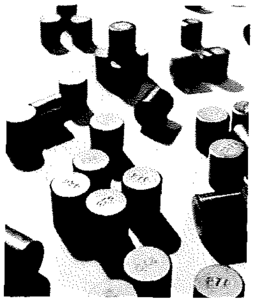

Raw Materials Supply: Planning for Alternatives

by Hugh Douglas

Mr. Douglas, a senior economist with Dames & Moore, is a specialist in strategic resource planning for industry and government. He has more than 25 years of experience in the development and implementation of master plans for acquisition of minerals and energy resources including uranium, coal, oil and gas, copper, lead, zinc and other major metals. He has worked in the fields of energy policy formulation, supply-demand analysis of metals and minerals, and transportation economics.

Beginning in the early 1970s, the availability of basic raw materials for industry became an acute problem. Shrinking reserves, capital shortages, rapidly changing government regulations and laws–along with other constraints too numerous to list–all pointed to a need for better planning in the acquisition of these raw materials.

Forecasting and planning always require the assessment of future alternatives. This has always been so, but in the 1950s and 1960s, one could just extrapolate economic data into the future and feel fairly assured that a single forecast–that one dot or dashed line on a graph–represented a forecast the organization could live with. Today, however, we don't have that assurance, and several scenarios for alternative futures are needed. The post-World War II period can be viewed as essentially an aberration in economic history, which, before that, has always exhibited an unstable, changing and unpredictable nature; it appears that the future will see a return to the basic pattern.

One reason that futures research is a valuable planning tool is that it helps planners perceive and monitor change. If thought and care have been used in studying the dynamics of a particular industry, and if several futures are perceived, then when change does occur, the alternative actions and plans can be quickly implemented.

THE RELATIONSHIP BETWEEN POTENTIAL ENERGY DEMAND AND RAW MATERIALS REQUIREMENTS

Let's assume that the long-range goals and objectives of the particular industrial organization have been thought out and officially recognized. Only then can we discuss plans to assure a raw material supply for that organization–whether it be a petrochemical complex, a cement plant, or an electric

This paper is based on an oral presentation prepared for a group of utility executives.

generating station. (The latter will be used here as an example of the planning process.)

Seven basic elements in developing a strategy for raw materials supply are:

- Determining Future Energy Demand
- Requirements for Prime Mover
- Analysis of Costs and Benefits
- Modeling Determinants
- Environmental Impacts
- Input Analysis: parameters/events
- Futures Research

These items should be self-explanatory, but perhaps two words need to be clarified. The first, "prime mover," refers to the type of fuel powering an electric generating plant. The second word, "futures," does not mean commodity futures—such as pork bellies or eggs traded in Chicago—but rather alternative futures, or different scenarios of the future.

For an electric utility, planning obviously requires a balancing of future demands for electricity with the fuels required to generate that electricity. Figure 1 shows this relationship.

The potential demand can be calculated using four input variables. There are many, many more potential inputs, of course, but these four are quite basic—other inputs would affect potential energy demand only slightly.

The first of these variables is service area population. One of the characteristics that must be quantified is the mix between young people and old people and how this will change in the future. It is important to know whether the population profile is aging, for instance, because older people use less energy than younger ones. Another impact on changing energy use is family size.

Population can be thought of in a broader sense, too: it can also include the energy required by industries. Energy used in a market area could be calculated both for the industries selling products and services only in the market area, and for those manufacturing goods in the area and selling them outside of it.

A second variable for determining potential energy demand is the MSL (Material Standard of Living) Index. This is determined in part by "life style"—and, as we can all see, "life style" is changing. In the post-World War II era we could assume, for example, that people would graduate from the one-slot toaster to the two-slot toaster, and then up to the four-slot. We probably wouldn't make that assumption today, and there are other, more basic changes taking place in how man views his future.

An MSL Index is judgmental and requires the researcher to go beyond his immediate discipline or area of expertise. It's been said that advertising has an eight- to ten-year lag effect on the life styles of the population, that poets, writers,

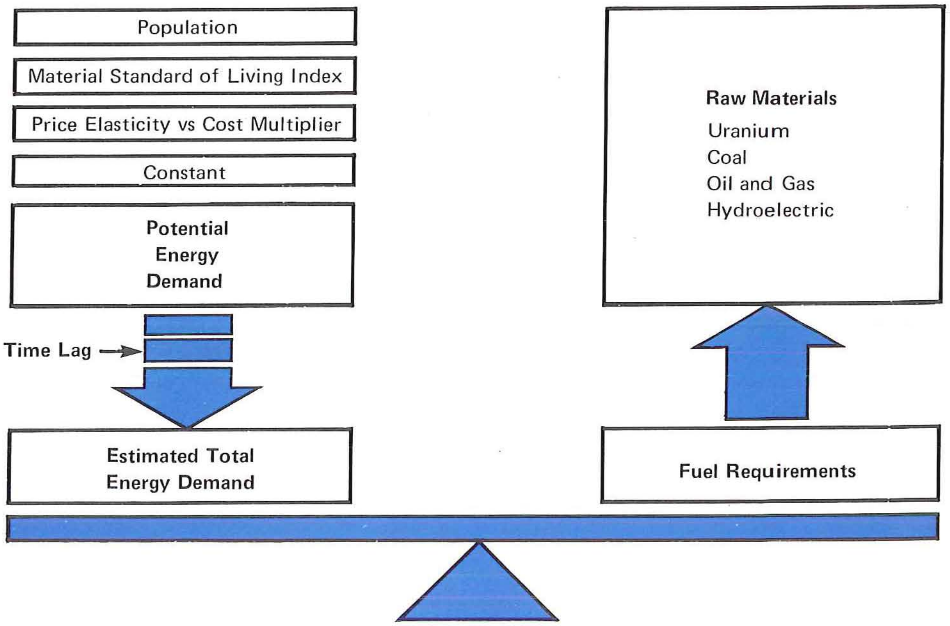

FIGURE 1. The relationship between potential demand and raw materials requirements

novelists, artists—those who are generally breaking away from traditional norms—have a high impact in the communications industry, particularly in advertising.

Thus, while in the short run, the words and pictures in newspapers, magazines and on your television screen might affect your purchases of the products advertised, in the *long run* it is the views, the images, and overall response in the ads to the types of clothing, hairstyles and so on, that will change a population's life style eight to ten years later.

A careful monitoring of life styles is required for development of an MSL Index and is very important in estimating potential energy demand; it goes far beyond merely quantifying economic data.

The third variable for estimating potential demand includes price elasticity and a cost multiplier. For an electric utility, price elasticity is the effect that a doubling, tripling, or quadrupling of the price of electricity will have on the demand for it. The cost multiplier—the extent that fuel costs can be passed through to the consumer—will in turn affect the price and the demand for electric power.

In addition to these three variable factors, which are somewhat judgmental in nature, utility planners must also apply a "constant"—also judgmental—to smooth out the forecast load trend lines.

Once this has been determined, an overall time lag must be taken into account for each of the inputs. And if the planner is estimating potential energy demand for several different energy forms, the time lag for each must also be considered. The net result is total energy demand, which is then converted to fuel requirements, and from that to requirements for raw materials.

Raw material requirements can be classified by prime mover: uranium, coal, fuel oil and gases (natural gas, substitute natural gas and liquified natural gas), and hydroelectric (small dams for example).

FUTURE DEMAND VERSUS SUPPLY

In economic studies, demand is matched against supply. For an electric utility, this is simply a balance between the energy that must be delivered and that which can be produced.

This balance is illustrated in Figure 2. The vertical scale is quantity in BTUs on a log or ratio scale. Time on an arithmetic scale is shown on the horizontal. At the point in time labeled "now," a utility knows that certain amounts of raw materials, expressed in BTUs, are required to deliver electricity as of the moment. (This figure does not account for peak shaving, etc.; base-load demand is levelized.) If future sales of electricity were projected as perfectly flat,

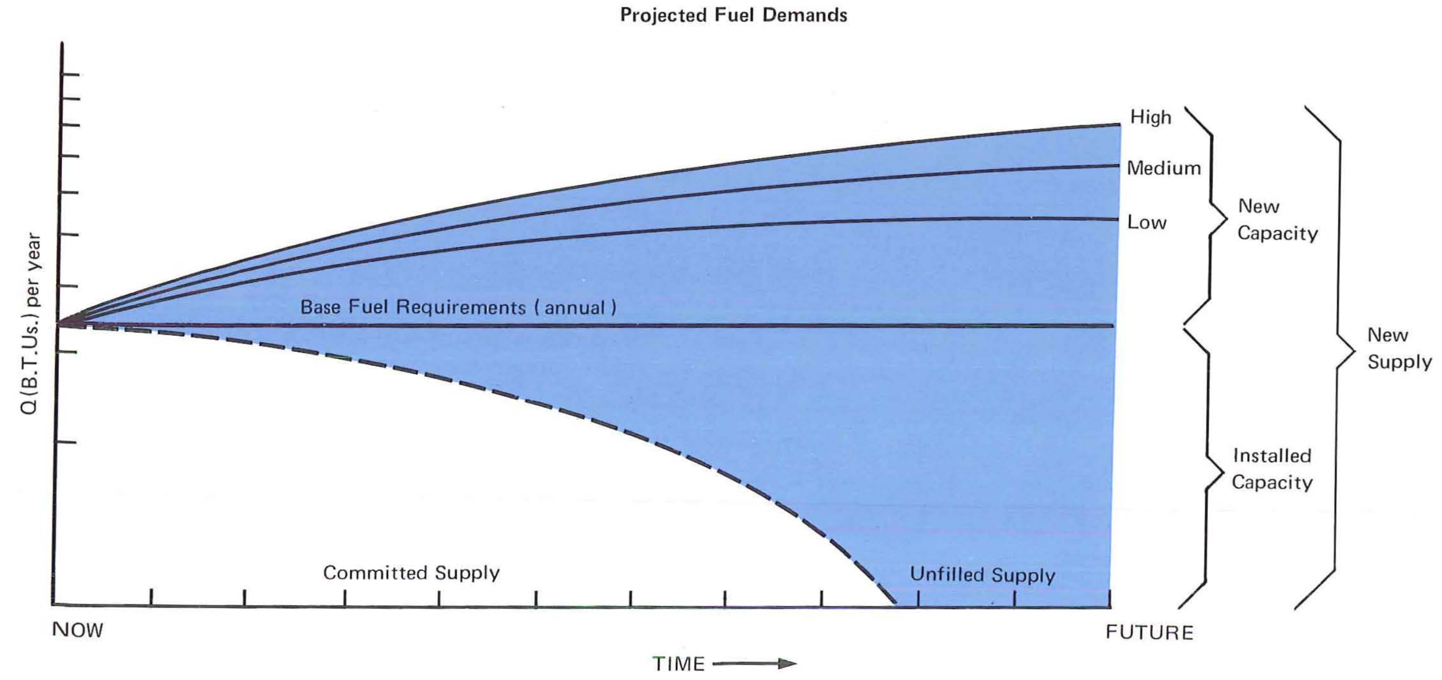

FIGURE 2. Future demand vs. supply

then obviously no increase in the annual amounts of raw materials would be needed as we move into the future.

Whatever the projected fuel demand, however, it is unlikely that the utility would be fully committed to purchasing fuels too far into the future. These committed purchases normally decline with time and are shown as an arbitrary dashed line declining to zero. The area above the dashed line represents unfilled raw material requirements needed to keep the existing power plants operating.

Three forecasts of future fuel demand are shown above the horizontal base fuels requirement line. Fuel demand is directly related to kilowatt-hours of electricity, and is shown for high, medium, and low forecasts.

Future fuel requirements now consist of both unfilled orders for existing plants and future requirements to meet projected demands.

A conservative fuel acquisition strategy should not commit the utility to early decisions. Some fuels supply must be committed, of course, to keep present and immediately planned power plants operating, but as one moves farther into the future, options on fuels acquisition must be held open. This is to allow for unexpected changes in future supply/demand balances and other future uncertainties.

COSTS VERSUS BENEFITS

Those utilities acquiring, or planning to acquire, future fuel supplies will have to consider both the costs of different courses of action and the benefits that might be derived. Table 1 lists four typical costs, and four examples of benefits.

Holding costs for a futurity might best be explained by way of example: Suppose that current XYZ Electric Co. studies have determined that low-sulfur coal from Virginia or West Virginia might be an attractive fuel alternative. Suppose further, however, that their planners have also foreseen that the changing price of coal relative to the cost of nuclear generation several years hence might make coal a less attractive alternative. The utility, of course, doesn't *know* what the future price of coal will be or how the equations will work out in real life, but it wishes to hedge. The best decision in that instance, then, might be to go ahead and purchase land near a railroad siding, or at a river site, that could be used for coal storage. The cost of acquiring that land, which may not ever be used for the storage of coal, is called the "holding cost for a futurity," or the price one pays to keep one's options open (perhaps the land would not have been available later, or would have been too costly).

Other costs, too, have to be considered in a cost-benefit analysis. The utility's decision to acquire land for future coal storage (or its decision not to) depends also on its decision regarding future "as-burned" costs and what it considers the costs of a coal-fired generating plant will be. If the utility adds new industrial customers—and thus requires new base-load power to meet the increased future demand—will it charge them the going rate for the additional (generally higher priced) fuel needed to generate that

TABLE 1. Cost Vs. Benefits

COSTS	BENEFITS
• Holding Costs For A Futurity	• Supply Security
• Future 'As-Burned' Costs	• Generating Reliability
• Fold-In Pricing	• Environment/Social
• Future Capital Costs	• Improved Cashflow

increased power, or will it "fold-in" the price of that fuel and simply average out fuel costs for all its customers? Sometimes that decision is made, not by the utility, but by the state regulatory agency.

Similarly, the utility must determine what future capital costs will be on the per-kilowatt-hour price or whatever other measure is to be used.

These are all very difficult things to quantify in terms of dollars and cents, but they must be considered carefully in completing the cost-benefit analysis. For if this analysis and futures planning can lower the costs of generating power, and can assure security of supply, this in turn might improve the utility's cash flow and increase its rating in the investment community. This could lead to better financing, lower interest rates on long-term debt, and help increase the utility's ability to develop the capital needed to meet long-range requirements for generating capacity.

MODELING DETERMINANTS

Figure 3 shows the relationship of various elements that would be used in developing a plan. Let's review this diagram, beginning with

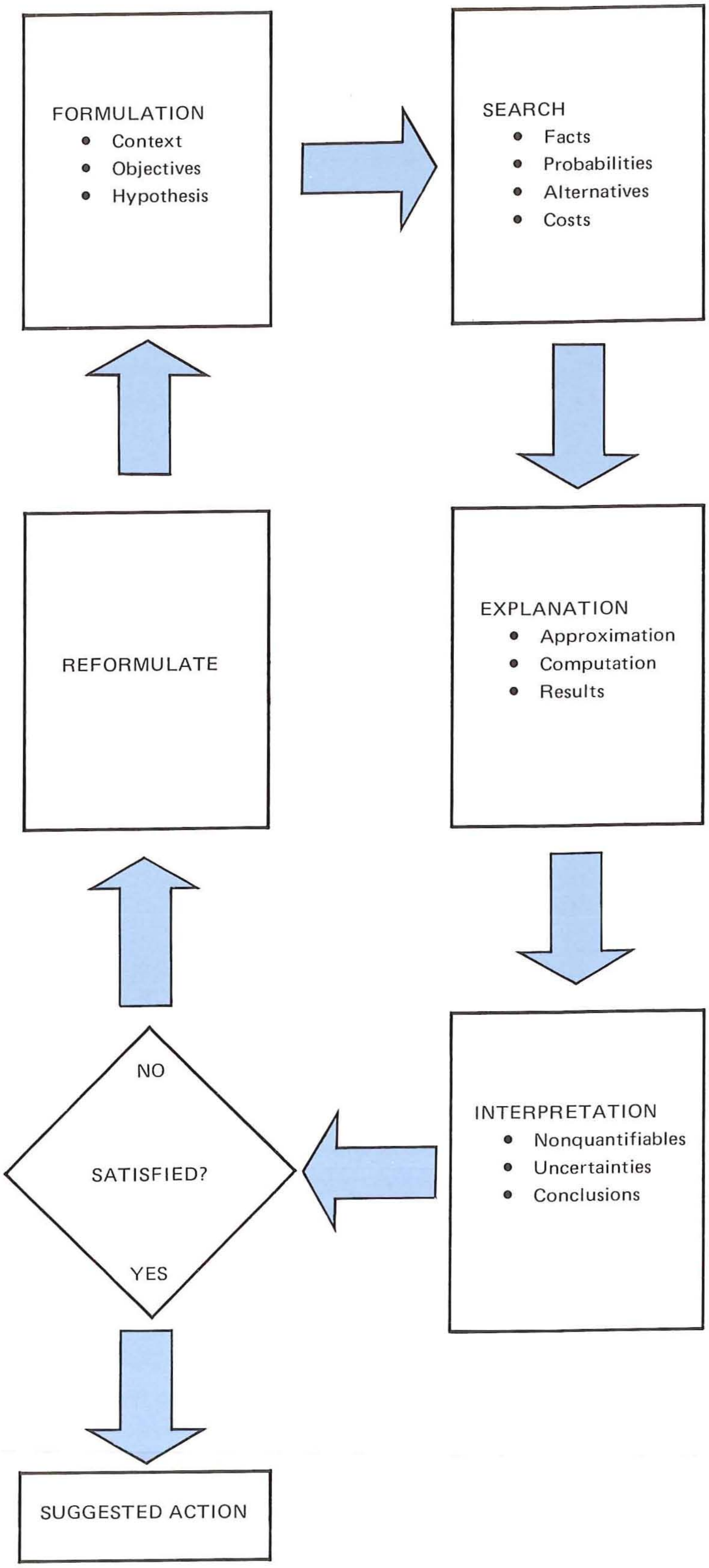

FIGURE 3. Modeling determinants

Formulation. "Context," for example, means the environment in which the utility will operate in the future. One can speculate on this point. What are the utility's objectives? Is it just to be a seller of electricity and natural gas, or is the utility going to sell energy in all forms? Is the problem—or the opportunity—merely in selling electricity or gas for hot water heaters, or is there a market opportunity for selling *systems* to make that hot water? The latter, for instance, might involve installation and maintenance of solar heaters.

