Faculty Working Papers

FORECASTING PETROLEUM DISCOVERY, DEVELOPMENT AND PRODUCTION

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College of Commerce and Business Administration
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Summary:

Work is under way on a forecasting method that incorporates explicit representations of the steps in the oil supply process: exploration, reservoir development, and production. The discovery history of a region and other geological data are inputs to a statistical analysis of the exploratory process. The resulting estimate of the size distribution of new reservoirs is combined with an evaluation of reservoir economics -- taking account of engineering cost, oil price, and taxes. The model produces a forecast of additions to the productive reserve base and oil supply. Progress to date is demonstrated in an application to the North Sea.

The authors are indebted to Arlie G. Sterling for his excellent research assistance in many parts of this work, and to M. A. Adelman and H. D. Jacoby for helpful comments.

The research was supported by the Norwegian Research Council for Science and the Humanities (NAVF) and by the U.S. National Science Foundation (NSF) under grant No. SIA75-00739 as part of a larger M.I.T. project to develop analytical models of the world oil market. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of NAVF or NSF.

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by

P. L. Eckbo and J. L. Smith

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FORECASTING PETROLEUM DISCOVERY, DEVELOPMENT AND PRODUCTION

Various methods have been applied by economists to forecast the future supply of petroleum. Current researchers in this area benefit from a substantial literature that has developed over the past fifteen years, since the publication of Fisher's pioneering work [9]. The range of techniques developed in this literature is quite broad. There are conventional econometric studies of petroleum supply, which essentially extrapolate historical trends into the future, conditional on certain market parameters [7, 8, 9, 12, 13]. There is a separate collection of studies whose main focus is on engineering-based cost estimates pertaining to the various activities and investments involved in the supply process, the objective generally being to provide a minimum cost estimate at which additional quantities of reserves and production could be made available [14, 15]. Also, there is a rather large set of supply forecasts, most commonly made by the oil companies themselves, which incorporate a relatively detailed knowledge of specific producing fields and prospective new areas.

Each method has particular advantages and all have contributed to our knowledge of future oil supplies. Nevertheless, many of the studies have in common two limitations which seriously impinge on their forecasting performance and usefulness for policy discussions of the current energy situation. Perhaps the most basic limitation is that few of the forecasting methods are equipped to deal with the phenomenon of resource depletion in a way that consistently reflects underlying geological realities. This aspect of the forecasting problem is of undoubted

significance; indeed it is what gives the task of oil supply forecasting its main distinction, and we are rather uncomfortable with any study which deals with it only superficially or in an ad hoc manner.

A second limitation involves the way in which economic incentives for oil production are represented in the analyses. All econometric studies naturally consider the well-head price of oil to be a key determinant of supply. But what really matters is the net price received by producers after allowing for tax payments which have typically varied significantly over the period for which the econometric models have been estimated. Consequently, the effective level of economic incentives for oil production has varied in a way that is difficult to reconstruct on the basis of available economic time-series data. In any event, if the influence of tax provisions and the cost structure is not represented explicitly in the model, it becomes difficult to apply the model, as the policy-maker would like, to trace out the implications of future changes in these factors.

The studies based on engineering cost estimates have generally included an explicit representation of the economic incentive to produce oil, perhaps more so than the econometric approach. But the preoccupation of such studies with the so-called average or "representative" oil field makes it difficult for the economist to then infer the required level of incentives to elicit production from the marginal sources, which are of most interest [15]. Presumably, the oil companies have implicit in their forecasts an estimate of the contribution from marginal fields, but company forecasts are too often reported without reference to the underlying economic assumptions or scenarios to be of much use to the

policy-maker who would use the estimates to evaluate the effects of alternative policy actions.

The Disaggregated Process Model

In response to these two limitations of existing forecasting techniques, work was begun by a group (then working at the MIT Energy Laboratory) to develop an alternative methodology better equipped to deal with the issues of resource depletion and economic incentives. Some of the fruits of this research are embodied in what is called a "disaggregated process model" of petroleum supply, which has been described in a recent paper by Eckbo, Jacoby, and Smith [5]. The basic elements of this model will be reviewed below.

The term "disaggregated" means simply that a forecast of aggregate oil supply from some producing area is built up from individual forecasts pertaining to specific reservoirs within that area. The disaggregation achieves a "plant-level" unit of observation, and is an important element of the analysis due to the heterogeneous nature of petroleum deposits. Not only are the scale economies of producing from reservoirs of differing size significant, but also the effect of most local and national tax regimes depends on the characteristics of the individual reservoirs which contribute to supply. Moreover, as reserves are exhausted, the composition of the stock of reservoirs changes, with the result that tax incidence and production costs may change as depletion proceeds. Without some means to deal with the composition of producing reservoirs it is difficult to identify and interpret the influence of these factors.

We call the forecasting method a "process model" because separate components of the supply mechanism are distinguished (e.g., exploration, development, and production) and modelled after the actual physical activities involved. The general structure of the model is illustrated in Figure 1.

The sequence of activities begins in the upper left corner of the diagram (Box 1), where the level of exploratory drilling is determined. Drilling is undertaken with the expectation of discovering some volume of new reserves, the quantity and composition being dependent on the geological potential of the area in question (Box 2). The supply potential of newly discovered reservoirs depends on the prevailing level of economic incentives (prices, costs, and taxes), and the characteristics of the reservoirs themselves (Box 3). Under prevailing economic conditions some reservoirs will be economic to develop and enter the production stage (Box 4). Subeconomic reservoirs revert to an inventory of known reserves that may enter into production at a later time if economic conditions improve (Box 5). Finally, production from new reservoirs is complemented by continuing production from reservoirs that are known to exist at the time the forecast is made (Box 6). Of course, there are interactions among the separate stages in this process. For example, the level of exploratory effort that initiates the sequence is generally sensitive to the economic characteristics of the potential discoveries that may result.

