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United States Uranium Resources—An Analysis of Historical Data

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The success of discovery indicates that little high-grade uranium ore remains to be discovered.

M. A. Lieberman

Practically the entire amount of high-grade uranium ore in the United States occurs in the sedimentary sandstone and mudstone deposits of the Colorado Plateau, the Wyoming Basins, and the Gulf Coastal Plain of Texas (*1, 2*). Currently, about 98 percent of U.S. uranium production is mined from the deposits in these three districts.

Sandstone ores occur in two major forms (*3–5*): either as relatively flat, lenslike deposits or as crescent-shaped rolls. The grade of ore is typically in the range 1000 to 5000 parts per million (ppm) of U_3O_8 by weight. The lenslike deposits are found in reduced rock which is generally surrounded by oxidized rock, while the crescent-shaped deposits are found at the boundaries between reduced and oxidized rock. It is believed that the deposits were formed by reduction of the soluble hexavalent uranium ion to its insoluble quadravalent form. The deposits are sharply bounded and very little U_3O_8 is found in these rocks at grades below 500 ppm (*6*).

Small deposits of sandstone ores have been discovered in Argentina, Gabon, and Niger. However, as far as is now known, the western sandstone deposits are a unique geological occurrence in terms of their extent and magnitude. The Colorado Plateau and Wyoming Basins are among the best explored of all the world's uranium-producing provinces. Exploration has taken the form of aerial and ground radiation surveys, radon gas evolution measurements, and an extensive program of exploratory drilling.

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The primary source of information about the domestic uranium industry is the report series GJO-100, published yearly by the Energy Research and Development Administration (ERDA) (formerly the Atomic Energy Commission, or AEC), Grand Junction Office, Grand Junction, Colorado. The most recent report (*2*) gives data on the production and reserves of U_3O_8 for various cost categories, and the exploratory footage drilled, for each of the years from 1947 through 1974.

An important similarity between the accumulation of uranium in sandstone deposits and the accumulation of petroleum underground is noteworthy (*5*). That is the occurrence of many small deposits and comparatively few large ones, with the latter containing most of the uranium. Out of the 284 known deposits in the $8 per pound (1 pound = 0.453 kilogram) U_3O_8 cost category, the three largest deposits account for 23 percent of the reserves and the ten largest deposits for 52 percent of the reserves (*1*, p. 33). The similarity to petroleum accumulation is an indication that the techniques developed for petroleum estimation are applicable to uranium estimation in these deposits.

Two procedures are adapted to provide objective estimates of Q_∞, the ultimate recoverable resource of U_3O_8 that is available from the western sandstone deposits. They are mathematical and based on published statistical data. (i) The historical data on the quantity of U_3O_8 discovered per foot of exploratory well drilled are established. The data are shown to fit an exponential curve, and the parameters of the curve, including Q_∞, are determined. (ii) The yearly data on production and reserves of U_3O_8 are fit to a logistic growth curve, and a least-squares error technique is used to determine the parameters of the logistic growth curve, including Q_∞. Because of the irregular history of uranium discovery and production, this procedure is considered as a verification of the estimate derived from the exploratory drilling data. Both procedures were originated (*7*) and have been applied (*8*) with considerable success to the estimation of the ultimate recoverable resource of U.S. petroleum by the geologist M. King Hubbert.

Classification by Foward Cost

In order to define the meaning of the term "reserves" in the present context, some consideration of U_3O_8 costs and their history is necessary. The uranium industry has traditionally considered the U_3O_8 producible at forward cost of $8 or less per pound to be its stock of resource immediately at hand. The reason is partly historical. Early prices were in the range of $9 to $11 per pound of U_3O_8. From 1961 to 1968 the Atomic Energy Commission paid a flat price of $8 per pound of U_3O_8, after determining that such a price was equitable to the uranium industry. From 1969 to 1971, the government terminated its buying program, paying an average price of about $6 per pound. The price has since been in the range of $8 to $10 per pound, although prices were increasing rapidly in 1974–75.

The forward cost does not include "sunk" costs, such as land acquisition and exploration, or profits, taxes, and interest on capital invested. The forward

Table 1. Discovery rate R and cumulative exploratory footage h for 11 selected footage intervals, for U_3O_8 at \$8 or less per pound.