Having formulated the problem, the next task is to search for facts: how much energy is being consumed? what are the changes in the population? etc. Here, one has also to assess what the probabilities are that one or more of the forecasts will take place. The utility has to look at some alternatives in those forecasts—a sort of alternatives futures forecasting—and finally has to develop projected costs for some of the more likely eventualities.

Then, moving to the next box, utility planners must quantify and make some reasoned judgments about the future environment—they must "approximate" that future—and then measure the various relationships to get the optimum results.

"Interpretation," in the next box, is most difficult and requires a good deal of judgment; the nonquantifiables and the uncertainties regarding the alternative futures must temper the hard facts. Usually, the interpretations are expressed as probabilities of a future event taking place. After assessing all the results, by taking account of the nonquantifiables and uncertainties, one will then come to conclusions about what the future holds and how the utility should react to it.

If one is satisfied with the results (the "yes" path), then the utility can develop a suggested action plan. If the planners are not satisfied, however, they must go back and rethink the context, objectives, and hypotheses through a second time (or a third time), and begin the process again. It's important to keep going through the cycle until all requirements are satisfied. Only then can a tactical plan be developed.

PARAMETERS FOR PLANNING

Having developed a strategic plan for acquiring raw materials, the utility must then carefully study each individual source of supply, both on its own merits and also to see how it fits into the overall plan.

There are at least nine main parameters to consider in selecting a source of raw material supply:

- Reserves/Capacity
- Location
- Quality
- Transportation
- Water
- Economic Size
- Mineability
- Equipment
- Manpower

An assessment of uranium reserves, for example, would require an estimate of when the United States would deplete those domestic reserves known to be minable at today's costs and technology. Let's assume that a severe supply or reserve crunch is forecast for the United States after 1990. If a utility were planning for long-range uranium supplies it might therefore have to look abroad.

This is to suggest that a conservative strategy for acquisition of uranium must certainly take into account not only reserves in the United States but the foreign potential as well. The capacity of the mining industry to produce these reserves over the short term—five to ten years—must be determined, and this must be matched against future needs, market availability, and whether the utility must have a "captured" supply.

Another point to assess is the location of the identified reserves. This is particularly important in the case of coal. Three or four viable coal properties might be optioned, but location can be a very important factor in the final decision as to which of them would eventually be acquired. For example, the utility might move coal to the plant site by an all-rail route from one location, or by a rail and barge (or pipeline) route from another. Transportation costs can vary tremendously, particularly if a barge route is used most of the way (barging tariffs are unregulated by the ICC). These costs alone might be the deciding factor in selecting coal from one location over that from another.

Water can be a problem, too, especially if one is going to option coal in the western United States; water availability can be a very serious constraint on any mining operations in the west, or in moving coal by slurry pipelines.

The other parameters—economic size, minability, etc.—must also be considered in detail and balanced against the overall plan.

EVENTS

A number of external political, social, economic and technological events will also influence utility planning.

As an example of events that must be considered, let's look at the four basic ones included in Table 2: politics, regulation, changing prices or costs and technological change.

In considering alternative futures, political and legislative events are an important input. For example, laws requiring the mandatory use of coal by electric utilities in certain areas of the country is a possibility. Another might be the reimposition of an embargo on uranium imports into the U.S. Similarly, regulatory changes affecting land use, water and air will certainly influence utility decisions.

The movement of prices for alternative fuels must be also assessed. What would be the effect on a utility's fuel choices should OPEC prices drop? What effect would this have on the availability and the security of fuel oil supply? And what would happen to the price of coal, which is directly competitive with fuel oil? Answers to these and other questions affect the plan.

"Inflation" is another factor that influences utility planning. Besides its other impacts, it affects full recovery of capital investments. At inflation rates of 5 or 6 percent (assuming a 30-year life on a capital-intensive nuclear reactor, and not being able to index the depreciation charges), the utility will never fully recover its investments through the depreciation account. Are there alternatives to the capital intensity of energy production? Some economists believe that the world may be entering a period of deflation—not collapse-type deflation as in 1929-31, but a long period of an unraveling of the price structure. But, whether one has inflation or deflation, it is an economic event which must be evaluated in deciding whether to use fuel oil, nuclear, or coal as the prime-mover.

Other inputs to the planning process concern the degree to which the government will subsi-

TABLE 2. Events

POLITICS	• Mandatory Use • Embargoes
REGULATION	• Land Use/Water/Air • MESA (Mine Equipment Safety Act)
CHANGING PRICES/COSTS	• Interfuel Competition • Controls • Inflation • Subsidies • Reserves
TECHNOLOGICAL CHANGE	• Productivity • Costs • Reserves

dize certain industries, the changing prices and costs that affect reserves, and the impact of technology on recovery of those reserves.

In sum, then, events which are not quantifiable—that are largely judgmental, in fact—must also be assessed in order to develop meaningful alternatives for fuel supply acquisition.

RAW MATERIALS: FUTURES RESEARCH

In conclusion, planning a raw materials acquisition program involves alternative futures research (Table 3). There is no unique and true picture of the future; there are several of them. (Soothsayers are not often right—perhaps a few mystics and psychics are, but they are not believed or accepted anyway.) Therefore, in planning, more than one forecast is required.

One has to inventory possible or probable future events. Appropriate planning parameters can be developed to meet client objectives, but identifying the critical events that might take place is not easily done—even though it is part of the planning process. This events inventory requires a group of interdisciplinary professionals who have an overview, who know more than just one industry. It involves an in-depth interaction among economists, sociologists, and engineers—and the disciplines of geology, mining, and the environmental sciences. Once the utility has identified an inventory of these possible or probable critical events, a certain number of potential bottlenecks, or—to look at it another way—potential opportunities, will become apparent.

So the action plan should concern itself with how the utility overcomes the bottlenecks to get where it wants to go—to the goals and objectives set at the beginning of the process. How does one plan the action to take advantage of opportunities one sees?

Futures planning, alternative futures planning—building scenarios, if you will—is an extremely important element in planning a raw materials acquisition strategy. This type of planning can be and is successful. It helps the utility cope with future shock.

TABLE 3. Futures Research

- No Unique And True Picture Of The Future Can Be Made
- More Than Forecasts Are Required
- Inventory Possible Events
- Identify The Critical Events
- What Are Potential Bottlenecks?
- Plan The Action To Overcome Bottlenecks

Future Uranium Supplies vs. Demand: The Strategic Position of the United States

by David J. Kroft, Ph.D.

Dr. Kroft is a minerals economist and economic geologist with Dames & Moore. During his professional career he has completed a number of mineral commodity studies, mineral property evaluations and nuclear power plant siting investigations. His doctoral dissertation at Stanford University on the strategic position of the United States with respect to uranium supply and demand in the foreseeable future formed the basis of the present article.

> "It is clear that uranium and thorium are materials of great strategic importance to nations seeking to establish for themselves a powerful position in the field of atomic energy. The fact that rich sources of such materials occur in a relatively few places in the world, as compared, for example, with oil, creates a competitive situation which might easily produce intolerable tensions in international relations."
>
> Acheson et al.
> *"The Elimination of International Rivalry"*
> 1946

As the United States enters its third century, there is much discussion concerning the adequacy of its energy resources. It is generally conceded that known U. S. reserves of oil and natural gas are insufficient to meet projected long-term domestic requirements. Energy planners have therefore suggested that, to satisfy future U. S. electrical demands, to help conserve domestic oil, gas, and coal resources, and to reduce the country's dependence on foreign energy imports, the utilities industry must develop a predominantly nuclear-powered generating capability.

The uranium resources of the United States are extensive. A number of economic, social, environmental, political, and technological factors, however, limit their utilization. Because of these constraints, the nation's identifiable, economically extractable reserves of uranium appear inadequate to meet domestic requirements as projected by the Energy Research and Development Administration (ERDA) and other organizations. Unless additional domestic uranium reserves are discovered and the attendant production capacity developed, Dames & Moore predicts that a shortage of uranium supply is possible in the United States by the mid-1980s.

To maintain maximum operation of nuclear generating facilities should a shortage in the domestic supply of uranium occur, many U. S. utilities may very likely be forced to obtain a portion of their uranium from foreign sources. However, either to promote self-sufficiency or to achieve political goals, many nations known or thought to have significant uranium resources have enacted restrictions on the exploration for, and/or exploitation of, uranium deposits within their borders. Increasing demands by foreign nations for imported uranium will intensify competition among both producers and consumers of nuclear fuel for the available reserves.

Given these considerations, as well as existing and projected geopolitical conditions, those domestic utilities which either have, or intend to adopt, a nuclear generating capacity may encounter numerous obstacles in attempting to meet future nuclear fuel demands with foreign uranium.

This paper briefly considers the near-term availability of foreign uranium for use by U. S. utilities in light of the various economic, social, environmental, political, and technological considerations. The assumption is made that, regardless of market forces, demand for uranium over the next decade may exceed domestic production capacity and/or the socially and economically exploitable uranium resource base of the United States. In light of recent U. S. energy policy statements, no attempt is made to analyze the impact on domestic uranium supply of the introduction of breeder reactor technology or limitations in enrichment capacity. Unless otherwise noted, all data are current as of mid-1977. Because disruptions in the political orientation/stability of nations can occur rapidly, however, any geopolitical evaluation of world uranium resources must be continually reviewed in light of those changes.

URANIUM RESOURCES OF THE UNITED STATES

Uranium mineralization occurs in many different geologic environments in the United States (Figure 1). Relatively few of these have been explored or developed, however, largely because of economic considerations. Regardless of location, uranium deposits can be broadly classified into one of two categories based on their present amenability to development—which is in turn largely affected by developments in the economy, world trade, and advances in extractive technology.

Conventional deposits are those from which uranium has been or is presently being extracted. These include: the sandstone deposits of the western U. S.; the vein deposits of Washington and Colorado; the uraniferous phosphate rock of Florida; and by-product uranium from copper leach solutions.

There are numerous occurrences of low-grade uranium mineralization in the U. S. which cannot be exploited profitably under either present or foreseeable economic conditions despite the fact that in many instances the extractive technology exists with which to develop them. These unconventional resources include the Chattanooga Shale as well as uraniferous coals, granites, carbonatites, conglomerates, salt deposits, sabkhas, and alluvial fans.

Many studies have attempted to determine the amount of U_3O_8 contained within domestic uranium

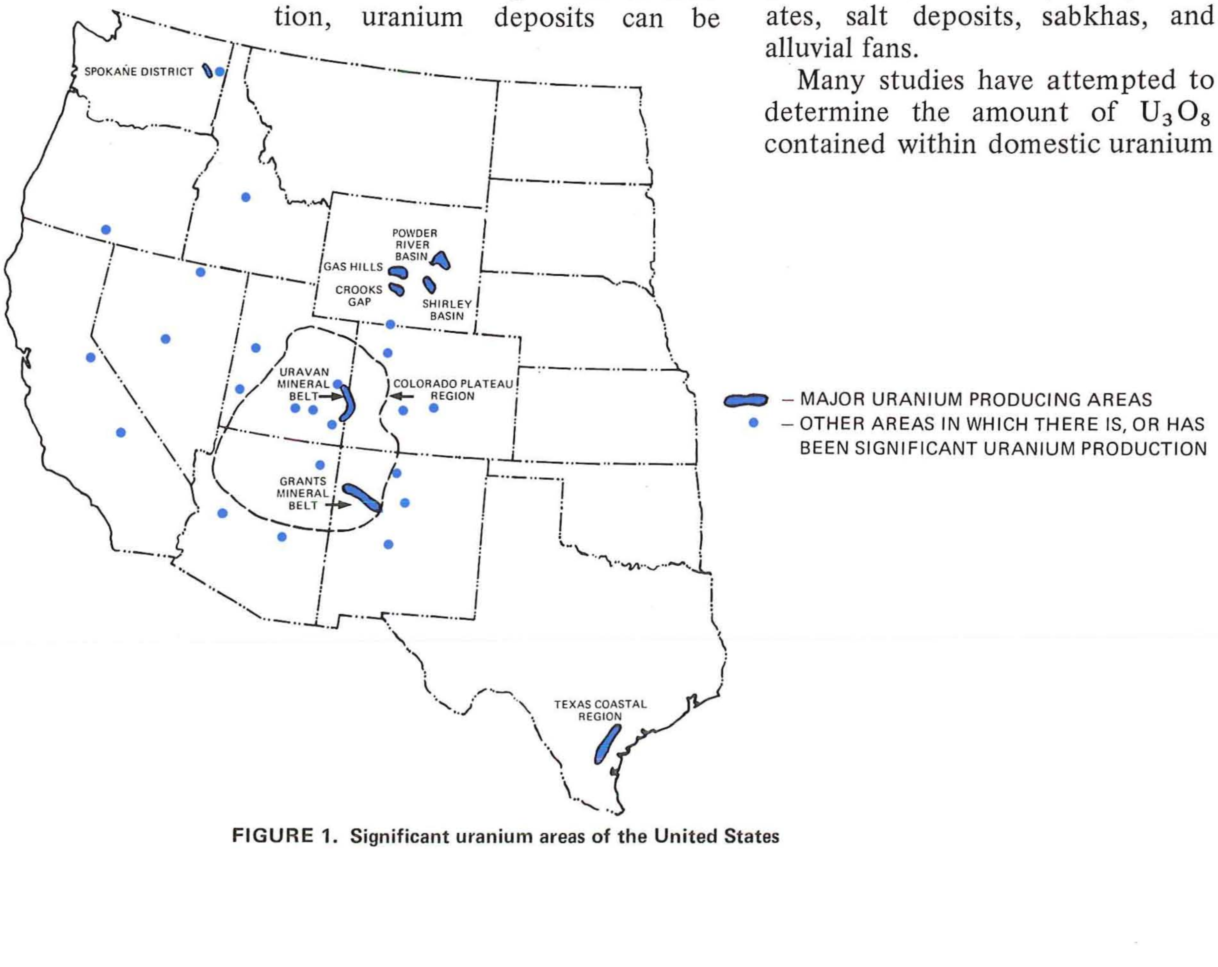

FIGURE 1. Significant uranium areas of the United States

deposits. These efforts have generally been unsuccessful, providing only an incomplete—and at times inaccurate—picture of the U. S. uranium resource base. This is due in large part to the fact that, at best, any effort to calculate the resources of virtually any mineral is not only subject to the biases of the organization or individual attempting such a task, but is also limited by the availability of exploration data. In addition, although a particular orebody might be amenable to development from an economic standpoint, its exploitation could be prohibited because of environmental considerations.

To determine the uranium resources of the United States, ERDA evaluates the exploration data provided by companies engaged in the search for, or mining of, uranium deposits. From this information, ERDA is able to determine both the U_3O_8 content and, to a lesser extent, the economic viability of uranium deposits by utilizing what is termed the "maximum forward cost concept."

Under the provisions of this concept, uranium occurrences are examined in light of projected mine development and plant construction costs and various direct and indirect expenses (such as mining, royalty, haulage, and milling costs). It is important to note, however, that the forward cost concept does *not* include either acquisition or exploration costs. Neither is provision made for the cost of capital, for profit, or for taxes.

Upon determination of the forward costs which might be incurred in the development of a given orebody, ERDA categorizes the deposit as a resource capable of being mined at a maximum forward cost of \$8, \$10, \$15, or \$30 or more per pound of U_3O_8 (Table 1).