The treatment of resource depletion and economic incentives enters this framework at several points, as discussed below.

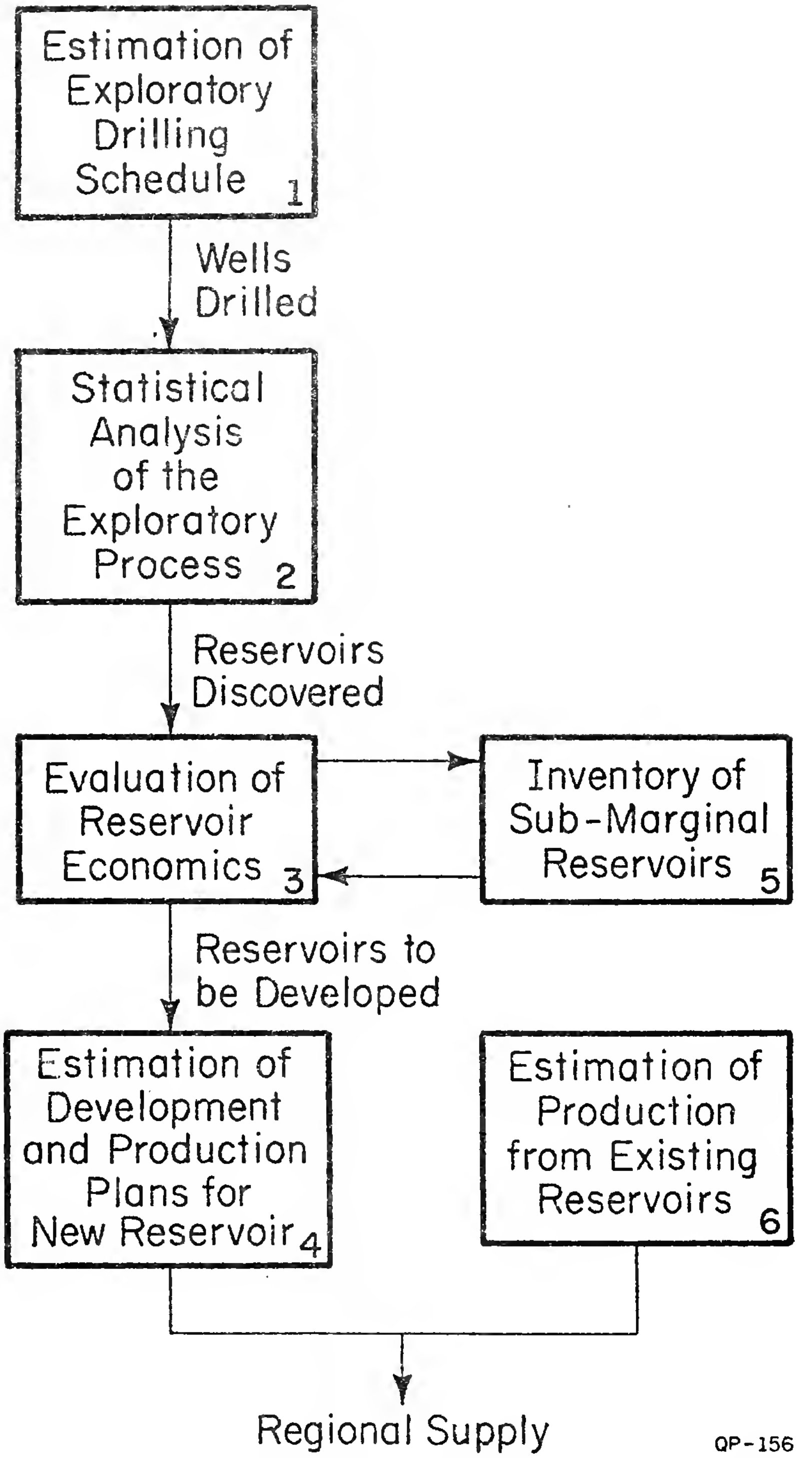

Figure 1. Schematic View of the Process of Exploration and Production in a Region

Resource Depletion

Resource depletion operates at two levels in the model. First, the existing stock of reservoirs is depleted as production from known reservoirs proceeds. The reserves of any reservoir may ultimately be exhausted, and in this manner the reservoir is eventually withdrawn from production. Secondly, the store of potential reservoirs from which the reserve base is renewed via exploration is depleted as the discovery process continues. The phenomenon of reservoir discovery is portrayed in the model as a stochastic process which proceeds in accordance with specified physical laws consistent with underlying geological facts. This process may be thought of as a "stochastic production function" which governs the relationship between exploratory effort and discovery success. The relationship is stochastic in that it allows that a given amount of effort may or may not result in success, or perhaps in successes of varying magnitude.

Two statistical postulates about the exploratory process constitute the stochastic discovery model:

(1) The discovery of reservoirs in the area of a petroleum play* can be modelled statistically as sampling without replacement. This means simply that once a reservoir has been indentified, it is then removed from the remaining population of potential new discoveries.

