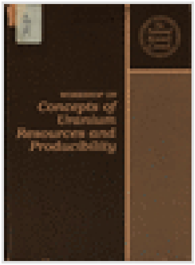

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Concepts of Uranium Resources and Producibility

A Report Prepared by the
Panel on Concepts of Uranium Resources
and Producibility

Board on Mineral and Energy Resources
Commission on Natural Resources
National Research Council

NATIONAL ACADEMY OF SCIENCES Washington, D.C. 1978

NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, The National Academy of Engineering, and the Institute of Medicine.

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INTRODUCTION AND EXECUTIVE SUMMARY

Nuclear energy for use in electric power generation has been assigned a significant role in the National Energy Plan now under development. More than 65 light-water reactors provided about 12 percent of the United States electricity in 1977. Although federal estimates of future nuclear power growth rates have declined dramatically in the last two years, the Department of Energy (DOE) expects nuclear power output to grow to at least 380 gigawatts by the year 2000. However, the deep concern for nuclear proliferation and terrorism around the world, combined with a reported availability of adequate uranium resources for a light-water-reactor economy, have led to executive decisions to defer plutonium breeder development and to delay the reprocessing of spent nuclear fuel for secondary recovery of fissionable components. Yet, the combination of anticipated energy requirements and national security needs make the magnitude and timely availability of the United States domestic uranium resources a technical subject of commanding national interest.

In 1976 domestic uranium concentrate production (short tons U_3O_8) was 12,750 tons; in 1977 it was nearly 15,000 tons. To meet uranium supply requirements now anticipated for electric power generation, production will have to double within the next five years and reach about 45,000-50,000 tons annually by 1990. Inasmuch as the highest level of production achieved in the United States has been less than 18,000 tons of U_3O_8, a remarkable growth performance will be required from the uranium exploration and production industry. Whether this growth performance can be met and whether the National Energy Plan objectives for nuclear power will be realized now appear to depend on optimistic and constructive interactions among the mining industry, the utilities, government decision makers, and the general public.

Large resources of uranium are reported in several foreign countries, notably Australia, but also including South Africa, central Africa and, perhaps, Canada. In each instance, national political considerations introduce significant uncertainties regarding development and export of uranium. International competition for these foreign sources of supply is intense. The objective of United States self-sufficiency in uranium is, therefore, an implicit element of national resource discussions.

Recent delays in the licensing and completion of nuclear power plants have led to interpretations of reduced demand for uranium and have generated confidence among some planners that on the basis of currently identified reserves and estimated potential resources there is an adequate supply of uranium for the next 25 years. Industry representatives, however, recognize continuing supply problems relative to existing production capabilities, as evidenced by their plans for a continuing growth in exploration and for increased capital investments for mining and milling facilities. Their interest in long-term contracts that are market-price related appear to reflect confidence in a strong world demand for uranium. But the problems of meeting demand remain especially significant ones. It is critically important that the annual development of new reserves consistently approach all-time previous highs if an adequate supply of uranium is to be provided in the years ahead.

In recognition of the importance of uranium supply problems, as discussed in two of its recent studies (NRC 1978, NRC 1975), the National Research Council convened a workshop* on concepts of uranium resources and producibility with the particular objectives of evaluating concepts and procedures for improving the estimation of national uranium resources, and for increasing our understanding of the factors which influence the time frames for exploration and production. The workshop not only provided a forum for communicating information on the various aspects of uranium resource assessment and production but more importantly resulted for the first time in documenting in one report the diverse views on concepts of uranium resources and producibility. Participants in the workshop were drawn from government, industry, universities, research organizations, and consulting practice. The vigorous participation of speakers and guests throughout the two-day program testified to the deep interest in and diverse approaches to the problems of assessing the magnitude and availability of United States resources of uranium.

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*Workshop on Concepts of Uranium Resources and Producibility, held September 20-21, 1977, at the National Academy of Sciences, Washington D.C.

The initial phase of the workshop discussion focused on current and developing methods of resource characterization and estimation. Among the government agencies responsible for research leading to resource assessment, there are significant differences in preferred classification of reserves (ores identified with various degrees of confidences) and potential resources (largely undiscovered but possibly economic concentrations of the metal). However, a far greater divergence exists in the selection of preferred models for gathering and organizing information into estimates of potential resources. From an academic viewpoint, the impressive array of newly proposed models offers promise of substantial theoretical innovation in resource appraisal. The better models, however, cannot be expected to mature in two or three years. It may be a decade before the next generation of assessment models is in active application. It is clear that near-term requirements for resource analysis (DOE's National Uranium Resource Evaluation [NURE]) must be satisfied by augmenting current practices with the acquisition of much more comprehensive tonnage and grade data, by utilizing the best available geological information and geological models for the major domestic sandstone-type uranium occurrences, and by relying upon the subjective analysis of these parameters by the best Department of Energy and U.S. Geological Survey specialists working both together and independently.

It is recognized that these short-term approaches cannot substitute for the ongoing need to build better conceptual models for the geological formation on ore bodies, ore districts, and mineral-rich regions. Continuation of basic research in these directions is as necessary for resource assessment as it is for successful exploration efforts. Any national decisions reached by 1981 (the nominal target date for completion of the NURE program), based on then-current uranium resource estimates, must include the creation of mechanisms for continuing improvement of data on resources. The national energy programs are too large, too dynamic and too expensive to proceed without effective and continuously updated information on resource availability.

The entire nuclear power cycle is uniquely dependent upon the peculiar economic aspects of uranium. It has a narrow resource base; there is a lack of suitable materials which can be substituted for it; it requires very large costs prior to actual production; it has a very short usage history; and government policies can drastically overturn almost any long-term economic assumptions concerning it. Analysis of grade and cost categorizations of uranium reserves and resources currently in use, therefore, received intensive consideration. Lengthy and critical discussion was given to the DOE "forward cost" classification of resources (the operating and capital costs still to be incurred to complete production from uranium resources to uranium concentrate). Because the forward cost concept does not take rate of return on investment into account there were some reservations expressed regarding its usefulness to the utilities. Nevertheless, as an initial approach to providing an economic measure of the cost of uranium production it has served a useful purpose. Other viewpoints on approaches to economic recovery of resources were also offered. Particular reference was made to discounted cash flow, which takes into consideration time differences between investment and return, and is thus a more dynamic and more nearly full-cost approach to estimating future uranium supplies. In addition, geologists argued that whatever cost index was applied, it should not be confused or substituted for tonnage and grade data which are essential to geologic analysis of resources. Finally, it was generally recognized that cost estimates or indices tend to fall short of being a satisfactory substitute for real price from functioning markets.

The time considerations involved in the conversion of potential resources to reserves received extensive discussion. It was noted that the problem is not just that of identifying potential resources but perhaps more importantly identifying the rate-limiting factors which control resource conversion to reserves and to production. In 1977, with gross revenues of about $400-500 million the industry expended about $240 million in exploration, even though a period of 8-10 years can elapse before any return appears on this investment. This level of spending and willingness to accept high risks reflect industry's view of the importance of nuclear power in meeting national energy needs. But there is great need to telescope the time required for successful exploration and development, for conversion of resources to reserves and for production, if projected time schedules for developing nuclear power generation are to be met.

Many factors affect the pace of uranium exploration. Land acquisition constraints can be restrictive, especially where federal lands are involved. Regulatory and licensing actions by federal, state, and local authorities tend to extend the period of exploration and development activities. A particular problem is the requirement that each venture obtain the consent of a large number of federal, state, and local agencies, some of which are poorly prepared to assess or monitor exploration and mining practices and are therefore unwilling to grant approval for exploration and mining activities until they are satisfied that proposed operations appropriately address a variety of regulations. A shortage of trained and experienced miners also restricts production in the short term. And a shortage of trained and experienced exploration geologists means not only a deficiency in field personnel but also a lack of innovative ideas for developing exploration models.

Yet, despite the many problems facing industry, there was general optimism in the exploration potential remaining in the United States, as evidenced by significant investment in risk ventures. There are signs, however, of growing concern for future trends: capital costs are rising faster than inflation rates; delays are becoming more costly; lead times to develop a productive mine are lengthening; market demand is less assured the farther it has to be projected into the future. Technical problems along with sociopolitical and legal uncertainties cause industry to wonder whether the climate for exploration and mining will improve sufficiently to attract the needed investment capital and whether the time requirements will make it possible to meet the anticipated demand for uranium. In this latter regard it was suggested that cooperative programs, if not formal partnerships, between government, industry, and academia might be effective in tackling existing problems and thus in compressing the time frame for uranium development.

The actual forecasting of uranium production by DOE was seen as moving from analysis of a theoretical optimum capability, the so-called "could" production, to a more pragmatic "will do" or "most likely" estimate. The "could" production capability provides only an upper level of possible production and is not a forecast of future uranium supply. It relies on the concept of production centers, which are attributed to known reserves and to anticipated but as yet undiscovered potential resources. Making allowances for necessary discovery and development lead times, and assuming a probable price base over a given time frame, the data on production capability of the several classes of production centers are summed into a "could" production capability.

A more realistic approach to supply forecasting now being developed is DOE's "most likely" supply projections, which are also based on the concept of production centers but which use a scenario approach that examines production schedules under specific assumptions about political, social, technical and business environments. This approach has the value of developing an understanding of the uncertainties associated with assuming a given level of future supply and provides a more useful projection for industry.

The history of uranium mining shows that actual production has been lower than anticipated because optimum market and production conditions rarely prevail. Thus "most likely" supply forecasts are difficult to make.

Nevertheless, careful consideration of the realities of uranium mining and milling should allow reasonable and credible supply estimates to be developed. However, in the final analysis, it is generally agreed that actual growth of production will be highly dependent on how industry perceives the future and the magnitude of the risks it must face.

The 1977 report, "Uranium: Resources, Production and Demand", compiled jointly by the Organization for Economic Co-operation and Development and the International Atomic Energy Agency, summarized the world situation realistically, viz. "Although these downward revisions [in demand] tend to increase the adequacy of existing uranium reserves, the longer-term increases in the energy needs of mankind, and the general recognition of the major role to be played by nuclear power, make it no less urgent that substantial additional uranium reserves be identified". The United States, increasingly dependent upon nuclear power generation, and constrained by nonrecycling policies relative to spent nuclear fuel, appears to require continuing vigorous national efforts on behalf of assessment and development of its domestic uranium supply.

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CHAIRMAN'S INTRODUCTORY REMARKS TO WORKSHOP

This workshop on Concepts of Uranium Resources and Producibility addresses the current national concern about the magnitude and availability of uranium resources in the United States. Different reports and presentations have offered conflicting interpretations which are confusing to national policy planners and to the public. There is a need to improve the process of estimating the potential resources of uranium and we are concerned with providing the means to do so. There is also a need to clarify for laymen and decision makers the basis for the resource estimates and to elucidate the factors that govern the rate at which potential resources of uranium can be discovered and produced.

As a nation we are recognizing the problems of defining resources in planning both energy and nonenergy mineral uses. We have been made keenly aware of the requirements for a sound information base on which to project plans for national materials usage. Unfortunately, the transfer of information from scientific and academic consideration to the social and political arena does not always take place easily and with clarity. In many cases the responsibilities for clarification of the concepts of resources and resource producibility for use in public discussion have been neglected. That is most unfortunate, and in the course of critical national discussions we are now seeing the consequences of failing to provide clear statements of just exactly what resources are, how they are estimated, and how they are made available.

In this workshop, we propose to stress better understanding of the fundamental concepts from which the public discussion should be drawn. The basic intent is to keep public information as scientifically sound as it can be. This requires that we maintain an intellectual discussion of approaches to the problems of resources.

In inviting participants to contribute to the concepts of resources, we have drawn on representatives of industry, where there is continual attention to resource problems; on those elements of the federal government that have the responsibility for resource assessment; and on members of the academic community. There has been, however, some difficulty in obtaining the complete participation in this workshop that we had originally looked for. That difficulty reflects the fact that, in matters concerning uranium, there are a number of important national issues of considerable controversy and a great deal of current litigation. These issues have in fact, persuaded a number of participants to withdraw from our program. I want you to know that although the program as originally conceived has not quite emerged, I am pleased to say that we will have important contributions from many people who are among the leaders in the field of uranium resource analysis.

The workshop concentrates on two aspects: one is the problem of estimating uranium resources, and the other, the problem of estimating the rate at which uranium can be produced. There will be four sessions: the first deals with the information base for estimating resources in each category; and the second with the use of grade and forward cost categories of classification of uranium resources. The latter part of the program takes up time factors to be considered in converting potential resources into reserves and production. Session three deals with time considerations in exploration; and session four takes up the methodology for production forecasting.

Our discussion leaders are, for the first session, Professor Arnold Silverman, from the University of Montana; for the second session, Dr. John J. Schanz, Jr., of Resources for the Future. The third session will be led by Richard F. Douglas of David S. Robertson Associates, and the fourth session by Dr. Joe B. Rosenbaum, who is a consulting metallurgist, formerly with the U.S. Bureau of Mines. Each of these individuals has a long history of active work in these subjects, and will help us focus on some of the significant concepts and questions which we are addressing.

This is an open workshop with open discussion. The chairman of each session will introduce the speaker and the commentators scheduled to make remarks. Then the floor will be available for questions from all those present. I would like to stress, however, that the intent of this program is to discuss concepts and to talk about resource problems from the point of view of need for better data and better methodology. It is not the intent of the program to dwell on the sensitive political aspects of the problems we are dealing with. The questions from the floor should be directed to matters of methodology, based on science and engineering information and the scientific approach.

I welcome you all to the workshop and invite you to participate.

Leon T. Silver
Chairman

PART I

THE INFORMATION BASE FOR ESTIMATING RESOURCES

CHAPTER 1

ESTIMATION OF POTENTIAL URANIUM RESOURCES

Donald L. Curry

INTRODUCTION

Since 1948, the U.S. Atomic Energy Commission (AEC) and its successor, the Energy Research and Development Administration (ERDA), have estimated uranium resources as the basis for determining the supply of available uranium, initially for the military needs of the nation, and more recently as fuel for the nuclear-electrical-generating industry. The military needs involved only a government market. Although the current electrical-generating phase is largely nongovernmental, uranium enrichment, the middle stage between uranium production and consumption, is still solely a government function. The accurate prediction of the available uranium supply is very important to the determination of future enrichment needs and schedules and to energy policy decisions.

Most of the uranium ore reserves discovered and developed through the 1960s were in the western United States. As a result, much of the potential uranium resources estimated prior to the beginning of the National Uranium Resource Evaluation (NURE) program four years ago was confined to the sandstone host rocks of the western United States.

INFORMATION BASE

The most important single element of information used in AEC/ERDA resource estimates has been the proprietary drilling data of the U.S. uranium industry. As a carryover from the AEC uranium-purchase program of the 1950s and 1960s, industry still provides ERDA with most of the gamma-ray and related drill-hole logs and other data needed to support the ERDA ore-reserves program. These data are used by ERDA's Grand Junction office to independently estimate the nation's uranium ore reserves. Reserves are the firmest element of resources, and provide a point of departure for estimating potential resources. Much information on results of industry exploration is acquired, although usually with some delay until land control has stabilized in competitive areas. This information materially assists in evaluation of potential resources. Statistics accumulated by AEC and ERDA (U.S. ERDA 1977) show that about 292 million feet of surface drilling was done by industry from 1948 through 1976, of which two-thirds was for uranium exploration.

In addition to the drilling data provided voluntarily to ERDA, the private companies engaged in uranium exploration and mining also furnish proprietary economic data on exploration, mine development, milling, and other activities, as well as access to mines and mills for examinations and special studies. This information is invaluable to the Grand Junction office in making its estimates of potential uranium resources.

Information of a more general nature, but which also is used extensively in developing relevant geologic concepts and models, favorability criteria, and mineralization factors, includes (1) surface and underground geologic mapping, (2) stratigraphic, petrologic, and ore genesis studies, (3) geochemical and geophysical investigations, (4) reports of new or improved mining and milling techniques, and (5) reports on uranium environments and other uranium-related investigations in other countries. This information is developed by various federal and state agencies, universities, private research organizations, and mining and oil companies. The quantity of this kind of material is enormous, although in many cases it requires rearrangement to facilitate its use for uranium evaluation.

Although a substantial quantity of data is available to ERDA from the uranium industry to use as a basis for uranium-resource evaluation, these data have two important limitations, namely (1) the geographic distribution is restricted largely to the low-cost sandstone-type uranium deposits of the western states, and (2) their reliability is low in the higher cost, low-grade ranges because of the unpredictability of disequilibrium relationships between radiometric values interpreted from gamma-ray logs and the actual chemical uranium content of the rocks. The NURE program has elements that will address both limitations. (The resource information base and the efforts of the Grand Junction office to improve this base through the NURE program were discussed in more detail in a paper presented by Bowyer [1975] before the National Academy of Sciences' Committee on Mineral Resources and the Environment late in 1974.) ERDA-funded geological, geochemical, and geophysical activities to accumulate data for use in uranium-favorability and potential-resource estimation are now in full swing, as are geophysical research and development activities that will lead to improvement in down-hole estimation of low-grade material. This effort is described in the 1976 annual NURE report of Bendix Field Engineering Corporation (1977), principal contractor for the Grand Junction office. Meanwhile, industry has been accelerating its drilling activities, both in terms of continuing exploration and development in known districts and exploration in new or frontier areas, and an estimated annual-record drilling rate of about 45 million feet appears likely in 1977. This drilling will continue to be an important source of data for the ERDA uranium-resource assessment program.

POTENTIAL RESOURCE CLASSIFICATICN

In planning the NURE program, it was apparent to AEC staff that expansion of the "potential" classification from the single class used up to that time was desirable to reflect the greater differences in reliability, as "potential" was to be estimated in new areas remote from known uranium areas. A study of existing classifications was undertaken, and one used by the Potential Gas Committee (Glover 1973) was deemed most appropriate. Slightly modified definitions were applied to the three potential classes of the Potential Gas Committee for use in uranium potential estimation. These classes and their definitions are as follows:

<u>"Probable" potential resources</u> are those estimated to occur in known productive uranium districts:

1. in extensions of known deposits; or
2. in undiscovered deposits within known geologic trends or areas of mineralization.

<u>"Possible" potential resources</u> are those estimated to occur in undiscovered or partly defined deposits in formations or geologic settings productive elsewhere within the same geologic province.

<u>"Speculative" potential resources</u> are those estimated to occur in undiscovered or partly defined deposits:

1. in formations or geologic settings not previously productive within a productive geologic province; or
2. within a geologic province not previously productive.

In these definitions the term "productive" means that past production plus known reserves exceed 10 tons U_3O_8.

POTENTIAL RESOURCE ESTIMATION METHODS

A commonly used approach to estimation of potential resources is the geological comparison of the area being evaluated with a known mineralized area. This approach assumes that if the geological characteristics of the area being appraised and the known area are sufficiently similar, then the area being appraised has the potential for the occurrence of deposits of similar tenor, size, and distribution frequency. Although this is the basic approach used by the Grand Junction office since 1948, only in the past decade has the methodology been systematized and refined to seek a more uniform approach by all of the various estimators. The steps followed in the estimation process are basically as follows:

1. Comparison of criteria of favorability for uranium in well-known uranium areas with those of the area to be evaluated, and selection of a control area. A preliminary evaluation of comparative costs also is made at this time, preparatory to selecting the base forward cost.

2. Delineation of the favorable ground (N, measured in linear miles, square miles, or cubic miles).

3. Derivation of a geologic favorability factor (F) from evaluation of applicable criteria.

4. Determination of the percent of unexplored (or undrilled) favorable ground (U).

5. Application of a mineralization factor (T, measured in tons U_3O_8 per linear mile or other appropriate unit of measure, derived from a known mineralized area) to the favorable ground.

The equation, Potential = N x F x U x T, which summarizes the above steps, is then used to estimate the base potential in the area being appraised. From this base, potential estimates for the other forward-cost categories are obtained, usually by extrapolation from the reserves of the control area, as described later in the case history.

Individual estimates undergo staff review to assure their reasonableness. Questionable estimates as well as questionable use of procedures are discussed with the estimator, and corrected with his concurrence where appropriate. Estimates are not arbitrarily changed by the reviewer.

It must be emphasized that the procedures used in the above methodology are continually reviewed for weaknesses that adversely affect the reliability of the estimates. Corrections or changes in procedure are made when it becomes clear that such changes will improve the methodology. In addition, new methodology is continually under investigation. For example, the Grand Junction office, with the guidance of Dr. DeVerle Harris of the University of Arizona and with the assistance of ERDA's Oak Ridge Operations Office, conducted a test assessment of potential uranium resources for the State of New Mexico using a subjective probability approach. A cross section of thirty-six geologists from industry, universities, and government participated on an individual basis. Results were published two years ago (Ellis et al. 1975). Using a revised format from the knowledge gained in the New Mexico test, a similar subjective probability assessment of the State of Wyoming is now in progress. If an acceptable methodology proves feasible for presenting revised estimates of potential uranium resources in probabilistic terms, such estimates will be published by 1979, possibly as a supplement to the June 1976 preliminary NURE report (U.S. ERDA 1976).

ERDA-sponsored outside research of resource-estimation methodology is continuing. For example, Dr. DeVerle Harris is conducting research into new and improved methods of potential estimation, and Dr. Young C. Kim of the University of Arizona is testing the application of geostatistical methods to uranium ore reserve estimation. One report by Harris (1976) and two by Kim and Knudsen (1975, 1977) on results of recent ERDA-sponsored research have been released by the Grand Junction office.

The U.S. Geological Survey (USGS) also has a program of research in uranium resource estimation methodology. ERDA and USGS efforts are being coordinated to minimize duplication of effort, and to assure that the best possible use is made of the results of the research of the two agencies.

ERDA POTENTIAL ESTIMATION--A CASE HISTORY

Southern Powder River Basin

1959 Situation

Uranium was discovered in the Pumpkin Buttes area of the Powder River Basin in 1951. Numerous additional discoveries quickly followed, and by the mid-1950s the pattern of near-surface uranium distribution was determined (Figure 1.1). Much of the early Powder River Basin exploration drilling was done on the premise that the uranium was at shallow depth in oxidized deposits that were largely at the sites of original deposition or only locally redistributed near the present water table. Drilling in the 1950s usually was less than 50 meters in depth, and nearly all exploitable uranium was found at depths shallower than 40 meters. By 1959, some 300 uranium occurrences were known, of which about 90 had attained some production. The largest known deposit, at Monument Hill (Figure 1.1), contained less than 50,000 tons of ore, but most were smaller than 1,000 tons. Most of the ore was in arkosic fluviatile sands of the Eocene Wasatch Formation.

Other factors known in 1959 included the lateral extent of favorable sandstone at the surface and the recognition that most commercial deposits were confined to channel-like trends commonly in areas of contact of the common buff sandstone with red hematitic sandstone. Also important was the realization that past drilling was inadequate from the standpoint of both hole spacing and depth. The assigned potential area was the belt of sandstone encompassing the known deposits and the numerous outcrops of red sandstone, and included a narrow "most favorable trend" extending northward for a few miles from Monument Hill.

Two concepts that proved to be incorrect because of inadequate geologic data in 1959 were: (1) the favorable arkosic sands were thought to be restricted to the Wasatch Formation and to be no deeper than 125 meters in the area around Monument Hill; and (2) the sediments of the Paleocene Fort Union Formation were believed to be too fine-grained to serve as hosts for significant deposits.

Post-1959 Situation

The stratigraphic knowledge of the Powder River Basin changed little between 1959 and the mid-1960s. Industry exploration was almost entirely confined to the proximity of the known ore deposits, and seemed predicated on the likelihood of finding neither larger nor deeper deposits than were already known. However, the solution-front (or roll-front) concept of uranium transport and deposition was becoming widely accepted in Wyoming, and the association of ore with the red-buff transition in near-surface sand units of the Powder River Basin was soon recognized as a roll feature.

Eventually, ore rolls were recognized in some of the mines. A model was then formulated in which two distinct

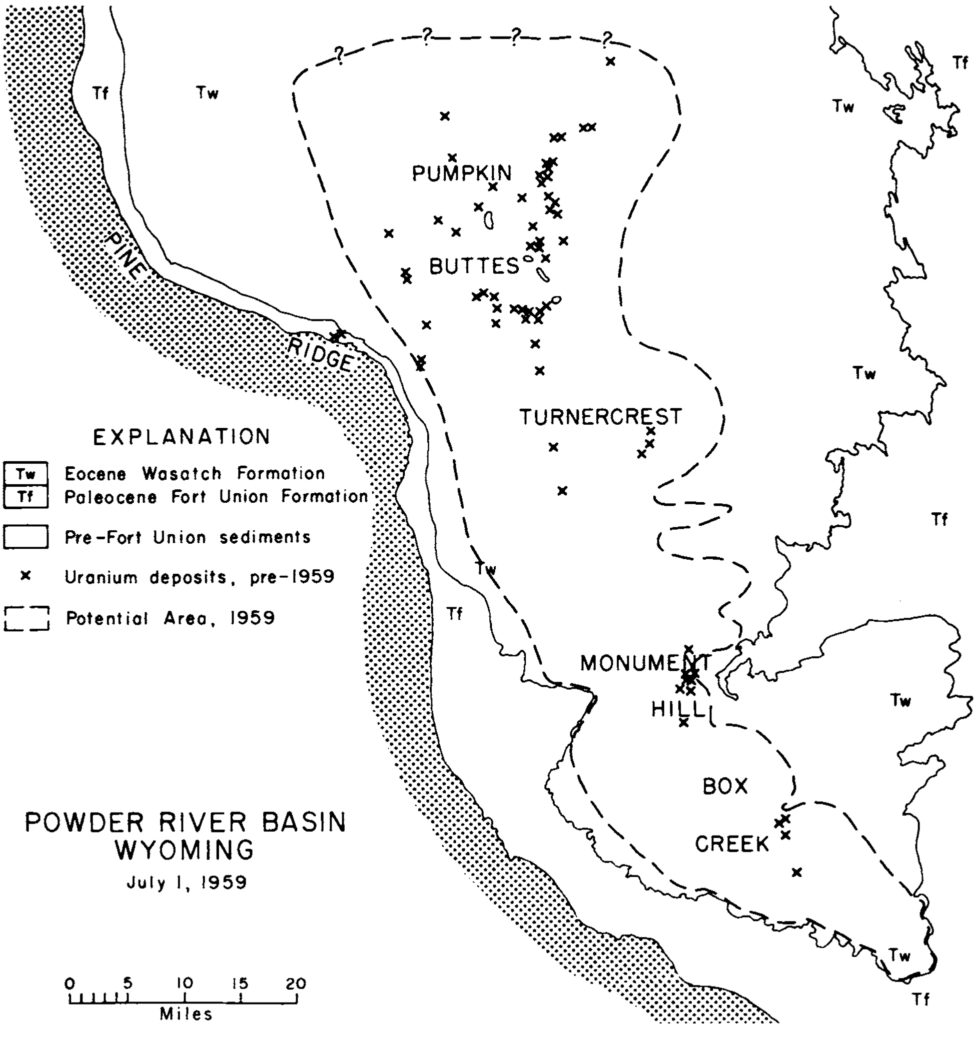


FIGURE 1.1 Uranium deposits and potential areas of the southern Powder River Basin, Wyoming, as of 1959.

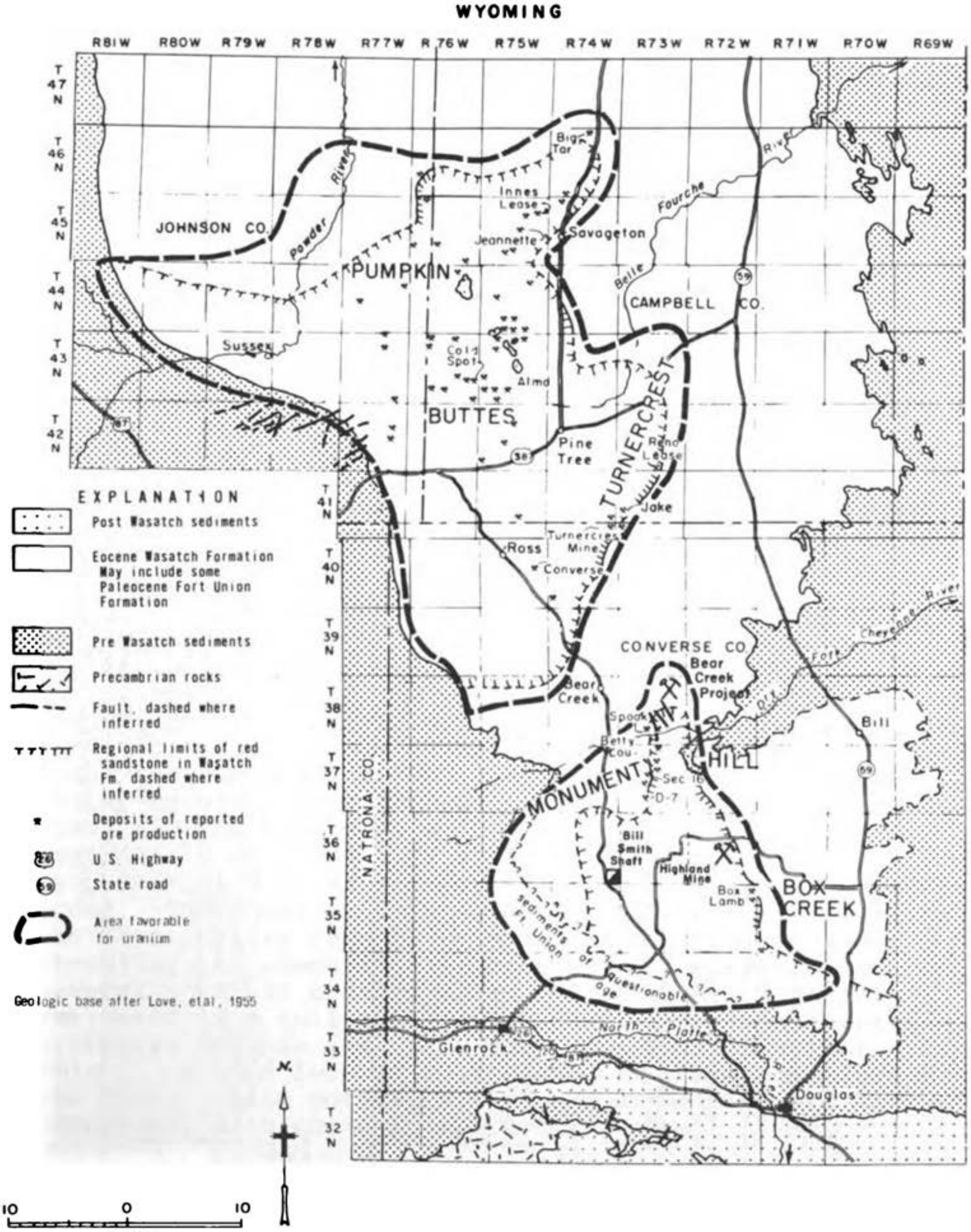
solution-front systems were recognized (Figure 1.2). The two systems, situated in the Monument Hill/Box Creek area at the southernmost part of the basin and in the Pumpkin Buttes/Turnercrest area somewhat farther north, are separated by a stratigraphic interval of fine-grained sediments that was little affected by solution activity. These systems are roughly defined in the field by the aforementioned red hematitic (altered) sandstone outcrops. Uraniferous oxidizing solutions are envisioned as having moved down dip from outcrops to the southwest. The uranium deposits would be found at the position of maximum encroachment of perimeter of alteration, in any given sandstone host bed.

Despite the apparent applicability of the roll-front theory, the factual field data did not change sufficiently until 1967 to justify revision of potential estimates. Subsequent drilling data generated by the new exploration programs showed that the solution-front theory was indeed applicable. In addition, favorable sands were found to be substantially deeper than previously thought, thus greatly expanding the thickness and volume of known favorable sediments. Most important, uranium deposits larger than any heretofore known in the region were found substantially below the present water table.

1972-1976 Situation

By 1972, drilling had more precisely defined the perimeters of the frontal systems in the subsurface. The perimeters shown in Figure 1.2 represent the approximate position of farthest advance of the roll fronts, irrespective of stratigraphic horizon. The sands are: (1) wedge-like, usually thick and continuous within a few kilometers of the outcrop; (2) become finer-grained, thinner, less permeable, and less continuous to the north and east farther from the source; and (3) eventually give way to silt or finer-grained facies. These relationships exercised considerable control over the migration of mineralizing solutions and uranium deposition. Because of the multiplicity of sand horizons, the deposits may be found anywhere within the potential areas shown, but most are likely to be found some distance downdip from the outcrop, most commonly where solution transmissibility is considerably lessened. Figure 1.3 shows these relationships in a 1972 cross section of the southern Powder River Basin. For comparative purposes, Figure 1.3 also illustrates, in cross section, the geologic concepts of 1959 based on the knowledge then available.

The Wasatch/Fort Union contact is shown to be at the same outcrop position at the west end of both the 1959 and



SOURCE: Curry (1976)

FIGURE 1.2 Potential uranium resources in the southern Powder River Basin, Wyoming, as of 1972.

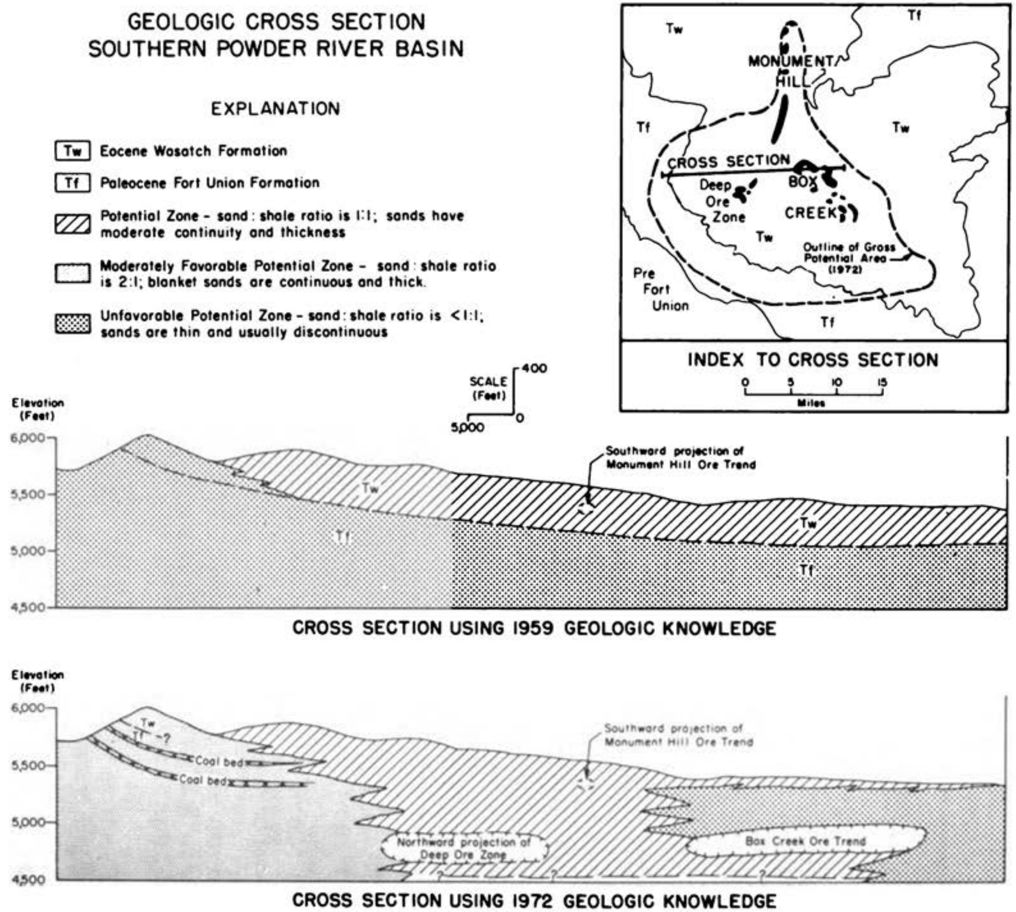


FIGURE 1.3 Generalized geologic cross sections of Powder River Basin, Wyoming, illustrating 1959 and 1972 geologic knowledge.

1972 cross sections. However, its position in the eastern part of the area is now disputed and is therefore not shown in the 1972 section. Therefore, comparing the two cross sections, it will be seen that the favorable sandstones, above the basal Wasatch contact, were considered to be only about 130 meters thick in 1959, whereas, based on 1972 data, the favorable sandstones are in excess of 300 meters thick and the deeper sandstones also contain ore deposits.

Estimation of 1976 Potential Resources

The Monument Hill/Box Creek estimate of January 1, 1976, will be used to illustrate the estimation methodology used by the Grand Junction office of ERDA. This estimate was one of those making up the totals of potential resources presented in the preliminary NURE report (U.S. ERDA 1976) of June 1976. Below is a step-by-step discussion of the procedure used, following the five-point outline presented earlier.

1. Comparison of criteria of favorability in control area with those in the area being evaluated. In some earlier estimates of uranium potential in the Powder River Basin, the Gas Hills and Shirley Basin were used as control areas. However, sufficient knowledge of the geological conditions and ore distribution in the Monument Hill/Box Creek area is now available for control purposes. Thus, the better-developed part of the area is used as the control area, and the less-developed part is the area being evaluated. Table 1.1 illustrates the criteria of favorability that are compared, using a basic sandstone-type model. The model is used primarily for the determination of the favorability factor, but also is very useful as a checklist for comparing the area being evaluated with several possible control areas. Because the area being evaluated is a roll-type environment, length of frontal system is used in the estimation formula rather than area or volume. A base forward cost of $8 per pound is selected, as the costs in the potential area are expected to be comparable with those in the control area.

2. Delineation of favorable ground (N). The altered (oxidized) ground through which the uraniferous solutions moved is the favorable ground. In Figure 1.2, this ground is that encompassed by the dashed line. The portion of the line used, which is considered to represent approximately the farthest subsurface advance of the solution front, extends through the Monument Hill and Box Creek localities from the vicinity of its intersection with the contact of the Wasatch Formation with sedimentary rock of the underlying Fort Union Formation at the outcrops both to the

TABLE 1.1 Derivation of Favorability Factors Based on Ranking of Favorability Criteria

Sandstone-Type Deposits

Criterion-Scale	Scores: Control Area	Scores: Area to be Evaluated
1. Depositional Environment of Potential Host Rocks 0-20	20	20
Fluvial: coalesced alluvial fans Fluvial: stream channel and flood plains Marginal marine: deltaic, lagoonal, barrier bar Lacustrine and marine Aeolian and glacial		
In general, order is from most favorable to least favorable; however, highest score in area being appraised would be for whichever environment is most important in geologically similar area with important deposits.		
2. Lithology of Potential Host Rocks		
A. Composition 0-10	10	10
0 is least favorable and 10 is most favorable sedimentary rock based on comparison with similar geologic environments with important deposits.		
B. Sand-Shale Ratios 0-15	15	10
0 is least favorable and 15 is most favorable ratio based on comparison with similar geologic environments with important deposits.		
C. Sandstone Thickness 0-15	15	10
0 is least favorable and 15 is most favorable thickness based on comparison with similar geologic environments with important deposits.		
D. Grain Sizes 0-15	15	15
0 is least favorable and 15 is most favorable grain size based on comparison with similar geologic environments with important deposits.		

TABLE 1.1 CONTINUED

Criterion-Scale	Scores: Control Area	Scores: Area to be Evaluated
E. Favorable Permeability Relationships 0-15	15	10
Score on basis of comparison with similar geologic environments with important deposits.		
F. Reductant 0-40	40	40
Score high for abundant reductant (carbonaceous trash or H_2S) and low for little or no reductant.		
G. Tuffaceous Content in Overlying or Interbedded Sediments 0-30 (pre-erosion)	30	30
Score high for abundant, altered or unaltered, tuffs and low for tuffaceous content minor or absent.		
3. Source Area of Host Rocks 0-20	20	20
Score high for predominately granitic rocks and low for no granitic rocks in provenance.		
4. Alteration		
A. Anomalous Iron Staining (limonite-hematite)		
(1) Outcrops 0-20	20	20
0 is no anomalous iron staining in outcrops and 20 is abundant anomalous iron staining in outcrops based on comparison with similar geologic environments with important deposits.		
(2) At Depth 0-20	20	20
0 is potential host sediment completely oxidized or oxidized to great apparent depths and 20 is potential host sediments oxidized at outcrops and to shallow depths only.		
(3) Bleaching 0-20	0	0
Score on basis of importance in similar geologic environments with deposits.		
(4) Calcification 0-15	15	12
Score on basis of importance in similar geologic environments with deposits.		

