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HTGR FUEL CYCLE ASSESSMENT STUDIES

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May 11, 1965

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I. INTRODUCTION

The AEC Civilian Nuclear Power Report to the President, which was published in 1962,(1) presents an excellent analysis of the long-range importance of nuclear energy in the United States and outlines a proposed program to meet both the intermediate and the long-range objectives of our power generation industry. The report discusses the potential roles of both the advanced converter and the breeder reactors in meeting the over-all objectives of the program.

More than two years have elapsed since the 1962 report was prepared, and additional studies on both the advanced converter and the breeder reactor concepts make it possible to examine in somewhat greater detail the probable roles that these concepts will fill in the next few decades. The purpose of this paper is to indicate the potential role we anticipate for the advanced converter reactor based on recent work done at General Atomic. In order to assess the potential of the HTGR, we have examined the probable fuel utilization and projected fuel cycle economics of the HTGR relative to existing reactor concepts, to other advanced converters, to fast breeder reactors, and to combinations of reactor systems.

In the subsequent discussions, results of calculations and analysis will be presented that support the following conclusions:

1. A high conversion or breeding ratio, per se, does not assure minimum nuclear fuel requirements in a growing nuclear power economy.

2. Minimizing the fuel requirements in a power reactor complex does not, per se, assure the long-range effective utilization of nuclear resources.

3. The amount of uranium ore projected(1) to be available in the United States at prices less than $10 per pound is insufficient to support the expected energy requirements for the next fifty years almost independent of the types of reactors built.

4. Since a rapidly growing, large nuclear power industry will almost certainly require the use of more expensive ore, the most critical index for choosing an attractive reactor concept is the economic performance potential of the reactor relative to

other energy-conversion systems when the price of uranium ore has risen to, say, \$20 or \$30 per pound. It is within this context that we must interpret the objective of maximum utilization of nuclear resources. Conservation of nuclear resources for its own sake is, therefore, not the overriding consideration in the maximum utilization of nuclear resources. It is generally true, however, that reactor concepts capable of generating economic power with relatively expensive ore are also concepts that use the uranium ore efficiently and therefore tend to conserve resources.

5. In order to meet the objectives of favorable utilization of nuclear resources under economically attractive conditions, it is found that a reactor concept should simultaneously have the following four characteristics:
    a. A high thermodynamic efficiency.
    b. A high conversion ratio.
    c. A high specific power.
    d. A reasonably long fuel irradiation time relative to the time spent by the fuel outside the reactor core.

6. When one judges reactor concepts on the basis of economic attractiveness under conditions of increasing ore prices, the potential for the HTGR appears to be better than that of other advanced converter concepts, and in many circumstances competitive with fast breeder reactors.

The basis for these conclusions will be developed in the succeeding discussion. Section II will review the electric power and energy forecasts for the next few decades and the estimated availability of uranium and thorium resources. Section III will examine the cumulative resource requirements of various reactor types. Section IV will then look at the fuel cycle economics under conditions typified by the various reactor concepts. Section V will cover in somewhat closer detail the uranium commitments and fuel cycle economics associated with combinations of converter and recycle reactors including both near breeders and breeders.

II. NUCLEAR POWER FORECASTS AND RESOURCE REQUIREMENTS

The projected growth of the United States nuclear power generation capacity to the year 2020 A.D. as forecast by the AEC(1)(2) has been taken as the basis of the analysis to be described in this report. An interpretation of the nuclear electric generating capacity and doubling time projected by the AEC in 1962 was presented by Dietrich(3) in his paper on efficient utilization of nuclear fuels. In this growth curve, a linear increase of generating capacity after the year 2000 A.D. was assumed. This has the effect of increasing the doubling time from six years to thirty years over a time interval of thirty years. In view of the fact that the doubling time for total electricity generating capacity is projected by the Federal Power Commission(4) to be about twelve years in 2000 A.D. relative to about ten years in 1960, such an abrupt change in the doubling time after 2000 A.D. does not seem realistic. A modified electric power capacity projection that was recently presented by Swartout(2) in testimony before the Joint Committee on Atomic Energy shows a more rapid growth in the period before 1990 and a more gradual decrease in growth rate after 2000 A.D. The two curves are shown for comparison in Fig. 2.1. This new AEC projected growth curve has been used as the basis for studies presented in this paper.

Before leaving the discussion of the projected growth of nuclear power in the United States, some discussion of the factors that will affect the rate of growth is, perhaps, appropriate.

1. Nuclear power plants will replace coal stations only if the cost of nuclear power can be less than that of the coal-produced power in a particular region. The fraction of the country's power that will be produced by nuclear power will then depend on the fraction of coal-produced power that is higher in cost than that achievable with nuclear power. As will be shown later, approximately half of today's electric generating market could be provided by nuclear power if a fuel cycle cost below 1.7 mills/kw-hr could be assured. This appears to be possible, even with the relatively inefficient converter reactors now being planned and built. Hence, one would expect, other factors allowing, that the nuclear power industry would grow rapidly to 50% of the total generating capacity if a fuel cycle cost of 1.7 mills/kw-hr can be assured. It should grow still further if the fuel cycle cost decreases still more relative to coal costs.