In 1969, ERDA began to calculate potential, or undiscovered, uranium resources in the western United States on an annual basis (Table 2). This was done primarily

TABLE 1. Historical Estimates of Uranium Ore Reserves

As of	\$8.00/lb (tons U_3O_8)	\$10.00/lb[1] (tons U_3O_8)	\$15.00/lb[1] (tons U_3O_8)	\$30.00/lb[1] (tons U_3O_8)
1/1/65	151,000	175,000	-	-
1/1/66	145,000	195,000	-	-
1/1/67	141,000	200,000	-	-
1/1/68	148,000	190,000	248,000	-
1/1/69	161,000	200,000	265,000	-
1/1/70	204,000	250,000	317,000	-
1/1/71	246,000	300,000	391,000	-
1/1/72	273,000	333,000	520,000	-
1/1/73	273,000	337,000	520,000	-
1/1/74	277,000	340,000	520,000	634,000
1/1/75	200,000	315,000	420,000	600,000
1/1/76	200,000	270,000	430,000	640,000
1/1/77		250,000	410,000	680,000

[1] Reserves reported at \$10, \$15, and \$30 include reserves in all lower costs categories.
Source: ERDA, 1976, 1977

TABLE 2. U. S. Uranium Resources
January 1, 1977
(tons U_3O_8)

\$/lb U_3O_8 cutoff cost	Reserves	Potential		
		Probable	Possible	Speculative
\$10	250,000	275,000	115,000	100,000
\$10-15 increment	160,000	310,000	375,000	90,000
\$15	410,000	585,000	490,000	190,000
\$15-30 increment	270,000	505,000	630,000	290,000
\$30	680,000	1,090,000	1,120,000	480,000
By-product 1975-2000[1]	140,000	-	-	-
	820,000	1,090,000	1,120,000	480,000

[1] By-product of phosphate and copper production.
Source: ERDA, 1977

by extending known deposits of uranium into adjacent areas possessing either the same or similar geologic hosts. The estimates are categorized as "probable," "possible," and "speculative." Table 3 lists the criteria by which these resources are evaluated.

Insofar as *all* estimates of uranium resources are speculative, the ERDA compilations should not be taken as absolute. Therefore, with advances in extractive technology, increased price levels for U_3O_8, and improved exploration techniques, it is entirely possible, if not probable, that the domestic uranium resource base will expand. However, should that base not increase at a rate at least commensurate with the quantity demanded by the nuclear power industry, a serious shortfall in supply could very likely develop within the next decade.

WORLD URANIUM RESOURCES: ALTERNATE SOURCES OF SUPPLY

Uranium is known to exist in anomalous concentrations throughout the world. However, the majority of these occurrences cannot be exploited with present technology—either at existing or projected uranium market conditions—and, therefore, do not constitute an immediately available source of supply. Generally, information concerning the location and quantities of uranium in various countries is publicly available, but some nations—particularly those with centrally planned economies—attach a strategic importance to their deposits and thus do not disclose descriptive or quantitative data.

Aside from those in the United States, the principal uranium resources of the world are located in Australia, Canada, the Republic of South Africa, Namibia (South West Africa), Niger, and Gabon (Table 4, Figure 2).

Most estimates of world uranium resources are compiled on an irregular basis by the International Atomic Energy Agency (IAEA). As with ERDA estimates of domestic uranium resources, the cost categories of $15 and $30 per pound U_3O_8 refer to the costs (exclusive of exploration and acquisition) likely to be incurred in the mining, milling, and extraction of these resources. These categories, however, also include the projected cost of capital necessary to provide and maintain production facilities.

AUSTRALIA

The uranium resources of Australia are second in size only to those of the United States. Because of numerous and continuing discoveries, estimates of Australia's uranium resources vary considerably, depending upon the time they were made. However, most industry analysts believe that those reasonably assured and estimated resources which can be extracted for less than $30 per pound total approximately 500,000 short tons of U_3O_8.

TABLE 3. Definition of Probable, Possible, and Speculative Resources

Probable

Probable potential resources 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.

Possible

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

Speculative

"Speculative" potential resources are those estimatd 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.

NOTE: "Productive" means that past production plus known reserves exceeds 10 tons U_3O_8.

Source: ERDA, 1976

Australia's uranium deposits are found in four major regions: Rum Jungle–Alligator Rivers (Northern Territory); Mary Kathleen–Westmoreland (Queensland); Lake Frome–Mt. Painter (South Australia); and Yeelirrie (Western Australia). Because of the variety of geologic environments in Australia known to contain uranium, and because there has been relatively little uranium exploration there to date, it is likely that additional reserves will be located. With increased exploration, it is quite possible that Australian uranium resources will, in the near future, be found to exceed those of the United States. This is despite the fact that most estimates of Australian uranium resources have tended to be conservative, based not on the likelihood of new discoveries or possible extensions to known orebodies, but rather on resource availability as publicly disclosed by mining companies operating on that continent.

CANADA

Nearly 20 percent of the western world's proven reserves of uranium are in Canada.

Canadian uranium resources are located primarily in nine districts: Beaverlodge; Rabbit Lake; Elliot Lake; Agnew Lake; Bancroft; Makkovik; Cluff Lake; Baker Lake; and Birch Island (Figure 2). Over 80 percent of the reasonably assured, and the majority of Canada's estimated additional uranium resources, occur in the basal Precambrian pyritic quartz-pebble conglomerates of the Elliot Lake and Agnew Lake districts of Ontario (IAEA, 1973; Adler, 1974).

The remainder of Canadian uranium resources are vein and/or replacement deposits, pegmatite deposits, and roll, peneconcordant, and channel deposits in post-Silurian nonmarine sedimentary basins (Little, 1974).

AFRICAN CONTINENT

In Africa, uranium is found in virtually every geologic environment. Of the nations in Africa, over half are known either to possess significant reserves of uranium, or to have minor occurrences within their borders (Table 5). Aside from those in the Republic of South Africa and Namibia (South West Africa), the principal uranium resources of Africa are located in

TABLE 4. Non-Communist World Resources (\$30/lb U_3O_8) (Short Tons)

	Reasonably Assured	Estimated Additional	Totals
United States	637,000	1,066,000	1,703,000
Australia	429,000	104,000	533,000
Canada	221,000	793,000	1,014,000
Sweden	390,000	-	390,000
So. & SW Africa	364,000	-	364,000
Other	377,000	403,000	780,000
	2,418,000	2,366,000	4,784,000

Source: Wright, 1976

TABLE 5. African Nations Known to Possess Uranium Deposits

- Algeria
- Angola
- Botswana
- Cameroon
- Central African Empire
- Chad
- Egypt
- Gabon
- Ivory Coast
- Libya
- Malagasy Republic
- Malawi
- Mauritania
- Morocco
- Mozambique
- Namibia (South West Africa)
- Niger
- Republic of South Africa
- Rhodesia
- Senegal
- Somalia
- Spanish Sahara
- Uganda
- Zaire
- Zambia

Source: DeKun, 1965

Niger, Gabon, the Central African Empire, and Algeria.

Virtually all the uranium presently produced by the Republic of South Africa and Namibia (South West Africa) is a by-product of gold production from the Precambrian quartz-pebble conglomerates of the Witswatersrand, Dominion Reef, Ventersdorf, and Transvaal formations. Some uranium, however, is obtained as a by-product from the copper-rich carbonatite intrusive pipe at Palabora and as the primary ore from alaskitic (granitic) rocks at Rossing, Namibia (South West Africa).

Aside from the reserves already discussed, recent discoveries of uranium have been made in the sandstones, mudstones, shales, and conglomerates of the Karroo supergroup near Beaufort West. Because this supergroup underlies over 40 percent of the Republic of South Africa—as well as much of Rhodesia, Botswana, Namibia (South West Africa), and Swaziland—it is possible that, should the uranium mineralization be continuous throughout the sediments, additional economically exploitable deposits will be located (IAEA, 1973; von Backstrom, 1974; World Mining, 1974).

Although a large percentage of South Africa's uranium is associated with gold deposits, not all South African gold mines have installed facilities to recover it from gold solutions. Large amounts are thus contained in the slimes and tailings from gold processing plants. Estimates indicate, in fact, that the quantity of uranium in South Africa's waste dumps is as great as that remaining in place in the auriferous conglomerates.

Nearly all the uranium deposits in Gabon, Niger, and the Central African Empire are found in sedimentary rocks. In Gabon, uranium is localized for the most part along structural and lithologic features in detrital sediments of the Precambrian Franceville series. Uranium deposits in Niger occur in Carboniferous and Jurassic sandstones as rolls similar to those in the western United States. Uraniferous phosphorite fills karst depressions in Precambrian dolomite in the Central African Empire. Vein deposits

FIGURE 2. Nations possessing major uranium resources (exclusive of Centrally Planned Economies)

of uranium occur in the Hoggar Mountains of southern Algeria (IAEA, 1973, 1975; Adler, 1974, 1975; Woodmansee, 1975). Extensive deposits of uraniferous phosphate rock exist in Algeria, Egypt, Libya, Mauritania, Morocco, Senegal, and Spanish Sahara.

EUROPE

The reasonably assured and estimated additional uranium resources of Europe economically recoverable at a market price of less than $30 have been estimated by ERDA to exceed 810,000 short tons U_3O_8. Of this amount, over 60 percent is contained in the uraniferous black shales in the vicinity of Billingen, Sweden. Significant occurrences of uranium, however, exist in at least 10 European nations.

Three-fourths of the uranium reserves of France are found in vein-type deposits in Permo-Carboniferous granites. The remainder, such as those at Lodeve, occur along fractures and faults in intercalated beds of lacustrine sediments and volcanic ash of Permian age (IAEA, 1973; Adler, 1974, 1975).

At Illimaussaq, in south Greenland, up to 325,000 short tons of U_3O_8 occur in a Precambrian, highly alkaline nepheline syenite intrusive.

As far as can be determined, the uranium deposits of the Soviet Union are not geologically unique. Although several high-grade deposits are known to exist in Ferghana province and in the Urals, most Soviet uranium deposits are extremely low-grade by Western standards and are confined to sandstones and conglomerates (Siegers, 1974).

McKinney (1960) estimated that the uranium resources of the Communist Bloc could be as much as 611,000 short tons of U_3O_8. Of this amount, the Soviet Union was thought to have between 104,000 and 351,000 short tons of U_3O_8; the People's Republic of China 26,000 to 130,000 short tons of U_3O_8; and the Democratic Republic of Germany 130,000 short tons of U_3O_8. Because these estimates were made nearly 20 years ago, however, it could be expected that additional deposits have since been discovered.

It is difficult to determine either Soviet uranium production or its exploration-development activities. There is speculation, however, that the Soviet Union is preparing to begin extraction of uranium from seawater.

SOUTH AMERICA

Although deposits of uranium are to be found in almost every Latin American nation, only those of Brazil and Argentina are presently of economic significance.

Brazilian resources total approximately 24,000 short tons of U_3O_8. Two deposits near Pocos de Caldas, in the state of Minas Gerais in southeastern Brazil, contain one-fourth of the country's known uranium reserves.

Argentina's reserves total more than 66,000 short tons U_3O_8 and are, for the most part, in sedimentary rocks ranging in age from Permian to Tertiary. Most are in western Argentina, in the provinces of Chubut (Los Adobes deposit), Mendozo (Sierra Pintada and Malargue), and Salta (Don Otto).

OVERVIEW

As is evident from the foregoing, the uranium resource base outside the United States is extensive. Exclusive of those countries with centrally planned economies (generally Communist Bloc nations), the reasonably assured and estimated additional uranium resources of less-developed nations are approximately one-fifth of the known world's uranium resources. As industrialized nations deplete their own reserves of uranium, they will most likely become increasingly dependent on imports from less-developed nations. To what extent the United States and other First-World nations can rely on this source of supply will depend not only on the success of consuming nations in discovering and developing foreign uranium deposits, but also on the geopolitical and socioeconomic aspirations of Third-World* countries.

WORLD GEOPOLITICAL AVAILABILITY OF URANIUM

Because there has been relatively little exploration for uranium in most Third- and Fourth-World nations, it is probable that many undiscovered deposits exist in these countries. However, it is questionable whether nations having favorable geologic environments for the concentration of uranium will permit U. S. mining companies to conduct exploration programs within their borders.

In mid-1975, a survey sponsored by Dames & Moore was conducted to determine the amenability of foreign countries to uranium exploration by U. S.-based mining companies (Kroft, 1976). In each of 72 countries suspected or known to have deposits of uranium, the bureau of mines (or its equivalent) and the United States Embassy were contacted. The following questions were asked of each agency:

- Have any restrictions and/or incentives been established by the *(name of country)* Government with respect to exploration for uranium or thorium by foreign mining companies? If so, could you advise me of what they are and whether it is likely that these conditions will change in the future?
- What are the presently established regulations regarding the development and/or exploitation of uranium or thorium deposits by foreign based mining companies in *(name of country)*? Does it appear likely that any changes in these regulations are forthcoming?
- What limitations have been enacted by the *(name of country)* Government with regard to the exportation of uranium as either yellowcake (U_3O_8) or in a more processed form such as uranium hexafluoride (UF_6)?
- Have any restrictions been set by the *(name of country)* Government with regard to the degree of participation which foreign mining companies may have in the development of uranium deposits either singly or in conjunction with *(name of country)* based mining firms?

SURVEY RESULTS

Information was received from 50 nations. Of those which responded, 28 would at the time of the survey permit foreign mining firms to explore for uranium within their jurisdiction. Twelve countries, however, either reserved uranium exploration, development and exploitation activities to the government, or established conditions under which most U. S.-based mining firms would find it difficult, if not impossible, to operate. No

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*There is no universally accepted definition of what constitutes a Third-World nation. (Or, for that matter, what constitutes a First- or Second-World nation, although in common usage these have come to mean, respectively, the industrialized Western democracies and the Communist states.) Most economists arbitrarily classify a Third-World nation as one which is economically and industrially underdeveloped (Bergsten, 1975). Nearly all Third-World nations strive to achieve Second- or First-World status. However, not all have been endowed with abundant natural resources. Because of this inequitable distribution of resources, the meaning of the term "Third World" has been expanded to include *two* groups of nations.

According to Bergsten (1975), first-order Third-World countries are those which possess one or all of the following attributes: key natural resources (Gabon, Niger); a highly competitive manufacturing sector (South Korea, Taiwan); and a large and rapidly growing market (Indonesia). For the most part, these nations seek not only continued economic progress, but also political independence and meaningful participation in the determination of the world order.

The second group of countries comprising the Third World are those which possess relatively few, if any, economic resources. Termed Fourth-World nations, these "have-nots" are not so concerned with gaining political independence as they are with keeping their populations alive. Because most Fourth-World countries have little or no economic power, they are largely impotent politically, at least on a world scale.

determination could be made as to whether any policy had been formulated by 10 countries (Table 6).

Because of the strategic nature of uranium, many nations have determined that radioactive minerals are a national reserve, the ownership of which is vested in the state. Under this classification the exploration for, and/or development of, uranium deposits can only be undertaken by the country's government or a state enterprise. Several nations, however, made provisions in their laws which enable the government to hire foreign mining firms as contractors to evaluate the country's uranium potential. If deposits were located, the government would allow the contractor a predetermined percentage of actual production or profits from uranium sales.

Inasmuch as increased demand by utilities for nuclear fuel is a relatively recent development, many countries have not yet formulated specific laws or policies pertaining to the exploration for, and the discovery and exploitation of, uranium deposits. Therefore, until such policies are enacted a number of nations have simply extended their existing mining laws to include radioactive substances. Other nations, however, have indicated that when and if uranium deposits are found within their borders, they will follow the legal precedents set by neighboring countries. For example, U. S. Embassy

TABLE 6. World Uranium Mining Policy Status

Central and South America

▲	Argentina
☆	Bolivia
★	Brazil
○	Chile
○	Columbia
○	Costa Rica
△	Ecuador
☆	Guatemala
▲	Honduras
★	Mexico
▲	Nicaragua
☆	Panama
☆	Paraguay
☆	Venezuela

Africa

○	Algeria
☆	Botswana
○	Cameroon
☆	Central African Empire
△	Chad
○	Congo
★	Ethiopia
☆	Gabon
☆	Ghana
☆	Guinea
△	Ivory Coast
○	Kenya
○	Libya
○	Malagasy
○	Mali
★	Mauritania
☆	Morocco
★	Mozambique
○	Niger
☆	Nigeria
☆	Rhodesia
☆	Senegal
☆	Rep. of South Africa
★	Sudan
☆	Tanzania
○	Uganda
☆	Upper Volta
☆	Zaire
☆	Zambia

Europe

○	Austria
☆	France
★	Greenland-Denmark
☆	Greece
☆	Italy
○	Portugal
★	Spain

Middle East

☆	Afghanistan
★	India
★	Iran
○	Iraq
☆	Jordan
☆	Pakistan
☆	Saudi Arabia
○	Syria
★	Turkey
☆	UAR

Pacific

△	Australia
△	Indonesia
△	Japan
▲	Malaysia
☆	New Zealand
★	Philippines

KEY

○	No response received
☆	United States mining firms permitted
★	United States mining firms not permitted
△	Questionable response favorable
▲	Questionable response unfavorable

officials in Upper Volta believe that if deposits of uranium were discovered in that nation, its government would adopt a compromise policy based on legislation previously enacted by Niger, Ivory Coast, and Togo.

