initial time

3. Rearrange equation (H1) as

$$\ln[(Q^*/Q_t)-1] = \ln(a) + b(t-t_o) \qquad \text{(H2)}$$

4. Estimate the parameters of equation (H2) by ordinary least squares regression for various values of $Q^*$, and select $Q^*$ from the regression that yields the highest $R^2$.

In Hubbert's original work, Q* was estimated by "a trial and error graphical method" in which he plotted the data on semi-log paper and, judging by eye, chose the Q* that best fit the data (MIT 1982, III-2-10). We have used regression so that our results are reproducible. Hubbert's graphical method is equivalent to the regression technique if one is willing to assume that the "best" fit judging by eye is roughly equivalent to the least squares estimates of the parameters in equation (H2). No measurement error is introduced, as we are primarily concerned with the tendency of estimation methods to overshoot even when perfect information is assumed. The robustness of the protocols in the face of process noise and measurement error is left as a topic for future research.

Values of Q* were estimated by the protocol above using the model generated data from 1900 to 1970, 1900 to 1980, and so on. The results are shown in exhibit 11, compared against the "true" ultimate recoverable resource. The Hubbert method eventually provides an unbiased estimate of URR, settling within 11 percent of the true value by 2000 and reaching it by 2040. However, before the year 2000, the estimated value of Q* exceeds the true value considerably. Up to 1970, the best fit to the logistic curve actually yields an infinite value for Q*. Up to that year, cumulative discoveries have been growing at an increasing exponential rate, rather than the continuously declining exponential rate presumed by a logistic curve. Between 1900 and 1970, the rate of economic growth accelerated, causing total demand for oil to grow at an increasing rate. In addition, the declining real price of oil encouraged growth of oil demand over and above the rate of economic growth, further adding to the growth rate of production. Finally, improving technology caused reserves to grow faster than production, in contrast to Hubbert's original model which presumes a constant average reserve-production ratio.

After 1970, the rate of growth of cumulative proved discoveries slows, and the estimated Q* falls rapidly. By 1980, Q* has dropped to between 5500 and 6500 billion barrels; by 1990 it is between 3500 and 3800 billion barrels. As the life cycle unfolds, the estimate falls towards the true value, and the range of uncertainty shrinks.

The life cycle approach relies on the fact that the finite nature of the resource necessarily implies a roughly S-shaped path for cumulative production and discoveries. The logistic model satisfies this requirement, but imposes the constraint that the fractional rate of growth declines continuously throughout the life cycle. In order to estimate the logistic successfully, therefore, the data must continuously reflect the decline in the growth rate caused by depletion. As demonstrated by the simulation, this need not be the case even when depletion of the resource is in fact strictly monotonic. Because rising rates of demand growth and improving technology dominate over the depletion effect in the first third of the life cycle, depletion, though occurring continuously, is masked in the aggregate data.

The life cycle approach, therefore, is only likely to give accurate estimates after the depletion effect dominates over other forces that may conspire to cause the fractional rate of production or discovery to rise. In the simulation, that shift in dominance occurs between 1980 and 2000. By 2000, eighteen years before the peak in production, the Hubbert estimate is within 11 percent of the true value. The results suggest the life cycle approach is only now becoming a reasonable guide to estimating the world's ultimate recoverable resource, at least at the global level of aggregation.

It is interesting to compare the results above to Hubbert's astonishingly accurate forecast of production in the United States. In 1956, Hubbert forecast that the ultimate recoverable resource for the lower 48 states and adjacent offshore areas would be between 150 and 200 billion barrels, and projected "the peak in production should probably occur within the interval 1966-1971" (Hubbert 1975, 371). At the same time, the USGS, using the geologic analogy method (Zapp 1962) projected ultimate recoverable resources of 590 billion barrels, and concluded that

> ...the size of the resource base would not limit domestic production capacity 'in the next 10 to 20 years at least, and probably [not] for a much longer time' (Gillette 1974, 129).

Production actually peaked in 1970, and, as Renshaw and Renshaw (1980, 58) have pointed out, Hubbert's "projected values for cumulative discoveries and production have not yet been exceeded." Assuming 1970 was the true peak of production, Hubbert's 1956 forecast leads the peak by some fourteen years, well within the twenty-year lead generated in the experiment.

<u>The Geologic Analogy Method</u>: Geologic analogy methods, sometimes called volumetric methods, are a common approach to estimating ultimate recoverable resources. In essence, the method consists of

...projecting average yield factors (barrels of oil per cubic mile of sedimentary rock or per square mile of surface area) uniformly over a sedimentary rock stratum (Mathtech 1978, III-297).

The USGS estimates of 1975 present one of the most comprehensive and detailed uses of these techniques to date. The essence of the method was described by the Survey as follows:

Estimates of recoverable oil and gas resources are based upon a series of resource appraisal techniques....The techniques used include: (1) an extrapolation of known producibility into untested sediments of similar geology for a well-developed area; (2) volumetric techniques using geologic analogs and setting upper and lower yield limits through comparisons with a number of known areas; (3) volumetric estimates with an arbitrary general yield factor applied when direct analogs were unknown; (4) Hendricks' (1965) potential area categories; and (5) comprehensive comparisons of all known published estimates for each area to all estimates generated by the above methods (USGS 1975, cited in MIT 1982, III-5-13).

Despite the apparent rigor, the USGS study actually involved a high degree of subjective judgment and discussion, and the protocols used to reach consensus have been criticized as "mismanaged" (MIT 1982, III-5-19). Our representation of the process abstracts from the subjective and political nature of the process to focus on the sources of information for the economic, technical, and geologic assumptions made in the study.

The survey divided the resource base into the standard classifications of the McKelvey box, and assumed

...that undiscovered recoverable resources will be found in the future under conditions represented by a continuation of price/cost relationships and technological trends generally prevailing in therecent years prior to 1974. Price/cost relationships since 1974 were not taken into account because of the yet undetermined effect these may have on resource estimates....

These assumed conditions permit the appraisal of recoverable oil and gas resources to be made on the basis of: (1) relevant past history and experience concerning recovery factors; (2) the geology favorable to the occurrence of producible hydrocarbons; and (3) the size and type of reservoirs which have geen found, developed, and produced....

The economic recovery factor used was based on a current national average of approximately 32 percent....Sub-economic identified resources of crude oil were calculated on the following assumptions: (1) that on the average, 32 percent of original oil-in-place is recoverable if there are no substantial changes in present economic relationships and known production technology, and (2) that ultimately the recovery factor could be as large as 60 percent....

It is extremely optimistic to assume that 60 percent of the oil-in-place will eventually be recovered. If [this] becomes a

> reality, it is likely to occur only through gradual development over an extended time period. The remaining 40 percent of oil-in-place is not included as it is considered to be nonrecoverable.... (USGS 1975, cited in MIT 1982, III-5-9, 10).

The protocol used to test the geologic analogy method appears in the appendix. The protocol assumes far better information than is actually available to real estimators. Cumulative production, technically recoverable reserves, cumulative identified oil-in-place, the current recovery factor, and the area explored are assumed to be known exactly. The only potential sources of error are in the estimation of the future recovery fraction and in the expected yield of oil-in-place in unexplored areas. In both of these cases, the model, like the Survey, assumes "a continuation of price/cost relationships and technological trends generally prevailing in...recent years...."

Applying the geologic analogy protocol to the data generated by the model yields the path of estimates summarized in exhibit 12. The components of the estimates are shown in exhibit 13. The estimates start low, rise rapidly, overshoot the ultimate quantity recovered, and settle at a level in excess of the ultimate quantity recovered.

Exhibit 13 tells the following tale. In 1900 the estimates are very low--only a small fraction of the sedimentary basins in the world have been surveyed, both discovery and recovery technology are primitive, and little of the resource has been identified. With increasing exploration experience, improving exploration technology, and growing knowledge of sedimentary basins, the estimates steadily rise, reaching almost 600 billion barrels by 1940. In 1940, reserves are small and recovery technology has not grown enough to warrant substantial forecasts of future improvement. The majority of the estimate consists of probable recovery from unidentified resources--the quantity expected at current recovery factors from known sedimentary basins that are as yet unexplored, assuming historic yields.
Between 1940 and 1960 the estimate more than triples, reaching nearly 2000 billion barrels. Though all components of estimated ultimate recovery are growing, the bulk of the estimate (60 percent) is still due to probable future discoveries. By 1960, the accelerating growth of recovery technology is beginning to cause the expected recovery fraction to exceed the current fraction. Expectations of technical improvement for both the identified and estimated unidentified resource is still quite cautious, however, accounting for less than 20 percent of the estimate.

The estimate continues to grow between 1960 and 1980, surpassing the ultimate quantity ultimately recovered in the early 1970s. In contrast to previous years, the majority of the growth is due to expectations of continuing improvement in recovery technology. Between 1960 and 1980, the fraction recoverable rises from 24 percent to 35 percent; based on that growth, the expected fraction recoverable doubles, rising from 29 to 60 percent. In fact, the USGS estimated the recovery fraction might rise to as high as 60 percent when the recovery factor was actually 32 percent (see appendix). As a result, the estimated ultimate recoverable resource rises to 3280 billion barrels, of which 15 percent has already been produced and fully 40 percent is based on the expectation of continued technical progress.

By 1980, the estimated quantity of oil-in-place remaining to be identified is declining, the combination of declining area unexplored and particularly of declining yield. The decline in yield that began in the 1940s has accelerated, causing the expected yield to fall as well. Nevertheless, as a consequence of the lags in recognizing and adapting to lower yields, the expected yield is 36 percent higher than the actual yield in 1980.

After 1980, growth of the estimate slows as the unexplored area and expected yield to exploration continue to drop. Recovery technology continues to improve, however, which causes the expected recovery factor to overshoot the true value. The expected fraction recoverable peaks at 73 percent in 2010, compared to the true long-run value of 59 percent. The resulting overestimate of recovery helps boost the estimated URR to a peak of about 3550 billion barrels. After 2010, the expected recovery fraction approaches the actual fraction, and the estimated recoverable resource declines to an equilibrium value of about 3000 billion barrels, approximately equal to the ultimate quantity that could have been recovered if the resource had been fully exploited.