TABLE 1.1 CONTINUED

Criterion-Scale	Scores: Control Area	Scores: Area to be Evaluated
B. Reduced Beds (bleaching) in Thick Red Bed Sequences 0-20	0	0
Score on basis of importance in similar geologic environments with deposits.		
C. Pyrite Content in Unoxidized Zone 0-15	15	15
Score on basis of abundance in area being appraised relative to abundance in similar geologic environments with important deposits.		
5. Structure		
A. Dip of Beds 0-25	25	25
Score high for gentle dips and low for steep dips.		
B. Significant Unconformity or Erosional Surface Subjacent or Superjacent to Section Containing Favorable Host Rocks 0-25	25	25
Score high for widespread unconformity or erosional surface and low for no unconformity or erosional surface.		
C. Structural Terraces or Flattening of Dip 0-25	0	0
Score on basis of importance in similar geologic environments with deposits.		
D. Faulting or Graben Structures 0-20	0	0
Score on basis of importance in similar geologic environments with deposits.		
6. Regional Tectonic Environments 0-20	20	20
Intracratonic basins on forelands of foldbelts Intrafoldbelt basins Geosynclinal margins Continental platforms Shields Geosynclines		
Order is from most favorable to least favorable; however, certain exceptions exist as in the Texas Coastal Plain where the most important regional environment is a geosynclinal margin. Also in		

TABLE 1.1 CONTINUED

Criterion-Scale	Scores: Control Area	Scores: Area to be Evaluated
the Rocky Mountain Province, the most important environment for Tertiary deposits is intrafoldbelt basins. In area being appraised, score highest for environment that is most important in geologically similar areas with important deposits.		
7. Age of Potential Host Rocks 0-20	20	20
Triassic, Jurassic, Tertiary Cretaceous Permian Pennsylvanian Other		
Order is from most favorable to least favorable; however, exceptions include Black Hills (Cretaceous), Anadarko Basin (Permian), etc. In area being appraised, score highest for host rock age that is most important in similar geologic environments with important deposits.		
Geophysical Surveys		
A. Ground and Air Radiometric Surveys 0-50	50	30
Score high for numerous strong anomalies; score low for no anomalies.		
B. Radiometric Anomalies in Oil and Water Wells 0-40	0	0
See 8A		
C. Randon Surveys 0-10	0	0
See 8A		
Geochemical Surveys		
A. U in Waters 0-30	0	0
See 8A		
B. U in Potential Host Rocks 0-20	0	0
See 8A		
C. U in Soils 0-10	0	0
See 8A		

TABLE 1.1 CONTINUED

Criterion-Scale	Scores Control Area	 Area to be Evaluated
Total score for geologic, geophysical and geochemical criteria	390	352
10. Character of Mineralization		
A. Persistence of Mineralization 0-30	30	25
High score for demonstrated significant lateral and/or vertical continuity; low score for uranium mineralization restricted to shallow depths or to small pod-like occurences.		
B. Distribution Patterns 0-25	25	20
Score high for known deposits in established or inferred trends or other predictable patterns; score low for no recognized trends.		
11. U Deposits [a]		
A. Size (Reserves + production; enter appropriate Roman numeral in scoring column)		
large deposits, $>$ 5,000 tons U_3O_8 (I) medium deposits, 1,000-5,000 tons U_3O_8 (II) occurrences & small deposits $<$ 1,000 tons U_3O_8 (III) mineral occurrences (IV) no mineral occurrences (V)	I	III

[a] These criteria are not to be given numerical values; however, the relative size and the distribution of deposits in the area being appraised should be considered as a basis for adjusting the favorability factor derived by scoring geologic, geochemical, and geophysical criteria in items 1 through 9.

west and south. The total length of solution front represented by this line is 107 kilometers, of which segments aggregating 32 kilometers were used in the determination of the mineralization factor. Thus, N equals 75 linear kilometers of solution front.

3. Assignment of geologic favorability factor (F). The list of criteria of favorability (Table 1.1) is perused to select criteria most pertinent to the control area, and a weight is assigned to each. The selected criteria are then weighted for the area being evaluated, using no higher value than the assigned value for the control area. Each column is then totaled. At this point, the geologist must evaluate the results of the exercise to determine whether the ratio of the total for the area being evaluated to that of the control area truly reflects his judgment of the favorability. If not, the ratio is adjusted accordingly. Thus, the favorability factor determined for the 75 kilometers of solution front being evaluated was adjusted from 90 percent (352:390 [totals of weighted scores, Table 1.1]) to 50 percent. The principal rationale for this adjustment is that, at comparable early stages, exploration in the portion of the front being evaluated has not resulted in the same rate of discovery of sizeable deposits as in the control portion. This downgrading is supported by the entries in items 10 and 11 of Table 1.1, where neither character of mineralization nor deposit size are scored as high for the part of the frontal system being evaluated.

4. Unexplored area (U). The unexplored parts of the 75 linear kilometers of solution front being evaluated amount to 40 percent of the total area under consideration. This is an approximation based on knowledge of uranium exploration activities in the area.

5. Mineralization factor (T). A factor of 1,210 tons U_3O_8 per linear kilometer of roll front was determined by dividing the sum of production plus reserves (at $8 per pound U_3O_8) associated with the fully developed portion of the solution front by the length of that portion of the front. Thus, by substituting these factors in the equation: Potential = N x F x U x T = 47 miles (about 75 kilometers) x 0.50 x 0.40 x 1,950 (about 1,210 tons per linear kilometer) = 18,330 tons U_3O_8.

To determine the quantity of uranium in higher cost categories, the ratios of contained U_3O_8 in $10, $15, and $30 per pound reserves to the $8 reserves for the Wyoming Basins were applied to the newly determined 18,330 tons of $8 per pound potential resources, as follows:

Reserve Category, $/lb	Ratio to $8/lb Reserve
$10	1.2
$15	1.5
$30	2.0

The average grade assigned to each cost category of potential resources was extrapolated directly from the grade of the same cost categories of reserves in the Monument Hill/Box Creek area. Thus, the ore tonnage, grade, and contained U_3O_8 of estimated potential resources for the Monument Hill/Box Creek area are as follows:

Category, $/lb.	Tons Ore	$\%U_3O_8$	Tons U_3O_8 (rounded)
$ 8	12,250,000	0.15	18,500
$10	17,000,000	0.13	22,000
$15	27,500,000	0.10	27,500
$30	52,500,000	0.07	37,000

The potential resources of the Pumpkin Buttes/Turnercrest area were estimated by the same procedure used for the Monument Hill/Box Creek area. Potential resources for these two areas of the Powder River Basin were assigned to the probable potential class, as the areas are well-defined productive uranium districts.

Comparison of 1959 and 1976 Resource Estimates

Because of economic changes, particularly inflation, resource figures in a single forward-cost category for 1959 and 1976 are not directly comparable. However, the total estimated low-cost resource base (production plus reserves and potential) increased about twenty-fold as a result of the acquisition of new knowledge of the region between the late 1950s and 1976.

CONCLUSIONS

Potential estimates, like reserves, are limited by the information on hand at the time and are not intended to indicate the ultimate resources. Potential estimates are based on geologic judgment, so their reliability is dependent on the quality and extent of geologic knowledge. Reliability differs for each of the three potential resource classes. It is greatest for probable potential resources because of the greater base of knowledge resulting from the advanced stage of exploration and development in established producing districts where most of the resources in this class are located. Reliability is least for speculative potential resources because no significant deposits are known, and favorability is inferred from limited geologic data.

Estimates of potential resources are revised as new geologic concepts are postulated, as new types of uranium ore bodies are discovered, and as improved geophysical and geochemical techniques are developed and applied. Advances in technology that permit the exploitation of deep or low-grade deposits, or the processing of ores of previously uneconomic metallurgical types, also will affect the estimates.

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CHAPTER 2

DATA INTEGRATION AND URANIUM RESOURCE ESTIMATION

Richard B. McCammon

The purpose of this workshop is to offer constructive new directions to policy planners for designing more effective programs of uranium resource analysis and utilization. The particular new direction I propose is to improve the present methods for obtaining uranium resource estimates from reconnaissance and exploration data. To date, estimates of potential uranium resources have been derived mainly from past production and current reserve data in known productive uranium districts. Such estimates, by their nature, tend to be conservative and, therefore, not entirely satisfactory.

A vast amount of new geologic, geochemical, and geophysical data is now being collected, or will be collected, in areas where uranium occurs in unknown amounts; the problem has become how to estimate reliably the uranium resources in these areas. Presumably, this will be accomplished by integrating the data being collected with the data already available from known productive districts. As an approach to this problem, I propose the use of "characteristic analysis," which has been applied recently to silver-bearing vein deposits and to copper-bearing massive sulfide deposits with considerable success (Botbol et al. in press; Sinding-Larsen et al. in press). A similar approach should be just as effective for uranium deposits.

Characteristic analysis was developed to allow the geologist to compare the attributes of a region to the attributes of a model. It amounts to nothing more or less than a mathematical realization of a geologic analogy. A model is specified by the geologist. Within the framework of characteristic analysis, a model consists of a set of weighted attributes--geologic, geochemical, geophysical, or remote-sensing attributes, or, for that matter, anything that can be considered as a trait of the model. A model can be defined conceptually; for example, a Wyoming-type uranium ore roll where the attributes and their associated weights are determined a priori. On the other hand, a model can be defined as real where the attributes and their associated weights are determined according to a mathematical criterion evaluated for data collected in a uranium producing district. However any particular model is defined, for any given region in which the appropriate data have been collected, characteristic analysis can provide a quantitative measure of comparison between the given region and the particular model. Simply stated, it provides a measure of similarity. Properly scaled, it provides a measure of the degree of similarity. The latter can be interpreted as a probabilistic measure that can then be used to discount the resource potential of the region relative to the assumed known ultimate yield of the model. The total resource potential of a region is obtained by aggregating resource estimates of individual models.

Implementing characteristic analysis as a part of a national program in uranium resource assessment, however, will require policy planners to give serious consideration to the volume of data that must be computerized. Characteristic analysis relies heavily on the development of data bases and supportive computer programming for accessing, processing, and graphic display of the basic data. For this reason, the decision to produce quantitatively defensible estimates of uranium resources for the United States by using characteristic analysis must be made early in the program; such estimates cannot be obtained at some later date by reverting from an ongoing program that was designed to produce these estimates by essentially manual methods.

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CHAPTER 3

NEW ANALYTICAL METHODS OF ESTIMATING URANIUM RESOURCES

Warren I. Finch

Constructive new directions and considerations for policy planners in the field of uranium resource assessment requires research into better methods of integrating and converting raw geologic, geochemical, and geophysical data as input into reliable and credible resource estimates. This short paper is an attempt to offer new directions in the developing and difficult science of resource prediction.

In the past USGS has used favorability methods similar to the one used currently by ERDA (Butler 1975: 26, 81; Lupe 1977) and as described by Curry in Chapter 1 of this report. The Geological Survey of Canada, also, uses a formula similar to ERDA's, except it does not contain the percent-of-explored ground (U) factor (Ruzicka 1977). I am going to present an alternate method, namely, one based on genetic-geologic models. An earlier version of plans to develop the method was presented to a joint ERDA-USGS workshop in July 1977. Much of what is presented here is based on input from numerous individuals in the Geological Survey, but it would be impractical to identify and credit them. I take responsibility for this synthesis and for any shortcomings.

As is well known, uranium is a very mobile element that moves about readily in the earth's crust, and throughout geologic time uranium has been concentrated by various geologic processes into deposits of different sizes, grades, and forms in numerous geologic environments. Even though each individual deposit differs from all others, most can be classified into distinct types based on observable characteristics and in part on genetic ideas. Some types are more closely related and can be classed into major groups. The various features that describe the geologic environment are called attributes. Even though our knowledge of the genesis of the deposits is not perfect, and never will be, we can devise models based on the geology as well as genesis of the specific types or classes of deposits. Thus, a genetic-geologic model may be defined by specific attributes of the observable geologic environment that relate to the preparation of the site for uranium deposition in the host rock; the source, transport, and deposition of uranium; and the history of post-depositional modification through to present-day preservation.

The advantages of the use of genetic-geologic models in resource assessment are that they allow the evaluation of areas or provinces in which there are no exposures of uranium, allow the classification of uranium "shows" into a model type and therefore aid in better assessments, and most importantly, permit the evaluation of areas for the types of deposits for which there are no known examples in the United States. Emphasis in the model development will be on non-sandstone models. The genetic-geologic model will provide an alternative to the favorability method used thus far.

The models are not yet fully developed, so I will present to you our progress and plans to develop them over the next year. The models are to be used in fairly large irregular geologic provinces rather than the regular quadrangle-cell areas being used presently by ERDA in the NURE program. Fewer areas, perhaps only one-half of the number of 2° quadrangles that cover the United States, would be used in the genetic-geologic models method for assessing undiscovered uranium resources. Thus, it would probably require less manpower, time, and dollars to make the assessment, but the method is not without its problems, both theoretical and practical. A practical problem is the lack of adequate knowledge on tonnage/grade relations of uranium deposits, either as a whole group or for the various classes of deposits. These tonnage/grade distributions need to be compiled and analyzed. The genetic-geologic models method is a natural extension of the current U.S. Geological Survey program on uranium exploration research and resource assessment as I have outlined in two previous Survey reports (Finch 1975, 1977). For example, the sandstone uranium model will be closely developed from the basin analysis or genetic stratigraphic principles developed over the past three years.

Despite the problems, assessments using genetic-geologic models should have both high reliability and high credibility.

The bar diagram shown in Figure 3.1 outlines the effort underway within the Survey to develop the genetic-geologic models method. I will go through the plan pointing out problems, progress, and thoughts about this and other methods. My intention is to provoke thoughts about the method, not to give you a fully developed method.

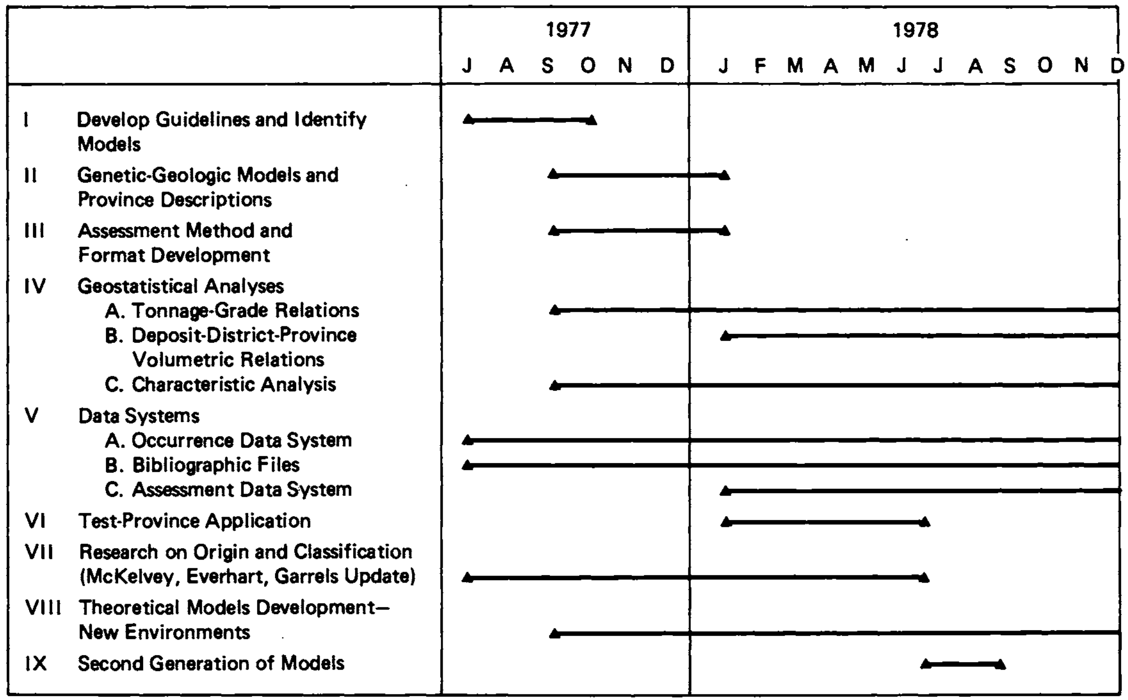

FIGURE 3.1 Schedule for developing genetic-geologic models for uranium resource assessments.

The first step, now underway, is to develop guidelines and identify the models or types of deposits (step I). After each model is identified, several task forces will be set up to describe the geologic attributes of each model and identify known geologic provinces in which occurrences like each model are likely to be present (step II). Concurrently and in cooperation with those describing models and provinces, the assessment procedure and formats will be developed (step III). In order to make the assessments, several data systems and statistical analyses will be required--particularly tonnage/grade relations, deposit/district/volume relations, and uranium occurrence data (steps IV and V). As soon as individual models are developed, the data will be gathered and integrated, and assessments made by a small group of experts to test the model in an appropriate geologic province (step VI). Concurrently with the efforts just described a separate task force is updating the 1955 paper in Economic Geology on the origin of uranium deposits, by McKelvey, Everhart, and Garrels (McKelvey et al. 1955) (step VII). As part of this effort, theoretical models for economic uranium occurrences in new environments will be studied (step VIII). As a result of these two research efforts and the testing of models in a single geologic province, a second generation of genetic-geologic models will be developed (step IX).

Finally, implementation of the method developed through the nine steps just described could begin throughout the nation in September 1978. Recent cooperative agreements between the USGS and ERDA require that any such action would be closely tied and coordinated with ERDA's on-going NURE program.

Now I will return to the development of the models and comment about each step. Our present thoughts on fundamental guidelines for model development are:

1. There should be a small number of models; and

2. The model must describe the geologic environment--not the deposit.

3. The model should be applicable to one, or perhaps two or three, kinds of geologic provinces.

4. The model must be usable with geologic maps and field-observable and drill-hole data.

5. Each model must have an open-ended list of attributes.

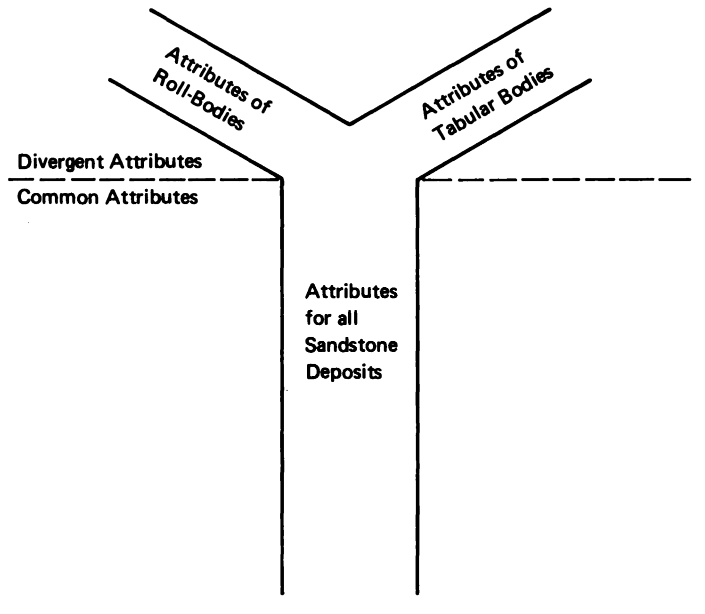

FIGURE 3.2 Genetic-geologic model tree for sandstone deposits.

6. Attributes should fall into common classes that allow computer manipulation and possible redefinition of model designs.

The number of models should be small--on the order of a half-dozen, probably not more than ten. Consideration of only those types of deposits that have production plus reserves of 1,000 (metric) tons U_3O_8 will help limit the number. Because the world's production and reserves are largely in the "elephant-sized" deposits, it is the largest deposits that interest us most in assessing undiscovered resources. If this relation continues to hold true, we can estimate the number of potential elephants and simply increase the resource value an appropriate percent for the smaller deposits. Perhaps more important in limiting the number of models is that several researchers (for example, Rich et al. 1977) feel that various types of deposits are more similar than dissimilar in genesis or genetic characteristics.

For model types that vary significantly in their geologic environment or where conditions permit more than one origin, a genetic-geologic model tree can be drawn as shown in Figure 3.2. Points of divergence can be marked by branches; attributes common to each branch will form the trunk. This feature of the method highlights its flexibility of use and revision, which is essential with continued research and discovery of new types of uranium ores.

The models are to be described by attributes of the geologic setting and genetic controls within a given geologic province. The attributes fall into seven broad classes:

1. Pre-structural, pre-metamorphic, and/or precursor conditions;

2. Deposition of host rock (provenance of sediments, magmatic series, etc.);

3. Potential sources for uranium;

4. Transport system for uranium;

5. Primary deposition of uranium;

6. Post-deposition modification (supergene enrichment, leaching, etc.);

7. Preservation;

An example of a model is as follows:

Sandstone model (preliminary)

1. Precursor conditions

    a. Foreland structural province

    b. Pre-host rock erosion (unconformity)

    c. Intermontane or graben structure

2. Depositional conditions of host rock

    a. Continental and marginal-marine sedimentary environment

    b. Tertiary, Cretaceous, Jurassic, Triassic, Carboniferous, Devonian, or Proterozoic age of host rock

    c. Quartzitic, volcanic, or arkosic sandstone intermixed with mudstone

    d. Low-dipping strata, basinal structure

    e. Mid-fan facies versus proximal and distal facies

3. Potential sources of uranium

    a. Granite provenance

    b. Acid volcanic provenance

4. Transport system for uranium

    a. Relative permeability of host rock

    b. Favorable aquifer conditions

5. Primary deposition of uranium

    a. Presence of pyrite or altered products

    b. Presence of organic matter

        1. Impregnation

        2. Plant fragments

    c. Alteration of host rock

        1. Reduced rock

2. Oxidized rock

d. Presence of abnormal concentration of V, Cu, Mo, Se

6. Post-deposition modification

a. Supergene processes evident

b. Post-ore faulting

7. Preservation

a. Arid (positive) versus humid (negative) modern climate

b. Badly leached outcrop

c. Thick regolith

It has been said that the scale of the observation creates the phenomenon. In the case of mineral resource assessment the natural entity is the geologic province. This is preferable to artificial cell sizes, such as quadrangles, arbitrary rectangles, and political areas. Geologic provinces are the building blocks for a national or continental resource assessment. An initial compilation of potential uranium provinces in the United States resulted in less than 275 provinces in the lower-48 states and about 30 in Alaska. This compares to about 640 two-degree quadrangles in the whole of the United States.

The models will be applied to appropriate geologic provinces; for example, the sandstone model to nonmarine basins and the quartz-pebble conglomerate model to 2.2-billion-year and older Precambrian sedimentary terranes. For each model, maps of the lower-48 states and Alaska will be prepared showing potential geologic provinces. As the assessment process goes forward, the maps for each model will be updated. Each will show relative favorability and eventually the resource numbers. The scale of each map will be chosen to best display the data. Initial compilations will be as overlays on the geologic map of the United States (1:2,500,000 scale).

Two essential data sets needed for the assessment are tonnage/grade analyses and the location and description of all known uranium occurrences. A file has been begun on the latter and its formation will be accelerated this year. All known occurrences, anomalies identified in the U.S. Geological Survey computerized geochemical files, and "red-ball" spots from ERDA's national aerial radiometric and hydrogeochemical programs will be classified and entered into the system so that occurrence plots for each model type may be made.

Tonnage and grade variations within a deposit are primary characteristics just like alteration, mineralogy, and other observable features. But our knowledge of tonnage and grade variations is very poor because little effort has been put into the determination of tonnage/grade relations. Tonnage and grade distributions of deposits within each model type are essential for calibration. Cnly with adequate calibration can reliable resource estimates be made. Tonnage and grade analysis will be undertaken immediately.

The genetic-geologic models can be used in several ways to assess the resources. The actual evaluation format and preferred procedure have not been worked out, but let me outline some thoughts concerning them. McCammon has addressed in Chapter 2 the possible use of characteristic analysis in the design of the procedures.

The data for each model in a given test area will be compiled on uniform formats by the most expert people available within the Geological Survey, and where possible from other organizations. Forms designed to extract judgment for each attribute will guide the evaluator.

Attributes can be evaluated as to presence (+) or absence (-), and where data are either absent or uncertain (0). It would be well to indicate a range of uncertainty for both the plus and minus values. Each attribute could be weighted equally or in a subjective way by different values. It is to be hoped that a system of weighting can be worked out empirically by the use of the characteristic analysis or some other analytical procedure.

Based on the scoring of the attributes and on the tonnage and grade relations for a given model, or submodels where appropriate, the evaluation of the resource with attached probabilities is to be worked out in the characteristic analyses program.

Another method to be tried will use a small group of specialists in the Geological Survey's Uranium Resource Assessment Group to make subjective estimates based on the scoring of attributes by other specialists. The following decisions will be made by each participant:

1. The probability of uranium deposits of the particular model or models occurring in the geologic province is evaluated between 100 percent and 0 percent chance. If no chance is chosen the decision process ends.

2. The province is likely to contain deposits of average grade X. If more than one grade is estimated, the probability of finding the higher grades is estimated.

3. The province is likely to contain deposits of what tonnage in each grade class.

4. Predict the number of deposits in each grade class--giving low estimate, high estimate, and most likely estimate.

5. If depths to potential deposits are greater than 2,000 meters divide the estimates into two classes: 0 to 2,000 meters; greater than 2,000 meters.

6. Finally, the estimate of the total undiscovered resources in terms of tonnage and grade is calculated giving low estimate, high estimate, and most likely estimate.

After each team member has made an independent estimate, the team meets to discuss differences and reasons for differences. A second set of estimates is then made. The last phase is to resolve differences at least to the degree that final resource numbers range within individual estimates. The resultant undiscovered resource numbers are presented as high (95 percent probability) for the hypothetical resource category and low (5 percent) for the speculative resource category.

The estimates then can be analyzed and modified by various mathematical techniques.

After the assessment has been made by the two methods described, and even others, the differences in estimates will be analyzed. From these experiments a decision can be made as to which one or more method will be best for additional assessments.

In the fiscally-lean year of 1972, the Geological Survey undertook a Phase I activity to appraise the resources of some 75 mineral and fuel commodities, which resulted in Professional Paper 820--Mineral Resources of the United States--published in 1973 (Brobst and Pratt 1973). A Phase II was initiated in 1974. As part of uranium Phase II, one effort was to update the paper by McKelvey, Everhart, and Garrels (1955) on the origin of uranium deposits. This update was started in the Branch of Uranium and Thorium Resources by Harry C. Granger, but for many reasons has not been completed. This is probably just as well because in the meantime we have gained new insights into uranium geology as a result of recent research by the U.S. Geological Survey and others, and because of discoveries of several new significant types of uranium deposits since

1974. Now we plan to push this updated paper through to completion by mid-1978.

Although the first models will be patterned after productive and reserve districts, some thought needs to be given to theoretically possible deposits where little or no production is known anywhere in the world. These theoretical models will aid in the evaluation of what appear to be minor uranium occurrences and will be used where appropriate to determine the low probability levels or speculative resources.

After the initial testing in selected geologic provinces, the McKelvey-Everhart-Garrels update, and theoretical-models development, a second generation of models should be a natural outcome. After this review of models and assessment procedures, the method should be ready for implementation nationwide. Such an undertaking would be fully coordinated with ERDA's NURE program. Ways to integrate the genetic-geologic models method with the current quadrangle-favorability assessment will be devised.

It will be our policy to publish each step in the development of the genetic-geologic models and their application to test areas. For it is with complete disclosure of the models, data formats, and assessment procedure that credibility of the assessment can be attained.

The methodology outlined above provides an alternative to the present method in use in the NURE program. In many ways it will complement ERDA's as it is designed specifically to assess speculative resources, which have received limited attention to date.

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CHAPTER 4

UNDISCOVERED URANIUM RESOURCES AND POTENTIAL SUPPLY*

DeVerle P. Harris

INTRODUCTION

One of the major obstacles to a proper perception of uranium resources is the difficulty of communication. Therefore, I will introduce my presentation with a brief review of terminology and of the concepts involved in the analysis of uranium resources and potential supply. This review will establish a framework for the examination of some of the models that have been used to estimate potential supply. As a result of this examination, comments will be made about the problems and virtues of the models and about the estimates which they have produced. I shall conclude my presentation with a brief description of a research effort now in progress at the University of Arizona on an extended model for the assessment of potential mineral supply. Much of my presentation is based on two of my earlier papers on uranium resource appraisal: "A Critique of the NURE Appraisal Procedure as a Basis for a Probabilistic Description of Potential Resources, and Guides to Preferred Practice" (1976b) and especially Part VI, ("Undiscovered Uranium Resources and Potential Supply: A Nontechnical Description of Methods for Estimation and Comment on Estimates made by U.S. ERDA, Lieberman, and the European School [Brinck and Pau]. ") of "Mineral Endowment, Resources, and Potential Supply: Theory, Methods for Appraisal, and Case Studies" (1977b).

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*This chapter was prepared from a recording of an oral presentation to the National Academy of Sciences, with some modifications by the author.

RESOURCE TERMINOLOGY

First, I propose two new terms: "uranium endowment" and "potential uranium supply," or more generally, "mineral endowment" and "potential mineral supply." "Mineral endowment" (see Figure 4.1) is distinguished from the resource base, which consists of the totality of material, in that it includes only those accumulations of uranium in deposits of some minimum grade (q), a minimum tonnage (t), a maximum depth (h), and perhaps, even some specified mode of occurrence. Economics does not figure in the definition of "mineral endowment". Under some specified economics, we have what is referred to as resources, which by general reference do not have to be known resources unless we use the qualifier that they are known. If we specify current economic conditions and that the deposits are known, we then have known economic resources, which are commonly referred to as ore reserves. For policy evaluation and economic analysis, we need to be able to generate from an estimate of mineral endowment, different levels of resources. More specifically, we need to be able to describe how the quantity of resources varies in response to a change in economics. Additionally, we would like to know how much of these resources would be discovered under some specified exploration effort. In effect, the requirement of being producible and discovered translates material from resources to a quantity which I refer to as "potential supply." "Potential supply" would be both economic to produce, because of its characteristics and our stated conditions, and likely to be discovered given the stated exploration effort.

QUANTITATIVE METHODS

Geologic Analogy

Let us take a look at some of the techniques that have been used in achieving these objectives. The first of these techniques, one which is widely used, is geologic analogy. Since we already have had some comment on geologic analogy (Figure 4.2), my description will be brief. In geologic analogy a control area is selected which by preliminary geologic analysis is perceived to be similar to the study area. Using a density factor of mineralization computed on the control area, an initial estimate of the resources (and I am using the term resources loosely at this point) of the study area is made by multiplying this density factor by the appropriate dimension (length, area, or volume) of the study area. Then, this estimate may be modified for what is perceived as differences in the geology of the two areas.

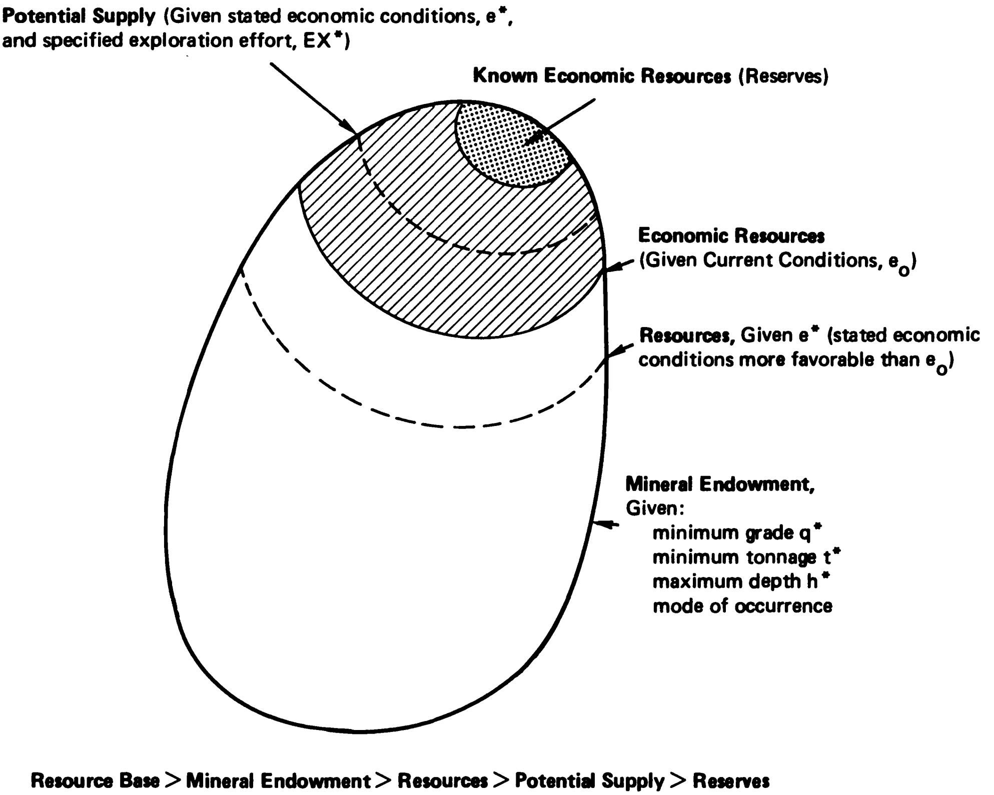

FIGURE 4.1 Resource terminology and relations.

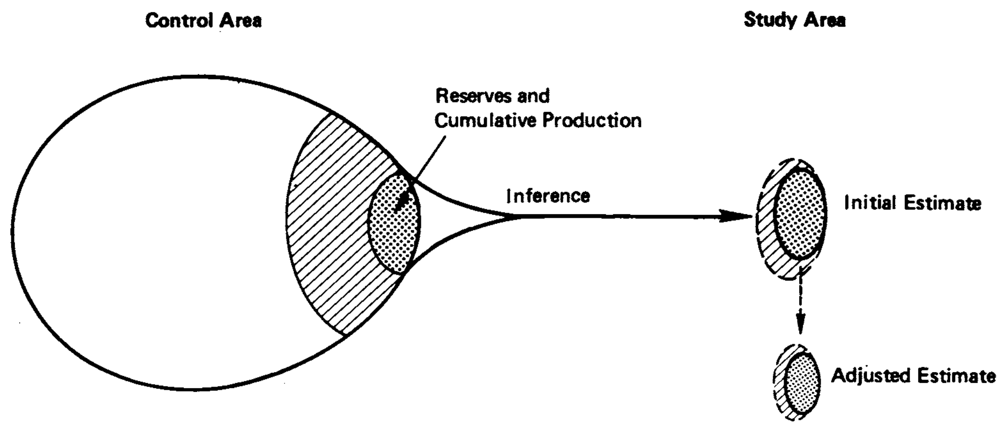

FIGURE 4.2 Estimation of potential supply by geologic analogy.

Such an appraisal could be a basis for a single-point estimate, as we have had in the past, or for probabilistic estimates, as in a recent study of the uranium resources of New Mexico.

Let us take a look at this process again, only this time with geologic analogy examined with respect to the relationships in Figure 4.1. Consider first the endowment, the resources, and the reserves plus production on the control area. What we have done in the past (and I am not saying this is what geologic analogy is for, or ought to produce) is to make an initial estimate of potential supply for the study area based on the reserves and past production of the control area. This total, as previously indicated, might be modified and adjusted.

Some studies have gone farther by attempting to estimate potential supply at costs 20 percent higher, 50 percent higher, etc. Generally, the economic analysis is implicit and at best loosely stated. Often, nothing is said about the technologies involved, or the efficiency of exploration, or the costs of translating what is enclosed within the outside boundary into potential supply. Furthermore, it is difficult to estimate, using geologic analogy, potential supply for specified economic and technologic conditions different from those currently prevailing: it cannot be determined from the stock figures that are produced routinely by simple geologic analogy.

Time-Rate Models

Another approach that has received some attention in the appraisal of potential supply of oil and gas and, recently, of uranium, is that of the "time and rate analysis" performed by Lieberman. This approach utilizes either 1) a time series of reserves plus past production or of cumulative annual discoveries, or 2) the relationship between rate of discoveries and cumulative drilling effort (Figure 4.3). In each case, a model is selected for the apparent pattern: the logistic curve has been used to describe the time series of annual production or discoveries, and the negative exponential curve for the relationship of discoveries per foot of drilling to cumulative drilling. The idea then is to extrapolate the curves to infinity to infer what would ultimately be produced, thereby enlarging upon reserves and production to include all that would ever be produced within the region. In the case of uranium, that was done for an $8 forward cost category; then multiplication factors were used to enlarge it to what might ultimately be produced at $30. This procedure gives an estimate of potential supply. But there are some difficulties attendant to this approach: although

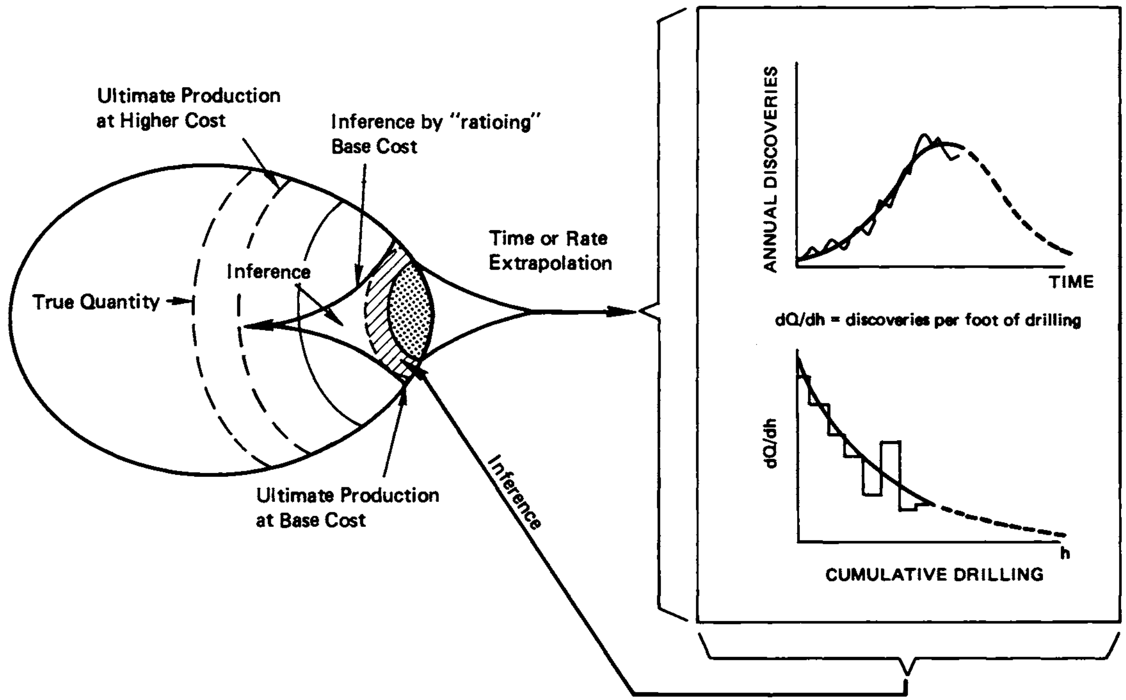

FIGURE 4.3 Estimation of potential supply by time and rate methods.

it is based upon reserves and production at some stated cost level, by extrapolating to infinity one is really extrapolating trends in productivity, costs, prices, etc., as though they were a single entity, and the result is an estimate for which the associated economic conditions are unknown. The approach, as currently practiced, does not describe the economics associated with the estimates of potential supply. Furthermore, with respect to the discovery-rate model, the aggregation across regions and drilling depths of discoveries per foot of drilling creates such a mixed measure of exploration performance that it raises a question as to whether it is an acceptable model for the estimation of potential supply. Unfortunately, all models have deficiencies.