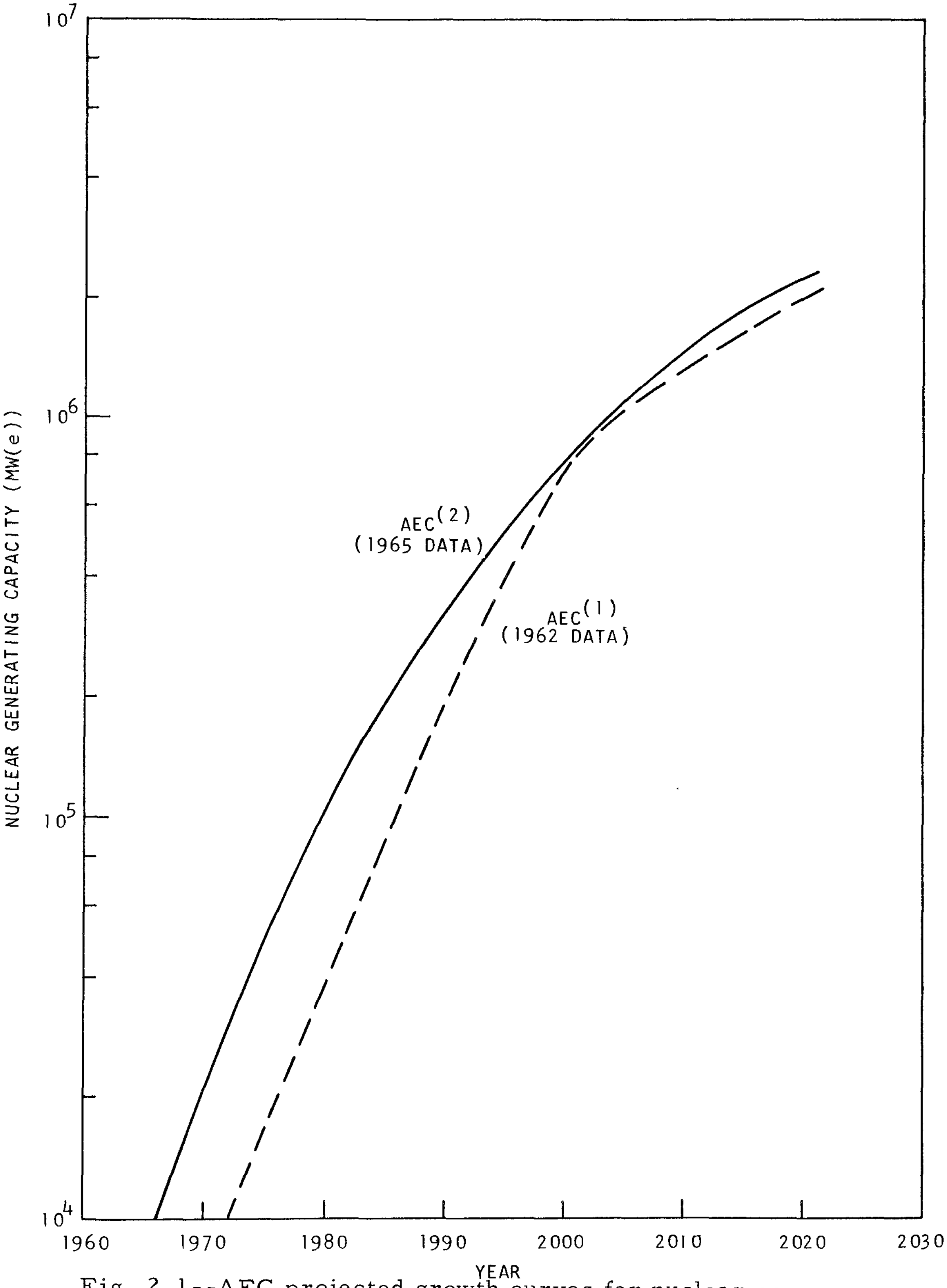

Fig. 2.1--AEC projected growth curves for nuclear power generating capacity in the United States

2. The above arguments assume that coal costs will not decrease appreciably in at least the upper 50% of the power cost range. Actually, with improved coal mining, transportation, burning, and electric transmission technology, the target fuel cycle cost may decrease to less than 1.7 mills/kw-hr, so that nuclear power plants may have to do even better than indicated to gain wide acceptance.

3. The cost of electricity with nuclear power is most favorable when the size of the station is large. This could again impose a limitation on the growth of nuclear power, since much of the power generating capacity today is provided by relatively small power stations. However, with a power growth having a doubling time of about ten years, it can be seen that much larger power generation stations should be common within a few decades. Furthermore, the trend toward long-distance transmission and transmission line interconnections will tend to encourage the use of larger central-station power plants.

4. The fuel cycle cost achievable with the nuclear power plants must remain below the target or "critical fuel cycle cost" independent of changes in uranium ore and production costs. This will be discussed in some detail in Sections IV and V of this report.

5. The rate of nuclear power growth will also depend on the confidence of the utility industry in the economics, reliability, and safety of nuclear plants. Hence, there may be some time lag between the demonstration of a new reactor concept and its general acceptance by the utility industry.

With the exception of fuel cycle economics, these factors will not be discussed further in this report. We therefore depend on more careful analyses by other sources for the validity of the assumed nuclear power growth curves. One such analysis has recently been reported by the Federal Power Commission.(4) However, it is again emphasized that the fuel cycle cost for nuclear power plants is of great importance in assuring acceptance of nuclear power, and this subject will receive considerable attention in this report.

The basic data on recoverable uranium and thorium reserves, as outlined by the AEC report,(1)(2) are used throughout this analysis. Since it is more convenient to have the reserves expressed in metric ton units of metal, the data summarized in Table 2.1 are expressed in these units. The last line in the table, however, refers to the estimated cost of separating uranium from sea water.(5) If this process proves to be feasible for the costs estimated, this development would have important implications on

Table 2.1

URANIUM AND THORIUM* RESOURCES IN THE UNITED STATES(1)

Cost Range ($/lb of U_3O_8)	Reasonably Assured Resources (10^6 metric tons)		Estimated Total Resources (10^6 metric tons)	
	Uranium	Thorium	Uranium	Thorium
5-10	0.3	0.1*	0.6	0.3*
10-30	0.3	0.1*	0.5	0.15*
30-50	3.8	2.4	6.2	8.0
50-100	4.6	6.4	12	20
100-500	380	800	1500	2400
11-22†			4000	

*Incomplete estimates exist for thorium resources at recovery prices below $30 per lb.

†Estimated cost of recovery from sea water.(5)

the necessity for developing fast breeder reactors. This will be discussed more completely in Section IV.

The important point to be gained from an examination of the resource data is that the total quantity of recoverable nuclear resources is enormously large. Consequently, to achieve the maximum utilization of our nuclear resources, the primary problem is to find a way to use the resources economically, in spite of the cost of recovery. Hence, conservation of resources, per se, is only of interest insofar as good conservation can delay the time when it will be necessary to use the more expensive ores. Even this consideration is of only minor long-range importance, as will be seen in the following section.

III. URANIUM REQUIREMENTS OF VARIOUS REACTOR CONCEPTS

In a growing nuclear power economy the fuel requirements depend both on:

1. The increase in fuel inventory required to start up new reactors, and
2. The fuel required to replace the net fuel consumed in generating energy.

The fuel requirements to allow for new reactor startups depend, of course, on the growth rate of the total nuclear capacity and on how much fuel inventory is held up by the reactors. The inventory requirement for a nuclear plant is inversely proportional to the system specific power measured by the kilowatts of electricity generated per kilogram of fuel held up both in the reactor and in the fuel fabrication and reprocessing plants. Specific power is more usually specified in units of kilowatts of heat per kilogram of fuel in the reactor core, i.e., kw(t)/kg. In comparing the inventory utilization of different reactor concepts, it is necessary, then, to adjust the specific power in kw(t)/kg for the thermal efficiency of the plant and the fuel turnaround time relative to the irradiation time. For example, a reactor with an apparently high specific power of 2000 kw/kg, a fuel life of two years, a fuel turnaround time of one year, and a thermodynamic efficiency of 30% has an effective system specific power of 400 kw(e)/kg of fuel held up. In contrast, a reactor with a more modest specific power of 1000 kw/kg, but with a fuel life of four years and an efficiency of 45% would have an effective system specific power of 450 kw(e)/kg of fuel held up. Hence, the higher efficiency and longer fuel life for the second reactor would more than make up for the higher apparent specific power of the first reactor. Furthermore, the low efficiency of the first plant would impose an additional penalty on the utilization of the fuel resources in the fuel burnup requirements.

The net fuel consumption depends on the conversion ratio of the reactor. A reactor system having a conversion ratio of 1.00 at equilibrium, including allowance for fuel losses in reprocessing, would be self-sustaining, i.e., would require no external fuel feed makeup after the reactor system had reached equilibrium. Obviously, a self-sustaining reactor is of only minor importance in a growing power economy. For a reactor system to be truly self-sustaining in a growing nuclear power economy, it would be necessary that the yearly breeding gain relative to the total inventory of the system be equal to the nuclear power growth rate. Hence, both the breeding ratio and specific power of the system must be considered simultaneously. The argument that a self-sustaining reactor is of interest for the long-range future when the power economy has reached a steady state would appear to be fallacious, since the growth rate is unlikely to decrease to zero for at least a century, if ever. Aside from resource considerations, reactors with low specific powers are of little interest, since they tend to be uneconomic.