Few governments offer incentives to foster exploration for, and/or development of, uranium deposits. Since uranium is often classified as a strategic or critical mineral, most governments have decided that if uranium deposits are found within their jurisdiction, the state has the right to dictate conditions under which a mining company will operate.

One notable exception to this more or less universal policy is the Central African Empire. To foster the additional exploration for uranium, as well as the exploitation of previously discovered deposits at Bakouma, that government will grant tax concessions and amortization allowances. This is due to the government's desire to improve socioeconomic conditions in the sparsely populated and underdeveloped eastern half of the nation.

THE STRATEGIC POSITION OF THE UNITED STATES

As is evident from the results of this survey, political considerations have and most likely will continue to affect the quantity of uranium available for purchase on the world market. Many of the countries possessing the world's largest uranium resources have established export limitations so as to maintain a degree of energy self-sufficiency. The question facing U. S. utilities is whether they can rely on foreign imports to satisfy their future requirements for nuclear fuel.

Despite the fact that Australian reserves of uranium are extremely large, there has been only limited development of known resources because of an embargo on the export of yellowcake. Although it is not known precisely when Australia will offer uranium for sale on the open market again, the previously enacted export embargo will probably be partially rescinded within the next two years. There is concern, however, that when mining companies do receive approval to export uranium, the Australian government will limit development of the country's U_3O_8 production capacity so as to prevent collapse of the world uranium market through oversupply.

Several potential constraints exist in Canada, too, which may limit full development of uranium resources there. To maximize the nation's return for the depletion of its uranium resources, as well as to guarantee that adequate reserves are maintained to satisfy Canada's own projected needs, the Canadian federal and provincial governments have—in many instances through formal legislation—established policy guidelines designed to assure that these goals are achieved.

Because of its by-product relationship with gold, the production of uranium in the Republic of South Africa is highly dependent on fluctuations in the world monetary market. As the price of gold rises, lower-grade auriferous ores are mined to maximize mine life. Because of the decreased uranium content of lower-grade gold ores, each increase in the price of gold results in the reduction of uranium production (Gordon, 1975). Conversely, when there is a long-term drop in the value of gold, total mine output of uranium rises.

In 1974, the French government withdrew its uranium production from export. This action was taken in realization of the fact that, should the French goal of energy independence be achieved, as much as 100,000 tons of U_3O_8 would be required cumulatively by that nation over the next decade (NUEXCO, 1975).

Although the uranium resources of the Soviet Union are believed to be extensive, it is thought that Russia's presently installed U_3O_8 productive capacity is inadequate to meet its immediate requirements. The possibility therefore exists that the Soviet Union may seek to obtain indirect control of the world's largest low-grade uranium deposit—at Rossing in Namibia (South West Africa)—to satisfy its own U_3O_8 needs. Support for this argument can be found in an article from the 2 March 1975 issue of *Pravda*, in which it is stated that "the main concern of Moscow is to deprive the West of minerals in South West Africa, especially the uranium which Britain and Japan need for their nuclear energy programs" (World Affairs Report, 1975).

CONCLUSIONS

As is true with any other internationally traded commodity, there is no guarantee that consumers can depend on existing or potential sources of uranium even over the short-term. Because of the changing political, social and economic aspirations of nations, foreign resources of uranium presently believed to be available for development by, and/or export to, other countries may in future be reserved for use solely by the nations in which they occur. Alternatively, as nations come to the realization that the "Uranium Age" will not last indefinitely, there is also a high probability that uranium resources currently under state control will be released for exploitation in order that the governments of these countries might capitalize on their mineral endowment.

Given the two scenarios above, it is in the best interests of those U. S. utility and mining companies seeking secure sources of uranium supply to promote the exploration for, and development of, both domestic and foreign uranium resources. However, if this goal is to be achieved, domestic companies engaged in the search for foreign uranium resources must be willing to meet at least some of the following demands, which will likely be made by the governments of uranium-rich countries:

- Host country ownership or participation in mining ventures
- Investment for local processing of uranium before export
- Foreign investor technology transfer and local infrastructure development
- Tariff concessions, loans and technological assistance from the United States

In conclusion, unless effective steps are taken by both producers and consumers of uranium and their representative governments to promote exploration for and exploitation of uranium resources necessary to meet projected world demands for nuclear fuel, the prediction which prefaced this paper (Acheson et al., 1946) may ultimately prove to be correct.

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Uranium Production Methods and Economic Considerations

by Douglas J. Lootens, Ph.D.

Dr. Lootens, an associate of Dames & Moore, has more than 20 years of training and experience in the field of mineral exploration, evaluation and development. As manager of the firm's exploration geology group, he is responsible for consulting services in the area of uranium resource development, including economic evaluations of uranium properties. He has designed a number of studies to evaluate the long-term nuclear fuel requirements of electric utilities.

The development of uranium resources is a complex and lengthy process: claims must be located; mining titles and exploration permits must be secured; joint venture arrangements made as appropriate; and exploration and evaluation programs carried out. All this, though, is essentially prologue to the main event, that is, the mining and processing of uranium ore to produce uranium oxide (U_3O_8) or "yellowcake," the primary saleable commodity of the uranium industry.

Even after presumably economic deposits of uranium have been identified and evaluated, still more detailed engineering and economic feasibility studies are required before it can be said with any certainty whether a given deposit is, in fact, economic. We cannot arbitrarily say that a reserve of one million pounds, contained in a deposit whose average grade is 0.2 percent U_3O_8, is economic; neither can we arbitrarily say that a reserve of 250,000 pounds at an average grade of 0.03 percent U_3O_8 is uneconomic.

Each case must be examined on its own merits. A given reserve may be economic in one setting and uneconomic in another. Likewise, a deposit which was uneconomic when uranium brought $6 per pound may be very attractive with uranium prices hovering around their current level of $40 per pound. One of the operator's primary aims in developing a property is to show the best return on invested capital that he can. To do this he must maximize the amount of product recovered and minimize the capital investment and operating expenditures necessary to produce that product—insofar as consistent with good engineering practices and environmental considerations. This paper considers a number of mining and processing methods in current use, their approximate costs and the economic implications of each.

PRODUCTION OF URANIUM OXIDE (YELLOWCAKE)

First, a brief overview of the uranium production process might

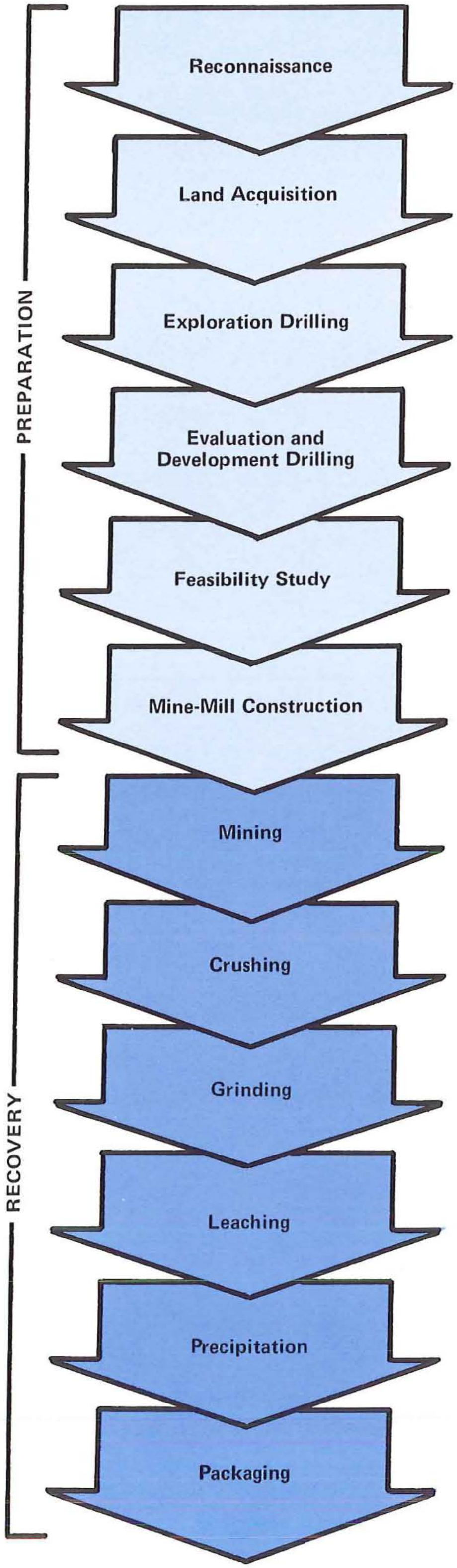

FIGURE 1. The uranium production process

be in order (Figure 1). The basic task is to liberate and concentrate, or upgrade, the uranium from its host rock. Generally, we are dealing with ores containing one to six pounds of uranium *per ton of ore.* In a conventional mining system, the ore is mined, either by open-pit or underground methods, mechanically crushed to expose more uranium-bearing surfaces, and chemically leached to take the uranium into solution. From this solution the uranium is precipitated in a more concentrated form.

In the *in situ* or solution mining system, the ore is not mined in the conventional sense. Instead, solutions pumped into the ground dissolve the uranium and take it into solution. These "pregnant" solutions are then recovered and the uranium is precipitated much as it is in a conventional milling operation.

BASIC MINING CONCEPTS

Having defined a potentially economic uranium reserve by exploration and development drilling, the mine operator must develop an efficient, cost-effective scheme for converting that uranium in the ground to yellowcake in the can. About 98 percent of the 1975 production utilized conventional mining and milling technology.

Open-Pit Versus Underground Mining. The decision to mine a deposit by open-pit or underground methods is largely dictated by physical factors: how deeply buried it is and its three-dimensional configuration.

The economics of overburden removal and handling serve to effectively limit open-pit mining to depths of about 500 feet or less. This can be easily seen in Figure 2, which shows the basic geometry of an open-pit mine. As depth to ore increases, the amount of overburden to be removed also increases—and increases dramatically, because of the angle of the pit slopes. The break-even stripping ratio, or the point at which the costs of overburden removal equal the ore revenues, determines the ultimate economic extent of an open-pit mine.

If the deposit is too deeply buried to be recoverable by strip-mining techniques, an underground mining system must be utilized. Generally speaking, such a system includes at least one production shaft (for hoisting ore), a shaft for movement of men and equipment, and one or more ventilation shafts through which fresh, non-radioactive air is forced, so as to provide healthy working conditions for the miners in the underground workings.

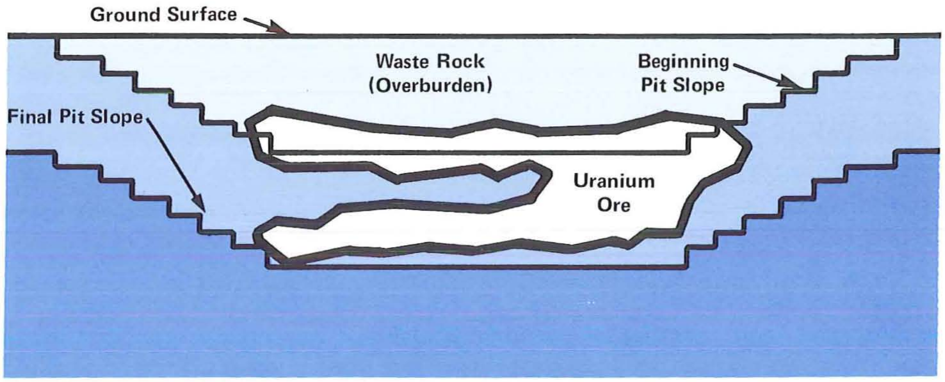

FIGURE 2. Cross-section of a typical open-pit mine

A commonly-used underground mining method is known as "room-and-pillar" mining (Figure 3). This technique involves removal of the ore in a systematic fashion, while leaving a series of posts or "pillars" in place to support the roof of the workings. This approach is particularly suitable for deposits which are relatively flat-lying and two-dimensional in nature, as are many uranium deposits. One disadvantage with room and pillar mining is the necessity of leaving as much as 20 or 30 percent of the total reserve in the ground for roof support.

With other underground mining systems, however, such as longwall or panel-retreat methods, up to 100 percent of the ore can be recovered. But these methods tend to be substantially more expensive and require a rather particular set of mining conditions before they can be employed.

Open-Pit Mining. While each open-pit mine is unique in its detail, the basic approach is the same for all such mines.

The orebody is first exposed by stripping off the overburden. Depending on the hardness of the rock, this is accomplished by large scrapers, bulldozers or combinations of shovels, front-end loaders and haulage trucks.

The exposed ore is removed in much the same way, except that instead of the material being placed on a waste dump, or stored for use in reclamation, ore-grade materials are trucked to a mill for processing.

The ratio of waste rock to ore varies, of course, from mine to

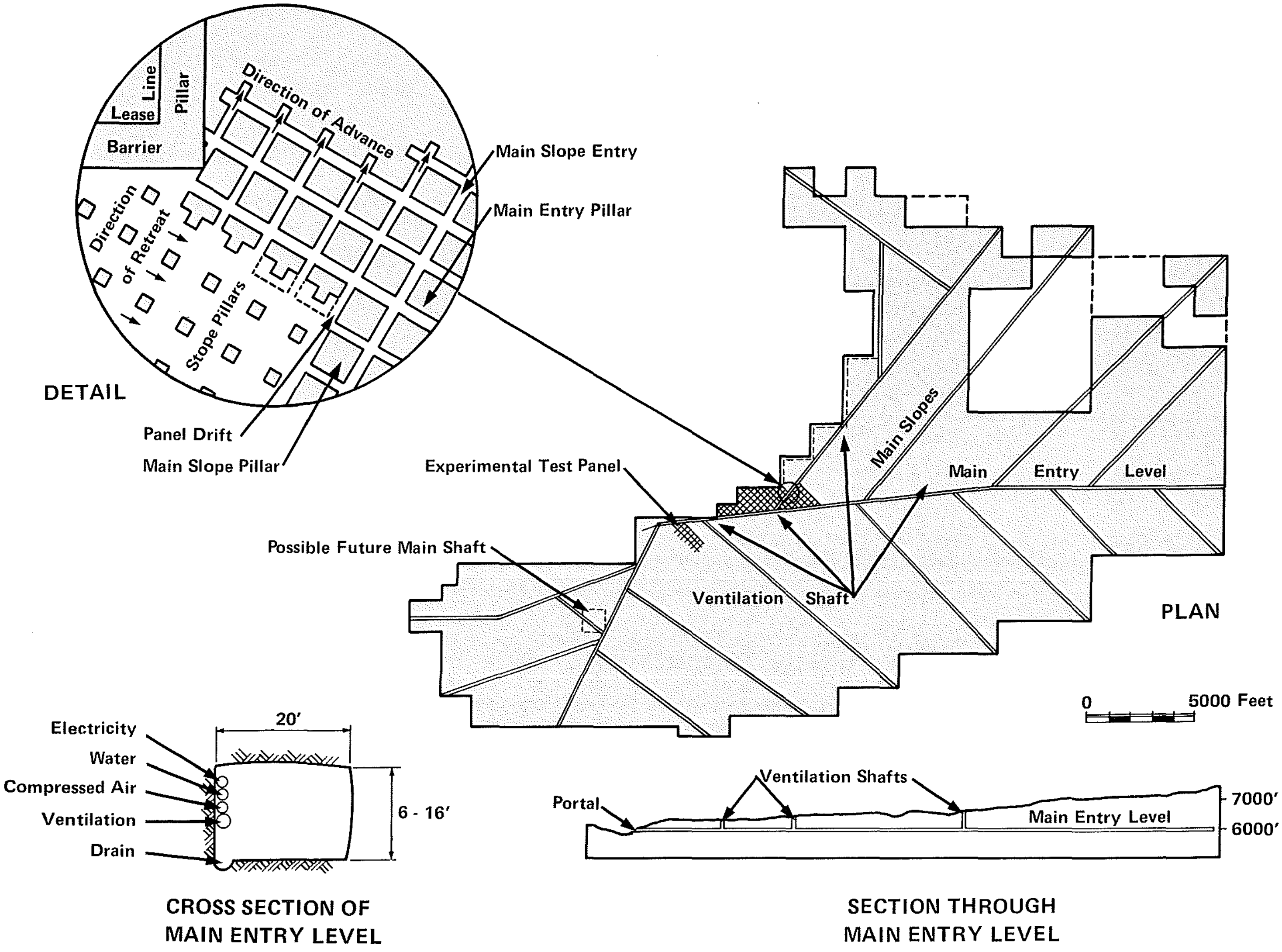

FIGURE 3. Conceptual layout of a hypothetical underground mine

mine, but a ratio of 40:1 is not uncommon. Thus, for a mine producing 1,000 tons per day (TPD) of ore, an additional 40,000 tons of waste must be moved. In some cases, however, this waste rock is not a total loss. If it contains uranium in concentrations too low to be recovered by conventional milling technology, it may be placed on a specially prepared "pad" to allow recovery of the low-grade uranium through the percolation of solutions through the materials. This is known as "heap" or "dump" leaching.