Crustal Abundance-Geostatistical Models

A totally different approach is embodied in the crustal abundance-geostatistical models. There are two of these that have received attention. One was developed by Brinck and the other by the Programmes Analysis Unit (PAU) of Great Britain. Figure 4.4 is a crude diagram of the PAU model. It proposes that there is a log-normal distribution of tonnage and of grade per deposit and that the population for grade covers all occurrences. The mean of this grade distribution, taken worldwide for all concentrations, is crustal abundance. It is assumed that deposit grade and tonnage are statistically independent. In a plot of the logarithm of grade and tonnage, the concentric circles then represent probability contours, and a mean grade across all of these tonnage categories of the population of deposits is crustal abundance. Another postulate is that a cost can be described as a function of deposit tonnage and grade. If that function is specified, the known deposits can be considered to be a representative sample of Economic Resources, the shaded area in Figure 4.4.* Simply stated, the idea of the PAU approach is that this function is known or can be determined; therefore through calculus and

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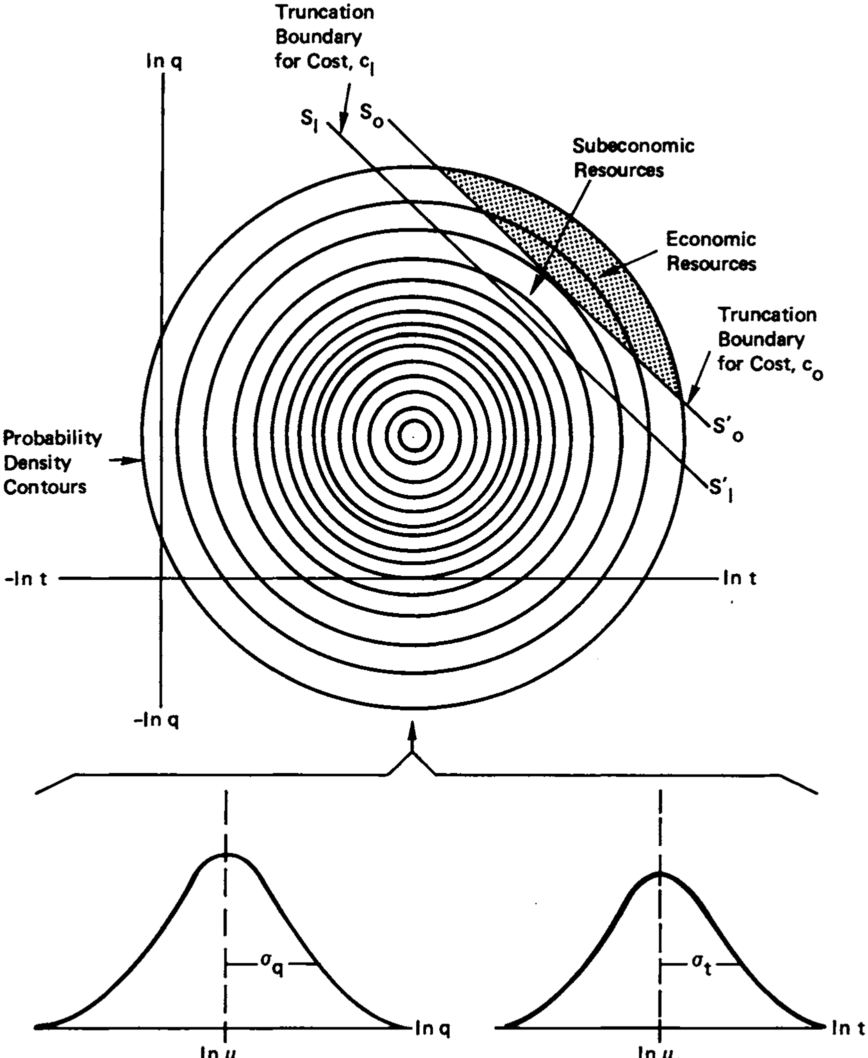
*This model employs another important premise which for the sake of simplicity of exposition has not been included in Figure 4.4. This premise is that known deposits are considered size biased: exploration identifies the largest first; therefore, data on ore deposits do not represent a random sample. The estimation procedure adopted by PAU compensated for this bias.



Note: q = deposit average grade; t = deposit tonnage.

SOURCE: Harris (1977b)

FIGURE 4.4 Schematic representation of crustal abundance/geostatistical model of PAU.

probability theory, one can determine those parameters such that expectations** of tonnage and grade on these two distributions match the statistics on known deposits. Once these parameters are known, the cost level can be changed, and the amount of resources available at various costs can be estimated.

The appealing thing about these models is that they are quantitative and easy to manipulate; potential supply for high costs, hence low-grade endowment, is easily estimated. But, they raise some basic questions that are difficult to answer. One of these is best illustrated by collapsing the two distributions into one, a grade distribution. In this form the area under the curve (Figure 4.5) represents the rock of the earth's crust. Given this perspective, is this really a log-normal curve, describing the amount of material for all grades from recovery grades (i.e., from high grades) down to and beyond crustal abundance as shown on the left in Figure 4.5? Or, do we possibly have a bimodal distribution as shown on the right in Figure 4.5, where the small blip represents the distribution of mineral materials in ore deposits with which we are familiar, and the largest part of the curve represents the distribution of mineral materials in common rock types. Experts divide on both sides of this argument. There is good argument to support bimodality, but at the same time, there is no statistical evidence of it, and there is a possibility that material with grades in the in-between area exist but simply has not been recognized yet. Right now we are not prepared to answer this question.

The Estimates

After examining three very different methods, let us look at some of the estimates that have resulted. For the United States (correcting for differences in cost and using standard 1975 dollars) Figure 4.6 is my suggested comparison between the studies by Brinck, the British Programmes Analysis Unit, the NURE (DOE) figures, and Lieberman. Lieberman's estimates, based on discovery-rate extrapolations, are the lowest in the $30 range; the next is

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**Allowance is made for the exploration bias and for cost truncation of the bivariate population.

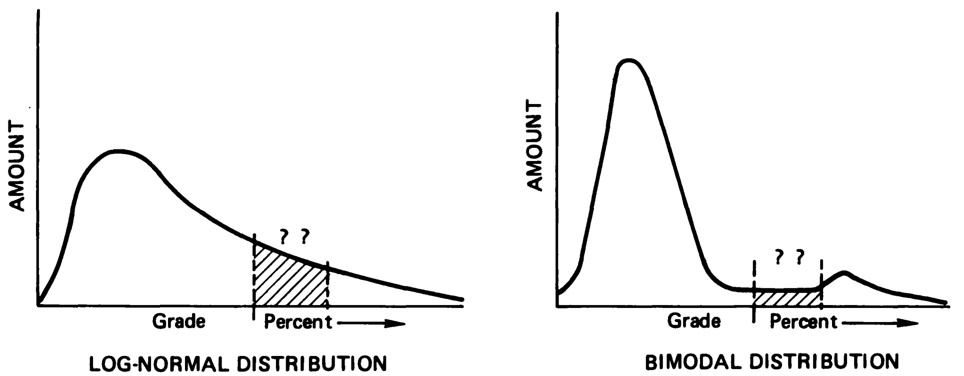
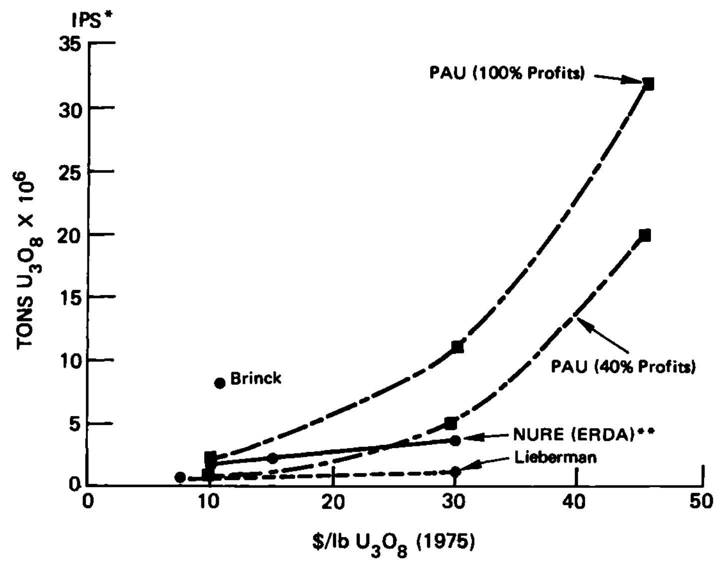


FIGURE 4.5 Possible distribution of mineral materials in the earth's crust. (A basic question is the distribution of materials in the shaded area.)



*Initial Potential Supply = Production + Potential Supply of Undiscovered Deposits + Reserves
**Excludes by-product uranium

SOURCE: Harris (1977b)

FIGURE 4.6 Initial estimates of potential supply for the United States.

the NURE estimates from ERDA, and the highest estimate at $30 is that by PAU. If we had Brinck's estimate for $30, it probably would be above those of the Programmes Analysis Unit. With regard to the analysis by PAU, there is some question whether to use the estimate associated with the 100 percent profit plowback into exploration or the 40 percent level. According to PAU, firms in the United States typically plow back 40 percent of profits into exploration. So, PAU concludes that if industry behaves as it has in the past, then it is appropriate to use the curve for 40 percent profit. PAU suggests in a recent article in Resources Policy that the fact that firms invest only 40 percent of profits in exploration may be an argument for government involvement in exploration, for investing all profits would foster a much larger potential supply, as indicated in Figure 4.6. Here, it should be noted that this relationship between profit and exploration is relevant only for profit as it is defined in the PAU model.

A comparison of resource estimates for uranium in New Mexico was made using subjective probability methods and Brinck's crustal abundance-geostatistical model. The two estimates compare very closely down to a grade of 0.10 percent U_3O_8 (see Figure 4.7). Perhaps this is not too surprising because the geostatistical models are quantified on some of the same information that the geologists use implicitly in their subjective assessment. The differences in the modeling assumptions show up in the extrapolation to 0.01 percent. In the New Mexico study the subjective assessments combined with a grade/tonnage extrapolation gave considerably larger resources than those at higher grade (greater than 0.1 percent), but crustal abundance calculations at less than 0.1 percent gave extremely large resources. They were larger by a factor of 100 than the subjective probability assessment. Are these large tonnages really there? According to geologists who participated in the subjective probability assessment, if these resources do exist, much of them must occur, in other than sandstone deposits.

REASONS FOR VARIATIONS IN ESTIMATES

There are a number of reasons why estimates by various models differ. One is that different explicit or implicit models of endowment are employed. Another is the different stated or implied technologies, and this is particularly at issue in Lieberman's work in which time is extrapolated to infinity. No one knows just what the technologies will be at such a distant time or even 50 years in the future. A third reason is the different costing of the endowment. To demonstrate this, I applied the cost models used in the New

	CUTOFF GRADE (% U_3O_8)			
	0.10		0.01	
	Rock Material (short tons)	U_3O_8 (short tons)	Rock Material (short tons)	U_3O_8 (short tons)
Based On:				
Brinck Model	8.43×10^8	1.10×10^8	3.0×10^{12}	4.4×10^8
Subjective Probability Model	6.09×10^8	1.26×10^6	3.8×10^9	1.4×10^6

SOURCE: Harris (1977b)

FIGURE 4.7 Estimates of the endowment of New Mexico in U_3O_8: Brinck model compared to subjective probability model.

Mexico study (I refer to these as the ERDA cost relationships, although they are not the ones used in the NURE program. They were adopted for the New Mexico study alone.) and found that for a deposit of 100,000 tons, costs by Brinck, ERDA and PAU, are very close (Figure 4.8)--much closer than I would have expected. But at a million tons (Figure 4.9) we find some departure, with greater economies of scale present in Brinck's model than in either PAU's or ERDA's.

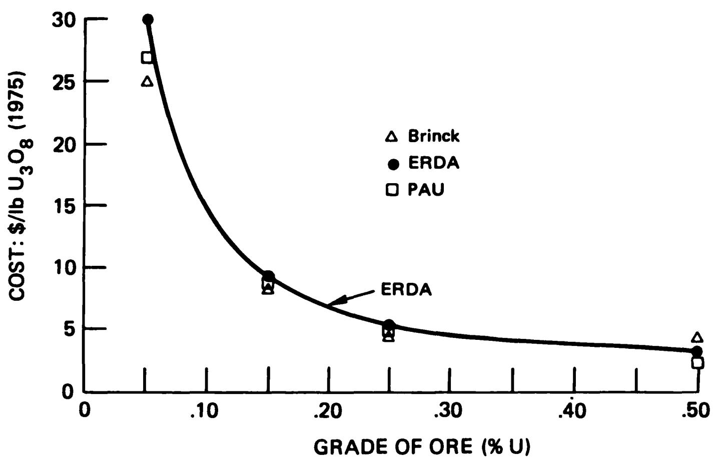
The biggest disparity is between ERDA and the other two, and this disparity increases with an increase in the size of deposit. Figure 4.10 shows costs for ten million tons of ore; the difference between the cost relations used in the New Mexico study and those by Brinck and Programmes Analysis Unit is considerable. The costing relations used in the ERDA study basically show that economies of scale are achieved very quickly. According to ERDA, a million-ton deposit has captured nearly all economies of scale; but the PAU and Brinck models describe continuing economies of scale progressively achieved as larger and larger deposits are exploited. I have discussed these results with people at ERDA and they verify that economies of scale are achieved rather rapidly.

GEOLOGY AND BIASED ESTIMATES

Now I am going to shift from this cost perspective to the use of geology in resource analysis, both as a basis for geologic analogy and as a basis for subjective assessment. Generally, estimates based on geologic analogy have been conservative. One reason for this is that we find in retrospect the geologists did not include (and did not intend to include) the impact of improvements in productivity through technology. This is an important consideration over a long time horizon.

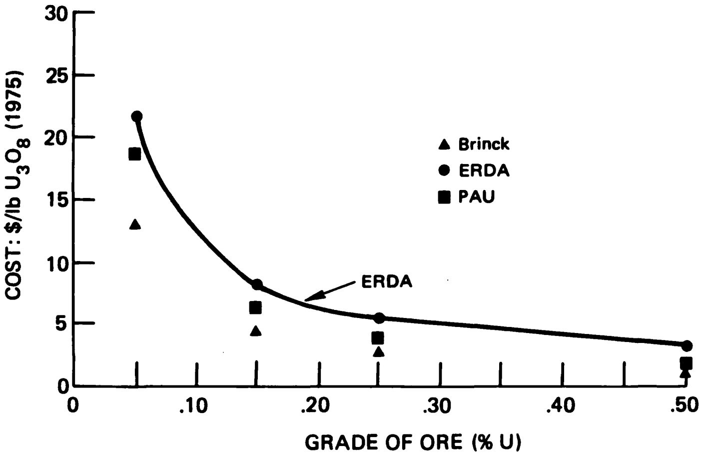
Underestimation by geologic analogy is due in part to the use of the mineral-density factor, which is generally understated. This factor is determined on control areas, and often there is considerable potential in these areas for additional deposits or for additional ore in existing deposits. Thus, by nature of its derivation, the mineralization factor is conservative. Actually, its use provides estimates of potential supply under current economic conditions (including exploration), not endowment or resources.

Geologists are faced with a very difficult task, namely, to translate geology into a statement of endowment or resources even though a deposit is not known to be present,



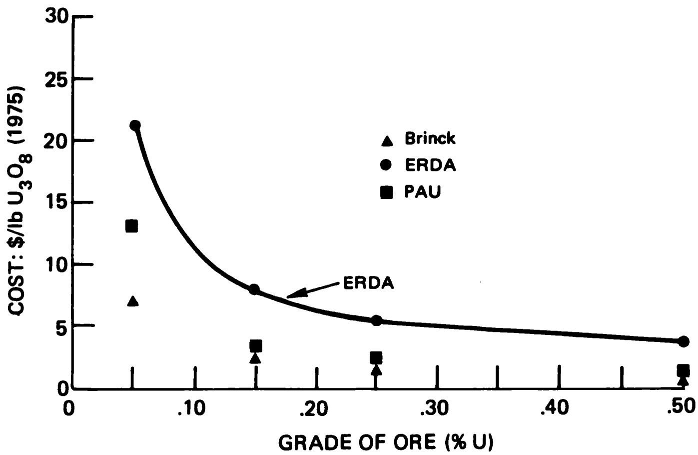
SOURCE: Harris (1977b)

FIGURE 4.8 Discounted production costs for a deposit of 100,000 tons of ore, based on Brinck, ERDA, and PAU models.



SOURCE: Harris (1977b)

FIGURE 4.9 Discounted production costs for a deposit of one million tons of ore, based on Brinck, ERDA, and PAU models.



SOURCE: Harris (1977b)

FIGURE 4.10 Discounted production costs for a deposit of ten million tons of ore, based on Brinck, ERDA, and PAU models.

often when there is no direct evidence indicating a deposit may exist. Because of this uncertainty, the geologist makes adjustments in his resource estimates. I have found that he discounts downward from what is his best estimate. Additionally there is reluctance on the part of the geologist to ascribe a higher endowment to a study area than a control area, even if the geology looks more favorable, simply because to date there is no ore known there. Even if the geology looks extremely favorable in terms of the characteristics in, for example, the NURE checklist, or whatever genetic models are being used, the geologist, by and large, will not give that area a higher potential than the control area.

To some, if not most, geologists the issue of professional modesty is very real. I find the philosophy heavily ingrained in some geologists that it is always better for society to be pleasantly surprised than to be occasionally disappointed. Knowing that his estimates are going to be passed on to policy makers but not knowing how they are going to interpret and use the numbers, the geologist has a tendency to provide conservative estimates. The geologist typically is concerned that too much confidence will be given to his estimates, that the numbers will be overinterpreted. One cannot fault some of this caution in principle, but if there were some way to avoid the difficulties and still have our best estimates of each of the resources, it would be better than having purposely biased estimates for the setting of policy. Mineral policy is like a sword that cuts on both edges: one cannot avoid the consequences of uncertainty by using conservatively biased estimates without running the risk of setting nonoptimum energy policy. A policy made with respect to uranium influences the petroleum, natural gas, and coal industries. Clearly, from the point of view of making energy policy, we need to have our best estimates of potential supply of each energy resource.

The geologist is taught that ore deposits are a result of earth processes. Through some kind of geological function earth processes are translated into endowment. He is also taught that these same earth processes give rise to geologic conditions which are observable. Therefore, under ideal conditions of perfect information about these relationships, even when dealing with concealed deposits, we would be able to infer from observable geologic conditions to earth processes, hence to endowment. Some geologists may attempt to do this, even without complete information, but many do not. Rather, they adopt certain shortcuts. Sometimes they will actually pay little attention to this relationship; instead, they will take a few statistical measures and infer directly to endowment. Others might resort to geographic extrapolation and bypass geology almost totally. More commonly, geologists adopt heuristics ("trendology" is one of them).

The literature on psychometrics suggests that the behavior of geologists in treating the difficult, uncertain task of resource assessment is not unique to them--experts in other fields when faced with estimating an uncertain event behave similarly. Of course the particulars are certainly different.

Man has been found to exibit certain patterns when faced with making a decision under uncertainty. These patterns develop because the mind rebels at synthesizing a great volume of information and making complex calculations when it does not have a means to help integrate it. To counter this, the mind employs heuristics. One of them is called "anchoring and adjustment." Anchoring and adjustment is characterized as picking some feature of the known, ascribing that feature to the unknown, and adjusting it for perceived differences between the known and the unknown. In other words, one makes an initial estimate by using some simplistic criteria, then adjusts for some of the uncertainty, i.e., information not then available. What does that sound like? It sounds quite a bit like geologic analogy; that is exactly what geologic analogy is, a form of anchoring and adjustment, a heuristic.

Another heuristic that is employed is availability--how frequently we experience the event in question. The idea here is that the more probable the occurrence of an event, the more frequently we should have experienced it. But there are problems with this heuristic, for ability to recall an event reflects more the relative frequency of its occurence. We remember preferentially things that are favorable. For example I have found that geologists can speak easily about the characteristics that are associated with known deposits. But, if you turn it around and ask how often these characteristics occur when there is no deposit, the geologist has much difficulty in responding. For very sound reasons, geologists study deposits much more carefully than they study barren areas. One excellent reason is that more information is available.

This raises a basic issue. If we are going to make analogies or subjective assessments, should geologists be encouraged to use heuristics? (Analogies are not all bad; at some point we have to make them). Or, should the geologist, at least to begin with, be required to work within a formalized casting of his science, delaying the introduction of analogy until the conceptual model is no longer useful because the information has been exhausted. This seems to be what we should do, and I am interested in following this up to see how far we can pursue it. But in practice, we will be limited by the state of our geoscience and by data availablity.

SOME PROPOSITIONS

Let me present a few propositions, some of which are a little stronger than I really believe. I have left them that way for purposes of discussion.

1. Resource assessment by "natural" heuristics consists primarily of "trendology" and is of limited use for regions other than those adjacent to producing regions. Here, I am referring to analogy as it has been used, not necessarily improved analogy methods, particularly where they are based on genetic models. Simple geologic analogy is of limited value for estimating potential supply. That is not a criticism of analogy; it merely states the fact that simple geologic analogies cannot produce estimates of potential supply as we want them. They should be used to estimate numbers of deposits and their characteristics, not resources or potential supply.

2. Single-point estimates are inadequate; a statement of reliability is required, which raises the importance of adopting probability analysis in association with our inference method, whether it is geologic analogy or crustal abundance. The numbers currently produced need to be described in terms of confidence, or probability. The methods of geostatistical appraisal should assist the geologist to relate geology, endowment (not resource but endowment), and probability. This is a difficult task and we are not going to achieve it with any degree of rigor for a long time.

3. Formalizing the reasoning process should receive high priority. By this I am suggesting that instead of having the geologist look at maps and derive some intuitive feeling for the number of deposits and their characteristics, we have the geologist examine the pertinent geologic conditions or processes and we ask for his opinion about the likelihood that certain earth processes have transpired, and at some point these probabilities would be combined through a model. The appraisal methodology should assist the geologist in using his geoscience by disaggregating, formalizing the inference rules, and combining the probabilities for earth processes so that they describe the probability for uranium endowment.

4. Comprehensive analysis of potential supply requires improved models of exploration and exploitation. If we are going to estimate endowment, and then use computer models to

translate that to resources and potential supply, we have to have better data and develop better models of exploration and exploitation than we now have. For example, if our endowment includes deposits down to 300 meters in the San Juan Basin, instead of 150 meters, what is the exploration efficiency and cost associated with finding those deposits? And what are the production costs associated with them? We need to have information to quantify these models so that they can be related to the endowment to generate measures of potential supply.

5. We need data on deposit tonnages and grades. I've underlined deposits because I want to emphasize the mineral deposit, not just the ore deposit. For our geology-endowment models and for our exploration and exploitation models, we need to be able to characterize the mineral deposits, not the ore deposits. Data on ore reserves often convey a misconception of the size, grade, and morphology of the mineral deposits as a geologic phenomenon. In order to estimate endowment by geologic assessment, we must have a better perception of the characteristics of the mineral deposit. The data we currently use in assessing an ore deposit is a mix of economics and endowment.

Another reason for needing data on mineral deposits as well as on ore deposits is so we can model the translation of mineral to ore. This is required if we are going to use the endowment estimate as a basis for estimating potential supply.

SOME CURRENT RESEARCH ON AN ENDOWMENT MODEL

Lastly, I present a summary description of a new approach to the assessment of uranium endowment. This work is in progress at the University of Arizona, under contract to the Department of Energy.

Basically, this approach employs subjective probabilities; however, it is very different from previous subjective probability surveys, because the probabilities given by the geologist in the process of evaluating the uranium endowment of a region are for the transpiration of earth processes that cause endowment, not for endowment per se.

To put the approach in perspective, it is helpful to visualize the end product, the use of the appraisal methodology by a geologist to estimate the endowment of a region in U_3O_8. Imagine a geologist seated at a desk upon which there are all relevant geologic maps of the region. At his right and easily accessible to him is a computer terminal through which he can communicate in an interactive mode with a program which resides on the main computer installation. This program is a very special program, because it expresses that geologist's previously determined geologic-endowment model. In other words, it describes what he considers to be the earth processes involved in the formation of uranium deposits. For example, the elements of his model and their interrelationships might look like Figure 4.11.

The computer program contains more than the identity of the processes and their interrelationships. It also describes the probability that the intensity or magnitude of each process (in various combination with other processes) will result in the formation of uranium deposits. The identity of the processes, their interrelations, and the probabilities collectively constitute the geologist's inference net. This inference net is a statement of the geologist's perception of the geology-endowment function--it represents the geoscience of uranium occurence, as he sees it. It is important for proper perspective to understand that the elements of the inference net are processes, such as leaching and oxidation, not geologic observation, such as oxidized sandstone.

The purpose of defining the geologist's inference net is four-fold:

1. Specifying and quantifying such a net encourges the geologist to critical introspection regarding his geoscience.

2. Once it is formed, the inference net relieves the geologist of some of the mental burden of making a quantitative estimate of the endowment of each of many regions.

3. The inference net imposes consistency in the evaluation of regions.

4. The inference net conveys to others the logic structure employed by the geologist in making his endowment estimates.

The nature of the inference net and its use by a geologist in the appraisal of endowment can be demonstrated by the following, highly simplified mathematical analogue. Let endowment, E, be represented by two states e_1 and e_2. Suppose that uranium deposits, hence E, are a resultant of two earth processes: X_1 and X_2. Suppose further that each

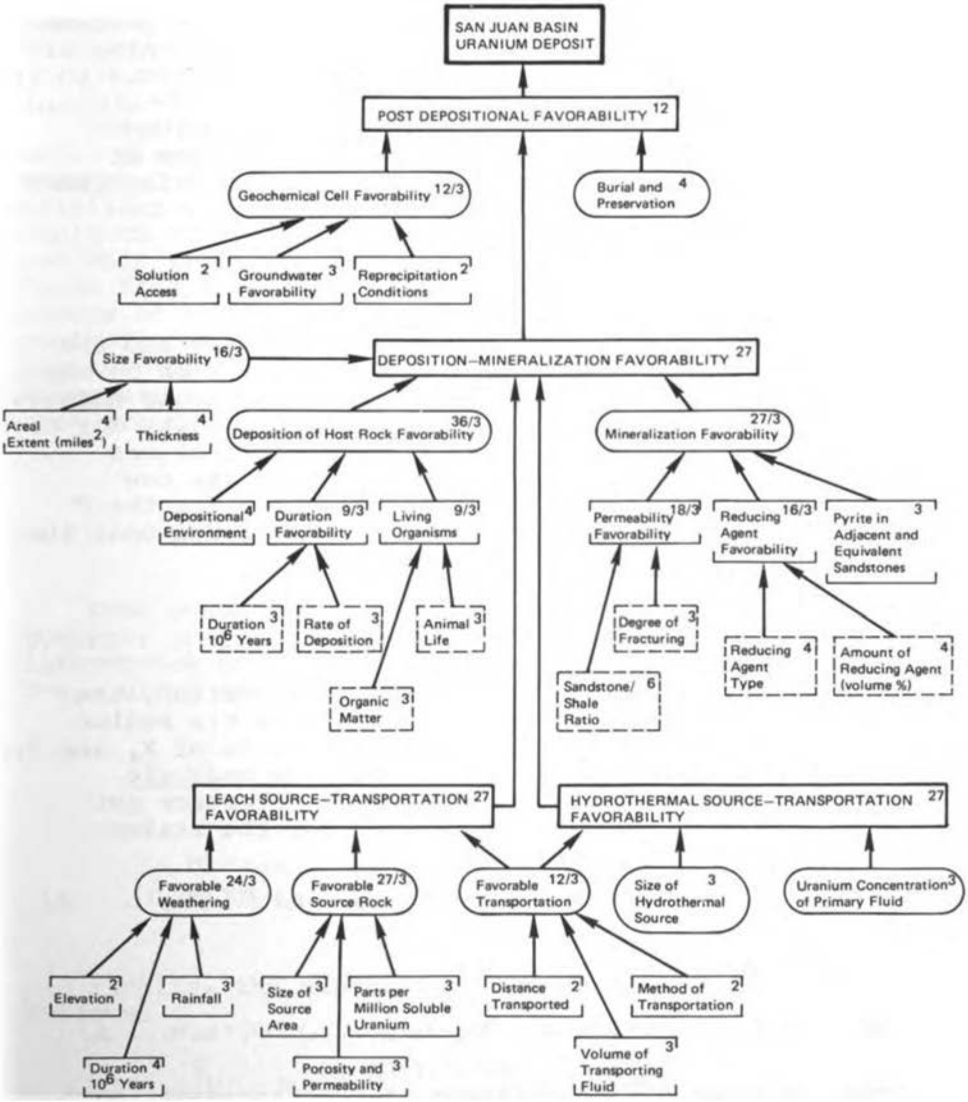


FIGURE 4.11 Elements and interrelations of an inference net.

process has only two states, and that the state of the process is denoted by a second subscript: $X_{11}, X_{12}; X_{21}, X_{22}$.

Then, we can represent the inference net by a set of relations that makes possible the computation of the conditional probabilities $P(E=e_1 | x_{1*}, x_{2*})$ and $P(E=e_2 | x_{1*}, x_{2*})$, where the subscript * represents the known state of the process. Suppose, for example, that it is known that the states are x_{12} and x_{22}. Then, upon communication of these facts to the inference net, it would return $P(E=e_1 | x_{12}, x_{22})$ and $P(E=e_2 | x_{12}, x_{22})$. Thus, the endowment of the region would be described probabilistically. If desired, the expected value of endowment, E, for the region could be computed using these probabilities:

$$\bar{E} = e_1 | \cdot P(E=e_1 | x_{12}, x_{22}) + e_2 \cdot P(E=e_2 | x_{12}, x_{22})$$

Typically, a process may have several states and the geologist may not have absolute knowledge of which of the possible states actually transpired during geologic history. Usually, the best he can do is impute a probability for each possible state by interpretation of geologic features (stratigraphy, lithology, geophysics, etc.). We can represent this by postulating the probability for the i^{th} earth process having state j as being conditional upon the states of n geological variables.

$$P(X_i = x_{ij} | g_1, \ldots, g_n)$$

Suppose that through his subjective evaluation, the geologist determines these probabilities for the region under evaluation. Then, assuming independence of X_1 and X_2, the probability for e_1 conditional upon the <u>geologic variables</u> is determined by combining the inference net probabilities with these probabilities for the states:

$$P(E=e_1 | g_1, \ldots, g_n) = P(E=e_1 | x_{12}, x_{22}) \cdot P(X_1 = x_{12} | g_1, \ldots, g_n) \cdot P(X_2 = x_{22} | g_1, \ldots, g_n)$$

Or, generally

$$P(E=e_r | g_1, \ldots, g_n) = P(E=e_r | x_{i\ell}, x_{jk}) \cdot P(X_i = x_{i\ell} | g_1, \ldots, g_n) \cdot P(X_j = x_{jk} | g_1, \ldots, g_n)$$

Thus, in this simple analogue of two processes, each having two states and of two endowment states, the expected endowment is defined as follows:

$$\bar{E}_{g_1, \ldots, g_n} = \sum_{\ell=1}^{2} \sum_{k=1}^{2} \sum_{r=1}^{2} e_r \cdot P(E=e_r | x_{i\ell}, x_{jk}) \cdot P(X_i = x_{i\ell} | g_1, \ldots, g_n) \cdot P(X_j = x_{jk} | g_1, \ldots, g_n)$$

Consider a numerical example. Let $e_1 = 0.0$, $e_2 =$ 100,000 tons of U_3O_8:

$$P(E=e_1|x_{11},x_{21}) = .5 \qquad P(E=e_2|x_{11},x_{21}) = .5$$
$$P(E=e_1|x_{12},x_{21}) = .2 \qquad P(E=e_2|x_{12},x_{21}) = .8$$
$$P(E=e_1|x_{11},x_{22}) = .3 \qquad P(E=e_2|x_{11},x_{22}) = .7$$
$$P(E=e_1|x_{12},x_{22}) = .1 \qquad P(E=e_2|x_{12},x_{22}) = .9$$

The foregoing probabilities constitute the inference net. Since these describe how the probabilities for endowment states vary with the states of <u>processes</u>, these relations and probabilities are invariant by region. They apply to all regions. Consider now that the geologist is to use this inference net to estimate the U_3O_8 endowment of the Black Rock Region. To do so, he must be able to specify the states of two processes, X_1 and X_2, for that region. The geologist examines all his geologic information; this is represented by the n geologic variables $(g_1,\ldots,g_n)$. Given this information, he estimates the probabilities for the state of each process:

$$P(X_1=x_{11}|g_1,\ldots,g_n) = .4 \qquad P(X_2=x_{21}|g_1,\ldots,g_n) = .2$$
$$P(X_1=x_{12}|g_1,\ldots,g_n) = .6 \qquad P(X_2=x_{22}|g_1,\ldots,g_n) = .8$$

Upon communication of these probabilities to the computer program, they are combined by the program with the infererence net to yield expected probabilities for $E=e_1$ and $E=e_2$, given the geologic observations:

$$P(E=e_1|g_1,\ldots,g_n) = (.5)(.4)(.2) + (.2)(.6)(.2) + (.3)(.4)(.8) + (.1)(.6)(.8)$$
$$P(E=e_1|g_1,\ldots,g_n) = .208$$

$$P(E=e_2|g_1,\ldots,g_n) = (.5)(.4)(.2) + (.8)(.6)(.2) + (.7)(.4)(.8) + (.9)(.6)(.8)$$
$$P(E=e_2|g_1,\ldots,g_n) = .792$$

Finally, the expected endowment is calculated as follows:

$$\bar{E}_{g_1,\ldots,g_n} = (0)\cdot(.208) + (100{,}000)(.792) = \underline{79{,}200}$$

Reduced to its simplest form, the methodology under development at the University of Arizona can be considered to consist of the two major components demonstrated by the simplistic mathematical analogue:

1. The inference net, which consists of those relations required to compute $P(E = e_r | x_{i\ell}, x_{jk})$.

2. The algorithm for the combining of the subjective probabilities for the processes, $P(X_i = x_{i\ell} | g_1, \ldots, g_n)$ with $P(E = e_r | x_{i\ell}, x_{jk})$.

Of course, there are many processes and many geologic conditions, so that the task is much more complex than the simple analogue here described for the purpose of demonstrating the essential concepts.

A major task in real application is the qualifying of the inference net. This will proceed in stages (see Table 4.1). The first stage is simply the identification of the processes. The only contraint imposed is that there are to be three major process combinations:

(1) Source-Transport

(2) Deposition-Mineralization

(3) Postdepositional Preservation

Within each of these combinations, the geologist is free to identify the subprocesses which he believes are important (see Figure 4.11 for an example).

Subsequent to the identification of the elements of the inference net and their interrelations, the geologist is asked to assess the strength of the relations. For example, he would provide the probability for a favorable source, given say, that the source area was large, rising, and contained 10 ppm U. And, he would provide conditional probabilities for the endowment, such as the probability for each of several endowment states, given say, that source, transport, depositional environment, mineralization factors, and postdepositional conditions are all favorable.

Once the inference nets of all participating geologists are formed and specified, each geologist will be provided access through the computer terminal to the inference nets of all other participating geologists. The anonymity of each geologist will be preserved. The purpose here is to promote an examination and comparison of the premises, the concepts embodied in the inference nets. Subsequent to this examination, each geologist is allowed to modify his inference net. The final step of modification will be

TABLE 4.1 Generalized Framework of a Structured Subjective Probability Model for Uranium Resource Appraisal under Development at the University of Arizona

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STAGE I. FORMALIZING GEOSCIENCE

Solicit geologist's inference structure (geologic conditions-->earth processes-->endowment--> probability)

Design computer interactive computer graphics system. Tie to geologist's inference structure

STAGE II. EXCHANGE OF GEOSCIENCE AND MODIFICATION OR REFINEMENT OF SYSTEM

Geologist examines and tests the behavior of his system

Geologist examines and explores through the interactive terminal the inference system of other unidentified geologists

Geologist makes final adjustments on his inference structure

STAGE III. COMPUTATION OF PROBABILITY DISTRIBUTIONS FOR MINERALIZING PROCESSES

Geologist considers the geology of the region and specifies probabilities for each combination of geologic conditions

Probabilities are relayed via computer terminal to the appraisal system

STAGE IV. EVALUATION

Appraisal system computes probability distribution for U_3O_8 using inference structure

Computation of probability distributions for number of deposits, using the U_3O_8 distribution and a tonnage/grade distribution of known deposits

Economic evaluation (simulation of exploration and exploitation)

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calibration. This will be done by specifying various combinations of the states of the processes and modification of the previously specified strengths of relations (probabilities) so that the probabilities computed from the net for each of the states of endowment are acceptable to the geologist who identified and specified the inference net.

Once the inference net is calibrated, it will be ready for use in the appraisal of uranium endowment. For each region of interest, the geologist estimates, after examination and appropriate review of geologic information, the probabilities for each state of each earth process. These are transmitted to the computer program which combines them with the inference net probabilities, thereby producing expected probabilities for each endowment state.

The methodology just described clearly provides estimates of endowment in the aggregate. In order to estimate potential supply for specified costs, the product of this methodology would be the input to an economic evaluation routine. In this routine, the aggregate of endowment would be decomposed using the log-normal probability distributions for deposit size and grade. Then, the expoloration for and production of each of these deposits would be simulated for each of a number of specified prices. In this way, the potential supply of the region could be described (see Figure 4.12).

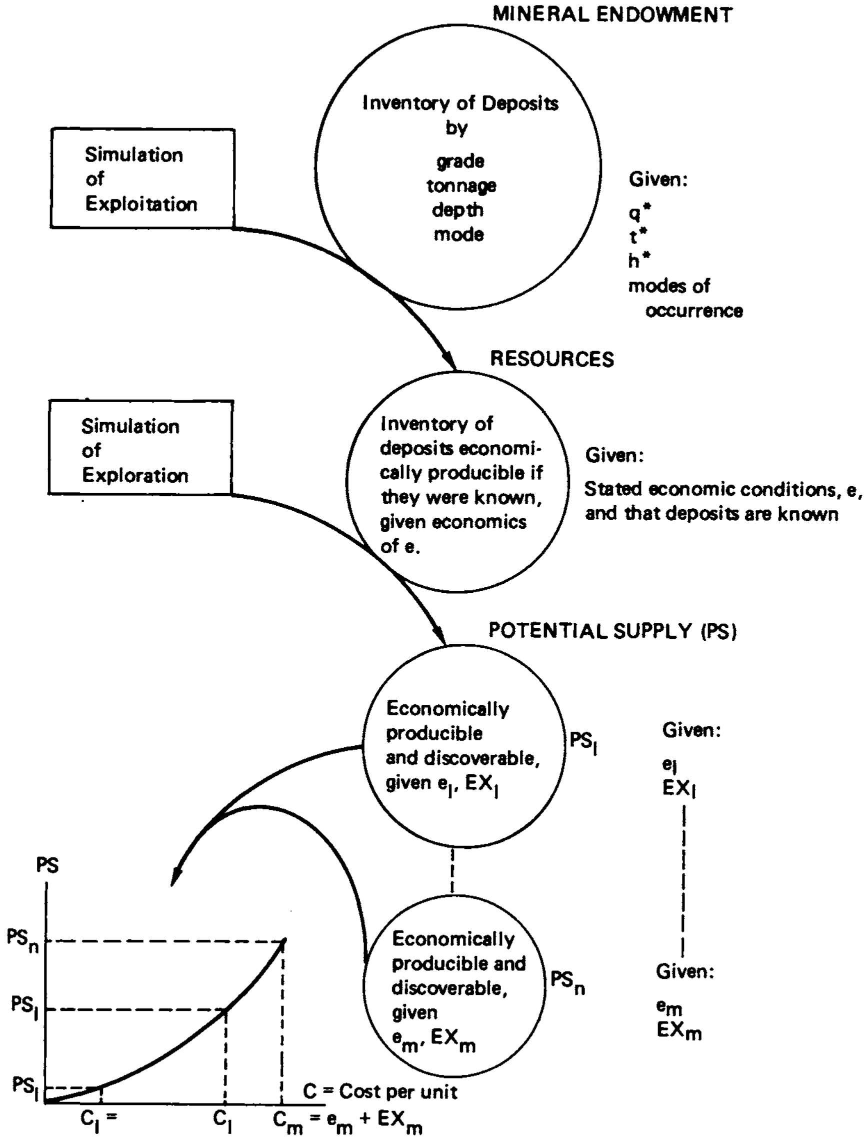

FIGURE 4.12 A potential supply system (model).

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CHAPTER 5

DISCUSSION

INVITED COMMENTS

RICHARD F. DOUGLAS: First, what is the definition of "resources"? Assuming that we expect identified resources will be extractable in a certain time period, what is that time period in this discussion? Is a 25-year period reasonable, or are we discussing a much longer period? Second, is there a limitation on depth of mineral deposits in our discussion? If we are going to talk about something that is extractable, we have to deal with a realistic depths, ones within which we can operate. These are two points that I did not catch in the discussion if they were mentioned.

In connection with a point made by Curry, it should be noted that in the years 1959 to 1965 industry did not drill in the Powder River Basin to any substantial depth largely because of a lack of incentive to do so. The market was poor and industry was restricting exploration to a known shallow horizon; there was no point in spending money when it might not be returned. When the market improved, industry did drill to greater depths.

