Appendix B
Estimation Methods for Undiscovered Resources

The purpose of any resource estimate is to produce the best possible guess about the extent of resources in the absence of data which would allow one to calculate a more precise figure. Reasonably accurate data about oil and gas resources can only be generated through extensive drilling; however, geological and geophysical information prior to extensive drilling and preliminary exploratory drilling at a later stage does provide information which can be used for gaining some insight into the amount of resources in an area. This information can be used to estimate resources. Methods have been developed to estimate both undiscovered, in-place resources and economically recoverable resources. Geological factors are the main consideration in estimating in-place resources; estimates of economically recoverable oil and gas must take into account various economic and technological factors and regulatory policy as well.

Although methods for estimating resources have become sophisticated, estimates are only as good as the data used to produce them. An estimate may represent the best appraisal that can be made at the time, but only by the greatest of luck will the amount of resources eventually found in an area be similar to the amount originally estimated. As relevant today as in 1934 is J.T. Hayward's remark, "... we must not fall into the error of believing that because we have attached a number to a chance that we have thereby made a successful issue more sure, or have in any way altered its probability. Further, we must be ever on the watch for that most insidious and widespread superstition that assumes that mathematical manipulation, if sufficiently accurate, involved, and prolonged can transmute doubtful data into positive scientific fact."[1]

In a recent study of hydrocarbon estimation techniques the National Research Council pointed out that the quality of an estimate of undiscovered resources is highly dependent upon: 1) the quantity and quality of the geologic information available; 2) the knowledge, experience, and awareness of the group making the estimate; 3) the appropriateness of the estimation methodology; and 4) (for estimates of economically recoverable resources), the economic assumptions used. Moreover, they noted that users of any resource estimate must recognize **its** probabilistic nature and resulting inherent uncentainty.[2]

The variability between estimates made by different people using the same method (as well as between estimates made using different techniques) can also be wide. This is so because each model calls for a number of subjective inputs. For example, many models depend in one way or another on the use of geologic analogy. Differences of opinion easily can exist over what geologic analogy is most appropriate. When little information is available, structural geology and stratigraphy can and are interpreted differently. For example, in evaluating the resource potential of the Arctic National Wildlife Refuge, geologists from the State of Alaska and from the Department of the Interior used similar play analysis methods; however, they identified the plays differently.

A number of methodologies have been devised to help estimate, with limited data, the expected amount of resources in an area. Some of the methods are fairly crude; others are quite sophisticated, although again it must be stressed that even the most sophisticated methods produce only estimates, and many of these estimates require numerous assumptions and much subjec-

1. J.T. Hayward, "Probabilities and Wildcats Tested Through Mathematical Manipulation," Oil and Gas Journal, vol. 33, No. 26, Nov. 15, 1934, pp. 129-131.

2. National Research Council, Offshore Hydrocarbon Resource Estimation, p. 7.

tive **input. Five basic types of assessment methods are currently in use. These include:**

1. Areal and volumetric **yield methods in combination with geologic analogy. These** techniques range from worldwide average yields applied uniformly over a sedimenta~ basin to more sophisticated analyses in which the yields from a geologically analogous basin are used to provide a basis of comparison.
2. Delphi or subjective consensus methods. In this approach, the estimation of petroleum resources is the consensus of a team of experts who review all the geologic information available in an area or basin.
3. Historical performance or behavioristic methods. These methods are based on extrapolating historical data, such as discovery rates, drilling rates, productivity rates, and known field size distributions.
4. Geochemical material balance methods. These methods are used to estimate how much oil or gas was generated in source rocks of a given area, how much was involved in migration, probable losses during migration, and the quantity that accumulated in deposits.
5. Integrated methods. These methods use a combination of some or all of the above and incorporate geological and statistical models.[3]

The integrated methods, such as play and prospect analyses, are the most sophisticated. Play analysis methods have become popular in recent years for assessing conventional petroleum resources in identified or conceptual exploration plays in a basin or province.[4] These methods produce a range of estimates related to the probability of occurrence of certain amounts of oil rather than a single estimate of resources expected in one or more plays. Since much effort has been expended by State and Federal resource agencies applying these methods to estimating the resources of both the National Petroleum Reserve in Alaska and the Arctic National Wildlife Refuge, these methods and the assumptions that go into them will be described in greater detail.