(2) The discovery of a particular reservoir from among the remaining population is random, with probability of discovery being proportional

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*A "play" is defined as a group of similar geological configurations generated by a series of common geological events, forming a population of prospects that is conceived or proven to contain hydrocarbons.

to reservoir size. The concept of an underlying reservoir size distribution is implicit here. The postulate has the effect of a discovery law which generates the "largest-first" phenomenon so familiar to explorationists.

These two postulates and their usefulness to us have grown out of the research of Kaufman and his associates [1, 10, 11]. We follow their work closely in the application discussed below.

The postulates enable one to formulate the probability of observing any particular sequence of discoveries, conditional on knowledge of the parameters of the underlying size distribution of reservoirs (which Kaufman, et. al. take to be lognormal). Conversely, conditional on an observed discovery sequence, it is possible to estimate the parameters of the underlying size distribution by the method of maximum likelihood. Moreover, having obtained these estimates, it is possible to derive predictive probability distributions which characterize the size of each succeeding discovery in the play. Consequently, it is possible to generate a sequence of expected discovery sizes, and their variances, upon which a forecast of future production can be based. The details of this procedure have been described elsewhere [1, 5].

In a previous paper [5], we have used this predictive discovery sequence estimated for the North Sea petroleum province to construct estimates of future supplies. Figure 2, below, illustrates schematically the way in which the predictive distributions evolve as exploration proceeds. Figure 3 shows the sequence of expected discovery sizes computed from these distributions, as compared to the historical sequence of 60 discoveries upon which the estimation was based. The phenomenon of