Regarding the formula that Curry presented, I think one of the critical difficulties with it is the "favorability factor". Unfortunately, geologists do not have the detailed knowledge of favorability that is needed to come up with a reasonable numerical factor for such a formula. There are numerous cases of exploration in what was generally considered as favorable areas, but in which no mineralization was found. There is a great amount of uncertainty as to whether we recognize all the factors which create the favorable conditions. We know them in gross fashion but not in detail. There is an X factor that appears to be missing from our understanding of "favorability". Because of the dynamic processes involved in ore formation, we may not be able to examine an ore deposit and observe all the factors that produced the favorable conditions which controlled the localization of mineralization. The reason is, I believe, that some important factor making up part of the "favorable condition" was obliterated as ore was formed. What is there now is something different which cannot be, in total, directly related to the localization of the mineral deposit. Unfortunately, we cannot examine barren but favorable-appearing areas in an attempt to discover the X factor, for the area may be barren because the X factor was never present. If what I say is valid, then the formula which Curry presented will not provide a very accurate picture of resource potential. In the initial evaluation of the Powder River Basin, the estimators assigned a 90 percent favorability factor which, based on later data, had to be reduced to 50 percent. And I would not be surprised if, with additional data, they might have to reduce it some more. If this approach is used, it may not provide assessments of the right magnitude. In other words, the result could be an overestimate of resources for public planning.

In regard to Finch's progress report, I agree wholeheartedly that we should evaluate geologic provinces rather than arbitrary areas. The study Finch described is in its early stages. I wonder if we will not face the same kind of problems in relating tonnage and grade to resources that we do in judging favorability factors. The models for Curry's uranium deposits are not new; indeed, much that Finch showed in the table in regard to the sandstone uranium deposits has been recognized. My question is: how will this modeling give us a better resource understanding, or indeed, show us what the resource of the area might be? I frankly do not think that we can make a straightforward analogy between a known area and an unknown area, measure the volume of the unknown, and determine the magnitude of the resource. I think we have to go back to collecting basic geologic and geochemical data--for example, lead isotope distributions. It is possible that with this approach (basic-data collecting and analysis) we could outline favorable geologic provinces regardless of the type of host.

Finch divided his model on the basis of depths of less than 2,000 meters and greater than 2,000 meters. I wonder if the category of resources at greater than 2,000 meters is realistic in terms of uranium extractable in the next 25 years. It would be interesting to know but it may not solve our problems.

As to McCammon's talk, I am always concerned that the manipulation of subjective data through the use of a computer gives some appearance of greater accuracy to the end product than is truly there. I think the computer is great in its flexibility and is useful in analyzing large quantities of data, but it is subjective data that goes in and what comes out has no greater accuracy than the input.

Is it really the ultimate resource that we are interested in, or is it our ability to produce uranium at a rate to maintain the health of the nation? The slope of the production curve is far more important than the total quantity of resources that anyone may estimate. Let us recognize that the curve is likely to be skewed but once we go below what is called the "health" line, the total resource will not make any difference. We should study the slope of the rate of discovery and the rate of extraction as intensely as we study the ultimate resource.

With regard to Harris's talk, I think it is true that, historically, geologists working on uranium reserves have been conservative. It is true because geologists were on a learning curve. That is not necessarily true today in terms of calculating ore reserves, but we will have to wait and see. I have been involved in ore reserve studies for some years, so speaking from personal experience I can say that I do not adjust reserves downward as a hedge against uncertainty; I establish what I consider to be reasonable factors based on data available and geology, and I estimate reserves on that basis. There may be a conservative factor in the geological projection, but I make no deliberate attempts to downgrade the reserve estimate because I feel uncertain about it.

I would agree with Finch's statement that you cannot project or postulate an ore trend out of its own particular district. Also, I do not think one can use simple analogy to estimate the potential uranium resource for the country.

Through the various studies that are to be made, we can hope to improve our exploration models, but we need a lot of improvement, especially in some basic factors. For example, there were interesting observations in the 1950s that, as far as I know, were never followed up. One of these was the study by Gene Shoemaker and several others on whether the size of a uranium ore body in the Uravan mineral belt could be predicted by studying various ratios of trace elements. Results suggested that they could. As far as I know, that was never followed up and never attempted outside the Uravan mineral belt. It would be interesting to do some research along that line.

MILTON O. CHILDERS: I think that anyone who believes he can come up with a realistic estimate of our resources is either conceited or ignorant as regards uranium geology. I think we are interested in the small portion of the total resources that is properly called a potential reserve--something we would be capable of discovering and producing in a reasonable period of time such as 25 years. My perspective is that of an exploration geologist and not a statistician; and I am not personnally involved in trying to make realistic estimates of uranium resources. But from my experience as an explorationist I can conceive of many models and of many areas which are, potentially, uranium producing areas. I think that the total potential is many times what we will be capable of discovering and producing in the next 25 years.

The USGS and ERDA have been coring in the Granite Mountains of Wyoming. Most of the genetic models for uranium occurrences in Wyoming postulate that the uranium came from the Granite Mountains. The core hole data reported in open file by Stuckless and others indicate that uranium has been mobilized to very considerable depths in those granites, possibly to 600 meters. Previous calculations based on estimates of the amount of the uraniferous granite weathered during Eocene and post-Eocene time gave us a high potential for uranium occurrences in the Wyoming uranium province. The new data from this core drilling will expand the potential (if the most commonly accepted genetic model is valid) to where we should have plenty of uranium for the next 25 years in the United States.

I think another problem is that the models described by Curry and Finch tend to reflect what we have considered significant U.S. occurrences in the past. If the same approach had been used for estimating the resources in Australia a few years ago, they would have come up with practically nothing of consequence; yet the major new reserves that have been added to the world supply are in Australia and are in a type of deposit that we had not considered to be as important as the sandstone-type deposits. Look also at the calcrete deposits that have been developed in Western Australia.

If we are concerned with how much uranium we can produce in the next 25 years we should re-examine the types of models we are dealing with. I think we have tremendous possibilities for deposits in the United States, including Alaska, in what I call structure-controlled deposits, similar to those in Northern Territory, Australia, and those that have recently been discovered in Saskatchewan. These are major new reserves but these genetic types were not considered significant a few years ago and I do not think they are being adequately considered in the United States now.

In regard to time factors, it takes a few years, say three or four years, to drill out 500 million pounds of reserves in the case of Jabiluka, Northern Territory, Australia, whereas it takes ten to fifteen or twenty years to drill out that amount of reserves in Wyoming roll front deposits, especially the present lower grade deposits. The roll front deposits being drilled today are not comparable to the old Gas Hills and Shirley Basin occurrences, so it takes a lot of drilling per pound compared to the structure-controlled deposits.

With regard to the models that Finch is describing, I like to look back at some of the exploration and the theories and models that geologists used in the past and see how this would affect our projection of reserves or resources for the future. The model of the Powder River Basin used initially by most geologists indicated that most of the significant deposits would be limited to the early Eocene, Wasatch or Wind River Formations. Later work showed that we had roll fronts in the Fort Union and older formations. Now roll fronts are being drilled in the Fox Hills and Lance formations.

One theory popular for the origin of those deposits was that the uranium was leached from overlying tuffaceous rocks of post-Eocene age. A lot of information now available indicates that the uranium came from the granite and that the roll-front deposits might have developed as an early diagenetic feature almost at the time the sediments were accumulating in the Eocene.

Last spring (1977) I was present at discussions concerning deposits found at depths of 900 meters in one of the new trends of the San Juan mineral belt in New Mexico. The question was raised of placing a hydrodynamic limit on the depth that uranium can theoretically occur in the San Juan Basin based on the old concept that the uranium was introduced at a time much later than the origin of the sedimentary host. But data now coming out indicate that there would theoretically be no limit to depth because the uranium was deposited in those sands very soon after the sediments themselves were deposited. The conceptual models that we use can either downgrade or upgrade the estimates very significantly, and typically, the factors introduced tend to reduce our estimates.

As an explorationist I very often find it impossible to rate these concepts in a meaningful way. I have seen the forms that ERDA sends around to industry and I consider the procedure unrealistic. I think the idea of projecting our discovery and production capability is better than trying to estimate the total potential resources. This number would not be a significant number if it were many times larger than the realistic amount we can find and produce.

CHARLES D. MASTERS: National resource assessments are intended to give some insight into future possibilities for the recovery of a desired resource. The resource numbers themselves are only useful when related to economically controlled factors, such as industry capability as reflected in rates of production, rates of discovery, and technology development. To that end, it is useful to divide the resource base into component parts to which appropriate econometrics can be applied. A system of resource reporting adhering to these principles has been agreed to by the two major resource agencies in Government, the U.S. Geological Survey and the U.S. Bureau of Mines (see USGS Bull. 1450-A). Conceptually, then, a plan for resource reporting has been devised and all resource reporting by these two agencies follows the agreed upon pattern. Though conceptual agreement has been reached, each commodity has its own peculiar data problems; hence an operational definition to fit the conceptual pattern must be evolved for each mineral. Coal is the only commodity to date for which an operational agreement has been reached (see USGS Bull. 1450-B), but the essentials of an operational classification within the guidelines of Bulletin 1450-A have been reported for oil and gas in USGS Circular 725. The basic classification system is now well established and has received general endorsement by Resources for the Future in a study of mineral resource classification systems prepared for the Electric Power Research Institute (Schanz 1976), and with respect to coal by the International Energy Agency.

Resource assessments, in general, are prepared for a very broad audience, and they must be both reliable and credible to that audience. The reliability, of course, depends on the data and methodology used in developing the assessment. Its credibility, however, depends on many subjective factors including consistency and clarity of presentation to that large audience. To the extent that all mineral assessments are reported in similar terms, greater understanding can be anticipated. I recommend, therefore, that the Department of Energy (DOE) abandon its system of classification and that DOE and the Department of the Interior (DOI) devise operational definitions for uranium resource reporting that are consistent with the conceptual classification system reported in USGS Bulletin 1450-A.

Following the concepts developed for other minerals, certain resource reporting factors are important for uranium and thorium: (1) there should be a clear distinction between identified and undiscovered resources, (2) the undiscovered resources should be reported as a range of values reflecting a spread of uncertainity about the resource base, (3) to avoid assessing elements in crustal abundance, there should be a lower-boundary limit, and (4) reporting units should be in physical terms (tonnage and grade) with inferences as to specific cost or price reserved for separate analysis.

The USGS-USBM system (see Fig. 5.1) attempts to clearly separate those resources which are truly "undiscovered" from those portions of the resources that will become reserves as a result of extensions and revisions to already identified measured reserves. The former are classified as "undiscovered-hypothetical" (USGS Bull. 1450-A), whereas the latter are classified as "identified-inferred"; identified because they are a part of a known accumulation, inferred because they have not yet been delineated by mining or drilling. Those deposits that are not an extension of existing measured reserves clearly cannot be assessed with the same degree of probability as those that are; therefore, it is not statistically accurate to combine the two estimates. For this reason, the DOE classification of "probable potential" (see Fig. 5.1) should be abandoned because of its inclusion in a single category of resources attributed to deposit growth as well as resources attributed to new discoveries, however well controlled by geology.

The undiscovered resources (DOE's "possible" and "speculative potential" plus part of "probable potential" that is related to deposit growth) should be recorded as a range of values (Harris 1976), reflecting on the one hand a high probability of occurrence and on the other hand a low probability of occurrence. The former can be considered hypothetical resources in USGS-USBM terminology, and the latter speculative resources (Sheldon 1975). The range of probabilities for national resource reporting should represent a substantial portion of the resources conceived possible to exist but it need not include those resources, conceived or unconceived, that are of such low probability of occurrence as to be an inappropriate basis for the development of national resource policy. For oil and gas, the Geological Survey estimates have included 90 percent of the conceived potential by reporting a range of probabilities from 95 percent to 5 percent probabiltity. In my judgment, this is an appropriate range of probabilities for most natural resource reporting.

Because a resource represents an accumulation of minerals that has the potential of becoming a reserve, it is important to exclude from the designation of resources, large low-grade deposits that in the perception of the estimator will never become a reserve. The idea here is to exclude "gold in the ocean" from the resource concept, or specifically, in this case, uranium in the Chattanooga shale, to give one example. The highest grade reported in the Chattanooga shale is 0.007 percent U_3O_8; and the lowest cutoff grade in a commercial deposit is probably about 0.02 percent U_3O_8, in a deposit where the average grade is close to 0.1 percent U_3O_8. A lower limit of 0.01 percent U_3O_8, therefore, would encompass all known commercial deposits and would exclude an accumulation that in many people's judgment

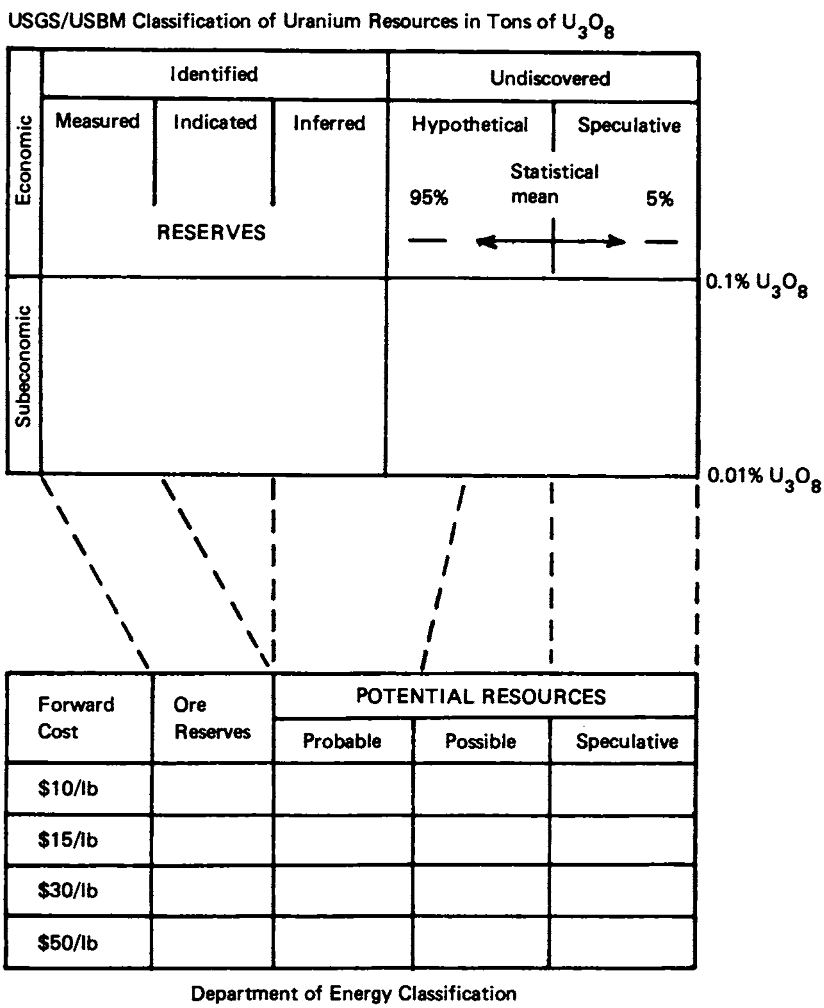

FIGURE 5.1 Approximate correlation between U.S. Geological Survey/U.S. Bureau of Mines and Department of Energy resource classification systems.

probably will never be a resource. At this stage, the precise recommended grade is not so important as the concept of a lower-boundary limit determined by an assay grade rather than by an economic measure. A grade limitation does not preclude the assessment of Chattanooga uranium content but it does relegate that assessment clearly to a non-resource category of reporting where the tonnage reported will not likely confound the issue of reasonably expected potential availability of uranium resources.

In any resource assessment, a distinction must be made between accumulations perceived now to be economic and accumulations considered only potentially economic or subeconomic. When considering the economics of a deposit, there are obviously many variables. Physically, the variables of greatest concern are deposit size, grade, and location (geographic as well as geologic). All of these factors must be considered in an economic analysis but probably grade is the most important consideration. In that all uranium ore that is being mined today can be presumed to be economic, a weighted average grade (approximately 0.1 percent U_3O_8) of the total tonnage mined is a useful national measure of approximate economic richness and serves as a guide to project into the category of undiscovered resources. It must be remembered that the numbers being reported are national averages and that it is expected that local exceptions occur; for national planning, the local conditions are not significant. This system is to be preferred over reporting numbers in forward cost categories, because variatons in inflation can change the tonnage reported in a given forward cost category with there having been no additions or subtractions of the physical resource. Resources should be defined physically as well as economically but the two should be kept separate except in very general terms (see also Harris 1977).

One final area of resource reporting that is included in the USGS-USBM system is the category of "indicated reserves". That category is intended to describe reserve potential that is intermediate in geologic assurance between measured and inferred reserves. In fact, it has proved difficult to delineate quantitatively that segment of reserves. In oil and gas, indicated reserves are those accumulations that are potentially subject to fluid injection but the engineering has yet to be applied to commence production of the additional oil. The category is useful to describe known reserves of any kind that are not yet readied for production by whatever appropriate engineering applications. I recommend that the category "indicated reserves" remain only loosely defined until such time as studies of the reserve data permit a clearer distinction to be made.

In conclusion, it is my considered judgment, given the high visibility of uranium resource reporting in the next few years, that the government should change the reporting classification now to conform to the USGS-USBM classification. Such a change would make resource reporting parallel with that of other minerals and thereby improve overall understanding. The valuable economic analyses represented by forward cost can be retained but as a separate presentation. Failure to change the reporting classification will obfuscate the national assessment to be presented in 1981, and to delay for any substantial period of time will weaken the impact of that assessment.

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GENERAL DISCUSSION

CURRY: In the 1950s there were programs for the purchase of uranium which were cut back by the allocation system. That does not alter the fact, however, that the information we had for estimating potential resources at that time was based upon all that had gone before. In 1959, we lacked an understanding of the geologic environment because it simply had not been developed. But in something like a 15-year interval, a considerable amount of information was generated on which to substantially increase our estimates. Our estimate of potential plus production plus reserves in 1959 was 5,000 tons of U_3O_8 but there is no question that our 1959 figure could be raised substantially after new knowledge was acquired. As time goes on, we improve our information base and make revisions. I am not prepared to say that the estimates will go up or go down. The principal thing I was trying to bring out by comparing 1959 and 1972 figures is that changing knowledge of the geologic environment has an impact on adjustments to resources.

The model presented as part of the basis for estimating capability was simply one model of a sandstone environment. Finch and I acknowledge a need for new models, covering new environments, and this is one of the things Finch and his group are working on. Some of our Bendix counterparts in Grand Junction are working on new models, and we will utilize the information as it becomes available.

Calcrete deposits were mentioned. An ERDA contract with UCLA is underway to investigate the calcrete environment. This has been in progress for something like ten months, and we hope information will be generated under this contract that will be useful in constructing a model. We have other ongoing contracts and we just completed one at the University of North Carolina to evaluate granite. The information from these contracts and all other information available to us will be used in the development of new and different models and improving old models. We are looking at more and more environments and getting away from reliance on simple models based on the sandstone deposits.

FINCH: I will comment first on the matter of depth. I mentioned two depth categories: one down to 2,000 meters, and the other greater than 2,000 meters. At present, deposits at less than 2,000 meters may prove to be economic, but greater than 2,000 meters would probably be subeconomic. With new technologies, maybe the deposits at depths greater than 2,000 meters would become economic within a 25-year period.

My paper was just a progress report, and it pointed out that we will put emphasis increasingly on the non-sandstone models. I used the sandstone model as an example because the others are not as well developed.

There is another relationship that I did not dwell on, and that is, we need to know the volumetric relation between the deposits and the geologic provinces in which they are found. The metamorphic unconformity-related deposits that occur in Northern Australia and Saskatchewan, Canada, are among the largest and highest grade deposits that we know of. They are associated also with rather large geologic provinces, measuring several hundred miles across. The Pine Creek province in Northern Australia is a couple hundred miles across; the Saskatchewan province is equally large in size. Do we have provinces in the United States that are as large for finding those kinds of deposits? Is it necessary that the province be large to find the very large deposits? Is it reasonable to expect to find five or six major types of deposits in the United States? On the North American continent we have already identified quartz-pebble conglomerate deposits and the metamorphic unconformity-related deposits, and the two major kinds in the United States, the sandstone deposits and the classic vein-type deposits. Is it reasonable to expect to find in the lower 48 states and Alaska all the various major types of uranium occurrence? This is a question that can be addressed if we develop the models to a fuller extent than we have so far.

CURRY: Modelling has its advantages in that anybody who has tried it finds out pretty fast what he does not know about what he is doing. A model forces you to challenge or to come to grips with some of your basic assumptions. In order for any of these models to be useful you have to state your ground rules and identify the assumptions in order to move forward and I think this is healthy. The model should force the geologist to think more about what he is actually doing in the field when he is making his geologic investigation.

UNIDENTIFIED SPEAKER: When the geologist in industry is working on a conceptual model and he tells management that he would like them to spend a million dollars to drill on the basis of this theory, he is forced to consider all possibilities. He does not look at it lightly. The trouble with programming on the computer is that you tend to assign numbers to things that are not known in quantifiable terms; and once the number is assigned it becomes fixed in people's minds as being a quantitative thing when it really is not. The numbers are based on very subjective, very tentative feelings. There are many different things the geologist considers when appraising the favorability factor and I challenge anyone to say that it is quantitative.

GREENWOOD: Harris argues that geologic analogy tends to have a conservative bias. But I wonder whether the history of oil and gas does not belie the argument. The estimates made before the 1970s by geologic analogy have turned out to be generally higher than what most people consider to be realistic today. I'm wondering whether that experience applies to uranium or is uranium somewhat different from gas and oil, and therefore, one ought to accept the statement that resource estimation based on geologic analogy is conservative in this area.

KOCH: I would like to expand on Greenwood's statement. The estimates are low because we are trying to talk ourselves into scarcity. We will have to wait a few years to see who was right: the optimists of the 1950s or the pessimists of the 1970s. I think the high estimates are correct or even low. I think Harris's factors shown on the slides are much too rough on our profession. The professional modesty he depicted is overpowered by professional immodesty of other people who are making policy. When you say professional modesty makes mistakes remember that professional immodesty also makes mistakes.

SCHANZ: The 25-year time limit mentioned earlier refers to what will become usable, not what will be found and produced in that time. The time factor limits what you have access to in the way of ore, assuming discovery. That means that you advance your concept of the technology of exploration, of development and of mining to a greater depth than at present, but that does not mean you are going to detect something or mine material that you could not detect or mine now. Considering a 25-year time factor sets a limit to your imagination in terms of technological advancement or economic changes.

On the matter of declining estimates over time, I don't think we should confuse analogs with resource forecasts. In building analogs we use some familiar geologic environment and compare it with an area that appears to have the same geological characteristics. We use analogy as a means of interpreting what we find in the new area. The estimates that have declined were forecasts of undiscovered resources where we have had a change of judgment, but I do not think we should confuse the growing pessimism in judgments with the analog problem. On the other hand, an analog can show us only what we know about a given environment, and cannot tell us what we have not yet discovered. For these reasons we should not push the analog too far as a means of assessing regional endowment. However, it still has use in evaluating resources, perhaps not in assessing the mean expectation of endowment but perhaps our minimum expectation.

On the resource-definition problem many of us are trying to refine the different kinds of occurrences that fall in the subeconomic category but without including everything. There are gradations in this category that we want to take into consideration, but we do not want to mislead the uninitiated. I would like to underscore the necessity for clarity in definition and the immediate need to get our definitions in order. And this brings in the question of accuracy of measurement versus confidence factors versus probability. These numbers are sometimes intermingled indiscriminately. In estimating the size of a deposit I can state a tonnage and say the figure is plus or minus 20 percent and that is an accuracy factor. The next thing is a confidence factor which evaluates the data on which the judgment is based, i.e. how good a forecast have I made? I can make a very poor confidence forecast of a very high probability event. If I am right, the probability is it will be very big but that is different from assigning a probability to it. I think some people intermingle the confidence of what they are able to say about something with the probability of what might be there. The question is, "what is the likelihood of something happening?" If I have hazy impressions of the geology, I am going to have a low confidence value. On the other hand, once I have decided what I think the geology is, then I can assign a probability to the characteristics of the deposits, e.g. size distributions, etc. I think we are indiscriminately rolling these numbers together, and it is about time we straighten them out.

MASTERS: Greenwood raised the question of comparing the history of estimating oil reserves with estimating uranium. It seems to me that the earlier oil estimates were not based on a true geologic analogy similar to what we are doing in uranium or similar to what we are doing in USGS Circular 725. I think they were real estate analogies rather than geologic analogies as we are trying to do them now.

I would like to ask the commentators whether it is fair to characterize their response by saying their perception is that there are uranium resources of such a magnitude that the primary problem of the next 25 years is not in the size of the resource but rather our ability to find a producer.

This is, in effect, a judgment that the resources are large, and that we are not working on the right problem.

CURRY: That is certainly my opinion.

DOUGLAS: No, I think the size of the resource and the ability to produce it are equal problems. In the near term the problem is planning and producing, but in the long term the size of the resource becomes crucial depending upon the viability and vitality of nuclear power.

UNIDENTIFIED SPEAKER: Part of the problem is that we have to look beyond 25 years. We visualized having the breeder reactor around the end of the century. If you are looking at resources being adequate in 25 years and you are working on technologies that take 25 years to develop, the decision points do not hold up. You have to be able to look beyond 25 years and make judgments about uranium availability and economics 50 or perhaps 75 years from now.

DOUGLAS: On that basis, then, I feel that uranium resource is a problem and therefore there should be some concern about the fact that there is not going to be a breeder reactor at the proper time.

ZODIACO: There are a lot of government people here who were talking about national planning. The implementation of any national plan requires commitment through a lot of private decisions and that detracts from the credibility of any short-term or long-term assessment of resources. That ought to be kept in mind when we are trying to decide what task we are asking the scientific and engineering communities to address, and what priorities ought to be assigned.

I think this relates to the point that was just raised. Is it a problem of production capability or is it a problem of resources? I agree with Douglas: both are parts of the problem. But I think the horizon ought to be limited or at least the emphasis should be placed on that portion of the horizon that requires capital commitment. Nothing is going to happen no matter what plan is developed unless someone is willing to risk a sizeable amount of capital.

McCAMMON: Regarding the point about limitation on resources: as I understand it, there is no limitation in terms of the earth. Is there a limitation in terms of grade? Is the Chattanooga shale or sea water going to be taken into account in this identification of resources?

MASTERS: We have a concept of how to report resources although we have not yet refined it to an operational procedure for uranium. We have not done so because the flow of dollars in the government budget for the last two or three years has given ERDA the responsibility for national resource assessment figures and the USGS did not work on detailed definitions. We are working now on an operational concept, and we have tried to sort out crustal abundance, because those are very big numbers that tend to confuse the issue of near-term producibility. In thinking of operating cutoffs, I do not like to think of Chattanooga shale as being realistically available in the next few decades. My suggestion has been to make the bottom at 0.01 percent U_3O_8, and make the break in the economic and subeconomic categories at a grade of 0.1 percent U_3O_8. It really does not matter in detail where you put the cutoff but conceptually the resources beyond that cutoff should be reported separately.

DOUGLAS: I would agree with you . Let's report conceptually. I think that has been one of our problems: we have been reporting as producible reserves different classifications which should not be reported together.

FLAWN: The discussion of methodologies has presented a very useful and stimulating checklist that has given a sense of order and a sense of near-quantitative respectability to numbers that are based on subjective judgments. I think subjective judgment in all of these methods is so large that it is the determining factor.

We have been talking about the physical resource base but we also have a technology resource base; we have a financial resource base; we have a manpower resource base; and then inevitably we have a policy resource base, which is the legal, political, judicial, administrative structure that makes it possible to take a piece of what we have found and put it to use. I do not see how you can spend two days talking about potential uranium resources, unless you have in the back of your mind the reality that finding it is not nearly as big a piece of the puzzle as it used to be.

SILVERMAN: Your observations are very pertinent. It is a question of where in the total discussion and analysis of the problem those considerations are brought to bear. I think that many social-political aspects of the problem are outside the competence of most of the people who are here, except where it bears on their role as producers and on the problems of production. But we have not considered that an appropriate theme for discussion. There are many additional considerations which relate to the theories of assessment that still need to be raised.

The speakers at this session, especially the speakers with geologic backgrounds, have strongly emphasized the importance of developing adequate genetic models and of developing methodology for using the models in order to process data. Only one person discussed the problem of getting more data and kinds of needed data. He felt it would be advantageous if we could hold geologists to a formal thinking, a formal logic, which would require them to discuss the non-occurence of uranium, as well as the occurrences of uranium. We could then place the whole matter in a context which would then permit us to use crustal abundance data as well as ore deposit information in our considerations.

Both ERDA and the U.S. Geological Survey have massive programs of data collection which are directed toward supplying new information to feed the models from which appraisals of resources will be made. The question can still be asked as to whether or not the right kinds of data are being obtained, and whether we will be able to build better models of uranium occurrence and distribution after this massive effort is completed. Perhaps we are thinking only in terms of existing models during this data collection effort rather than thinking in terms of the basic scientific information from which new models spring. Further consideration should be given to these questions: How good is the data base for assessment? What new information is required by the model? What should be done to ensure the dynamic development of new models as new information becomes available? And lastly, how can we test the models that we think closely resemble the real world?

PART II

GRADE AND FORWARD COST CATEGORIES OF CLASSIFICATION

CHAPTER 6

ERDA FORWARD COST CONCEPTS

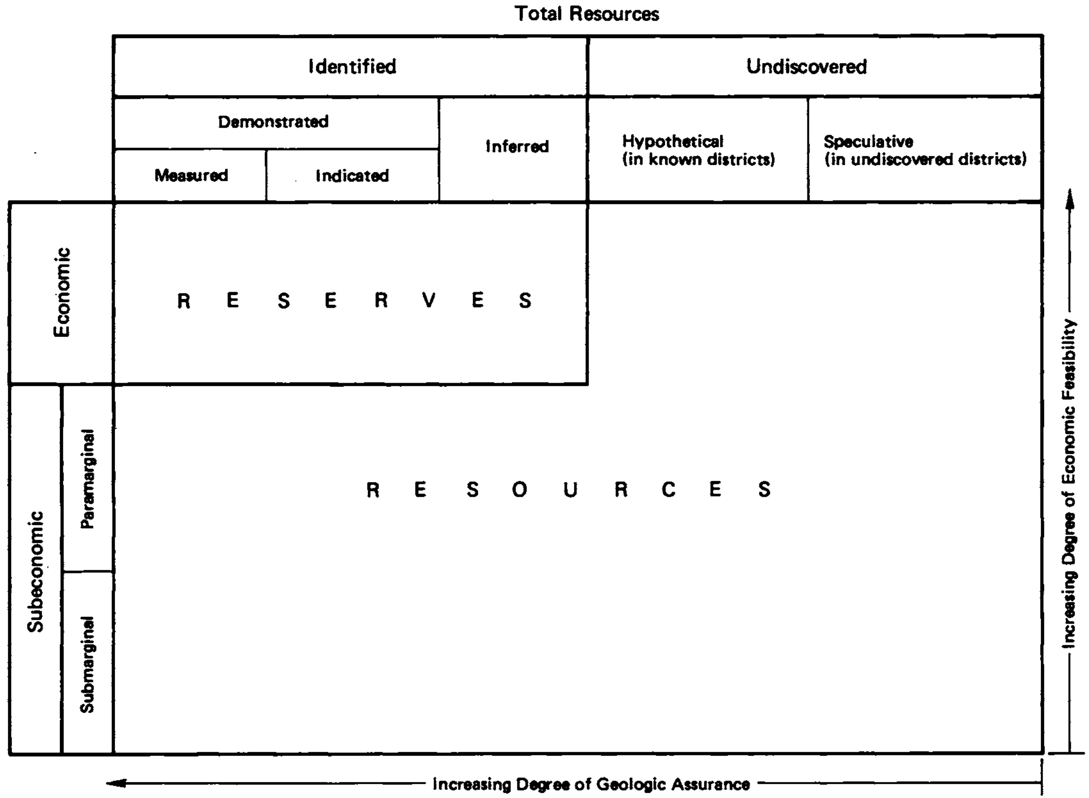
John A. Patterson

The basis for use of forward cost concepts for resource appraisal is sometimes misunderstood or misapplied. So I would like to review the historical basis for using the concept, how the concept relates to industry decision-making practice, and consider the possible choices in selecting economic appraisal criteria and their advantages and disadvantages.

HISTORICAL BASIS

It might be instructive to review how use of the forward cost concept got started in uranium resource appraisal. The concept evolved in relation to the responsibilities of the Atomic Energy Commission (AEC) in uranium procurement and resource evaluation. The initial AEC efforts in resource appraisal dealt with the uranium in properties tributary to mills from which the AEC was going to buy uranium concentrates. These mills were to be amortized by the Government, generally in a short period of time. The main concern of AEC was (1) to assure that a firm supply of uranium ore existed for the mill so we were sure of getting the uranium and (2) to assure that reserves were adequate for the amortization of the project.

The basic question being answered in such appraisals was: What quantity of material is going to be mined from the tributary deposits under various ore or uranium concentrate cost levels? This question underlies the appraisal work of the uranium procurement program of AEC and by ERDA. The purpose of our appraisals has not been to develop market prices, but rather to appraise resources. Misconceptions on this point have led to a lot of confusion. There have been a number of attempts, particularly in the last three or four years, to relate cost-based resource appraisal concepts to the market process, attempting to find market (sales) prices. However, since these appraisals were never intended



SOURCE: USGS (1976)

FIGURE 6.1 Classification of mineral resources.

to be models or bases for determining prices, the information resulting from such appraisals is generally inadequate for price estimation although it does provide some indication of prices. Additional data and analyses are needed for a proper evaluation of prices.

ECONOMICS AND RESOURCES

In dealing with resources, it is generally recognized that economics are an important consideration. Figure 6.1 presents the resource classification scheme of the Department of Interior (1976 USGS Bull. 1450-A). Note that the terms "economic", "subeconomic", "submarginal", and "paramarginal" are used as resource classes based on the criteria of economics. In our work we use dollar values rather than imprecise conceptual economic boundaries.

Some students of resource problems are more concerned about estimates of the total resource endowment. However, estimates of the total mineral endowment are not of much use unless there is some indication of whether those resources are economically available. For example, you can be assured that there are at least 20 million tons of uranium in the United States. If that estimate alone could satisfy our needs, there would be no problem of adequacy of domestic uranium resources. However, such an estimate does not meet our needs. From what we know now, a large part of a 20 million ton resource will require costs of production that are too high to be of interest even in a very efficient nuclear power plant. We must consider the availability of the resources under some reasonable economic criteria.

MINE PRODUCTION DECISIONS

In using economic criteria for resource appraisal, the primary question is: What can the miner produce from a deposit over the long term? An illustration may clarify the economic considerations that mine operators face. Figure 6.2 shows a truck loaded with uranium ore that has come out of a pit and is under a radiometric scanner. Three counters take radiation readings, and equipment in a shack nearby integrates the data and calculates a uranium grade for the load of ore. The truck will move out on the road from this site and the operator in the shack will flash a light hanging over the road to inform the truck driver where he should take that load. A decision must be made as to whether the truckload is going to the waste dump, the main ore bin for feeding to the mill, or to some intermediate-grade stockpile. At that point of the decision-making

FIGURE 6.2 Loaded truck under radiation counters—an ore or waste decision point.

chain, the question is: Does the ore in the truck have some economic value, shall we throw it away, process it, or set it aside for future use? If the ore has sufficient uranium content that would more than pay for the cost of hauling it to the mill and processing it, it makes sense to process it. In deciding which pile to put that truckload in, should one ask: How much did it cost us to find it? What are the expenses at the home office? What did it cost us to build the mill? I don't think so.

This choice is basically what the forward cost concept attempts--trying to identify and segregate the mineral material that has economic value to the operator and identifying the factors he consideres in his decision-making process about what materials he will mine. A number of decisions are made in this process. Back in the pit, the ore grade control man examines the ore exposures and stakes out the limits of material to be mined. This process delineates the area that will be segregated and carefully mined, as distinct from areas that will be handled as waste. But there were earlier decisions to be made: Do we sink a pit on a particular deposit or not? What are we going to include in a pit design? Where do we draw the lines on the pit limits? And so it goes, back through the history of the operation. At every decision point, we must look at where we are at that point and consider the operating costs and the capital costs that lie ahead for the operation. But once you have decided to go in and mine the deposit, you are back down to the decision of what ore to mine, what will be included in the production chain. These decisions determine the material that should be included in the resource estimate for that property. The same decisions must be made underground. Where are the limits of the vein you are going to extract so you can include it in your reserve and production plans? For new mines there is the decision on whether to put in the capital investment to open the mine.

In appraising potential or undiscovered resource areas, you must again face these decisions and consider what is going to be the cost of production and what is going to be the overall cost of producing materials expected to be found. You must analyze the cost chain ahead of you to decide whether you want to go into areas for exploration. But after you make an exploration or mine development decision, after you analyze the chain of expenditures to be faced, the final key decision is: What is the lowest grade material that you can plan to extract?

We do not usually take into account in our mineral resource appraisal work the fact that some rock not included in a reserve will be mined as a consequence of mine development and stoping activities. This material is usually set aside if it has any mineral content, to be used if prices increase or if there are shortages of mill feed. In the last two or three years with increased prices we have seen a lot of such material going through uranium mills.

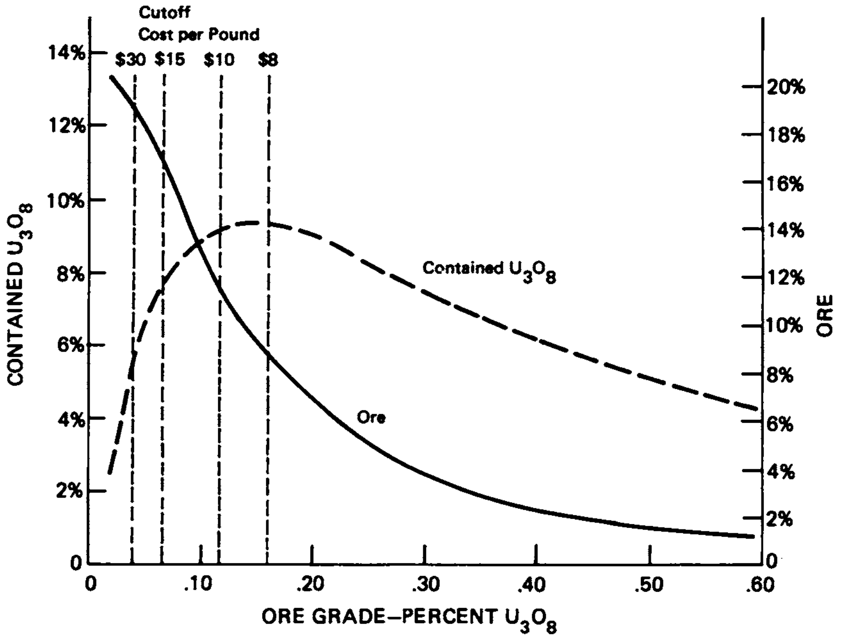
CHARACTER OF ORE DEPOSITS

An important characteristic of resources that we must not forget when considering economics is that ore deposits are not discrete individual units that have one specific ore grade and a specific tonnage. Deposits are populations of mineralized materials of varying grade, thickness and configuration. A typical sandstone-type deposit uranium-distribution curve is shown in Figure 6.3. The graph shows the distribution of ore and of the contained U_3O_8 as a function of grade. What is ore and what is an ore deposit depends on what we choose to include. This determination is done primarily through the "grade cutoff." The amount of ore and uranium that will be included will increase as cutoff grades are decreased.

Figure 6.4 shows the uranium distribution on a cumulative basis as a function of cutoff grade. The cutoff costs per pound of U_3O_8 are noted at the corresponding calculated cutoff grades for this deposit. It is a characteristic of most sandstone deposits, the type that contains most of U.S. uranium resources, that at the $30 cutoff cost the cutoff grade is below the grades that contain most of the uranium.