In-Place Resource Models: RASP and FASP

In-place oil and gas resources include all categories of resources still in the ground, that is, those that are considered to be economically recoverable, those that are technically but not economically recoverable, and those that cannot yet be technically or economically recovered. In-place resources, usually expressed in terms of original in-place volumes, constitute the resource base. Roughly 10 percent to at most 50 percent of in-place oil resources in any given resource area can typically be economically recovered using currently available technology and techniques. Estimates of in-place resources depend upon the interpretation of the geology, economic factors being irrevelant.

Play and prospect analysis models for assessing in-place resources include the Resource Appraisal Simulation for Petroleum (RASP) and the Fast Appraisal System for Petroleum (FASP). RASP has been used by the U.S. Geological Survey to assess resources in both the National Petroleum Reserve in Alaska (1979) and in the

3. Betty M. Miller, "Resource Appraisal Methods: Choice and Outcome," in Oil and Gas Assessment-Methods and Applications, AAPG Studies in Geology #21, Dudley D. Rice (cd.) (Tulsa, OK: American Association of Petroleum Geologists, 19S6), pp. 2-5.

4. Ibid., pp. 4-5.

Arctic National Wildlife Refuge (1980).5 More recently (1986) the State of Alaska used the RASP methodology to estimate resources in ANWR.[6] And the newer FASP method, which is more efficient but produces similar estimates, was used by the Department of the Interior in 1986 to estimate in-place resources in ANWR.[7]

Both methods are based upon the same geologic model and employ the same probability assumptions.[8] However, RASP employs a Monte Carlo simulation technique which typically requires 3000 to 5000 repetitions while FASP is an analytic method which uses statistical techniques and probability theory rather than simulation and thereby greatly speeds up and reduces the cost of the estimation process.

Both methods make extensive use of the judgment of geologists familiar with the geology of the area. In undrilled areas, geologists must depend on surface geology and geophysical data and consider possible geologic analogies with other areas when they make their appraisals. For each identified play (group of geologically related prospects with similar hydrocarbon sources, reservoirs, and traps) within an assessment area, RASP and FASP require that geologists judge the probability that a hydrocarbon source exists, that the timing of oil formation has been favorable, that oil migration from source to traps has been successful, and that the trap contains reservoir grade rock. The product of these four regional geological characteristics (assuming the probability of each occurring is independent of the others' occurrence) jointly determines the marginal probability– the probability that the play contains hydrocarbon accumulations.

Expert judgment is likewise called for at the level of individual prospects, the untested geologic features having the potential for trapping and accumulating hydrocarbons. The prospect attributes are the geologic characteristics common to the individual prospects within a play. Geologists must assess the probability of the existence of a trapping mechanism for the prospects, the likelihood that effective porosity exceeds a certain amount, and the probability that oil and gas exist in at least 1 percent of a trap, The product of these probabilities (again assuming independence) is the probability that a prospect is a deposit, but it is conditional upon the favorability of the play. Together the marginal play probability and the conditional deposit probability are the risk factors. If all attributes comprising these risk factors are favorable, it is likely that there will be hydrocarbons in at least some of the prospects within the play.

A third set of judgments is needed to determine how *much* oil may be contained in each prospect. Geologists are asked to estimate the range of possible values for each of five volume attributes (area of closure, reservoir thickness, effective porosity, trap fill, and reservoir depth) and to assign the probability of a given value to one of seven categories. For example, a geologist may estimate that there is a 100 percent probability that the reservoir thickness of a deposit is greater than or equal to 50 feet, a 75 percent probability that the thickness is greater than 80 feet, and a 25 percent probability that the thickness is greater than 100 feet. From these estimates, a probability distribution for each of the volume attributes can be made. A range of values is also estimated for the number of drillable prospects in each play, And finally, geologists are asked to as-