Therefore, both system specific power and conversion ratio, or breeding ratio, are important considerations in choosing a reactor concept to meet the long-range objectives. The relative importance of these two characteristics in the conservation of nuclear fuel will be illustrated for several typical reactor conditions in the succeeding discussion. It is again emphasized, however, that conservation of the nuclear fuel resources in itself is not of over-riding concern in the goal of maximum utilization. Of greater importance, as will be amplified later, is the economic use of a substantial fraction of all the recoverable resources.

Figure 3.1 indicates the inventory and burnup requirements for uranium in a reactor system typical of today's pressurized and boiling water reactors (BWR). For this example, a system specific power of 800 kw/kg and a thermal efficiency of 32% were assumed. The system specific power is based on the assumption that the fuel processing requires one year outside the reactor for each reactor cycle. Typical BWR plants with some stretch capability appear to have equilibrium loading conditions that lead to a reactor specific power of about 800 kw/kg and a system specific power of about 700 kw/kg. Projected pressurized water reactor (PWR) plants are expected to have an equilibrium feed reactor specific power of about 1200 kw/kg, but a system specific power of about 900 kw/kg. The bottom curve in Fig. 3.1 represents the cumulative number of metric tons that would have to be mined simply to put new reactors into service to meet the growing demand for power under the assumptions indicated in the previous section.

In addition to the uranium requirements for starting up new plants, uranium is also required to replenish that consumed in generating the energy. For each gram of fuel consumed, CR grams of fertile material will be converted to new fuel. (CR is defined as the net conversion ratio for the reactor system.) Hence, the net fuel burnup is proportional to 1 - CR. The electric energy produced per gram of fuel consumed is, of course, proportional to the thermal efficiency of the plant. The difference between the top curve in Fig. 3.1 and the inventory curve represents the amount of uranium that would have to be mined to meet the burnup requirements for the reactor conditions specified. A conversion ratio of 0.6 was assumed for these calculations; this value is probably reasonable for projected light-water-moderated reactors using low-enrichment uranium.

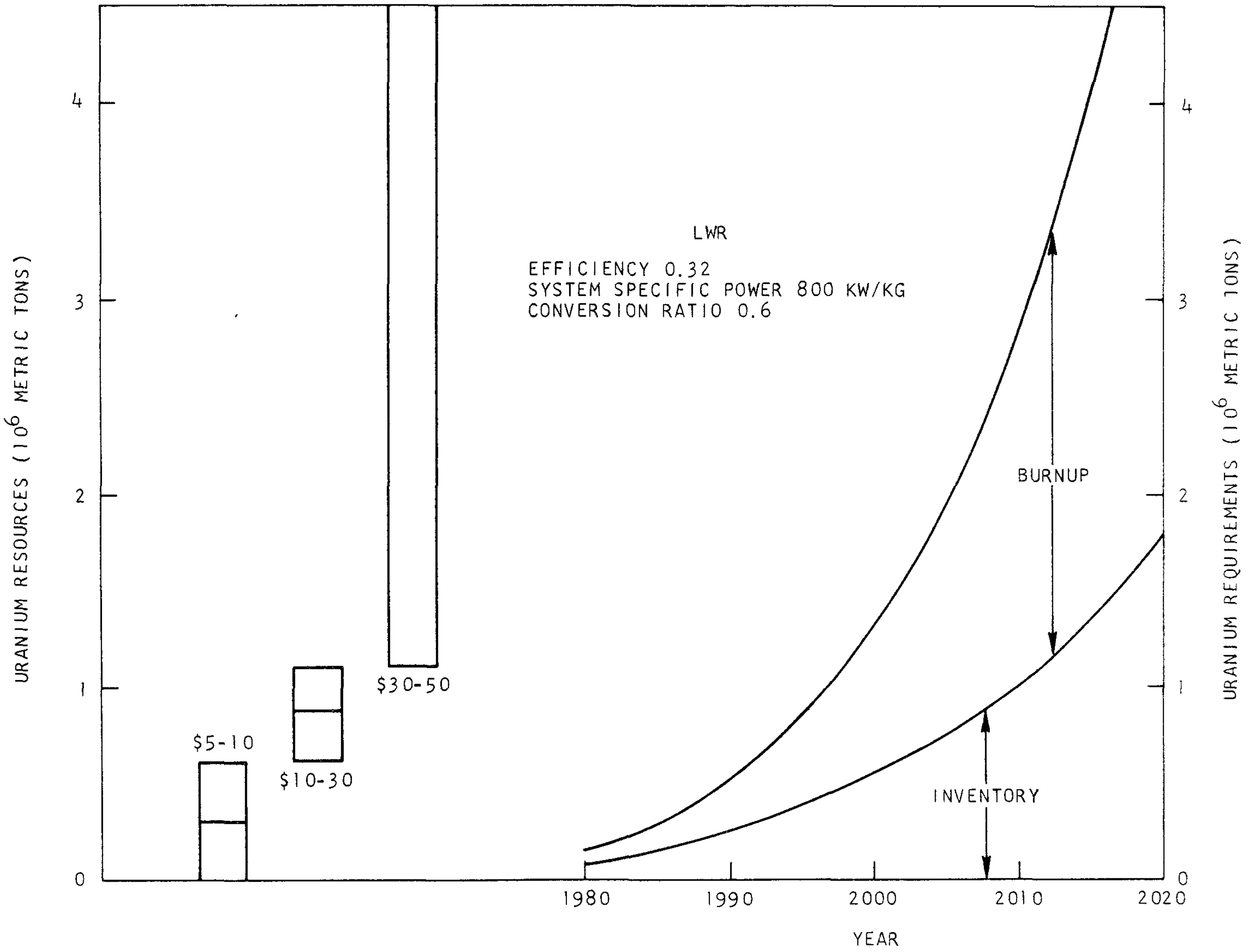

Fig. 3.1--Projected uranium requirements for the United States assuming all nuclear power to be supplied by light water reactors

It has been assumed in the calculation of the burnup requirements that all of the plutonium produced is recycled. If the plutonium is not recycled, the uranium requirements would be approximately twice that shown for fuel burnup, even after allowing for the plutonium that is burned before fuel discharge in the first cycle.

On the left side of Fig. 3.1, the amounts of uranium recoverable in different price ranges are shown, based on data from the AEC report.(1) The bottom segment of the bar represents the assured reserves and the top segment the total reserves estimated for each price range. It can be seen that a continuing trend of building the present-day inefficient reactors would exhaust the low-cost ores shortly after the year 1990. Indeed, reactors of this type that are constructed after 1970 would almost certainly have to be operated for some part of their plant lifetime on uranium ore costing more than $10 per pound of U_3O_8. Hence, it can be seen that the near-term low cost of $5-$6 per pound for ore is not a good basis for evaluating the long-range economic potential of this type of reactor. It can be argued that more vigorous prospecting activities will probably uncover substantially more low-cost ore deposits. However, because of the fast growth anticipated for nuclear power, doubling the amount of ore only postpones the day of reckoning by about five years. Even if the amount of low-cost uranium is an order of magnitude higher than that estimated, the low efficiency converters could survive for only a few more decades. While new discoveries could change the degree of the problem slightly, only a major breakthrough, such as the economic separation of uranium from sea water,could change the over-all picture significantly. However, it is not likely that this development could assure uranium resources at costs less than $10 per pound of ore. Clearly then, either we must look to other types of reactors to postpone the time when we will exhaust our low-cost uranium ore, or we must design our reactors to utilize the more expensive ores economically.

