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URANIUM RESERVES AND PROGRESS IN EXPLORATION AND DEVELOPMENT [1]

By Arthur P. Butler, Jr.

Gentlemen, although I consider it an honor to have been asked to tell you something about uranium reserves and resources and progress in exploration, a glance through your association bulletin, Coal News, indicates that the editor is doing a very good job of informing you about events in the nuclear industry and about interpretations of its resource base. As a result, many of you may be more or less aware of the general content of what I can present. Perhaps, however, a review of estimated demand for uranium in relation to the known and potential resource base will be useful.

In this review the general magnitude of the demand will be indicated, the general quantity of reserves will be outlined as they may stand when the Atomic Energy Commission buying program ends in 1970, and the general character and distribution of known reserves will be summarized to provide a perspective for considering the outlook for exploration.

It should be recognized that, in dealing with estimated or anticipated demand, I am relying on the public statements of others who have made projections of the likely growth in use of electric power and of how that growth is likely to be shared by various fuels. As many of you know, nuclear-powered generating equipment installed or on order had reached a total of 39,000 megawatts by early June of this year (1967). The AEC estimates that by 1980 installed nuclear power capacity in the United States will probably be about 150,000 megawatts (Nininger, 1967).

Plants built or now on order will require about 175,000 tons of U_3O_8 for fuel throughout their lifetime. Those which are projected to be in service by 1980 will, on the same basis, require an additional 500,000 tons. This quantity is based on the assumption that the reactors going into service by 1980 will have about the same characteristics as reactors now on order; that is, they will not regenerate as much fissionable material as they consume.

Reactors of the present generation are fairly prodigal of fuel, for they depend largely on the fissioning of the isotope U^{235} for generating energy. This isotope makes up only 1 part in 140 of natural uranium. In reactors, some of the much more abundant isotope U^{238}, which is not naturally fissionable, captures neutrons from the fissioning U^{235} and is converted to fissionable Pu^{239}. But not enough U^{238} is converted in these reactors to replace the U^{235} used. Therefore, only a fraction of the energy latent in the uranium resources is actually used by reactors likely to go into service in the next dozen years.

The significance of these numbers may be a little clearer if we look at the demand in relation to known reserves and estimated resources and in terms of coal equivalents familiar to all of you.

Table 1 compares the energy in uranium and coal with respect to the amount of U_3O_8 needed as fuel for reactors on order and in use. The energy derived from U^{235} that will be used in these reactors is large in terms of coal equivalents but is dwarfed by the amount that would be available if all the accompanying U^{238} were converted to Pu^{239}.

The 175,000 tons of U_3O_8 needed to supply reactors now on order is somewhat larger than the AEC's estimate of 141,000 tons of indi-

[1] Presented at Department of Interior–Coal Industry Executive Conference, Washington, D.C., August 16, 1967.

TABLE 1.—*Bituminous coal equivalents of energy in uranium*

	Bituminous coal (tons)
1 lb U^{235} or Pu^{239} [1]	[2] 1,3[illegible]0
1 ton natural uranium [1, 3]	~19,000
1 ton unenriched U_3O_8 [3]	~16,000
175,000 tons U_3O_8 (amount required for reactors in service or on order)[3]	~2,800,000,000
175,000 tons U_3O_8 if all U^{238} is converted to Pu^{239}	[4] 140×2,800,000,000 =392,000,000,000

[1] 1 ton natural uranium contains 14 lb U^{235}.
[2] Hubbert (1962). Equivalent to 33×10^9 Btu.
[3] Using only U^{235}.
[4] 140 is the ratio of $U^{238} + U^{235}$ to U^{235} alone.