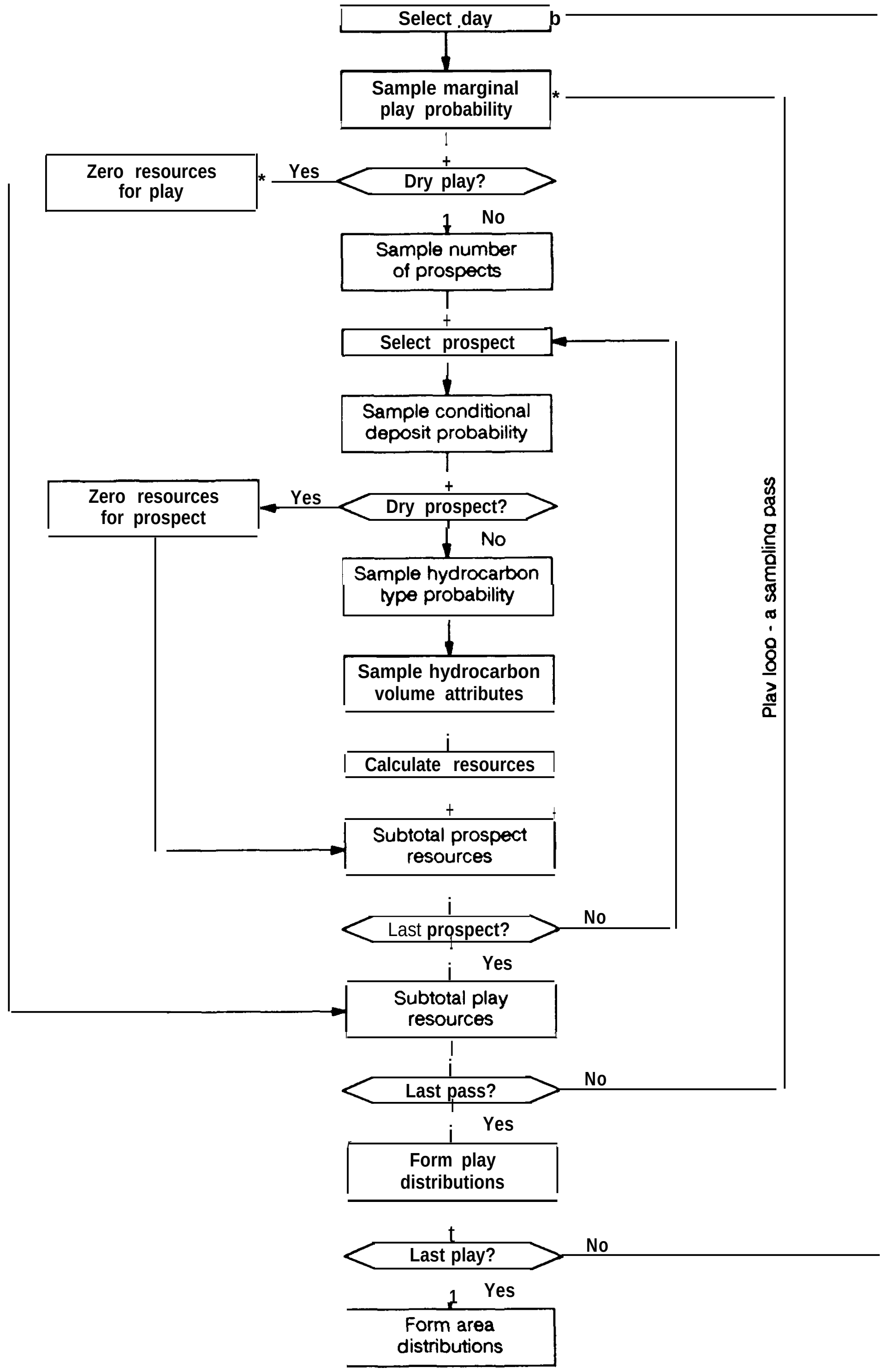
5. Kenneth J. Bird, "A Comparison of the Play Analysis Technique as Applied in Hydrocarbon Resource Assessments of the National Petroleum Reserve in Alaska and the Arctic National Wild like Refuge, " in Oil and Gas Assessment – Methods and Applications, Dudley D. Rice (Tulsa, OK: American Association of Petroleum Geologists, 1986), pp. 133-142.