One of the key considerations in open-pit mining is grade control. Uranium deposits often consist of interlayered bands of ore and waste material, sometimes as little as one foot thick. In order to maintain a relatively constant grade of material being fed to the mill, the operator must constantly decide whether material being mined should go to the dump (waste), the leaching pads (low-grade ore) or the blending stockpiles (ore grade). This requires near-continuous sampling of the active mining areas and frequently involves blending or mixing of higher grade ore from one area of the mine with lower grade ore from another area. In many mines, each truckload of material is scanned with scintillometers to determine its uranium content and the driver directed to specified dumping areas based on the readings.

Underground Mining. Here again, each mine varies in specifics, but a typical underground mine is characterized by a series of shafts through which ore, men and materials, and fresh air are moved. These shafts, which can range from a few feet up to 25 feet in diameter, are sunk either with large-diameter shaft-boring equipment or by drilling, blasting and hoisting the rock out.

Once these shafts have reached the orebody, it is developed for production by driving a network of horizontal tunnels or "drifts" in and adjacent to the ore zone. A number of active mining areas are required because productivity from a given mining face is limited.

The ore itself is mined by drilling a series of short holes into the wall or "face," loading them with explosives and blasting the ore loose. The loose rock is then mechanically loaded onto ore haulage trucks and taken to a central collection point for hoisting up the shaft and transportation to the mill.

Since the size of each mining area is limited, mining is carried out very selectively; essentially no waste material is removed. On the contrary, as was pointed out earlier in describing the room-and-pillar method, a considerable amount of ore-grade material must be left in place for support purposes.

Underground mining has a number of obvious economic and environmental advantages, but they are often offset by the need for extensive mine ventilation systems. This is particularly true of uranium operations because of the presence of radioactive decay emissions. Strict regulations concerning radon gas levels and individual cumulative exposures have been established, and are monitored closely by State and Federal agencies.

BASIC PROCESSING TECHNIQUES

It was indicated earlier that the choice between surface and underground mining was largely dictated on a physical basis (how deep the ore is and what its configuration is), but the choice of milling techniques

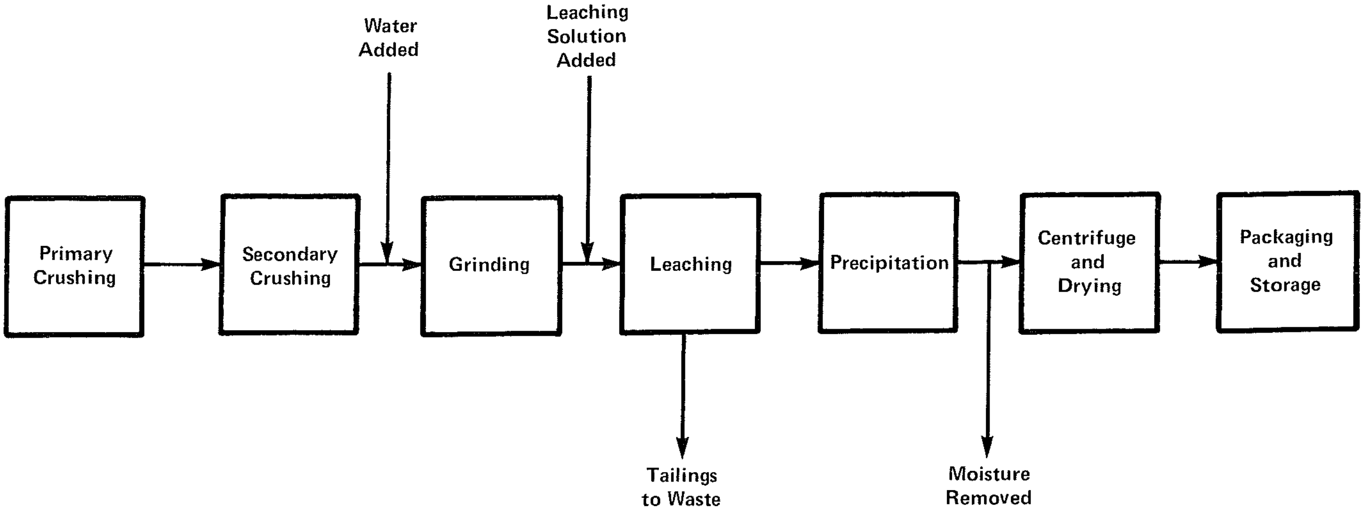

FIGURE 4. Basic uranium processing steps

is primarily a function of chemical parameters of the mined ore.

The main purpose of the processing step is to upgrade the uranium ore from a grade of perhaps 0.15 percent U_3O_8 to a product containing 80 to 85 percent U_3O_8 (yellowcake). This is accomplished in several stages, as shown in simplified diagram of Figure 4.

Crushing and grinding usually involves three steps:

- Primary crushing to minus 4-inch size
- Secondary crushing to minus 1-inch size
- Grinding in a rod mill to minus 28-mesh size

The finely-ground ore is transported as a slurry to leaching tanks, where the uranium is taken into solution. Depending on the chemical nature of the ore, either an acid-leach (dilute sulfuric acid) or an alkaline-leach (ammonia) is used.

The uranium values are reprecipitated from the solution as yellowcake, and then dried and packed in 55-gallon drums for shipment.

The milling system described above is obviously much simplified from actual practice. In reality, it is a highly sophisticated chemical process involving several substeps of leaching, chemical transformation, ion exchange and recycling of solutions at various points. These subtleties, however, are not really germane to our discussion and are, for the most part, custom-fitted to each operation. Suffice it to say that the process as practiced is very efficient, recovering 90 to 95 percent of the uranium contained in the ore.

SOLUTION MINING

The discussion thus far has concentrated on conventional systems for uranium recovery; this technology accounts for nearly all primary uranium recovery today. In recent years, however, an increasing amount of attention has been given to solution mining, that is, the removal and recovery of uranium values from a deposit without actually extracting the rock.

There are several reasons for the current interest in solution mining. Figure 5, a breakdown of yellowcake production costs, shows that two-thirds of the cost is incurred in stripping and mining the ore. Obviously, if these steps can be eliminated, or replaced with lower-cost alternatives, substantial cost savings are possible.

A second reason is that there are very definite economically dictated grade limits below which conventional mining is not profitable. Heretofore, deposits below those limits simply represented a resource—something of value known to exist but not recoverable within the constraints of current technology and economics.

Equipment costs, labor costs and development lead-time have all escalated dramatically in recent years; any system that can significantly reduce any or all of these

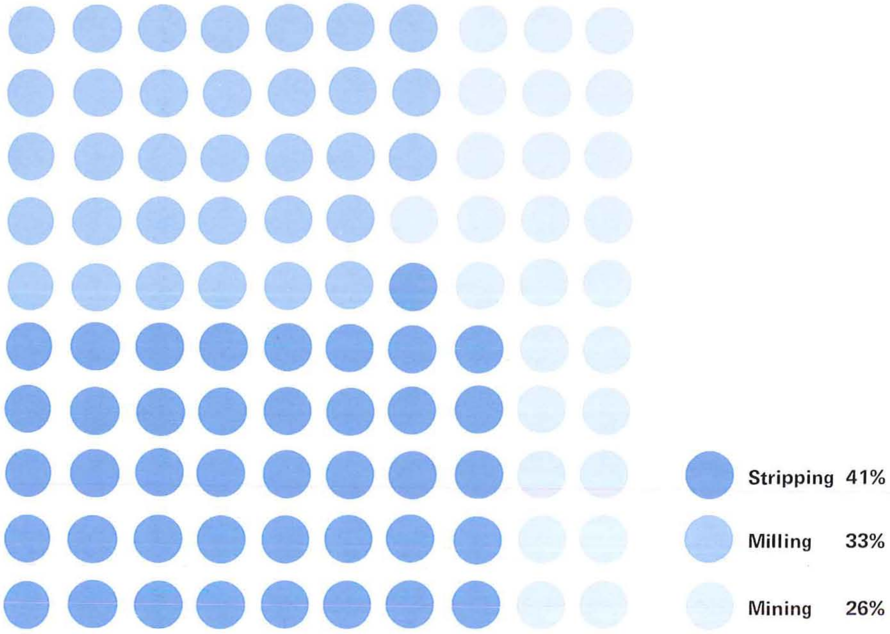

FIGURE 5. Yellowcake production cost distribution

Source: Lang and Archibald, 1975

factors will get wide attention. Table 1 shows a comparison of the major processing steps involved in different uranium recovery systems. Clearly, solution mining demonstrates significant advantages in terms of equipment needs, manpower utilization and development time.

Solution mining involves the extraction of uranium values from a deposit without the introduction of men or major equipment into the orebody. In a general sense, an acidic or alkaline leaching solution is injected into the mineralized zone through a series of drill-holes. The leaching agent migrates through the zone taking uranium into solution and is recovered through a production well. The uranium-bearing solution thus recovered is processed through a conventional mill recovery system to produce yellowcake.

The advantages of this system are obvious:

- Minimum capital investment
- Low manpower requirements
- Better worker safety
- Less land, air and water pollution
- Shorter development time
- Low ore grade “mineable”.

The disadvantages are not so obvious and are at least in part related to the fact that solution mining is a developing technology. Among the disadvantages are:

- Percentage of uranium recovery unknown
- Potential toxic spills
- Loss of leach solutions
- Contamination of ground water
- Disposal of waste solutions
- Restriction on the types of deposits suitable

Large amounts of money and effort are currently being expended

TABLE 1. Comparison of Major Process Stages of Typical Uranium Mine-Mill Complexes and Solution Mining

Open Pit Mines	Underground Mines	Solution Mining
Development drilling	Development drilling	Development drilling
Stripping[1]	Shaft sinking[1]	-
Mine waste[1]	Development drifting	-
Waste dump[1]	Waste dump[1]	-
Develop ore faces	Develop stopes	Drill wells
Drill, blast[1]	Drill, blast	Leach uranium
Load	Muck out	-
Haul	Haul	-
-	Hoist	-
-	Haul to mill	Pump solution to mill
Crush[1]	Crush[1]	-
Grind[1]	Grind[1]	-
Leach uranium	Leach uranium	-
Liquid-solid separation	Liquid-solid separation	Liquid-solid separation
IX[2] or SX[3] concentration	IX[2] or SX[3] concentration	IX[2] or SX[3] concentration
Precipitate, dry, package	Precipitate, dry, package	Precipitate, dry, package
Tailings dam[1] operations	Tailings dam[1] operations	Recirculate leach solutions
Stages to Produce Saleable Product		
15	17	8

[1] Stages generally producing significant changes in or affecting land surface, water quality, personnel safety or radiation exposure.

[2] Ion extraction

[3] Solvent extraction

Source: Hunkin, 1975.

to perfect solution mining technology but, while some uranium is being produced in this manner, total production is not yet significant. However, it is estimated that as much as 10 percent of total production will come through solution mining by 1985.

ECONOMIC CONSIDERATIONS

With this overview of uranium production methods as a background, let us now look at some of the economic implications of uranium mining and processing.

As with any new business operation, an economic analysis of a uranium complex involves an examination of the capital investment required and an estimation of operating costs. For conventional mining and milling operations, a considerable body of historical cost data is available. In contrast, though, little definitive information exists for solution mining. For this reason, these two areas will be treated separately in the following sections. Some useful comparisons, however, have been made where possible.

CAPITAL COSTS

Uranium mining and milling facilities are very capital-intensive installations. Table 2 shows a summary of capital requirements for both surface and underground mines in Wyoming and New Mexico. Note that mine-related capital costs for surface mines are equal to or higher than similar costs for underground mines except in the case of very deep underground operations. This grows largely out of the requirement for extensive pre-production stripping of the overburden to prepare a surface mine for operation.

It should be noted that the figures given in Table 2 do not represent actual mine-mill developments, but rather illustrate "typical" capital requirements for average surface and underground mines of the types listed.

To give some idea of the types of things involved in these capital cost estimates, Tables 3 and 4 illustrate the detailed breakdown of capital costs for a surface mine in New Mexico. Table 3 shows the investment required in the surface plant, while Table 4 provides a detailed listing of the mining equipment

TABLE 2. Capital Cost Estimate Summary — Hypothetical Uranium Processing Operations (New Mexico and Wyoming)

		Capital Cost Estimates (1975 Dollars)		
Underground Mining	**Tons per Day (TPD) Milled**	**Mine ($000)**	**Mill ($000)**	**Total ($000)**
New Mexico				
2000 feet deep	500	$11,200	$ 5,700	$16,900
	1000	12,397	9,630	22,027
	2000	14,602	12,370	26,972
4000 feet deep	500	25,048	5,700	30,748
	1000	26,353	9,630	35,983
	2000	28,010	12,370	40,380
Wyoming				
500 feet deep	500	4,748	5,700	10,448
	1000	5,721	9,630	15,351
	2000	7,241	12,370	19,611
Surface Mining	**TPD Milled**	**Mine ($000)**	**Mill ($000)**	**Total ($000)**
New Mexico[1]	500	12,618	5,700	18,318
	1000	15,463	9,630	25,093
	2000	24,331	12,370	36,701
Wyoming[1]	500	13,955	5,700	19,655
	1000	16,906	9,630	26,536
	2000	25,226	12,370	37,596

[1] Provision for pre-production stripping is included.

Source: Dames & Moore, 1975

required. Note that pre-production stripping costs account for anywhere between 20 and 50 percent of total mine-related capital costs.

Table 5 shows typical capital investments required for a processing facility of the size indicated.

The economic impact of this capital investment depends, of course, on the size of the ore reserve, that is, the number of tons mined and the total number of pounds of uranium recovered over the life of the investment. Thus, for example, if a 500-TPD surface mine-mill complex were constructed to recover one million pounds of yellowcake, each pound would carry a direct capital burden of something in excess of $18.00, exclusive of the cost of money.

OPERATING COSTS

Table 6 shows "typical" operating costs per ton of ore mined and milled for both underground and surface operations. It is interesting to note that, as was the case with capital investment, operating costs for surface mines are equal to or higher than comparable costs for underground mines. Again, the reason lies in the amount of effort devoted to overburden stripping. Table 7, typical operating costs for a surface mine in New Mexico, illustrates this very graphically. Approximately 80 percent of the total mine operating cost is attributable to overburden stripping.

To assess the economics of operating a mine-mill complex, the per-ton cost figures provided in Tables 6 and 7 must be related to the grade of ore being processed. Thus, for instance, a surface mine-mill complex in New Mexico operating at 500 TPD would incur costs of $29.41 per ton of ore milled. If that ore averaged 0.15 percent (three pounds of U_3O_8 per ton of ore), operating costs would amount to about $9.80 per pound of U_3O_8 recovered. To carry that one step further, if the reserve being mined contained one million recoverable pounds, total direct capital costs of $18.00-plus, combined with operating costs of $9.80, yields a total production cost of about $28.00 per pound—excluding land acquisition and exploration costs, taxes, royalties, and profit. Clearly it is problematical whether a reserve of this size and grade could support an installation of this magnitude.