Simulation of the geologic analogy method produces estimates which are consistent with the historical estimates of world ultimate recoverable resources (exhibit 14). Nevertheless, the geologic analogy method substantially overshoots the true ultimate quantity recovered. The overshoot begins in the 1970s and reaches a peak over 30 percent greater than the ultimate resource recovered. The overshoot is caused by two major factors, visible in exhibit 13. First, the extrapolation of past improvements in recovery technology leads to forecasts of ultimate recovery factors that exceed the true factor. Second, lags in the recognition of declining yields to future exploration activity cause the estimates of unidentified oil-in-place to overshoot the true quantity. And when the extrapolation of recovery technology is applied to the estimated unidentified oil-in-place, the overestimation is compounded.

Viewed from another perspective, however, the estimation procedure does not perform badly. Exhibit 15 compares simulated estimated recoverable resource remaining to simulated true recoverable resource remaining. The history of resource estimation divides into two distinct phases. At first, estimates rise steeply as more knowledge is gained. The estimated recoverable resource remaining overtakes the true quantity remaining in the 1970s. The estimates then reverse and fall as the true quantity remaining falls. The estimates lag behind the true quantity remaining due to the expectations of continued technical progress and near-historical yields.

Viewed as a learning process in the presence of limited and uncertain information, the estimation procedure performs rather well. Note, however, that though there is no change in the way estimates are being made, there is a dramatic shift in perspective between 1970 and 1990. Within twenty years, the historic trend of growing estimates reverses. The result of such a shift is likely to be conflicting estimates and methodological disagreements.

Interestingly, the USGS recently lowered its estimate of world ultimate recoverable petroleum resources (Science, 27 January 1984, 382). Citing continued disappointments in finding rates as the main reason for the decline, the USGS report may represent the beginning of an overshoot in actual estimates of world petroleum resources.

## Implications: the Accuracy of the Estimation Methods

The synthetic data used in this experiment to evaluate the estimation methods represent but one of many possible scenarios for the development of world petroleum. Other scenarios can and should be developed to test the robustness of the results. Yet the estimates generated by the two methods are sufficiently different to warrant comment (exhibit 16).

Hubbert's method has been criticized as merely an exercise in fitting data to an arbitrary curve. Yet these results show the life cycle approach can yield an accurate estimate of the ultimate recoverable resource, provided the resource is far enough into its life cycle so that the depletion effect begins to dominate other factors and depress the growth rate of cumulative discoveries. In the scenario tested, this point is reached approximately twenty years before the peak in production. Before then, the life cycle method overestimates the ultimate recoverable resource. The results are consistent with the impressive accuracy of Hubbert's projections for the United States but suggest the method may only now become useful for estimating world resources. It is worthwhile noting that Hubbert presumed a logistic curve and has been criticized for not using a more flexible functional form that allows the data to dictate the presence of asymmetries (MIT 1982, III-2). The model used to generate the synthetic data does not presume a logistic curve, nor does it generate one,[3] but Hubbert's approach eventually produces accurate estimates nonetheless.

Analysis of the geologic analogy approach shows the history of rising estimates of world ultimate recoverable petroleum resources can be explained in terms of the information sources available to resource estimators and the estimation procedures used. Though ostensibly superior to the Hubbert method, because it involves the use of disaggregate, primary geologic data, the analogy method actually involves a high degree of judgment, extrapolation of past trends, and educated guessing. Results show the analogy method can lead to a substantial overshoot of the world ultimate recoverable resource, even when a high degree of perfect information is assumed.

The results demonstrate that the pattern of rising estimates is perfectly consistent with the continuous depletion of the resource, and show it is quite possible that estimates may have already exceeded the true resource base. Further, the results suggest there is absolutely no basis, other than faith, for estimating the ultimate recoverable resource by extrapolating past estimates. Odell's statement, quoted earlier, that

> ...the resource base,...given the extrapolation of the calculated trend, would reach almost $4,000 \times 10^9$ barrels by the year 2000....

reveals a potentially serious confusion between the estimated resource base and the actual resource base. The estimated resource base may rise, but the actual resource base is constant and the remaining quantity of oil-in-place is monotonically declining. To illustrate, extrapolation of the model-generated analogy estimates would exceed Odell's figure by the year 2000, increasing the overshoot to more than fifty percent. Indeed, given the historic rising trend of estimates, any simple extrapolation of past estimates must necessarily overshoot the true resource, even if the estimates themselves do not. And when the estimates themselves show the potential for overshoot, as shown by the model and by the experience in the United States, the error in extrapolating is magnified even further.

## Methodological Conclusions

Most previous critiques of resource estimation techniques have focused on the sources of information, the statistical procedures, and the analytic framework used by the various estimators. This work suggests that a complementary approach based on simulation of the various methods offers important insights into the dynamics of the resource estimation process. By formalizing the protocols for making estimates and applying them to synthetic data, it is possible to assess the tendency for an estimation technique to overshoot the true resource before the true resource base is known. Further, it may be possible, as in the Hubbert case, to identify time frames in which the method is accurate.

The work reported here demonstrates the potential of the synthetic data approach. More work needs to be done both refining the model and the estimation protocols. Other estimation methods, such as rate-of-effort, need to be examined. The model could be calibrated to portray the United States to see if the pattern of overshoot can be generated. The robustness of the results in the presence of process noise and measurement error should be explored. Other models of the resource life cycle should be used to generate the synthetic data used by the estimation protocols to see if these results can be replicated.

This work opens a line of research that could contribute to increasing the reliability of resource estimation methods. It is possible to develop causal, structural models of nonrenewable resources that incorporate geologic, technical, and economic factors, and which endogenously generate the complete life cycle. We have shown that it is possible to use such models to evaluate various methods of estimating resources. The approach helps resolve the apparent paradox of rising estimates and inexorably declining resources.

## APPENDIX: PROTOCOL FOR THE GEOLOGIC ANALOGY METHOD

In the equations, the prefix 'G' denotes a quantity estimated by the geologic analogy protocol; other variables denote the true values generated by the model. A '<P>' denotes the assumption of perfect information.

$$GEURR_t = GCUMPR_t + GTRRR_t + GEATRR_t + GEFD_t \quad \text{(G1)}$$

<P> $GCUMPR_t = CUMPR_t$ (G2)

<P> $GTRRR_t = TRRR_t$ (G3)

where

GEURR = Estimated ultimate recoverable resource (bbls)
GCUMPR = Estimated cumulative production (bbls)
GTRRR = Estimated technically recoverable resource remaining (bbls)
GEATRR = Estimated additions to technically recoverable resource (bbls)
GEFD = Estimated future discoveries (bbls)
CUMPR = Cumulative production (bbls)
TRRR = Technically recoverable resource remaining (bbls)

The expected ultimate recoverable resource is divided into four basic categories: cumulative production, technically recoverable reserves, expected additions to technically recoverable reserves, and expected future discoveries. The estimated values of cumulative production and technically recoverable reserves are assumed to be equal to the true values.

$$GEATRR_t = GETRRR_t - GTRRR_t \quad \text{(G4)}$$

$$GETRRR_t = GCUMAIR_t * GEFR_t - GCUMPR_t \quad \text{(G5)}$$

<P> $GCUMAIR_t = CUMAIR_t$ (G6)

$$GEFR_t = GFR_t + GEIFR_t \quad \text{(G7)}$$

<P> $GFR_t = FR_t$ (G8)

$$GEIFR_t = (1-GFR_t)*f_1(GEGFR_t) \quad f_1(0)=0,\ f_1' \geq 0 \quad \text{(G9)}$$

$$GEGFR_t = TREND(GFR_t) \quad \text{(G10)}$$

where

GEATRR = Estimated additions to technically recoverable resource (bbls)
GETRRR = Estimated expected technically recoverable resources remaining (bbls)
GTRRR = Estimated technically recoverable resource remaining (bbls)
GCUMAIR = Estimated cumulative additions to identified resource (bbls)
CUMAIR = Cumulative additions to identifed resource (bbls)
GEFR = Expected fraction recoverable (dimensionless)
GCUMPR = Estimated cumulative production (bbls)

GFR = Estimated current fraction recoverable (dimensionless)
FR = Fraction recoverable (dimensionless)
GEIFR = Expected increase in fraction recoverable (dimensionless)
GEGFR = Expected growth in fraction recoverable (1/years)
TREND = Function to estimate growth rate of a variable

Technically recoverable reserves include all the known resource that can be recovered with current technology, whether it is currently economic to do so or not. Expected additions to technically recoverable reserves represents the additional recovery from currently identified resources due to anticipated advances in recovery technology. The expected addition is given by the difference between what could be recovered at anticipated levels of technology and what is currently recoverable. We assume perfect knowledge of the quantity of identified resource and of the cumulative original oil-in-place identified. Similarly, the current fraction recoverable is assumed known.

The expected increase in the fraction recoverable is based on the expected rate of technical progress. The expected rate of technical improvement is based on the trend in the recovery fraction over the past ten years. We assume changes in the trend in recovery factors are incorporated in the forecast after an average lag of ten years. The lag stems from the time required to become aware of new recovery techniques, to evaluate and build confidence in their effectiveness, and for that information to diffuse through the geological community and become enough a part of "conventional wisdom" to be included in government projections.

