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URANIUM AVAILABILITY AND THE BREEDER DECISION

by

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Abstract

The high priority assigned by the Federal government to the early development and commercial deployment of the Liquid Metal Fast Breeder Reactor (LMFBR) is attributed by some to the supposition that, without the breeder, a supply-price squeeze on uranium will soon materialize. The present paper examines this supposition by considering the technology and economics of uranium utilization in nonbreeder reactors, in the context of available information about uranium resources at various prices and projections of the growth of nuclear power through 2020. Reactor characteristics, cost sensitivities, and estimates of uranium resources used here are based largely on publications of the U.S. Atomic Energy Commission. The results show that existing reactor technologies -- light-water reactors (LWRs), high temperature gas reactors (HTGRs), or a mix of these -- could meet even the most enthusiastic projections of the expansion of nuclear generation through 2020 from presently known domestic uranium supplies, exploitable at $50 per pound of U_3O_8 or less. The increment in electricity costs that arises from increasing uranium prices in the absence of commercial breeder reactors is about 1 mill/kwhe in 2000 and about 2 mills/kwhe in 2020 in the worst case (very high growth, no HTGRs), and signficantly less in more plausible cases. In the prospective of the probable costs of the alternatives, these increments are modest; for example, the breeder's greater insensitivity to the cost of uranium ore could easily be cancelled out if capital costs for the LMFBR prove higher than early estimates.

Briefer attention is given here to potential difficulties with rapid expansion of uranium mining operations, with enrichment capacity, and with environmental impact of mining low grade ores. Timely action in the first two areas would be required to meet high growth projections, but no fundamental obstacles are apparent. The environmental issue needs more study, but on present evidence does not constitute a persuasive case for an early commitment to the LMFBR. It is concluded that the urgency often ascribed to early deployment of LMFBRs on grounds of uranium availability is, in fact, illusory.

Introduction

The program to develop and deploy liquid-metal fast breeder reactors (LMFBRs) for the commercial generation of electricity evidently is regarded by policy makers as the most urgent and deserving target of Federal spending on energy research and development. Of $772 million originally requested by the President for research and development related to energy technology in FY 1974, $323 million was earmarked for the LMFBR.[1] The LMFBR absorbed $272 million from a total of $642 million appropriated for Federal energy R&D in FY 1973, and $237 million from a total of $537 million in FY 1972.[1,2] It remains the largest single item in the $11 billion energy R&D budget proposed for fiscal years 1975-79, although its fractional share has dropped to about 25 percent of the total.[3]

Critics of the LMFBR have raised a number of major objections to the program. It has been asserted that the cost-benefit analysis perfomed by the U.S. Atomic Energy Commission (AEC) to justify the program was biased;[4] that the LMFBR is likely to be less safe against catastrophic accidents than existing water-cooled and gas-cooled reactors;[4,5] that protecting the large amounts of plutonium produced by LMFBRs against inadvertent dispersal or clandestine diversion for use as a nuclear explosive may prove too difficult to accomplish reliably;[6] and that some of the funds being devoted to LMFBR development would better be spent elsewhere -- for example, on the unresolved generic problems of fission reactors (such as management of radioactive wastes and fissionable materials), on the safety of the water-cooled reactors already being deployed, on alternative forms of breeder reactors, or on technologies that promise to be environmentally more benign than fission.

Some of these assertions are arguable, of course, and may or may not ultimately prove to be true. In any case, however, the points raised by the critics of the LMFBR are too substantial to be dismissed casually. In the face of the genuine uncertainties and substantial differences of competent opinion regarding the LMFBR, and in view of the considerable economic and environmental stakes, it seems prudent to ask whether the crash program to develop and deploy this technology is warranted. To question the urgency of the LMFBR program, of course, is not necessarily to dispute that the nation may eventually need the LMFBR, or to oppose continued research on LMFBR technology; it is rather to ask whether the need for commercial LMFBRs in the power grid by the mid 1980's is really as pressing as the AEC has implied.[7]

Examination of the literature of this subject leaves little doubt that the principal rationale for an early commitment to the LMFBR has been the prospect of a supply-price squeeze on uranium. More specifically, the AEC hypothesis is that the forecasted rapid growth of nuclear power would, in the absence of some form of breeder reactor, deplete the domestic supplies of low-cost uranium in the space of the next few decades. Thereafter, it is implied, the cost of electricity generated in water-cooled or gas-cooled non-breeder reactors would become prohibitive (or at least noncompetitive with fossil fuels), owing to rapidly climbing uranium prices as the industry resorted to the remaining poorer quality ores. Breeder reactors, the economy of which is very insensitive to the cost of raw uranium, can avert this premature demise of nuclear fission as a major energy source. The LMFBR, now the furthest along technologically of the various approaches to breeding, is the method of choice.

Although some observers may argue that the foregoing is an oversimplified view of the rationale for early deployment of LMFBRs, the testimony of those closest to the program indicates otherwise. A recent article coauthored by the deputy director of the Oak Ridge National Laboratory and by the manager of Oak Ridge's LMFBR program states:

> As we shall see, however, fission as now carried out in commercial nuclear reactors, which are all of a type known as converters, would soon use up the available nuclear fuel resources. Only if breeder reactors are perfected can we expect to utilize the essentially inexhaustible supply of energy that exists in reasonably assured, economical quantities.[8]

Further on in the same article, one finds:

> Note that, in a power economy based strictly on light water reactors (LWRs), for which CR (converstion ratio) is about 0.6, exorbitantly high-cost ore would be needed shortly after the turn of the century, and the situation would continue to worsen with no relief in sight. High-temperature gas-cooled reactors (HTGRs) for which CR is about 0.8, would give a slightly improved but essentially similar result.[9]

The situation is described even more bluntly by the manager of the LMFBR program at Westinghouse, the primary contractor for the LMFBR demonstration plant to be installed in the Tennessee Valley Authority grid. After noting that LMFBRs will present prospective utility buyers with uncertainties regarding reliability and licensability compared to more proven reactor designs, he and his coauthor wrote:

> No utility executive will therefore be willing to take licensing risks on the LMFBR unless he is confronted with a squeeze on fuel resources.[10]

It is the objective of this paper to examine the time scale and dimensions with which such a squeeze in uranium resources actually is likely to materialize, and, accordingly, to assess the validity of the hypothesis that the uranium situation justifies an early commitment to deployment of LMFBRs. No position is taken here on other aspects of LMFBR technology, safety, or environmental impact -- which certainly bear on the <u>ultimate</u> necessity or desirability of this technology -- except to note that only a strong conclusion in favor of impending serious uranium shortage would seem to justify a crash program toward LMFBR deployment in the face of existing unanswered questions about these other aspects.

The analysis begins with a brief summary of the physics, technology and economics of uranium utilization in light water reactors, high-temperature gas-cooled reactors, and LMFBRs. (LWRs completely dominate today's commercial reactor market in the U.S., and only HTGRs threaten seriously to intrude upon that dominance prior to the advent of breeder reactors.[11] There is no need, in the context of the issue being examined here, to complicate the discussion by including reactor types other than LWRs, HTGRs, and LMFBRs.) AEC estimates of uranium availability as a function of price are then reviewed, along with various forecasts of the growth of nuclear generation of electricity. These results are combined with AEC figures for the effect of uranium cost on the costs of electricity generated in LWRs and HTGRs, to determine the impact on uranium supply and electricity costs of achieving the forecasted levels of generation without the LMFBR or other forms of breeder. The issues of enrichment capacity and of environmental impact of mining low-grade uranium ores, which are associated with the prospect of expanded use of unclear energy in the absence of breeder reactors, are also briefly addressed.

Some Elements of Reactor Technology

Fissile isotopes are those that are capable of a self-sustaining fission chain reaction: the important ones are uranium-235, uranium-233, and plutonium-239. All fission reactors require one or more of these three as fuel. Only uranium-235 occurs naturally in significant quantities,[12] comprising 0.7 percent of natural uranium. Uranium-233 and plutonium-239 can be produced by bombarding the fertile isotopes, thorium-232 and uranium-238, with neutrons.[13] These fertile isotopes are much more abundant in nature than is uranium-235: uranium-238 comprises 99.3 percent of natural uranium, and natural thorium, which is about three times as abundant in the earth's crust as uranium, is virtually all thorium-232. The energy yield from the fissioning of any of the fissile isotopes can for practical purposes be considered to be 195 MeV per fission,[14] or about 22,000 kilowatt-hours-thermal (kwht) per gram of material fissioned.

Since the splitting of the fissile isotopes produces between 2.5 and 2.9 neutrons per fission, and since in principle only one neutron per fission is needed to maintain the chain reaction, it is possible to use some of the excess neutrons in a reactor to produce new fissile nuclei from fertile ones. In practice, not all of the neutrons can be used productively: some escape from the reactor core; some are absorbed by the fuel nonproductively (without inducing fission or transformation of fertile material); others are absorbed by the control rods, the moderator, fission products, and structural materials in the core. The number of fertile-fissile transformations actually occurring per fissile nucleus consumed is called the <u>conversion ratio</u>.

In the light water reactors that dominate U.S. commercial reactor technology at the present time, the conversion ratio is between 0.4 and 0.6. In these LWRs, the initial fissile material is U-235, the fertile material is U-238, and the fissile material produced is Pu-239. (Subsequent neutron absorptions by Pu-239 produce Pu-240, Pu-241, and Pu-242, of which only Pu-241 is fissile.) Some of the fissile plutonium created is consumed inevitably in the reactor, contributing to energy generation and supplying neutrons for further fertile-fissile conversions, or absorbing neutrons nonproductively; the remaining plutonium is recovered from the spent fuel at a fuel reprocessing plant. In an LWR, then, a conversion ratio of 0.5 means that for each two nuclei of uranium-235 or fissile plutonium destroyed, one new nucleus of fissile plutonium is produced.