TABLE 2.—*Uranium reserves in the price range of $8 to $10 per pound* U_3O_8 *as they may be at end of 1970*

[Values are U_3O_8, in tons]

Reserves, end of 1966 [1]		141,000	
Less total to be mined, 1967–70 inclusive:			
AEC procurement [1]	32,000		
Estimated commercial sales [1]	18,000		
		50,000	
Balance of present reserves			91,000
New reserves found at average discovery rate of 1962–66			24,000
Estimated reserves at end of 1970, assuming no increase in rate of discovery			115,000
Possible future releases from AEC stockpile [2]			50,000
Known resources at $8 per pound			165,000
Additional resources exploitable at $10 per pound			40,000
Total in conventional deposits and stockpiled (rounded)			200,000

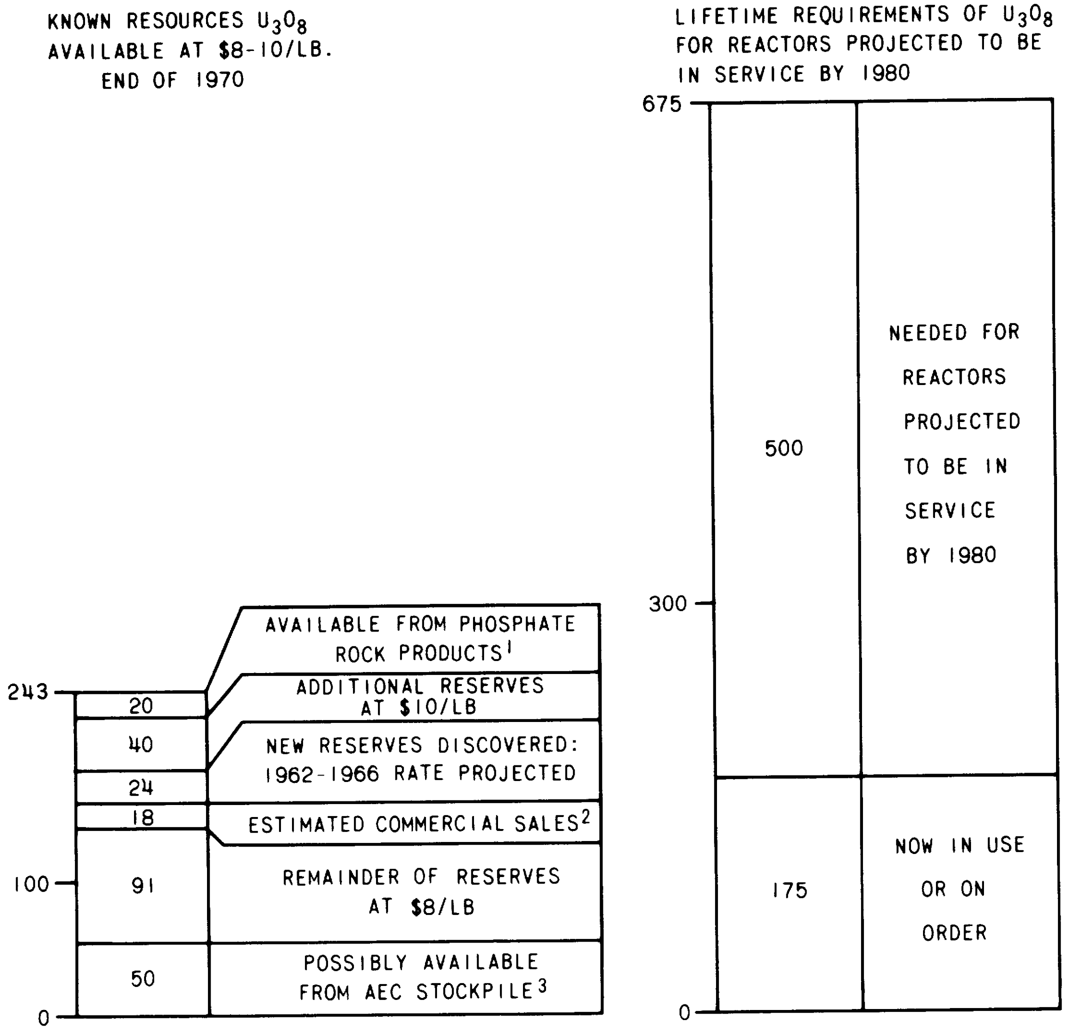
[1] Nininger (1967).
[2] Engineering and Mining Journal (1966).

cated and inferred reserves of U_3O_8 minable at $8 per pound but somewhat less than the estimated 200,000 tons U_3O_8 minable at $10 per pound. The uranium to fuel additional reactors will have to be provided by discovery of additional ore. To see what may be needed, it would be well to look at the reserve situation as it may be in 1970 when the AEC buying program is finished (table 2).