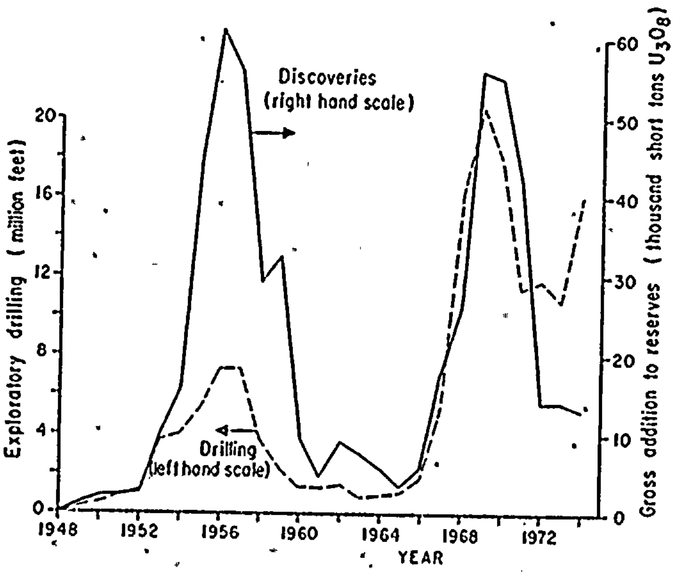
Interval	Drilling year(s)	Cumulative drilling h (10^6 feet)	Discovery year(s)	Discoveries (10^6 short tons of U_3O_8)	Discovery rate (pounds of U_3O_8 per foot drilled)
1	1948–54	11.25	1949–55	79.4	14.1
2	1955–56	23.8	1956–57	117.0	18.6
3	1957	31.2	1958	29.5	18.0
4	1958–61	40.0	1959–62	56.2	12.7
5	1962–67	51.7	1963–68	66.7	11.4
6	1968	68.0	1969	56.0	6.90
7	1969	88.4	1970	55.0	5.37
8	1970	106.4	1971	42.0	4.67
9	1971	117.8	1972	14.0	2.46
10	1972	129.6	1973	14.0	2.37
11	1973	140.5	1974	13.0	2.40

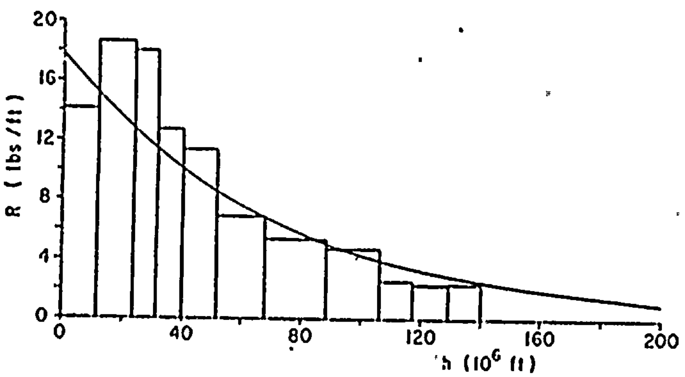
cost is therefore not the price at which the U_3O_8 will be sold. The selling price will be a function of the forward cost and these other factors, as well as the prevailing market conditions. A sellers' market has developed in 1975, and the price of U_3O_8 has been bid up considerably as a result.

From the above discussion, the following procedure is adapted. First, the historical data are analyzed and the value of Q_∞ is determined solely for those reserves producible at a forward cost of \$8 or less per pound of U_3O_8. This value of Q_∞ is then compared with published estimates of Q_∞ in this forward cost category. Second, an estimate is made of the ultimate recoverable resource Q_∞ for higher forward cost categories, with the use of published data giving the grade distribution of ores and the ratio of uranium producible for a given forward cost class to that producible at \$8 or less per pound.

Discoveries per Foot of Exploratory Drilling

The Grand Junction Office of ERDA issues yearly reports (2) summarizing gross and net tonnage additions of U_3O_8 to reserves in various forward cost categories, and exploratory and development footage drilled. Development footage is drilled for the purpose of blocking out ore bodies, sampling ore quality, and similar reasons, and is ignored in this discussion. Exploratory footage is drilled for the purpose of discovering new ore bodies in new or currently producing uranium districts. Net additions to reserves in a given cost category are calculated by subtracting the yearly production from discoveries (gross additions) and shifting those resources which have become uneconomic to produce as a result of inflation into a higher cost category. For example, in 1974 for the \$8 per pound U_3O_8 cost category, discoveries were 13,000 short tons of U_3O_8 (1 short ton = 0.907 metric ton), production was 12,600 short tons, and 77,000 short tons were removed from this cost category because of inflation. Thus net reserves fell by 77,000 short tons in 1974.