Now it is easy to show that, in theory, a reactor with conversion ratio $\underline{r}<1$ can ultimately produce $1/1(1-\underline{r})$ fissile nuclei for each fissile nucleus initially supplied to it, assuming that all fissile material is continuously recycled and that there are no losses in the recycling process.[15] This result might seem to suggest that the energy theoretically extractable from natural uranium by a reactor with conversion ratio $\underline{r}$ is $1/1(1-\underline{r})$ times the energy obtainable from fissioning just the U-235 content (i.e., 7 grams U-235 per kg uranium). If this were true, one would expect ultimately to fission $7/(1-0.5) = 14$ g per kg of natural uranium supplied to a reactor with a conversion ratio of 0.5. In reality, reactors do not do this well, for three reasons. First, not all fissile nuclei produced are consumed in the reactor; there are unavoidable losses in the recycling process, amounting at present to about 2 percent of the fissile material per cycle.[16] Second, not all fissile nuclei consumed in the reactor are fissioned; nonproductive absorption of neutrons accounts for the consumption of about one U-235 nucleus in seven and one Pu-239 nucleus in four in a LWR.[17] Third, not all the U-235 in raw uranium reaches the reactor at all; in addition to small losses in fuel preparation (on the order to a percent of the U-235 content), there is a very substantial loss of U-235 associated with the use of enriched uranium as fuel.* In the case of present LWRs, which use fuel with U-235 content enriched to 2 to 3.3 percent, the loss of U-235 in the enrichment process is on the order of 20 percent of the original U-235 content of natural uranium.[18]

Compensating for a small part of the losses of fissile nuclei just described is the fission of U-238 by particularly energetic neutrons.[19] This process is incapable of sustaining a chain reaction on its own, but it can add about 5 percent to the energy release in a chain reaction based primarily on fissile U-235 and plutonium.

Detailed analyses by the AEC of the fuel cycles of LWRs of contemporary design, taking into account the full details of the processes and losses sketched only superficially here, reveal that the overall uranium utilization of such reactors should be between 9.7 and 12.4 grams fissioned per kg of uranium mined, assuming that the plutonium produced is recycled.[20] These results are based on an operating lifetime of 30 years with average load factors between 80 and 85 percent, and they correspond to conversion ratios in the range 0.53 - 0.55. A figure of 10 g fissioned per kg of uranium mined means, of course, an absolute uranium utilization efficiency of 1 percent, measured against the (theoretically unattainable) situation in which every uranium nucleus is ultimately fissioned. A fuel-cycle flow diagram for LWRs is shown in Figure 1.

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*Enrichment of the U-235 content of uranium above its natural value of 0.7 percent is necessary to make reactors moderated with ordinary water -- and unmoderated (fast neutron) reactors -- practical at all. Reactors moderated by heavy water or graphite can operate on natural uranium, but for a variety of reasons may also be designed for enriched fuel.

It should be noted that, historically, the plutonium produced in LWRs in the United States has not been recycled. Instead it has been purchased by the government for use in nuclear weapons or stockpiled for eventual use in the initial inventories of breeder reactors. The latter course has been motivated by the ready availability of enough enriched uranium at low cost to meet the needs of LWRs up to the present time, and by the fact that Pu-239 is somewhat superior to U-235 as LMFBR fuel and slightly inferior to it as LWR fuel. There is, however, no significant technical obstacle to the recycling of plutonium in LWRs, and this is now being done in the Big Rock (Michigan) commercial LWR.[21] In comparing the long-term impact of alternative reactor technologies on uranium supplies, therefore, there is every reason to credit the LWR with its ability to recycle plutonium. (To fail to do so would be illogical, but it will be noticed that the associated change in computed uranium utilization in LWRs -- from about 10 g fissioned per kg of uranium with recycling to about 7 g per kg without it -- would not substantially change the outcome of this study.)

The high-temperature gas-cooled reactor of U.S. design differs from the LWR in its uranium utilization properties in two principal respects: the HTGR's conversion ratio of about 0.8 is substantially higher, and the fertile-fissile conversion employed is Th-232 to U-233 instead of U-238 to Pu-239. The initial fuel loading consists of fully enriched uranium (93.8 percent U-235) plus natural thorium, and in subsequent batches some of the U-235 is replaced by recycled U-233. (Note that if the initial uranium supplied were not fully enriched in U-235, the additional U-238 present would lead to unwanted plutonium production at the expense of that of U-233.)

It is the availability of U-235 rather than that of Th-232 that limits the fuel supply of the HTGR and, as shown below, governs its fuel cost by a large margin. Thus it makes sense to compute the fuel utilization of the HTGR in terms of total grams fissioned per kg of uranium mined, just as for the LWR, despite the fact that some of the material fissioning in the HTGR actually originated as thorium. On this basis, the AEC's computations for the actual uranium utilization of HTGRs with recycling of U-233 yield 14.2 to 18.8 grams fissioned per kg of uranium mined.[22] (Part of the advantage of the higher conversion ratio of the HTGR in comparison to the LWR is cancelled by a greater loss of U-235 occasioned by the higher degree of enrichment -- 28 percent of the initial U-235 content of the uranium remains in the "tails" of enrichment to 94 percent.) Figure 2 shows a flow diagram of the HTGR fuel cycle.

The definition of a breeder reactor is that the conversion ratio exceeds unity; when this is the case, the reactor produces more fissile material than it consumes. Once supplied with its initial fissile inventory, such a reactor thereafter need only be provided with fertile material. After a period called the doubling time (which depends on the conversion ratio, power level, and the size of the initial fissile inventory) a breeder reactor will have produced enough new fissile material to replace its own initial inventory and to provide such an inventory for a second, identical reactor. The liquid-metal cooled fast breeder reactor, which has been the most intensively explored of the various possible breeder technologies, uses either U-235 or plutonium as the initial fissile material and in operation breeds plutonium from U-238. According to the AEC, the conversion ratio for early commercial LMFBRs should be about 1.3, that of advanced ones about 1.5.[23] It is said that the ultimate uranium utilization of the LMFBR will be between 500 and 700 grams fissioned per kg of uranium mined.[24] (Since the LMFBR can even use the tails from the enrichment process as a source of fertile U-238, the only losses preventing 100 percent utilization are non-productive consumption of fissile nuclei in the reactor and the small percentage losses each time fissile material is recycled.) A fuel-cycle flow diagram for the LMFBR is shown in Figure 3.

A reactor of any kind contains a significant inventory of fissile fuel -- considerably greater, in fact, than one year's consumption. The cumulative demand for uranium at any given time therefore exceeds the cumulative consumption up to that time by the amount of the inventories in the existing reactors. The U_3O_8 requirement for the initial fuel inventory of a 1000 Mwe LWR is 300 to 600 metric tons, for an HTGR 400 to 500 metric tons, and for an LMFBR 500 to 900 metric tons.[25] (In a fission economy based on the LMFBR, of course, the U_3O_8 requirements for initial inventories would fall dramatically once bred plutonium became available to replace U-235 in new reactors.) Nominal values for inventories, fuel consumption, and related characteristics, as they will be used in the remainder of this paper, are summarized in Table 1.

Economics of Uranium Utilization

The cost of uranium is generally quoted in terms of dollars per pound of uranium oxide (U_3O_8), as purchased at the mill where this material has been separated from the raw ore. The figure most frequently seen in the literature is $8 per pound of U_3O_8 ($17.60 per kg), which during most of the 1960s was the price at which the AEC made its own uranium purchases. (In 1970 the AEC terminated its U_3O_8 purchasing program entirely.) In the late 1960s and early 1970s the average price of U_3O_8 at the mill in the private uranium market varied between $5.50 and $7.50 per pound.[26] These prices reflect both the cost of mining operations and the cost of extracting the U_3O_8 from the ore.

Beyond this point, the economics of nuclear fuel utilization becomes surprisingly complex, owing largely to the many steps in nuclear fuel cycles (see Figs. 1-3). The U_3O_8 is converted to UF_6, then separated in a gaseous diffusion plant into two streams, respectively enriched and depleted in terms of U-235 content; the enriched UF_6 stream is then converted to UO_2, which is fabricated into the fuel elements to be used in reactors. Following "burnup" in a reactor, the spent elements undergo chemical reprocessing to separate the remaining uranium and plutonium from the fission products. Then the uranium is reconverted to UF_6 and reenters an enrichment plant; the plutonium is stored, sold or recycled; and the fission products are committed to a waste repository. Analyses of the contribution of the costs of these various steps to the price of nuclear power generation vary in detail according to the assumptions used, but a rough average for LWRs is as follows:[27]

(a) 0.4 mills/kwhe for the purchase of U_3O_8, at $8/lb;

(b) 0.1 mill/kwhe for conversion to UF_6 and reconversion to UO_2, at about $2/kg;

(c) 0.5 mills/kwhe for enrichment, at $26 per kg of separative work;

(d) 0.4 mills/kwhe for fabrication at about $70 per kg U;

(e) 0.2 mills/kwhe for reprocessing and waste management (including shipping), at $45 kg of U;

(f) 0.5 mills/kwhe for carrying charges on the fuel inventory, at about 10 percent per year cost of money and 3-year fuel residence time;

(g) -0.2 mills/kwhe (credit) for plutonium, usually assumed in calculations of this sort to be sold at $8-$10/g rather than recycled. If the plutonium is recycled, one can reckon roughly that purchase of U_3O_8 contributes 0.3 mills/kwhe instead of 0.4, enrichment cost and carrying charges drop by a similar percentage, and fabrication cost increases a few hundredths of a mill per kwhe.

These figures assume a plant load factor of 80 percent and a thermal-to-electrical conversion efficiency of 32.5 percent.

If we consider the case with plutonium recycling, and ascribe to the U_3O_8 that fraction of the carrying charges corresponding to the contribution of U_3O_8 to the value of the finished fuel, we find that the cost of U_3O_8 at $8/lb contributes directly and indirectly about 0.4 mills/kwhe to the price of nuclear fuel. This is between a fifth and a fourth of the total fuel cost of 1.8 or 1.9 mills/kwhe, which compares in turn to a total nuclear generation cost of 7 to 8 mills/kwhe in contemporary LWRs.

The foregoing rough figures suggest that the sensitivity of electricity costs to uranium costs, for LWRs recycling their plutonium, amounts to about .05 mill/kwhe per dollar increase in the price of U_3O_8 per pound (above the base price of $8). More sophisticated fuel-cycle analyses performed by the AEC for various approaches to recycling plutonium in LWRs yielded sensitivities between 0.03 and 0.06 mill/kwhe per dollar increase in the price of U_3O_8 per pound.[28] The same AEC study indicated a sensitivity of 0.019 mills/kwhe per dollar increase in the price of U_3O_8, for the case of an HTGR with full recycle of U-233.