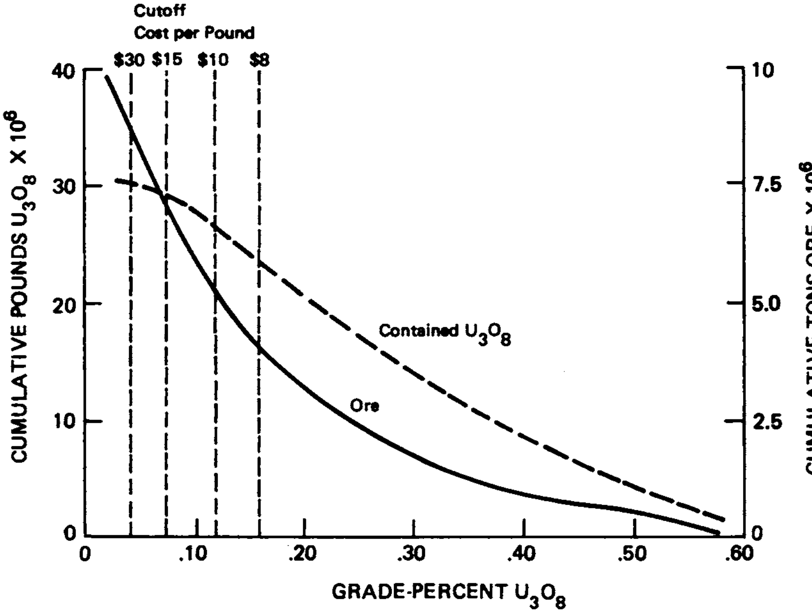
ECONOMIC APPRAISAL CRITERIA

We have considered the importance of decision making by mine operators in determining resources and the nature of the distribution of uranium in deposits. What are the different criteria we could use considering economics to evaluate resources? Table 6.1 is a list of some possible



SOURCE: U.S. ERDA (1974)

FIGURE 6.3 Incremental distribution of reserves by grade and cutoff cost per pound for a typical sandstone-type uranium deposit.



SOURCE: U.S. ERDA (1974)

FIGURE 6.4 Cumulative distribution of reserves by grade and cutoff cost per pound for a typical sandstone-type uranium deposit.

TABLE 6.1 Economic Criteria

1. Grade Cutoffs
2. Forward Cost (Operating and Capital)
3. Total Costs (Forward Plus Sunk Costs)
4. Forward Cost + Return on Investment (ROI)
5. Total Costs + ROI
6. Market Price

economic criteria. Let's consider them in order. Grade Cutoff is not strictly economic value but the grade is a useful measure as it generally is the variable most closely related to variations in the economics of ore deposits. In response to requests, DOE is now publishing data on the distribution of the mineral inventories down to a grade of 0.01 percent U_3O_8 grade cutoffs without regard to economics. However, in our view the use of cutoff grades alone is not an adequate measure of the economic availability of uranium resources. Uranium deposits are so variable in their individual nature that, although they may have the same grade, the variations in size, depth, location, thickness of ore, amenability to processing, and so on could result in widely varying development and production costs.

Another economic criterion is, of course, Forward Cost. We consider forward costs, operating and capital costs in a two-step basis following the procedures indicated in Table 6.2. In Section I, operating cost is the principal determinant as to what material will be included in a resource evaluation as it determines cutoff grades for the deposit in consideration. Capital costs, Section II, however, are estimated and average costs including capital costs have to be below the cost cutoff that we use. Total Costs would be forward cost plus sunk costs. Sunk costs present problems in that they are difficult to obtain from companies. And even if you had access to data, it is not clear what corporation sunk costs are appropriate to a particular deposit. For operating properties, or those tributary to existing mills, questions of past amortization are relevant. This is a data area where it is difficult to get the needed data or to make an estimate for that cost element.

Another possibility would be to use Forward Cost plus a Return on Investment rather than strictly production and capital expenditures. One could use Total Cost together

TABLE 6.2 Reserve Estimation Cost Procedure

I. Operating Costs

Calculate cutoff grade of ore to be included in estimate by

- estimating operating costs per ton of ore
- determining for the cost category (such as $15 per pound) the pounds per ton content at which costs equal estimated operating costs

With minimum thickness determine

- limits of deposit
- contained tons of ore
- average grade
- uranium content

Estimate average operating cost per pound of U_3O_8

II. Capital Costs

Estimate total capital costs required to develop mine and construct mill

Estimate average capital cost per pound

Sum of operation and capital costs per pound must be less than cost category level with a Return on Investment and/or Market Price. The term "Market Price" is used since some consider the criteria with return on investment as if they were price, which in my view, they are not. Price is what you can actually buy or sell something for in the market place which involves factors beyond costs and return on investment.

GRADE CUTOFF

Let's examine some of the options in more detail. Note that for the Grade Cutoff approach ERDA data (Table 6.3) shows the post-production uranium mineral inventory as of January 1, 1977 at various grade cutoffs. We call this an inventory, not reserves, as economics are not considered. However, the materials included are delineated to an extent that they would otherwise meet reserve criteria. The inventory includes material at least two feet thick for open-pit mining and at least six feet thick for underground mining. Shown for each cutoff are the cumulative tons of ore estimated, the average grades of that ore, and the cumulative contained U_3O_8. The total U_3O_8 is almost 1,200,000 tons. Since at $30 forward cost, we estimate 680,000 tons and at $50 we estimate 840,000 tons U_3O_8 you can get some idea of the importance of the distinction between simple grade cutoffs and the economic cutoffs based on forward costs.

FORWARD COSTS

In regard to Forward Costs in determination of what is to be included in an individual deposit, i.e., the cutoff grade, the concepts in Table 6.4 are very important to understanding how forward costs are used in evaluating uranium reserves. When we talk about including both operating and capital cost in forward costs, some tend to think that the cutoff cost value and cutoff grade automatically include each of these costs. I hope our discussion so far shows that is not correct. We consider operating costs--first and separately as the measure of where to draw the line between ore and waste--the assay wall.

As shown in Table 6.4 at the cutoff grade, the recoverable value of mineral in the ore equals the cost of producing that material. In other words, the recoverable uranium content of the ore has a value equal to the cost of drilling and blasting the ore, loading it, hoisting it to the surface, hauling it to a mill, processing it, and paying royalties--that is, paying all the out-of-pocket costs

Table 6.3 United States Postproduction Uranium Mineral Inventory, 1/1/77

Minimum Grade (% U_3O_8)	Cumulative Tons of Ore (millions)	Average Grade (% U_3O_8) of Cumulative Tons	Cumulative Tons U_3O_8 (thousands)
.01	2,748	.04	1,184
.02	1,791	.06	1,035
.03	1,206	.07	896
.04	872	.09	788
.05	656	.11	696
.06	456	.13	585
.07	365	.15	528
.08	298	.16	480
.09	250	.18	443
.10	211	.19	409
.11	181	.21	380
.12	156	.23	354
.13	135	.25	332
.14	118	.26	311
.15	104	.28	292
.16	92	.29	268
.17	83	.31	256
.18	74	.32	238
.19	67	.34	229
.20	61	.35	215
.21	56	.37	208
.22	51	.38	196
.23	47	.39	185
.24	44	.41	179
.25-Over	40	.42	169

NOTE: These figures do not represent ore reserves, since the economics of exploitation are not taken into account.

SOURCE: U.S. ERDA (1977).

involved in the production chain. All out-of-pocket operating costs can be recovered at the uranium value assumed. Any material at a lower grade than the cutoff involves more out-of-pocket expenditures than can be recovered and hence a loss of money. Any material with a higher grade than the cutoff will provide a return in excess of the out-of-pocket costs and would be produced. While some of such lower grade ores may not be paying a full share of what might be allocated on an average basis to every ton of ore considering sunk costs, overhead, etc., each ton will make some contribution to overhead or other costs.

Economic theory shows, and our studies have shown, that in practice, recovery of all material down to the cutoff grade will provide the maximum return from the exploitation of an ore deposit. The direct cost items included in this computation are shown in Figure 6.4. The recovered value is a function of the amount of uranium contained, the ore grade, the recovery rate to be achieved in processing the ore, and the U_3O_8 value assumed. To determine cutoff, we set value equal to costs and solve for grade.

In making an ore reserve estimate, we identify sample points equalling or exceeding cutoff grade and having at least the minimum thicknesses of ore required for the mining system that was assumed. This is done by estimating the operating costs and then determining for each cost category, such as \$10, \$15, \$30, or \$50, what the corresponding cutoff grade would be. We should note here that it is our practice in considering value of U_3O_8 to consider these values as cost-related rather than as being a price. We started to do this about five years ago as a more accurate description of our practice. While the differences may not have been obvious at the time, the difference between cost and price as a practical matter are more clear these days.

Using the cutoff and minimum thickness data and reviewing sample data, we can determine the limits of the deposit, the amount of ore contained, the uranium content of that ore, and the average grade. From this we can calculate what an average operating cost per pound would be for that deposit. Since we are only including material above a certain grade, the average grade of all material included will be higher than the cutoff. Similarly, the average operating cost per pound will be less than forward cost per pound that we selected.

Under the forward cost concept, we would then estimate the capital costs remaining to be expended to produce the reserve that we have estimated and which will have to be incurred subsequent to the time the estimate is made. At this point, we are seeking to determine if there is sufficient excess value in the ore over operating costs to

TABLE 6.4 Cutoff Grade

At Cutoff Grade, recovered value equals direct cost per ton of ore
Direct Costs = Mining + milling + haulage + royalty costs/ton
Recovered Value = Price per pound of U_3O_8 x mill recovery rate x ore grade x 20
Cutoff Grade = $\dfrac{\text{Cost of mining, milling, hauling, royalty}}{\text{Prices per pound of } U_3O_8 \text{ x mill recovery rate x 20}}$

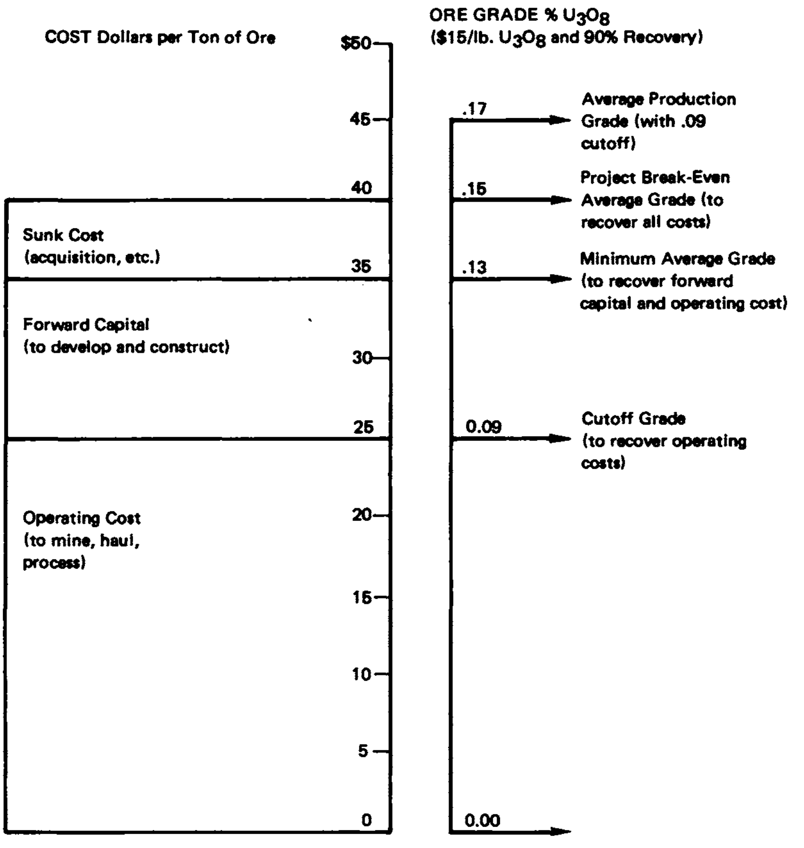
allow recovery of forward capital costs. For a new ore body, we estimate the needed costs of developing the mine (such as shaft sinking or overburden stripping), and the construction of a mill, or whatever facilities and equipment that may be needed to produce salable uranium concentrates. The total capital costs, when related to the uranium content of the deposit, gives us an average capital cost per pound of U_3O_8. The sum of the capital and operating costs per pound must be less than the cutoff costs criteria to retain the resource in the category.

We can see how this works for a specific deposit in Figure 6.5. On the left side cost items are shown, on the right the related ore grades. For an operating cost of $25 per ton of ore, we calculate that at $15 per pound U_3O_8 and 90 percent mill recovery our cutoff would be 0.09 percent U_3O_8. Anything of lesser grade than that is not ore under the assumptions. The average grade of all the ore 0.09 percent U_3O_8 and above was 0.17 percent, which is a typical relationship between cutoff and average grade for a sandstone-type uranium deposit. Continuing with the process, we then estimate the forward capital cost to be about $10 per ton and total forward costs then are $35 at which cost the ore from the mine would have to average at least 0.13 percent. If we were to include sunk costs, say at $5 per ton, a break-even grade to 0.15 percent on the entire project costs would be needed. The average grade of 0.17 percent is still higher than required by the economic criteria, and some additional return on investment will be received.

COST PROFILES

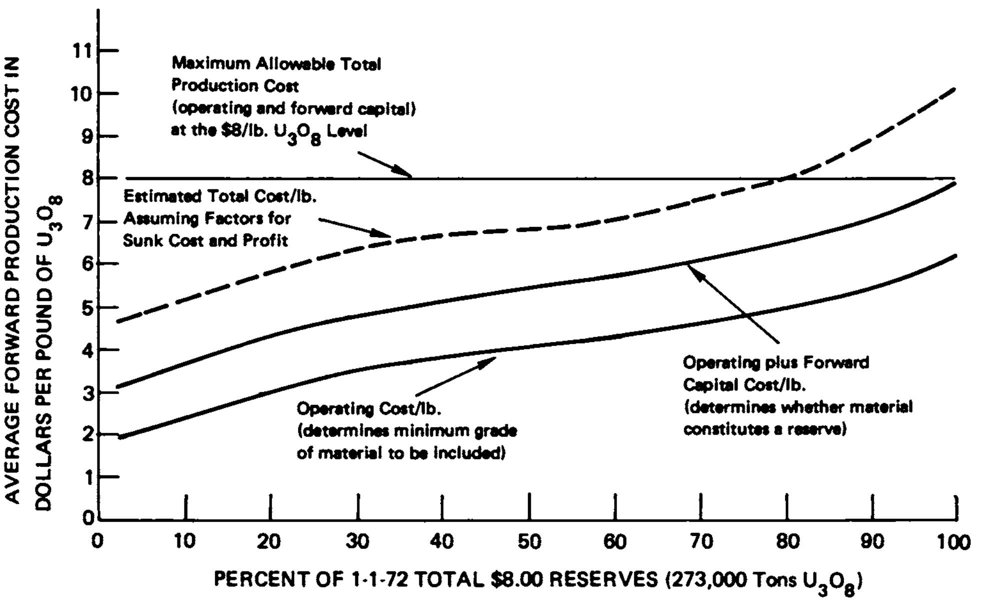
The other aspect of this approach which seems to be forgotten frequently is that when we talk about $15 or $30 material, it does not mean that all material which has been included in the estimate has that cost of production--actually, almost all of the material is of lesser cost. As the distribution diagrams we examined before suggest, there is a profile of grades for the reserves included in an overall estimate and there is a profile of costs.

A profile for an $8 reserve study done in 1972 is shown in Figure 6.6. The bottom line shows the profile of operating costs starting with the lowest cost material at the left. The next line shows the profile of operating plus capital costs. The third line is the cost profile adding a factor for sunk costs and return on investment. Note that on an operating cost basis, some properties had U_3O_8 production costs as low as $2 per pound while some were over $6 per pound. There are a few properties where total



SOURCE: Patterson (1976)

FIGURE 6.5 Ore deposit costs and ore grades (undeveloped ore deposit).



SOURCE: Patterson (1973)

FIGURE 6.6 $8.00 ore reserves cost profile (percentage of total reserves with respect to cost per pound of U_3O_8).

forward costs were almost at an $8 level. Including all costs, some 20 percent of the reserves had total costs of over $8 per pound.

SELECTING ECONOMIC CRITERIA

We must consider the realities involved in selecting and using economic criteria for resource appraisal. We can think about what we would like to have in the way of criteria and data, but in practice we will have to use what is workable, and for which the data are obtainable, and keep in mind that our objective is to estimate the contained and extractable resources. In Table 6.5 are listed some of the considerations involved under general headings of practicality and usefulness. First, are the data needed for using economic criteria available or can they be estimated? In other words, if you are going to use economic criteria, you must have cost data or there should be some way that you can approximate those costs. Secondly, there should not be too much dependence on data from the companies on their current costs or past expenditures. While you can estimate current costs, it is more difficult to deal with past expenditures. There should also be minimum information needed on corporate and financial policies such as cash flow goals, required rates of return, the company financial situation, investment opportunities, corporate financial goals or marketing policies. Trying to evaluate resources with criteria that involve company policy will be very difficult.

The economic criteria used should not be overly sensitive to changes in the economic conditions, such as those resulting from inflation, changes in price, changes in marketing practices, etc. These factors have been very significant for uranium the last several years. Inflation has been a problem. There has been a rapid increase in prices and in the costs of labor, materials, and power required to produce uranium. These changes would, of course, cause problems in any economic evaluation system. Marketing practice has also evolved considerably in the last three or four years. The short commercial life of the uranium business has seen remarkable variations in practice.

At the same time, we should have a system that provides some basis for assuring that we have consistent estimates between estimators--that we can deal with the economic criteria from one estimator to another in a reliable way, and consistent manner. One of the problems in the resource field is nomenclature and standards. In practice, nomenclature used tends to sweep problems under the rug. We say "economic" and "producible", etc., but those kinds of

TABLE 6.5 Considerations in Selecting Economic Criteria for Resource Appraisal

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Practicability--Workable System for Estimating Contained and Extractable Resources

- Data needed are available or can be estimated
- Minimal data needed on company current costs and past expenditures
- Minimal information needed on company corporate policies such as financial and marketing policy or alternative investment opportunities and financial situation
- Not sensitive to changes in economic situation - such as inflation, price changes, and marketing practice
- Allows consistent estimates by various estimators and between commodities

Usefulness--Results Can Be Used for Sound Decision Making

- Measures relative economic availability of the resource
- Useful for near-term economic decisions
- Useful for long-term planning

TABLE 6.6 Evaluation of Economic Criteria

	Grade Cutoffs	Forward Cost	Total Cost	Forward Cost and ROI	Total Cost & ROI	Market Price
Practicability						
Data accessibility	+	+	-	-	0	-
Insensitive to economic change	+	0	0	0	0	-
Consistency of estimates	+	+	-	0	-	-
Usefulness						
Measure of relative economic availability	-	+	+	+	+	0
Basis for economic decision	-	+	+	+	+	+

+ Strong Point (The economic criteria are especially practical or useful for the considera- noted)

0 Average (The economic criteria provide no special advantage or disadvantage compared to other criteria, for the consideration noted)

- Weak Point (The economic criteria are not practical or useful for the consideration noted) terms do not provide adequate guidance to estimators. Estimates can be made but they are not consistently done.

In addition to being practical, the criteria selected must provide results that are useful in decision making with assurance that decisions based on these data will be sound. The system should, therefore, provide, as a minimum, some measure of the economic availability of the resource. The data should also be useful for near-term economic decisions, primarily those related to what is going on in the market place, such as near-term production planning and actions responding to current price and economic changes. Also, the results should be useful for longer term considerations, such as national planning and developing corporate strategy that are related to long-term economic effects and costs rather than variations in the market place.

APPRAISING THE CRITERIA

How well do the different criteria that we identified earlier (Table 6.1) meet these considerations (Table 6.5)? Table 6.6 presents our appraisal. Grade Cutoff would be very good in terms of data accessibility. You do not have to worry about cost data; they are very insensitive to economic change. You could get consistent estimates with grade cutoffs, but the results are of little use for economic-related decisions.

For the Forward Cost concept, the data are either accessible from the companies or they can be estimated adequately. We do have complaints sometimes that our costs are low but this is a result of the inflationary conditions and of keeping up with what is going on. We can provide very consistent estimates that can be defined quite specifically as to what is included and how the system works. I think it provides a good measure of relative economic availability and the results are useful for economic decisions.

The Total Cost concept would pose some difficult problems for data accessibility and consistency of estimates.

Forward Cost with Return on Investment could also have some problems with data accessibility, but perhaps they could be handled. Consistency of estimates could be a problem as there are a number of different ways of handling rates of return. Results would be useful, again, in economic decisions.

Total costs with return on investment which include sunk costs would present data problems. Results would be very useful in economic decisions.

The Market Price criterion, which involves some intangibles that go beyond those included in cost concepts, would provide data problems. Systems related to market prices would have had a very difficult time over the last few years. This criterion, of course, would be very sensitive to economic changes. It would not be a good economic measure for the long term where costs are more relevant than market prices.

In summary, I have reviewed the history of use of Forward Costs by AEC, the relationship to decision making in the mining industry on what is to be mined, and for development of new mines. The forward cost system was compared with other possible systems considering practicality and usefulness of results. The forward cost system does provide a measure of economic availability. There are problems in trying to relate it to current or future prices. We have done some work in such relationships and will be doing more. While the forward cost system has received some criticism, most of the criticism I hear relates to misunderstanding or misuse. Unquestionably there are things we can do to better explain the system or to improve the methodology. I would be quite interested in having any comments or suggestions you might have.

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CHAPTER 7

DISCUSSION

INVITED COMMENTS

VINCENT P. ZODIACO: One of the most exciting moments at a baseball game is when a good defensive infield executes a crisp double play. The play-by-play announcer might describe it like this: "The ball is hit hard to the shortstop ... he goes to his left, fields the ball cleanly, tosses it to second base where the pivot man ... WHERE'S THE PIVOT MAN?" WHO'S THE PIVOT MAN?

That may be a clumsy and certainly a concocted way to introduce you to how the electric utility sees itself, but it perhaps makes a point that I believe is important.

Of course the utility sees itself as the pivot man--the man in the middle who must know when to move to the bag--take the toss from the shortstop, step on the base, pivot smartly, and fire the ball to the first base for the second putout. Oh--there's one other thing-- he has to avoid the sliding base runner's efforts to send him to the hospital and break up the play.

In the game of fuel supply let me just list the players, and you can put them in whatever position you like:

- the suppliers (the vendors)
- the electric customers
- the regulators (both state and federal)
- the stockholders
- the bankers and bondholders
- and, of course, the pivot man--the electric utility management

A current vintage nuclear generating facility can easily cost a thousand dollars per kilowatt of capacity to install--that's one billion dollars for today's typical size unit and then over a 30-year lifetime several billion dollars more to own and operate. The uranium to fuel one of these facilities for 30 years, at current prices, costs about 600 million dollars. The decision to commit that sort of money requires a judgment on the part of utility management that the nuclear facility will be able to operate for its planned lifetime well enough to not only return all the capital and operating expenses invested, but to provide some return (we used to proudly call this profit) to the stockholders.

The key words then for the utility become reliability and economy. And, historically, the selling of the nuclear power option to the utility required the establishment of the concepts of nuclear reliability and nuclear economy--of course, both of these were and are measured against the available fossil-fuel options.

Fuel supply, or more simply, uranium supply is a key issue influencing both the reliability and economy of nuclear power. The availability of a measurable quantity of uranium at some predictable cost is a key input required to the "build or not build a nuclear generating station" decision. In fact, it is difficult to answer the question "how much?" without providing some assumptions which address or directly answer the question "for how much?" Both questions must be asked and answered with some measured degree of certainty for the utility manager to prudently commit to any form of generation.

The idea of economically recoverable fuel reserves is natural and reasonably accepted by the utility manager. The concept of "forward cost" is perceived then as a way to address the "for how much?" or the "economically recoverable" criteria to the fuel resource question that the utility must ask. It is fair then to investigate the concept of "forward cost".

There are two reasons to test the "forward cost" concept. The first is so that the utility user is able to understand and apply the concept. The second is so that the user is able to properly represent the availability of fuel to the utility decision maker.

The problem is to understand and qualify how much of the "economically recoverable" or "for how much" answers are provided by forward costs.

The first confusion that the utility fuel manager is likely to experience is called the "forward cost for price syndrome". Although he can quickly learn that forward cost does not represent price if he just listens and believes what he is told, forward cost does not represent price.

Well, then, if forward cost doesn't represent or is not relatable to price, what does it measure? The answer given is that forward cost is the added cost to extract the uranium from the ground and process it to yellowcake in the can. It's legitimate to ask, "cost added to what?" Again the answer: Whatever is invested to date!

Well, even though at this point I've given up on the strict concept of economic recoverability because we've lost any absolute reference frame, I'm still intrigued with the concepts of added effort and dollar cost, and I continue my investigation.

As one digs deeper into the "forward cost" concept, the test becomes: How well is the added effort measured by the concept and application? For example: Does forward cost include the cost of capital to build a mine and a mill to recover the uranium ore? The answer is: No. The concept as now used doesn't include equity or interest returns as a cost. Nor does it include taxes or profit as components of forward cost.

How then does "forward cost" represent economic recovery or answer the question "for how much"? We're told that forward cost does attempt to measure the economic cost of labor, materials, and depreciation of assets to produce yellowcake; but admittedly, there are some problems there--especially with geographic location of ore deposits and the effects of inflation.

One can conclude then that what the forward cost concept does do it does marginally, and what it doesn't do is measure the "full" economic effort to extract uranium; and again, it certainly can't represent a selling price.

Now with some insight the utility fuel manager can accommodate to the system. As I observed earlier, the need for some economic measure is obvious. Also the utility fuel manager can recognize the difficulty of the task and the need for governmental objectivity and discretion. But in the absence of meaningful criteria, the usefulness of forward cost and the usefulness of the reserve estimates themselves become the real issues.

A real test of that usefulness comes in the Board Room as one tries to explain what "forward cost" means and how and why it is not related to price. After experiencing this a few times, the utility manager--our fictional "pivot man" from my earlier example--may, as I have done, abandon the use of the ERDA forward cost categories altogether and simply use the reserve/resource discriminator. But he may spend a lot of time worrying about where to really draw the line between reserves for future supply and resource as a gleam in someone's eye.

My task here was to present to you a utility viewpoint in the "forward cost" concept. I hope that I have succeeded in demonstrating that perspective. However, please allow me to attempt some constructive comments:

1. We recognize that a reserve is not a reserve unless someone either is committed, or can be economically justified, to take the ore out of the ground at today's price.

2. The forward cost concept has attempted to gauge, if crudely, just the above criterion--only it has worked backwards from geologic information to dollars.

3. Some multivariate approach may be necessary to do all that ERDA has tried to do with "forward cost". That is, some system that first considers: the ore body size and location, the ore grade and thickness, the depth and number of minable horizons, and whether the yellowcake is a primary or secondary product, and then applies some economic measure (using stated assumptions) of what price would be required to bring this ore to market.

LEWIS J. PERL: The purpose of these comments is to review the reasonableness of the forward cost concept as a measure of the costs of uranium extraction. In evaluating forward costs, I take the view that the best assessment of costs would be one that reflected the true resource cost to society associated with extracting uranium. In addition, it would be useful if such a cost assessment provided a guide to product price. My evaluation should be viewed in this context.

Forward costs have often been criticized on the grounds that they make no allowance at all for sunk capital expenditures for reserves which are already in production. From an economic perspective this criticism seems to me to be entirely inappropriate. In deciding whether or not to produce a particular reserve at a specified price, recovering a reasonable return on previous investments is a desirable goal which nevertheless should not influence the decision of whether or not to produce. Consequently, if the purpose of forward cost is to provide a guide to the _minimum_ supply price at which specific reserves would be produced, it is entirely appropriate to ignore such costs. Costs of

Table 7.1 Forward Costs and Economic Costs of Reserves by Type of Mine, Ore Grade, and Class of Reserves (based on the 15 percent discount rate and 3,000 T/CD milling capacity.)

Type of Mine	Ore Grade Percent U_3O_8	In Production			Not in Production		
		Economic Cost ($/lb)	Forward Cost ($/lb)	Ratio Economic Cost/ Forward Cost	Economic Cost ($/lb)	Forward Cost ($/lb)	Ratio Economic Cost/ Forward Cost
Open Pit	0.20	5.80	4.45	1.30	8.05	5.24	1.54
	0.10	9.86	7.65	1.29	13.90	9.08	1.53
	0.05	17.62	13.65	1.29	25.42	16.39	1.55
Underground	0.25	6.84	4.85	1.41	10.58	6.17	1.71
	0.10	10.88	7.72	1.41	20.47	11.09	1.85
	1.05	17.94	12.72	1.41	33.05	18.07	1.83

reserves in production should include only operating costs and deferred capital expenses; costs of reserves not in production but discovered should not include the capital expenditure associated with exploration and discovery; and all capital costs, including the capital costs of exploration, discovery, mining and milling, should be included when estimating the economic costs of resources.

The primary weakness of the forward cost concept is its failure to take into account a reasonable rate of return on invested capital. Since the investment in exploration and in mining and milling facilities commences substantially before the beginning of production, the construction cost of these facilities understates the resource costs of this investment. The cost to society of making these capital investments includes not only construction costs but the return which could have been earned had they been invested in other activities. A more appropriate assessment of mining costs is provided by discounted cash flow analysis which includes a reasonable rate of return on investment. Calculations which I have made suggest that the discounted cash flow cost of various reserves would range from 1.3 to 1.8 times the forward cost at a 15 percent discount rate. These ratios are reproduced in Table 7.1.

A third difficulty in either forward cost or discounted cash flow analyses is the handling of inflation. However, the seriousness of this problem is reduced because for any specified reserve, only capital investments which have not as yet been made should be included in economic costs. Consequently, in making forward cost or discounted cash flow calculations, the relevant capital costs are those which would have to be invested if a particular resource was to be discovered or a particular reserve was to be brought into production. In evaluating these capital costs, it would seem appropriate to use dollars for the period in which the calculation is being made. Thus, for example, if we are considering a reserve that is not yet in production as of 1977 and we wish to evaluate the capital investment in mining and milling facilities needed to bring these reserves into production, these would be the capital costs of those facilities in 1977. Once reserves have been brought into production, past capital expenditures become irrelevant and only the current operating costs are germane. Consequently, historic expenditures are irrelevant to either the forward cost or the discounted cash flow concept. This simplifies calculating the effect of inflation on mining cost.

Assuming that discounted cash flow analysis is used instead of forward cost analysis, it is important to recognize that the appropriate rate of return for discounted cash flow calculations depends upon the projected rate of inflation. In fact, one can view the rate of return as the sum of the constant dollar rate of return plus the rate of inflation. For this reason, it is generally convenient to make cost calculations using an inflation-free rate of return. In this way, future costs of specified reserve categories can be calculated by applying general inflation factors to these constant dollar estimates.

A fourth difficulty which I think has plagued the forward cost concept relates to the problems non-ERDA analysts have had in attempting to use the concept to estimate the costs of specific reserves with known characteristics. The most useful work on this subject, of course, is that of John Klemenic which does provide some indication of the effect of various characteristics on mining costs. However, in my view, this type of work could be advanced substantially if ERDA used the data which it has on costs of individual properties to estimate an explicit functional relationship between component costs and various mine characteristics. Thus, it would be useful to estimate separately the capital costs of developing underground and open-pit mines and within each of these categories to express these costs as a function of ore grade, depth and seam thickness. If other characteristics are important in cost, they should be included. Such explicit functional relationships, which might be estimated by econometric techniques, would be substantially more useful than the nomographs which have been more conventionally developed.

One area in which research is particularly needed is in developing reasonable functional relationships for estimating exploration and development costs. Particularly with respect to exploration costs, it seems to me unreasonable to attempt to associate these with any particular reserves. Since any particular exploration effort may lead to the discovery of a number of specific reserves or to none at all, it would, I think, be more reasonable to estimate these costs as a function of the total volume of exploratory effort being conducted in any period of time. As the volume of exploratory effort increases, it is likely that the average depth of holes drilled will increase and, in addition, holes will be drilled in increasingly costly areas. Consequently, one would expect an increasing relationship between the cost of exploratory drilling per foot drilled or per pound of U_3O_8 discovered and the number of feet that are drilled. In Table 7.2, I have shown the level of exploratory and developmental drilling and the cost per foot drilled which indicates that such a relationship has prevailed in the past.

TABLE 7.2 Drilling Expenditure, Drilling Effort, and Expenditure per Foot by Year

Year	Expenditure for Exploratory and Developmental Drilling (Thousands of Dollars)	Exploratory and Developmental Drilling (Thousands of Feet)	Dollars per Foot Drilled
1971	20,959	15,452	1.36
1972	18,100	15,424	1.17
1973	25,300	16,421	1.54
1974	44,760	22,000	2.03
1975	73,810	25,542	2.89

GENERAL DISCUSSION

PATTERSON: It is disturbing to hear serious criticism of the forward cost concept and it is difficult to deal with. On the other hand, I was pleased to have Perl comment that the thing that seemed to be bothering people the most was probably the strongest part of it. I wonder how much is a problem of nomenclature? How would Perl characterize the system that included forward cost plus the rate of return? How do we characterize that so the utility industry can deal with it?

ZODIACO: I thought Perl's comments were consistent with mine; he addressed the economic effort, the start-up costs, and that would satisfy my comments.

PATTERSON: Are you talking about sunk costs again?

ZODIACO: No, I'm not really concerned about the sunk costs for a known deposit. We are concerned with the problem of extrapolating resources, and you have not sunk any costs in resources.

PATTERSON: I think you were in error in your presentation of what we are doing. In dealing with projects that have yet to be developed, all costs are forward costs except perhaps for some exploration components. So all those cost items are included in our analysis.

ZODIACO: For my comments I have drawn only on material that is published.

PATTERSON: You may have been using secondary sources, and there is a lot of misinformation available.

ZODIACO: I will have to clarify my information. But the thing that bothers me is the true measure of the economic threshold that has to be crossed before the material in the ground can be translated into "yellowcake" in the can. And I think that the closer ERDA can come to making the forward cost concept measure that, even with stated assumptions, the more useful it will be to the utility field.

PATTERSON: How would you characterize that?

PERL: If it is done right, forward cost plus rate of return is discounted cash flow--they are the same thing. I think there is some question about whether you should or should not include taxes in that notion; if you do not include the taxes (including income taxes) it will not come out close to price. If you include the taxes, it will.

With any of these notions, whether you add the rate of return, or use a discounted cash flow method, you have to decide on a rate of return; having done that, you can tell what the taxes are going to be.

I do think that the confusion about whether forward costs include or do not include capital costs is one of the most prevalent problems. People who are probably reasonably expert about it are confused. And I think the reason for the confusion on forward costs is that the examples given present a wonderful, clear description for reserves in production. And then for reserves <u>not</u> in production, the sources become sort of vague. The fact is that for the reserves not in production, capital costs <u>are</u> included. Forward cost does not include, however, what many producers and many buyers say is the most important part of the capital costs, the return on capital. As anybody who has built a nuclear plant knows, when you get to the point where the interest on the investment runs to 30 or 40 percent of the investment at the time you bring the plant on line, it is a pretty chunky omission.

KLEMENIC: A lot of the points relate to the fact that the amount of sunk costs associated with reserves that are in production are different than the amount of sunk costs associated with reserves that are not in production. Then it goes on to potential resources, etc. There is a gradual transition from Class I, which deals with reserves in production, to where there are hardly any sunk costs involved in Class IV, which deals with resources rather than reserves. ERDA has a lot of cost data; most companies provided cost data in the past, although a minority of companies have not done so. Our cost data includes operating costs. In my opinion, we have good cost data for last year, although we may not have data for a specific producer.

PATTERSON: Would you comment on what Perl suggested: our process could be improved by adding the rate of return.

KLEMENIC: I have been an advocate of making comparisons on an economic cost basis rather than on a forward cost basis, but I think both are important, forward cost and economic cost. From the standpoint of production capability, we have not only looked at the forward cost component but also those segments shown on Patterson's $8/pound charts. These included the amounts that had to do with sunk costs, taxes, and earnings under an assumed rate of return, all of which I come back to as economic cost. We have done that in the past, but we are not currently doing it.

UNIDENTIFIED SPEAKER: These have been done in test fields but not for all the reserve properties, and I question whether it would be a practical thing for us to do. Would it solve the problem that each of us is having?

KLEMENIC: I think you could do it; it might be time consuming and take a lot of people to come up with those kinds of costs.

PERL: Given all the data that went into the forward cost concept, each of the capital cost components, and the operating cost components, it should be possible to compute quite easily a discounted cash flow price for every one of those reserves. It is a computerizable formula, just as the forward cost is, and it does not require a great effort to churn it out.

KLEMENIC: You have to put it in a time frame.

PERL: But so do you have to with forward cost. They are all time related. For reserves that are not yet in production, you have to postulate that they come into production in a certain set of years. If we had sets of reserves (divided by characteristics, and by whether they were in production, not in production, or classified as resources) and for each of those reserves, we knew whatever characteristics you had to know to construct forward costs, you would have all you need to know to calculate a discounted cash flow cost if you were willing to supply one other piece of information, a discount rate. The difference in cost of producing these figures would be trivial once you had written the program. They are just two different formulas for coming up with another.

KOCH: We know that the ERDA forward costs <u>are</u> being used by utilities for decision-making on when to buy and how soon to make commitments and by government agencies to determine the adequacy of reserves. And there are two things to worry about from a producer's standpoint about these forward costs: the timeliness of the cost data (as well as the quality) and the age of the facilities which are supplying the cost data. The uranium mining industry is very narrowly based geographically, has a life all of its own, and has experienced dramatic cost increases in as little as six months. No matter how up-to-date the cost data may seem to ERDA, by the time they crank in these costs, they will be from twelve to eighteen months old and can seriously understate what it would take to put reserves into production.

The costs that ERDA is getting right now are costs from facilities that were put in (some with AEC support money) many years ago. Many of the facilities have been written off, and some of the properties have been mined for the second and third time. These costs do not resemble the costs that are incurred in mining new deposits. Most of the new mines will be deeper than we have ever mined uranium before, and even the open pits will be deeper than the pits we are accustomed to. There is no experience available on the costs to be expected in these new facilities.

KLEMENIC: I did not mean to imply that we only use current costs of production when we estimate costs in a new environment. We make independent estimates, using all information available in order to project costs for a new center coming into production.

KOCH: Even if you escalate all costs by normal inflation, or by 8 or 10 percent, the figures will not be realistic because the uranium industry is so narrowly based geographically that it is at the mercy of contractors, labor and all kinds of things. In some instances 100 percent escalation is not enough. We are still using forward costs as if we were in an environment like that of ten years ago.

The second point I would like to make concerns the forward cost concept as a means of classifying reserves. It gives the illusion to the utilities that we are living in an ideal world where the ore of lowest economic rank will be put to use first. Nothing could be further from the truth. We are not in an ideal environment. More and more properties are being tied up for one reason or another and cannot be produced on a timely basis. Other ones, therefore, step into their places, and I would like to see the mine where you can mine $8 reserves first, then the $15 reserves, then the $30 reserves. This is the second greatest failing that we see in classifying reserves by forward cost. I'm suggesting that there is a remedy since we are really after some kind of rating system on a national basis that could be used by utilities and by government agencies. I don't think it is necessary to use the dollar sign in this rating system. It could be just as well done on an index. Just call what you now call $30 forward reserve, call it Index 30.

PERL: What's its use if you can't somehow convert it into what that stuff is going to cost from the utilities' point of view?

ZODIACO: Let me interject something. We do not use forward cost at the General Public Utilities Service Corporation to make decisions on when to buy. We do not use forward cost as an indicator of what the price is, because, as Patterson clearly stated (and I think most people in this room recognize) the price is what the price is. And when to buy is more often determined by an inventory or supply situation and demand. The decision that I was referring to is the decision to commit the company to the nuclear option, and that is a decision that is made well in advance of the decision of when to buy uranium or what the price of uranium is likely to be. The thing we were trying to get at was that reserves are quantifiable. And there is some way of getting a handle on the cost factor. We recognize that both answers vary with time. But the top manager, having to decide yes or no, is interested in some degree of certainty. That was the emphasis I was trying to get in my paper.

FLAWN: I have a very elementary question. Reserves of other mineral commodities are always cast in terms of tons, or short ton units, or barrels, etc. and qualified by grade cutoff or other physical or chemical classifications. Why is uranium different? I understand after you look at the physical nature of a mineral deposit, you look at all the costs. And you look at all the costs to determine whether or not you can mine it. Those are standard mineral evaluation techniques that have been followed for many years. The only way I can see that uranium is different is that we had an AEC. And I see how you got into this forward cost business, but for the life of me I can't see why you stay in it.

PERL: Are you saying that there should not be any costing business?

FLAWN: There is costing business in all mineral commodity evaluation. But the reserves themselves are not cast in terms of dollars. They are cast in physical terms by units of weight or volume, and by chemical content.

PERL: But isn't that the greatest virtue of the way in which uranium costs have been classified in the past? If the costing concept had been the right costing concept, then it seems to me that would be a tremendous virtue for uranium, not a deficiency. You would be able to say not how many barrels are available in the ground, but how many barrels at what cost.

FLAWN: It is such a virtue that utilities have had to stop using it, because they do not know what they are talking about.