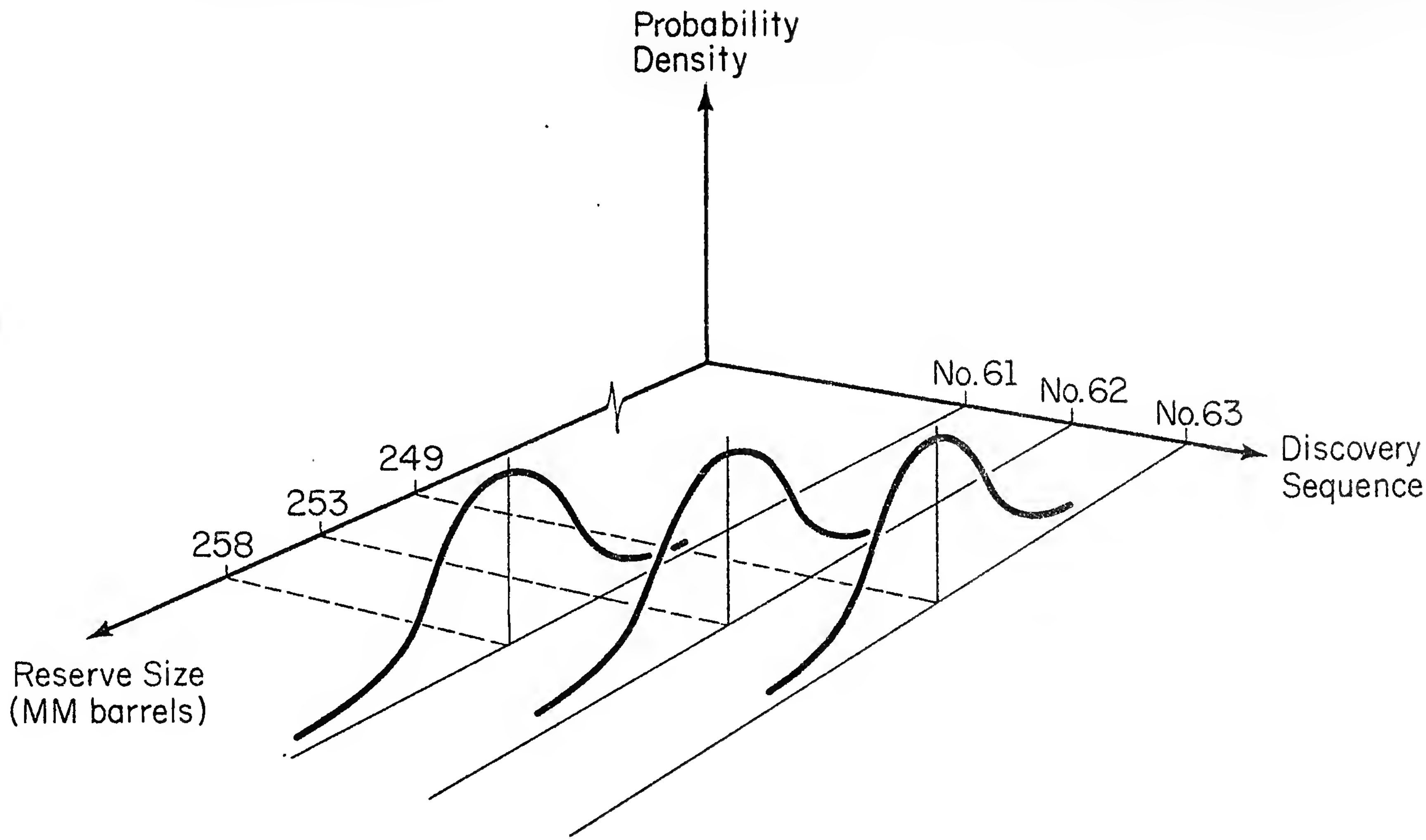

Figure 2. The Sequence of Predictive Discovery Distributions

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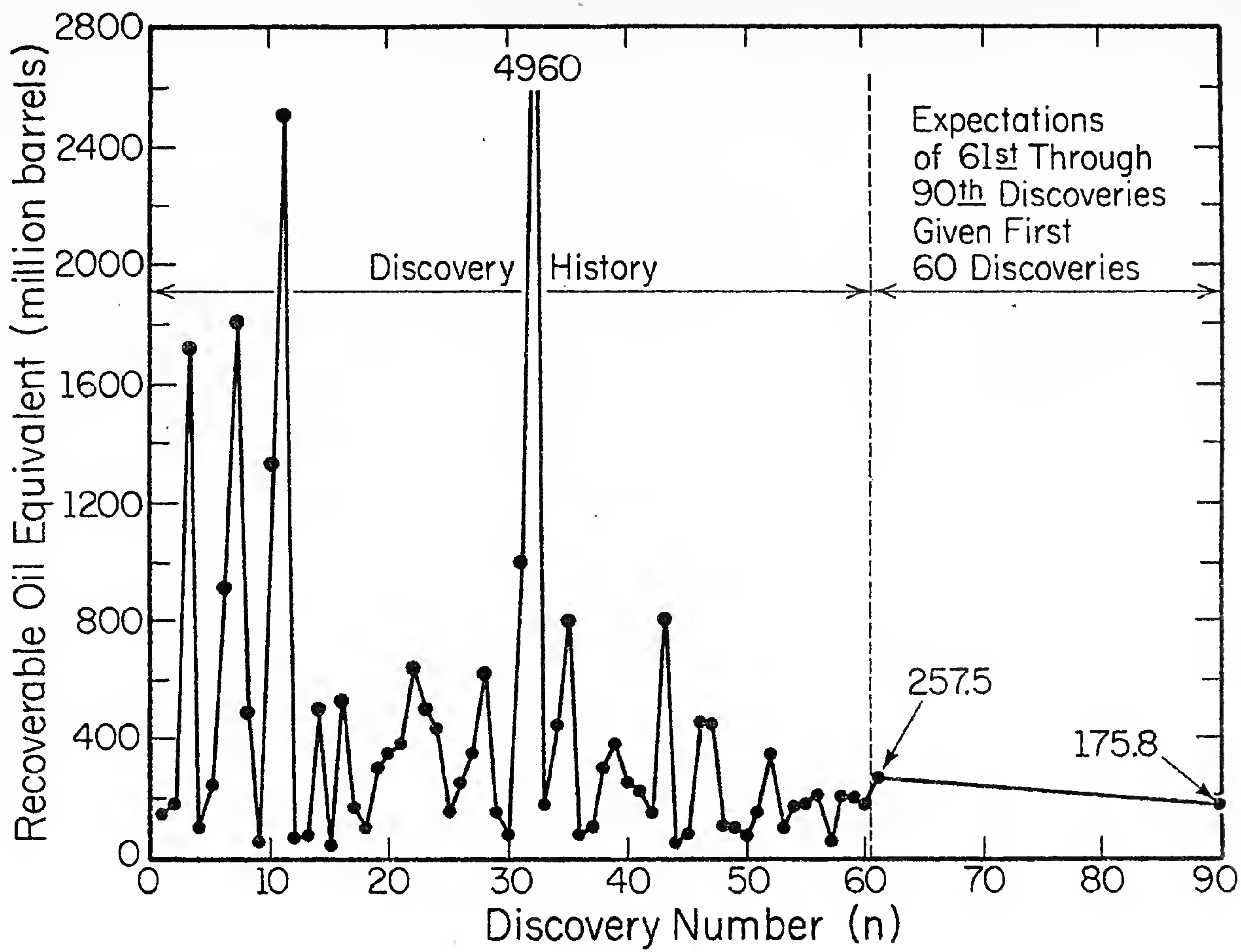

Figure 3. NORTH SEA-Discovery History and Forecast

QP-159

discovery decline is clearly evident, reflecting the influence of the two postulates.

Economic Incentives

The decision to produce from an existing reservoir is influenced by the sequence of discounted cash flows that would result, net of all operating and investment costs, and tax and royalty payments. We have constructed a model of reservoir development which computes the net present value of developing a reservoir of specified size. Included in this model is a fairly detailed representation of development and operating cost functions, estimated on the basis of North Sea reservoir-specific data [5]. In addition, the tax regimes of the British and Norwegian sectors are included in great detail, encompassing payments for accrued royalties, corporate tax, petroleum revenue tax, special tax, withholding tax, capital tax; and special deduction and depreciation rules, oil production allowances, and minimum liability provisions.*

The reservoir model is used to identify the minimum reservoir size that assures viable economic development, and thus to determine the economic margin which governs the entry of reservoirs into the production stage. Of course this margin is related to the price and tax

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*The tax systems of the Norwegian and British sectors of the North Sea are differentiated by several features which affect specific reservoirs in different ways. The net influence of the two tax regimes on the economic incentive for production, however, is thought to be quite similar [2, 5]. The forecasts presented below have been generated by applying the Norwegian tax regime to all reservoirs in the North Sea.

parameters assumed. The behavior of marginal reservoir size as it is influenced by the well-head price of oil is illustrated in Figure 4.*

North Sea Forecast

The general method of application to the North Sea petroleum province can now be outlined. First, a level of exploratory drilling is hypothesized. In the earlier paper this level was determined exogenously in accordance with the announced drilling plans of the operators in the area (44 exploratory wells per year), and extrapolated into the future. One justification for doing this is the apparent rigidity of the announced drilling program; the rigidity being enforced partly by the long lead times and budgeting cycles involved in planning an exploration campaign, and partly by the constraint on more rapid activity imposed implicitly by the pace of government licensing schedules. Using the predictive discovery sequence of Figure 3, in conjunction with an allowance for dry hole risk,** the expected number and respective sizes of ensuing discoveries is predicted for each year in the forecast period.