The economics of thorium utilization in HTGRs is, by comparison, straightforward. AEC materials balances indicate that a 1000 Mwe HTGR with thermal efficiency of 40 to 43 percent and load factor of 85 percent requires the mining of 11 to 12 metric tons of thorium per year, which is 12.5 to 13.5 tons of ThO_2. At the current market price of $7/lb for ThO_2[31] one finds that thorium's contribution to the price of electricity would be between 0.03 and 0.04 mills/kwhe, depending on interest charges. The corresponding sensitivity to increases in the price of thorium is 0.004 to 0.005 mills/kwhe per dollar increase in the price of ThO_2 above $7/lb.

Uranium Supply versus Price

The mean abundance of uranium in the earth's crust is about 4 parts per million (ppm). It is found in a wide variety of geologic formations in more than 100 different chemical forms. The principal deposits now being mined in the United States are the sedimentary rocks of the Colorado Plateau, which includes parts of Utah, Arizona and New Mexico, as well as of Colorado. Both open-pit and underground mining are practiced. The concentration of uranium in these ores is between 0.1 and 0.3 percent (1000 to 3000 ppm). Large quantities of uranium are also known to exist in western lignites (100-2000 ppm, and as much as 5000 ppm in the ash resulting from burning these coals), in phosphate beds underlying parts of Utah, Idaho, Wyoming and Montana (120 ppm), in the Chattanooga shales of Tennessee, Kentucky and Alabama (around 60 ppm), and in the 300 square-mile Conway granite outcropping of New Hampshire (12 ppm).[32]

Data on recoverable uranium resources in the U.S. are collected and published regularly by the AEC, based partly on its own investigations, partly on information provided by the uranium industry, and partly on the work of the U.S. Bureau of Mines. The AEC's figures for uranium producible at prices up to $100 per pound ($220/kg) of U_3O_8, estimated as of January 1, 1970,[33] are given in Table 2. The "reasonably assured" category of reserves refers to ore deposits that have been measured in extent and sampled with respect to quality. This definition corresponds roughly to that of "proved" reserves, as used in most minerals industries. The AEC's "estimated additional" category refers to uranium surmised to occur in unexplored extensions of known deposits or in undiscovered deposits in known uranium districts. This definition corresponds roughly to that of "potential" reserves in other minerals industries. The prices in the various categories reflect the prices per pound, in constant dollars, at which the AEC believes the respective amounts of U_3O_8 could actually be delivered. That is, these prices already account for the estimated cost of extracting the U_3O_8 from the ore of various grades. It is to be emphasized that the costs of the steps in the fuel cycle after the U_3O_8 leaves the uranium mill are independent of whether one has paid $5 or $100 for each pound of this material.

Since there has been little incentive to map and evaluate uranium resources in the greater than $30/lb categories in a period when the price of U_3O_8 has been below $8/lb and falling, it is to be expected that the estimates in these expensive categories are quite crude. At the same time there are good reasons to believe that the estimates in all the categories in Table 2 will prove to be very conservative. A uranium industry of any size has only existed in the U.S. since World War II, and during much of this relatively brief history a soft market has discouraged intensive exploration. A 1968 AEC document stated in this connection:[34]

> The outstanding fact is that what is known today about U.S. uranium resources is almost entirely a product of work that was done in the 1950s. With the renewal of uranium exploration activity it is anticipated that in this field, as in oil and other fields involving exploration activity, the more one searches the more one will find.

A more recent review of the situation contained the following observation:[35]

> Substantially all of the present proved reserves and approximately 85 percent of the potential reserves as determined by the AEC are located in the presently producing areas, yet these areas make up less than 10 percent of the total region in which uranium occurrences are found -- therefore, optimism is warranted regarding the ability of the uranium exploration industry to locate significant new domestic uranium resources, provided the necessary exploratory effort is mounted.

These optimistic views would appear to be supported by the historical record in most minerals industries, which in their early stages almost invariably have underestimated the ultimately recoverable resources by large factors. Further insight into the specific case of uranium is to be found in the recent history of additions to uranium reserves in the most solidly established category, reasonably assured reserves of U_3O_8 at less than $8/lb. Between January 1, 1969 and January 1, 1972, a period during which exploratory drilling for uranium was generally declining, these reserves increased by 60 percent.[36] The full figures are given in Table 3.

These considerations notwithstanding, the January 1970 figures for estimated uranium availability, given in Table 2, will be used in the remainder of this discussion. Although these figures almost certainly will prove to greatly underestimate the ultimately recoverable supplies of uranium, even in the least expensive categories, the point is that <u>no</u> special optimism about future discoveries is needed to reach the conclusion of adequate potential supply for the next fifty years.

Many of the same arguments apply in the case of thorium for use in HTGRs, except that the situation is even more clear-cut. There has been little demand for thorium to date, and hence very little exploration for it, but the estimated resources even on the basis of this scanty information are very large. The AEC's estimates[37] are given in Table 4.

Projected Uranium Requirements

Forecasting the scale of electricity generation over the next 30 to 50 years with any degree of confidence is impossible. The very high projections that have been widely published, based in general upon extrapolation of past growth rates in the range of 6 to 8 percent per year, seem on a variety of grounds unlikely to be achieved. Whether nuclear energy will or should play the increasing role its promoters have predicted for it, amounting to between 40 and 60 percent of all U.S. electricity generation in the year 2000, can also be questioned. Since the purpose of the present analysis, however, is to determine only whether fuel supply must constrain the growth of nuclear power in the absence of breeder reactors, I shall seek the answer to that question in the context of the more dramatic growth projections.

The projections used are shown in Table 5. The "medium" figures given there for total electricity are the base case used in the AEC's December 1970 report, "Potential Nuclear Growth Patterns."[38] They correspond to "medium" load forecasts by the Federal Power Commission, coupled with a very enthusiastic assessment of nuclear energy's contribution (more than 50 percent of all generation in 1990, and 60 percent in 2000). The "high" figures for nuclear generation in Table 5 are from the article on breeder reactors by Culler and Harms,[9] and appear to correspond to "high" FPC forecasts for total generation coupled with an equally enthusiastic assessment of the role of nuclear energy (62 percent in the year 2000). The figures for approximate cumulative nuclear generation since 1970 are obtained from the annual figures by integration with the trapezoidal rule.

Using the reactor characteristics summarized in Table 1, one can readily compute the cumulative uranium consumption implied by these cumulative nuclear-generation figures. Uranium requirements for inventories, which at any given time must be added to the cumulative consumption to obtain cumulative demand up to that time, can be obtained from the generation figures and the inventory requirement per reactor (given an assumption about average load factor, here taken to be 67 percent). Although more sophisticated analyses generally consider various time-dependent mixes of reactor types, the central question of uranium adequacy can be illuminated simply by examining the cases of LWRs only, HTGRs only, and a 50-50 mix of the two types. (Since the great bulk of the cumulative consumption takes place after 1990, for which period the choice of reactor mix is still largely open to us, these simple cases are not necessarily wholly unrealistic.) The cumulative uranium demand in these three cases, for the "medium" and "high" growth projections, is given in Table 6.

Can We Afford to Postpone the Breeder?

The numbers developed in the preceding sections permit one to estimate the time scale and magnitude of the uranium supply-price squeeze that has been so widely offered as the rationale for early deployment of breeder reactors. Figure 4 combines elements of Tables 2 and 6 to illustrate the main characteristics of the situation. One sees there that even under the "high" growth projection, with only LWRs available, the price of U_3O_8 is likely to be about \$15/lb in the year 2000, about \$30/lb in 2010, and in any case under \$50/lb in 2020 (all in 1967 dollars).

To reach a more pessimistic conclusion one must assume either that reserves classified in 1970 as "estimated" will in fact prove to be illusory or that for some combination of reasons the existing resources will not be made available in time to meet the need. The first assumption -- that presently "assured" reserves comprise the only uranium that will be found in the next 30 to 40 years -- is an unsound one for reasons already given above. The second assumption -- that uranium of known location will not be extracted in time to meet the needs of the nuclear industry -- could prove to be true, but such a situation need not be permitted to develop.

Restricting attention for the moment to the implications of the amount of uranium that exists, and deferring until later the separate issue of whether it will be made available in time, one finds that LWRs operating only on the presently assured reserves could sustain the "high" growth projection for the U.S. through 2018 without driving the price of U_3O_8 above $50/lb. Use of the cost sensitivities from Table 1 reveals the economic import of this result: in virtually the worst case imaginable (very high growth, no HTGRs, no "estimated" reserves materialize), the price of electricity need rise only 2 mills/kwhe by 2020 owing to rising uranium costs.

It may be useful to compare this figure with various costs associated with electricity in the U.S. in 1970: 2 mills/kwhe total nuclear fuel cost, 2-4 mills/kwhe for fuel in fossil-fueled plants, 6-9 mills/kwhe total generation costs, 17 mills/kwhe average price of electricity delivered to all consumers, 22 mills/kwhe average price of electricity delivered to residential consumers.[39] It is difficult to imagine, to say the least, that dire economic consequences would devolve from an increase in nuclear fuel costs, over the space of 50 years, amounting to 10 percent of the average delivered cost of electricity at the beginning of that period.

Under more realistic assumptions, of course, the increase in the cost of electricity owing to rising uranium costs is likely to be even smaller. Reliance on a 50-50 mix of LWRs and HTGRs, under the "high" growth projection, could keep the incremental contribution of rising uranium costs below 1 mill/kwhe through 2010 if "estimated" reserves at less than $30/lb materialize. In the same situation, reliance mainly on HTGRs could hold the increment to about 0.5 mill/kwhe in 2020. If "estimated" reserves under $15/lb materialize and are exploitable by the year 2000, the uranium-induced increment even without HTGRs should not exceed about 0.4 mills/kwhe in that year. These and other possibilities, which follow from Figure 4 and the cost sensitivities of Table 1, are summarized in Table 7.