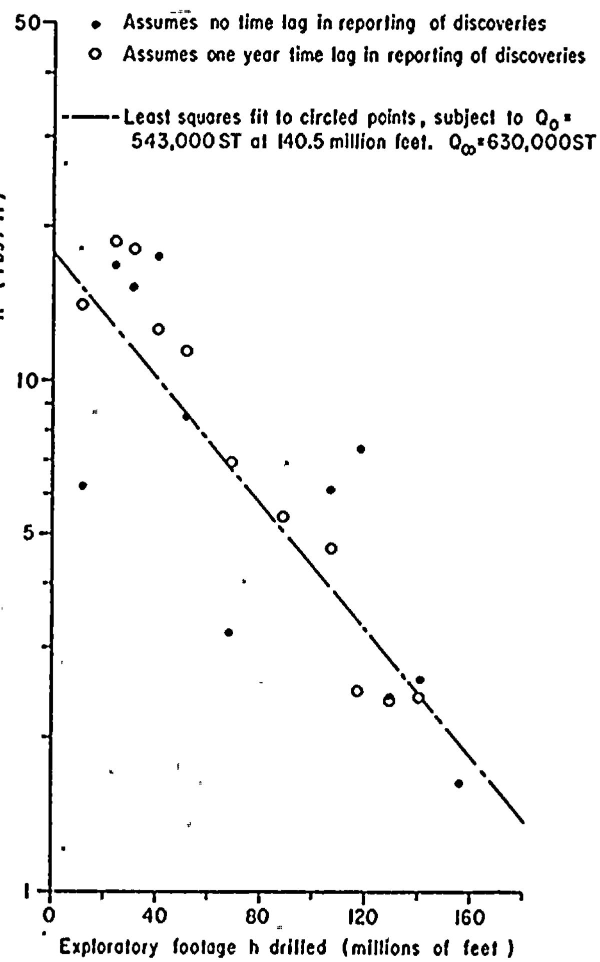


Fig. 1 (top left). History of exploratory drilling and discoveries of \$8 per pound U_3O_8 compared to cumulative exploratory footage h drilled. Fig. 2 (right). Discovery rate R of \$8 per pound U_3O_8 compared to cumulative exploratory footage h drilled. Fig. 3 (bottom left). Discovery rate of \$8 per pound U_3O_8 compared to cumulative exploratory footage h drilled, on a linear scale.

Table 2. The relation between forward cost and average grade

Forward cost ($ per pound)	Average grade (percent by weight)
8 or less	0.24
10 or less	0.19
15 or less	0.12
30 or less	0.06

It has only been during the last few years that the inflationary correction has been of importance.

Figure 1 shows the gross addition to reserves and the exploratory footage drilled for each of the years from 1948 through 1974. During the 1950's, the drilling pace built up and then rapidly tailed off as defense requirements reached saturation and incentives were removed. In the mid-1960's, an upsurge of drilling occurred with the advent of civilian nuclear power, but tapered off because of depressed market conditions, reactor licensing problems, and other uncertainties. A third upsurge in drilling activity began in 1974. Figure 1 shows that there is a close relation between exploration effort and uranium discovery, as expected. We also see that, qualitatively, the finding rates have fallen off markedly from the 1950's to the 1970's.

As has been noted, the history of exploration and discovery has been subject to the vagaries of economic and political conditions. Variations in discoveries due to these causes can be removed from finding rates, and the underlying pattern discerned, if discoveries are plotted as a function of cumulative footage drilled, rather than as a function of time. Economic and political conditions act to determine the exploratory footage drilled in a given year, but have little influence on the discoveries found per foot drilled. As Hubbert has stated in connection with petroleum exploration (8):

> . . . the officials of a large oil company may authorize its staff to double the amount of exploration drilling in any given year and consequently to increase discoveries per year; no oil company management, however, can successfully order its staff to double the quantity of oil to be found per foot of exploratory drilling.

To construct the graph of discovery rate R as a function of cumulative footage drilled, we divide the total footage drilled into intervals of between 10,000 and 20,000 feet (1 foot = 0.3 meter) each. For each interval, we calculate the total discoveries made as a result of that interval of drilling.

It can be seen from Fig. 1 that there is a time lag of about 1 year between the resurgence of drilling effort and the increase in discoveries. This lag is a measure of the time required to gather and evaluate the drilling data and report the results. Since the statistics are reported only on a yearly basis, it seems reasonable to choose a 1-year time lag. The assumptions of either a zero or a 2-year lag seem untenable. We therefore associate with a given time interval of drilling the discoveries made within an equal time interval, but with a 1-year time lag. The 11 intervals chosen, along with the cumulative footage drilled, the discoveries, and the discovery rate are given in Table 1 (9). It can be seen that the discovery rate has fallen off dramatically from its high of 18.6 pounds per foot during the second 10 million feet of drilling to the present low of about 2.4 pounds per foot and 140.5 million feet of drilling.