The economic viability and ultimate disposition of each expected discovery is determined using the reservoir model. If viable, the reservoir enters into the development and production stage, otherwise it

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*The exact form of this relationship differs from that reported in Eckbo, Jacoby, and Smith [5] due to the reestimation of the underlying cost function based on a new set of data that has recently become available. These estimates are discussed in more detail in a memorandum available from the authors.

**Dry hold risk is set at 75%, approximately the historical figure for North Sea exploration.

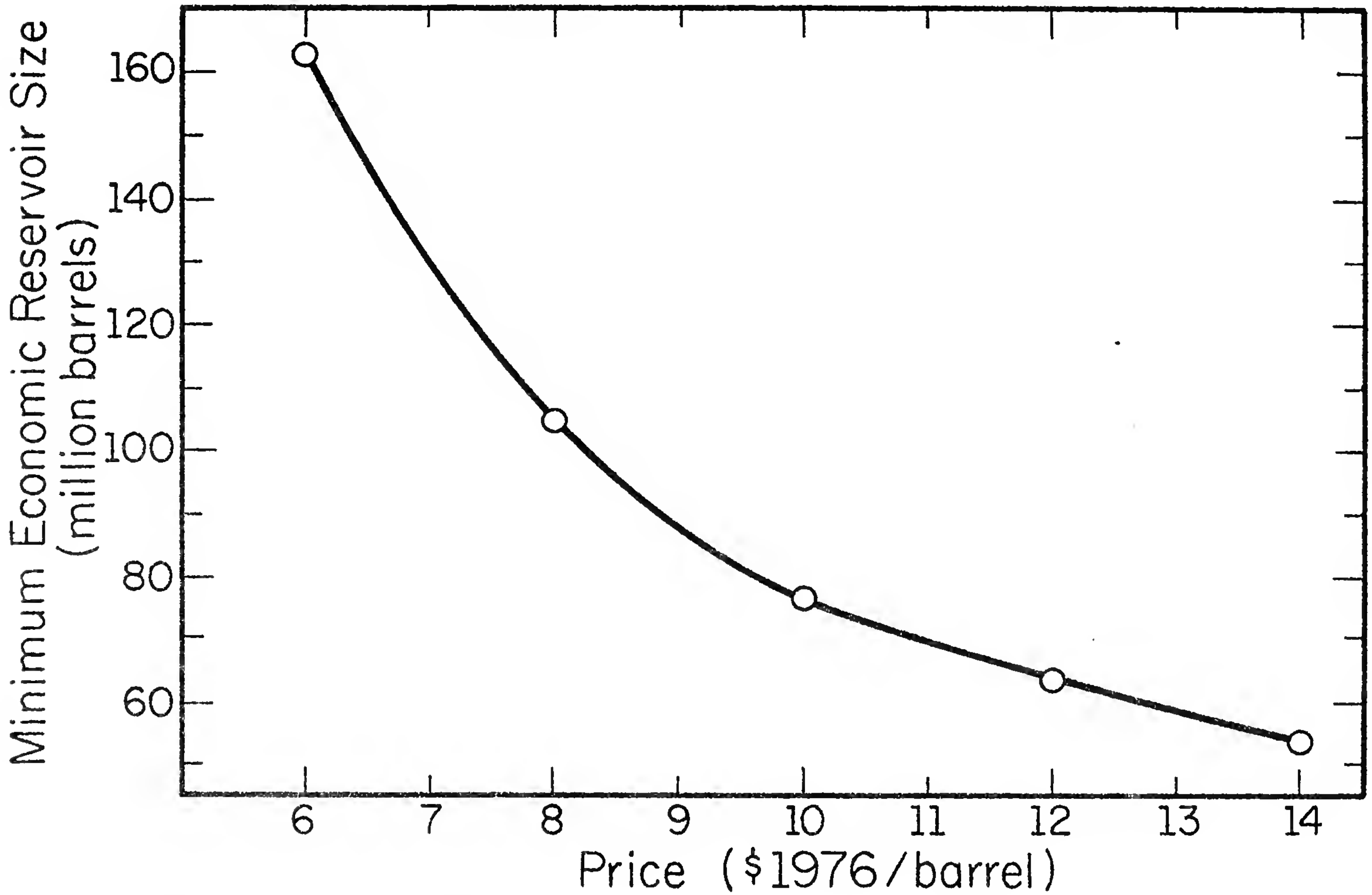

Figure 4. Minimum Economic Reservoir Size as a Function of Price

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is relegated to an inventory of submarginal reservoirs to await more favorable conditions. Annual production from all new reservoirs is then added to a forecast of production from existing fields to arrive at an overall forecast of production from the North Sea.* The forecast is conditional on the hypothesized level of exploration effort, and price and tax parameters; so one can observe the impact on future oil supplies as these factors are manipulated. The actual forecast of North Sea supplies generated in this fashion will be presented below.

Endogenous Exploration

A major limitation of the previous application of the model is that the pace of exploration is not permitted to respond to economic incentives, although such an interaction is clearly desirable and possible within the framework outlined in Figure 1. In this section we report on some new research which bridges this gap.