It is useful to compare the probable uranium-induced cost increments with possible increments to the cost of electricity from other sources. A combination of environmental standards, diminishing quality of resources, and need for expensive new technologies to expand supplies seems likely to increase the price of fossil fuels by at least 50 percent between 1970 and 2000. Such an increase would produce an increment of 1 to 2 mills/kwhe in electricity costs. If breeder reactors should cost more to build than do LWRs or HTGRs, the effect on total electricity cost could more than offset the breeder's more economical use of uranium. For example, a difference of $100 per electrical kilowatt of capacity translates to 1.85 mills/kwhe if fixed charges (interest plus depreciation) on capital investment are 13 percent per year and the plant runs at an average load factor of 80 percent.[40] No one can say with any assurance that the LMFBR will not cost $100/kwe more than LWRs or HTGRs, and the extreme materials problems and long history of development difficulties with the breeder argue that it might. The broader economic justification for the LMFBR has been challenged in detail elsewhere,[3] and it is not my intention to do so here. What is important, in the framework of the present analysis, is that the possible increase in future electricity costs arising from the drain on uranium resources by nonbreeder reactors is matched or exceeded by the possible increase arising from higher than anticipated construction costs for the LMFBR.

Problems Beyond Absolute Supply

It has been argued above that known domestic uranium resources could sustain the most dramatic projected increases in U.S. nuclear generation, without breeder reactors and with very moderate increases in the cost of electricity, for at least 50 years. Of course, there is more to the issue of fuel supply than the amount of material in the ground. The main additional questions usually raised in connection with uranium are three. First, even if the resources are adequate in an absolute sense, can they be developed at a rate sufficient to keep pace with the projected growth of demand? Second, what are the costs in energy and dollars of uranium enrichment on the scale that would be necessitated by reliance on LWRs and HTGRs, and can enrichment capacity be expanded at a sufficient rate? Third, what are the environmental consequences of mining uranium on the expanded scale that would be necessitated by rapid growth of nuclear power without LMFBRs?

With respect to the rate of resource development, it is certainly true that time and money are required to convert "probable" resources into assured reserves and to bring new mines and uranium mills into operation. Although the economic factor is accounted for in the U_3O_8 figures used above, in the form of projected costs of exploration, extraction and milling, the uranium simply will not be made available in time unless advance planning is adequate and investment is timely. As a measure of the lead times required, it is often stated that assured reserves at any given time should be adequate for at least the next eight years of projected growth in the nuclear industry. According to this rule of thumb, for example, all the uranium needed through the year 2020 should have been brought into the reasonably assured reserves category by the year 2012. (If we are willing to pay $50 per pound of U_3O_8, Figure 4 indicates that requirements through the year 2018 were already in the assured category in 1970.) In no event do the problems of lead time and capital availability constitute an *ipso facto* argument for a commitment to breeder reactors; an equally direct approach, given a consensus that fission power should be greatly expanded, would be to take steps insuring that adequate planning and investment in the uranium industry take place.

The issue of uranium enrichment capacity for a growing number of LWRs and HTGRs also requires adequate advance planning and investment, but it need create no fundamental obstacles. The economic cost of the enrichment process itself is independent of what one has had to pay for raw U_3O_8. The

AEC's analyses of nuclear fuel-cycle costs have assumed that the figure will remain at about $26/kg of separative work indefinitely.[41] In our plutonium-recycling LWR this contributes about 0.36 mill/kwhe to the overall fuel-cycle cost of about 1.8 mills/kwhe.[42] A recent analysis performed outside the AEC estimated enrichment costs in future gaseous diffusion plants at $40-$43/kg of separative work, presumably reflecting higher estimates of construction costs, interest rates, and the cost of electric power consumed by the plants.[43]

Data given in the same study enable one to compute that the electricity consumed to produce enriched uranium in gaseous diffusion plants is about 4 percent of the amount of electricity generated when this enriched fuel is consumed in LWRs, without recycling of plutonium. With plutonium recycle, the figure would be about 3 percent. The corresponding ratio for HTGRs with U-233 recycle is about 2 percent. It appears that the technology of uranium enrichment by means of gas centrifuges, now under intensive development, will be capable of reducing the energy consumption of the enrichment process by a factor of 6 or 7.[43] Even without such advances, however, the future economic and energetic costs of uranium enrichment do not alter the basic conclusions of this study. In the worst case, that of LWRs supplied with enriched uranium by gaseous diffusion plants, the situation is energetically equivalent to a reduction in efficiency of uranium utilization (mass fissioned divided by mass mined) from 1.0 percent to 0.97 percent. If the average cost of enrichment should actually increase from $26 to $40 per kg of separative work, the corresponding increase in fuel-cycle cost would be about 0.2 mills/kwhe.

Naturally, a decision to promote a major expansion of nuclear generating capacity in the form of LWRs and HTGRs would imply the construction of new enrichment capacity beyond what exists today. The capital costs of such new capacity are accounted for in the enrichment cost figures given above. Although there is in principle no reason why enrichment capacity cannot be expanded quickly enough to keep pace with the demands of new reactors, there are in practice some problems of logistics and economics, arising from a combination of factors: there is much uncertainty in the demand curve, one must plan well ahead because construction time is considerable, gaseous diffusion plants are economical only in very large sizes, and a commitment to more enrichment capacity than is actually needed at any given time would be an expensive error.[43] Again, the solution may lie in large part with the gas centrifuge, which, because it will be economical in smaller sizes, will permit the growth of enrichment capacity to match the growth of needs more closely and with less financial risk.

With respect to the environmental effects of mining low-grade uranium ore, some insight can be obtained by comparison with coal mining. Consider average Chattanooga shale, which contains 0.006 percent U_3O_8 and comprises a substantial part of the assured uranium reserves between $30 and $50 per pound. One cubic meter of this material, used as the raw feed for a plutonium-recycling LWR, is equivalent in energy content to about 2.5 cubic meters of bituminous coal or 4 cubic meters of lignite.[44] These volumes give at least a crude measure of the relative scale of mining operations needed to make available a given quantity of energy.

A detailed comparison of mining conditions for coal and low-grade uranium, which would have to include depth of deposits, thickness and orientation of seams, and other factors, is not possible here. One may note, however, that the direct health hazards to underground miners of coal and of uranium are not altogether dissimilar in kind. In each case, air in the mines contains toxic substances -- principally coal dust on the one hand and radon gas on the other. Both problems can be greatly alleviated with proper ventilation, and low-grade uranium ores will produce lower radon concentrations than do the high-grade ores mined today. Cave-ins are a universal hazard, although better mining methods may reduce this risk in time also.

The most serious environmental effect of mining uranium on the surface is land disruption by the excavation and by spoil banks. The principal impact on water is associated with milling the uranium and thus, for a given grade of ore, is the same whether surface or underground mining was employed. Some measures of the impact of uranium surface mining, and of milling, under different circumstances are given in Table 8, with some coal figures for comparison. The figures shown in the first column are based on recent studies of contemporary surface mining of uranium,[45,46] scaled to the case of LWRs recycling plutonium. These numbers correspond to the average grade of ore (0.2 percent U_3O_8) now being mined in the U.S. The figures in the second column are based on a detailed study of uranium recovery from one of the richer parts (0.007 percent U_3O_8) of the Chattanooga shales.[46] The third and fourth columns in Table 8 give the corresponding figures for LMFBRs operating on the Chattanooga shales and for surface mining of Eastern coal.[47] The reason for the surprisingly small land area excavated in the case of the Chattanooga shales is the great thickness of the minable seam.

It appears from these rough comparisons that the environmental effects of mining the lowest grades of uranium ore for use in LWRs would be somewhat smaller than those of mining coal to generate the same amount of electricity, although still potentially serious. The problem certainly deserves more careful study.

For several reasons, however, the potential environmental impact of mining low-grade uranium ore -- as important as it is -- does not in itself constitute a compelling argument for an early commitment to the LMFBR. First, reliance on HTGRs could cut the figures in column 2 of Table 8 by more than half, and would probably postpone the need for exploiting such low-grade ores to beyond 2020. Second, an expanded program of exploration for uranium is likely to yield large additions to reserves in the rich (low environmental impact) categories, for reasons outlined above. Such additions would postpone the escalation of the environmental impact of uranium mining, even without reliance on HTGRs. Third, other environmental liabilities of the LMFBR may be judged by many observers to offset its advantage in fuel extraction, just as its potentially high capital cost may offset its economies in the fuel cycle. Finally, and perhaps most importantly, the possibility of extracting uranium from sea water may render the question of mining very low-grade terrestrial ores entirely academic. The oceans contain about 4.2 billion metric tons of uranium (3.34×10^{-6} g/l), and estimates of the cost of extracting it, made in the mid-1960s, ranged from \$11 to \$100 per pound of U_3O_8.[48] It is astonishing, in the face of the USAEC's expressed concerns about uranium supplies, that no significant program has been mounted to narrow this range of uncertainty. A demonstration of the ability to extract uranium from sea water efficiently and with low environmental impact[49] would be of enormous importance, even if the cost of the process proved to be \$50-\$100 per pound of U_3O_8.

Conclusion

The foregoing analysis indicates that rapid development and deployment of LMFBRs in the U.S. is not necessitated by any impending supply-price squeeze on uranium. Existing, nonbreeder reactor technologies could meet the most ambitious projected increases in nuclear generation of electricity for at least the next 50 years, with very moderate uranium-related increases in the price of electricity. Indeed, these potential price increases appear to be of the order of or smaller than the potential costs of fossil-fuel alternatives. Reaching this conclusion required no optimism about discovery of presently unsuspected uranium resources. It holds, in fact, even if no reserves presently classified as "estimated additional" ever materialize -- a premise so pessimistic as to be almost absurd. Moreover, since LMFBRs could use even the uranium resources at $100/lb economically, there is no danger that early reliance on nonbreeders would close the door on later implementation of breeders.

Such problems as may arise in the next 50 years with respect to adequacy of U.S. uranium supply will be due not to lack of resources in the ground but to possible failures to deploy new facilities for extraction and enrichment in time. This need not be permitted to occur, and measures to prevent it comprise a more certain and simpler approach to assuring adequate supply on this time scale than does the early deployment of LMFBRs. In a similar vein, little attention has been given as yet to the optimization of LWR and HTGR fuel cycles for the case of relatively expensive uranium ores. A rough calculation indicates that reducing the U-235 content of the tails from the enrichment process from 0.2 percent to 0.1 percent (a change that would pay only if U_3O_8 were more expensive) stretches uranium resources about 15 percent above the figures used in the present analysis; an increase in the conversion ratio of LWRs from 0.55 to 0.65 could increase the efficiency of utilization of uranium in these reactors by almost 30 percent.