SOLUTION MINING

As was pointed out previously, little actual data on capital and operating expenditures are available for solution mining operations. However, a recent study published by ERDA (Frank, 1976) evaluates capital and operating costs for a

TABLE 3. Capital Investment Estimate for Surface Mine Plant (New Mexico)

	Mine Capital Investment ($000)		
	500 TPD Milled	1000 TPD Milled	2000 TPD Milled
Shop/warehouse, surface buildings	$ 601.5	$ 1,121.9	$ 2,475.0
Office buildings	86.4	141.4	188.0
Access road, 8 miles	80.0	80.0	80.0
Initial haul road, 1 mile	22.9	22.9	22.9
Magazines	12.4	24.8	49.6
Crusher & load-out	250.0	300.0	350.0
Electrical supply	225.0	300.0	350.0
Well drilling & pump installation	40.0	40.0	40.0
Piping, 1 mile	10.5	19.5	19.5
Ambulance	11.1	11.1	22.2
Pickups, ¾-ton	52.8	96.8	158.4
Service & maintenance trucks	54.0	99.0	162.0
Fork lifts	44.4	77.7	133.2
Subtotal	$ 1,491.0	$ 2,335.1	$ 4,051.3
Contingency @ 10%	149.0	234.0	405.0
Mining equipment	4,218.0	7,164.0	14,335.0
Total Mine Investment	$ 5,858.0	$ 9,733.1	$18,791.3
Pre-production stripping[1]	6,760.0	5,730.0	5,540.0
TOTAL CAPITAL INVESTMENT	$12,618.0	$15,463.1	$24,331.3

[1] For 10,000,000 tons of overburden @ 125 % of estimated operating stripping costs

Source: Dames & Moore, 1975

TABLE 4. Estimated Capital Requirements for Stripping & Ore Mining Fleets (New Mexico)

	500 TPD Milled			1000 TPD Milled			2000 TPD Milled		
	Size	Units	$ (000)	Size	Units	$ (000)	Size	Units	$ (000)
Overburden Fleets									
Drills	6-¾"	1	$ 180	6-¾"	3	$ 540	6-¾"	5	$ 900
Powder truck	5 ton	1	20	7 ton	1	31	10 ton	1	34
Front-end loaders	15 yd	2	700	15 yd	3	1,050	15 yd	6	2,100
Trucks	50 ton	9	1,620	75 ton	12	3,024	120 ton	15	6,705
Graders	150 HP	1	58	150 HP	1	58	150 HP	2	116
Rubber-tired dozer	300 HP	2	262	300 HP	2	262	300 HP	3	393
Water trucks	4000 gal	2	185	8000 gal	2	370	8000 gal	3	555
Stripping Subtotal			$3,025			$5,335			$10,803
Ore Zone Fleets									
Dozer w/ripper	375 HP	1	200	375 HP	2	400	375 HP	4	800
Loading	6 yd	2	272	6 yd	3	408	6 yd	5	680
Trucks	22 ton	5	475	22 ton	8	760	22 ton	17	1,615
Rubber-tired dozer	300 HP	1	131	300 HP	1	131	300 HP	2	262
Ore probe towers		2	30		3	45		6	90
Air trac with portable compressor		1	85		1	85		1	85
Ore Zone Subtotal			$1,193			$1,829			$ 3,532
TOTAL EQUIPMENT INVESTMENT			$4,218			$7,164			$14,335

Source: Dames & Moore, 1975

TABLE 5. Mill Capital Construction Cost Estimates

	Mill Capital Cost ($000)		
	500 TPD	2000 TPD	1000 TPD
Unloading, crushing, sampling	$ 650.0	$1,215.0	$ 1,550.0
Grinding	320.0	470.0	680.0
Leaching	460.0	715.0	1,100.0
Classification, purification	540.0	1,200.0	1,430.0
Precipitation, filtration	200.0	245.0	335.0
Tailings disposal	55.0	60.0	75.0
General facilities and utilities	2,100.0	4,100.0	5,300.0
Engineering and field expense	1,100.0	1,150.0	1,350.0
Contractor fee, contingency	275.0	475.0	550.0
TOTAL COST	$5,700.0	$9,630.0	$12,370.0
COST/TON CAPACITY	$ 11.4	$ 9.63	$ 6.185

Source: Dames & Moore, 1975

TABLE 6. Operating Cost Estimate Summary — Hypothetical Uranium Processing Operations (New Mexico and Wyoming)

		Per Ton Operating Cost Estimates (1975 Dollars)		
Underground Mining	**TPD Milled**	**Mine**	**Mill**	**Total**
New Mexico				
2000 feet deep	500	$18.27	$12.98	$31.25
	1000	15.78	11.18	26.96
	2000	13.76	9.59	23.35
4000 feet deep	500	23.68	12.98	36.66
	1000	20.43	11.18	31.61
	2000	18.19	9.59	27.78
Wyoming				
500 feet deep	500	18.55	12.98	31.53
	1000	16.13	11.18	27.32
	2000	13.84	9.59	23.43
Surface Mining	**TPD Milled**	**Mine**	**Mill**	**Total**
New Mexico[1]	500	16.43	12.98	29.41
	1000	14.29	11.18	25.47
	2000	13.74	9.59	23.33
Wyoming[1]	500	22.12	12.98	35.10
	1000	19.43	11.18	30.61
	2000	19.72	9.59	29.31

[1] Provision for surface land reclamation is included.
Source: Dames & Moore, 1975

TABLE 7. Estimated Cost Summary New Mexico Open-Pit Uranium Mine

	$ Per Ton Milled		
	500 TPD	**1000 TPD**	**2000 TPD**
Dewatering	-	-	-
Topsoil	$ 0.05	$ 0.05	$ 0.05
Stripping	13.51	11.43	11.06
Development drilling	0.17	0.17	0.17
Ore mining	2.47	2.41	2.23
Crush and loadout[1]	0.20	0.20	0.20
Reclamation	0.03	0.03	0.03
TOTAL MINE OPERATING COST ESTIMATE[1]	$16.43	$14.29	$13.74

[1] No provision for ore transportation to mill site.
Source: Dames & Moore, 1975

hypothetical solution mining operation. Table 8 summarizes the capital expenditures required to construct a solution mining system with a capacity of 750,000 pounds of U_3O_8 per year. That is equivalent to a 1,000 TPD conventional mining operation at a grade of 0.15 percent U_3O_8.

Though the figures are not directly comparable (the ERDA study includes land acquisition, exploration and development drilling as capital cost items), a comparison of the capital investment costs required for a solution mining system with those required for a conventional system of similar capacity shows them to be nearly the same. One important difference is the lead-time required to bring each system on stream; a solution mining system should be capable of producing yellowcake in considerably less time than a conventional system once a recoverable reserve has been defined.

Table 9 summarizes the projected operating costs for a solution mining system. Again, these costs are not directly comparable with those shown earlier for conventional systems since the ERDA study includes payment of $1.216 per pound in royalties, assuming a royalty rate of 6.25 percent and a selling price of about $19.50 per pound. However, it is clear that operating costs for a solution mining system are equal to or less than those for a surface mining operation and substantially below those for deeper underground mines. Solution mining techniques can also be applied to ore reserves of a grade too low to be economically recovered by conventional systems.

NOVEL URANIUM RECOVERY SYSTEMS

Finally, mention should be made of a couple of uranium recovery schemes that are getting an increasing amount of attention in the industry.

Over the past few years, both the demand for, and price of, uranium have risen so rapidly that reserves previously considered simply scientific curiosities are now getting close examination. The recovery of uranium as a by-product of copper and phosphate mining operations are two worthy of mention.

URANIUM IN COPPER DEPOSITS

Many large copper deposits, such as the one at Bingham Canyon, Utah, carry minute amounts of uranium minerals along with the copper. By itself, the uranium content is far too low to be of interest, nor is it feasible to develop and construct a separate mill circuit to recover the uranium as part of the copper milling system.

However, large tonnages of low-grade copper ore are placed in special dumps through which acidic solutions are percolated to recover the copper by leaching. These leaching solutions, in addition to dissolving the copper, also dissolve the uranium.

Recently, technology has been developed to recover the uranium in the leaching solution (about 10 parts per million) in parallel with the copper. For all practical purposes, this represents "free" uranium because all of the costs attributable to mining, haulage and leaching of the rock are charged against the copper content. The only direct costs attributable to uranium recovery are those involved with precipitation and drying the values of uranium recovered from the leaching solution.

While uranium production from this source is not likely to be a major factor in total production, it does nevertheless represent a significant potential for development. It would be premature to attempt to estimate production rates or economics for this scheme.

URANIUM IN PHOSPHATE DEPOSITS

Many phosphate deposits contain small amounts of uranium. Attempts to recover this uranium began in the 1940s and continued into the 1950s when several pilot-scale plants were built and operated. Interest waned, however, when low-cost Western uranium became available.

With recent price increases and escalation of demand, however, several companies have undertaken extensive research and development programs to perfect the process. Conceptually, it is not unlike that described for recovery of uranium from copper ores. Phosphate rock is processed to produce phosphoric acid, a basic industrial chemical, which carries with it the uranium from the original phosphate ore. Technology has been developed to recover the uranium from the acid.

One point worth noting with regard to both of these novel recovery methods is that they depend on the continued processing of copper and phosphate deposits. Thus, they are dependent on the market conditions for those commodities rather than on the economic conditions extant in the uranium market.

TABLE 8. Solution Mining System – Capital Costs
750,000 lbs. U_3O_8 Annually

	Total Cost	Cost Per Lb.	Percent
Acquisition	$ 1,148,000	$0.170	3
Exploration	4,725,000	0.700	13
Development drilling	1,012,000	0.150	3
Mine equipment	2,356,000	0.349	6
Mill plant	9,500,000	1.407	25
Primary development	18,515,000	2.743	50
TOTAL CAPITAL COST	$37,256,000	$5.519	100

Source: Frank, 1976

TABLE 9. Solution Mining System – Operating Costs
750,000 lbs. U_3O_8 Annually

	Total Cost	Cost Per Lb.	Percent
Mining	$26,690,000	$3.954	43
Pumping	1,316,000	0.195	2
Milling	25,967,000	3.847	42
Royalty	8,208,000	1.216	13
TOTAL OPERATING COST	$62,181,000	$9.212	100

Source: Frank, 1976

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Computer Processing of Multispectral Satellite Data for Mineral Exploration

by Robert J. Reed
Richard F. Pascucci
Roland C. McEldowney

Mr. Reed is a staff geologist with Dames & Moore. He has specialized in the application of remote sensing data to geologic problems, especially those associated with exploration geology and major construction projects. Much of his recent work has been directed toward the computer analysis of multispectral satellite imagery, the results of which are described in this article.

Mr. Pascucci, a senior geologist with Dames & Moore, is responsible for the design and management of a wide variety of programs utilizing remote sensors to collect hydrological, geological and pedological data for earth resources exploration efforts. A number of his projects have dealt with systems integration of remote sensing data and analysis of such data for geologic and other field surveys.

Mr. McEldowney, a senior geologist with Dames & Moore, has both field and managerial experience in economic and engineering geology, geochemistry and feasibility studies. He has specialized in regional and site geologic investigations, primarily in the area of uranium exploration and evaluation, and has completed a number of site studies for nuclear power plants in the United States and Europe.

In July, 1972, the Earth Resources Technology satellite (now known as Landsat-I) was launched by the National Aeronautics and Space Administration. Since then it has circled the earth 14 times each day, at an altitude of 570 miles, acquiring reflectance data in four spectral bands, two in the visible light portion of the electromagnetic spectrum and two in the near-infrared.

Visual analysis of the imagery composited from these reflectance data has come to be recognized by exploration geologists as a useful tool for identifying regional fault zones (lineaments), for mapping rock types in rugged or otherwise uncharted portions of the world, and for identifying large alteration patterns.

In the past several years, computer enhancement of satellite images has permitted effective mapping of altered ground in some uranium-bearing areas (Offield, 1976); and hybrid analog/digital methods (Alexander *et al.*, 1974) have been used successfully to detect vegetation patterns, with the potential application of mapping geobotanical indicators.

More recently, however, computer techniques of digital analysis have been applied to spectral reflectance values associated with orebodies. These digital techniques have the advantage that original raw satellite data are used (i.e., tapes of the original telemetry as received and recorded).

One such technique for analyzing multispectral Landsat data has been tested at Dames & Moore and is producing some excellent results. To date, two contractual exploration programs have proved successful in locating mineralized areas—one in the humid southeastern U. S. and the other in the arid southwest—and an internally funded research and development program has produced some promising preliminary results in uranium prospecting.

RATIONALE

The spectral data used in these multispectral computer analysis programs are acquired by the Landsat satellite and consist of numerical values of intensity levels within four discrete portions, or bands, of the electromagnetic spectrum. For each "pixel"—which is, for all practical purposes, the smallest unit area that can be detected by the satellite (56m X 79m)—there are four unique numerical values that define it. That is, each pixel has a "signature" composed of four unique numbers, one for each of the four spectral bands. The range of intensity values in each band is from 1 to 256. This means that there are potentially 4.3×10^9 possible numerical combinations, or signatures, for each of the 7.5×10^6 pixels in a Landsat frame.

The use of multispectral computer analysis programs for mineral exploration is based on the potential correlations between anomalous ground surface features or conditions and mineralization. When anomalous surface or near-surface conditions (such as alteration halos, geobotanical relationships or unique lithologies) occur, a computer-derived "spectral signature" for them may be developed. The ability to derive such signatures, however, is dependent on many factors, some of which are inherent in the spectral data themselves and others that are a function of external conditions.

For instance, sun angle, atmospheric conditions, steepness and direction of slope and other illumination factors are external conditions that affect the values recorded in the four Landsat bands; the size, spectral uniqueness and weathering characteristics of the desired mineralization are inherent conditions that influence the ability to develop a suitable signature. While it appears that these factors and their relationships are at least generally understood, it must be emphasized that natural conditions are highly variable, and success in one area does not automatically guarantee success in another. Specifically, a signature developed for a particular type of mineralization in a particular area can be used for other, similar, areas only if the natural conditions are similar. It would be inappropriate, for example, to use a uranium signature developed from a dry, sedimentary rock terrain to search for uranium in an igneous terrain having a humid climate.

DATA PROCESSING SYSTEM

The multispectral analysis programs used by Dames & Moore were developed by Pennsylvania State University (Office of Remote Sensing of Earth Resources), and adapted for use with the firm's computer facilities. Peripheral equipment includes a Data 100 remote batch terminal, Digital Equipment Corporation DEC writers and a Texas Instruments TI 725 portable terminal. Processing is performed on an IBM 360/65 computer located in Kansas City, Missouri, where the vendor (International Time Sharing Division of United Computing Services) provides a tape library, systems analysis, and hardware support.

PROCESSING PROCEDURES

In determining the spectral signatures that appear to be associated with mineralization, two techniques are applied, as shown in Figure 1.

The first of these is called "unsupervised" classification. In this mode, the computer programs derive signatures based on clustering algorithms; in a sense the computer decides, based on the data themselves, what constitutes a signature.

With the second technique, "supervised" classification, signatures are developed by spatially locating areas of uniform spectral response, which are then analyzed statistically by computer. Using a highly interactive process, these statistics are then used by the geologist to define signatures by which the area is classified.

The major difference between

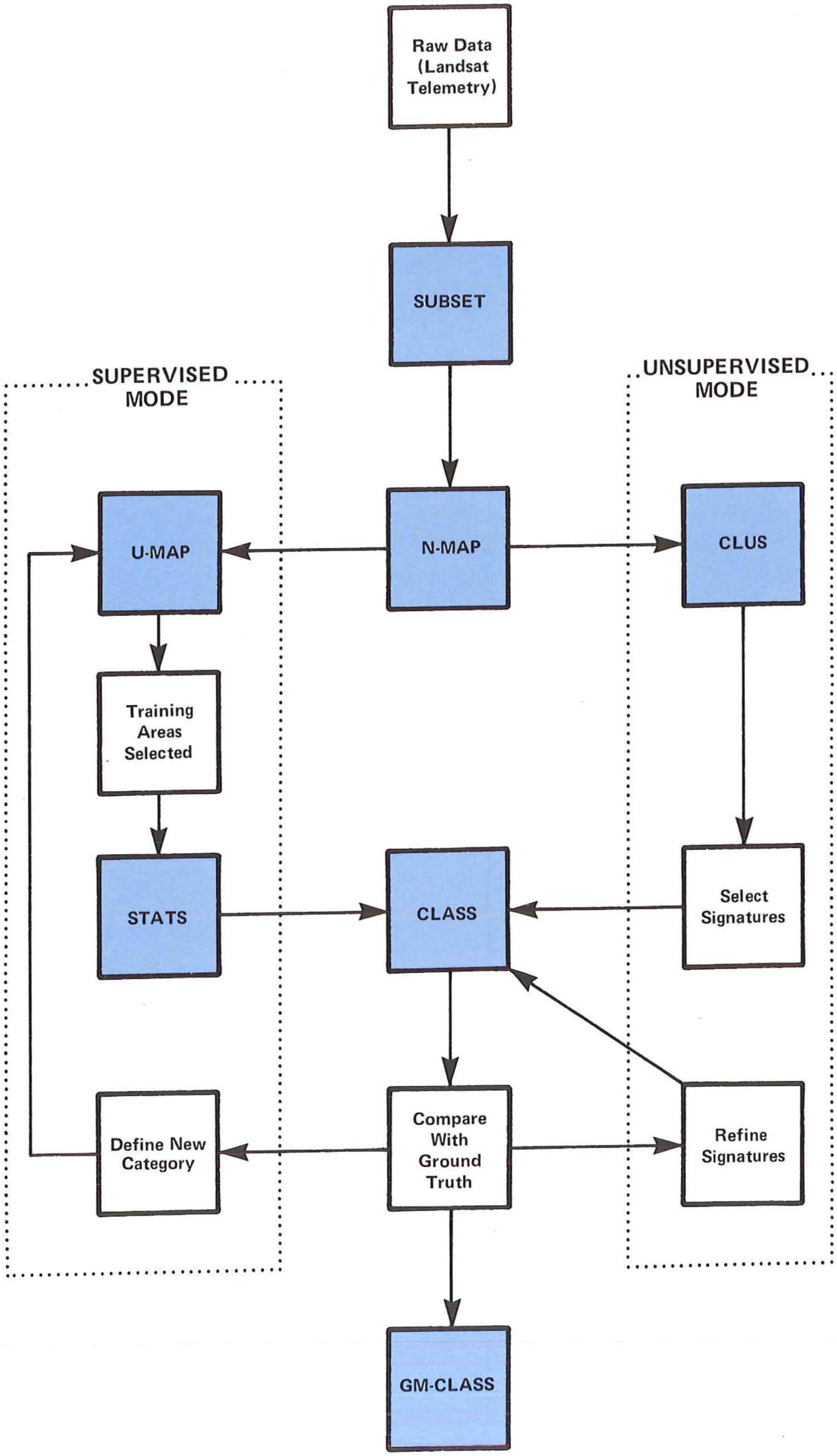


FIGURE 1. Data flow diagram

the above two procedures is that, in the latter technique, the data are organized spatially by the investigator, while in the former, the data are organized automatically by spectral similarity alone.