PERL: We are in danger of killing the goose that laid the golden egg. The concept has obviously had flaws which were not apparent to people when the cost and price seemed to be pretty much in line.

FLAWN: When AEC started, the price was the independent variable. It was what they said. I do not understand how you get into this.

PERL: It seems to me from the suppliers' point of view, if you think the problem is that ERDA is stating poor numbers for cost, not because they are calculated using a formula that is wrong, but because the data are fundamentally bad, it is easy for the suppliers to solve that problem: all they have to do is supply better data.

MASTERS: I would like to comment on this business from the point of view of total resource assessment. I would guess that whatever you do in terms of the dollar value has to be determined by the economists and the public utilities. But I dislike taking perfectly good resource numbers and messing them up with dollar values. It would seem helpful if we could argue tonnage and grade figures between geologists, and get some sort of resolution on probabilities and related matters. Don't confuse us with the forward cost; make that as a separate analysis and let the arguments be between economists.

KOCH: Almost every metal commodity has a published price and a price history that can be used for forecasting. That is why every copper company recasts its reserves every year, as you can read in the annual reports. But this is beyond the capability of ERDA to do on a national basis.

FLAWN: Look in the Bureau of Mines Minerals Yearbook; you will see these reserve data for all commodities. Now Schanz is probably saying "they are not as good as uranium data."

KOCH: We are pretending that there is no uranium price line--this is one of our problems.

MCSWEENEY: I would like to pick up on the last remark: it would be helpful if future systems would go as far as they can. I can understand that the government does not wish to forecast commodity prices, whether it is the Department of Agriculture for agricultural commodities, or the Department of Energy for fuel. Each company has its own kinds of decisions to make and they cannot be based just on the supply curve. But nobody here knows what the demand curve will look like five years from now, so you really can't tell the prices. Until those judgments are made, the market price is not determined.

UNIDENTIFIED SPEAKER: Regarding the suggestion that you abandon the forward cost system: this would be a step backward. If you substitute reserve grades and tonnages for it, somebody is still going to have to make economic analyses from these figures. And tons and grade are not enough; you have to know at what depth these deposits are and all the other physical parameters that would allow somebody in the utilities or government to analyze the economics and come up with a cost.

FLAWN: My question was, why is uranium different? Is it different because we have more information about it?

GUILD: It is different because you have enormous forward costs and capital costs, and no possibilities for substitution. If you commit yourself to a nuclear plant, you commit yourself for many years in the future and the price tag may be 10 billion dollars. You make the decision on a pretty small resource base, with a pretty small amount of data, and only a relatively few potential suppliers. But in coal, you are working in terms of hundreds of years of supply; copper, for many tens of years and from many alternative sources, and with possibilities for substitution. But with a nuclear plant you are working on a small resource base, with tremendous chances for future disaster if you commit yourself early on without having enough information.

UNIDENTIFIED SPEAKER: Still, I think you are working on a rather small developed reserve inventory without much appreciation of the character of the resources beyond what has been developed.

GUILD: And the short history we talked about makes it necessary for the utilities to project 30 years into the future with less than 20 years of operating experience.

UNIDENTIFIED SPEAKER: The other comment I was going to make is that I think everybody is talking cost while many of you are thinking price. There is more than one kind of cost. Perhaps ERDA's forward cost is about as close as you are going to get to the marginal cost concept. If you need to know what it is going to cost you, as "price" in the market, realize you are going to have to contract many years ahead. That is going to be totally different from the marginal costs associated with producing the reserves.

PERL: Two of the last speakers have said essentially the same thing: there is either no relationship between market price and cost, or it is so confusing a relationship that we can never figure it out. My own feeling is that they are not precisely related, and simply telling me the discounted cash flow for all the available reserves will not tell me what the price is going to be next year or ten years from now. But they are not unrelated. We and others have experimented with using forward costs or discounted cash flow costs to develop supply curves for uranium in various time frames, and then superimposing a demand curve on the results to see whether we could predict the price. I think you can--I do not suggest it will be perfect, but it can be better than a guess.

The second point I want to make is that the notion that the forward cost is not influencing people's decisions whether to buy or not buy is wrong. One of the reasons for the crisis in 1973 to 1975, with a tremendous jump in the price of uranium, was that purchasers thought there was $8 ore and the suppliers were saying "No, there isn't. And you're not going to have any ore until you're ready to pay $15." And the purchasers were saying, "You must be lying to us. We know it's there for $8". If the purchasers had recognized earlier that the price really was $15 or $18, and contracted for it then, the price would not have gone up as fast as it did. Because what made it go up, at least in part, was that nobody developed any new reserves. If you are going to publish cost numbers, people are going to use them to make decisions. And there is no way to escape that. The only choice is either publish good cost numbers or do not publish cost numbers at all.

The last point I would make is that forward costs or discounted cash flow or any sort of cost concept is not a substitute for knowing ore grade or depth or thickness. It is additional information. There are lots of reasons for knowing grade that have nothing to do with the costing. It seems to me these ought to be thought of as separate things, not substitutes.

Again, a great virtue of the data on uranium is that ERDA has made an effort to produce data on costs, and I think the only legitimate criticism is whether the concept is as close to the right concept as possible. If the data are bad, we ought to try to correct the data. If the concept is bad, improve the concept, not throw it out. You ought to be criticizing the other fuels, not criticizing uranium.

ZODIACO: In 1973, the General Public Utilities Service Corporation committed to the long-term supply of uranium at above $8 a pound. One company was not fooled by the availability of $8-a-pound forward cost material. In general, the lesson has been learned (with the going price today and the categories that are still published--$10, $15 and $30 a pound forward cost--) that forward cost does not reflect price, and I doubt that there is any confusion unless it is in the naive or new people getting involved in the nuclear effort.

The idea that I was striving for is to establish some measure of economic effort required to get the ore to market--some way of knowing if it is material with a $200 per pound forward cost, or it is sea water at $400 per pound forward cost. That can give the manager a measure for deciding whether or not he wants to play that game. If it is something less than that, we abandon the categories and simply rely on the $30 per pound number because ERDA has made the judgment and has the confidence that there are reserves in this forward cost category. I do not know what price these reserves are going to sell for, but ERDA classified them as economic reserves, and I can use that number as my cutoff. I do not think there is any confusion with price and I applaud ERDA for even attempting to apply the forward cost concept; I do not intend my remarks to be so critical as to indicate it should be abandoned. I think it is a valuable measure and is needed for the decision maker faced with investing a huge amount of money.

PLATT: I have prepared some written comments on the form of published data.

SILVER: We will be glad to receive your written comments and consider them for inclusion as part of the workshop report. (A summary of Platt's comments follow this discussion chapter.)

FINCH: Patterson showed a page out of the blue book of the various grade cutoffs and the tonnage of each grade category. I would like to ask if the 0.01 percent grade cutoff is determined on forward cost? The figure does not appear to be based on geology but on economics.

CURRY: The so-called uranium mineral inventory is actually an inventory which presents the lowest interpretation down to a grade of 0.01 percent within a deposit. The inventory includes a figure for the minable thickness, stating the particular mining conditions. For example, if the deposit is considered suitable for an open-pit operation an arbitrary cutoff of three or four feet may be used; for an underground mine something like six or seven feet may be the cutoff. With a 0.01 percent cutoff the only economic reservation is the thickness concept.

This is one of the problems that I would stress in any attempt to work up a statistical approach in determining resources--perhaps we should not even put this kind of strain on the mineral inventory estimates.

UNIDENTIFIED SPEAKER: Are you limiting yourself to assured ore above 0.01 percent?

CURRY: That is probably true. The mineral inventory is not complete in that the estimates in the book represents 300 of the better properties. And they probably are salable.

DOUGLAS: How do you handle the problem of the greater unreliability in the interpretation of grades below 0.05?

CURRY: That is a real problem. And we do have a certain number of ways that we hope will improve the accuracy of the estimation of grade. In estimating our ore reserves (at least for the reserves that are being presented in terms of forward cost) we are starting to work out a pattern which recognizes the uncertainties and makes allowances for them.

SILVER: Would you caution everybody that figures for reserves below 0.05 have considerable uncertainty?

CURRY: There is no question about it.

SILVER: Since nearly 40 percent of the total reserves in terms of properties were below 0.05, it would lead people to believe that there was confidence in those figures.

LING: In listening to the discussion of the forward cost concept, it occurred to me that the problem is typical of a lot of things which seem to stem from the time the government gave up the uranium monopoly. My question to the Panel, is what about having the government reestablish a monopoly?

SILVER: Is there a response to that? (Silence.) Let it be noted that the question was asked.

HARRIS: There is more than one tonnage/grade relationship that is required. One relationship is particularly sensitive to whether your data represent deposits or parts of deposits. One to consider is in connection with projected probability studies where you require some economic rate that they are familiar with. The estimate is added to the known reserves and production to yield a logarithm of cumulative tonnage to establish grade. The curves can represent a number of different grade distributions, depending on the population of deposits included, and whether the blocks of properties being considered as "deposits" are large ones or small ones. If we take ERDA data on properties and use them to determine the kind of tonnage/grade relationship, we should be aware that on some properties we are not sure of the population of deposits. It is very important whether or not we have deposits or properties, or even parts of properties.

DOUGLAS: In connection with the discussion of forward cost, the suggestion was made of using discounted cash flow. I do not see how we could use a discounted cash flow because of the problems of handling tax liabilities, interest on capital, delays in starting, and other factors in the opening of new properties. If ERDA could not obtain this information from industry, ERDA would have to proceed by making assumptions. The result would be perhaps an average (and perhaps even of the right magnitude) but since you had discounted cash flow attached to it, everybody would start taking it as gospel, and you would be no better off than you are at present with forward cost. I would suggest to the utilities that the cornerstone for their index should be price, production capability, and reserves. Those are the considerations on which they should base their decisions.

If we are getting down into the speculative end of things, I would say that a decision where industry might spend $10 billion should not include something as speculative as potential reserves. In the classification of the USGS, it certainly would have to be "indicated", and at the very least, "inferred" reserves, as something on which to base a $10 billion decision.

ZODIACO: My in-house geologist and I keep having an argument. He tells me that a reserve is not a reserve until someone is committed to take it out of the ground or that it is economically feasible to take it out of the ground. And that is the only point that I was trying to make. I would not attempt to take any machine-cranked-out number that was based on geologic information plus some standard set of assumptions and a discounted cash flow calculation and plug that into my long-term model which compares coal generation with nuclear generation or any other generation. I believe it is important to have a measure of the social and economic effort required to extract the resource in order to be able to classify it as a reserve, and I think an order of magnitude estimate is almost enough. The point is, is it the gleam in someone's eye or is it real? That's the only point I was making.

UNIDENTIFIED SPEAKER: In addition to the points that have been raised, I think there is another important concept to consider and that is the stripping ratio because this makes different thicknesses and different grades minable. I think it is important to relate tonnage and grade to relative amounts of waste rock that have to be removed. Estimating reserves and the inventory of uranium is an economic process, because the efficiency of removing waste rock increases--this is a constantly changing factor. A study such as this was done for low-grade iron resources at the University of Michigan where they took in all the factors including the stripping ratio.

CONNOR: In connection with new approaches to stating forward cost, or some variation thereof, I would like to make a suggestion. It seems to me that when we hear Perl advocating the discounted cash flow approach, we are trying to take time into account. When we try to estimate reserves, using the forward cost or some other kind of classification, we are trying to get as close to pure data as we can but we recognize there is a tremendous amount of subjectivity involved. We try to minimize subjectivity or identify those areas with a high content of subjectivity so that the analyst can make his own study of the basic data. I wonder whether or not it would be possible when we say that there are 680,000 short tons of $30 material to say, for example, 300 of those short tons are estimated (by the group putting out the report) to be producible starting within one year, starting within three years, or over thirty years; another subgroup of 200 tons could not start to be produced for five years; another subgroup could not start to be produced for ten years, and so on. If you saw the time component laid out, it might give more meaning to the forward cost. In reserves on which mining will not start for ten years, a lot of forward cost is included in the numbers. If mining is starting in one year, a lot of sunk costs are probably included.

KLEMENIC: There are production capability estimates but they do not appear in the blue book. Data like that comes forward each year. We are compiling it this year for the $30 ore and it will clearly show how much production year by year comes from reserves, and how much comes from the highest classification of resources, and whether it is from probable ore, potential ore, and so forth. Everything we do is based upon an economic assessment, subjective though it may be. There has been in the past and there will continue to be an estimate of how much we believe could be produced as time goes on.

CONNOR: What I was suggesting was an approach for your "could do" case in production capability. I am really suggesting that we look at going another step and display it in terms of the reserve classification or resource classification.

KLEMENIC: I can see where we might display the data better, perhaps both on a year by year basis and cumulatively. We do not show it as a percentage; we show it in tons of concentrates. Perhaps that is what you are referring to: how much do you get in five years, how much do you get in 10 years.

GUILD: Are the figures in the reserve stated as recoverable U_3O_8 or are they in the ground?

KLEMENIC: In the ore reserve calculations made up to now, the numbers show what would come out of the ground in tons of U_3O_8 and take into account the dilution in mining. The trend for the future seems to be to show quantities in place; it will be up to the estimators of production capabilities to recognize dilution in the ground and situations where no recovery is obtained, and then show the quantity in the can.

SILVER: Are you telling us that ERDA will change the format?

KLEMENIC: I think it is gradually changing. The portion that is now shown as grade in place is a minor part, perhaps one or two percent of the reserve in the $30 capability. There are some deposits included in the reserves that need to be looked at more critically in terms of the grades to be expected. In the estimates of production capability, we are recognizing that this year we have a capability of one or two percent of the reserves.

CURRY: Perhaps this one percent number, which represents a small portion of the ERDA estimate, consists of material that probably will be extracted by solution mining rather than by conventional mining techniques.

SUMMARY OF WRITTEN COMMENTS SUBMITTED BY JEREMY PLATT

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Fundamental to an assessment of uranium costs and availability is information on the existence and characteristics of uranium reserves and resources. This information underlies one's estimate of the nature of the exploration environment (what geologic types of uranium occurrence are being sought? what types of targets, exploration tools and intensity of effort are necessary?) as well as one's estimate of the producing environment (how many mines and mills, with what capacities, are required?). Although other information is critical--such as the level and certainty of uranium demand, the cost-availability of imports, enrichment policies, mining and milling costs, technological problems and prospects for new technologies, availability and cost of financial and human resources--my comments are restricted to the question of what can we learn about the physical exploration and production environment from information on the characteristics and magnitude of reserves and resources. The extent to which any of the above factors may constrain uranium supply is invariably linked to certain assumptions and perceptions about the nature of the physical resource. For this reason, the geological information is considered fundamental to assessing uranium supply; and yet the existing information appears to be inadequate in several respects.

Estimates of exploration levels and production requirements are based on certain assumptions about deposit characteristics. Particularly important are the assumptions made about ore grades and tonnages. ERDA has provided most useful data in this regard (see ERDA 1977).

From an analysis of changes in reserves by cost categories during 1976 (ERDA 1977:29) it can be shown that 62 percent of the $30 reserves of U_3O_8 are contained in 29 percent of the deposits. The size distribution of uranium deposits appears to be log-normal. Patterson provided evidence of this in 1970 for 3100 deposits, noting that the median deposit size was 2.5 short tons of U_3O_8. It can also be shown from ERDA data (ERDA 1977:29) that 97 percent of

$30 U_3O_8 reserves are contained in only 17 percent of the deposits.

Meehan (1975) presented data showing that 88 percent of the $30 U_3O_8 reserves is contained in deposits having lower cost ($10 and $15) reserves. The significance of this fact is open to question--it may reflect the fact that, historically, many "deposits" which would only qualify in the higher cost ($30) category were uneconomic, were not drilled out, and consequently were never included in the AEC data base. The question that arises then is what is the potential for uranium deposits in the intermediate grade (0.0x%-0.x% U_3O_8) category? This is a very different question from whether or not significant haloes of lower grade ore exist in the known deposits. Although Nininger (1974), for example, has shown that the ore and U_3O_8 content tends to fall off quite sharply in a "typical" sandstone-type uranium deposit, such observations have little bearing on the presence of unassociated low-grade ore deposits ("unassociated" in the sense that litle or no higher grade material is present).

The data provided by ERDA (1977:29) on changes in reserves by cost categories during 1976 show the effect of ore grade on the economics of extraction; this is one of the chief questions in estimating the timing of ore grade decline into the future. From the ERDA data one can calculate, for the 526 properties listed as having $10 reserves, the average grade of the incremental tonnage added at the $15 forward cost cutoff, and then at the $30 cutoff. These grades are 0.08 percent and 0.05 percent respectively. For the 843 listed properties added at $15/pound the average grade of the incremental tonnage at $30 is 0.06 percent. In all cases the average grade of the incremental tonnage, by being associated with lower cost ore, is less than or equivalent to that of unassociated ore. This is summarized in Table 7.3, compiled from ERDA data (ERDA 1977:29).

It is not obvious, then, what constitutes a logical pattern of exploitation of these reserves. In a deposit containing a range of grades, mining may proceed from richer to leaner ore or the leaner material might be blended or stockpiled. And at a given forward cost the proportion of production from deposits containing unassociated ore further influences the average mill feed grade. Looking at the $30 reserves, a number of different exploitation paths are possible. At a minimum, it would appear that the average grade of the last ton mined could range anywhere between 0.10 and 0.05 percent U_3O_8. One's choice of assumptions, therefore, needs to be clearly stated since the issue of grade decline is not simply a geological problem.

TABLE 7.3 Average Grade of Incremental Tonnages of U_3O_8 at Different Forward Cost Cutoffs

	Forward Cost Cutoff	Grade (percent)	Tons of U_3O_8
526 properties at	$10/lb	0.19	250,000
associated at	$15/lb	0.08	64,000
associated at	$30/lb	0.05	107,000
843 properties at	$15/lb	0.10	96,000
associated at	$30/lb	0.06	81,000
432 properties at	$30/lb	0.06	82,000

SOURCE: Modified from U.S. ERDA (1977).

It is important to point out that "average grade" is, except in the grossest sense, a rather meaningless concept. In each cost category, hundreds of deposits are represented. In any ore deposit, the ore grade appears to follow a log-normal distribution (see Nininger 1974). Current mill-feed grades span a surprising range from 0.03 to 0.5 percent U_3O_8.

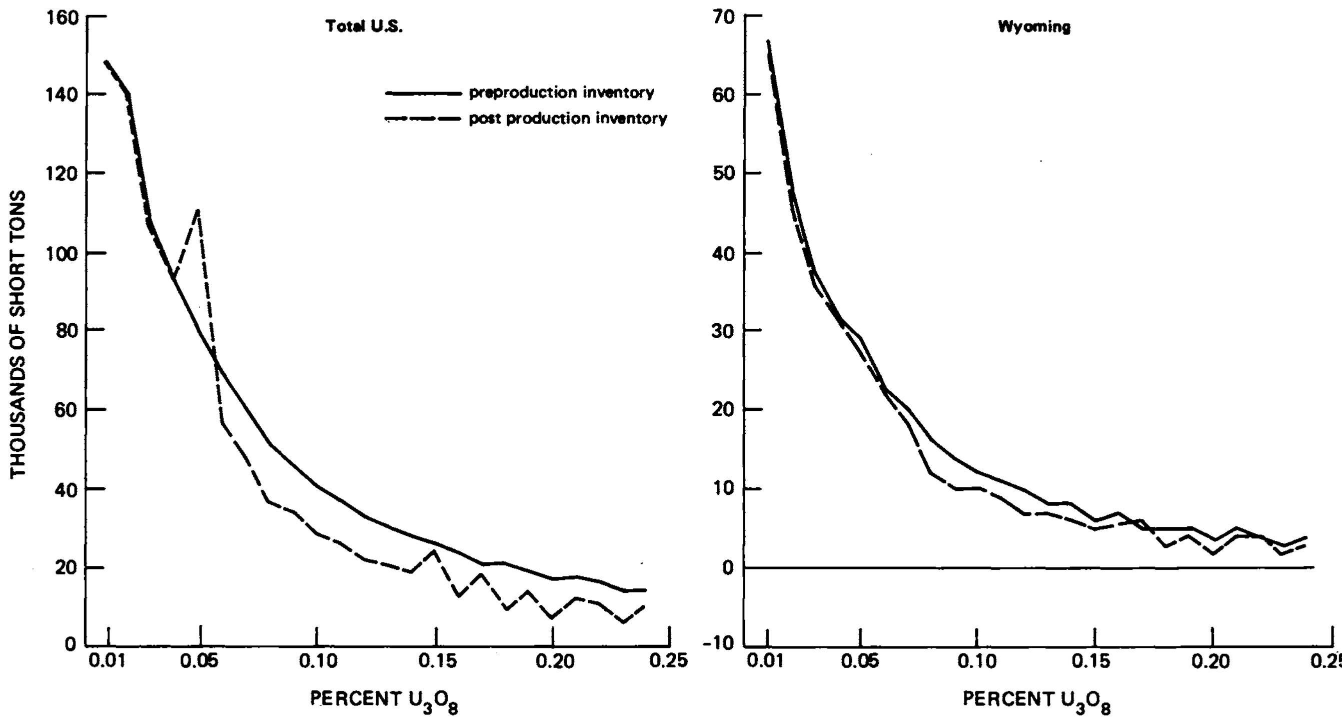
ERDA has regularly compiled data on the number of uranium deposits and their combined ore and U_3C_8 tonnage in various size categories (see ERDA 1977:47, 53 and 59). In this presentation format, information on individual deposit grades is all but lost. A less ambiguous format of data presentation, initiated by Meehan (1975), is a uranium mineral inventory giving information on the number of properties and their ore and U_3O_8 tonnage at successively higher cutoff grades (for format, see ERDA 1977:68). However, several difficulties limit the usefulness of this format for examining the question of grade decline. Most importantly, this presentation represents a preproduction mineral inventory and is of little use as an aid in showing the characteristics of deposits that remain to be produced. It is difficult to obtain a detailed view of the tonnage/grade characteristics of remaining reserves since the remaining reserves are calculated by substracting production from the preproduction inventory of uranium in each property. Although a relatively fine-tuned picture is given of the numbers of deposits at any particular grade, the information on the size of those deposits is all but lost through the process of averaging.

Another problem which limits the usefulness of Meehan's approach in predicting grade decline is that information on the forward costs associated with production from these deposits is not in some manner retained, except to the extent that all material shown is considered producible at $30 forward costs.

ERDA presented information in 1977 (ERDA 1977:34-39) for the first time in a grade increment inventory format. But no information was given on individual deposits, even though a single deposit might contribute tonnages to various grade intervals. The incremental U_3O_8 tonnages at successive ore grade intervals have been plotted in a series of graphs (figures 7.1 and 7.2) to show both the preproduction and postproduction inventory for various regions. In all but the lowest grade intervals, the incremental preproduction tonnage of U_3O_8 appears to increase at an increasing rate as the minimum grade is lowered. The two divergent cases are Wyoming, where there is no drop at the range of grades considered in this tabulation, and New Mexico, where the rate of increase in U_3O_8 appears to be flatter as grade declines and where the tonnage drops off at an earlier point (at 0.02 percent U_3O_8) and more severely than in the other cases.

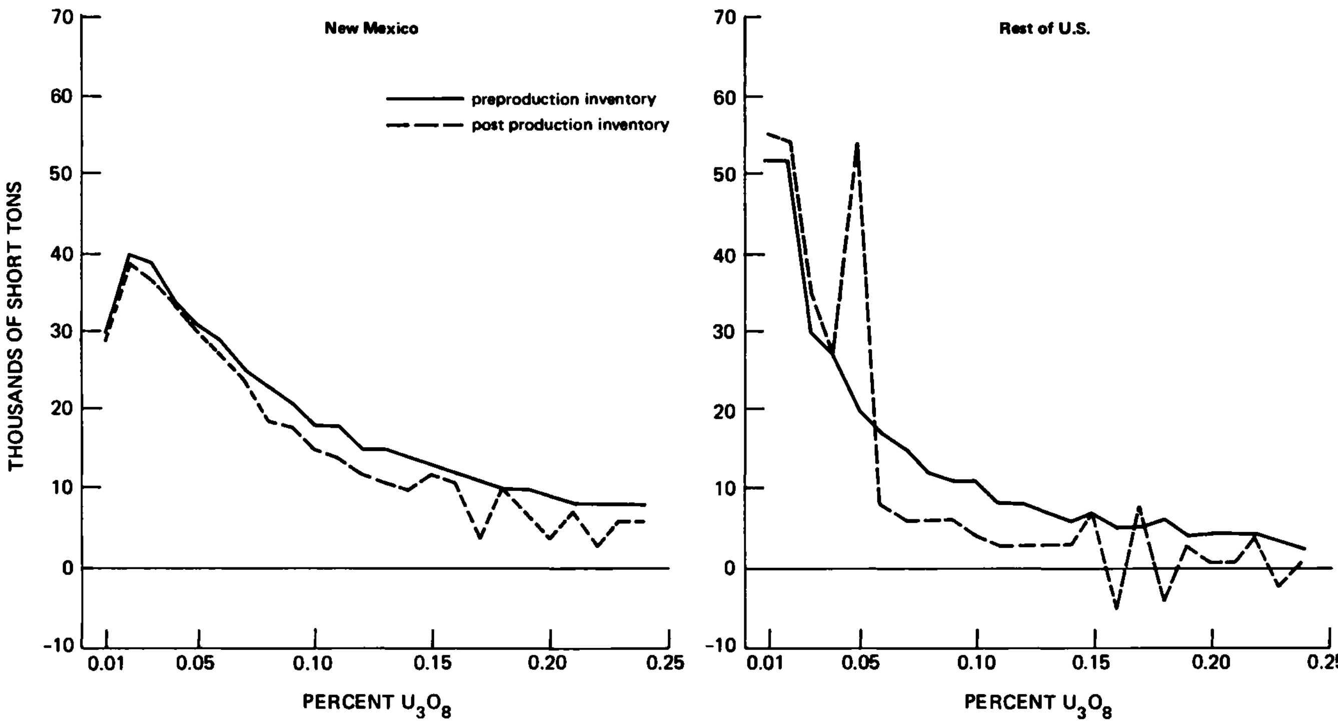
Another feature of these graphs is that the postproduction plot is considerably more irregular than the preproduction plot. A clue to the reason for this is the postproduction plot for the "rest of the U.S." (Figure 7.2) where, at 0.16, 0.18 and 0.23 percent U_3O_8, negative increments are shown. Probably the only explanation for more material being produced in any category than was originally estimated is that records of production are cruder than those of the preproduction inventory and that ores of various grades may have been blended to achieve a run-of-mine average grade which, in fact, does not accurately depict the grade and tonnage of the mined rock. Thus it is questionable whether the postproduction inventory reflects the grade/tonnage characteristics of remaining ore. The large spike at 0.05 percent on the graph in Figure 7.2, as well as the few other places where more material is shown in the postproduction than in the preproduction plots, remain unexplained.

An important question that is raised by this economics-free mineral inventory and which bears on projections of production requirements is whether a significant tonnage of producible uranium exists which, for various reasons, has not been included in the $30 reserve. In Table 7.4 the cumulative tonnages in the postproduction mineral inventory are compared with reserves.



SOURCE: Modified from U.S. ERDA (1977)

FIGURE 7.1 Incremental tonnages of U_3O_8 at various minimum ore grades.



SOURCE: Modified from U.S. ERDA (1977)

FIGURE 7.2 Incremental tonnages of U_3O_8 at various minimum ore grades.

TABLE 7.4 Comparison of Cumulative Tonnages of U_3O_8 in Postproduction Mineral Inventory and Reserves

	Postproduction mineral inventory, in tons (economics not taken into account)	\$30 reserves	\$50 reserves
<u>Total U.S.</u>	<u>1,184,000</u>	<u>680,000</u>	<u>840,000</u>
New Mexico	493,000	357,000	———
Wyoming	385,000	216,500	———
Rest of U.S.	306,000	106,500	———

SOURCE: Modified from U.S. ERDA (1977).

In each area the \$30 reserves correspond quite closely with the postproduction inventory at the 0.05 percent U_3O_8 minimum grade. Whether this is fortuitous, and how much of the additional 344,000 tons of U_3O_8 (the difference between 1,184,000 and 840,000 tons) not included as reserves is recoverable at any cost (perhaps by solution-mining methods or heap leaching or upon the advent of milling facilities into remote areas) needs to be determined. Presumably some of the material would be essentially unrecoverable--left over in abandoned mines--and some would only be recoverable at the estimated forward costs if the previous mining history favors its recovery.

ERDA has presented especially useful data for assessing deposit production characteristics in its matrix listings of deposit tonnages and grades, where numbers of properties in different regions and falling into particular size and grade intervals are shown (see ERDA 1977:66, 69). Taking into consideration past production on these properties should be of value in determining a credible future production pattern. ERDA points out that the general effect has been to reduce the size and grade of deposits. However, it is still difficult to design an exploitation path through these properties that will reflect the influence of different forward costs. It is possible, however, to see that the geologic provinces differ in detail while remaining similar in the overall pattern of their tonnage/grade distributions by property. One caveat is in order: the reserves-plus-production view represents a somewhat biased sample because only those deposits currently containing \$30 reserves are shown.

ERDA has also provided data on tonnage and grade of deposits where average grades for aggregate numbers of properties, broken down by size, depth, and thickness intervals, are listed (see ERDA 1977:67, 70). This approach is highly informative; nevertheless, it is again difficult to see how one might logically, rather than arbitrarily, plot an exploitation path using the ERDA data so as to arrive at a picture of grade decline. The difficulty here lies chiefly in the interpretation of the data, and not in the data themselves.

These comments have reviewed the type of information available on deposit (or "property") tonnages and grades and have outlined the difficulties in attempting to project the decline in grade using these data. The focus of these comments has been reserves or reserves-plus-production data. Although reserve data might form a reasonable basis for informed analysis, the characteristics of reserves become increasingly less important as newly found deposits and new production techniques account for an increasing share of production. The success in discovery and the characteristics of what are now potential resources become increasingly important. It is especially important that the analysis examine realistically the limits of production from byproduct sources and the likely contribution from such types of deposits as volcanic extrusives which may have the potential to change the character of the production environment. If it is difficult to develop a clear understanding of the grade, tonnage, and costs of production associated with known deposits, it is clear that these difficulties are only compounded when attempting to assess the costs and characteristics of undiscovered deposits and untapped types of occurrence.

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PART III

TIME CONSIDERATIONS IN EXPLORATION

CHAPTER 8

R&D PROBLEMS IN CONVERTING RESOURCES TO RESERVES

Carl H. Roach

(NOTE: Roach presented a series of transparencies and slides accompanied by an informal commentary. Some of the illustrations and examples appeared in the following reference:

Roach, Carl H. (1973) Total System Approach to Rapid Excavation and its Geological Requirements. In Geological Factors in Rapid Excavation, edited by Howard Pincus. Geological Society of America Engineering Geology Case History Number 9, p. 69-78.

The main points in Roach's presentation are summarized below.)

The need for a program to develop uranium resource technology is based on the following:

-- the 1982 demand for domestic uranium (assuming plutonium recycling and a 0.20 percent enrichment tail assay) will exceed 30,000 tons of U_3O_8.

-- the 1976 domestic production was 12,100 tons of U_3O_8.

-- the 1976 production rate must be more than doubled to meet 1982 demand.

-- to meet this domestic demand, many new ore bodies must be found and evaluated, and new mines and mills installed within a very short time.

-- new or improved uranium exploration, mining, and metallurgical technology will be needed to help meet these short-term demands.

The best approach to the required development is through a cooperative program, nationally oriented, which will bring together industry, government, and the academic community. It will be necessary to do more than discuss research and development or to coordinate the elements of different activities; it would be desirable to establish formal relationships and actual partnership relationships.

The selection of subjects for research and development can be guided by considering important systems concepts bearing on the R&D problem:

- life cycle concept
- selection of critical path R&D
- system environment

The uranium supply life cycle consists of the following stages:

- preliminary market analysis
- land acquisition
- exploration
- economic evaluation
- development
- mining
- extraction
- enrichment
- fabrication
- marketing

All stages are important but only certain ones lend themselves to improvement by the development of technology. A technology development strategy can be worked out by:

-- technological forecasting: the description or prediction of a foreseeable invention, specific scientific refinement, or likely scientific discovery that promises to serve some useful function.

-- sensitivity analysis: a measure of the effect in quantitative terms that a specific improvement of some component of the system has upon the output of the entire system.

-- implementing the critical path R&D.

By way of perspective, the estimated cost to supply needed uranium for the next 15 years exceeds $30 billion, and one-third of this cost will be for exploration. Drilling is a significant part of exploration: in 1976, the uranium industry drilled 35 million feet and will probably drill 50 million feet in 1977.

The present status of uranium exploration leaves little doubt that research and development are needed:

-- the rate of success in uranium exploration appears to be declining.

-- the drill bit, guided by sound geological analysis and inference, is probably still the best uranium exploration technique.

-- new subsurface technology is critically needed to get better information than the current "hit or miss" drilling technology.

Exploration is also inhibited by non-technological factors, as for example, land acquisition constraints and government regulations. The mining industry must deal with many federal, state, and local government agencies to comply with all existing regulations and practices regarding the environment, health and safety, leasing, land uses, etc. Satisfying all government regulations can delay acquisition of some lands for mineral exploration purposes for several years. A possible solution would be for the new Department of Energy to work cooperatively with the mining industry to draft proposed legislation that would simplify governmental regulations on exploration for energy minerals and would centralize these activities entirely within one DOE office.

Present detection tools seem to lose their reliability at a grade of about 0.05 percent U_3O_8. This provides a convenient starting point for plotting the critical path of exploration R&D for detecting the "high grade" uranium deposits, that is, those above 0.05 percent. Promising approaches include the following:

-- improvements in "near-miss" technology,

-- ore zone emanometry

-- ore zone geochemistry

-- ore zone solid-state physics

-- develop isotopic exploration methods

-- develop in-situ recovery preconditioning technology

-- develop ore occurrence models

-- develop optimal exploration systems.

For lower grade uranium deposits the critical path for exploration R&D seems to lie along the following lines:

-- uranium detection technology

- direct uranium detection by neutron interrogation

- KUT (potassium-uranium-thorium) spectrometric methods

-- delineation technology through geostatics

The critical path for R&D in mining is to apply the systems approach, as has been done for strip mining in the past, to the whole mining system. The subsystems representing such aspects as health and safety, environmental restoration, and others should be considered in designing and operating the mining system so the total system has been optimized.

The critical path for R&D in uranium extraction includes:

-- developing economic metallurgical systems for large low-grade deposits, e.g., in the 30,000 to 50,000 tons-per-day class.

-- developing labor-saving automation for large production metallurgical systems.

-- developing optimized metallurgical systems for in-situ recovery.

In addition to the physical research and development that has been suggested, some institutional innovations would accelerate technology development. These are:

-- close industry-government-university R&D partnership.

-- quicker technology transfer methodologies.

CHAPTER 9

EXPLORATION PROBLEMS IN CONVERTING RESOURCES TO RESERVES

Ian G. Northern

As a representative of a uranium resource organization there are two reasons why I believe this workshop and its end objectives are important. I wholeheartedly concur with the utility viewpoint concerning the need for a reasonable degree of assurance that long-range uranium fuel supply will be adequate. Without reasonable comfort in this area, utilities will not adopt the nuclear option, and the uranium industry will fade away. Secondly, and given that the resource base is adequate, individual company long-range strategies and business plans must reflect the market place as it is expected to develop. Even recognizing the difficulties and imperfections in long-range planning, today's decisions on how much money to expose in exploration, where to explore, when to develop, and how to market the product have to anticipate demand and supply factors that will exist for many years into the future. In our own case, that of a company that elected to resume a uranium exploration program only fifteen months ago, business success will depend in large part on how the nuclear and uranium industries develop at least through the end of this century.

The point was made many times in discussion that the problem from a long-term national viewpoint is not just one of potential resources, rather it is the rate at which potential resources are converted through exploration into reserves that can be developed to meet needs. Those words, "can be developed," were chosen carefully. Whether or not they will be developed, indeed whether or not the exploration effort will be forthcoming to convert resources into reserves, depends on much broader business and economic considerations that cannot be divorced from these deliberations. For this reason I have organized my remarks under two broad headings: general industry considerations, and secondly, specific exploration constraints.

In looking at the uranium industry it is important to recognize that it is still very youthful. As Curry pointed out in the first presentation, the total amount of surface drilling to find and delineate ore through the end of 1976 was 292 million feet. Half of that was completed in the 1970-76 period.

A second broad point of importance is cash flow. This year, for example, expenditures for exploration will probably approach $240 million and at least a matching amount will be invested in new mine and mill development. Very conservatively the total exploration and development commitment will be half a billion dollars. And what about income? Gross revenues, assuming a U_3O_8 production level in the 25 to 30 million pound range and an average realization in the mid-teens, will approximate $400 million. I cannot enlighten you on the relationship of net production income to total cash outflow, but the point must be made that for a number of years in the past and for quite a few years into the future the raw material sector of the nuclear industry is piling up deficits.

What then influences companies like our own to get involved in uranium exploration? Partly it is because we recognize the need for nuclear power development to help meet national energy needs. In terms of corporate responsibility, it is because we believe possible long-term gains outweigh short-term risks. There must be willingness to accept the high risks associated with uranium exploration, the chance that all monies spent in exploration will fail to uncover commercial reserves.

Willingness to accept high risk is only part of it. The ability to survive as a corporate entity if exploration is unsuccessful is even more important and it accounts in large part for the way in which the uranium industry is structured today. According to a May 1977 ERDA report, a total of 108 companies was surveyed in developing information on 1976 exploration expenditures. Total expenditures were reported to be $170 million. I will speculate that a dozen or so companies, most of the major corporations, accounted for at least half of the total outlay.

Building further on this point, the uranium business is not only high risk, it requires high cash input and long lead times. In ball park numbers, it may require exploration outlays upwards of $2 per pound to bring a discovery to the point where development appears feasible. Development investment, depending on particular orebody characteristics and recovery method, may require a further $2 to $6 per pound. This would imply in the case of a 20 million pound find, expenditures in the $100 to $150 million range before the receipt of first revenues from the project.

And what of timing? While we can all point to exceptions in the past ten years or so, a reasonable expectation is that at least eight to ten years will elapse between the birth of an initial exploration concept and the time that first production is obtained. This period contemplates the emergence of the exploration idea, its testing and support through regional geoscience studies, the creation of a land position, initial reconnaissance drilling, sequential exploration drilling to broadly define mineralization, delineation drilling, exploitation feasibility studies, internal and external authorizations to develop, and the period of time then needed to construct facilities. The probability is that this time period will grow longer as exploration and development activities are pushed to greater depths.

I must at this point, Dr. Silver, beg your indulgence if I violate slightly the ground rules that you laid down in your opening remarks. I do so in order to make a critical point in connection with the timeliness with which new reserves and producing capacity are brought into being. Those companies whose primary business is petroleum are playing a very important role in uranium exploration and development work. They have a propensity for risk taking, financial capability to take a long-term business view, and in broad terms, technical capabilities that are adaptable to uranium work. Proposed legislation to force petroleum companies out of the uranium business would by all counts be detrimental to the task of providing users the very assurance they seek on future uranium supply adequacy. Forced horizontal divestiture would be a major national disservice.

One final point should be made in this broad industry overview as it addresses time considerations. The charge has been made that current exploration is too conservative, that too much effort is being directed to work in established provinces like the San Juan Basin, the balance of the Colorado Plateau, the Gulf Coast area, and Wyoming basins. Why isn't more exploration being directed to some of the other resource regions that have been assigned significant resource potential in the preliminary NURE report? The answer is that industry is widening its search effort. The recent ERDA drilling survey revealed that almost a quarter of the exploration money spent in 1976 was in areas remote from existing producing centers. Moreover, 17 percent of the total outlay was incurred in exploration for non-sandstone type deposits, environments that have historically contributed only minimally to the proved ultimate reserve base in this country.

Let me now mention five specific items that are influencing the pace of uranium exploration in the United States.

First, acreage availability. Statistics on land held for uranium exploration are of dubious reliability. ERDA surveys suggest, however, that some 27 million acres are currently controlled by exploration companies, over half of it in the form of mining claims on the public domain. Continued tenure under the mining claims systems is uncertain because of proposed new legislation to replace the 1872 Mining Law. The status of certain leases on Indian Lands is also in dispute. A recent court decision has raised questions on the validity of mineral leases where surface and mineral rights are divided. Finally, inroads constantly are being made in the resource inventory through land withdrawals.