At the end of 1970, counting in material that the AEC has said might be available for release from its stockpile (Engineering and Mining Journal, 1966), known resources derived from conventional deposits at $8 per pound U_3O_8 would be about 165,000 tons U_3O_8. Allowing a price of $10 per pound U_3O_8, the resources would be 200,000 tons U_3O_8. With either tonnage, the supply for reactors now built or on order is reasonably well assured. This relation between the amount of uranium reserves at $8 and $10 per pound is also shown graphically in figure 1.

The uranium needed for reactors that are projected to be placed in service by 1980 will have to come mostly from resources in conventional-type deposits not yet discovered, a category which the AEC has termed "possible additional resources." The resources of this sort that could be found and mined for $8 to $10 per pound are estimated to be 325,000 tons (Organization for Economic Cooperation and Development, 1965, table 1).

Most of these additional resources are probably in the same regions as the known deposits. Those from which ore is currently being mined are in the western part of the United States.



[1] Organization for Economic Cooperation and Development (1965, table 1, footnote 1).
[2] Nininger (1967).
[3] Statement attributed to AEC chairman, Glenn Seaborg (Engineering and Mining Journal, 1966, p. 83).

FIGURE 1.—Estimate of U_3O_8 (in thousands of tons) mined and in reserves at the end of 1970 compared to amount required for nuclear reactor fuel.

Their general distribution is shown in figure 2. A small amount of ore also has been mined from a deposit in Pennsylvania.

About 95 percent of the uranium produced has come from deposits in continental sedimentary rocks, mainly sandstone. A like proportion of the reserves and probably of undiscovered resources is in this same type of deposit. Most of my subsequent remarks will be concerned with resources in such deposits. But first, I think, other sources of supply should be mentioned. Fracture-controlled deposits, principally veins, have furnished most of the remainder of the uranium mined. Some of these deposits are important as individual mines but not as major contributors to total supply. Uranium has been recovered as a byproduct of the manufacture of phosphate products from marine phosphorites. The volume of these rocks is very large and a sustained supplementary supply of uranium can be obtained from them at a price of about $10 per pound of U_3O_8. This supply, however, is geared to the rate of production of refined phosphate products. Similarly, a small but steady byproduct contribution may come from leaching of copper mine tail-