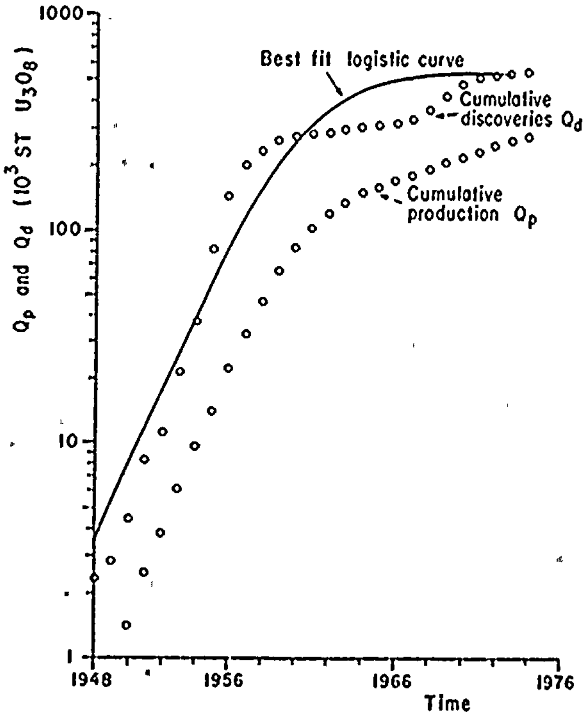
In Fig. 2, the discovery rate R is plotted against the cumulative footage h drilled, using a logarithmic scale for R and a linear scale for h. The 11 drilling intervals are shown as circles in the figure. The circled points fall approximately along a straight line, indicating that the rate of discovery has decreased exponentially with cumulative footage drilled.

For comparison, the discovery rate was calculated for the same 11 drilling intervals, on the assumption that there was no time lag in the reporting of discoveries. The results are plotted (Fig. 2) as

Table 3. Estimates of the ratio $r(c/8)$ of U_3O_8 available at $c or less per pound to that available at $8 or less per pound. Values shown are calculated from discovered resources (production and reserves), while those in parentheses are calculated for undiscovered resources.

Year	r(10/8)	r(15/8)	r(30/8)
1967	1.13 (1.43)	1.31 (2.33)	(4.08)
1969	1.11 (1.56)	1.28 (2.49)	(4.16)
1970	1.12 (1.39)	1.31 (2.12)	(3.27)
1971	1.12 (1.41)	1.49 (2.17)	(3.48)
1972	1.12 (1.56)	1.48 (2.22)	(3.56)
1973	1.12 (1.56)	1.46 (2.22)	1.60 (3.56)
1974	1.24 (1.81)	1.47 (2.89)	1.85 (5.45)
1974*	1.10 (1.80)	1.44 (2.87)	1.76 (5.48)

*See (6).



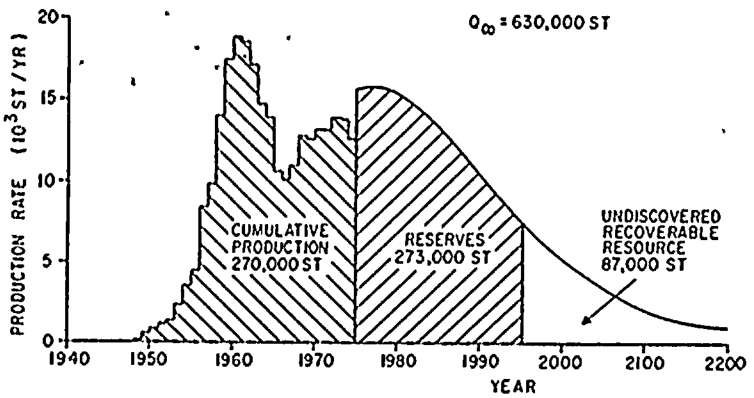


Fig. 4 (left). Cumulative production Q_p and cumulative discoveries Q_d as a function of time in years. Fig. 5 (right). Actual production rate and a possible cycle of production for U_3O_8 at $8 or less per pound.

Table 4. Estimates for U_3O_8 resources, obtained with a prudent ratio of $r(c/8)$ and the value Q_∞ = 630,000 short tons, as described in the text.