The forecast already described is conditioned by an exogenous specification regarding the rate of exploratory drilling. However, it is possible for the forecaster to conduct a search over the range of feasible drilling rates and identify the specific rate which leads to a maximum net present value of the ultimate production that is expected to result. Presumably, this is the criterion by which industry formulates its

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*Production from existing fields is forecast on the basis of announced plans, and is insensitive to changes in the price level. Although the recovery factor for these reservoirs might be expected to respond to changes in price, at the present cost level methods of pressure maintenance are nearly universal, while the next stage in methods for enhanced recovery is significantly more expensive, and unlikely to see widespread use at prices in the range $9-$18 ($1976).

drilling plans, and it is the link we use to relate the pace of exploration to prevailing economic incentives. By presenting the one forecast which embodies the drilling program associated with maximum net present value, the rate of drilling is made endogenous to the forecasting procedure.*

A Myopic Drilling Model

The search for a value-maximizing drilling program may be carried out subject to a number of behavioral constraints which reflect the way in which the industry makes drilling decisions. A strong assumption would be that industry makes "near-sighted" drilling decisions on an annual basis; that is, drilling would be carried out each year at the level which maximizes the expected net present value of that year's exploration campaign considered in isolation. In this formulation the companies would be assumed to look ahead and foresee the economic rewards ultimately accruing to discoveries resulting from present exploration; but they would not take into account the diminished potential for future discoveries which this entails. Of course, the companies might have reason to regret this type of myopic decision-making if, for example, prices subsequently rose when no more oil was available for market.

In spite of this limitation of the myopic formulation, we have carried out the analysis under this assumption; mainly to provide a benchmark, but also because the necessary computations and programming

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*In practice the examination of alternative drilling rates and selection of the optimum is done internally by computer, so the search procedure is not cumbersome.

difficulties are greatly simplified in this case. The resulting forecast will admittedly be unsatisfactory if the ignored element of "user cost" (foregone profits due to premature development) turns out to play a significant role in the North Sea. In defense of our simplification however, it should be said that there is fairly strong evidence, to be discussed later, which suggests that user cost does not dominate in North Sea drilling decisions, and hence that the myopic formulation can be expected to give reasonable results.

One determinant of the rate of drilling in the North Sea is the availability of rigs. The short run availability of rigs is determined by the cost at which existing rigs can be bid away from other parts of the world and brought into service in the North Sea. The long run availability of rigs is determined by the production costs at which existing capacity can be expanded over the long term. The short run constraint on rig capacity is represented in our model by a cost-of-adjustment factor which imposes additional costs whenever annual drilling activity in the North Sea is expanded beyond its previous maximum. This cost function takes the simple constant elasticity form, such that short-term drilling costs are increased by 1/2% above the long run level during any year when drilling activity is extended by 1% above the maximum historical rate; thus, the short-run elasticity of drilling costs beyond the point of full capacity is assumed to be 0.5.*

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*This elasticity is a parameter that can be manipulated by the researcher, but we do not experiment with it further in the present paper.

Four forecasts have been constructed, corresponding to alternative assumptions regarding future prices and taxes. A "baseline" scenario is first considered, in which the well-head price of oil remains constant at $12 per barrel ($1976) and the current tax regime remains in effect. This is compared to the forecast that obtains at the $12 price if the tax regime were abolished altogether (the "no-tax" scenario). The baseline forecast is also compared to the case where the real price of oil is assumed to rise above $12 at the constant rate of 2% per year (the "rising price" scenario). Finally, we present a forecast predicated on the baseline economic conditions, but with a government constraint on the pace of development which limits exploratory drilling to 44 wells per year (the "constrained" scenario treated in the previous paper [5]).

The respective forecasts of annual drilling effort and exploratory success are presented in Table 1, below. Three conclusions of general interest emerge from the table. First, the "constrained" drilling program of 44 wells per year, which was hypothesized in the previous paper on the basis of the industry's announced drilling plans, coincides with the value-maximizing program obtained under the assumptions of the myopic model (cf., columns 1 and 2). Consequently, the forecast obtained earlier is consistent with the present formulation of the drilling problem. Second, the current tax regime appears to impose a significant distortion of North Sea development (cf., columns 2 and 3). Industry's activity is affected in two ways: The pace of development is slowed considerably due to taxes; and ultimate resource recovery from the area is diminished (the cumulative number of wells declines by 6.8%, while cumulative additions to reserves declines by 4.2%). The implication here is that in spite of

TABLE 1

Drilling and Discovery Forecasts*

Year	Wells Drilled				Number of Discoveries				Additions to Reserves**			
	1	2	3	4	1	2	3	4	1	2	3	4
76	44	44	76	44	11	11	19	11	1.95	1.95	3.21	1.95
77	44	44	84	44	11	11	21	11	1.70	1.70	2.77	1.70
78	44	44	84	44	11	11	21	11	1.48	1.48	2.14	1.48
79	44	44	52	44	11	11	13	11	1.30	1.30	1.07	1.30
80	44	44	0	44	11	11	0	11	1.13	1.13	0.00	1.13
81	44	44	0	44	11	11	0	11	0.99	0.99	0.00	0.99
82	12	12	0	44	3	3	0	11	0.25	0.25	0.00	0.86
83	0	0	0	44	0	0	0	11	0.00	0.00	0.00	0.75
84	0	0	0	44	0	0	0	11	0.00	0.00	0.00	0.66
85	0	0	0	12	0	0	0	3	0.00	0.00	0.00	0.16
Total	276	276	296	408	69	69	74	102	8.80	8.80	9.19	10.98