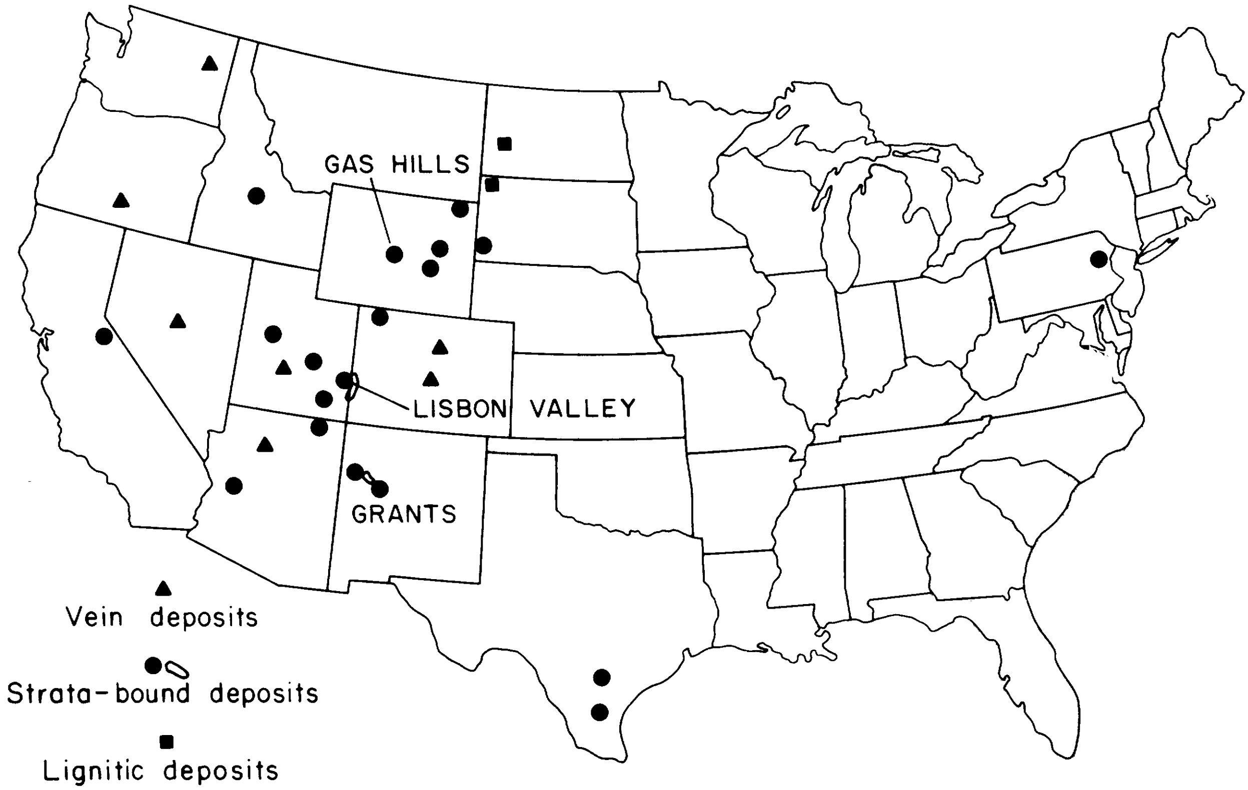


Figure 2.—Principal deposits mined for uranium in the United States.

ings, which has been recently announced as a possibility (Nininger, 1967).

All other identified resources are materials from which uranium could be recovered only at a cost that would range from a few to many times the cost of recovering it from the ores now mined.

Additions to supply will come mainly from discovery of new deposits and districts in the same geologic units of continental sandstone from which ore is now mined and possibly in units where small deposits have been found but where the presence of large deposits has not yet been demonstrated. In considering the outlook for exploration for additional deposits, an outline of the general distribution of the known deposits and of some of their principal characteristics provides an essential frame of reference.

As can be seen in figure 2, most of the productive deposits are in a broad poorly defined belt that extends from northeast Arizona and northwest New Mexico to northeast Wyoming and the western part of the Dakotas. A few are in the Gulf Coastal Plain in south Texas. Others, largely isolated and not shown on the map, are in the Texas Panhandle, western Oklahoma, and in States west of the main belt.

Within the areas of their distribution, the principal deposits tend to occur in parts of a few units of sedimentary rocks. In the region of the Colorado Plateau, the large deposits are in three particular units whose designations I shall omit. In northwest Colorado and much of Wyoming, they are mainly in two rock units younger than those of the Colorado Plateau. In northeast Wyoming and the adjoining part of South Dakota, they are in rocks intermediate in age between those of the Colorado Plateau and those in central Wyoming. The Texas deposits are in relatively young rocks.

Deposits in these major host units are distributed across areas that range in size from a few tens of square miles in parts of Wyoming to 9,000 square miles in one unit in the Colorado Plateau region. The aggregate area of favorable rock within which the principal deposits occur is about 30,000 square miles. The discovered deposits are in tracts of still incompletely explored ground that constitute not more than one-quarter of this aggregate area. This is a point to which I will return subsequently. Other bodies of continental sandstone that contain small and generally scattered deposits collectively underlie an aggregate area of another 160,000 square miles.

The large deposits generally occur in somewhat lenticular bodies of sandstone interbedded with mudstone. Almost all of them are not only in parts of the sandstone that are appreciably thicker than adjoining parts but mostly in sandstone that is at least 30 feet thick.