Forward cost category ($ per pound)	Q_∞ (10^3 short tons)
< 8	630
< 10	756
< 15	945
< 30	1134

dots; the dots are scattered much more than the circles, although the decline in discovery rate is still apparent.

For the circled points, the rate of discovery may be written:

$$R(h) = R_0 e^{-\beta h} \quad (1)$$

where β is a constant. The quantity of U_3O_8 discovered by the drilling of the cumulative footage h_0 is given by

$$Q_0 = \int_0^{h_0} R_0 e^{-\beta h} \quad (2)$$
$$= R_0 \beta^{-1} (1 - e^{-\beta h_0})$$

The ultimate recoverable resource is given by

$$Q_\infty = R_0/\beta \quad (3)$$

The procedure for estimating Q_∞ is to fit the exponential curve (Eq. 1) to the circled data points in Fig. 2 and to determine the "best fit" values of the parameters R_0 and β. Inserting these values into Eq. 3 yields the estimate for Q_∞.

Putting $y = \ln R$ and $y_0 = \ln R_0$, Eq. 1 becomes

$$y(h) = y_0 - \beta h \quad (4)$$

For the circled data points, we let $y_i = \ln R_i$, where i is the interval. We then choose y_0 and β to minimize the mean square error

$$E = \sum_{i=1}^{11} [x(t_i) - x_i]^2 \quad (5)$$

between the theoretical curve $y(h_i)$ and the data points y_i, subject to the condition that Q_0 = 543,000 short tons at h_0 = 140.5 million feet. This ensures that the curve correctly predicts the cumulative discoveries as of 1974. The result is R_0 = 17.75 pounds per foot, $\beta = 1.41 \times 10^{-8}$ per foot, and Q_∞ = 630,000 short tons. We therefore have the following amounts (short tons):

Cumulative production through 1974	270,000
Reserves	273,000
Remaining undiscovered resource	87,000
Total recoverable resource Q_∞	630,000

The drilling statistics indicate that very little resource (87,000 short tons) remains to be discovered in the $8 or less per pound cost category. Figure 3 shows a plot of the actual discovery rate as a function of cumulative footage on linear scales, along with the analytic curve.

Cumulative Production and Discoveries

On general principles, we expect the production (p) and discovery (d) rate curves (where t is time) dQ_p/dt and dQ_d/dt to rise exponentially, display one or more maxima, and then fall to zero when the resource is exhausted. Cumulative production Q_p and cumulative discoveries Q_d should be roughly S-shaped growth curves which rise exponentially from zero and asymptotically approach a common final value Q_∞.

The procedure for determining Q_∞ from the data on cumulative production and cumulative discoveries versus time is as follows. A growth curve known as the logistic curve, which has the required S shape, is used to fit the data for Q_p and Q_d. This curve is given by

$$Q(t) = \frac{Q_\infty}{1 + ae^{-b(t-t_0)}} \quad (6)$$

where t_0 is an arbitrary time; and a, b, and Q_∞ are constants to be determined so that the curve best fits the data.

It was pointed out that the yearly production and discovery rates are strongly influenced by economic and political conditions. This has been especially true of the domestic uranium industry, which has gone through several cycles of "boom and bust." Therefore, the production and discovery rates cannot be expected to display the classic bell shape that is obtained from the logistic curve. The effects of economic and political conditions are considerably smoothed when the data on cumulative production and discovery are considered. It is therefore of interest to determine Q_∞ by fitting a logistic curve to the cumulative production and discovery data. The values of Q_∞ as so determined are subject to considerable uncertainty and are intended primarily to verify the estimates derived from drilling statistics.

The data on cumulative production and discoveries are plotted on a logarithmic scale in Fig. 4. The procedure adopted was to put $x(t) = \ln Q(t)$ for the logistic curve (Eq. 6); to put $x_i = \ln Q_{pi}$ or $x_i = \ln Q_{di}$ for the data points, and to determine Q_∞, a, and b so as to minimize the mean square error

$$E_{p,d} \sum_i [x(t_i) - x_i]^2 \quad (7)$$

Table 5. Estimates for uranium resources, obtained by using large $r(c/8)$ ratios for the 87,000 short tons at $8 per pound not yet discovered and smaller ratios for the 543,000 short tons at $8 per pound already discovered, as described in the text.

Forward cost category ($ per pound)	Q_∞ (10^3 short tons)
< 8	630
< 10	808
< 15	1067
< 30	1456

With a value of t_0 = 1948, the results for the cumulative discovery data were a = 220, b = 0.41 year^{-1}, and Q_∞ = 534,000 short tons. For the cumulative production data, the results were a = 20,000, b = 0.73 year^{-1}, and Q_∞ = 550,000 short tons.