*1 = "constrained" scenario
2 = "baseline" scenairo
3 = "no-tax" scenario
4 = "rising-price" scenario

**billion barrels.

the incentives which encourage development of marginal fields (e.g., sliding scale royalties), the current tax system is far from a position of neutrality.* Finally, we see from the table that the supply of North Sea oil is highly sensitive to fluctuations in the well-head price (cf., columns 2 and 4). A sustained 2% increase in price results in a 48% increase in total drilling activity over the 10 year period and a 25% increase in expected additions to the reserve base.**

The effect of price and tax changes on ultimate production takes longer to become visible because of the lags which intervene between the discovery, development, and production stages. The effect of these lags is seen in Table 2, which translates the reserve additions of Table 1 into annual production flows. One pattern is common to all four scenarios: after the initial four-year lead time, production gradually rises to a peak and thereafter declines continuously as the producing reservoirs are depleted, with no additional discoveries to take up the slack. The three specific comments regarding Table 1 also apply to Table 2. The "constrained" production forecast coincides with the results of the "base-line" value-maximizing drilling program. Production flows are considerably slowed by the influence of the tax regime, and ultimate recovery is diminished. The rising well-head price of oil effects a sustained increase in the level of production.

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*A more detailed discussion of the distortions created by the North Sea tax regimes may be found in a paper by Eckbo [2].

**The difference between the price responsiveness of drilling versus discovery is due to the fact that the finding rate (barrels/well) decreases as the resource potential is exhausted.

TABLE 2

Production Forecast - New Discoveries

Year	Production - million barrels/dry			
	constrained	baseline	no tax	rising price
76	0.00	0.00	0.00	0.00
77	0.00	0.00	0.00	0.00
78	0.00	0.00	0.00	0.00
79	0.00	0.00	0.00	0.00
80	0.16	0.16	0.26	0.16
81	0.57	0.57	0.93	0.57
82	1.03	1.03	1.66	1.03
83	1.43	1.43	2.19	1.43
84	1.78	1.78	2.46	1.78
85	2.09	2.09	2.52	2.09
86	2.31	2.31	2.52	2.36
87	2.40	2.40	2.52	2.59
88	2.30	2.30	2.34	2.69
89	2.10	2.10	2.01	2.64
90	1.88	1.88	1.66	2.48
91	1.62	1.62	1.32	2.26
92	1.35	1.35	1.04	2.01
93	1.11	1.11	0.87	1.80
94	0.78	0.78	0.52	1.46
95	0.53	0.53	0.26	1.16

One further point emerges from the forecasts, that is the flexibility of the current forecasting approach and its ability to monitor the influence of well-defined policy actions directed at the petroleum sector.

A Two-Period Drilling Model

As noted above, a significant limitation of the myopic approach is that no account is taken of the industry's incentive to schedule development to achieve an optimal intertemporal management of their primary capital asset, oil reserves. Thus far, we have imagined reservoir development to proceed today as if there were no opportunity to postpone it for tomorrow. Certainly, if costs and/or prices were expected to deviate significantly in the future, this aspect of the problem would have to be considered.

To gain some insight in this matter, the myopic drilling model has been extended to incorporate the influence of future profitability on current development decisions. This extension is achieved by the use of a two-period optimizing criterion, wherein the current and succeeding years' drilling plans are determined simultaneously to maximize the combined net present value of both years' operations. Consequently, if a sufficient price jump or cost reduction were anticipated in the ensuing year, it would pay to postpone resource development.

A set of North Sea forecasts, similar to those of Table 1, has been constructed using the two-period optimizing criterion. Each forecast consists of a sequence of overlapping two-period plans. A plan is initially made for the first two years' development. The first year's

plan is immediately carried out; the plan for the following year may or may not be carried out, because when the time arrives a new two-year plan will be formulated and displace the previous one. By examining the sequential behavior that emerges from this model, it is possible to learn what level of price and cost fluctuations would be required to induce deviations from myopic plans as economic changes appear on the horizon.

Before discussing the results of this exercise, it is necessary to describe one added simplification imposed on the two-period drilling model. To simplify the computation, a simplified characterization of the North Sea tax regime has been used, in which the only component is a 10% production royalty. This model of government receipts is not as realistic as it might be; however the abstraction is not expected to significantly influence the basic pattern of the industry's inter-temporal response to changing prices and development costs.*

Three forecasts have been generated using the two-period drilling model, corresponding to alternative scenarios regarding prices and costs. First a baseline scenario is considered, in which the real well-head price of oil remains constant at $12 per barrel ($1976), and development and operating costs remain constant at their 1976 levels. Then we examine the impact of a sudden jump in price from $12 to $15 occurring in the third year of the forecast period. Finally, we examine the impact

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*It is possible to carry out the analysis under a more complete description of the North Sea tax regime, but due to time limitations this has not been completed.

of a similar 20% decrease in costs, perhaps caused by the eventual introduction of sub-sea completion systems. The resulting forecasts of drilling activity are presented in Table 3.