6. J.J. Hansen and R.W. Kornbrath, "Resource Appraisal Simulation for Petroleum in the Arctic National Wildlife Refuge, Alaska," Professional Report 90 (State of Alaska: Department of Natural Resources, 1986), pp. 1-13.

7. U.S. Department of the Interior, Arctic National Wildlife Refuge, Alaska, Coastal Plain Resource Assessment (Washington, DC: U.S. Fish and Wildlife Service, U.S. Geological Survey, and Bureau of Land Management, 1987). See chapter III, "Assessment of Oil and Gas Potential and Petroleum Geology of the 1002 Area, " pp. 55-81.

8. Robert A. Crovelli, "An Analytic Probabilistic Methodology for Resource Appraisal of Undiscovered Oil and Gas Resources in Play Analysis, " U.S. Geological Survey Open File Report 85-657, 1985.

Figure B.I.— Flow Chart of Simulation Method for Play Analysis



SOURCE: Robert A Crovelll, "A Comparison of Analyhc and Simulation Methods for Petroleum Play Analysls and Aggregation " U S Gaologlcal Survey Open-File Reporf 86-97 1985 sess the likely reservoir characteristics and hydrocarbon mix.

If RASP is used, a simulation is run using the probabilities estimated in the geologic model (figure B-l). First, the marginal play probability is sampled. If the sampled play is "dry," zero resources are assigned to that play on that pass. If the play is not dry, the number of prospects in the play are sampled. Then each of the prospects in the play are examined in turn. Sampling the conditional deposit probability for each prospect determines whether the prospect is dry or contains oil and/or gas. If hydrocarbons are simulated as present, each of the hydrocarbon volume attributes are sampled, and the resources within the prospect are calculated using standard reservoir engineering equations. After the last prospect within the play is sampled, the resources are totaled for that play, and the simulation proceeds to the next play. The process is repeated until all the plays have been examined. The resource estimates for all the plays are summed to obtain the total amount of simulated oil in the assessment area. The simulation is then rerun as many as *5,000* times. Probability distributions can then be derived by ranking results for each ass and dividing the rank ordering into fractiles.[8]

The simulation method is easier to understand than the analytic method, but the outcomes are much the same. In the FASP analytic method, the simulation is replaced by a statistical procedure which calculates means and variances of the same geologic variables to derive an estimate for one play (figure B-2). Results for individual plays are then aggregated using the aggregation model FASPA. Comparisons of RASP and FASP have been made, and results show excellent agreement.[10] The analytic method, however, 'as some advantages. A principle one is that it is thousands of times faster. The cost to run the program is therefore negligible and FASP can be rerun frequently, incorporating new data as available. The analytic method is also potentially more useful because it produces mathematical equations of probabilistic relationships involving petroleum resources.