In this section, we will be primarily concerned with an examination of a few reactor types to see how effective these reactors might be in conserving the low-cost uranium ores. We will not give particular attention to combinations of reactors in this section, and will not question where recycle fuel might be obtained for the fast reactors that operate most effectively with plutonium. This will be discussed in another section. The economics of reactor operation with the more expensive ores will also be discussed in another section of this report. It will be seen from succeeding comparisons that the HTGR and high-performance fast breeder reactors are, indeed, more effective in conserving the uranium resources than are the light-water and heavy-water reactors using the low-enrichment-uranium cycle.

Figure 3.2 shows the inventory and burnup requirements assuming all nuclear power in the future is generated from the HTGR plants. First of all, it is interesting to note that the difference between systems having conversion ratios of 0.95 and 0.90 is not very significant, since the predominant requirement, with such excellent neutron economy, is for supplying the fuel inventory to start up new reactors in the expanding nuclear power industry. It also is noted that the better characteristics of the HTGR result in uranium requirements that are only about one-third of the requirements previously shown for the less efficient reactors. In spite of this improvement, however, the critical date for exhaustion of uranium at any particular ore cost is delayed only about ten years.

The HTGR resource requirements shown in Fig. 3.2 are based on a fuel element design using BeO spines. If an all-graphite fuel element is assumed, the optimum conversion ratio is about 0.85 instead of approximately 0.95. However, the optimum specific power for the all-graphite core tends to be somewhat higher, and the total uranium requirements are about the same. Some improvements in the HTGR uranium requirements might be realized by future design developments, such as the controlled release of volatile fission product poisons. However, it is not likely that the total uranium requirements would be changed substantially. As will be shown in the subsequent discussion, it is also unlikely that other reactor systems could improve significantly, if at all, over the HTGR unless very-high-performance fast-breeder reactors should become economically and technically feasible within the next twenty years.

It is, perhaps, of special significance to examine the fuel requirements for a heavy-water reactor, since much attention(3, 6, 7) has been given to its potential for high specific power and good neutron economy. Several versions of the heavy-water reactor (HWR) have been developed or proposed involving different coolants and different fuel cycles. This discussion will be limited primarily to the heavy-water-cooled, heavy-water reactor described by the DuPont Laboratory(6, 8) and reviewed in the Comparative Evaluation of Advanced Converters by the Oak Ridge staff.(9) Based on reported data, the following characteristics were used for the HWR:

Reactor specific power, kw/kg 4000
System specific power, kw/kg 2000
Thermal efficiency 0.267
Conversion ratio 0.7

Figure 3.3 illustrates the uranium requirements for a power economy consisting entirely of HWR plants. It can be seen from the figure that the inventory requirements of a heavy-water reactor tend to be very modest, whereas most of the uranium requirements arise from the net fuel burnup.

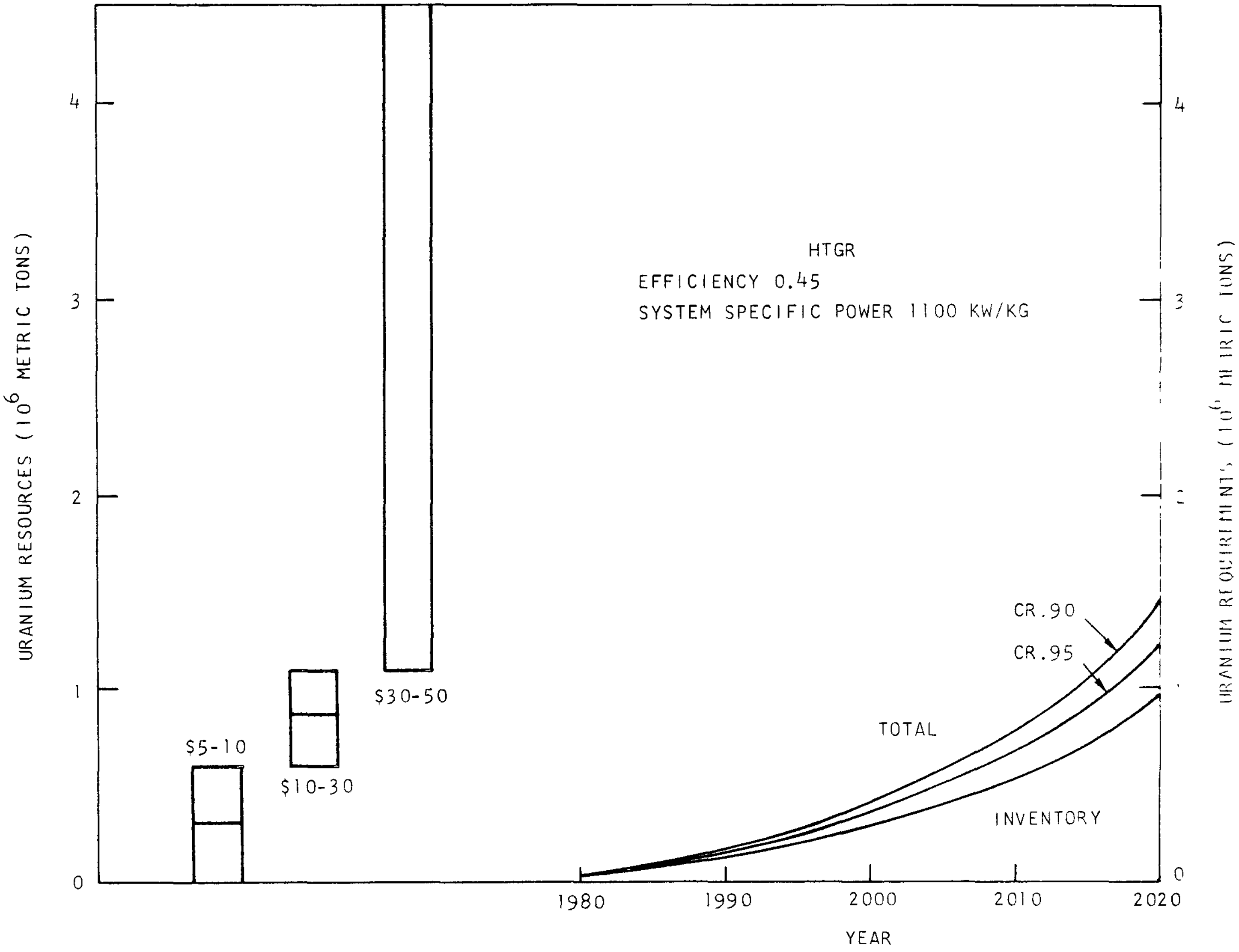

Fig. 3.2--Projected uranium requirements for the United States assuming all nuclear power to be supplied by HTGR plants