Deposits range from a few tens of feet long and a few feet wide to many thousands of feet long and a few hundred feet wide. Small ore bodies contain a few tons of ore; large ore bodies contain hundreds of thousands to several millions of tons. They have a variety of forms from crudely tabular to markedly elongate masses of crescentic cross section. In most of the major producing areas, the deposits tend to be arranged in notably elongate groups or clusters, as in the large Ambrosia Lake district, New Mexico (fig. 3). The length of these clusters and connected mineralized rock that is too lean or too thin to be mined ranges from a few to many miles.

Almost all deposits are closely associated in one way or another with color differences in parts of their host rocks. In some areas, rock near deposits differs slightly in color from rock farther away. In other areas, notably in Wyoming and Texas, deposits are mainly along the color boundary. The contrasts in color range from subtle to easily distinguishable. They reflect differences in mineralogy that are more difficult to recognize than even a subtle color contrast.

Because the color differences are more extensive than conspicuously mineralized rock, color differences provide preliminary targets for exploration that are larger than those for strongly mineralized rock. Thus, nearly the whole area included in the line patterns in figure 3 constitutes a preliminary target that could be diagnosed from drill holes spaced at 1-mile intervals as potentially favorable for the presence of deposits. Radioactivity logs of drill holes would also aid materially in the interpretation.

Color differences in different parts of the host rocks have for many years been recognized as a useful exploration guide. It is probably only within the last half-dozen years, however, that an integrated concept has evolved of how the various color manifestations can be most effectively applied.

The present resurgence in exploration starts with a much broader, but still incomplete, base of knowledge than prevailed 20 years ago. More is known about the general distribution and habits of deposits, about the characteristics of the rocks that indicate favorability for the presence of deposits, and about how to apply recognition of those characteristics in guiding search for them. For example, it is known that the targets for preliminary evaluation of favorability are measurable in square miles rather than in hundreds to a few thousands of square feet and that significant bodies of mineralized rock are many thousands of feet to several miles long. In addition to the characteristics of bodies of sand likely to be favorable receptors for deposits, the interpretation of differences in color from place to place within a rock unit can be used to estimate favorability for deposits and to direct exploration into particular parts of areas where these differences are recognized. Still lacking are criteria for determining which parts of large unexplored areas offer the best chance of rewarding the preliminary stages of exploration.

The increase in orders for nuclear-fueled plants and the expectation of a sustained and growing market for uranium provide a strong stimulus to exploration, spearheaded by many experienced concerns in the mineral industry. These include major and several small domestic uranium-mining companies, companies with large interests in uranium mines in Canada, and some major oil companies. Acquisition of land, either by lease or by the staking of claims, has reached the proportions of a land office rush.