In both cases the fit of the data to the logistic curve was not especially good, and equally satisfactory fits could be obtained over a range of values of Q_∞. The fit to the discovery data is shown in Fig. 4. The above results are therefore not conclusive, but do indicate that values of Q_∞ in the range of 500,000 to 800,000 short tons of U_3O_8 are consistent with the cumulative production and reserve data.

If we assume that Q_∞ = 630,000 short tons is the best estimate, choose a reasonable peak production rate of about 16,000 short tons per year, and require $Q(1974)$ = 270,000 short tons, then one possible cycle of production is that shown in Fig. 5, along with the actual production data. The early distortion of the defense buying program should be noted. The shortfall between the predicted production rates and the uranium actually consumed will have to come from the higher cost categories of U_3O_8 resource.

Higher Cost Categories of U_3O_8

From the data on production, reserves, and potential (undiscovered) resources (2), it is possible to derive estimates for the ultimate recoverable resource Q_∞ in the higher cost categories. The cost categories analyzed are forward costs of $8, $10, $15, and $30 per pound of U_3O_8.

There is a rough correspondence between the forward cost category and the average grade of the ore, although smaller ore bodies must have higher than average grade in order to qualify for a given cost category. The relation between forward cost and average grade is given in Table 2 (2).

From published data (2, 6), the ratio (where c is cost) $r(c/8)$ of U_3O_8 available at \$$c$ or less per pound to that available at \$8 or less per pound has been calculated for each year since 1967 that such estimates have been made. This ratio is shown separately for the discovered resources (the sum of production plus reserves) and the undiscovered resources in Table 3. The ratio for undiscovered resources is given in parentheses in the table. For estimates based on discovered resources, the ratios $r(c/8)$ are fairly constant from year to year. Presumably, these ratios are determined from actual physical samples of ore bodies that have been mapped or produced.

From the published estimates on undiscovered resources, the ratios $r(c/8)$ shown in parentheses in Table 3 have been calculated. The estimates are uniformly higher than those derived from resources already discovered. It is difficult to understand why the ratios for undiscovered ore bodies should be so much higher than for already discovered ore bodies. Since the method by which the estimates of undiscovered resources has been derived has been entirely speculative, there is no way of refuting these estimates. However, a prudent approach to estimation suggests that the ratio $r(c/8)$ for undiscovered resources should be the same as for discovered resources, unless there is some objective means of showing that this is not the case. Therefore, the ratios used in estimating Q_∞ will be $r(10/8) = 1.2$; $r(15/8) = 1.5$; and $r(30/8) = 1.8$. From these ratios and the value of $Q_\infty = 630{,}000$ short tons as derived

Table 6. Year of exhaustion of U_3O_8 for the various cost categories, assuming plutonium recycling.

Forward cost category (\$ per pound)	Q_∞ (10^3 short tons)	Year of exhaustion
< 8	630	1986
< 10	756	1988
< 15	945	1990
< 30	1134	1992

above, we obtain estimates for Q_∞ as shown in Table 4. Conversely, if the very large ratios $r(10/8) = 1.8$, $r(15/8) = 2.9$, and $r(30/8) = 5.5$ are used to extrapolate from the 87,000 short tons at \$8 per pound which remains to be discovered, while the smaller ratios are used to extrapolate from the 543,000 short tons at \$8 per pound which has already been discovered, then the estimates shown in Table 5 are obtained. The use of the high ratios does not make very much difference, since very little resource at \$8 per pound remains to be discovered.