The maximum possible addition to the fraction recoverable is, of course, the fraction unrecoverable. The fraction of this maximum improvement that is expected is nonlinearly related to the expected rate of technical improvement. When the recovery fraction is not growing, no improvement in technology is expected and the anticipated increase in the recovery fraction is zero. When the growth rate is higher than 1.5 percent per year, the expected increment in the fraction recoverable reaches a maximum, assumed to be 40 percent of the fraction unrecoverable. (The USGS assumed a maximum potential recovery factor of 60 percent compared to an average of 32 percent in 1975. Thus the anticipated improvement was expected to be 28 percentage points out of a maximum of 68, or .41 of the maximum.)

$$GEFD_t = GPFD_t + GSFD_t \quad (G11)$$

$$GPFD_t = GFR_t * GEUR_t \quad (G12)$$

$$GSFD_t = GEIFR_t * GEUR_t \quad (G13)$$

where

GEFD = Expected future discoveries (bbls)

GPFD = Probable future discoveries (bbls)

GSFD = Speculative future discoveries (bbls)

GFR = Estimated current fraction recoverable (dimensionless)

GEUR = Estimated undiscovered resource (bbls)

GEIFR = Expected increase in fraction recoverable (dimensionless)

Expected future recovery from unexplored areas is the least certain component of any resource estimate. We have disaggregated the total into two components: (1) the quantity of currently unidentified oil expected to be recovered at current recovery factors (GPFD) and (2) the additional quantity expected to be recovered at anticipated recovery levels (GSFD). Both of these quantities depend directly on the estimate of unidentified oil-in-place (GEUR).

$$GEUR_t = GAU_t * GFD_t * GEYUA_t \quad (G14)$$

$$GAU_t = GAS_t - GAE_t \quad (G15)$$

<P> $$GAE_t = AE_t \quad (G16)$$

$$GAS_t = f_2(t) \quad f_2' \geq 0 \quad (G17)$$

<P> $$GFD_t = FD_t \quad (G18)$$

where

| | | |
|---|---|---|
| GEUR | = | Estimated undiscovered resource (bbls) |
| GAU | = | Estimated area unexplored (sq. mi.) |
| GFD | = | Estimated fraction discoverable (dimensionless) |
| GEYUA | = | Expected yield from unexplored area (bbls/sq. mi.) |
| GAS | = | Surveyed area of sedimentary basins (sq. mi) |
| GAE | = | Estimated area explored (sq. mi.) |
| AE | = | Area explored (sq. mi.) |
| FD | = | Fraction discoverable (dimensionless) |

Estimated unidentified oil-in-place is the product of the area unexplored, the fraction of that area in which exploration is feasible given current technology, and the expected yield in that area. The fraction of oil-in-place that is currently discoverable is assumed to be known exactly.

The area unexplored is given by the total global area in which sedimentary basins are known to exist less the area already explored. The area in which sedimentary basins are known to exist is specified exogenously. Assumed to be quite small in 1900, knowledge of sedimentary basins expands to 25 million square miles by 1980 (Grossling 1977) and is assumed to rise an additional 20 percent to 30 million square miles by 2020. The area actually explored is endogenously generated by the model and is related to the cumulative resource identified. If oil were distributed uniformly over the total area of sedimentary basins, and if exploration activity were no better than random, the relationship between area explored and identified oil-in-place would be linear. However, oil is distributed very unevenly, and exploration activity is better than random. Giant and supergiant fields account for one percent of known fields but 75 percent of known reserves and 65 to 70 percent of current production (Klemme 1977). The assumed curve is therefore highly nonlinear.

$$GEYUA_t = GWD * GAWD * GEYE_t \quad (G19)$$

$$GWD = .5 \quad (G19.1)$$

$$GAWD = 6000 \quad (G19.2)$$

$$GEYE_t = GHYE_t * GFHYE_t \quad (G20)$$

$$GHYE_t = DLINF3(YE_t, GTAEY) \quad (G21)$$

$$GTAEY = 10 \quad (G21.1)$$

$$GFHYE_t = f_3(GTY_t) \quad f_3(0)=1,\ f_3' \geq 0 \quad (G22)$$

$$GTY_t = TREND(YE_t) \quad (G23)$$

where

| | | |
|---|---|---|
| GEYUA | = | Expected yield from unexplored area (bbls/sq. mi.) |
| GWD | = | Estimated well density (wells/sq. mi.) |
| GAWD | = | Estimated average well depth (ft/well) |
| GEYE | = | Expected yield to exploration (bbls/ft) |
| GHYE | = | Estimated historical yield to exploration (bbls/ft) |
| GFHYE | = | Fraction of historical yield expected (dimensionless) |
| DLINF3 | = | Third order exponential information smoothing |
| YE | = | Yield to exploration (bbls/ft) |
| GTAEY | = | Time to adjust estimates of historical yield (years) |
| GTY | = | Estimated trend in yield to exploration (1/years) |
| TREND | = | Function to estimate growth rate of a variable |

The expected yield of oil-in-place per square mile of unexplored area is based on the density of wells, the average well depth required to explore a region fully, and the expected yield per foot drilled. We assume average well density and depth to be one well every two square miles and 6000 feet per well, respectively (Gillette 1974). Expected yield per well is based on historic yields, discounted according to past trends in the yield. The historic yield is assumed to lag the actual yield by ten years. The delay reflects the time required to compile yield data, to separate a systematic change in the yield from the noise, and for the revised yield estimates to become accepted throughout the geologic community. For example, the largest decline in yield per foot drilled in the United States occurred between 1940 and 1950. Hubbert pointed out the declining trend in yield per foot in the United States in 1962. Until 1965, the USGS continued to use the so-called "Zapp hypothesis" of constant future yield. Even then the Survey assumed a value that exceeded more recent yields (Gillette 1974, 129):

> That year, the USGS noted a 'definite decline' in discoveries and postulated now that oil would, on the average, prove to be only half--not equally--as abundant in unexplored rock as in explored rock. Now this number is in contention, with Hubbert claiming that it's at least five times too large for onshore terrain. [USGS director] McKelvey acknowledges that the figure of one-half was largely a 'subjective judgment' and another official describes it as 'mostly a guess.'

It is assumed in the model that the expected yield in unexplored areas is discounted below the historic yield when the yield is perceived to be falling. In the USGS study, the choice of the discount factor was highly subjective. The Survey acknowledged that

> ...the proper [discount factor] is open to conjecture. The fraction can range from one (or greater) to zero. Precedents exist for both 1.0 and 0.5. Qualitatively, 1.0 seems optimistic but not unreasonable; 0.5 seems conservative; less than 0.5 seems pessimistic (Mallory, 'Synopsis of Procedure' cited in MIT 1982, III-3-12).

The assumed discount becomes progressively larger as the decline rate grows.

## NOTES

0. We gratefully acknowledge the helpful criticisms of M. K. Hubbert, Gordon Kaufman, Robert Fildes, and three anonymous referees.

1. The discussion of Warman's and Odell's views is based on Seidl 1977.

2. The oscillation stems from delays in adjusting energy demand to price and in bringing investment in exploration to fruition. No significance should be attached to the timing of the resulting gluts.

3. An interesting extension of the present work would apply alternative functional forms which do not presume a symmetrical life cycle, such as the Gompertz, Weibull, or Richards curves, to see if the lead provided by the logistic curve can be extended.

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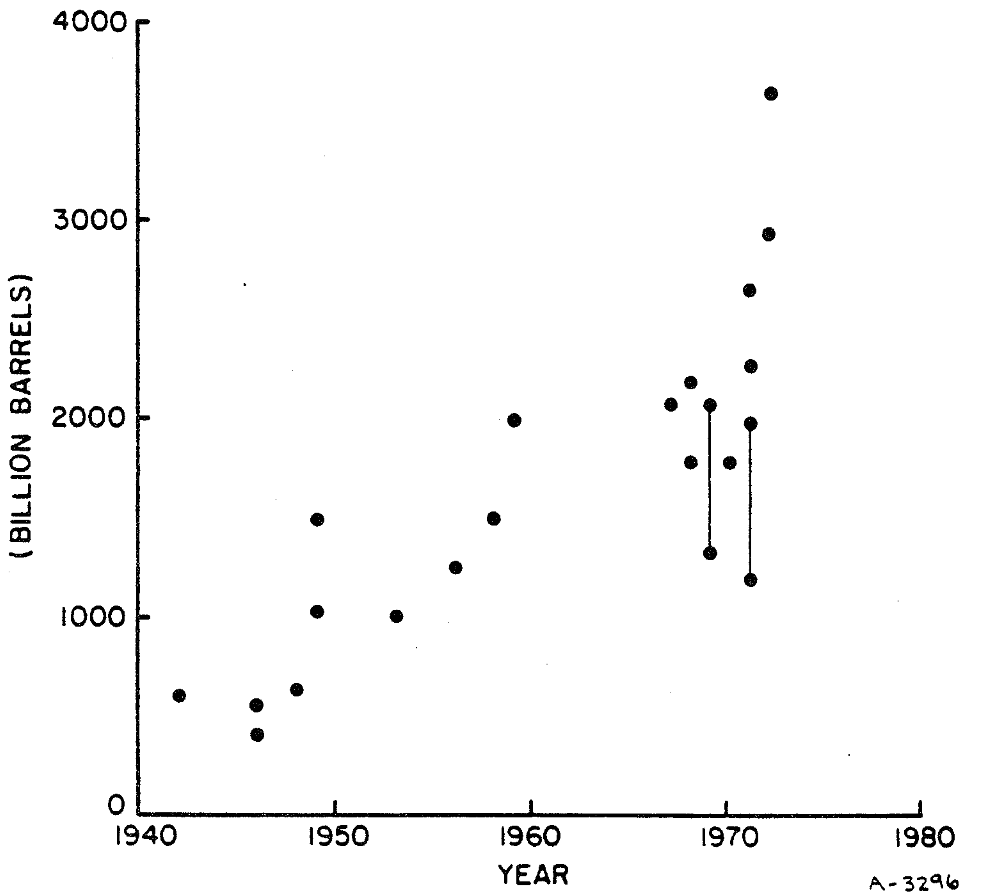


Exhibit 1: Estimates of the world's ultimate recoverable petroleum resource. Source: Seidl 1977.