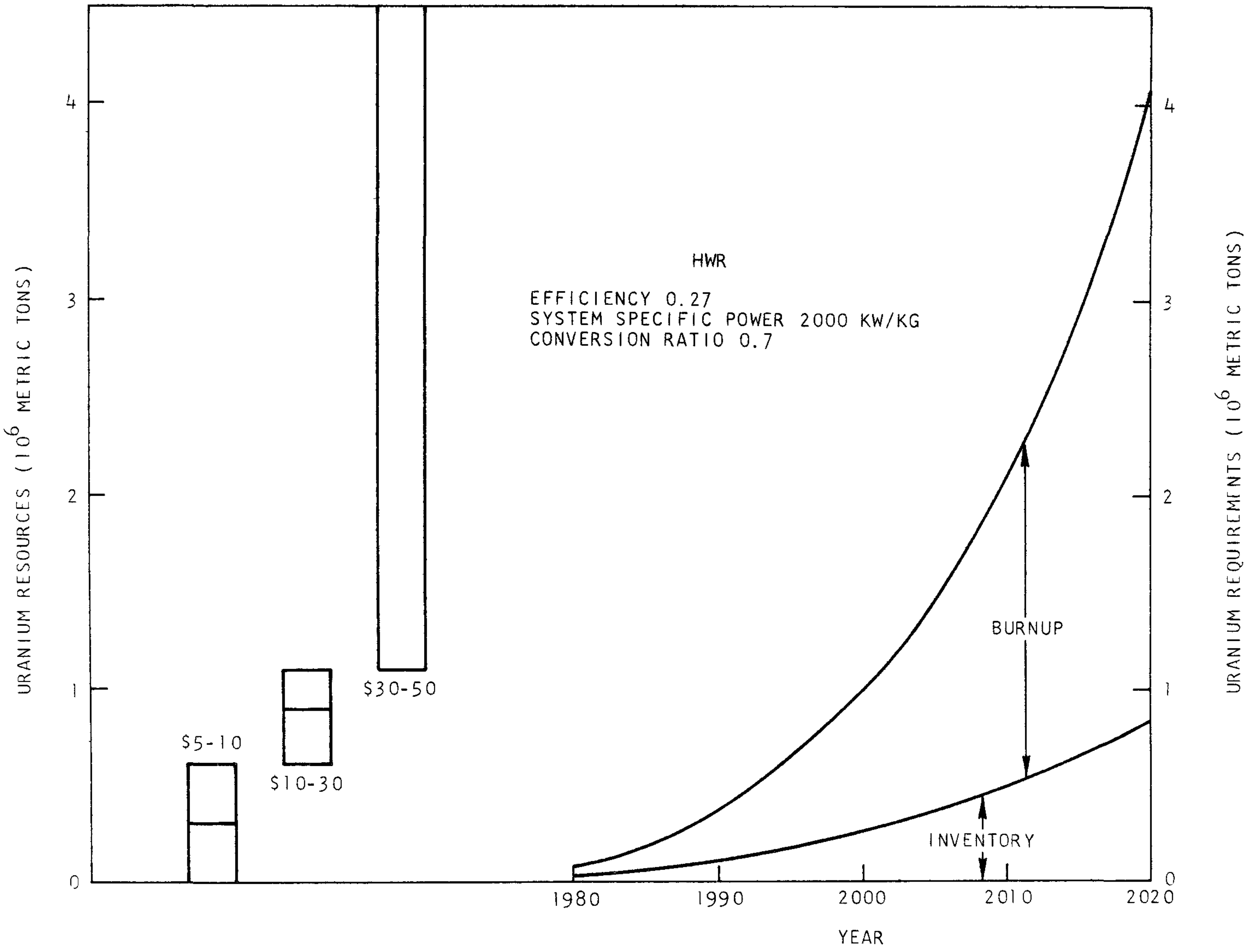

Fig. 3.3--Projected uranium requirements for the United States assuming all nuclear power to be supplied by heavy water reactors

Some consideration(8) has also been given to the U^{233}/Th^{232} cycle in the heavy water reactor. Although the net fuel burnup is considerably better for this fuel cycle, the inventory requirements are somewhat larger because of the low thermal efficiency and the limitation on specific power that is imposed by neutron losses to Pa^{233}. Furthermore, the fuel cycle costs tend to be higher for the U^{233}/Th^{232} cycle, so that there is little incentive to use this cycle in the heavy-water reactor.

The organic-cooled, heavy-water reactor (OHWR)(7) shows approximately the same over-all uranium requirements as the heavy-water-cooled, heavy-water reactor. Whereas the thermal efficiency of the OHWR is higher than the HWR, the specific power is lower, so that the effects compensate. In general, it can be seen that the uranium requirements for the heavy-water reactors are somewhat lower than those for the light-water reactors, but are significantly higher than for the HTGR.

Before leaving the subject of uranium conservation, it is of some interest to examine the performance of the fast-breeder reactors (FBR). This evaluation is even more difficult because of the very large uncertainties in the operating characteristics of this type of reactor arising particularly from materials problems and safety considerations. Because of heat transfer and physics considerations, it is generally more difficult to achieve a large specific power in the fast-spectrum reactor than in the thermal-spectrum reactor. Furthermore, it may be necessary to degrade the spectrum in at least some types of fast breeder reactors, in order to enhance the Doppler coefficient sufficiently to assure safe operating characteristics. Under these conditions, the breeding gain may optimistically be about 1.3, and possibly even smaller. A burnup time of 100,000 Mwd/T has generally been established as an objective for the fast breeder reactors using uranium and plutonium oxide fuel elements, but it is possible that materials damage problems could limit burnup times to less than 50,000 Mwd/T, thereby making the out-of-reactor inventory about as large as that in the reactor.

Figure 3.4 shows the uranium requirements that might be expected of fast-breeder reactors under various assumed conditions, if plutonium resources were immediately convertible from the U^{235} in uranium ore to start up the fast reactors. Curve A in the figure indicates the uranium requirements assuming the FBR plants have, on the average, a conversion ratio of 1.3, a reactor specific power of 800 kw/kg, and a fuel exposure time of about 100,000 Mwd/T. Curve B shows the requirements should it be necessary to degrade the conversion ratio to 1.1 and the fuel exposure time to 50,000 Mwd/T to avoid safety and materials damage problems. Curve B' indicates the effect of degrading only the conversion ratio.