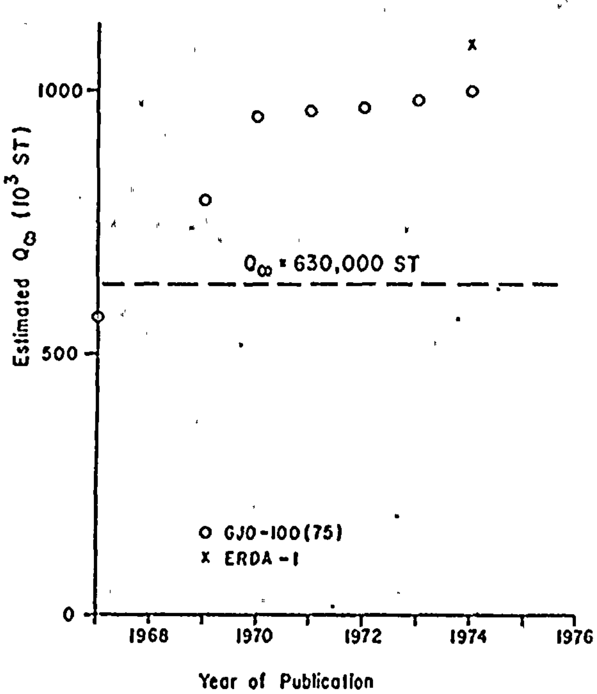
Comparison with Published Estimates

The preceding estimates may be compared with values of Q_∞ derived from the production, reserve, and potential resource data of (2, 6). The year-by-year estimates of Q_∞ for \$8 or less per pound of U_3O_8 are plotted in Fig. 6. There has been a sizable increase in the estimated values of Q_∞ over the last 5 years. The discrepancy is even larger when cumulative production and reserves are subtracted out and only the remaining undiscovered resource is considered. The estimate of 457,000 short tons in 1974 is higher by a factor of 5 than the estimate of 87,000 short tons derived here. An estimate in (6), plotted as the x in Fig. 6, gives a grand total for Q_∞ of 1,090,000 short tons.

The latest ERDA estimates for the remaining recoverable resource up to a forward cost category of \$30 or less per pound are given in (6). To the grand total of 3,450,000 short tons must be added the cumulative production of 270,000 short tons for a value of $Q_\infty = 3{,}720{,}000$ short tons. This is a factor of about 3.3 times larger than the estimated value obtained here, $Q_\infty = 1{,}134{,}000$ short tons. This very large discrepancy is a result of estimates of undiscovered resources which are not based on any objective procedures that I can discern (10). It is important that this discrepancy should be resolved by an exposure of the methods used to derive such subjective estimates, as well as by a critique of the methods used here, in order that a prudent estimate of U_3O_8 resources can be made.

Conclusion and Recommendations

The impact of my estimate of Q_∞, which is one-third of the ERDA estimate, is now considered. It will be shown that, if the expansion of nuclear electric power proceeds as planned, a serious shortfall in uranium supply will develop during the late 1980's.



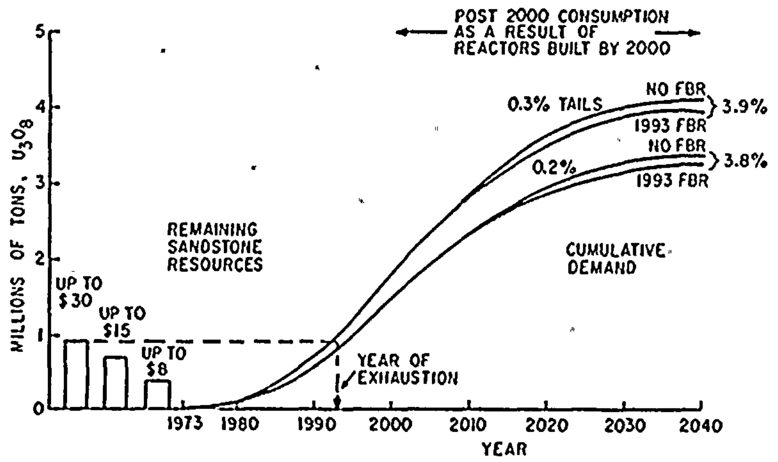


Fig. 6 (left). Published estimates of Q_∞ for \$8 per pound of U_3O_8. Fig. 7 (right). United States cumulative demand for U_3O_8 [case A in (17)]. Construction of light water reactors and high-temperature gas-cooled reactors (15 percent) ceases in year 2000. Plutonium is recycled. Resource costs are forward costs only, not prices.

ERDA, on the basis of its own estimate of Q_∞ and its projection for the growth of nuclear power, has long recognized that a serious shortfall in uranium supply will develop toward the end of the century. In response, it has established the National Uranium Resource Evaluation Program to assess all geologic environments in the United States for potential resources of uranium. It has also decided to lift the embargo on foreign uranium imports and has pressed for vigorous development of the liquid metal fast breeder reactor. However, the development of a uranium supply shortage in the late 1980's poses a serious question for the continuous and orderly expansion of nuclear power during the next 15 years.