In the interests of holding the future environmental cost of uranium extraction to a minimum, two straightforward courses of action can be recommended: a vigorous program of exploration for additional high-grade ores, both within and beyond the presently producing regions; and a program to clarify the technology and costs for extraction of uranium from sea water. These two steps would be cheap compared to the LMFBR program itself, and success in either one would extend the time period in which fission without the breeder remains an economically viable option.

No account has been taken here of foreign uranium resources that might be sold to the U.S., nor have I made any detailed attempt to extend the conclusions to choices about fission power facing the rest of the world. Most parts of the world have been even less thoroughly explored for uranium than has the U.S. Since geological formations of the type that contain uranium in the U.S. are common and widespread, however, it is reasonable to suppose that world land-based reserves of uranium will eventually be discovered roughly in proportion to land area. If this is even approximately true, the conclusions reached here for the U.S. will certainly apply on a similar time scale for the rest of the world as well (although not necessarily for each individual country).

Finally a few cautions. First, the use here of projections showing rapid growth of electricity generation through the year 2020 does not imply approval of such growth; there are reasons for believing that these massive increases in electricity use in the U.S. are unnecessary and, indeed, unlikely to take place, and these points have been amply made elsewhere.[50] Similarly, the assumption of a rapidly increasing nuclear share in electricity generation does not imply advocacy of this scenario; in my view, serious questions of radioactive waste management, reactor safety, and safeguards against diversion of fissionable material remain to be resolved before rapid proliferation of nuclear reactors of <u>any</u> kind can be recommended. At the same time, it would be unwise to terminate research on the LMFBR simply because it is not needed now and because important questions about it remain to be resolved. If fission is to be a long-term mainstay of civilization's energy supply, breeders will be needed eventually. Perhaps solar energy or fusion will eliminate the need for fission altogether, but it is too early to be sure; in the meantime, the breeder option should be kept open with a program of research and development short of commercial deployment.

It was the intention here, however, to focus on a much narrower question with a specified time horizon: whether uranium supplies are adequate to meet the most ambitious projections for the growth of nuclear power (irrespective of plausibility or desirability) for the next 30 to 50 years, without breeder reactors and without dramatic increases in the price of nuclear-generated electricity. The answer obtained here is yes, indicating, in turn, that the urgency that has been ascribed to the LMFBR program primarily on grounds of limited availability of uranium is illusory.[51]

Uranium Notes

1. Energy Digest (Washington, D.C.: Scope Publications), January 30, 1973, p. 30. The $323 million for the LMFBR should be compared to $152 million for all other nuclear fission technologies, $88 million for controlled thermonuclear fusion, $120 million for research related to coal, and $12 million for solar energy. In his energy message of June 1973, President Nixon asked for an additional $100 million for energy research and development in programs other than the LMFBR in FY 1974, at least half to be devoted to coal (Energy Digest, June 30, 1973, p. 1).

2. "Energy Research and Development," Hearings before the Subcommittee on Science, Research, and Development, Committee on Science and Astronautics, U.S. House of Representatives, May 1972 (Washington, D.C.: U.S. Government Printing Office, 1972), p. 321.

3. Robert Gillette, "Energy Research and Development: Under Pressure, a National Policy Takes Form," Science, Vol. 182, 30 November 1973, pp. 898-900.

4. T. B. Cochran, The Liquid-Metal Fast Breeder Reactor; an Economic and Environmental Critique (Washington, D.C.: Resources for the Future, in press). An early version was summarized in Allen L. Hammond, "The Fast Breeder Reactor: Signs of a Critical Reaction," Science, Vol. 176, 28 April 1972, pp. 391-393.

5. See, e.g., Dean E. Abrahamson, "Energy: The Nuclear Fast Breeder," Environment, Vol. 15, No. 2, March 1973, pp. 3-4.

6. Donald P. Geesaman, "Plutonium and the Energy Decision," Science and Public Affairs: The Bulletin of the Atomic Scientists, Vol. XXVII, No. 7, September 1971, pp. 33-36; Deborah Shapely, "Plutonium: Reactor Proliferation Threatens a Nuclear Black Market," Science, Vol. 172, 9 April 1971, p. 143.

7. U.S. AEC, Environmental Statement for Liquid-Metal Fast Breeder Reactor Demonstration Plant, WASH-1509 (Washington, D.C.: U.S. Government Printing Office, April 1972).

8. Floyd L. Culler, Jr. and William O. Harms, "Energy from Breeder Reactors," Physics Today, May 1972, p. 28.

9. Culler and Harms, op. cit., p. 29.

10. John H. Taylor and Nicholas A. Petrick, "LMFBR: Keys to Industrial Success," Nuclear News, January 1973, p. 43. Petrick is the demonstration-project manager.

11. All 26 utility-owned power reactors over 100 Mwe capacity in operation in the U.S. at the end of 1972 were LWRs. Of the 129 additional plants under construction or on order at that time, seven were HTGRs and the rest LWRs. (Nuclear Industry, February 1973, pp. 26-33.)

12. Trace quantities of Pu-239 are produced in nature by the same transformations described later in the text and in Note 13.

13. The reaction scheme for plutonium production is ${}_{92}U^{238} + n \rightarrow {}_{92}U^{239}$, ${}_{92}U^{239} \rightarrow {}_{93}Np^{239} + \beta^-$, ${}_{93}Np^{239} \rightarrow {}_{94}Pu^{239} + \beta^-$; and for production of U-233: ${}_{90}Th^{232} + n \rightarrow {}_{90}Th^{233}$, ${}_{90}Th^{233} \rightarrow {}_{91}Pa^{233} + \beta^-$, ${}_{91}Pa^{233} \rightarrow {}_{92}U^{233} + \beta^-$.

14. Although an average of 200 MeV or a bit more is released per fission, the small fraction of the energy carried by neutrinos is not deposited in the reactor and so is not available to the power production process.

15. If $\underline{r}$ fissile nuclei are produced for each one consumed, and if those produced remain in the reactor or are recycled without loss, then after a long time the total number of fissile nuclei consumed per fissile nucleus initially supplied to the reactor is $1 + \underline{r} + \underline{r}^2 + \underline{r}^3 + \ldots = 1/(1-\underline{r})$.

16. U.S. AEC, "Potential Nuclear Power Growth Patterns," WASH-1098 (Washington, D.C.: U.S. Government Printing Office, December 1970) (hereafter cited simply as WASH-1098), p. D-5; U.S. AEC, "Reactor Fuel Cycle Costs for Nuclear Power Evaluation" (Washington, D.C.: U.S. Government Printing Office, 1971) (hereafter cited simply as WASH-1099), p. 134, Fig. A.1.

17. If σ_f is an isotope's cross-section for neutron absorption leading to fission and σ_a the cross-section for nonfission absorption of a neutron by the same isotope, then the ratio of nonproductive consumption to total consumption of nuclei of this isotope in a thermal-neutron-spectrum reactor is approximately $\sigma_a/(\sigma_f + \sigma_a)$, where the cross-sections are taken to be those corresponding to neutrons moving at 2200 m/sec. One has, for U-235, $\sigma_f = 577$ and $\sigma_a = 106$ barns, and for Pu-239, $\sigma_f = 742$ and $\sigma_a = 287$ barns. See, e.g., Samuel Glasstone and Alexander Sesonske, Nuclear Reactor Engineering (New Jersey: D. Van Nostrand Co., 1963), p. 88.

18. This figure assumes depletion of the tails stream in the enrichment process to 0.2 percent U-235. A simple mass balance gives $f_{loss} = (P_t/0.7)[(P_e - 0.7)/(P_e - P_t)]$, where f_{loss} = (U-235 remaining in tails)/(U-235 entering enrichment plant), P_e is the mass percentage of U-235 in the enrichment stream, and P_t is the mass percentage of U-235 in the tails stream. With $P_e = 2.5$ and $P_t = 0.2$ one obtains $f_{loss} = .224$. A more complete AEC analysis, which includes a stream of uranium recycled from the reactor entering the enrichment plant, gives $f_{loss} = .193$ for $P_e = 2.55$ and $P_t = 0.2$ (WASH-1099, p. 134). Note, however, that the "loss" in tails need not be permanent, inasmuch as this material can be used as feed to breeder reactors at some later time, or, augmented with recycled plutonium, as feed for LWRs.

19. The isotope U-238 can be induced to fission only by absorption of a neutron with energy in excess of 1 MeV. Since, on the average, the neutrons produced by the fission of U-238 have less energy than this, there is no possibility of a self-sustaining chain reaction in U-238 alone. See, e.g., Glasstone and Sesonske, op. cit., pp. 87-88, and Robert L. Loftness, Nuclear Power Plants (New Jersey: D. Van Nostrand Co., 1964), p. 15.

20. Mass balances described in WASH-1098 (p. 5-12, Table 5.3) give consumption of 0.22 metric tons (te) of U_3O_8 per Mwe-yr of electricity generated in LWRs without recycling of plutonium and 0.15 te U_3O_8/Mwe-yr with Pu recycled by adding it to natural uranium. At the LWR thermal efficiencies of 32.5 percent and a fission yield of 22,000 kwht/g, these consumption figures correspond to 6.6 and 9.7 g fissioned per kg of U mined, respectively. The reference LWR mass balance in WASH-1099 (p. 134, Fig. A.1) gives .203 te U_3O_8/Mwe-yr without Pu recycling (7.2 g fissioned/kg U mined). If the Pu is recycled by adding it to enrichment tails containing 0.2 percent U-235, one finds from the appropriate additional mass balance in WASH-1099 (p. 157, Fig. A.24) that a balanced combination of LWRs running on enriched uranium and Pu in tails needs only .117 te U_3O_8/Mwe-yr. This figure corresponds to 12.4 g fissioned/kg U mined. Considering the same strategy (which is the most uranium conserving one because it exploits U-235 remaining in the tails and not otherwise used), but with the mass balances from WASH-1098 instead of WASH-1099, one obtains 10.8 g fissioned/kg U mined.