Estimating Economically Recoverable Undiscovered Resources: PRESTO

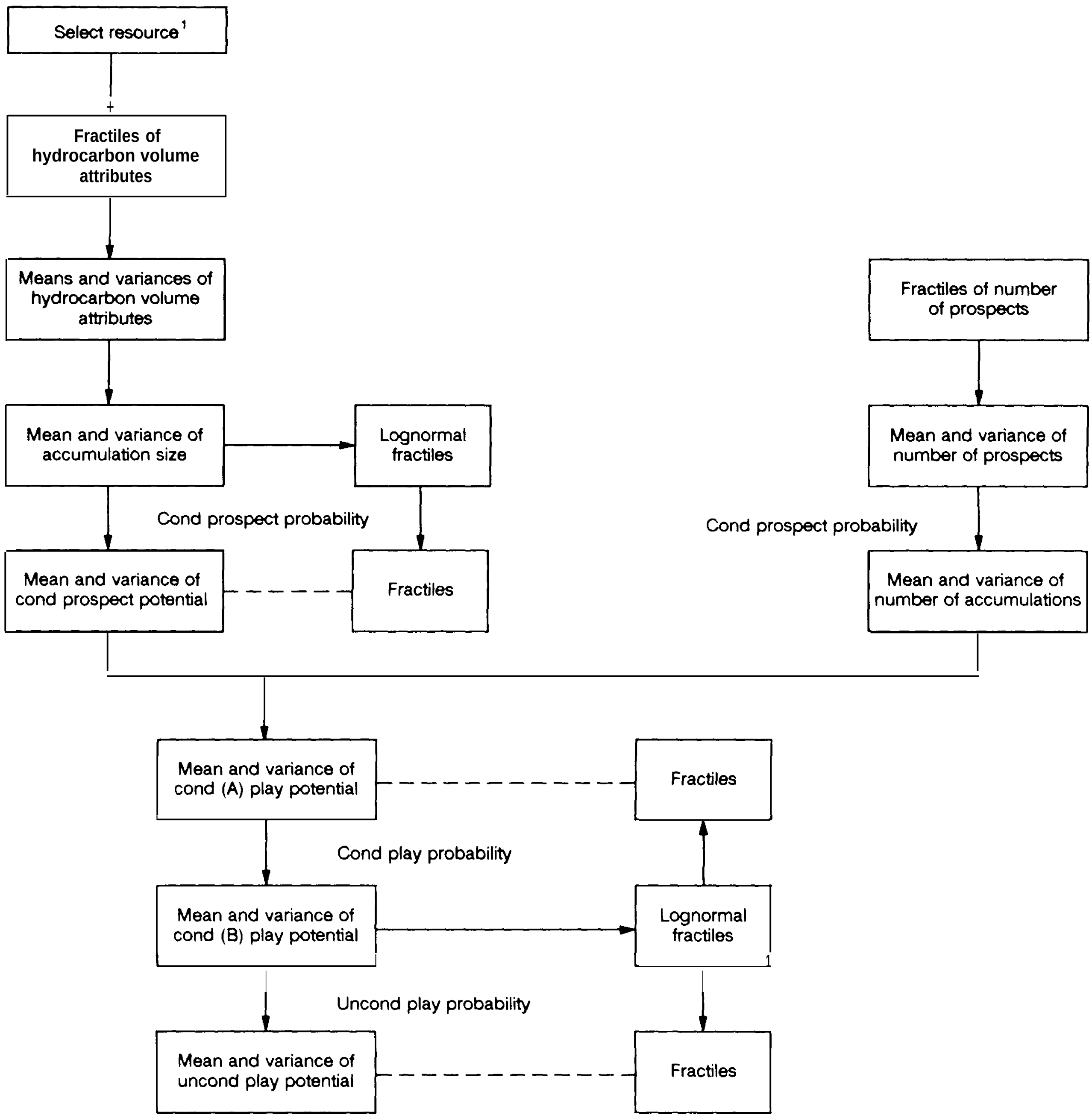
Models have also been developed to estimate the amount of undiscovered but economically recoverable resources in a given area. In particular, the Minerals Management Service's PRESTO (Probabilistic Resource Estimates-Offshore) model (now in its third version) has been used to estimate undiscovered, economically recoverable resources in arctic offshore areas and, recently, in the Arctic National Wildlife Refuge. Conceptually, the model has much in common with RASP, in that it incorporates Monte Carlo simulation, ranges of values for volumetric input parameters, and risk analysis.[11] The most important unit of analysis used to derive PRESTO estimates is the prospect, or individual potential oil or gas field. As in RASP, marginal and conditional risks are determined. The marginal basin risk is the probability that no prospect within a given basin contains hydrocarbons; the conditional prospect risk is the probability that an individual prospect modelled is "dry," conditional upon the basin containing at least some economically recoverable hydrocarbons. These risks are determined by geologists using all available geological and geophysical data. Needless to say, in undrilled and largely unexplored areas, the data are usually scanty. Moreover, PRESTO, like other resource estimation models, uses the judgment of experts when "hard" data are unavailable. Identification and characterization of prospects, for instance, calls for significant subjective input in the absence of substantial drilling.