It is not within the scope of this article to develop a projection of U.S. U_3O_8 requirements in the near future. Figure 7, reproduced directly from (6), shows the most recent ERDA projection of U_3O_8 requirements if nuclear power follows a pattern of low growth. Assuming plutonium recycling and an 0.25 percent uranium enrichment tails assay, the year of exhaustion of the U_3O_8 resource for the various forward cost categories, using the estimate for Q_∞, is shown in Table 6. If plutonium is not recycled, then cumulative U_3O_8 requirements are about 25 percent higher, and the year of exhaustion will occur about 1½ to 2 years earlier than given in Table 6. If the high growth pattern from (6) is used, then the year of exhaustion will occur 2 years earlier. If the above projections and resource estimates are correct, then a severe restriction of U_3O_8 supply will develop in the late 1980's. To prevent this from happening, at least one of the following courses of action must be pursued:

1) Severely limit the growth of nuclear power to rates far below the "low growth pattern" shown in Fig. 7.

2) Undertake an extensive and successful program of exploration for uranium resources in the intermediate grade range from 500 to 100 ppm of U_3O_8 by weight. Such resources exist in other countries but have not yet been discovered in the United States.

3) Develop the production of the large western lignite deposits (~ 25 ppm of U_3O_8) for use in coal-burning and electric power plants, and develop the means for recovery of uranium from the ash (~ 250 ppm of U_3O_8). A recent study (11) has concluded that the forward cost for production of U_3O_8 from this ash will be $25 to $45 per pound of U_3O_8, and that the ash of a 1600-megawatt (electric) coal-burning plant will supply the uranium requirement of a 1000-megawatt (electric) light water reactor.

4) Develop the means to obtain the uranium requirements from the extensive Chattanooga shale deposits (60 to 80 ppm). An updated study suggests forward costs in the range of $125 to $225 per pound of U_3O_8 (12). It should be pointed out, however, that for use in light water reactors, the energy content of a ton of shale is roughly equal to that in a ton of coal, implying a very extensive mining operation.

5) Undertake a research and development program to obtain uranium from seawater. Cost estimates currently range from $50 to $1000 per pound of U_3O_8 (13).

6) Import the necessary uranium from foreign sources. To this end, the ERDA has already decided that the embargo on foreign uranium imports should be gradually lifted (14). However, large quantities of foreign uranium have already been spoken for by foreign customers, and there may very well not be much left for the U.S. market in the late 1980's.

It should be pointed out that the lead time between proving (after discovery) a uranium ore body and the forward delivery date of the uranium is roughly 8 years. The lead time for putting a nuclear power plant on-line is currently in excess of 10 years. Therefore, decisions on a course of action must be made within the next 5 years.

It is clear that on the time scale discussed, the planned introduction of the breeder reactor can play no role (15). This can be seen from Fig. 7. Even a "crash program" to develop the breeder will be unable to forestall the coming supply and demand uranium squeeze; it is far too late. [Whether the breeder will ever compete economically with light water reactors is another question which is not addressed here and is still unresolved. The breeder will have a higher capital cost than a light water reactor, but negligible fuel cost. For a given light water reactor fuel cost, breeders will be unable to compete if their excess capital cost is too high (16).]

If any significant growth in U.S. nuclear power is to be sustained over the next few decades, then either a marked increase in the rate of discovery of new, high-grade reserves must occur, contrary to past trends in exploration statistics, or the development of low-grade ores (lignites, shales, phosphates, or seawater) must be undertaken immediately and vigorously. The alternative is dependence on foreign sources of supply which may be uncertain both politically and as to the quantities actually available. If the uranium supply does not materialize, then nuclear electric power will saturate at levels far below those now projected for the next few decades.

References and Notes

1. A high-grade ore is considered to have a uranium content exceeding 500 ppm of U_3O_8 by weight.
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8. ———, *U.S. Energy Resources, a Review as of 1972*, Ser. No. 93-40 (92-25) (U.S. Senate Committee on Interior and Insular Affairs, Government Printing Office, Washington, D.C., 1974), part 1.
9. The data for discoveries reported in early GJO-100 documents are sometimes revised in later documents. In all cases the revisions are minor and do not affect the analysis presented here.
10. The ERDA estimates for remaining uranium resources are provided in a two-dimensional form in which forward cost categories of $8, $8 to $10, $10 to $15, and $15 to $30 per pound of U_3O_8 are given along a vertical axis, and categories of "identified, probable, possible, and speculative" are given along a horizontal axis. An estimate is provided for each pair of vertical and horizontal categories, yielding 16 separate estimates whose total is 3,450,000 short tons of U_3O_8. For this classification scheme, it is practically mandatory that these 16 numerical values be provided, although of necessity many are based on considerable speculation. The way this procedure may tend to produce large overestimates is described extensively in (8, pp. 170–180).
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