21. For extended technical discussions see U.S. AEC, "Current Status and Future Technical and Economic Potential of Light Water Reactors," WASH-1082 (Washington, D.C.: U.S. Government Printing Office, March 1968) (hereafter referred to simply as WASH-1082), pp. 5-84/5-100; and D. E. Deonigi, "The Value of Plutonium Recycle in Thermal Reactors," Nuclear Technology, Vol. 18, May 1973, pp. 80-96. Commencement of Pu recycling at the Big Rock reactor is noted in Loren C. Schmid, "Preface: A Review of Plutonium Utilization in Thermal Reactors," Nuclear Technology, Vol. 18, May 1973, pp. 78-79.

22. The mass balance in WASH-1098 for an HTGR with full recycle of U-233 (p. 5-14, Table 5.3, 1978 Reference HTGR No. 4) gives .06 te U_3O_8/Mwe-yr, corresponding at 43 percent thermal efficiency and 22,000 kwht/g to 18.2 g fissioned/kg U mined. Mass balances in WASH-1099 for "reference" and "backup" HTGR designs (p. 136, Fig. A.3, and p. 137, Fig. A.4), both recycling U-233 and operating respectively at 43.1 percent and 40.7 percent thermal efficiency, give 18.8 and 14.2 g fissioned/kg U mined.

23. WASH-1098, pp. E-6/E-7. According to a personal communication from Thomas Cochran (Nov. 1973), recent information indicates that the conversion ratio of early breeders is more likely to be 1.2 or less.

24. See, e.g., Floyd L. Culler and William O. Harms, op. cit., p. 29, for the higher figure. The reference breeder of WASH-1099, p. 153, would fission 570 g/kg mined.

25. These figures have been computed from specific inventories (in kg fissile/Mwe) given in Tables E-1, E-4, and E-5 of WASH-1098, taking into account the losses in enrichment corresponding to LWR, HTGR, and LMFBR fuel cycles.

26. Walter C. Woodmansee, "Uranium," in U.S. Department of Interior, Minerals Yearbook: Vols. I-II, 1971 (Washington, D.C.: U.S. Government Printing Office, 1972) p. 1197; see also the chapters on uranium in the 1968, 1969, and 1970 editions of the Minerals Yearbook.

27. The figures given here are a composite from WASH-1082 (p. 5-42, Table 5.7), WASH-1098 (p. 5-11, Table 5.2), and National Petroleum Council, U.S. Energy Outlook: Nuclear Energy Availability (Washington, D.C.: National Petroleum Council, 1972), p. 14, Table 7.

28. WASH-1098 (p. 5-11, Table 5.2). The figure of 0.03 mill/kwhe corresponds to a PWR that runs on natural U augmented with recycled Pu for the first 10 years of its 30-year lifetime and on enriched U for the last 20 years. This strategy actually produces slightly more plutonium than consumed. The figure of 0.06 mill/kwhe corresponds to the WASH-1098 analysis of an LWR of somewhat higher conversion ratio, running on enriched U for the first 20 years and natural U plus Pu for the last 10. In this case the excess Pu produced is equal to one-eighth of the net consumption of U-235, so I have revised the WASH-1098 sensitivity from 0.07 to 0.06 mill/kwhe per dollar per lb. of U_3O_8. The difference between 0.03 and 0.06 mills/kwhe for different LWR fuel cycles, both recycling plutonium, presumably reflects a sensitive interplay among interest charges, accounting procedures, and the details of the fuel cycle. The "balanced" combination of LWRs described in Note 20, which consists of three reactors running on tails augmented by Pu for every four running on enriched U, would appear from the WASH-1098 figures to have a sensitivity of 0.04 mills/kwhe per dollar per lb. of U_3O_8.

29. WASH-1098 (p. 5-11, Table 5.2). Of the several HTGR fuel cycles analyzed, the figure of 0.019 mill/kwhe corresponds to the one with exact recycling of U-233 -- i.e., no excess production of U-233 and no make-up required from outside the cycle. This cycle is described in Table 5.2 as "HTGR Ref., U-233 Startup."

30. WASH-1098, pp. 136-137, Figs. A.3-A.4.

31. Charles E. Shortt, "Thorium," in U.S. Department of Interior, Mineral Facts and Problems, 1970 (Washington, D.C.: U.S. Government Printing Office, 1970), p. 203.

32. Joseph E. DeCarlo and Charles E. Shortt, "Uranium," in Mineral Facts and Problems, 1970, op. cit., pp. 223-224.

33. WASH-1098, p. 2-11.

34. WASH-1082, p. 5-68.

35. National Petroleum Council, U.S. Energy Outlook: Nuclear Energy Availability, A Report of the Nuclear Task Group of the Other Energy Resources Subcommittee of the National Petroleum Council's Committee on U.S. Energy Outlook (Washington, D.C.: National Petroleum Council, 1972), p. 6.

36. WASH-1098, p. 2-11; sections on uranium, U.S. Department of Interior, Minerals Yearbook, 1970 and 1971 (Washington, D.C.: U.S. Government Printing Office, 1971 and 1972).

37. WASH-1098, p. 2014.

38. WASH-1098, p. 6-34.

39. U.S. Department of Commerce, Statistical Abstract of the United States, 1972 (Washington, D.C.: U.S. Government Printing Office, 1972); Edison Electric Institute, Statistical Year Book of the Electric Utility Industry for 1971 (New York, N.Y.: Edison Electric Institute, 1972).

40. One has (\$100/kwe) x (1000 mills/\$)(13%/yr) ÷ (.80 x 8760 hrs/yr) = 1.85 mills/kwhe. A rate of 13 percent per year for fixed charges (interest plus depreciation) is typical for investor-owned utilities.

41. WASH-1098, p. 3-12.

42. In WASH-1098, pp.5-12/5-14, Table 5.3, the separative work (SW) requirement is given as 95.6 kg SW/Mwe-yr for an LWR recycling plutonium in natural uranium and 61.3 kg SW/Mwe-yr for the HTGR with full recycle of U-233. For the LWR, e.g., one has (95.6 kg SW/8760 x 10^3 kwhe) x (26 x 10^3 mills/kg SW) = 0.28 mill/kwhe. Adding carrying charges at 10 percent per year for a three-year fuel residence time gives 0.36 mill/kwhe direct and indirect costs associated with enrichment.

43. Vincent V. Abajian and Alan M. Fishman, "Supplying Enriched Uranium," Physics Today, Vol. 26, No. 8, August 1973, pp. 23-29.

44. With its density of 2,300 kg/m^3, Chattanooga shale that is 0.006 percent U_3O_8 contains 117 g of U per cubic meter. At our nominal LWR efficiency of 10 g fissioned per kg U and at 22,000 kwht/g fissioned, one has an effective energy content of 25,800 kwht/m^3 of shale. Bituminous coal with density of 1,400 kg/m^3 and energy content of 12,000 BTU/lb yields 10,800 kwht/m^3, and lignite with density of 1,200 kg/m^3 and energy content of 7,000 BTU/lb yields 5,400 kwht/m^3.

45. U.S. AEC, "Environmental Survey of the Nuclear Fuel Cycle" (Springfield, Va.: National Technical Information Service, November 1972), pp. 0-4 to 0-9; Thomas H. Pigford, Michael John Keaton, Bruce J. Mann, "Fuel Cycles for Electrical Power Generation," Teknekron Report EEED 101 (Teknekron, Inc., Berkeley, Calif. 94704), pp. 9-11.

46. U.S. Department of Interior, "Availability of Uranium at Various Prices from Resources in the United States," Bureau of Mines Information Circular 8501 (Washington, D.C.: U.S. Government Printing Office, 1971), Appendix D. The deposit studied lies horizontally and is exposed along one side on a hillside; the top of the minable part of the formation, which is 14.5 feet thick, lies 180 feet below the top of the hill. The study assumed a form of room-and-pillar underground mining that uses tunnelling machines boring in horizontally. If, instead, surface mining were used to exploit this deposit, the overburden removed would amount to about 2.1 million metric tons per billion kwhe generated in a plutonium recycling LWR. (I assume 90 ft average overburden depth, given zero at the outcropping and 180 ft at the hilltop, and I assume the density of the overburden is the same as that of the shale.)

47. Thomas H. Pigford et al., op. cit., pp. 61-65.

48. U.S. Department of Interior, Bureau of Mines Information Circular 8501, p. 12.

49. The volume of sea water that would have to be processed poses problems, but is perhaps not altogether impractical. A coastal sited plutonium-recycling LWR using sea water for once through cooling passes 1/20 as much uranium through its condensors in a year as it requires for fuel (assuming 10° F temperature rise in the cooling water, 80 percent plant load factor, and 3.34×10^{-6} grams of U per liter of sea water).

50. See, e.g., John Holdren, "Energy: Resources and Consumption," in John Holdren and Phil Herrera, Energy (N.Y.: Sierra Club Books, 1971), Chaps. 1 and 7; A. B. Makhijani and A. J. Lichtenberg, "Energy and Well-Being," Environment, June 1972, D. Chapman, T. Tyrell, and T. Mount, "Electricity Demand Growth and the Energy Crisis," Science, Vol. 178, 17 November 1972, pp. 703-713.

51. The basic conclusion is not new. Less elaborate summaries of the likely supply-price situation for uranium, raising the same questions about the justification for an early commitment to LMFBRs, have been published before. See, e.g., John Holdren, op. cit., pp. 60-62; H. C. Hottel and J. B. Howard, New Energy Technology (Cambridge, Mass.: M.I.T. Press, 1971), pp. 220-231; and Note 3. And, of course, the AEC's own computations of the sensitivity of generation costs in various reactors to the cost of raw uranium have been available in WASH-1098 to those who knew where to look. Nevertheless, the claim that, without the LMFBR, the U.S. faces a serious supply-price squeeze on uranium in the next few decades appears to have been widely and uncritically accepted in the technical community. This situation has motivated the present work, which might appear to those who have already looked carefully at the uranium situation to be belaboring the obvious.