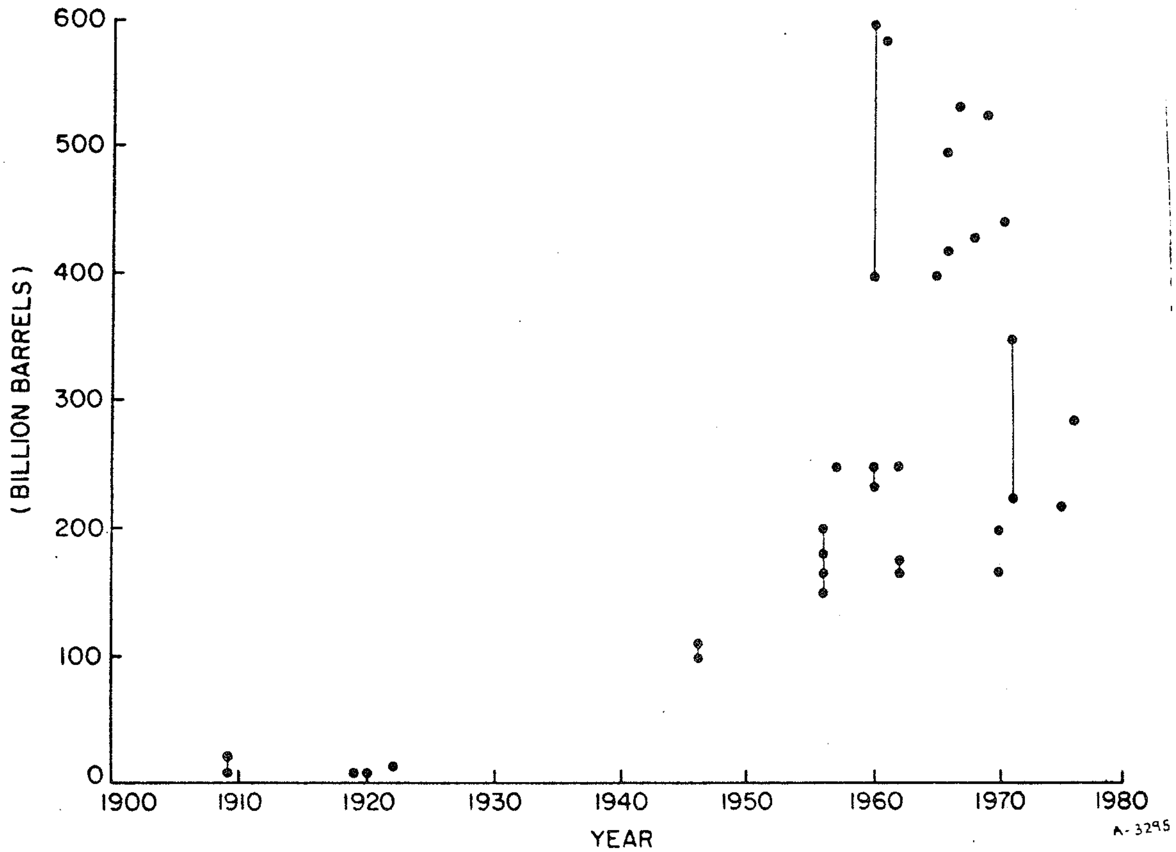


Exhibit 2: Estimates of ultimate recoverable petroleum in the coterminous United States and adjacent offshore area. Source: MIT 1982, II-1-3.

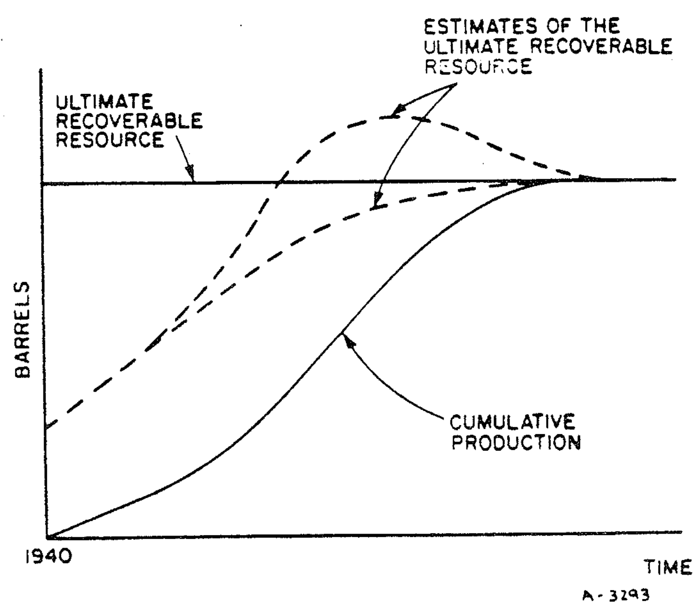


Exhibit 3: Possible paths of estimates of the world ultimate recoverable resource.

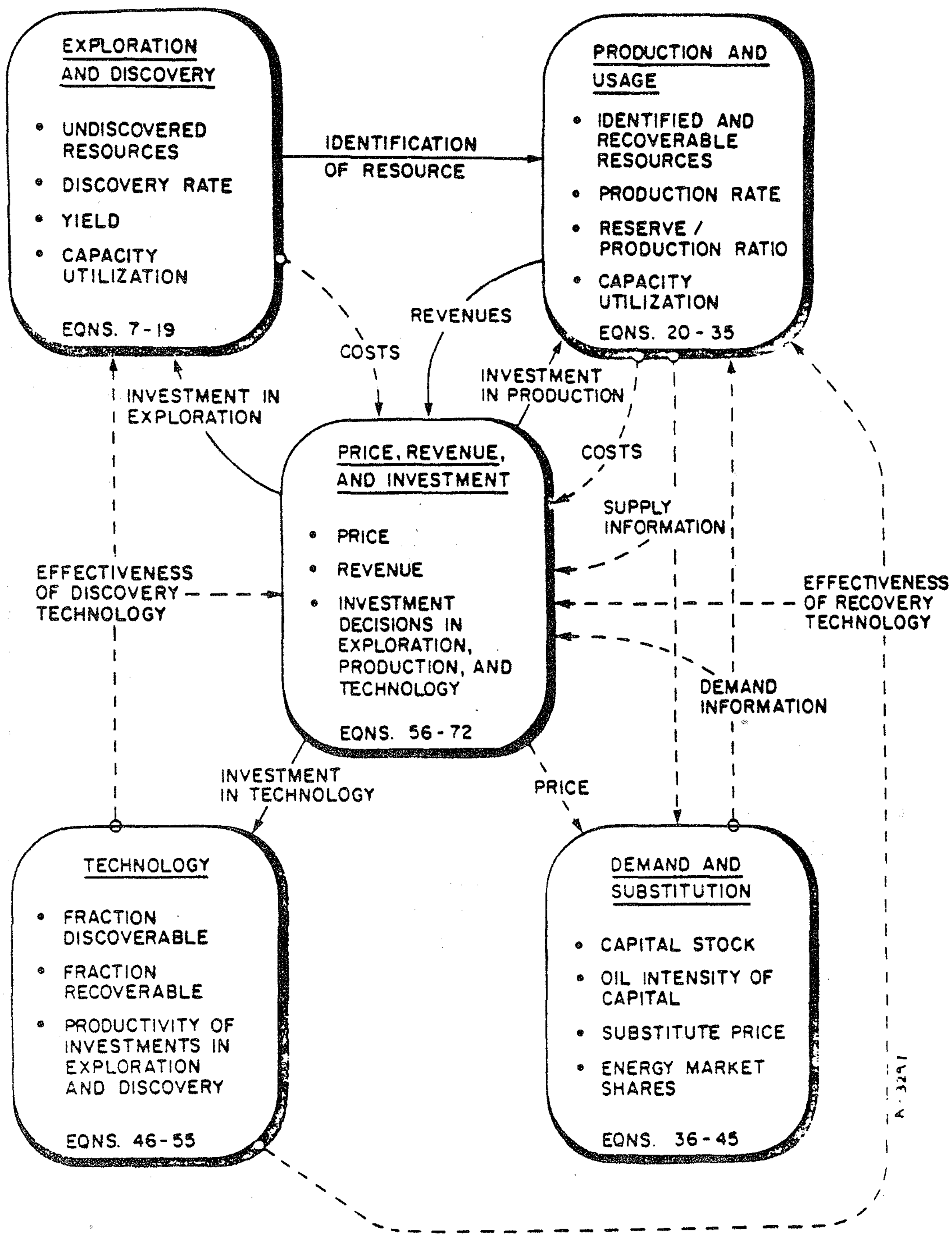


Exhibit 4: Model overview.