PROGRAM FUNCTIONS

SUBSET – SUBSET allows specific areas of interest to be extracted from the total data set contained on the satellite tapes and reformats the data to a format compatible with succeeding programs.

N-MAP – After the area of interest has been subset, these data must be more precisely located in a geographical sense. In other words, it is necessary to know the geographic location of various points within the data. In order to "fit the data" to a map, the N-MAP program is used to produce a printout of spectral brightness values. An N-MAP has the appearance of a facsimile image.

U-MAP – The U-MAP program measures the spectral uniformity of the data. Those areas suitable for "training" the computer (i.e., those areas that are spectrally uniform) are delineated in the supervised mode by overlaying the output U-MAP over target areas. Ideally, "target areas" are defined as those in which mineralization is known to have occurred.

STATS – The STATS program develops spectral signatures and their associated statistics for those training areas identified by the U-MAP program.

CLASS – The CLASS program classifies the entire area of interest according to the signatures input from STATS. The program is usually iterated several times to obtain satisfactory correlations with ground truth (known mineralized areas). In these iterations, the signature limits—or even the signature itself—are altered as required. Output from CLASS is a map showing each spectral signature as represented by a symbol indicating the spatial location of the spectral signature within the area of interest.

CLUS – In the unsupervised mode, the CLUS program uses a clustering algorithm to develop a set of spectral signatures. It classifies the area of interest according to the signatures thus developed.

GM-CLASS – The function of the GM-CLASS program is to remove inherent distortions in the spectral scanner data and to produce a map that is geometrically correct. This program is used for producing the final map.

PRACTICAL RESULTS

To date, two studies have been completed for exploration groups, and a third is in progress as a research and development project at Dames & Moore.

SOUTHEASTERN U. S.

The first of these studies involved examination of the spectral characteristics surrounding two ilmenite deposits in certain Pleistocene beach ridges in the southeastern United States. A spectral signature common to both deposits was found using the unsupervised method, and the computer was then instructed to print out this signature wherever it was found to occur in a surrounding area comprising two U. S. Geological Survey 7½ minute topographical quadrangles. Of the areas that were printed-out as being spectrally similar to the known deposit, five occurred over high-yield boreholes. To date, two of the others have been checked in the field with scintillation counters and both are associated with high readings.

SOUTHWESTERN U. S.

Following these highly successful results, a second study was undertaken to examine the spectral responses associated with a group of carbonatite outcrops in the Mohave Desert of California.

There were four areas in which

carbonatite was known to be present. In two of the areas, the presence of the carbonatite was essentially a point occurrence (that is, the areas were small and were not characterized by any distinguishing shape or structure). Of the other two occurrences, one was known to be in the shape of a 180-degree arc, and the other was mapped as a possible ring dike. These areas were used to train the computer, and the results were printed out. When the known occurrences were accurately plotted on a base map, and the base map overlaid on, and registered to, the computer printout sheets, the following points were noted:

- All four occurrences of carbonatite were found in association with the same symbol (that is, the same signature)
- The two "point" occurrences were overlain by a single symbol each
- The two arcuate occurrences were associated with two arcuate arrangements of the symbols, one arc consisting of four symbols and the other of six

In addition, the carbonatite signature was seen to be scattered throughout the study area, occupying about 2 to 3 percent of the total. Significant groupings of signatures were found in a number of locations, and five of these were identified as prime exploration targets as a result of their size and the concentration of signatures.

Subsequent field examination of several of the targets revealed a carbonatite float or outcrop in each. One of the targets identified by computer is of particular interest due to the fact that its economic value is higher than that of the original discovery area. Detailed mapping and trenching is presently in progress at this site.

Future work will include a field evaluation of all of the targets identified by computer.

IN-HOUSE R&D PROJECT

Results of the third study, the Dames & Moore research and development project, are preliminary as of this writing. This study has focused on the identification of alteration halos associated with uranium mineralization occurring in sandstones of the Wasatch formation in the Powder River Basin of Wyoming (Figure 2). In this study

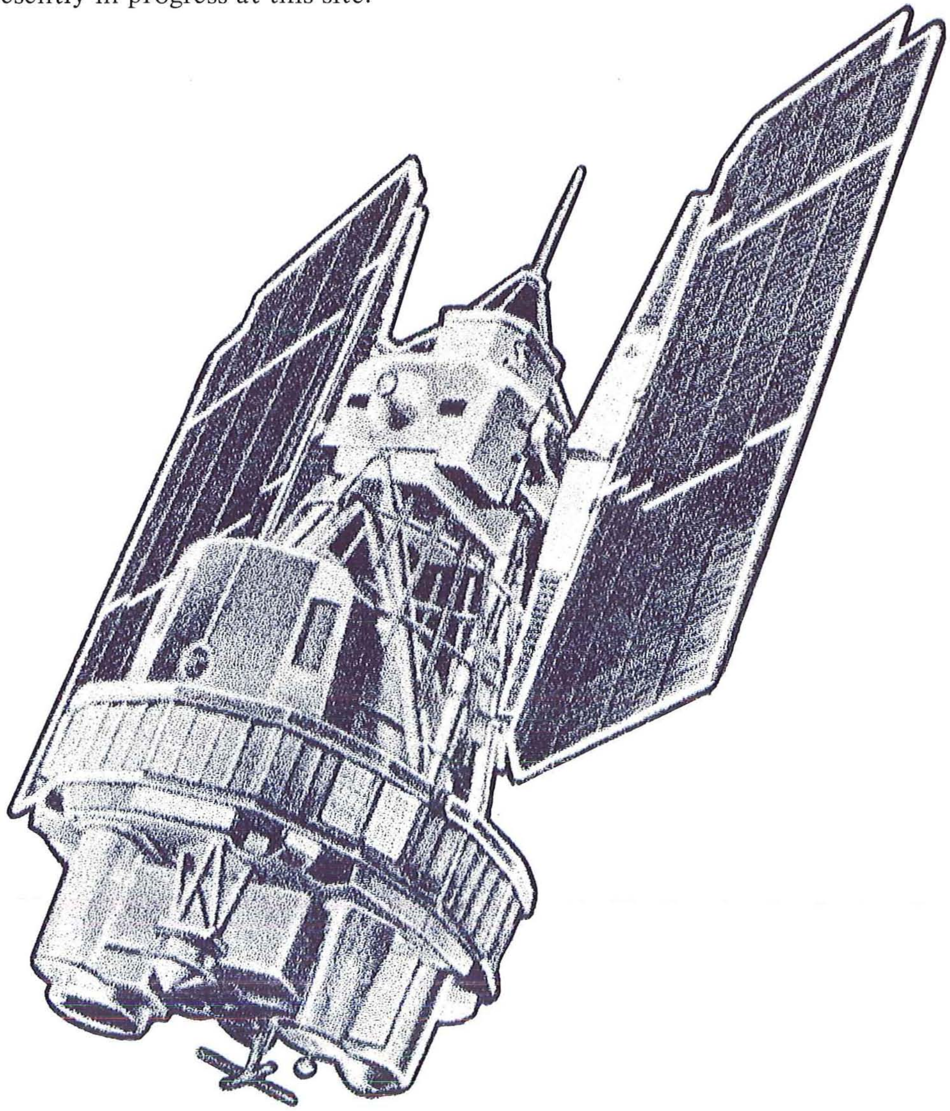
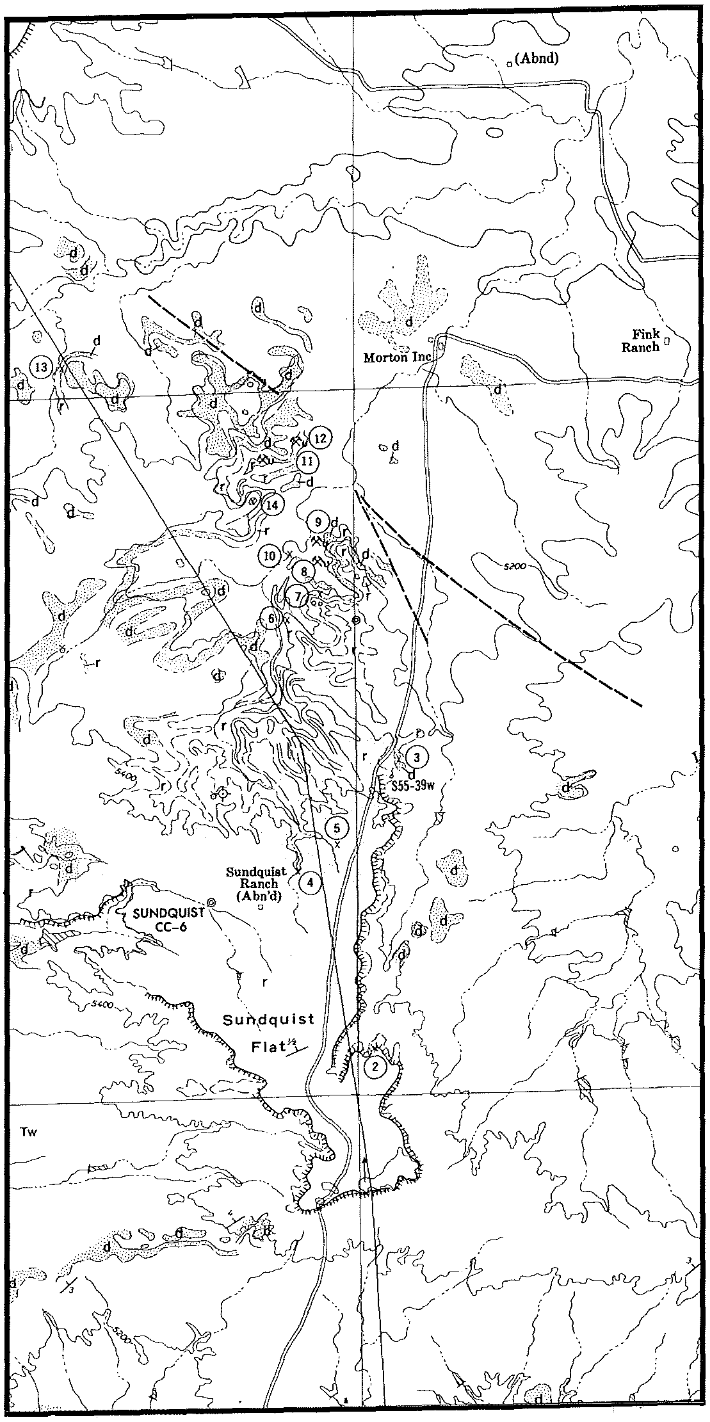
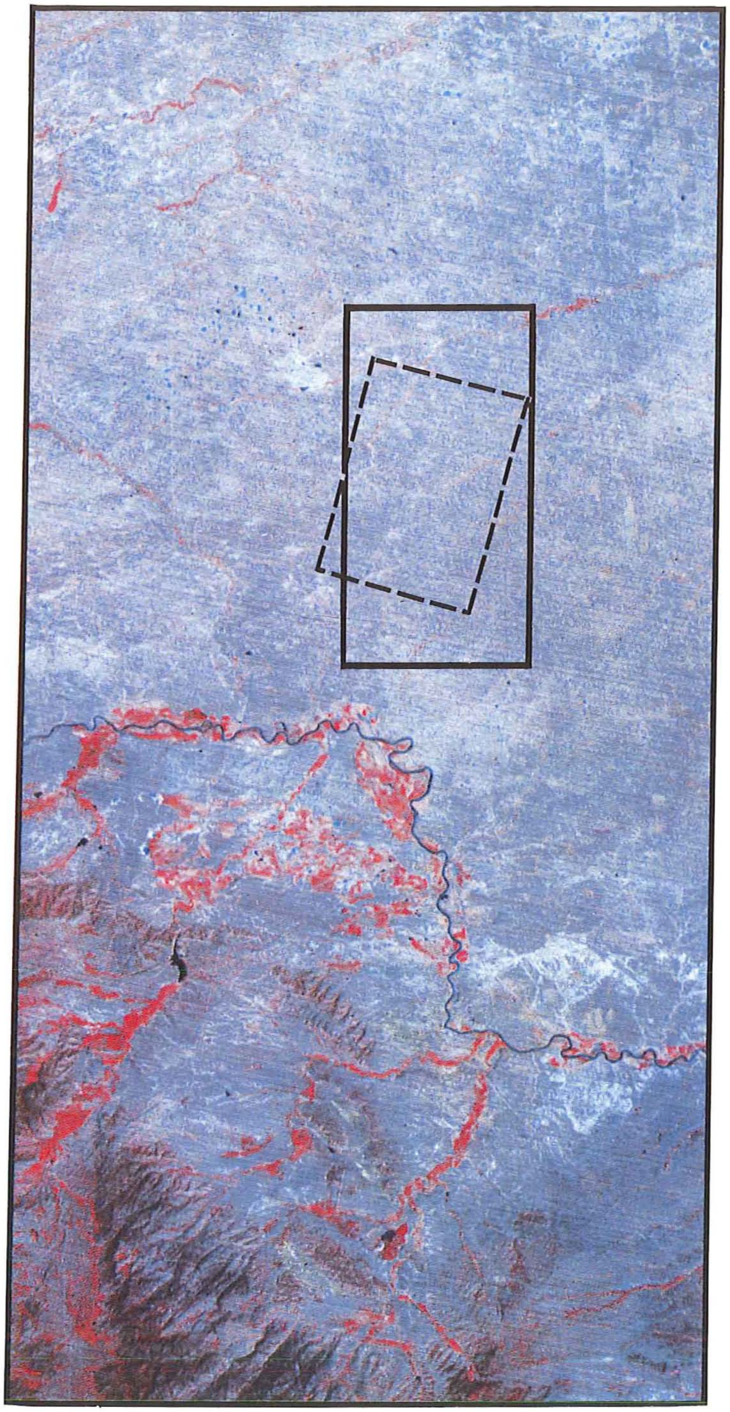
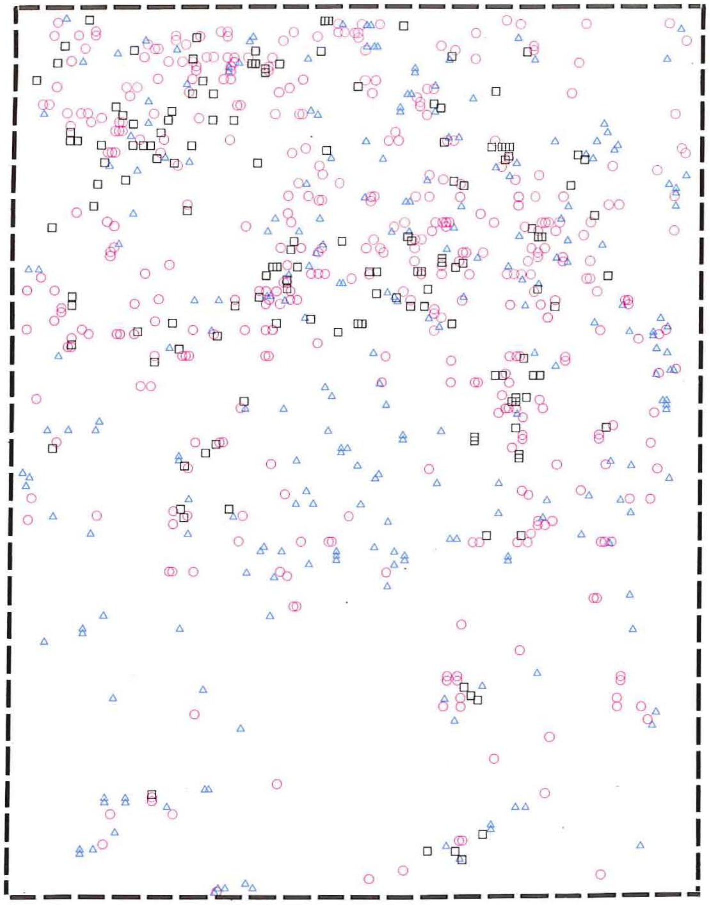


FIGURE 2. An on-going Dames & Moore research project dealing with the use of satellite digital data in the identification of potential uranium mineralization is being conducted in a portion of the Powder River Basin in Wyoming (see text). The study area is shown on the geologic map at the left; that area is bounded by a solid line on the Landsat color composit image (center). The area indicated by the dashed line was subset onto a working tape and subjected to computer analysis. (The subset area is rotated with respect to the map area because the satellite image is rotated with respect to true north.) Preliminary results of the computer analysis are indicated on the overlay at right, which was taken from a computer printout (the form was altered for clarity of reproduction).