52. The comments of Thomas Cochran and Lester Lees are gratefully acknowledged.

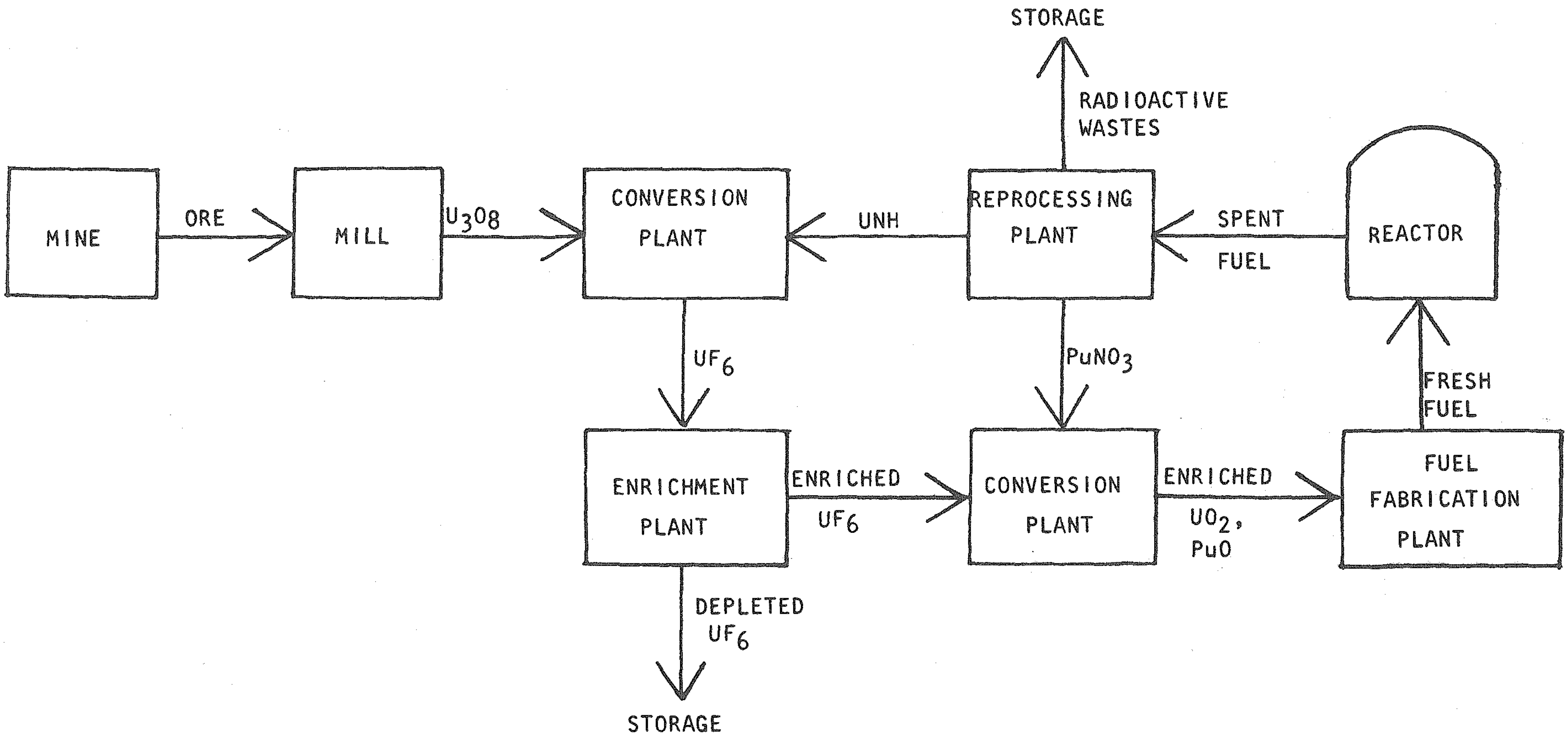

FIGURE 1. FUEL CYCLE FOR LWR WITH PU RECYCLE

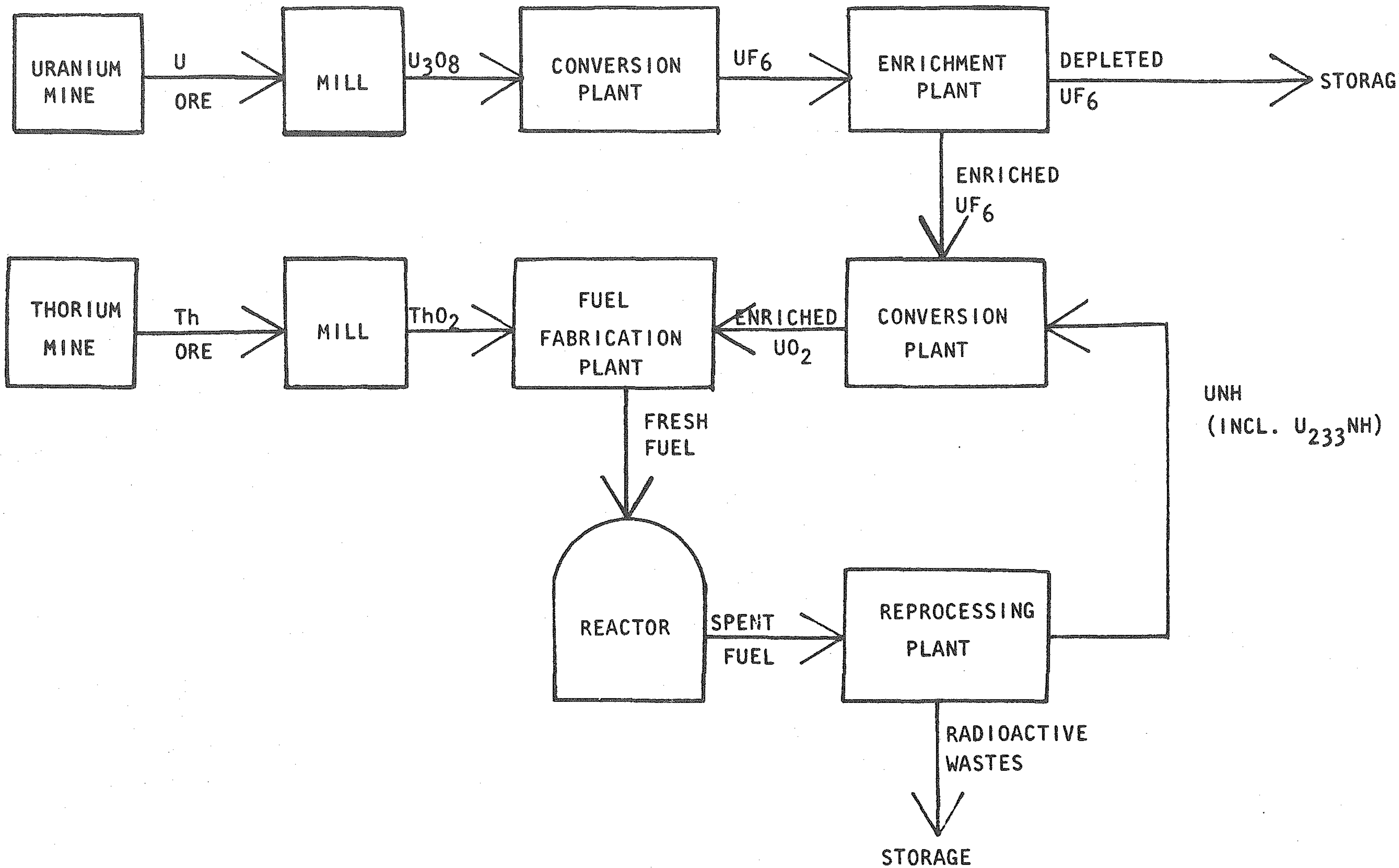

FIGURE 2. FUEL CYCLE FOR HTGR WITH U-233 RECYCLE

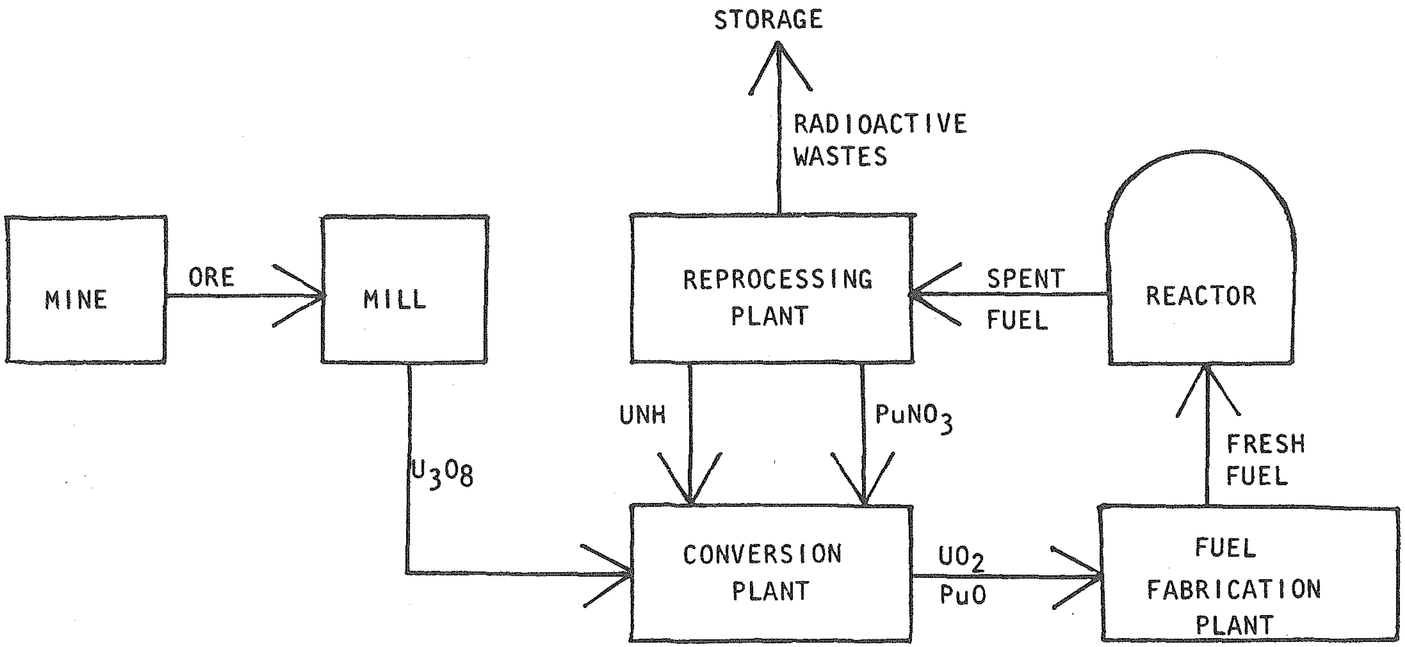

FIGURE 3. FUEL CYCLE FOR LMFBR USING NATURAL URANIUM AND RECYCLED PU

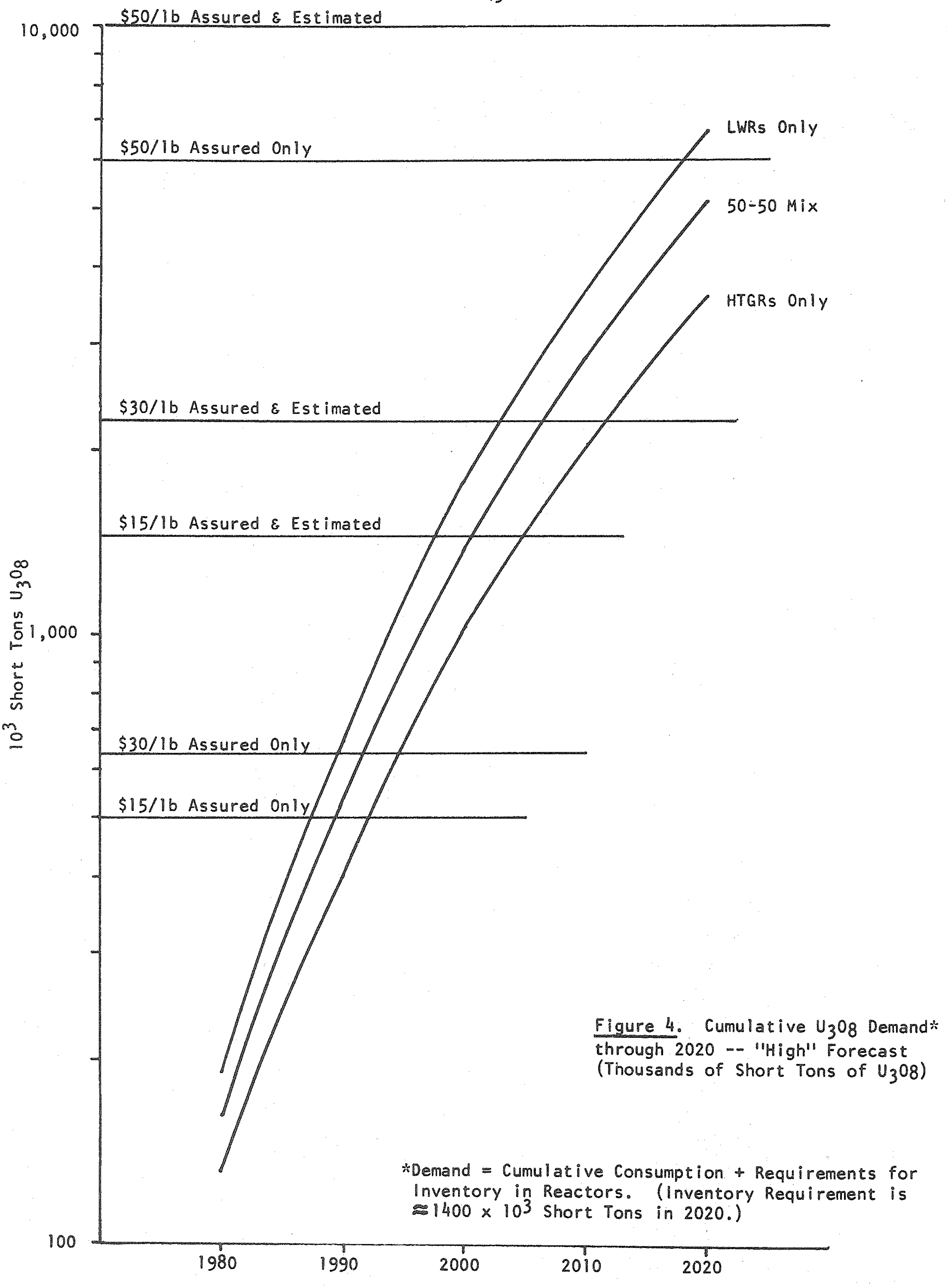

Figure 4. Cumulative U_3O_8 Demand* through 2020 -- "High" Forecast (Thousands of Short Tons of U_3O_8)

*Demand = Cumulative Consumption + Requirements for Inventory in Reactors. (Inventory Requirement is ≈1400 x 10^3 Short Tons in 2020.)

TABLE 1. Summary of Nominal Reactor Characteristics

	LWR	HTGR	LMFBR
thermal efficiency (%)	32.5	43	40
thermal power for 1000 Mwe (Mwt)	3,077	2,320	2,500
conversion ratio	0.55	0.80	1.30
grams fissioned/kg U mined*	10	18	570
kg U mined*/billion kwhe	14,000	5,900	200
short tons U_3O_8 mined*/10^9 kwhe	18.2	7.6	0.3**
specific inventory, kg fissile/Mwe	2.0	1.8	3.0
short tons U_3O_8 for inventory	480	470	740
mills/kwhe increase in electricity cost per dollar per lb increase in U_3O_8 cost over $8	0.05	0.02	0.001
electricity cost increment in mills/kwhe if U_3O_8 costs:			
$15/lb	0.35	0.14	0.007
$30/lb	1.10	0.44	0.022
$50/lb	2.10	0.84	0.042
$100/lb	4.60	1.84	0.092

* Consumption, not inventory.

**Actually, LMFBRs would be able to use the accumulated tails of the uranium enrichment process as a principal source of U-238 for some time to come. The number given here corresponds to a "self-contained" breeder reactor economy, generating all its own fissile material and obtaining fresh fertile material from ore, as would be the case in the long term.

Sources: See text.

TABLE 2. U.S. Uranium Reserves versus Price

Price $/lb U_3O_8	Reasonably Assured	Estimated Additional	Cumulative Total*
	---------reserves, thousand short tons U_3O_8-------		
less than 8	204	390	594
8-10	136	210	940
10-15	160	350	1,450
15-30	140	650	2,240
30-50	5,400	2,400	10,000
50-100	6,000	9,000	25,000

*Each figure in this column includes reserves in all cheaper categories.

Source: See Note 32.

TABLE 3. Reasonably Assured Reserves of U_3O_8 under $8/lb

As of January 1	Thousand short tons of U_3O_8
1969	161
1970	204
1971	246
1972	273

Sources: See Note 35.

TABLE 4. U.S. Thorium Reserves versus Price

AEC estimates, 1970

Price $/lb ThO_2	---------reserves, thousand short tons ThO_2-------- Reasonably Assured	Estimated Additional	Cumulative Total*
less than 10	100	500	600