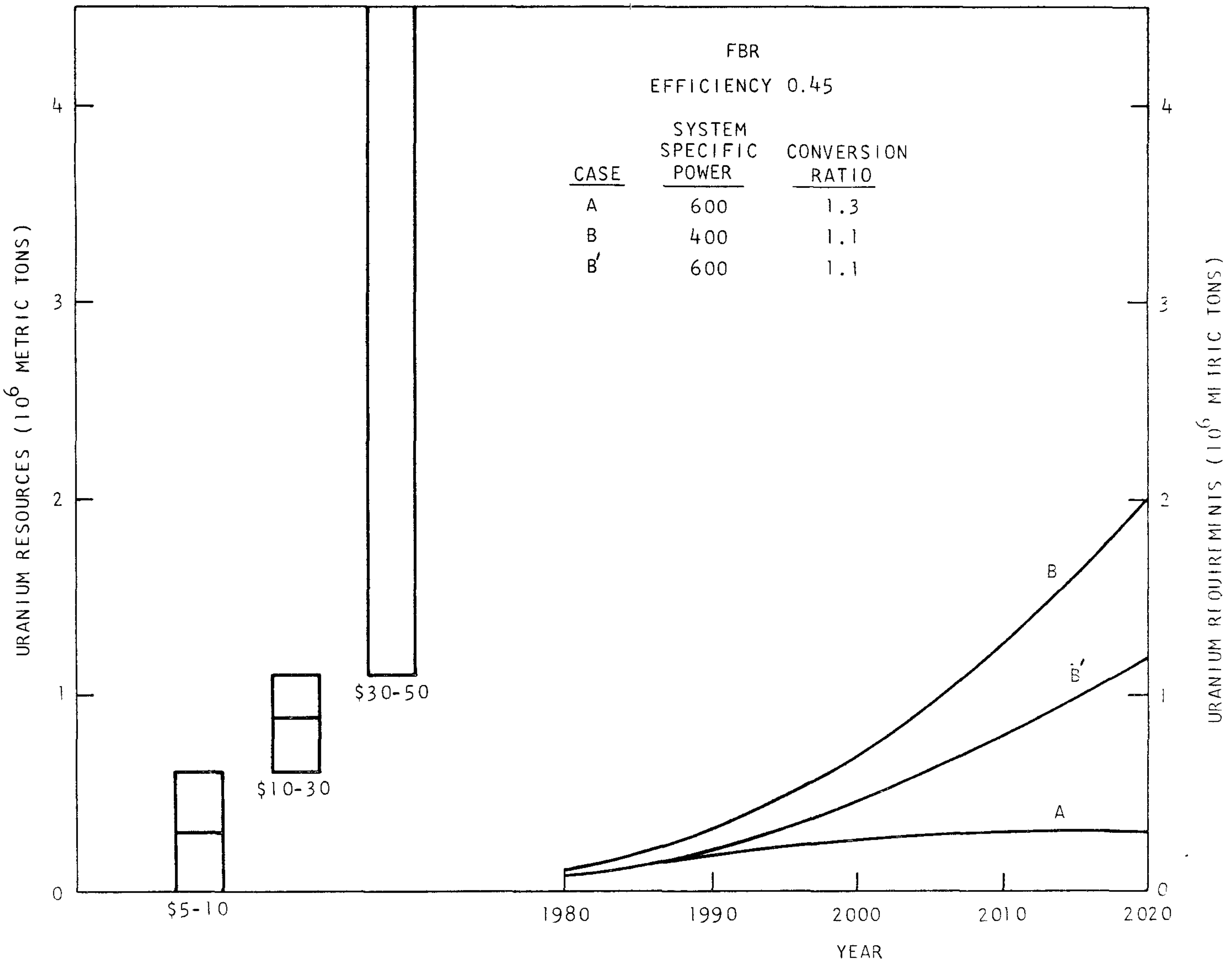

Fig. 3.4--Projected uranium requirements for the United States assuming all nuclear power to be supplied by fast breeder reactors

Under the assumption of immediate availability of plutonium from U^{235} with no loss of fissile material, it would appear from this analysis that the FBR typified by conditions A could utilize the resources quite effectively. In Section V we will examine the uranium requirements of a reactor system consisting of a converter and a breeder reactor. Under these more practical conditions, it will be seen that the total uranium requirements of the FBR will be affected quite strongly by the type of converter reactor used to supply the plutonium for the FBR. Under these more practical conditions, it is very probable that the low-cost uranium ores would be exhausted even with breeder reactors. The more important subject is, then, the potential economic performance of the various reactor concepts under varying conditions of uranium ore cost.

Consequently, the next section will deal with the economics of the various reactor systems under different assumptions of the nuclear ore cost. In the final analysis, our economic system will naturally select the reactor concept or concepts that will offer the most advantageous economics. If this system can maintain its economic advantage in the face of rising uranium ore costs, then, and only then, will our nuclear resources be utilized to the maximum extent.

IV. FUEL CYCLE ECONOMICS OF VARIOUS REACTOR CONCEPTS AS AFFECTED BY CHANGING URANIUM ORE COSTS

Nuclear power can contribute to the rapidly growing energy economy if the cost of generating nuclear power becomes and remains competitive with the cost of power from other sources, primarily the fossil fuels. While the discussion in this report is limited to the component of power cost associated with the fuel cycle, the fuel cycle cost objectives can be put in proper perspective by some reference also to the relative capital costs of fossil-fired and nuclear power plants. On the basis of experience to date, it appears that the capital cost of a large fossil-fired power station will be approximately $20/kw cheaper than that of a similar nuclear power station for a number of years. Consequently, in a private power economy the fuel cycle cost of a large nuclear power station must be at least 0.4 mill/kw-hr lower than that of a plant using fossil fuels. Approximately 50% of the installed generating capacity in the United States uses coal having an energy cost of 23¢/10^6 Btu, or greater. When used in a typical modern plant with a thermal efficiency of about 38%, coal at 23¢/10^6 Btu will generate electric power having a fuel cost component of about 2.1 mills/kw-hr. Nuclear power plants should, therefore, promise a fuel cycle cost of no more than 1.7 mills/kw-hr to be economically competitive with about 50% of our coal-fired power plants. Throughout our discussion of nuclear power economics we will, then, refer to 1.7 mills/kw-hr as a critical number for the acceptance of nuclear power stations. Obviously, reactors having higher capital costs would have to show an even lower fuel cycle cost.

It will be seen in the subsequent discussion that large nuclear power plants should have no difficulty in achieving fuel cycle costs below 1.7 mills/kw-hr, at least for the next two decades. This objective should, in fact, be made easier by the near-term decreases in uranium ore cost that are expected. In the long range, however, the uranium ore cost is expected to increase as the higher grade ores are exhausted. Under these conditions the critical fuel cycle cost becomes increasingly hard to meet, and the reactor performance characteristics become increasingly important.

In this section the importance of the various reactor performance characteristics will be examined by observing their effects on the fuel cycle cost for some very elementary reactor examples. The effect of ore costs on fuel cycle costs will then be illustrated for a few typical reactor conditions, and finally, the effects of probable economic and fuel availability trends will be examined as a basis for selecting appropriate combinations of reactor concepts to utilize uranium economically over the long range.

The relative importance of thermal efficiency, specific power, conversion ratio, and fuel burnup time on fuel cycle economics can be illustrated quite graphically by observing the cost effect of degrading successively each of these reactor performance characteristics in a simple recycle reactor. The following arbitrary economic assumptions have been made for these simplified fuel cycle calculations:

1. The fabrication charge is $100 per kg of metal.
2. The reprocessing and shipping charges are $50 per kg of metal.
3. The Th/U ratio is 30.
4. The interest rate is 10%.
5. The fuel turnaround time is 1 year.
6. The fuel value is $14 per gram of fissile material.