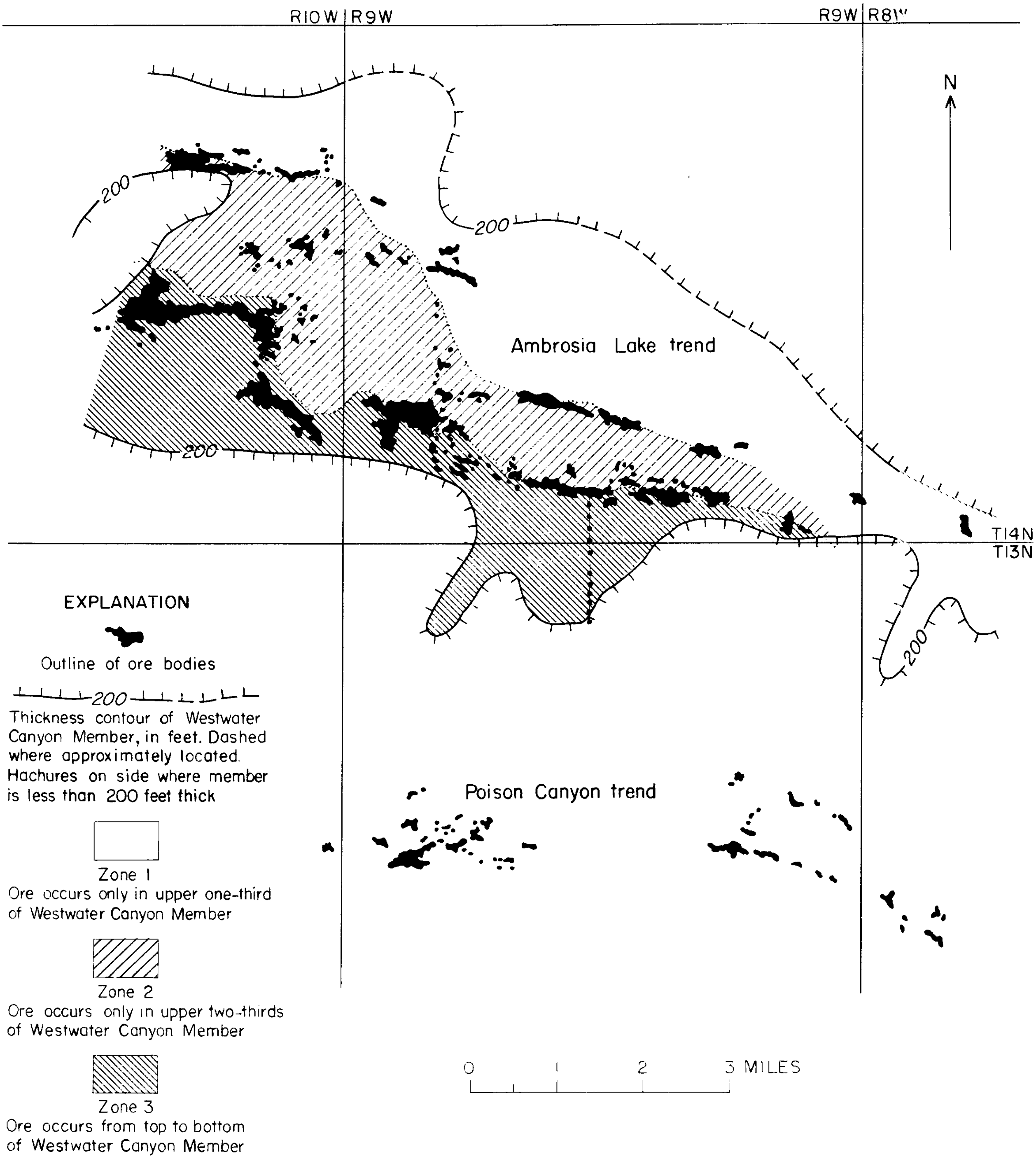


Figure 3.—Map of ore deposits in the Morrison Formation, Ambrosia Lake area, New Mexico (from Santos, 1963, fig. 1).

The extent of solid effort is shown by the increase in exploratory drilling. The amount of such drilling in 1966 exceeded that in 1965 by 30 percent, and the rate in 1967 is about four times that of last year. Next year, if not this, it will exceed the previous high of 1957.

No remarkable new discoveries have yet been announced, but this is not surprising in view of the time necessary to start soundly conceived exploration projects and of the relatively short interval of time that has elapsed from concern about a market to full realization of the probable magnitude of the demand for uranium to be used in reactors. Moreover, even if a company has made a significant discovery, it may well prefer to refrain from announcing it immediately. The reasons could be the competitive situation in land acquisition or concern over the effect an announcement might have on negotiating price with potential customers. Even slight optimism on the part of a mining company might make buyers more cautious.

Despite the lack of news of any really new discovery, there are reasons for thinking that the present round of exploration will be successful in finding the concealed deposits from which future supplies of uranium will have to come.

Much of the exploration in the last few years has been confined to the immediate vicinity of known ore deposits. This has met with reasonable success. For example, a continuation of the large deposits in the Lisbon Valley area, Utah, has been found in the downdropped block across a fault from the known deposits. This exploration has been carried on at a depth approaching 2,000 feet. In 1963, when exploration was at a low ebb, a new deposit discovered in the coastal plain in Texas was significant not only because it turned out to be larger than any previously mined there, but also because it demonstrated that good-sized deposits occur at some distance from the outcrop in that region. During 1962–66, a period of little incentive for exploration, 24,000 tons of new reserves was found in the country as a whole.