This leads me to a second area of concern, the regulatory environment. Actions by federal, state and local authorities are slowing down exploration and development activity, are retarding the rate at which new supply can be created, and are injecting increasing uncertainty into business planning. I refer, for example, to the restrictions imposed by air and water quality legislation, the Surface Mining Control and Reclamation Act, the battle over authority for mill licensing, and exploration permitting procedures.

Third is the people question. The level of exploration activity has fluctuated considerably in recent years. In terms of drilling activity, footage climbed from 2 million in 1965, to 29 million in 1969, fell to half that level in 1971 and 1972, and has since climbed to a projected 1977 peak in the 45 to 50 million foot range. Experienced explorationists to serve in this new boom period are in tight supply. This is especially true when considering prospective targets in non-sedimentary environments. In addition, there is the potential for a critical shortage of mine labor, especially underground in the next few years.

The fourth factor is hardware. Roach has already discussed the need for improved tools and techniques. Problems exist too in the availability of drilling rigs and logging units. Based on compilations from scout reports, the number of drill rigs working in the United States climbed steadily from 174 in January of this year to 361 in June. Drills are in tight supply, especially those with depth capability in the 650-meter-plus range. The problem could become even more acute if coal evaluation picks up in the western states in anticipation of renewed federal lease sales. The situation with logging units is equally worrisome. Units with advanced capability of the delayedfission-neutron or prompt-fission-neutron-type are in high demand and downtime is a major problem.

Finally, let me touch on inflation. Costs for contract services, equipment and skilled labor have been increasing at a rate that considerably exceeds the general rate of inflation. In my own experience, the all-inclusive costs for exploration drilling in the Gulf Coast areas six years ago was in the range of \$.50 to \$.75 per foot. Today it is \$1.75 to \$2.50, up by a factor of 3 or 4. This reflects not only higher contract costs but also changes in depth mix and broad demand/supply factors.

So what's the bottom line? I would not be in my present position or talking to you today unless I believed in the viability and necessity for the nuclear option and the uranium industry that must support it. Clearly I believe in the ability of our own organization to succeed in this business. I suggest that the exploration arm of our industry is thinking equally positively. What better evidence than the fact that exploration expenditures increased from some \$32 million in 1972 to over \$170 million in 1976, and will probably increase by close to 50 percent again this year.

CHAPTER 10

DISCUSSION

INVITED COMMENTS

MICHAEL J. CONNOR: The uranium industry is a young industry, being not more than 30 years old. It is fair to note that quite a bit has been accomplished in 30 years, both in the United States and in other countries, in developing an important body of knowledge. To preface my comments, I would like to make one simplifying statement. Resource appraisal and resource estimation are the responsibility of government. Improving of reserves by exploration is a responsibility of private industry.

The subject of our session is the time consideration in moving through the transition from resources to reserves. I have questions and comments addressed to Roach. Roach mentioned that it is possible, at least theoretically, to telescope achievements. I would like to ask: Is that really true? What are the constraints that we can expect? I would question how long he estimates it would take to hit two or three major Hahn-Strassman target points. Are we talking about one year or ten years? It has an effect on how we move today.

I do agree that the development of the neutron interrogation techniques represents a major development, as does the development of geostatistics, and the development of computer-assisted reserve calculation capabilities. I would also note that, at least in my experience, in industry none of these three developments are in common use today and I question just how long it will be for them to come into common use. We may have to come up with answers in the meantime.

These techniques do, in fact, represent activities of private industry, and they are part of the process of proving up reserves. I am not sure what they contribute to resource estimation other than to help one check the resource base earlier, faster, and cheaper.

The timing and mechanics of technology transfer is an interesting subject and is worthy of additional study. It seems to me that a valid test of the existing transfer mechanics would be to look at the NURE program, and then ask the question: to what extent is private industry following up on the findings of the NURE program? And after how long? And what is the nature of the follow up? I would like to believe that we are not throwing money away; yet I have seen few statistics that show the follow up.

The only comment I can make on Northern's paper is that I agree with everything he said.

The question of the transition from minerals in the natural world to something called a resource base has been the subject of a fair amount of discussion and it is a valid area to investigate because national and international policy and the future of mankind depend on these things. Japan and Germany, not having a uranium resource base, have to adapt their economy and their political and economic system to the concept of reliance on other countries for their major source of energy. The United States has not had to take that position with respect to uranium because we possess about a quarter of the world's reserves. In the past it has been concluded that, if hard pressed, the United States could satisfy domestic demands through domestic production. New concepts in international policy, though, have been moving toward a pure uranium economy, a concept advocated by President Carter in April, 1977. Of course, this places an increased need on developing a relatively confident position on our natural resources.

Improvements in reserve estimation can be approached from two or three different directions. I am intrigued by the characteristic analysis that has been mentioned in the first session, although I am a fan of scenario analysis myself. In this particular case, the characteristic analysis is a better tool but it is only one tool. We can afford the luxury of using two or three different tools or models to arrive at resource numbers. But a collection of resource numbers simply allows the broad base strategic plans to fit into a big puzzle. It does not really mean much in terms of energy until we can get the uranium into the can and delivered to the reactor. This transition from reserve to product is, to say the least, an intriguing area.

In addition to all the physical problems, there are the political, the economic, and the financial problems. Uranium is a nuclear energy commodity. Those three words are significant in that the combination makes one realize we are dealing with the most complex trade issues and products that have ever existed. We have people who are experts in commodities and there is a history to commodities. We have people who are experts in energy. We have people who are experts in nuclear problems. The cadre of scholars on nuclear energy commodities, combining all three, however, is limited indeed.

In dealing with nuclear energy commodities the inclusion of the word "nuclear" means that governments are never going to be able to keep their hands out of the business. The technical aspects of proliferation require government involvement. The role of government is going to be incredibly important in the transition from reserves to "yellow cake in the can". One has only to look at Australia, for example--it has had the world's biggest and best reserves since 1969 and there is not a pound of production yet from those deposits. Even with the recent announcement it is questionable when the first pound is going in the can. It is nice to know the reserves exist and one transition from resource to reserve has been made, but what meaning does the reserve from Jabiluka have for the utility which needs uranium for its reactor?

Let me refer to the table headed Projected World Flow of Uranium in the period 1977-1990 (Table 10.1). It highlights the real issues in the nuclear industry. One product of the Nuclear Assurance Corporation is a report called Fuel-trac, based on a computerized data system on the nuclear industry. Table 10.1 is the quarterly report for U_3O_8. There are other reports on fabrication, for enrichment, conversion, etc. Fuel-trac is generally considered to be the most comprehensive data base in private industry in the field. One could take issue with any number in this table, so let's try and be liberal in our handling of it. It is important to understand how the Fuel-trac system works. It develops demand, not from the top down in the traditional forecasting manner, but from the bottom up by taking each reactor, and each region, fuel cycle by fuel cycle, and building the demand for each year in each area. The demand numbers come from the electric utility companies which provide the data, so the demand numbers represent the utilities' outlook which is an important point to note later.

The significant points shown in the table are as follows. The 1977 production of the various countries totals some 47,000 short tons of U_3O_8. Additions to world production capacity amounting to 38,000 short tons have been announced, bringing total capacity for 1990 to 85,000 short tons of U_3O_8. The reserve numbers that I have given here are a mixture representing a judgmental type of reserve estimate based on reserves considered to be producible. The one number that I would say is a bit questionable is the large reserve of 497,000 short tons of U_3O_8 for other countries, because that includes the Ronstadt deposit of Sweden. These numbers do not include, however, the latest

TABLE 10.1 Projected World Flow of Uranium in the Period 1977-1990. (Quantities are thousands of short tons of U_3O_8).

SUPPLIERS/PRODUCERS

	Australia	Canada	U.S.	Africa	Others	Totals
Current production capacity	1	9	19	15	3	47
Planned production capacity	10	5	11	7	5	38
Total 1990 capacity	11	14	30	22	8	85
Reserves	494	273	435	514	497	2213
Sales commitments	12	113	155	200	142	622

622

Utilities			Agents
Delivered to utilities	221	401	Delivered to agents
Utilities add to inventories	(-60)	(-30)	Agents add to inventories
Leaving for reactors	161	371	Then flows through to reactors
Requirements not yet committed	(+441)	(+83)	Currently uncommitted by agents
Total U_3O_8 to reactors by utilities	602	454	Total U_3O_8 to reactors by agents

Total U_3O_8 to reactors 1056

versus

1060 Gross reactor requirements

14 Recycle planned

1046 Net reactor requirements

REACTORS

	Europe	U.S.	Japan	Others	Totals
U_3O_8 requried for reactors	368	482	105	91	1046
Quantities still uncommitted	124	241	22	54	441
Percent by region of uncommitted	28	55	5	12	
For reference: 1990 demand U_3O_8	30	45	11	9	96
(based on 1990 MWe of)	(132)	(202)	(50)	(27)	(411)

SOURCE: Modified from McGraw-Hill (1977). Connor finds huge gap between world uranium need and planned production. Nuclear Fuel 2(20):12-13.

new deposit announcements. Compare the reserves with the sale commitments that have already been made--they total 622,000 short tons and are for delivery between 1977 and 1990. Deliveries are made to two types of buyers: to utilities and to agents. The utilities will receive 221,000 short tons and will add 60,000 of those short tons to inventory, leaving a net for the reactors of 161,000. Agents will receive 401,000 short tons with 30,000 going to inventories, leaving 371,000 to flow through to reactors. The agents have a total commitment to supply 454,000 short tons of uranium leaving 83,000 short tons currently uncommitted. Utilities are currently uncommitted for 441,000.

When the net material flows to the reactors, we will see a reactor demand of about 1,060,000 short tons of U_3O_8 between now and 1990. The geographic sources and principal tonnages are distributed as shown in the bottom part of Table 10.1: 368,000 for Europe, 482,000 for the United States, 105,000 for Japan, and 91,000 for the other countries; another 14,000 tons will be derived from recycled material. The uncommitted quantity of 441,000 short tons is distributed among the four geographic areas. The market share is apparent by noting the percentage that the uncommitted amount in each area represents of the total tonnage that remains uncommitted. For reference purposes the bottom line of Table 10.1 shows the megawatt demand for 1990 on which all of these numbers are based. For the United States the figure is 202,000 MWe; that number is somewhat higher than the 177,000 MWe that FEA is projecting as the median case for 1990. That pinpoints the major uncommitted demand within the United States. The tabulations shows a total of 30,000 short tons of capacity being definitely planned by U.S. producers by 1990 in contrast with the 1990 demand of 45,000 short tons. Reserves of 2.2 million short tons are adequate to handle the 1,046,000 short tons of world requirements. We only need about 11,000 short tons of capacity announcement to handle the 1990 world demand of 96,000. Where is this tonnage going to come from? Is it going to come in the United States or is it going to come elsewhere? When one realizes that the United States is the highest cost producer of uranium it becomes a question whether the new production will come from the United States or from areas of lower cost production like Australia and Africa.

Another thing you can conclude is that with the megawatt forecasts being as they are, there does not seem to be much of a market for forecast plans between now and 1990. If you recognize that utilities are becoming concerned about stockpiling a two to four year supply, particularly outside the United States, to guard against being sanctioned for one reason or another by their suppliers, you begin to see that the major market (other than the requirements for the reactors) would be additions to strategic stockpiles. Selling into inventories is different from selling into empty reactors. It is a different type of marketing problem and creates different pressures on the industry. Our projection for the open market (giving the utilities two years inventory coverage and handling the still open uncommitted requirements, leaving those agents who now say they are intending to be long by 1990, leaving them long, and letting those agents who are now projected to be short, having them catch up and cover their shortage) creates a total demand between now and 1990 of 685,000 short tons, broken down as 33 percent in Europe, 55 percent in the United States, 3 percent in Japan, and 9 percent in other countries.

ROBERT V. BAILEY: I believe I can fairly represent the viewpoint of the small uranium exploration and production company. Power Resources Corporation is four years old; in that time we have grown from four to about 55 employees. About 95 percent of our effort is in uranium exploration. We deal on a day to day basis with problems of land acquisition, drilling, exploration technology, and the other difficulties of finding minable deposits and bringing them into production. Most of our activities are in the Rocky Mountain region; we feel this area has tremendcus potential for additional uranium production.

Roach stressed the need for a close working partnership between federal agencies and industry. I feel that we have a good working relationship but it can probably be improved. At the present time there is a good flow of the data gathered by ERDA which is disseminated through the industry. Those of us in industry do look at these data and we try to use that information which appears to us to be of value. Roach emphasized the problem of speed of data usage and questioned how quickly industry may make use of new exploration or development techniques or ideas generated by ERDA or USGS or other agencies. I can tell you we do not waste any time at all in using new techniques that we feel have validity--if we found a new technique today that we thought would help our exploration or development program, it would be implemented tomorrow. There is no delay because we are the ones spending dollars for exploration and we like to stretch those dollars as far as we can.

Roach also mentioned that the rate of uranium exploration success appears to be decreasing. We should take into account the fact that many of the early discoveries were easily made primarily because of the surface exposure of mineral materials. After these deposits were found extensions and enlargements were discovered within these same areas. In current exploration we are seeing a movement away from the areas of known deposits, such as the San Juan Basin, to places where significant new discoveries have been made; exploration groups are also working in poorly known areas. Perhaps we are seeing a decrease in the exploration success rate, but it does not necessarily mean that this is going to continue. There are excellent areas remaining in the United States for exploration, and we are confident that new large minable discoveries are going to result.

Roach mentioned that drilling is still the best exploration technique. This is true once you have developed a concept and actually want to test a particular area. But someone has to come up with the concepts--where are the new areas, and what are the possibilities for finding significant new deposits?

We all realize that new subsurface techniques are needed to assist some of the current hit or miss drilling that goes on. For example, in the San Juan basin explorationists can drill a hole within ten feet of ore and not know they are so close to an ore body. This is obviously a problem which deserves study. Geologists with Power Resources Corporation have suggested downhole geochemistry such as setting packers and testing formation fluids for radon to see if we can determine how close we might be to a deposit. Other new ideas must be generated to avoid hit or miss drilling; but yet we must recognize that in some areas we have a tremendous tool for recognizing where uranium might exist, and that is the roll-front concept. Through the use of this concept we can drill two or three miles away from ore and still have good evidence that ore may exist in the area. This can be achieved simply through distinguishing altered from unaltered sandstone.

Land acquisition constraints were discussed by Roach who suggested the possibility of Department of Energy cooperation to help industry short circuit or at least cut down the amount of red tape we have to go through with land problems. That sounds like a good idea. I am generally not in favor of creating additional bureaucracy, but it would be an immense improvement if we could come up with a single point where all regulatory procedures would come into focus and we could deal with one agency that in turn would help us deal with other agencies. Unfortunately, the theory is much better than the actual practice will turn out to be. For example, in the State of Colorado within the last two years tremendous authority has been given to the county government; counties have a land-use planning commission, county commissioners, county engineers, and various other county agencies. These are in addition to the state agencies that we have to deal with such as the state health department, state engineer, state land-use planners, state environmental impact assessment groups, and others. On top of that are federal agencies to be dealt with.

I would like to think that the federal government would be able to step in and help us but in practice this is probably impossible. We have found state and county agencies to be extremely independent and to take their time making decisions. Many of the personnel involved know absolutely nothing about exploration or mining and it often takes six months to a year of educational programs by the exploration and/or mining companies before they finally understand what you are proposing to do. For example, on a proposed uranium solution-mining project in Colorado we had to take county commissioners, the county planning commission and their staffs on a tour of producing uranium areas because they had never seen exploration or a mine. They were not about to give us a permit, even to move equipment onto the site until they were satisfied as to our intent. A lot of time and expense can be consumed in such exercises, and I am quite pessimistic that a federal agency could help significantly even though the idea sounds good.

Mention was made of some concepts for in-situ leaching that the federal government is attempting to develop. Industry, of course, is looking into this, too. We could use some new ideas, but industry is fully capable of carrying out research and experimental programs in this area.

But all of the ideas mentioned above will not help us find the large uranium reserves that are needed. Other than land availability, the major problem for the small exploration company and beginning producer is that we do not have the money available to go about the business of converting resources to reserves. This is our largest single stumbling block. We have good ideas about areas with tremendous uranium potential, and we have proven exploration concepts. In some instances we establish a property position, but then we must find financially capable joint-venture partners. Finding the money or the joint-venture to fund the exploration is not easy. To us it seems incredible that $250 to 300 million is spent each year in the total U.S. uranium exploration industry. Yet just one nuclear power plant costs a billion dollars or more, and we therefore are spending for uranium exploration each year only 25 percent or less of what it costs for one nuclear power plant. This simply is not enough money for us to accomplish the task of converting resources into reserves, so we need to find additional sources of capital with which to conduct exploration. It is my opinion that much of these funds should come from the electric utilities. Exploration costs should be passed through to utility customers, the ultimate consumers of the electrical power. We know that some of the utilities have stepped into exploration but there are others that have not yet obtained approval from public utility commissions to allow them to pass along the exploration costs.

Northern touched briefly on legislation to block large energy companies from participating in uranium exploration programs. Speaking on behalf of a small company which is a competitor of the large energy companies I am pleased to say we welcome them and feel we need their participation in these programs. Breaking up the large companies or precluding them from participating in the uranium business is going to do more harm than good and we believe such legislation would be very destructive.

In summary, those of us at Power Resources Corporation believe there are large undiscovered uranium deposits in the United States. We have heard much rhetoric at these meetings about resource estimates and I would like to make a prediction about these estimates: I predict that 25 years from now a group similar to this one will convene in Washington to estimate uranium resources. By then we will likely have mined all the uranium now listed as resources by ERDA, and the group meeting here will be discussing uranium resources just as large as were estimated in 1977. It is my view that as we find and mine resources, continued exploration will result in discoveries of deposits equalling those that have already been exploited. It follows that I am stating that our current estimates are low by a wide margin and further that the exercises in estimation that ERDA and the USGS go through may be suitable as confidence factors for those outside the industry but resulting estimates will not have much meaning to those in the industry. The real danger in these resource estimates is that if they are overly conservative the low numbers resulting will have a negative effect on nuclear energy planners, both in government and industry.

We have plenty of uranium out there in the United States, but we are going to have a lot of trouble estimating how much there is. Uranium resource estimates cannot be made quantitatively, but yet it seems an effort has to be made. Our concern lies with the matters of: 1) identifying prospective areas for exploration which are available and not withdrawn, segregated, reserved or otherwise removed from the diminishing role of lands where exploration can be conducted; 2) obtaining funds for exploration; 3) carrying out exploration and ultimately making a discovery; 4) going through the time-consuming and costly processes of getting licenses and permits to mine; 5) arranging mine financing; and 6) mining and milling. There is plenty of uranium. What we have to do is get out and get on with the business of exploring for it and ultimately producing it.

PART IV

METHODOLOGY FOR PRODUCTION FCRECASTING

CHAPTER 11

PRODUCTION FORECASTING METHCDOLOGY

John Klemenic

This paper provides insight on two aspects of uranium production forecasting. First, the methodology of the "could" capability as used by ERDA's Grand Junction Office is reviewed with emphasis on production. Secondly, ideas for generation of a "most-likely" case are provided, and efforts to develop a system to provide multiple supply projections are reported.

A thorough understanding of ERDA's definitions of ore reserves, potential resources, and the concept of forward cost categorization is required to grasp the methodology of ERDA's "could" capability. ERDA defines ore reserves as uranium which occurs in known deposits of such grade, quantity, and configuration that it can be recovered at, or less than, the stated cost utilizing proved mining and processing technology. Estimates of tonnage and grade are based on specific sample data and measurements of the deposit, and on knowledge of orebody habit.

Estimates of three classes of potential resources are made by ERDA, "probable", "possible", and "speculative". "Probable" potential resources are those estimated to occur in known productive uranium districts in extensions of known deposits or in undiscovered deposits within known geologic trends or areas of mineralization. Since this category of potential resources is considered the most reliable of the three classes, and in most instances would be expected to be converted into ore reserves sooner, "probable" potential is the only class of potential currently used in production capability studies.

The term "production capability" is defined as the estimated ability of the mining and milling industry to produce uranium concentrate to specifications acceptable for conversion to uranium hexafluoride. A "could" capability will be defined later in this paper, but for now view it as an upper target of what industry might do. The building block of production capability studies is the individual "production center". A production center is an economic unit, consisting of mining facilities, a uranium ore processing mill, and reserves and/or "probable" potential resources. The uranium recovery scheme for the production center may be conventional underground or open-pit mining, solution mining, heap leaching, or byproduct recovery. For conventional operations, the size of the mill is determined by the tributary resources and the rate at which they could be exploited.

Production centers are grouped in four classes, depending on the relative certainty of future production. Class I centers include the existing mills with supporting mines and other facilities at which concentrate is being produced at the time the capability estimate is made. Ownership of the facilities and tributary sources can readily be identified. Production costs can reasonably be defined, and future production is well assured. Class II centers include those uranium mills and supporting resources for which construction commitments are evident and mine development has been announced or is underway. While the ownership is established, the cost of production and even the quantities to be produced are much less certain than for Class I centers. Class II centers are generally converted to Class I centers within 3 years.

Class III and IV centers refer to mills which may be constructed at a future date. Classes III centers are postulated uranium mills in regions where the amount and grade of reserves justify production, but where commitments for mill construction are not yet evident. Three to five years lead time is estimated for mine and mill installation. Finally, Class IV centers are possible centers postulated for areas in which present reserves are insufficient to support production facilities, but where exploration and/or geologic evidence has indicated sufficient "probable" potential resources to warrant the assumption of eventual production. The assumed cumulative lead time to develop reserves and construct mining and milling facilities for Class IV centers generally ranges from 4 to 12 years, and averages 10 years. Class III and Class IV production centers are postulated without strict regard to current land ownership. In some instances, it appears that land holdings would have to be consolidated, either through purchase or joint-venture, before construction of a production center would actually begin. It is recognized that time-consuming negotiations may be necessary to effect consolidations.

ERDA utilizes a "forward cost" basis not only to establish the resource base but also to define the production centers that are acceptable for inclusion into a given capability study. In the context of production capability studies, "forward costs" are defined as the direct capital and operating costs that would be incurred in converting potential resources to reserves, and in building, maintaining, and operating new and existing mine and mill facilities beyond the date of analysis. Sunk costs, or those costs incurred prior to the analysis, and subsequent costs such as income taxes, interest on debt, and earning on equity capital, are not included as forward costs. In production capability estimates the proportion of sunk costs to total costs changes from production center to production center and from class to class.

In Class I, II, and III a significant portion of production comes from reserves. The cost of finding these reserves is a sunk cost (since the ore reserves were found and developed prior to the production capability estimate), whereas the cost of converting potential resources to reserves is a forward cost. For last year's $15 production capability estimate, about half of the concentrate production from Classes I and II was estimated to be derived from reserves and about half from probable potential resources. Nearly all of the production scheduled for Class III centers was from reserves, mainly because these centers come on stream late in the 15-year period covered by the estimate. By definition, only minor production from Class IV centers can come from presently defined reserves. In last year's estimate over 90 percent of the production from Class IV centers was predicted to come from potential resources that have yet to be converted into reserves.

All Class I production centers have mills operating at the time the analyses are made, but the impact of future mill expansions and renovations are also included. In last year's study, mill expansions were included for 14 of the 19 centers and significant renovations were provided for all of them. In some cases the companies' plans had already been announced. In other cases expansions were provided because the capability of increasing production was clearly evident. Mills included in Class II centers still need to be constructed or completed. In some instances only a small portion of the total costs still need to be expended; but, in others, construction has only begun, so essentially all of the costs are yet to be incurred. Obviously, all mill expenditures for Class III and IV centers are included in "forward" costs, since planning for mill construction has not yet been initiated.

Most uranium mines have a relatively short life; therefore multiple mines need to be developed over the time span of the production capability estimate. At the beginning of the time span only a small fraction of the total development cost has been spent. This is especially true for open-pit mines for which stripping is done only 1 to 1 1/2 years prior to production.

I. "Could" Capability

The first phase of the assessment of future uranium supply is referred to as the "could" capability and is the phase of production forecasting that Rosenbaum has asked me to address. The first step in the study of "could" production capability is the selection of the maximum forward cost (in constant dollars as valued at January 1 of the analysis year) of production that a production center can incur, and still be included in the analysis. Last year, a maximum cost of $15/lb was used, primarily because the grade of $15/lb (forward cost) resources was about the same average grade that industry was mining. For the first time, the production capability of the industry based on a $30/lb (or less) forward cost is being examined. It appears that, sometime in the future, prices may support production of the $30/lb resource base, which represents an average ore grade of about 0.09 percent U_3O_8.

The second step is to choose a time frame for the analysis. Until last year, the examination of production capability has been limited to a 15-year period, beginning in the year of analysis. We are now extending our view to a 30-year period, as this longer period may be more advantageous in examining the larger quantity of higher cost resources.

The third step is to examine the resources, the reserves and "probable" potential, which the ERDA-GJO Resource Division has indicated to be available at the stated forward cost. This "production center by production center" evaluation, which involves the examination of more than 1,800 properties, is conducted by experienced mining engineers, as it requires a subjective assessment of how much of the potential resources can be converted to reserves and ultimately recovered. Massive amounts of data about uranium resources, production plans, and costs, obtained from the industry, ERDA geologists, and the news media must be reviewed. Where feasible, a mining engineer is assigned to evaluate the resource possibilities of those areas where he has personal experience of the geology and mining practices.

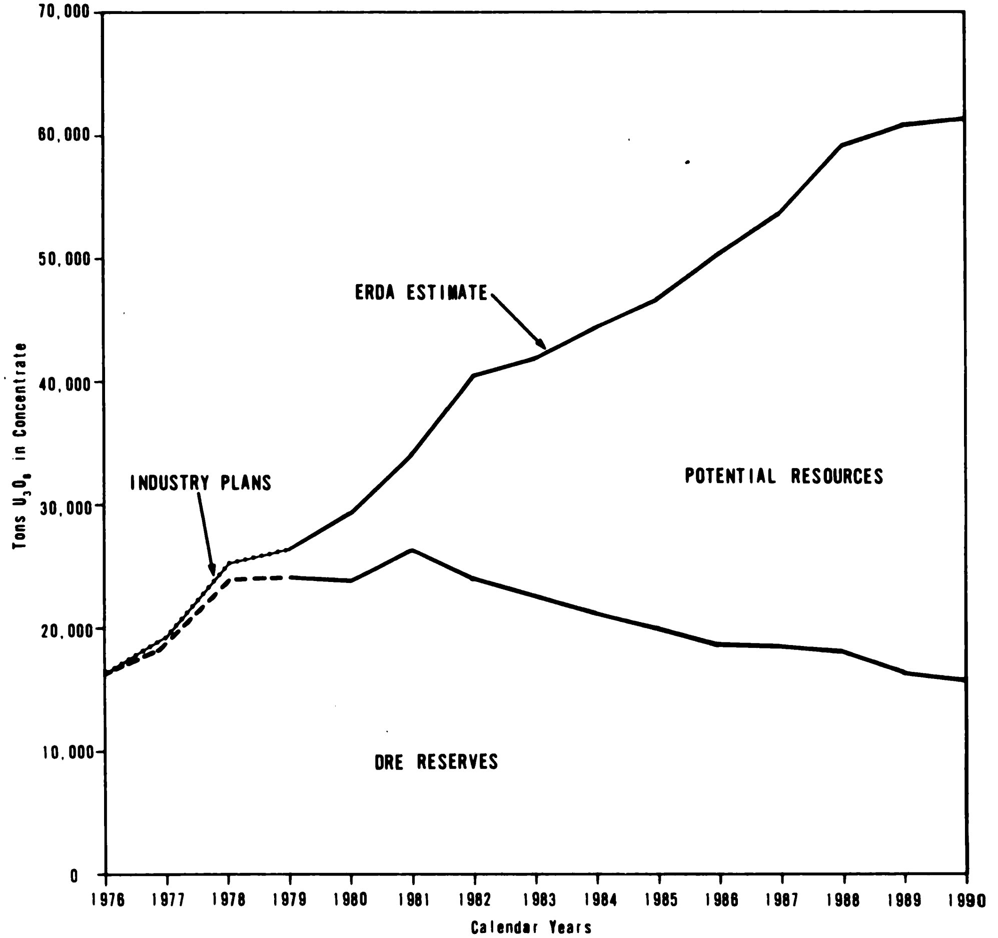
The examination produces two results. First, resources are assigned to existing or planned production centers, or new production centers are postulated based on adequate resources to support a mill for a reasonable economic life. Second, a production schedule for each center is developed, based on prudent mining engineering practice and a feasible economic life. In most instances, a maximum ore haulage of 50 miles is assumed, unless the plans of the controllers of the uranium resources indicate a greater haul distance. The schedules generally reflect a technically feasible production rate of uranium concentrate, and may not be optimum from either a profit-making, or total resource recovery point of view. However, to avoid confusion in the case of existing production centers, the company's own production plans are reported for the short term, as these plans for the total industry fit well the concept of the "could" capability.

As previously mentioned, ERDA makes estimates of three classes of potential resources, "probable", "possible", and "speculative". The production capability studies utilize "probable" potential because it is reasonable to assume that most of the material assigned to this resource class can be converted to reserves, and a portion of those reserves mined, within the study period. Even though only the most reliable potential resources are included in the studies, the introduction of these potential resources decreases the confidence in the accuracy of the production schedule in the future, since in the latter years of study, the key contributor to uncertainty in the production schedule is the timely conversion of "probable" potential resources to reserves.

The final step in assembling the "could" production capability is making a cost calculation for each production center, based on its postulated production schedule, to confirm that the center could produce uranium for its productive life at a cost equal to or less than the stated maximum forward cost. Those production centers which are found to be acceptable are summed into the "could" production capability. In the 1976 studies, 49 production centers were examined and 46 were included in the "could" capability at the $15/lb (1976 dollars) forward cost.

As the "could" capability (Figure 11.1) is the year-by-year summation of the production schedules of the individual production centers, it reflects the assumptions made in developing the individual schedules. Primarily, the "could" capability assumes a favorable economic climate which would allow each individual operator in the uranium industry to operate at full mine-mill capacity, without regard to nuclear fuel requirements, inventories, or manpower or capital constraints. The "could" uranium supply projection incorporates expansions of Class I and Class II facilities, and utilizes early production from Class III centers.

Land acquisition, exploration, and development activities required to convert "probable" potential to reserves are assumed to start immediately for Class IV centers, with timely construction of mill and mine facilities.



SOURCE: Modified from Klemenic (1976)

FIGURE 11.1 Industry production plans (1976-79) and estimated production capability (1980-90), annual by resource type.

The "could" capability is intended to provide an upper "benchmark" of uranium supply, as constrained only by an economic resource base as currently known, and prudent engineering practice. It is not intended to be a forecast of future uranium supply, but is the product of carefully defined rules and assumptions. The items that are quantitatively considered are summarized in Table 11.1.

The "could" capability represents one scenario. Historically, the industry has expanded at a lower rate than indicated by the ERDA "could" capability studies. The industry has not enjoyed either the optimistic market conditions (spot market prices on all sales) or the low-level of constraints to expansion (e.g., ready availability of skilled miners and other resources), which are assumed for the "could" case.

As the underlying topic of this workshop is time considerations in converting potential resources into saleable uranium, let us examine the scheduling of "probable" potential with the aid of Figure 11.2. This figure is a graphic summary of the assumptions made about the conversion of resources to reserves, and then to U_3O_8 in the can, in the $15/lb "could" study.

The upper line of the graph, based on data supplied by the Potential Resources Branch, Resource Division, GJO, is an assessment of the conversion of $15/lb "probable" potential to reserves. Note that of the 655,000 tons of "probable" potential assigned as of January 1976, it is estimated that 38 percent could be converted in 5 years, 50 percent in 7 years, and 80 percent by the 15th year.

The lower line represents the cumulative production of U_3O_8 in concentrate from "probable" potential, as estimated in the $15/lb "could" capability. As an average, the lag between definition of new reserves and production is a little more than 9 years. Notice that only about 40 percent of the "probable" potential (or about half of the reserves delineated in the 1976 to 1991 period), could actually reach the market in the next 15 years.

While a lead time of 9 years for production of newly discovered reserves appears to be a reasonable average, Figure 11.3 indicates regional differences, depending upon the blend of various mining methods. Future production centers in New Mexico will be based primarily on deep, large underground mines. However, most of Wyoming's potential is projected to be shallower and minable by open-pit methods. Hence, Wyoming resources, on the average, could be produced with a shorter lead time.

TABLE 11.1 Items Considered in Scheduling "Could" Production Capability

Available Resources	
	Chosen cost base - \$10, \$15, \$30
	Reserves - ore tons and pounds U_3O_8
	Potential - ore tons and pounds U_3O_8
Lead Times	
	Exploration
	Mine development
	Mill construction
Production Schedule	
	Period - 15 years, 30 years
	Joint venture arrangements
	Mining methods and rates
	Milling processes and rates
	Increase of capacity - mines, mills
	Mill recovery

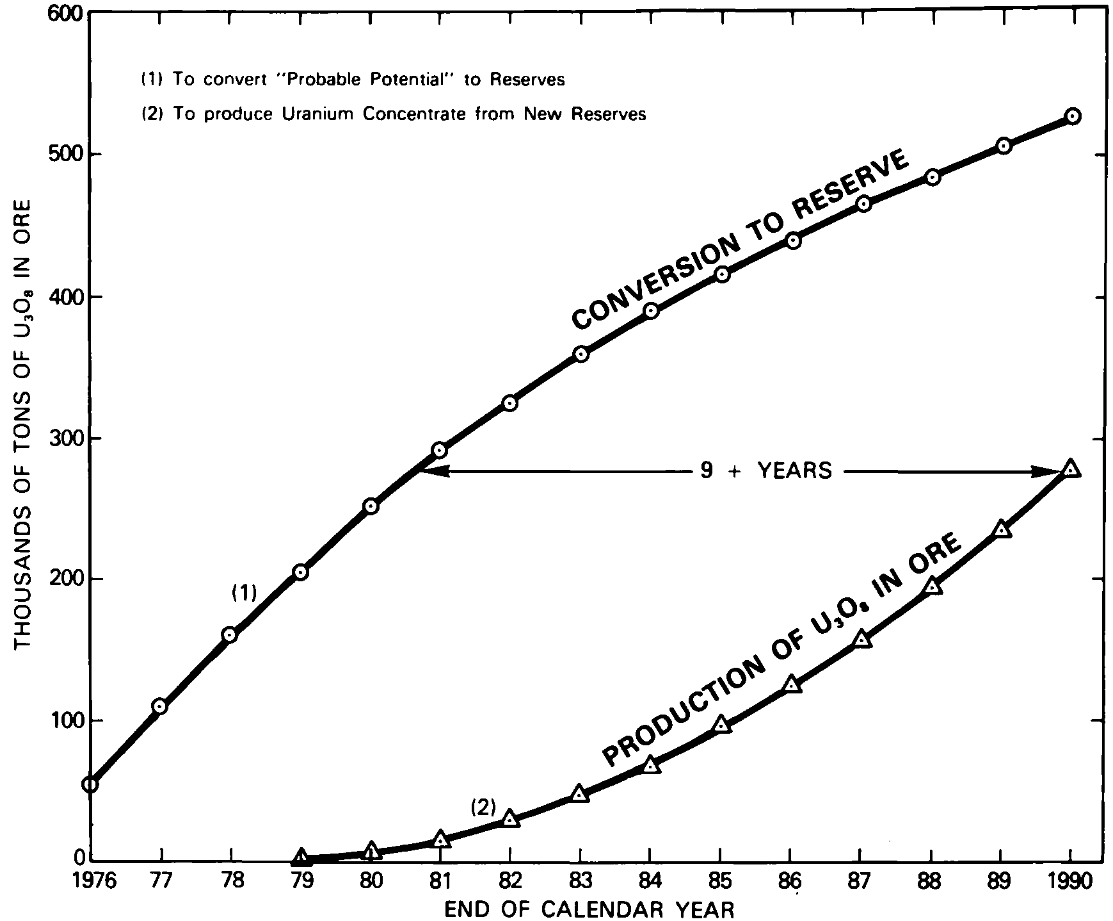


FIGURE 11.2 Lead times used in the \$15/lb "could" study.

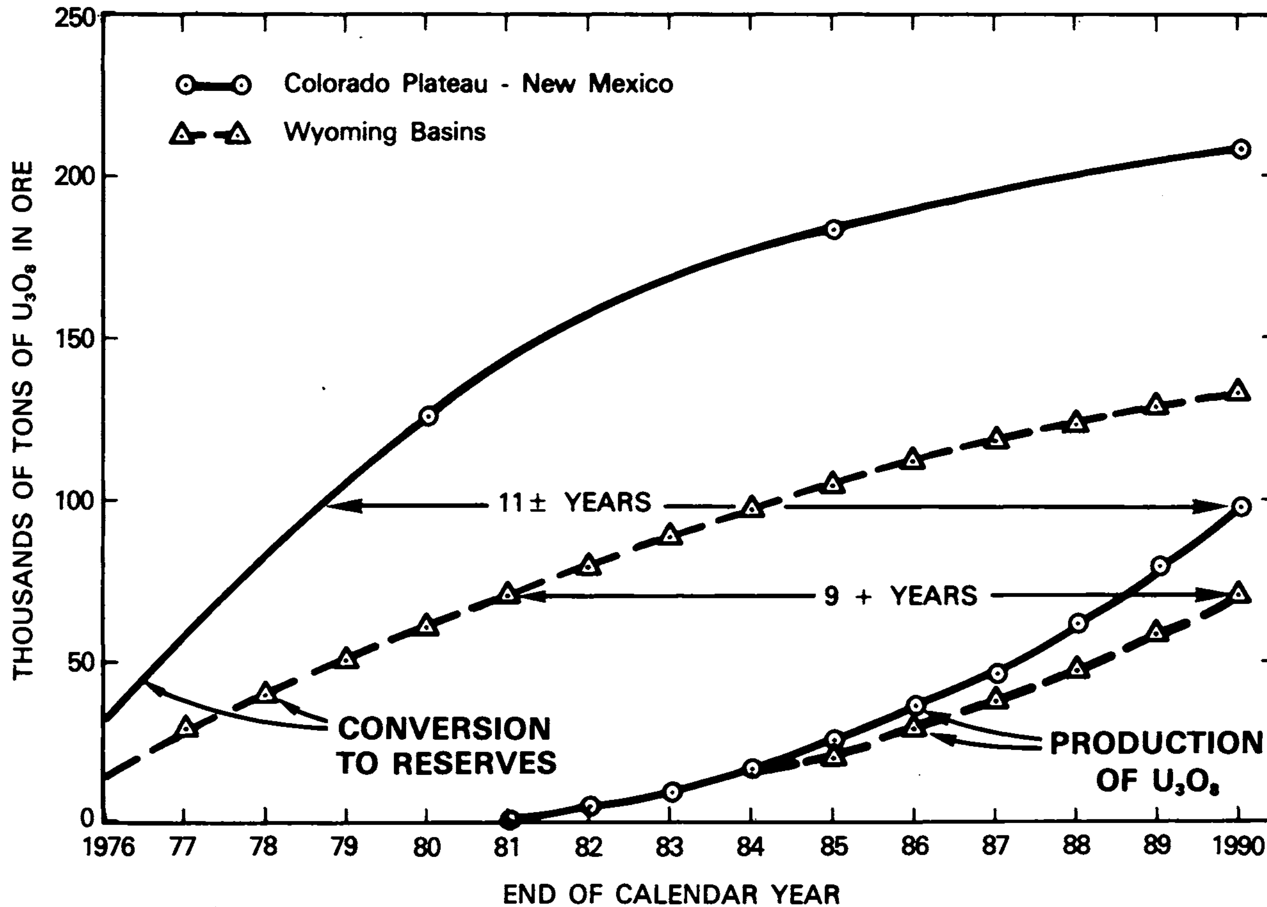


FIGURE 11.3 Regional lead times ($15/lb "could" study).

Of course, the lead time to bring new individual production centers into commercial operation can and does vary widely. Table 11.2 displays five key time-consuming activities which are examined when scheduling future production of today's resources. Some of the activities may occur concurrently, such as mill construction during the latter stages of mine development. The estimates of "time to perform" each activity are intended to cover 90 percent of the projects. However, situations may occur where the time to perform one or more of these steps may be considerably longer than indicated in the table.

The numbers listed in Table 11.2 were generated subjectively and are not the product of a detailed statistical analysis of the time delays that recently constructed production centers have encountered. While trend analysis is useful in examining some aspects of the industry, it may be quite misleading in understanding the probable magnitude of future lag-times.

The trend in the 1960s and early 1970s was clearly to "stretch-out" the development of newly discovered ore. In simplistic terms, the market was not there. The "real value" of uranium, in terms of constant 1967 dollars, declined all through the 1960s and up to 1974. Short-term production exceeded short-term demand. Uranium projects were de-emphasized or shelved during the period. "Internal Review" lag times were high.