Because of the different representation of the tax regime we cannot compare this set of forecasts directly with those presented earlier. However one can inspect the results to learn to what extent myopic plans are revised in response to foreseen changes in the economic parameters. For example, consider the case of a price-jump. As of 1976 operators plan to drill 60 exploratory wells both in 1976 and 1977, in accordance with an expected price of $12 in both years. In 1977, however, operators see that the price will subsequently jump to $15, and they reconsider the extent of current drilling in light of this factor. Conceivably, they might slow the pace in 1977 to await the more favorable circumstances in 1978. In fact, they do not postpone development, but complete the 60 wells as planned (indicated by the arrow), and contemplate an additional 64 wells in 1978. The hypothesized price jump of 25% is apparently not a sufficient inducement to cause a revision in their short run plans, because the additional revenues that would accrue in the later year (discounted at 12%) would be insufficient to compensate them for the loss of current revenues.

A similar conclusion emerges from the cost-reduction analysis. Foreseeing a 20% cost reduction is not a sufficient incentive to postpone development; this is evident from the comparison of 1977 plans with actual drilling.

There are two factors in the present analysis which contribute to this effect. First, anticipated profit margins in the North Sea are

TABLE 3

Forecast Drilling Activity - Two Period Model

Year	Baseline		Price-Jump		Cost-Reduction	
	current drilling	ensuing plan	current drilling	ensuing plan	current drilling	ensuing plan
76	60	60	60	60	60	60
77	60 ←	60	60 ←	64	60 ←	60
78	60	24	60	60	60	60
79	20	0	60	52	60	4
80	0	0	48	4	0	0
81	0	0	4	4	0	0
82	0	0	0	0	0	0

relatively large, so that any delay in revenues constitutes a significant deduction from net present value. In addition, the influence of the cost of adjustment function inhibits large build-ups or sudden transfers of drilling capacity from one period to another. A third factor, which is left out of the analysis, would be expected to contribute further to the reluctance to concentrate development in future periods; that is the investment depreciation allowances and special capital write-offs that are permitted under the North Sea tax regimes. These provisions make it desirable to schedule development in the present, if for no other reason, to provide deductions from income to be earned in the future. Consequently, any change in economic incentives which promises to enhance net revenues in the future simultaneously gives rise to an additional incentive to accumulate a depreciable capital stock in the present.

Our interpretation of the results of the two-period analysis is that current costs, prices, and tax provisions in the North Sea combine to minimize the significance of user cost. Rather dramatic fluctuations in future prices and costs would seem to be required before the industry could gain much from a truly dynamic, long-range formulation of the drilling problem. Consequently, the forecasts predicated on myopic behavior may not be such bad approximations to the true state of affairs. But, of course, there is no assurance that this conclusion would apply to other

areas of the world, or under different economic circumstances even in the North Sea.*

Concluding Remarks

The many factors which influence the supply of petroleum reflect the complexity of the underlying activities which lead to ultimate production of the resource. We hope the disaggregated process approach provides a general conceptual framework which identifies these factors, but we cannot pretend to have dealt with all of the important issues in the work completed to date. In the previous paper [5] analysis was focused on the potential to augment the current resource base through exploration, and the impact of extending the economic margin to encompass the many small reservoirs which are generated by the discovery process but held in abeyance until favorable economic incentives warrant their development. In the present paper we have also considered the tempo (measured in terms of wells drilled and annual reserve additions) at which this process is likely to proceed; assuming throughout that the decisions which govern the speed of exploitation are made in accordance with the well-defined economic principles of profit and loss.

At least two apsects of the supply process deserve more attention than they are given here. The first concerns the speed with which oil

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*The significance of user cost in the North Sea basin has been explored further by Eckbo and Hnyilicza [4], who formulate the choice of a drilling program as an optimal control problem. That approach is a direct generalization of the two-period model discussed above. While their results are generally consistent with the conclusions of the current paper, it is difficult to compare the two sets of results in more detail due to the imposition of several additional constraints that were required to render the control problem tractable.

is extracted from individual reservoirs. We have used actual reservoir development plans in the North Sea as a guide in specifying reasonable time-profiles for production. However, what is desired is an extension of the reservoir model that would make the speed of extraction endogenous to the forecasting system. As described here, fluctuations in the speed of extraction would affect the timing of deliveries rather than the total amount of resource ultimately recovered. But the recovery factor (i.e., the fraction of oil ultimately withdrawn) is a second variable that may respond to economic incentives, and an idealized model of reservoir development would also account for this factor. One agenda for research in this area, and its relation to the present work, has been described elsewhere [3].

Perhaps the most serious limitation of the current form of the disaggregated process model is that it abstracts almost entirely from the risks inherent in petroleum exploration. The assumed criterion governing development plans is that of maximizing the value of expected discoveries and production. Of course, substantial fluctuations do occur around the average success ratio and mean discovery size, and these may be expected to slow the pace of development and eliminate certain petroleum prospects from the category of economic viability. Industry's response to these uncertainties is conditioned not only by the inherent geological risks, but also by the licensing provisions decreed by governments. Conversely, the policies adopted by governments, and their consequences, are shaped by the ability of the industry and the governments to assume financial risks. Some analysis of the magnitude of these risks (geological and financial) is possible within the present framework [6], but the

associated difficulties are not small and further discussion goes rather quickly beyond the scope of the present paper.

On the bright side there remain several considerations which recommend the disaggregated process model as a useful tool for studying the future supply of oil. A major virtue of the technique is that the influences of resource depletion and economic incentives are represented explicitly in the analysis. Consequently, it is possible to identify those aspects of the supply mechanism which are influential in obtaining a specific set of results. In addition, the technique satisfies the most basic requirement of all forecasting procedures; that it can be practicably applied to petroleum provinces in the real world that may be of strategic importance to policymakers. The North Sea illustration is intended to be one demonstration of the feasibility of this particular course of research.

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