Large areas underlain by the principal ore-bearing strata and other possibly favorable stratigraphic units are still relatively unexplored. As already mentioned in reviewing the distribution of deposits, solid exploration effort in the past was restricted to only about one-fourth of the area where the particularly favorable strata are present. Even this one-fourth is still incompletely explored. Although it would be incorrect to jump to the conclusion that all the relatively unexplored areas would be as strongly mineralized as the explored parts, it would seem very fortuitous and most unlikely that a large part of the known deposits are confined to the more accessible one-quarter of the particularly favorable units which is also the more intensively explored part of the total possible area. Almost inevitably, successful exploration in one place will focus attention at that place, perhaps to the virtual neglect of others, because reward is likely to come more quickly there in the form of finding nearby extensions of the initial discovery. The new round of exploration will, however, be seeking concealed deposits that are more deeply buried and more remote from outcrops than the known deposits. These concealed deposits will be more difficult and more costly to find and mine. But the probabilities are good that the deposits are there, and industry has now developed the experience and skill to apply knowledge of their distribution and habits effectively in exploring for them.

Additionally, the continental basement of Precambrian rocks which is concealed under younger rocks in the vast area between the Appalachian and Rocky Mountains represents a more distant possibility for exploration. The large uranium deposits in southern Canada are in exposed parts of this basement. Identifying its concealed parts that may be favorable for deposits and exploring those parts will be a formidable task, inasmuch as the blanket of overlying rocks is 3,000 to 5,000 feet thick in much of the continental interior. However, an increasing store of geophysical data, coupled with data from scattered drill holes, is improving interpretation of its characteristics.

Finally, the experience of other segments of the mineral industry furnishes some analogies relevant to the exploration for uranium. For example, although we had been using oil at an increasing rate for about 100 years, by 1958 proved reserves were still larger than they had ever been before (adapted from Zapp, 1962, table 2). Exploration for lead in Missouri during a period of 20 years has resulted in discovery of a whole new group of districts in which resources are estimated to be three times the amount that had been mined from the original lead belt in 100 years (Weigel, 1965). Copper reserves in 1964 were more than three times the reserves estimated in 1935 (Everett and Bennett, 1967, p. 26). The situation in copper may not be exactly comparable to that for uranium because the price of copper also rose markedly but less than the increase in reserves. In comparison, reserves of uranium at $15 per pound U_3O_8 would be about 60 percent larger than at $10. The known geology of uranium deposits in continental sandstone suggests that the chances are good that exploration for uranium will follow a course generally similar to the examples just cited. I think that the remarks of McGee (1967) to the Atomic Industrial Forum nearly a year ago deserve repeating in this context; he said, "The past achievements of the uranium industry in finding, developing, and producing * * * uranium beyond the requirements of the AEC are a significant indication that the challenges of the future will be met."

In the present review it has been pointed out that:

1. Reserves, when projected to the end of the AEC buying program in 1970, are adequate to meet the lifetime needs of nuclear reactors for generating electric power ordered up to the end of May or now in use.
2. The uranium needed to fuel reactors ordered in the future will have to come largely from deposits yet to be discovered.
3. The distribution of known deposits indicates that these concealed deposits are most likely to occur in strata of continental sandstone.
4. Unexplored areas of these rocks are large in relation to the still only partly explored areas where deposits are known.
5. Other similar, less intensely mineralized strata extending over very much larger areas offer less clearly definable possibilities for future discoveries.
6. Although knowledge about uranium deposits is still incomplete, it is more broadly based than it was 20 years ago and can be effectively used in the search for deposits by an experienced industry.
7. The possibilities are good that with intensive exploration the search for uranium will be successful.
8. The technology in the use of uranium is certain to improve just as the technology in mining and use of coal has improved.

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