This situation has clearly turned around; the 500 percent price rise of the spot market during the 1974 to 1976 period is a strong incentive to bring new resources to market. While some companies are proceeding cautiously, waiting for low-risk contract arrangements, others are proceeding rapidly to develop resources without firm market commitments. The market is now an incentive, rather than a deterrent, for accelerated uranium resource development. Industry spending is at an all-time high.

Governmental hindrances have also contributed delays to new projects in recent years. These hindrances will probably grow worse in the short-term, primarily due to new state, county, and local regulatory agencies becoming involved. But at the federal level, some of the old problems are already easing. Industry is reporting that the Nuclear Regulatory Commission regulations are solidifying, and application processing is speeding up. A major portion of industry's problems in dealing with the regulatory agencies has been because of loosely-defined rules which are frequently changed or reinterpreted. We believe that this aspect of the problem will ease over the next few years.

TABLE 11.2 Lead Times to Develop New Production Centers

Activity	Time to Perform: Range	Time to Perform: Average	Contribution to Total Lead Time
Consolidation of Property	0-8 years	4 years	4 years
Feasibility Studies	½-2 years	1¼ years	1¼ years
Internal Review	½-2 years	1¼ years	1¼ years
Property Development	2-5 years	3½ years	3½ years
Mill Construction	1-2 years	1½ years	0 years
	3-17 years		10 years

Figure 11.4 illustrates the recent history of the changing status of nuclear power reactors. The quantity of nuclear power capacity planned, with reactors ordered, has declined steadily to about half the peak of 120 GWE "on order" in early 1974. Uranium producers are watching this trend very closely, and some large mine development-mill construction projects may be stalled unless positive signs of a strong long-term market become more readily apparent.

Other dark clouds exist, and the threat of oil company divestiture is one of the largest. If major oil companies are forced to sell their uranium holdings, uranium exploration and resource development may be profoundly affected. Because of divestiture fears, several large companies have stated that their uranium exploration programs are much more modest than they might have been. Today, most of the industry's exploration and plant investment capital is coming from outside sources, primarily oil and gas revenues, and not from profits on the 12,000 to 14,000 tons of U_3O_8 it is producing annually. Exploration expenditures alone nearly match total concentrate sales revenues.

Let us return to the subject of supply forecasting methodology and the generation of a "most likely" supply projection.

II. "Most-Likely" Supply Projection

Last year, ERDA contracted with the Industry Economics Division of Denver Research Institute to assist in developing a conceptual uranium supply assessment system. The first phase of the work has been completed. Conclusions concerning the efforts required to generate a credible "most-likely" case, or a "true forecast" of uranium supply are as follows.

First, the retention of the concept of individual, independent production centers is essential in building supply projections. The use of most industry growth curves and trend analyses, particularly for short-term and mid-term projections are questionable, in that too great a reliance is placed on the assumption that whatever caused a particular behavior in the past will continue to cause similar behavior in the future without taking changing conditions into account.

Secondly, a "scenario" approach is recommended, wherein the production schedule of each individual production center is examined for several alternate scenarios, or "assumption-

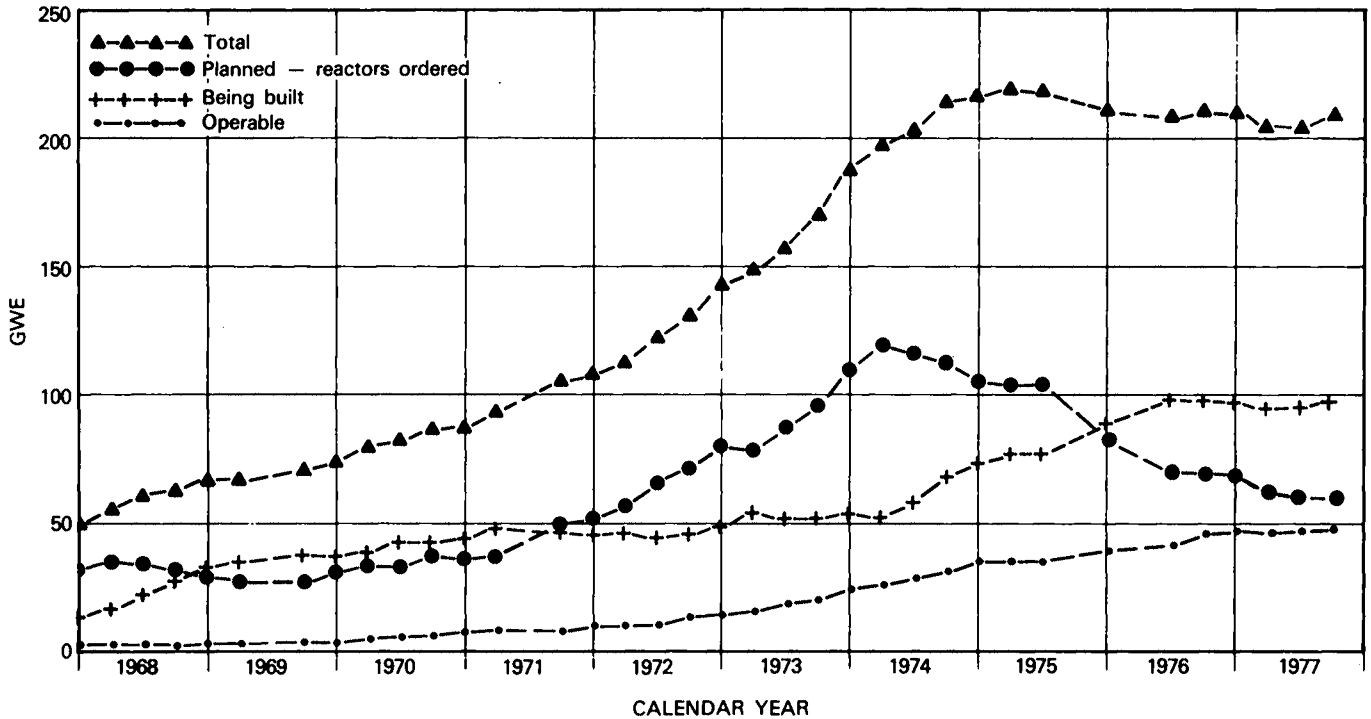


FIGURE 11.4 Changes in status of nuclear power reactors.

sets". Each scenario will contain specific assumptions about the political, social, technical, and economic environments. A series of projections based on alternate scenarios would have to be examined before it would be appropriate to select a "most-likely" case. The real value of such an approach is not the generation of a "most-likely" case, but an understanding of the uncertainty associated with assuming a given level of future supply.

Our recommendations to use a "scenario approach" involved the observation that future uranium ventures are likely to be even riskier than in the past. The industry has long recognized the risk of sinking a shaft, only to find that the reserves are not of the grade or continuity projected, or that the mining control program is not as effective as planned. These hazards remain, but as the exploitation of deep deposits becomes necessary, new technologic risks associated with large water flows, mine ventilation aspects, and high mine temperatures are introduced. But the biggest growth in risk to a uranium operator is not in the geologic or engineering uncertainties, but through the political and social forces which culminate in new laws, rules, regulations, standards, and prohibitions. Today, a real fear exists that a proposed mine or mill could be shut down or suffer reduced profitability shortly after start-up, because of a yet-to-be-devised environmental or health/safety rules.

Additional examples of new or added risks could be cited, but the point is that establishing a credible "most-likely" projection of uranium supply will require an assessment of developments in the social, political, and business environments, which in itself is a very risky business. Assessing the resource base and technical production constraints will not by themselves be adequate. The actual growth of the industry will be highly dependent upon how industry perceives its overall risks.

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CHAPTER 12

DISCUSSION

INVITED COMMENTS

LUDWIG W. KOCH: Klemenic ably and clearly described the methodology used to forecast uranium production capability. With regard to methodology, I will make three minor points, all of them debatable and a matter of judgment.

First, I question whether unconventional production methods such as in-situ leaching and byproduct recovery should be accorded production status before being fully proved as operational. These in situ methods are experimental as are the byproduct recovery facilities themselves, notwithstanding the big announcements. In situ recovery and byproduct recovery will make a contribution some day but it is misleading to give them production status now.

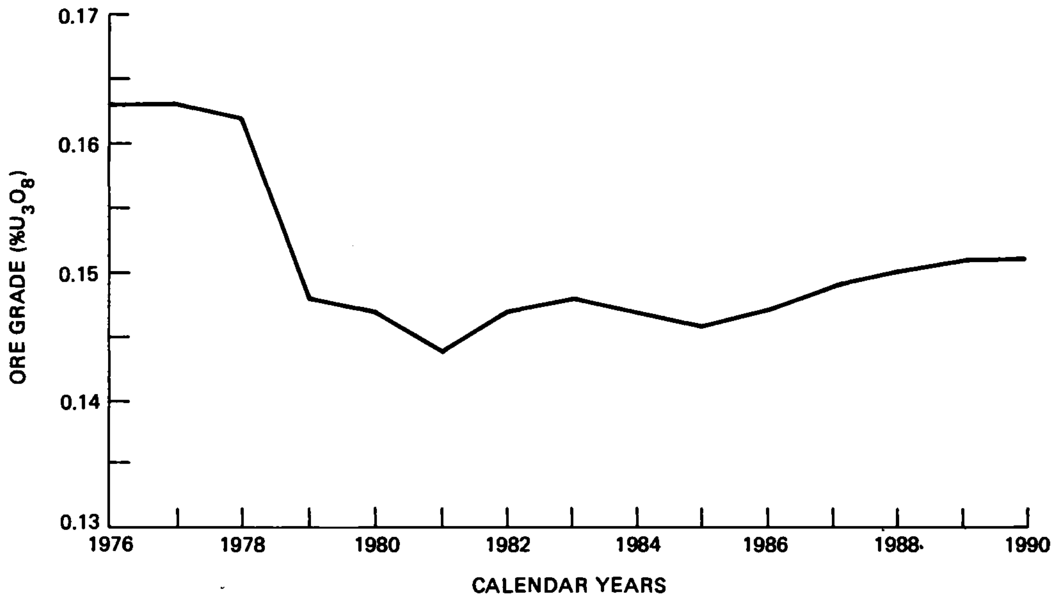
Second, the lead times for production from Class II, III, and IV production centers is too short because of the probability that some of the projects will be indefinitely delayed. There are no indications of any easing in the regulatory constraints at all levels of government. Note the recent statements in San Francisco of Interior Secretary Andrus.

Third, I do not agree with the assumption that expansion and modification of existing mills will be translated into additional uranium production. If recent experience is any guide, these changes have to be made to adjust to processing lower grades of ore just to maintain existing production rates. Our mill in Texas is a case in point: we are nearly doubling tonnage throughput just to get back to a uranium production rate that we had achieved in the first three years of the project.

The real problem with Klemenic's approach to production capability forecasting is the data base being used. He clearly states the definition of a "could" production capability as an ideal use of reserves and resources in more or less tailor-made production centers with ideal production rates that use up the reserves in an orderly manner over the presumed life of the facility; and most importantly the "could" forecast is unrestrained by financial, regulatory and environmental demands. Later in the paper, Klemenic notes these factors as the ones that make forecasting uncertain. Unfortunately, less than ideal people use Klemenic's data to arrive at less than ideal decisions and conclusions.

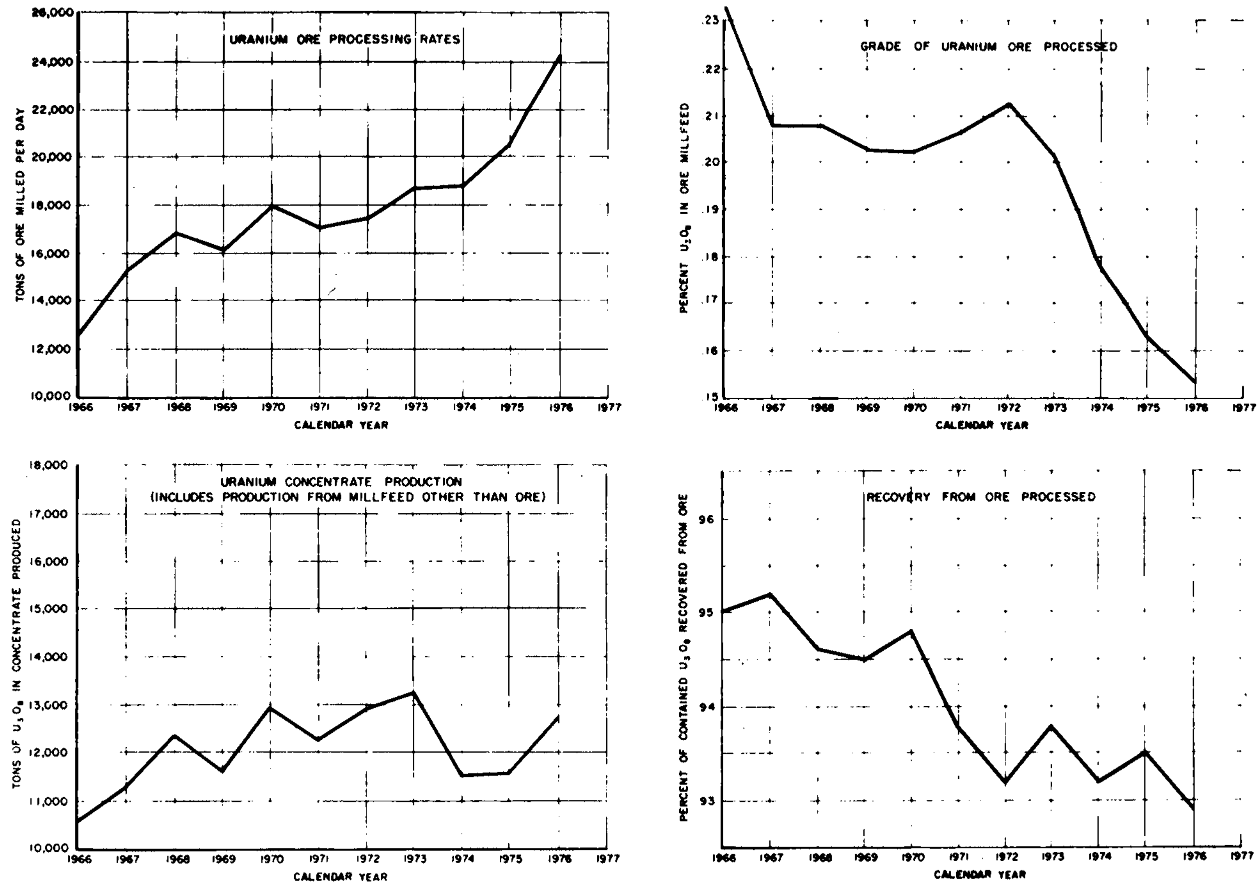
I think the "could" forecast should be replaced, or at least accompanied by, some more realistic forecast, as Klemenic has said in connection with ERDA starting on a "can do" or "will do" forecast.

The following figures illustrate the nature of the real problem. Figure 12.1 is from the paper that Klemenic gave in October 1976 at the Grand Junction uranium seminar for industry (Klemenic 1977). This figure is based on an idealized compilation which leads to the assumption that there are enough reserves and probable resources for industry to maintain reasonable grades and that at the end of the period the industry will actually have a little higher grade of ore to mine and mill than at the beginning. The paper which Klemenic has just presented does not show that the idealized forecast of production capabilities is based on an idealized use of reserves and resources. I submit that this is wishful thinking and does not agree with other statistics from ERDA. Figure 12.2 shows the actual history of 10 years of uranium production. We can clearly see that grades are constantly declining, a phenomenon that is age old, world wide, and applies to all mineral resources. Recovery has declined and therefore we are mining ever larger numbers of tons just to stay even. Mills have been running at almost full capacity, but because of declining ore grade they will never again turn out 18,000 tons of uranium concentrates per year; that level can only be achieved by truly new production facilities. In Figure 12.3 the data for 1966 to 1976 is taken from the four graphs in Figure 12.2; on the righthand side I have shown my own extrapolations without any manipulations or use of computer. I have shown the ore grade declining over the next 15 years from 0.15 to 0.12 percent. I have correspondingly let mill recovery go down from the present 93 percent to 91 percent, assumed as many mines as Klemenic is postulating, and increased the mining rate and milling rate to 100,000 tons a day in 1990, the end of the forecast period. The resulting production, because it is based on lower grade and lower recovery, will be somewhere around 40,000 tons a year. In Figure 12.4, the actual production is in the lefthand corner at a different scale than in Figure 12.3. The curve that is labelled "ERDA Production Capability" is the same curve that Klemenic discussed as the ERDA "could" production capability in chapter 11. It reaches 61,000 tons in 1990. My curve



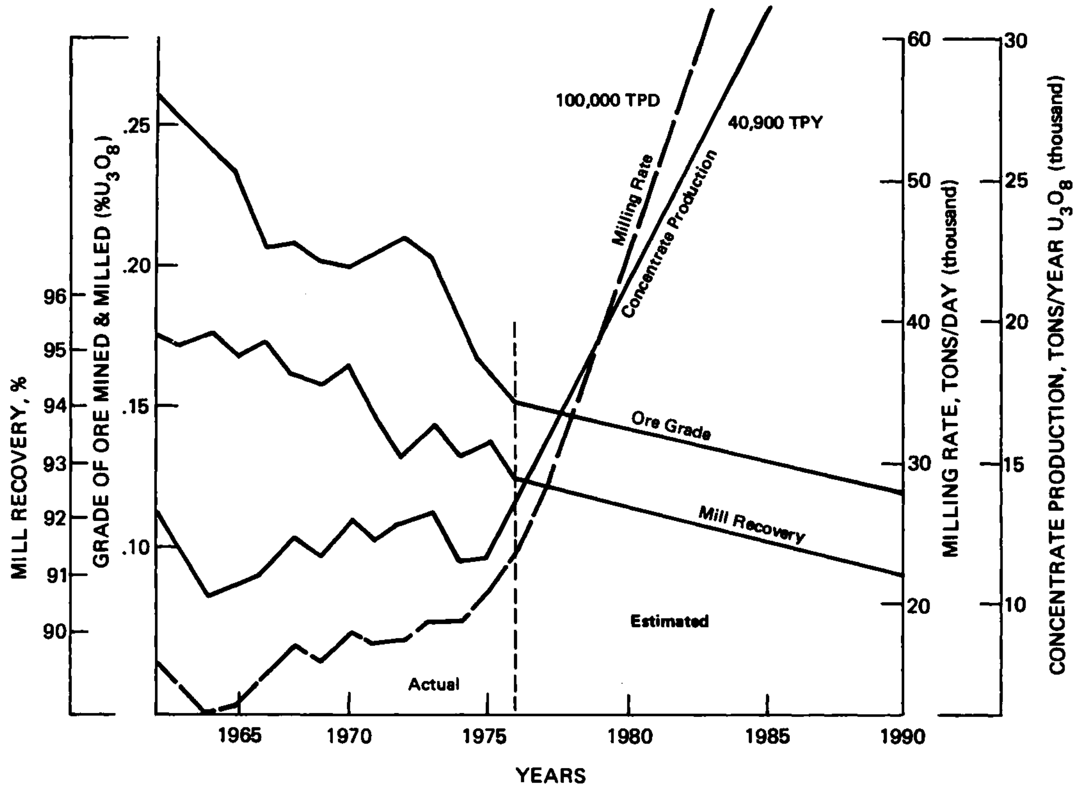
SOURCE: Klemenic (1976)

FIGURE 12.1 Estimated production capability from conventional ores.



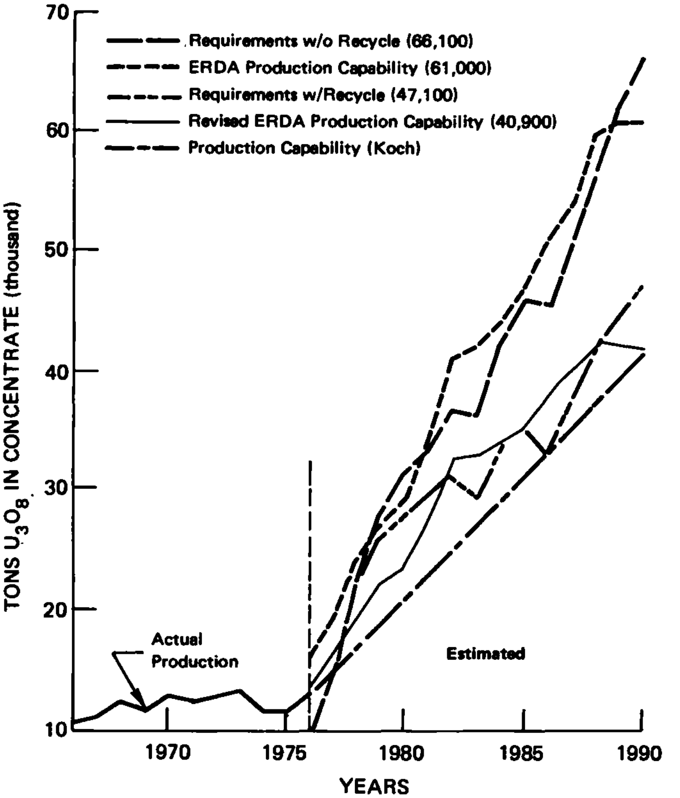
SOURCE: U.S. ERDA (1977)

FIGURE 12.2 Historical trends of uranium ore processing parameters, 1966-76



SOURCE: Koch (1977a)

FIGURE 12.3 Uranium production parameters, 1962-1990.



SOURCE: Koch (1977a); Klemenic (1976)

FIGURE 12.4 Comparison of uranium production capability and requirements.

for production capability (the line of circles) is at a 12 percent annual increase in tonnage capacity over 14 years resulting in a 10 percent annual increase in uranium production. An industry that can maintain production increases at such a consistently high rate for 14 years would be an exception to all other industrial efforts the world has ever seen.

I first gave this curve in January 1977 and it looked strange to be in the lowest position because my projection of production capabilities did not meet even the lowest requirements ERDA foresaw at that time. On the other hand, I objected to the fact that the ERDA production capability at that time exceeded even the highest requirement without recycle. In August 1977, six months later, I presented this same forecast as shown in Figure 12.5 at an Atomic Industrial Forum conference in Seattle. My simplistic straightline forecast had moved into the center of the range of forecasts. The ERDA forecast is still the highest; the upper line is the ERDA production capability curve given in the Klemenic paper today. The lower ERDA curve is given by Nininger in a recent paper and apparently is the first indication of the nature of the ERDA "will do" forecast. It may still be much influenced by overblown announcements or by the way ERDA keeps track of forward cost reserves.

Curved around my straight line (see Fig. 12.5) is a forecast by the Stoller organization (SMSC), a subsidiary of Arthur D. Little, Inc., based on a recent and comprehensive study. The SMSC and Koch curves are close in the early years but diverge markedly after 1985 because Stoller did not include production from facilities not yet on the drawing boards. The uranium mining industry will, of course, continue in some fashion. The most amazing curve on Figure 12.5 is the NRC/NAS forecast which stands out below the rest.*

I urge ERDA to produce an appraisal that can be labeled a "will do" or "can do" forecast. The new forecast should try to accommodate the multitude of problems of the real world and the methodology for the new forecast should not be based solely on scenarios. (I like specific forecasts and I do not like scenarios.) I also hope that ERDA will make

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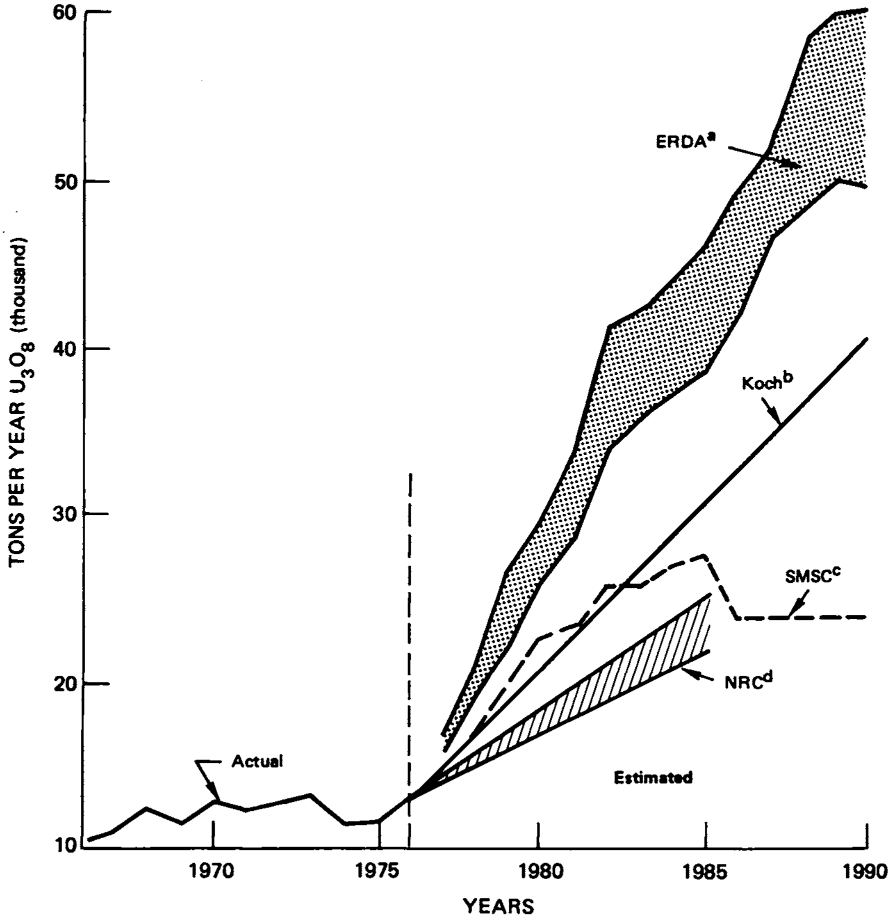
*CHAIRMAN'S NOTE: Mr. Koch here correctly quotes an industry news-letter source, which incorrectly quoted (and understated) the NAS-NRC uranium production estimates.



[a]U.S. ERDA (1977).
[b]Koch (1977b).
[c]U.S. Department of Commerce (1977).
[d]McGraw-Hill (1977).

SOURCE: a. U.S. ERDA (1977); b. Koch (1977b); c. U.S. Dept. Commerce (1977); d. McGraw-Hill (1977)

FIGURE 12.5 Uranium production capability.

provisions in the methodology for properly discounting speculation, optimistic production rates, and unwarranted company announcements. Perhaps few people realize that there are some 40 milling proposals in the talking stage, many of which may be figments of the imagination. I would suppose that not more than four or five of these mills will actually be built in the next 10 years.

I also hope that ERDA will avail itself of other cost sources than industry. I personnally believe that going to industry or waiting for industry to come to ERDA to divulge cost data or performance data of any kind is inadequate. There are good consultants in all fields and they can provide good data for production capability forecasting. ERDA will have to pay for the data but it is available.

Furthermore, I hope that the new forecast would truly reflect the realities of uranium mining and milling in the present environment. ERDA should not equate the price increases of the past few years with market incentives, because only a small percentage will report to profits. ERDA should temper any consideration of price with the fact that most costs, especially for new installations, have risen at least as much. In the next few years $40 a pound may be required as a break even point to bring new facilities on stream.

Any forecast should also consider the question of regulations, especially the federal ones. They have not eased. Nor have state regulations eased. Local governments, state governments, and county governments have too much influence already and the process of delegating responsibility downward is still going on. The federal government has not come out in positive tones supporting our industry and this hurts the uranium industry. For example, the Department of Interior has the final responsibility for signing a mining permit on federal land and not one has yet been signed. (Several of our permit requests are heading to Washington and I am pessimistic about whether any will be approved.)

Furthermore, it was stated that the mining industry is investing at an all-time record rate. When you deflate those numbers to adjust for present prices we are buying very little new capacity.

[NOTE: This session concluded with numerous technical comments and discussion of various details which do not lend themselves to orderly recording or systematic summarization.]

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RECAPITULATIONS AND COMMENTS BY DISCUSSION LEADERS

SILVERMAN: The session on the information base for estimating resources showed us the active pursuit of model construction through analogy, characteristic analysis, and the geostatistics of life cycles and discovery rates. As a matter of fact, it looks as if we are witnessing a cycle of more complex model building even before we fully understand, or can apply, the simpler models for the occurrence of uranium and assessment of the resource base.

We lacked a discussion of the data collection effort that is necessary to support the current model-building effort. Clearly, model building and data collection and selection are interrelated and interactive. It is the model itself that points out the kind of data that is most relevant to the relationship being studied, and it is the evolution of the data base which leads us to propose refined models that are more appropriate for simulating the natural world. I did not, however, get a sense of the direction in which data collection should be moving to enhance the impressive model-building effort underway. This point was a matter that concerned some of our commentators, as well, for what on the surface appeared to be a somewhat negative response to the subject of model building was primarily a response to the lack of discussion of the quality and quantity of data that is needed in order to build relevant models to guide explorationists. Harris pointed out the pitfalls of model building--the kinds of problems about which we must be aware as we build models and begin to test them.

And there is a second gap, which Silver pointed out to us: very little was said about the testing of uranium models. How does one construct a model-testing program that will enable us to understand whether or not the model we built is effective in predicting the occurrence, volume and grade of uranium ores? I think one ought to give some consideration to how one would test uranium resource models for their reliability and accuracy. A basic skepticism was expressed with respect to the utility of resource models and I think that skepticism can best be answered by a testing program.

Let me say in closing that there is enough uncertainty in the current data base with respect to quality, and, to some extent, quantity, so that the construction of truly useful exploration models, genetic exploration models, still needs to be demonstrated to the exploration community.

SCHANZ: In our second session we moved on to a discussion of "forward costs" by Patterson in response to the first of the questions I addressed to our Panel. This asked for a statement of the original intent and purpose of the use of "forward costs", how that concept has survived the test of time, and how it is currently used and misused. I asked our discussants to address themselves to the problems of inflation, varying times of calculation, absence of certain cost data in the calculation, the problem of comparability or consistency in results from property to property, the problems of treating "forward cost" using reserve-type data compared to <u>resources</u> data, and how to handle future exploration costs. We finally got down to the question: has "forward cost" outlived its usefulness? Is it subject to improvement and modification, or is there some need to turn back to a traditional or more conventional approach? Is there some new methodology that we might turn to?

To summarize how we responded to these questions in our discussion, I think we reaffirmed that uranium is unique to some degree. With its short history, with government involvement, and with the lack of an established market with a predictable character and known characteristics, we are dealing with a very capital-intensive industry which has a key role in the production of energy. It is also an industry which cannot change to alternative fuel materials. And in this particular type of resource we certainly would prefer not to turn too quickly or too heavily to foreign sources. Yet we do know from experience over a limited period of time, in spite of some gaps in our understanding of the genesis of uranium and how to go about finding it, there are lower grade deposits and the uranium industry probably can cope with higher cost resources somewhat better than other extractive industries. So there is interest in the magnitude of lower grades and having approximate measures of increasing costs--more so, I think, than with other major hard-rock mineral resources. Given that kind of setting, there seemed to be a reason to have gone to "forward cost" which reflects the nature of the industry.

We also heard about the problems of the misuse of numbers. In 1909 Herbert Hoover deplored the charlatons of mining who applied flights of imagination to quantities that appeared to be ore in sight when there was none at all. It reminds me of another workshop where a geologist was deploring the necessity to give any number at all about the offshore Atlantic resource potential for oil and gas because we haven't as yet discovered anything. As a consequence we were fooling the public when we gave them numbers. There is the further complaint that when we give the public numbers it does the strangest things with them. Despite this fear of misuse I do not think we can abandon the practice of looking beyond the measured reserves both geologically and economically, despite some concerns in our workshop audience.

It appeared that most of us favored improvements rather than abandonment of cost estimation. It seems that everybody urged the development of a good base of information. There is also a desire to bolster "forward cost" with details as to grades, tonnages, deposit sizes and depth, and then integrate the use of this information to enhance the quality of our understanding. We recognize that due to changes in technology and cost of inflation we have had some amazing and disconcerting migrations of quantities from one "forward cost" category to another; this presents a problem to the uninitiated. Some form of indexing was suggested to get away from the ten dollar, fifteen dollar, and thirty dollar labels, which have only transient usefulness, and perhaps go to present prices, multiples of present prices, or index numbers so as to avoid fixed dollar labels. We have, of course, in "forward cost" the problem of keeping our resource data up to date and, as is usually the case, we are dependent upon industry data sources.

It appears we will have to continue to seek refinements so we can deal with: the various types of future costs, the uncertainties of higher-cost deposits not as yet mined or being mined, and those undiscovered deposits, where expenditures are in the future and not in the past. "Forward cost", as has been emphasized, is not a proxy for market price. It was not meant to be and it need not be. I think care should be taken to avoid its use as price. But let's face it, it will be so used by some. The harm in this misuse seems relatively minimal and certainly does not justify discarding the concept. As it is now understood (and I think we can enhance the understanding in workshops such as this) "forward cost" seems to be in concept straightforward; it is now a well-established measure, but it can be improved in its usefulness.

The closer we can move "forward cost" to a full cost concept, the more useful it will become. We have had only one suggestion for forward cost to be replaced by a more dynamic, time-oriented system. Discounted cash flow was suggested. This has a flow-through-time characteristic and is less static. There are some reservations concerning the data that might be required, problems of that data, the level of effort required, problems of keeping the analysis current, and whether there is sufficient additional usefulness in such an approach to warrant it replacing or being used along side of "forward cost". Certainly this suggests further study.

DOUGLAS: We went on to consider the conversion of resources to reserves, and the time and constraints involved. Roach considered the technical problems which might yield to R&D efforts and whose solution could aid industry in converting resources to salable uranium; he felt that there was the need for more formal government-industry cooperation in working together on R&D programs. We discussed in a general way the time involved in converting new discoveries into useful applications for industry. I think the major point that Roach was making is that we do need new exploration techniques. As he pointed out, drilling is still the major tool for uranium discovery and it seems to me that it is about time we evolved new methods. Roach focused on the fact that we need new data, new techniques, and particularly subsurface techniques which would increase the yield of information from the drill hole.

Because exploration hole depths have increased significantly in the last five years, approaching 1,200 meters in some cases, research studies related to improving acquisition of data from drill holes, and extending the significance of data collected outward from any drill hole, are needed in order to improve the efficiency, lower the cost and increase discovery rate in exploration. It has been suggested that determination of lead isotope ratios from samples taken from a horizon of interest could define areas in which uranium might be found. It has also been suggested that new materials are available that would enable drill rods to bend 90 degrees within five meters. If such were the case, it would permit more effective exploration in sandstone environments. Further research in down-hole techniques, such as mentioned above, should be carried out and their effectiveness demonstrated.

Northern pointed out that any long-range strategy in exploration must reflect the market place. It should be noted that exploration companies do not explore for resources, in the strict sense, but for extractable reserves. A stable long-term market incentive is required. It takes 8 to 12 years to explore, discover, develop and bring a mine into production. Companies require, for any commodity, market assurance before committing the necessary funds for a long and persistent search.

Therefore there must be an assured market before companies will expend funds and go about the where and how of discovering the resources which could be (and I emphasize "could be") converted into extractable reserves. But you need the right sociopolitical climate and mineral market before converting resources into reserves. Implicit in this is that "reserves" could turn into uneconomic "resources" if the market is poor, or if sociopolitical forces prevent development.

Northern also pointed out that industry has been spending about $500 million in exploration and development, but is obtaining only $400 million in cash flow and therefore is engaged in deficit spending. Only because of industry's optimism on the future of the nuclear industry is it willing to continue such expenditures. Exploration companies are confident that they can discover the uranium required by utilities. However, should confidence in the future of the industry be damaged by continual erosion of reactor orders and regulatory obstruction, exploration will be reduced and reserves will not be discovered at the rate required.

The lead time required to discover deposits and bring them into production ranges between 8 and 10 years, according to Northern. I would suggest that it is more likely a range of 8 to 15 years. I am reminded of a case in which 2,500 prospects had to be looked at before 10 were selected as being of serious interest, and before one was discovered that turned into a mine. If we take into account how many people are required to look at that number of prospects, at the very minimum you are looking at five or six years before you get into any extensive drilling to define what really may be an ore reserve. This time range is likely to lengthen with rising inflation, with further regulation, with withdrawal of lands, and with changes in various regulations.

It has also been pointed out that important to the needs of the consumer is the timeliness of production capability. The total resource base is not important if it cannot be converted into production. Inflation rates are such that there is a relative reduction in spending. All of these are going to affect the rate of discovery.

Of the exploration money being expended in the uranium business, it is reported that about 17 percent is going into the search in other than sandstone environments. It should be understood in all of this that geological concepts are critical to any success obtained: key personnel and the organization to back them are therefore critical. Industry is hampered by the shortage of experienced and competent technical personnel. Mining companies are experiencing rapidly rising costs in part because of a decreasing rate of production per man shift. This has been caused by a shortage of experienced miners. Employment opportunities in mining have not attracted the caliber of workers required. There is also a shortage of experienced and competent exploration geologists, and as a corollary, a shortage of useful imaginative geological concepts.

Problems confronting exploration include a shortage of drill rigs and of competent crews, lack of capacity to build such rigs, and a shortage of gamma-ray probe trucks. Obviously, the length of time required to turn resources into reserves can be increased or decreased by the availability of drill rigs and crews.

In addition to problems outlined above, there is still the problem of regulatory authorities in county, state and federal bureaucracies with overlapping authorities. Common difficulties are lack of basic background knowledge of the subjects involved, and, in many cases, a seeming unwillingness to make a decision. All of the above can and do cause inordinate delays in planning and construction of facilities. The cost of delay can force abandonment of a once viable project, and, at the very least, is causing lead times in mine development to exceed 10 years. Land withdrawals are becoming a major problem to industry looking for new areas in which to explore.

ROSENBAUM: We are indebted to Klemenic for enunciating clearly that ERDA's projections of uranium production capability have been "could do" projections. These represented optimistic bench marks of what might be produced under ideal conditions of government suppport, uranium finds, conversion of resources to reserves, availability of capital, and a limitless market for uranium concentrates. The production capability for the first three years of a "could" projection was a summation of industry's announced plans. Over the past three years those estimates proved to be 30 to 35 percent high by subsequent production statistics. Koch made the point, and I think appropriately, that when the production capability curves are drawn, ERDA should give consideration to starting with the production figure which is already a matter of record rather than with the faulty estimate. I do think that the credibility of the numbers that are presented will be greatly enhanced by accentuating the "could" nature of the past presentations.

Koch takes issue with the ore grade projections used by ERDA in its production capability estimate. ERDA shows a decline from 0.16 percent U_3O_8 in 1976 to 0.13 percent in 1981, but is back to 0.15 percent in 1990. Koch believes the downward trend of the past several years will continue and will reach 0.12 percent U_3O_8 by 1990. He points out that most of the current and contemplated mill expansions are for the purpose of maintaining existing concentrate production rates because of declining ore grade (and concomitant decline in recovery). ERDA's ore grade projection may be influenced by its methodology of fitting production from individual production centers into designated forward cost categories.

As far as coming up with "will" or "most likely" numbers, Klemenic makes the case that this is a question of subjective analysis depending upon how optimistically or pessimistically an individual chooses to interpret and anticipate current and forthcoming technical developments and regulatory, political, and social constraints affecting nuclear energy. Despite its subjective nature, and the possible need to use alternative scenarios, a "most likely" production capability estimate would introduce a welcome note of realism as compared to the "could" capability projections as now presented.

Klemenic noted a sharp decline in the number of nuclear reactors being scheduled for construction. He attributed quite a bit of this decline to concern on the part of power companies about the adequacy of uranium resources and reserves. I think another reason may be epitomized by pickets at the gates of proposed sites and of operating nuclear plants, vehemently protesting plant construction or continued operation of nuclear reactors. There is tremendous social concern that relates nuclear reactors to nuclear proliferation, and distrusts available methodology for disposing or controlling nuclear wastes. These kinds of things may be having more of an adverse impact upon new nuclear power plant construction than questions about the uranium resource base and production capability.

SILVER: I have learned a great deal from the interactions among the representatives of the various important elements of the national uranium enterprise who have come here to exchange ideas. That was the fundamental intent in calling this conference--to create an environment where there would be profitable information personnaly derived by the participants. In that light, I consider the workshop to be a success.

We hope that the role of the Board on Mineral and Energy Resources in organizing this workshop has been one which in general meets with the approval of the community.

Once again I want to join with all members of the organizing committee in thanking you for your willingness to come and participate.

This workshop is hereby adjourned.