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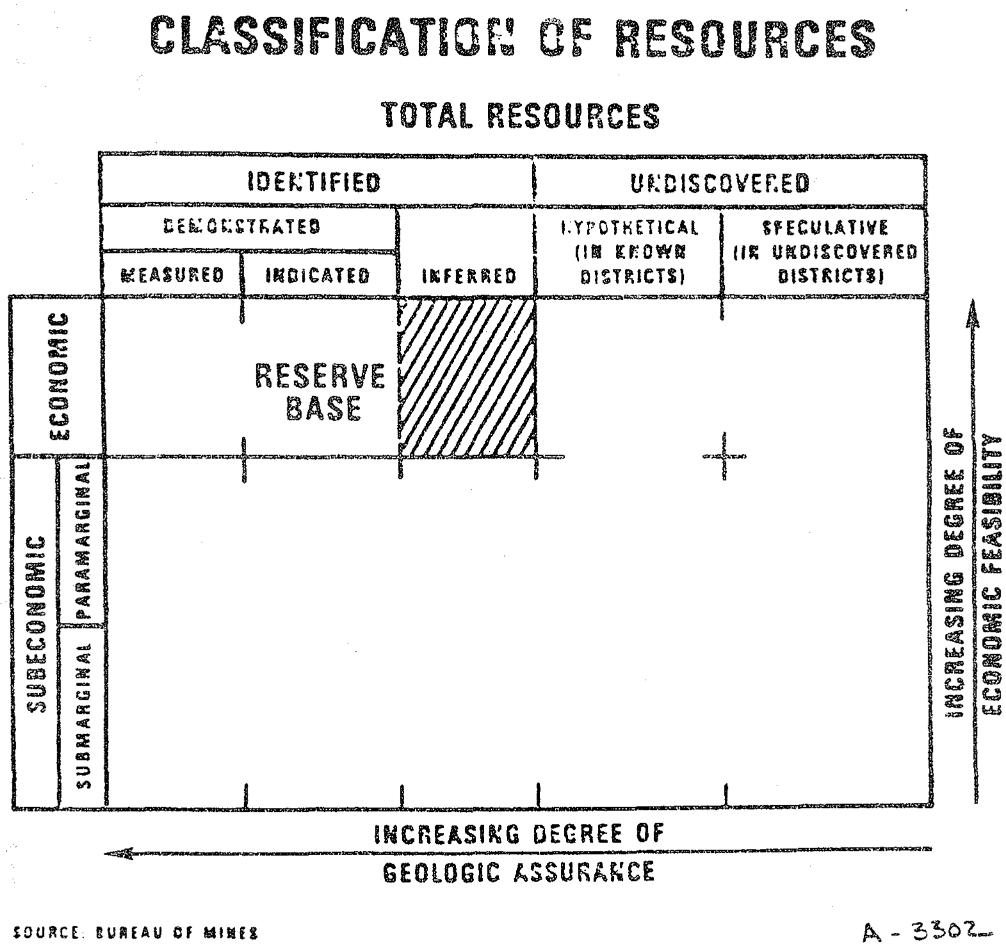


Exhibit 5: Classification of resources. Source: USGS 1976.

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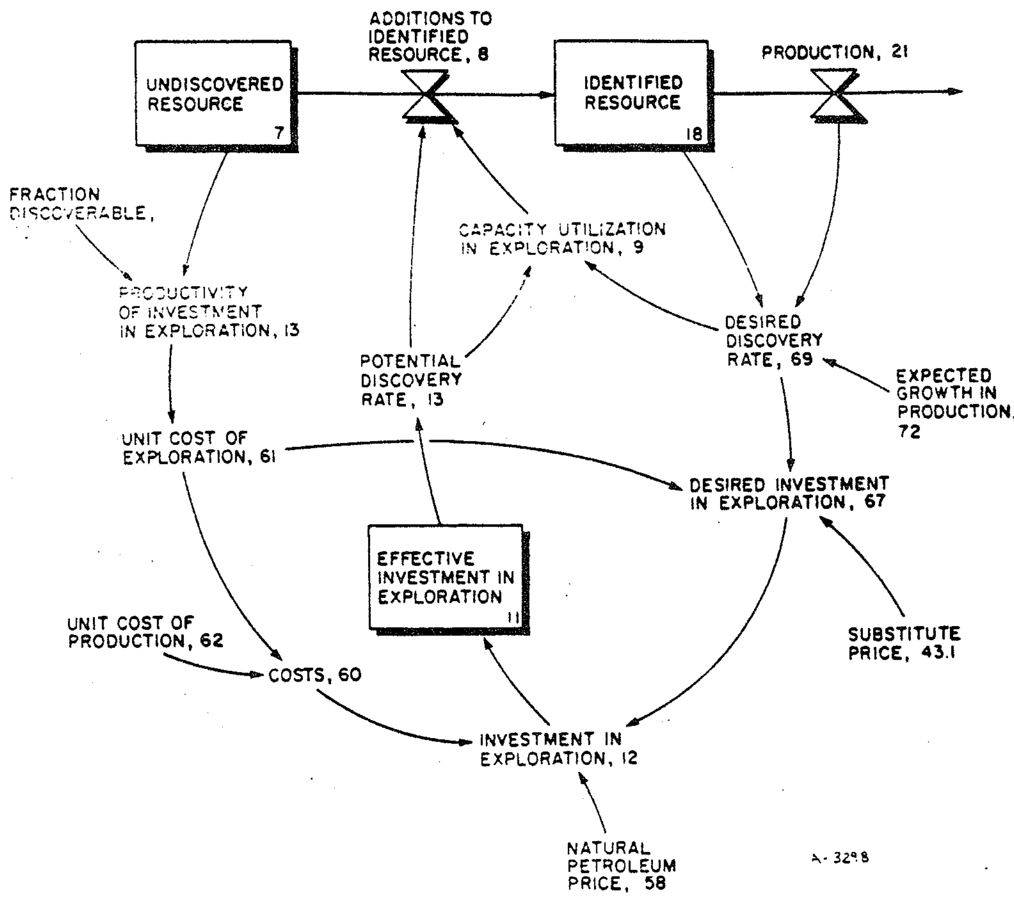


Exhibit 6: Overview of determinants of exploration and discovery.

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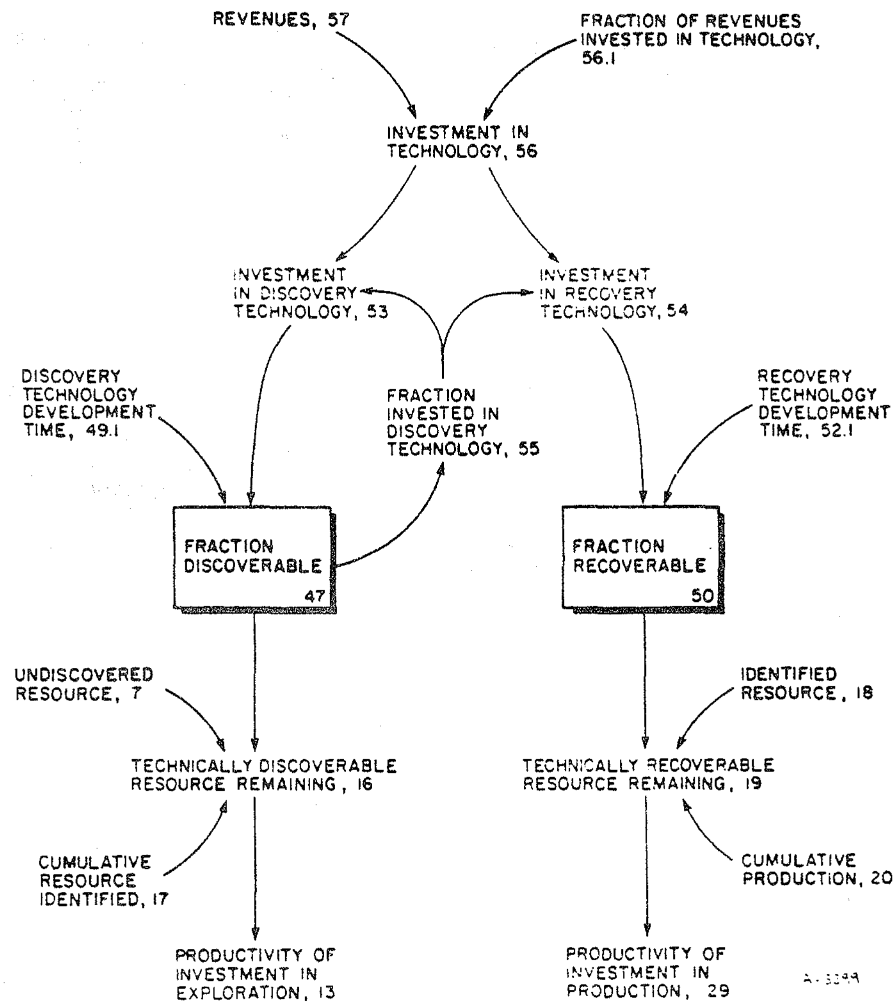


Exhibit 7: Overview of technology sector.

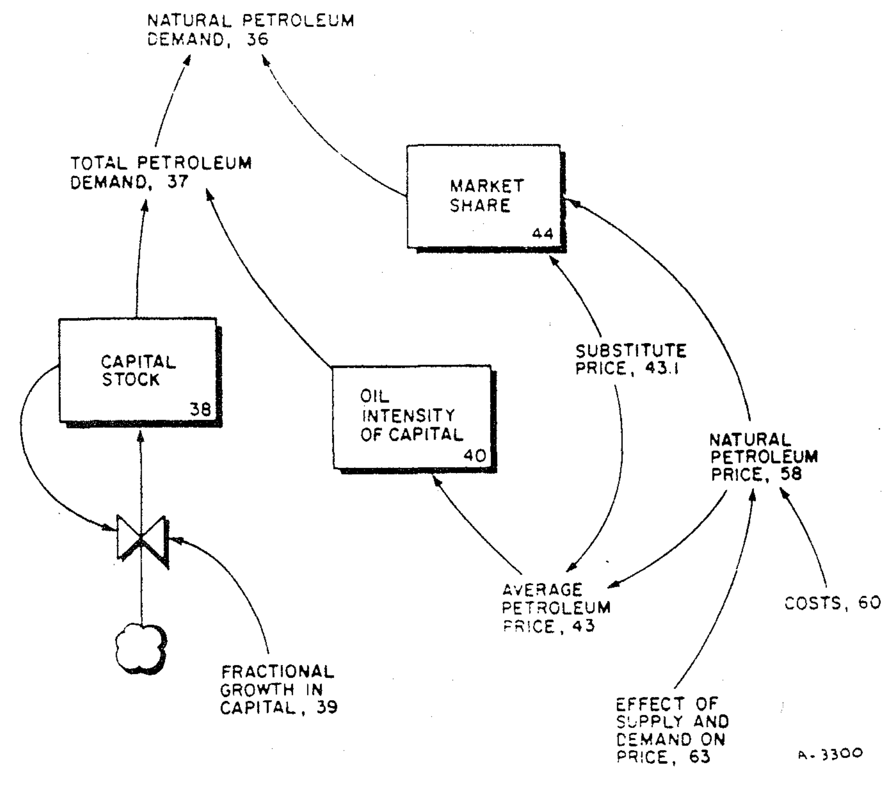


Exhibit 8: Overview of demand sector.