10-30	100	100	800
30-50	3,000	7,000	10,800
50-100	8,000	17,000	35,800

*Each figure in this column includes reserves in all cheaper categories.

Source: See Note 36.

TABLE 5. Projected U.S. Electricity Consumption and Nuclear Contribution

All figures in billions of kwhe

	TOTAL ELECTRICITY GENERATION		NUCLEAR GENERATION		CUMULATIVE NUCLEAR GENERATION AFTER 1970	
year	"medium"	"high"	"medium"	"high"	"medium"	"high"
1970 (actual)	1,640	1,640	24	24	--	--
1980	2,700	3,000	1,100	1,100	5,620	5,620
1990	4,800	5,750	2,500	2,700	23,620	24,620
2000	8,000	10,000	4,800	6,200	60,120	69,120
2010	12,500	16,050	8,600	10,600	127,120	153,120
2020	18,500	24,200	13,300	17,000	236,620	291,120

Source: See Notes 37, 9

TABLE 6. Cumulative Uranium Demand Without Breeder Reactors

All figures in thousands of short tons of U_3O_8

	LWRs ONLY		HTGRs ONLY		50-50 MIX	
year	"medium"	"high"	"medium"	"high"	"medium"	"high"
1980	192	192	131	131	162	162
1990	635	670	381	404	508	537
2000	1,486	1,768	842	1,023	1,164	1,396
2010	3,025	3,667	1,657	2,034	2,341	2,851
2020	5,410	6,695	2,870	3,575	4,140	5,135

Source: Computed from Tables 1, 5.

TABLE 7. Impact of Uranium Costs on Cost of Nuclear-Generated Electricity: A Range of Possibilities

All figures for "high" growth projection

		Year and cost increment in mills/kwhe associated with using U_3O_8 at:		
reactor mix	reserves available	$15/lb	$30/lb	$50/lb
LWRs only	assured only	1987 (0.35)	1989 (1.10)	2018 (2.10)
LWRs only	assured & estimated	1998 (0.35)	2003 (1.10)	>2020 (2.10)
50-50 mix	assured only	1989 (0.25)	1991 (0.77)	>2020 (1.47)
50-50 mix	assured & estimated	2000 (0.25)	2006 (0.77)	2020 (1.47)
HTGRs only	assured only	1992 (0.14)	1994 (0.44)	2020 (0.84)
HTGRs only	assured & estimated	2005 (0.14)	2012 (0.44)	2020 (0.84)

Sources: See Tables 1, 2, 6.

TABLE 8. Measures of Environmental Impact of Surface Mining and Ore Processing (all quantities per 10^9 kwhe)

	LWRs, Pu recycle 0.2% ore	LWRS, Pu recycle 0.007% ore	LMFBR 0.007% ore	Eastern coal
fuel input to power plant (te U_3O_8 or coal)[a]	16.5	16.5	0.24	347,000
ore extracted (m^3)	3,060[b]	147,000[c]	2,140	400,000[d]
overburden moved (te)	245,000	2,100,000	30,500	5,800,000
land area excavated (acres)	1.6	8.2	0.12	153
water use (10^6 gal)	5.9[e]	10.5[e]	0.15	260[f]

[a] te = metric ton = 1,000 kg

[b] density 2.7 te/m^3

[c] density 2.3 te/m^3, 70% extraction of U_3O_8 from ore

[d] density 1.4 te/m^3, 23% loss in coal washing

[e] milling only, which dominates water use

[f] coal washing

Sources: Notes 45-47.