With these assumptions and the assumed reactor performance characteristics shown at the top of Table 4.1, the fuel cycle cost components and total fuel cycle costs for six sample cases are shown in the bottom part of the table. Case A represents a reactor having a reasonably good performance in all four areas. Case B shows the effect of degrading the thermal efficiency, Case C the specific power, Case D the conversion ratio, and Case E the fuel burnup time. Case F shows the effect of degrading two characteristics simultaneously, in this case the thermal efficiency and the fuel lifetime. As can be seen, the fuel cycle cost penalty is between 0.2 and 0.5 mill/kw-hr for each of the single degradations, and almost 1.2 mills/kw-hr for the double degradation. Clearly, it is desirable to design a reactor with good performance characteristics in all four areas simultaneously in order to achieve the best possible economic performance. In this respect, the HTGR excels as an advanced converter.

It was pointed out in the previous section that the requirements for uranium ore will not exceed the availability of low-cost deposits for about 30 years, even if relatively inefficient converters are used for nuclear power plants. In fact, because of the surplus of uranium ore that now exists, cheaper mining operations, and the introduction of toll enrichment, the cost of uranium ore is expected to fall from $8 per pound to $5 to $6 per pound almost immediately and remain there for 15-20 years.

Taking a more long-range point of view, it would be expected that the cost of uranium ore would rise quite rapidly after 1995 as the low-cost, high-grade uranium ore deposits are exhausted. Although this may seem rather far in the future, it must be recalled that reactors built after about 1980 will probably have to use the higher cost uranium for some significant fraction of their normal operating lifetime. Consequently, it is pertinent to examine the fuel cycle cost behavior of reactor concepts now being developed under different assumptions on the uranium ore cost. In this context we will look at the effect of uranium ore cost on fuel cycle costs for a light water reactor, a heavy water reactor, the HTGR, and some fast breeder reactors.

Table 4. 1

EFFECT OF REACTOR PERFORMANCE CHARACTERISTICS ON FUEL CYCLE COST

(U^{233}/Th^{232} Recycle Reactors)

	Case A	Case B	Case C	Case D	Case E	Case F
Thermal efficiency, %	45	30	45	45	45	30
Initial specific power, kw/kg	1000	1000	500	1000	1000	1000
Conversion ratio	1. 00	1. 00	1. 00	0. 80	1. 00	1. 00
Fuel life, years	4	4	8	4	2	2
Fabrication	0. 25	0. 37	0. 25	0. 25	0. 50	0. 74
Reprocessing	0. 12	0. 18	0. 12	0. 12	0. 25	0. 37
Depletion	0	0	0	0. 31	0	0
Working capital	0. 56	0. 83	1. 00	0. 48	0. 67	1. 00
TOTAL, mills/kw-hr	0. 93	1. 38	1. 37	1. 16	1. 42	2. 11

The economic assumptions and reactor characteristics used for the comparison of the thermal reactors are summarized in Table 4.2. The data are generally consistent with information contained in the Oak Ridge evaluation report(9) for advanced converter reactors and with other published reactor data, although some of the data have been simplified and rounded off. The fuel fabrication costs and reprocessing costs have been deliberately chosen to be very low, reflecting the state of technology that could possibly exist in another 15 to 25 years.

Figure 4.1 shows the fuel cycle costs for the LWR, HWR, and HTGR for different uranium ore cost assumptions. The first two reactors are both low-enrichment-uranium reactors while the HTGR is assumed to use the Th/U^{233} cycle with U^{235} makeup. The D_2O working capital and make-up charges have been added to the fuel cycle cost of the heavy water reactor. It can be seen that the projected fuel cycle cost for the HTGR is uniformly lower than that of the low-enrichment reactors. Furthermore, the increase in cost per unit rise in ore cost is considerably smaller for the HTGR than for the low-enrichment reactors. It is noted that the fuel cycle costs for the low-enrichment reactors all cross the critical cost line in the ore cost range of $10 to $15 per pound. The HTGR costs appear to be competitive, relative to the critical cost, for uranium ore costs well in excess of $30 per pound. A recent report by Davies, et al.,(5) states that laboratory experiments have shown that the enormous uranium resources in sea water can apparently be recovered at costs in the neighborhood of about $20 per pound. The HTGR fuel cycle cost using $20 per pound uranium ore is seen to be sufficiently attractive to suggest that the HTGR can be a long-range solution to the energy production problem.

It has frequently been suggested that the HWR (and possibly the LWR) might benefit in the long range by using the Th/U^{233} fuel cycle instead of the low-enrichment-uranium fuel cycle. Figure 4.2 shows the fuel cycle costs (again including D_2O charges) as a function of ore cost for the HWR low-enrichment reactor and the HWR Th/U^{233} recycle reactor. The HTGR is again shown for comparison. It can be seen that the Th/U^{233} cycle for the HWR is less attractive than the low-enrichment-uranium cycle for uranium ore costs up to about $20 per pound. At this point the fuel cycle cost has exceeded the critical cost, so that it is doubtful that recycle operations will ever be attractive in the HWR. While results are not shown for the LWR, the same general behavior is found for this reactor also.

Although the HTGR appears to be capable of solving the long-range energy supply problem, the HTGR will be come a long-range solution only if its power cost promises to be lower than that of other power plants. The strongest competitor is undoubtedly the fast breeder reactor. Hence, some attention has also been given to the fuel cycle costs of various fast

Table 4.2

ECONOMIC ASSUMPTIONS AND REACTOR PERFORMANCE DATA USED IN ECONOMIC EVALUATIONS

Uranium ore cost	Variable
Separative cost, \$/kg	30
U^{233}/U^{235} value ratio	14/12
$Pu^{239} + Pu^{241}/U^{235}$ value ratio	10/12
D_2O cost, \$/kg	44
Finished graphite cost, \$/kg	6
Working capital interest rate, %	10
Fuel turnaround time, years	1

	LWR	HWR	HTGR
Fuel cycle	U/Pu	U/Pu	Th/U
Fabrication cost, \$/kg	50	20	100
Shipping and reprocessing cost, \$/kg	30	20	50
Fuel burnup, Mwd/kg	22	15	~60
Fuel burnup, years	~4	~1	4
Initial specific power, kw/kg	~700	~4000	~1300
Conversion ratio	~0.6	~0.7	~0.85
Thermal efficiency	0.32	0.267	0.45