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Exhibit 9. Major Parametric Assumptions

| Quantity | Value |
|---|---|
| Total resource (billion bbls) | 5042 |
| Initial undiscovered resource (billion bbls) | 5000 |
| Exploration development delay (years) | 4 |
| Average technology development time (years) | 6 |
| Initial fraction discoverable (dimensionless) | 0.1 |
| Maximum fraction discoverable (dimensionless) | 1.0 |
| Initial fraction recoverable (dimensionless) | 0.2 |
| Maximum fraction recoverable (dimensionless) | 0.6 |
| Growth rate of capital stock (1/years)[a] | |
| 1900 | .04 |
| 1925 | .045 |
| 1950 | .05 |
| 1975 | .05 |
| 2000 | .04 |
| 2025 | .03 |
| 2050 | .02 |
| 2075 | .01 |
| 2100 | 0.00 |
| Long run price elasticity of petroleum demand (dimensionless) | 0.75 |
| Average lag in adjustment of petroleum demand to price (years) | 15 |
| Price of petroleum substitutes ($/bbl) | 30 |
| Average lag in development of petroleum substitutes (years) | 10 |

[a] Linear interpolation between values.

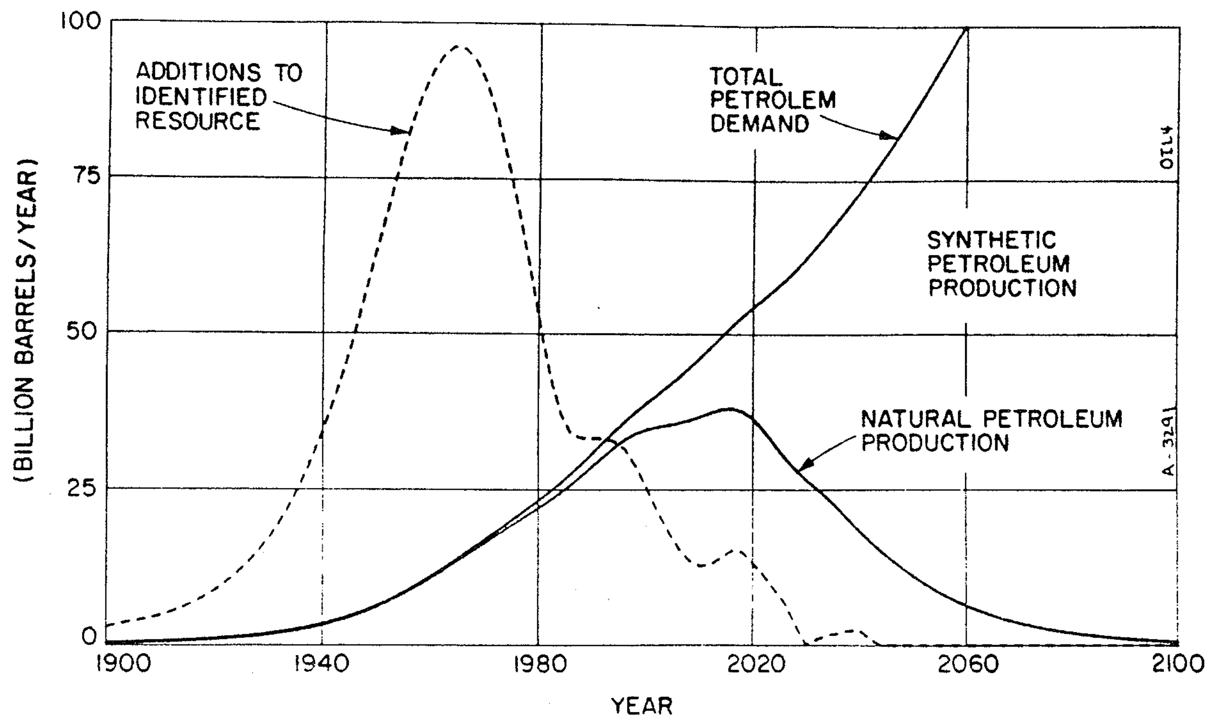


Exhibit 10a: Base run - petroleum demand, production, and discovery.

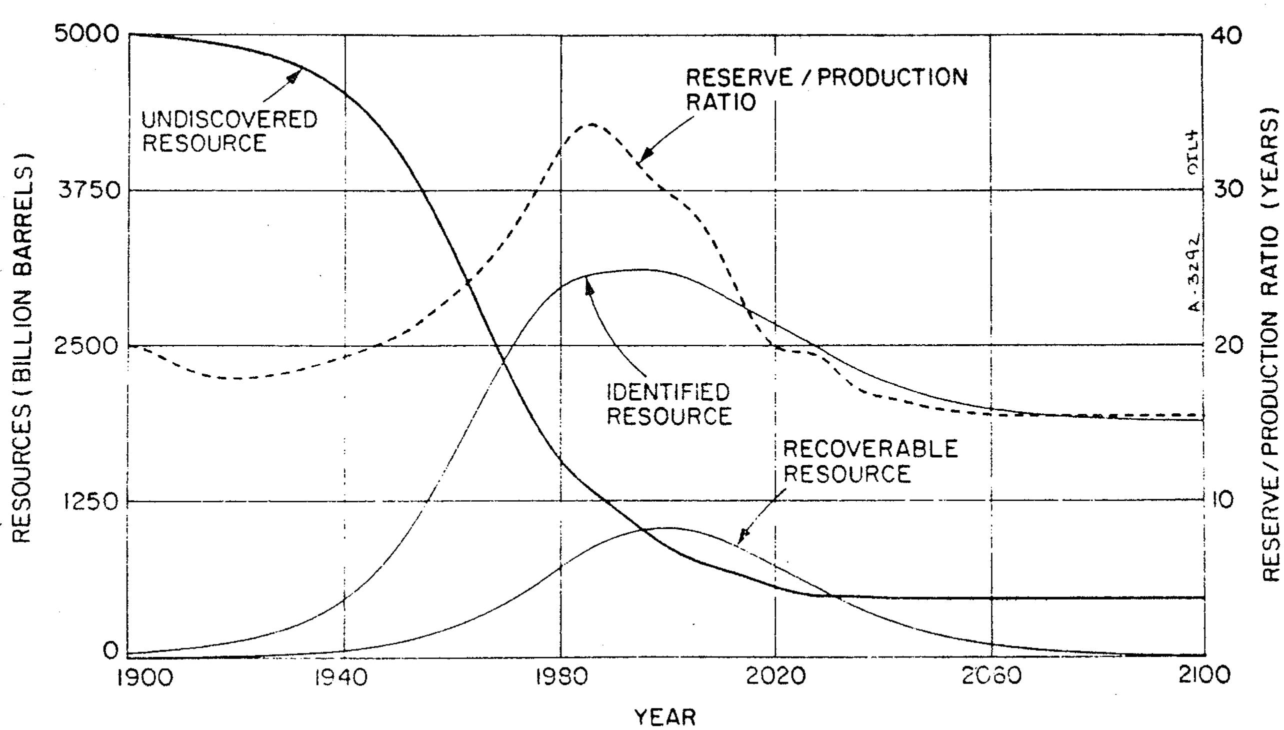


Exhibit 10b: Base run - resource levels and the reserve/production ratio.

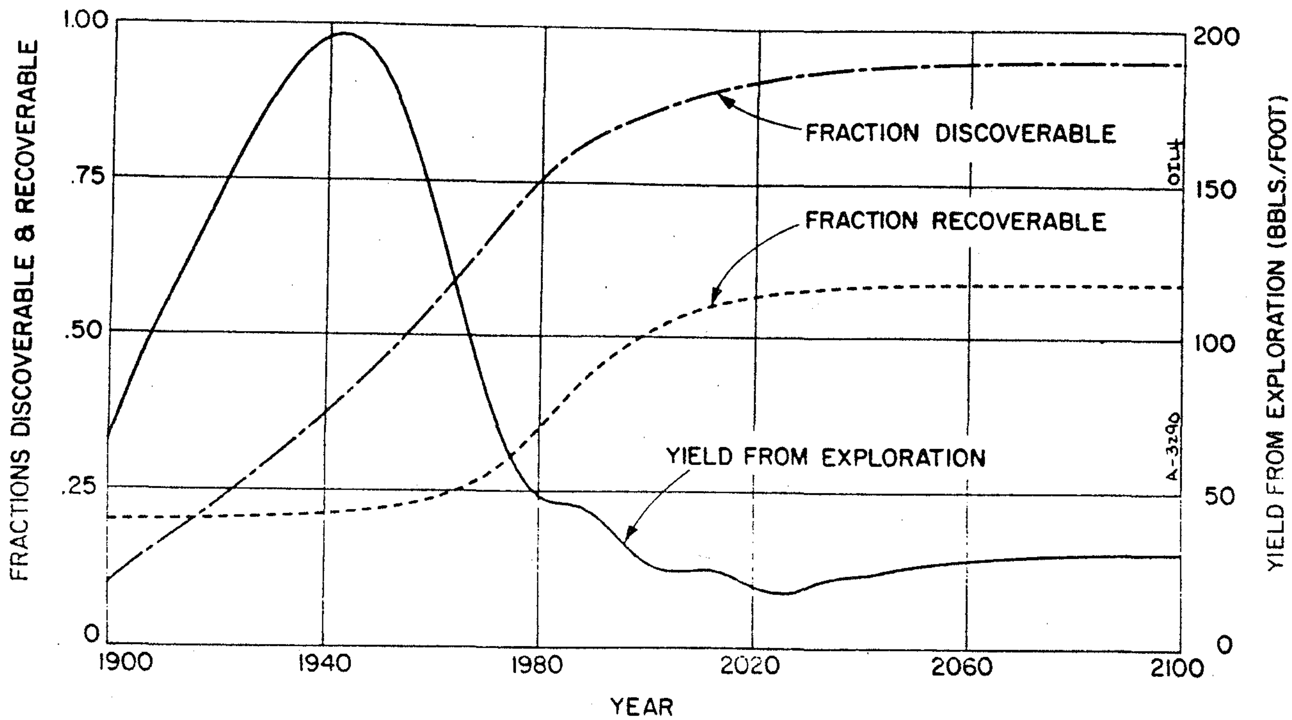


Exhibit 10c: Base run - technology and yield.