9. For additional information about RASP and FASP see Bird, "A Comparison of the Play Analysis Technique..."; Hansen and Kornbrath, "Resource Appraisal Simulation for Petroleum..."; and L.P. White, "A Play Approach to Hydrocarbon Resource Assessment and Evaluation, " in Oil and Gas Assessment– Methods and Applications, AAPG Studies in Geology #21, Dudley D. Rice ed. (Tulsa, OK: American Association of Petroleum Geologists, 1986), pp. 125-132.

10. R.A. Crovelli, "A Comparison of Analytic and Simulation Methods for Petroleum Play Analysis and Aggregation," U.S. Geological Survey Open-File Report 8&97, 1986.

11. L.W. Cooke, "Estimates of Undiscovered, Economically Recoverable Oil and Gas Resources for the Outer Continental Shelf As Of July 1984." U.S. Department of the Interior, Minerals Management Service, 198S, p. 9.

Figure B-2.—Flow Chart of Analytic Method of Play Analysis



[1] Oil, nonassociated gas, dissolved gas, and gas resources are each assessed in turn.

SOURCE: Robert A. Crovelli, "A Comparison of Analytic and Simulation Methods for Petroleum Play Analysis and Aggregation," U.S. Geological Survey Open-File Report 86-97, 1986.

Using risk factors and Monte Carlo simulation, PRESTO simulates an exploratory drilling program. For each PRESTO trial, every prospect in the basin is "drilled, " and discovered resources are summed to determine an area total. The simulation is repeated as many as 5000 times, and results are sorted, ranked, and divided into percentiles. Output includes the conditional 95 percent, 5 percent, and mean resource estimates for oil and gas and the corresponding probability of economically recoverable hydrocarbons after accounting for the possibility that there may be no hydrocarbons in the area (the '(risked" estimates).

The major difference between RASP and PRESTO is that PRESTO incorporates economic factors into the model. Thus, not only does PRESTO determine the amount of resources in each prospect, it determines whether the resources within each prospect are large enough to warrant development. To accomplish this, PRESTO uses a single point estimate of the minimum economic field size (MEFS) required for development in the area. The MEFS is derived from MONTCAR, a discounted cash flow analysis program. An important consideration in determining MEFS is the assumed price of oil – as the price of oil decreases, the MEFS increases. Other important considerations include development and operating costs, and distance from markets,

Significantly, the prospect's resources are added to the total for the area only if the MEFS is exceeded for the prospect being "drilled. " But if the MEFS is not exceeded, the prospect's resources are set to zero. Hence, PRESTO estimates of undiscovered, economically recoverable resources may be conservative. For example, a prospect that, in isolation, is not estimated to contain enough resources to be developed may nevertheless be developed if there are other prospects in the area that are large enough to develop, or even if a number of fields, all below the MEFS, are found in close proximity and can share infrastructure costs. The Lisburne, Endicott, and Milne Point fields, for instance, would never have been developed were it not for their proximity to Prudhoe Bay and the TAPS pipeline. PRESTO would have modeled these fields as having zero resources, but they are currently contributing to TAPS throughput, if only about 5 to 10 percent. Likewise, some geologists believe that PRESTO estimates of economically recoverable resources in ANWR are conservative.[12] The MEFS for ANWR as a whole has been determined to be about *440* million barrels (for a $33 per barrel price of North Slope oil in 2000 (1984 dollars)).[13] However, given the Possibility of shared infrastructure costs, recent declining development costs, the high probability that more prospects than were evaluated in DOI's ANWR analysis will subsequently be identified, and other factors, the estimate of economically recoverable resources do appear too conservative.[14]

12. For example, Joe Riva of the Congressional Research Service.

13. U.S. Department of the Interior, Arctic National Wildlife Refuge, Alaska, Coastal Plain Resource Assessment, April 1987, p. 79.

14. Energy Information Administration, Potential Oil Production from the Coastal Plain of the Arctic National Wildlife Refuge (Revised Edition), EIA Service Report, October 1987, pp. 15-17.