EXPLANATION OF SYMBOLS

The symbols indicate areas having spectral characteristics similar to those exhibited by, or attributed to, uranium deposits in the area of interest.

- □ Represents the outside spectral limits of the anomaly thought to be associated with altered sandstone.
- △ Represents the transitional spectral zone between the center and outside limits of the spectral anomaly.
- ○ Represents spectral signatures located at or near the center of the spectral anomaly thought to be associated with altered sandstone.

RESULTS OF THE STUDY

The following correlations were observed in the course of an on-site evaluation of 79 pixels:

- □ No consistent correlations were noted between these signatures and observable physical features.
- △ Of the occurrences of this signature, eighty-two percent correlated with pink, tan or red unconsolidated conglomerate, or with yellow or tan sandstone.
- ○ Sixty-eight percent of the occurrences of this signature correlated with outcrops of red or brown hematite-altered sandstone. This alteration is believed to be related to roll-front uranium deposition in the Wasatch Formation in this portion of the Powder River Basin.

an attempt was made to predict, based on a literature survey of uranium deposits in the area, just what the signature for alteration halos should be. The computer then searched for this signature in the study area.

Other applied techniques were based on identification of the host rock and, specifically, on anomalously altered areas within the host rock. These anomalous areas then became training areas from which a signature was developed and subsequently searched for in the study area.

Significantly, these different techniques complemented each other and resulted in three closely related signatures, as shown in Figure 2. These signatures were found to correlate with 12 out of 13 uranium prospects and mines—a 92-percent correlation. The signature areas occupy 2.6 percent of the total study area.

A field survey was then conducted in which 79 areas occupied by signatures were briefly visited on the ground. Results of the survey indicated that:

- one of the signatures showed no consistent correlation with physical features
- the second signature correlated with exposures of a rock unrelated to uranium deposition
- the third signature, occupying 1.2 percent of the study area, showed a 68-percent correlation with altered sandstone, the alteration of which is believed to be related to roll-front uranium deposition in the Wasatch formation in this portion of the Powder River Basin.

In short, a two-day field survey was able to reduce the number of significant signatures from 2.6 percent of the study area to 1.2 percent. This tends to demonstrate that computer multispectral analysis, *when validated by a modest amount of field work*, has excellent application to mineral exploration.

CONCLUSIONS

Results to date indicate that computer processing of multispectral satellite data affords a low-cost, effective tool in exploring for near-surface mineral deposits. It is believed, however, that the programs outlined here, although extremely useful, are still in their infancy. A regional, synoptic overview of Landsat satellite data, coupled with an ability to evaluate small areas within the region (1.1 acres), should offer exploration groups an abundance of untapped, detailed geologic information for all regions of the world.

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ACKNOWLEDGMENT

The authors wish to express their thanks to Dr. Leslie Skoski for his helpful suggestions and review of the manuscript of this paper.

Technical Bookshelf

Many Dames & Moore partners and employees have contributed papers and articles to professional societies and technical journals. Some of those items which may be of wide interest to our clients and friends are presented in the *Engineering Bulletin*.

A number of the papers, however, deal with more specialized subjects or are written to such technical depth that they would be of prime interest to a specialized audience. Since a number of our readers might find these of value, we are providing selected abstracts below.

Single copies of the following technical papers are available to interested readers of the *Engineering Bulletin*. Please direct your requests to:

Editor, Engineering Bulletin, Dames & Moore
445 South Figueroa Street, Suite 3500, Los Angeles, California 90071

*A NEW APPROACH TO DIVIDING THE NORTHEASTERN UNITED STATES INTO TECTONIC PROVINCES

Joseph A. Fischer (Partner, Dames & Moore)
Jerry C. Szymanski (Project Geologist, Dames & Moore)
Matthew L. Werner, III (Project Geologist, Dames & Moore)

From the Introduction: "The division of the northeastern United States into 'geologic' provinces is not new. Generally, the physiographic cycle and geomorphic history of the area have been major contributing factors in this decision, and geologic structures have been considered only to a limited degree. However, for the purpose of adhering to certain government regulations (NRC, 10 CFR 100, Appendix A), it is necessary to utilize geologic structural similarities in a manner not previously contemplated. This discussion, and the provincial subdivision of the Appalachians, utilizes the concept of plate tectonics. . . . This approach synthesizes the available knowledge of the Appalachian orogen and the dynamics of plate tectonics theory through geologic time. . . . The application of this approach results in the recognition of eleven tectonic provinces within the orogen's northern section. . . ."

*URANIUM SUPPLY AND NUCLEAR REACTOR FUEL EFFICIENCY

Peter Gottlieb, Ph.D. (Technical Manager, Dames & Moore)

Presented at the *Greater Los Angeles Area Energy Symposium, "Energy LA: Tackling the Crisis"*
Los Angeles
May 1976

The demand for uranium is expected to grow sharply during the next 15 years, greatly exceeding production capacity and using up nearly all of the proved domestic reserves. ERDA is presently trying to survey additional resources, but is not trying to promote reactor types, such as CANDU or HTGR, which offer considerable savings in uranium consumption. The latter, in particular, should not be overlooked because of its temporary lack of commercial success.

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* New Technical Bookshelf listing

*SITING CONSIDERATIONS OF SMALL (300-400 MWt) REACTORS FOR ON-SITE GENERATION

Jack A. Halpern (Partner, Dames & Moore)
Dennis M. O'Regan (Staff Geologist, Dames & Moore)
Maj. Anthony V. Nida, CE (U.S. Army Facilities Engineering Support Agency)
Gary Stewart (U.S. Army Facilities Engineering Support Agency)
John H. Crowley (United Engineers and Constructors, Inc.)
Dennis Cabrilla (United Engineers and Constructors, Inc.)

Presented at the *American Nuclear Society International Conference*
Washington, D.C.
November 1976

American industry and the military in 1974 accounted for about 40 percent of the nation's total energy consumption; over two-thirds of this was in the form of oil and natural gas, the fuel resources with the most unstable prices and sources of supply. The U.S. Department of Defense sponsored studies to evaluate economic and environmental considerations of using small nuclear power plants at military installations. A munitions manufacturing facility was chosen to effect a realistic evaluation of a 313 MWt PWR capable of supplying both process steam and electricity. Utilizing existing NRC criteria, a prime site was identified and evaluated in detail in order to disclose site characteristics that could preclude licensing. The factors identified did not significantly alter the substantial economic advantage of the small nuclear plant over a coal-fired plant. (This evaluation is of a specific site and specific energy requirements, and should not be considered a generalized evaluation of a small nuclear plant vs. a small coal-fired plant.)

*THREE APPROACHES TO COMMUNITY NOISE CONTROL

Frederick M. Kessler, Ph.D. (Pricipal in Charge, Dames & Moore)
T.T. Pluta (Director, Suburban Air Pollution Control Commission)

Presented at the *70th Air Pollution Control Association Annual Meeting and Exhibition*
Toronto
June 1977

Community noise can be abated using three control paths: federal and state activities; local regulation; and Environmental Impact Statements. The promulgation of noise level criteria, the providing of assistance to state and local jurisdictions, and the regulation of product noise were mandated by the Noise Control Act of 1972. This paper summarizes and discusses these activities at the federal level. The environmental agencies of many states have recently promulgated state-wide noise control regulations. The form and substance of these regulations are discussed and critiqued. Numerous towns, townships and cities have adopted Environmental Impact Statement regulations containing requirements for noise impact assessments. This requirement is an effective tool to aid planning boards minimize further degradation of local sound quality.

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*New Technical Bookshelf listing

*COMPUTER-ASSISTED SITE SELECTION

Jack A. Halpern (Partner, Dames & Moore)
William T. White (Project Sociologist, Dames & Moore)

Presented at the Instituto Nacional de Energia Nuclear/American Nuclear Society *Conference on Nuclear Power and Applications in Latin America*
Mexico City
September 1975

From the Introduction: "Computer-based information systems have been used in various aspects of the site selection process, but they have not been used in a comprehensive manner. . . . the problems and practices associated with nuclear facilities, which are similar to the problems and practices applicable to the siting of railroads, steel mills, airports . . . etc., combined with computer-based data management techniques can provide powerful tools in overall economic planning. . . . We believe that the data handling system to be discussed is ideal for the complexity involved in siting of nuclear facilities. We also think that such a system is quite capable, if used broadly, of reducing duplication of work, of encouraging systematic planning and of anticipating growth problems relating to basic planning goals."

*TAILINGS DAM CONSTRUCTED ON VERY LOOSE, SATURATED SANDY SILT

Keith E. Robinson (Partner, Dames & Moore)

Presented at the *29th Canadian Geotechnical Conference*
Vancouver, British Columbia
October 1976

This paper discusses the design and performance of a tailings dam constructed on a very loose, saturated sandy silt foundation, the result of a major slide in an iron tailings disposal area in 1948. The saturated tailings foundation soils at the site reached depths of 20 feet. Consolidation and strength parameters of the foundation tailings, design considerations (including liquifaction potential of the foundation soils and stored tailings), and the results of monitoring programs during construction of the starter dam are also discussed. Contrary to experience with other fine-grained angular soils with few clay-sized particles, the iron tailings foundation soils consolidated significantly under applied load; calculations indicate that consolidation under the weight of the starter dam would be sufficient to increase the relative density to a value that would remain stable under maximum anticipated earthquake loadings.

*A REVIEW OF SEISMIC RISK APPLICATIONS

Neville C. Donovan, Ph.D. (Partner, Dames & Moore)
Ann E. Bornstein (Computer Application Engineer, Dames & Moore)

Presented at the *Second International Conference of Applications of Statistics and Probability in Soil and Structural Engineering*
Aachen, Germany
September 1975

Seismic risk procedures have been available for several years in a form which can be used for engineering applications. These include procedures which use the knowledge of historic earthquakes to estimate the probabilities of specific levels of ground acceleration at a site and models which allow the inclusion of the type and location of possible seismic sources. This paper describes procedures developed by the authors using the results of published research in practical engineering situations where design decisions have been significantly directed by results of the seismic risk analysis. The paper first describes the sequential developments which have led to the current procedures, with discussion of specific parameters, and concludes with a detailed example of the procedure's application and the sensitivity of some of the input parameters on the results obtained.

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*New Technical Bookshelf listing

MINING AND THE ENVIRONMENT

W. Derek Bullock (Partner, Dames & Moore)
Richard L. Brittain (Partner, Dames & Moore)
Gerald A. Place (Associate, Dames & Moore)

Presented at *Exploration Update '75*
Calgary
May 1975

Environmental legislation enacted in Canada and the United States over the past five years has tended to make mining operations increasingly more complex. This paper briefly reviews the extent of such operations in both countries and lists the major environmental impacts of surface mining activities. The requirements of major U.S. and Canadian legislation affecting mining operations are discussed and the impact of the laws are evaluated. Also reviewed are the provisions and potential impacts of pending legislation of concern to mine owners and operators. A number of specific case histories are included which illustrate methods of compliance with existing environmental regulations.

REVEGETATION OF MINE WASTES AND DISTURBED AREAS IN AN ARID ENVIRONMENT

Roger F. Black (Senior Biologist, Dames & Moore)
John P. Trudinger (Associate, Dames & Moore)

Presented at the symposium *Landscaping and Land Use Planning as Related to Mining Operations*
Adelaide, South Australia
March-April 1976

Environmental concerns have spurred attempts to revegetate areas disturbed by mining activities. The problems of sucessfully revegetating such areas are often difficult, even under favorable conditions; under the severe conditions prevailing in the arid and semiarid regions of Australia, such difficulties may be extreme. An approach is described in which field trials are used for investigating factors adversely affecting revegetation and for evaluating optimum methods and treatments. A number of methods suitable for use in arid regions are also described.

DESIGN OF IMPOUNDMENT AND EVAPORATION PONDS AND EMBANKMENTS FOR CYANIDE AND OTHER TOXIC EFFLUENTS

George C. Toland (Partner, Dames & Moore)
Ronald E. Versaw (Project Engineer, Dames & Moore)

Presented at the *SME of AIME Fall Meeting*
Salt Lake City
September 1975

Most existing impoundment ponds and dams leak a certain amount of effluent into the soil or rock upon which they are constructed. Proposed legislation, however, will require stringent control of the release of toxic effluents such as cyanide. More exacting investigation, design and construction techniques than have been used previously will be required to meet these new regulations. This paper discusses the types of field and laboratory investigations required to develop data for the design of an impoundment system to contain toxic effluent. The technical considerations necessary to design such a system are also discussed in detail.

GEOTECHNICAL INVESTIGATIONS FOR MINE SHAFTS

James R. Swaisgood (Partner, Dames & Moore)
Ronald E. Versaw (Project Engineer, Dames & Moore)

Presented at the *AIME Pacific Northwest Metals and Minerals Conference,*
Coeur d'Alene, Idaho
April 1973

Hundreds of mine shafts have been sunk in the United States in the past. Most have been successful, but some have not. In some instances, much time and money has been lost while emergency measures were taken to control unexpected water flows. Many thousands of dollars have also been wasted in over-conservative support design for many "successful" shafts. As labor and material costs increase, unnecessary mine shaft expenses must be reduced. Shaft investigation techniques are therefore being perfected and support design methods are being developed.

This paper outlines and describes several new investigative methods used for shaft studies. Ways in which the data can be used are also described. In addition, typical costs are listed and benefits to be gained from proper use of the data are explained.

DESIGN DECISIONS FOR SEISMIC STRUCTURES

I-Hsin Chou, Ph.D. (Project Engineer, Dames & Moore)
J.E. Goldberg (Professor of Structural Engineering, Purdue University)
J.P.T. Yao (Professor of Civil Engineering, Purdue University)

Presented at the *5th World Conference on Earthquake Engineering,*
Rome
June 1973

The structural design problem of a seismic structure is formulated on the basis of decision analysis. For the purpose of illustration, the design of columns for a one-story building structure is considered in this paper. The decision involves the choice between two alternative materials, namely steel and reinforced concrete.

SELECTION OF SEISMIC DESIGN PARAMETERS FOR A NUCLEAR FACILITY

Joseph A. Fischer (Partner, Dames & Moore)
Harcharan Singh (Senior Engineer, Dames & Moore)
James G. McWhorter (Senior Geologist, Dames & Moore)

Presented at the *5th World Conference on Earthquake Engineering,*
Rome
June 1973

From the introduction: "Much of the recent controversy concerning seismic hazards to proposed nuclear facilities has centered not on the complexities of dynamic structural design but with the difference of opinion as to the maximum credible earthquake to be specified for a given area. Occasionally, some very legitimate geological-seismological questions have been raised during those controversies by those who tend to underestimate the overall safety aspects of the site. This has had in general a positive effect. Present day investigations for the earthquake design of nuclear facilities require increasingly more extensive and more precise geologic and seismologic data."

Index of Engineering Bulletins

1958

1 Experiences with Soil Expansion Through Chemical Action ... *Fenley Ryther, Jr.*

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1972

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1973

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Control of Water in Tailings Structures ... *James R. Swaisgood & George C. Toland*

42 Siting Constraints for an Offshore Nuclear Power Plant ... *Joseph A. Fischer & Fred L. Fox*

Regional Considerations for the Design of an Offshore Nuclear Power Plant ... *Joseph A. Fischer, James G. McWhorter & Harcharan Singh*

Site Investigations for an Offshore Nuclear Power Plant ... *James T. Dette, Lloyd E. Stahl & Joseph A. Fischer*

Considerations of the Geotechnical Engineer in Planning Transmission Lines to Offshore Nuclear Power Plants ... *Joseph A. Fischer, Ian Watson & Lawrence A. Salomone*

Environmental Studies for an Offshore Nuclear Power Plant ... *James R. Roney*

43 Ecological Considerations of Industrial Development: An Introduction ... *David W. Valentine*

Terrestrial Aspects of Ecological Surveys ... *Alan L. Smith*

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1974

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Environmental Impact Considerations in Dredging Projects ... *Ian C. Macfarlane*

45 Remote Sensing: Environmental and Geotechnical Applications ... *Larry Alexander, Leo Eichen, Frank O. Haselden, Richard F. Pascucci & Dermot M. Ross-Brown*

46 Earthquake Hazards for Buildings ... *Neville C. Donovan*

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1975

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1976

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