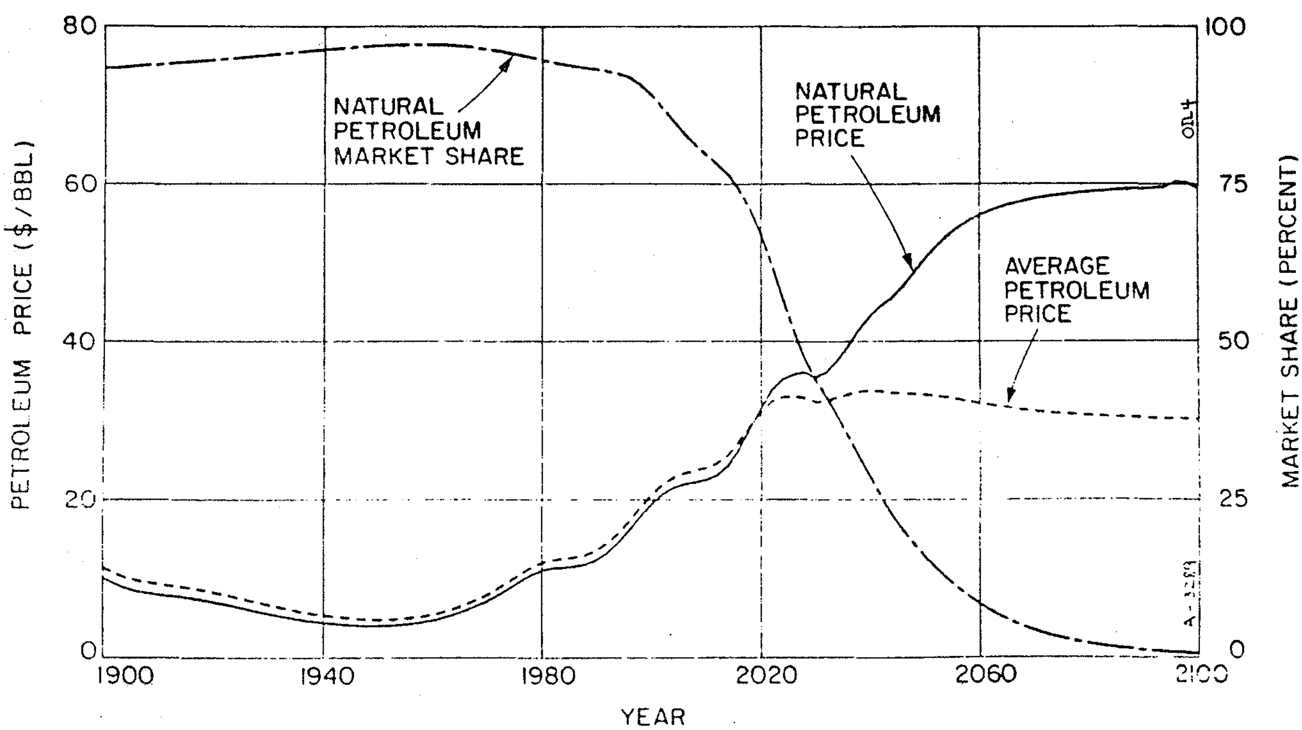


Exhibit 10d: Base run - prices and market shares.

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Exhibit 11. Estimates of Ultimate Recoverable Resource by the Hubbert Life Cycle Method

| Range | Estimated $Q^*$ [a] (billion bbls) | $R^2$ | Percent Error[b] |
|---|---|---|---|
| 1900 - 1970 | + ∞ | .99947 | |
| | 6000 | .99918 | |
| 1900 - 1980 | 6600 | .99937 | |
| | 6500 | .99938 | 141 |
| | + 5500 | .99938 | 104 |
| | 5400 | .99937 | |
| 1900 - 1990 | 3900 | .99930 | |
| | 3800 | .99932 | |
| | 3700 | .99932 | 37 |
| | + 3600 | .99932 | 34 |
| | 3500 | .99932 | |
| | 3400 | .99930 | |
| 1900 - 2000 | 3100 | .99923 | |
| | + 3000 | .99925 | 11 |
| | 2900 | .99921 | |
| 1900 - 2010 | 2850 | .99924 | |
| | + 2800 | .99927 | 4 |
| | 2750 | .99921 | |
| 1900 - 2020 | 2800 | .99912 | |
| | + 2750 | .99933 | 2 |
| | 2700 | .99922 | |
| 1900 - 2030 | 2800 | .99869 | |
| | + 2750 | .99941 | 2 |
| | 2700 | .99902 | |
| 1900 - 2040 | 2750 | .99873 | |
| | + 2700 | .99906 | 0 |
| | 2650 | .97445 | |
| 1900 - 2050 | 2750 | .97461 | |
| | + 2700 | .99947 | 0 |
| | 2650 | .99644 | |

[a] a '+' indicates the optimal estimate.

[b] 100*(Estimated $Q^*$ - True $Q^*$)/True $Q^*$

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Exhibit 12. Estimates of the Ultimate Recoverable Resource by the Geologic Analogy Method

| Year | GEUR ($10^9$ bbls) | Error[a] (%) | GEFR (dimensionless) | FR (dimensionless) | GEYE (bbls/ft) | YE (bbls/ft) |
|---|---|---|---|---|---|---|
| 1900 | 16 | -99 | .20 | .20 | 66 | 66 |
| 1940 | 598 | -78 | .23 | .21 | 175 | 196 |
| 1950 | 1177 | -56 | .25 | .22 | 192 | 187 |
| 1960 | 1952 | -28 | .29 | .24 | 181 | 140 |
| 1970 | 2668 | - 1 | .40 | .27 | 124 | 81 |
| 1980 | 3280 | 21 | .60 | .35 | 66 | 48 |
| 1990 | 3361 | 24 | .67 | .44 | 40 | 43 |
| 2000 | 3521 | 30 | .70 | .51 | 32 | 27 |
| 2010 | 3552 | 32 | .73 | .55 | 22 | 25 |
| 2020 | 3545 | 31 | .72 | .57 | 21 | 20 |
| 2030 | 3217 | 19 | .66 | .58 | 17 | 19 |
| 2040 | 3061 | 13 | .62 | .58 | 19 | 23 |
| 2050 | 3008 | 11 | .60 | .59 | 23 | 26 |
| 2060 | 3012 | 12 | .60 | .59 | 26 | 28 |
| 2070 | 3019 | 12 | .59 | .59 | 28 | 29 |
| 2080 | 3024 | 12 | .59 | .59 | 29 | 30 |
| 2090 | 3026 | 12 | .59 | .59 | 30 | 30 |
| 2100 | 3028 | 12 | .59 | .59 | 30 | 30 |

GEUR = Estimated Ultimate Recoverable Resource
GEFR = Expected Fraction Recoverable
FR = Fraction Recoverable
GEYE = Expected Yield to Exploration
YE = Yield to Exploration

[a] Error computed by comparison with ultimate quantity recovered.

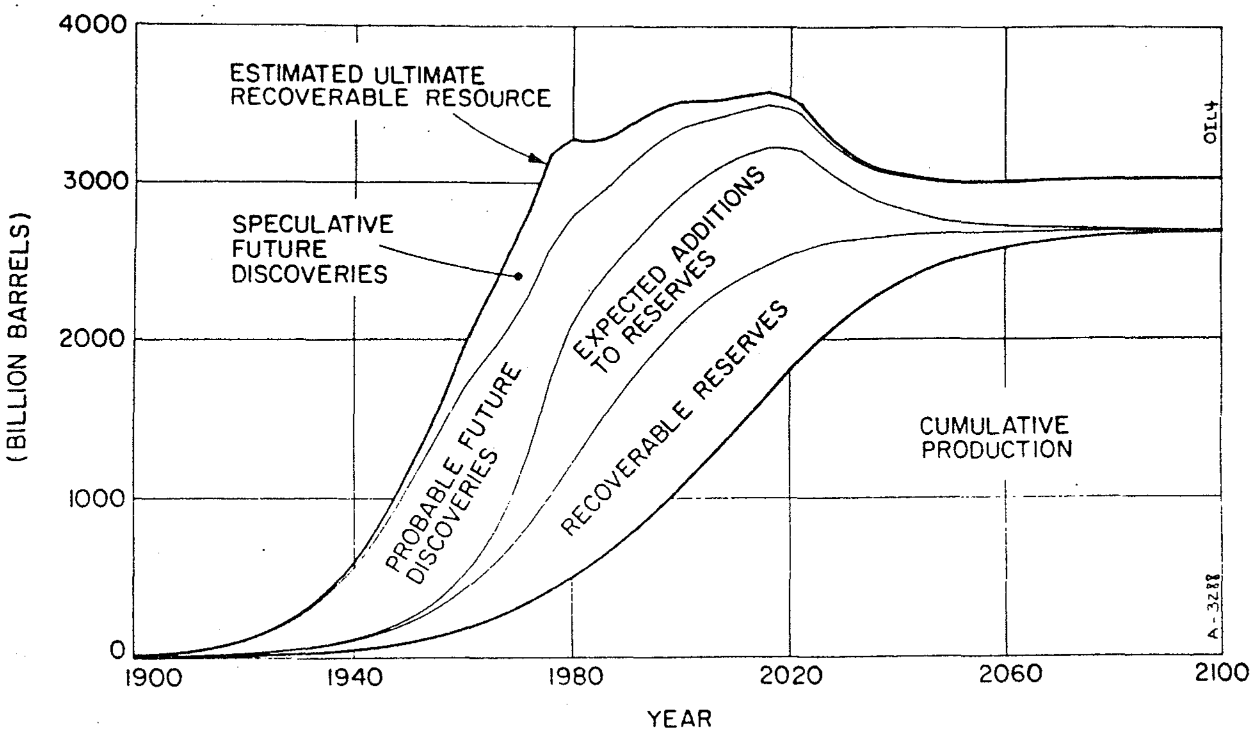


Exhibit 13: Geologic analogy estimates of the ultimate recoverable resource.

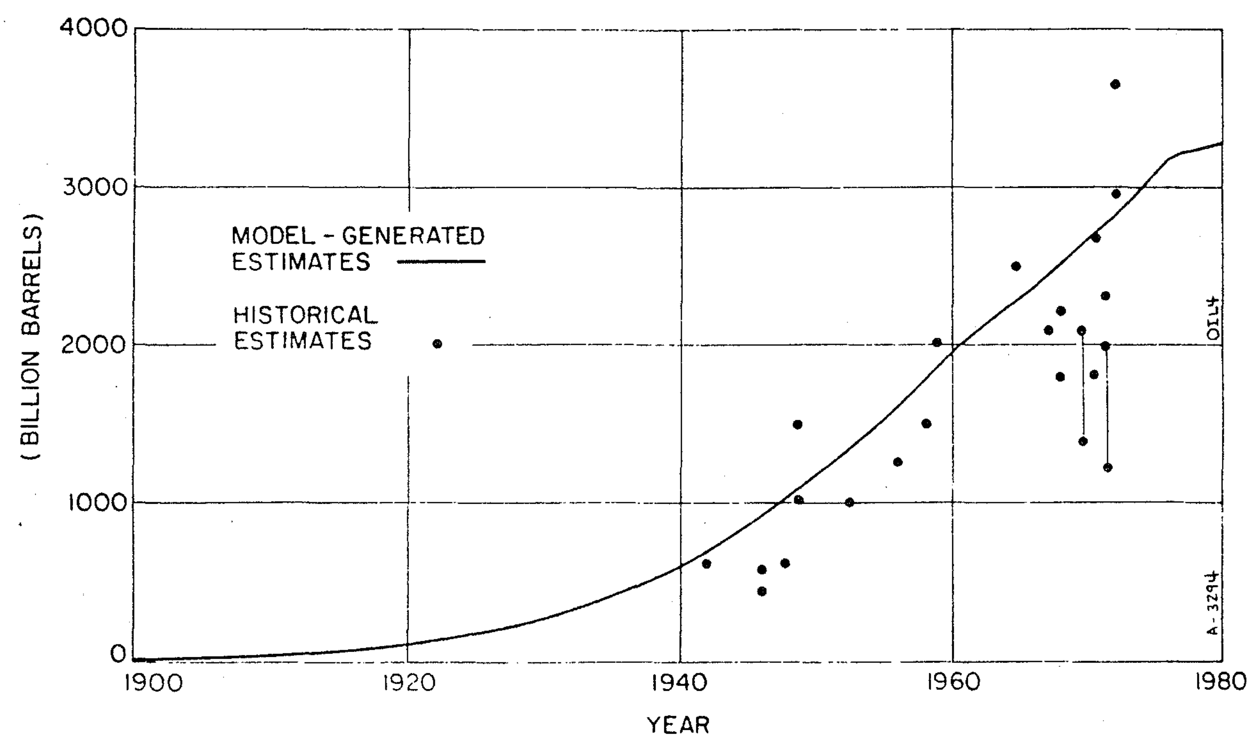


Exhibit 14: Comparison of model-generated estimates and historically observed estimates.

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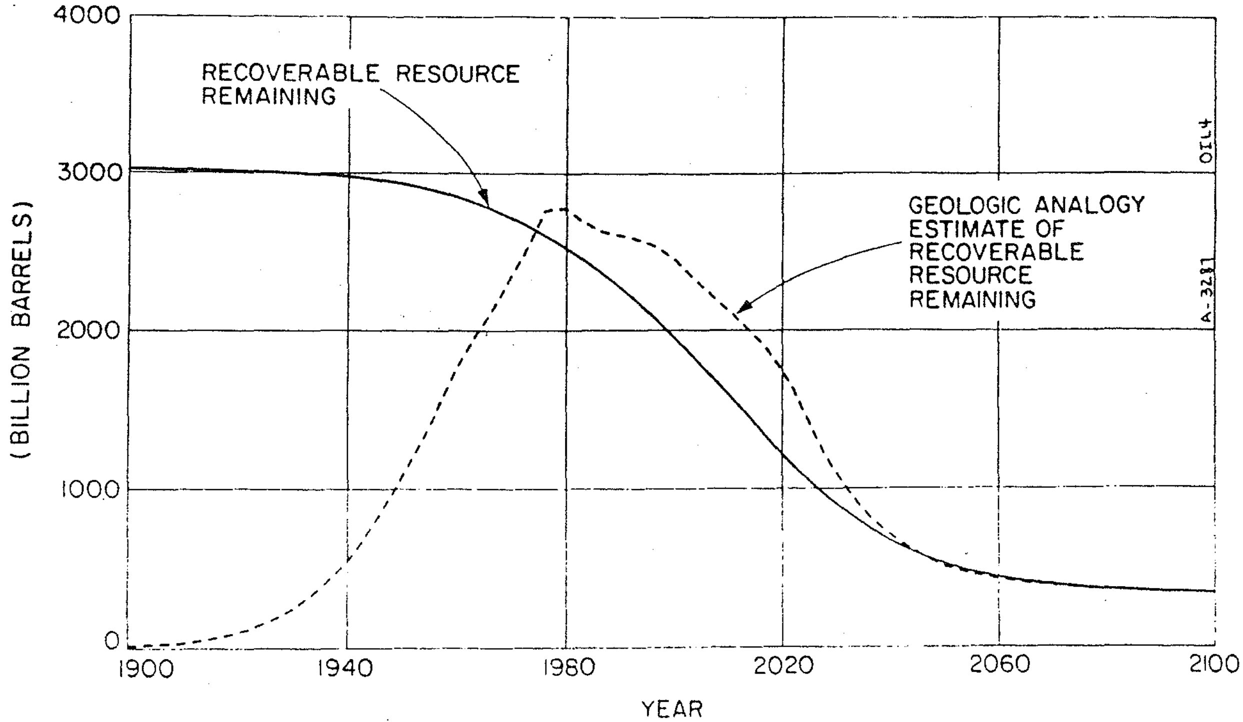


Exhibit 15: Geologic analogy estimate of the recoverable resource remaining, compared to correct value.

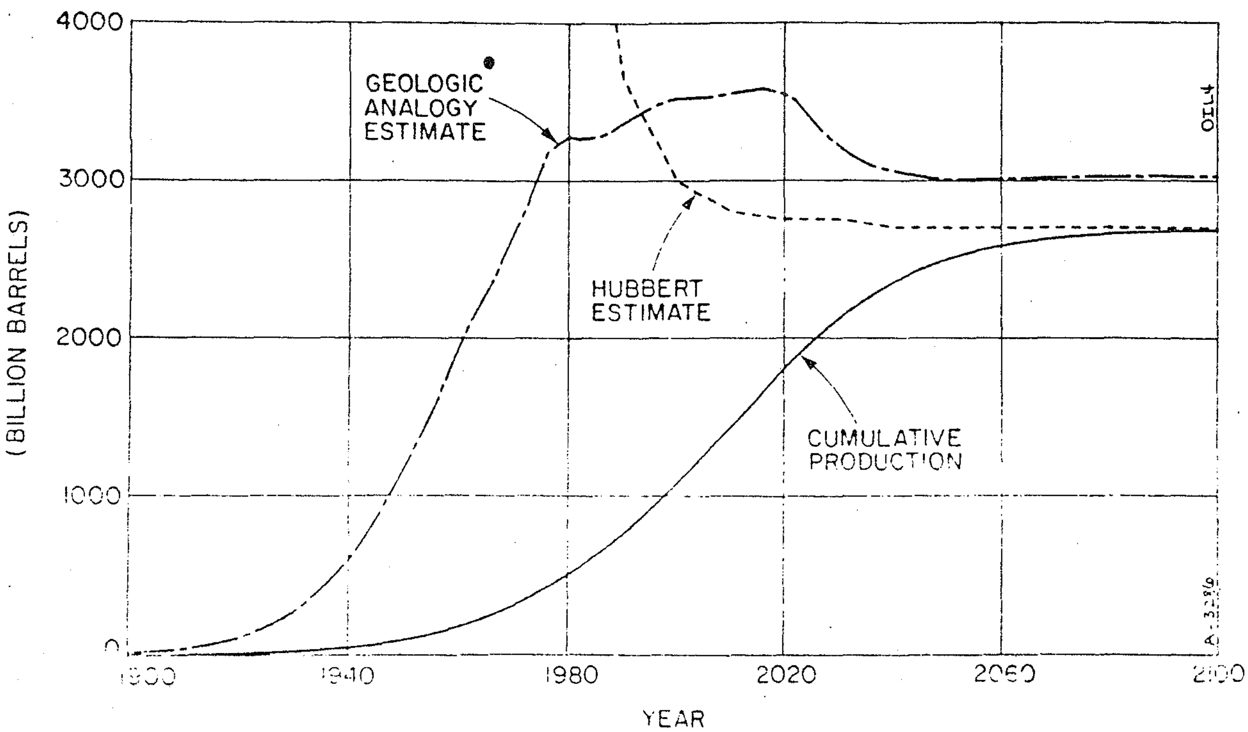


Exhibit 16: Comparison of the Hubbert and geologic analogy estimates and true cumulative production.