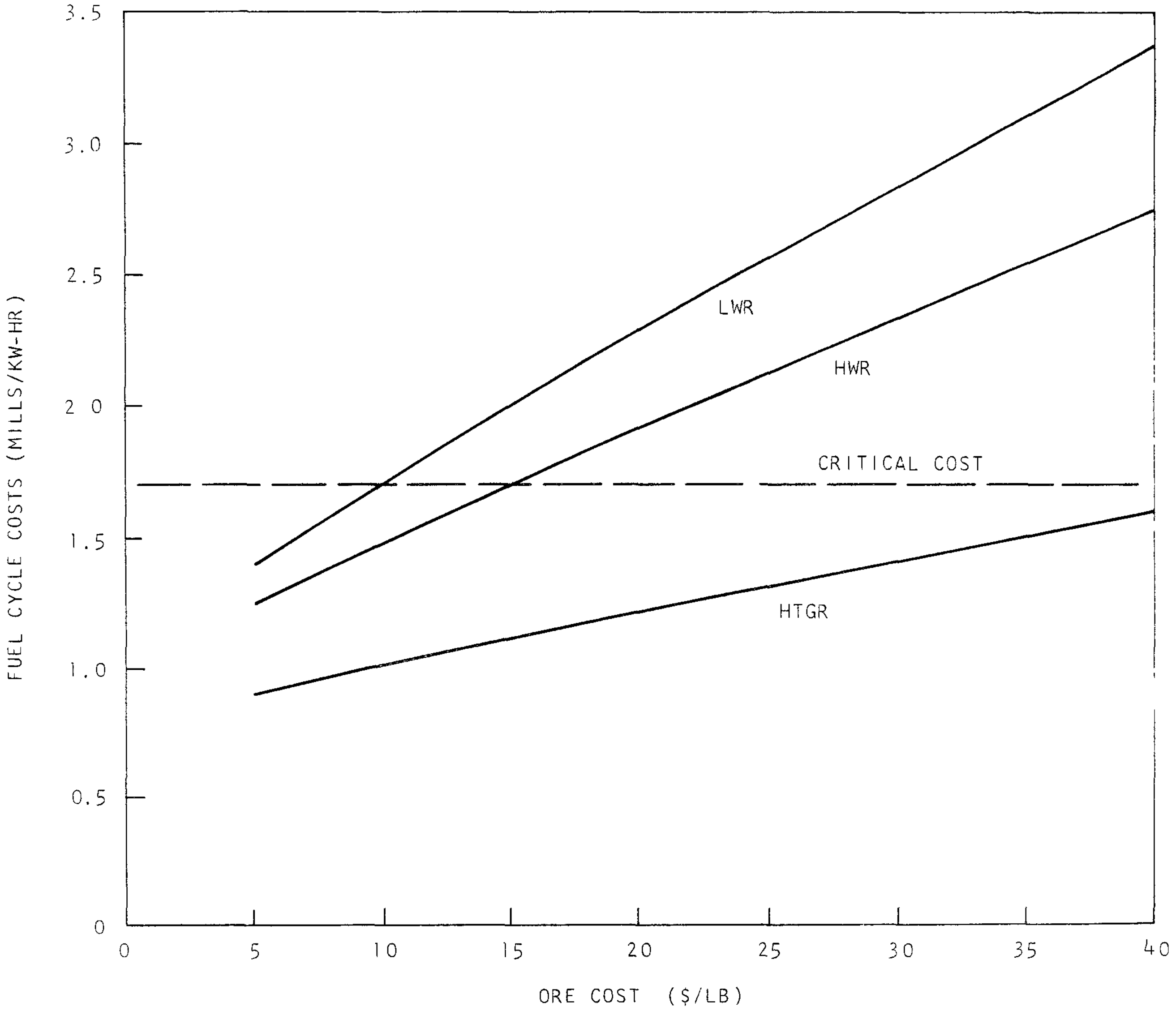

Fig. 4.1--Effect of uranium ore cost on fuel cycle cost for light water reactor and heavy water reactor using low enrichment uranium and the HTGR using the Th/U^{233} recycle

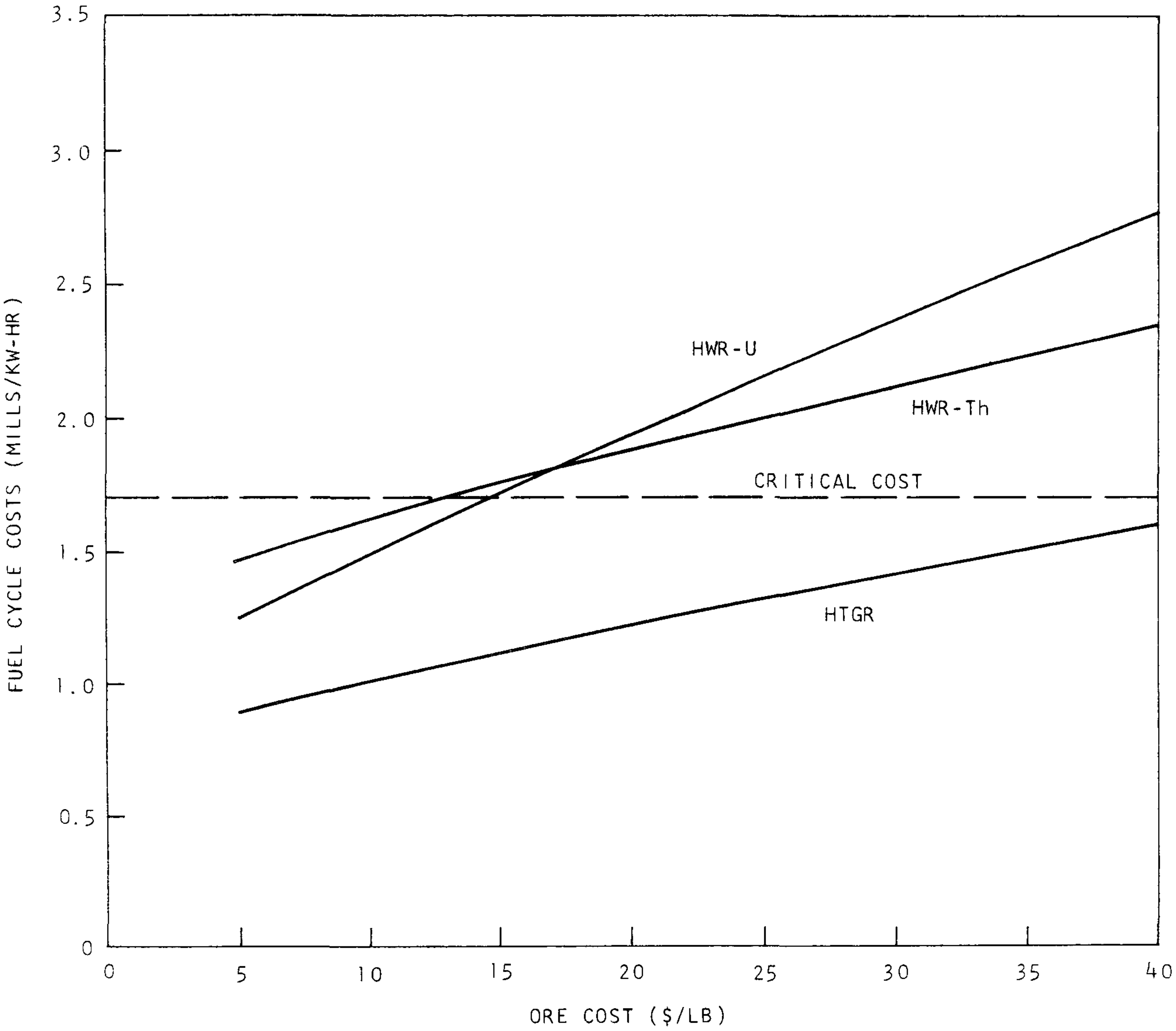

Fig. 4.2--Effect of uranium ore cost on fuel cycle cost for heavy water reactors using low enrichment uranium and Th/U^{233} recycle and the HTGR using the Th/U^{233} recycle

breeder reactors relative to the HTGR. An accurate appraisal of the fast breeder reactor is extremely difficult because of the many uncertainties in materials, physics, and safety problems. Some attempt has been made to estimate the effect of uranium ore cost on fuel cycle cost for the fast breeder reactors by using some of the results from the recent fast breeder reactor studies conducted by U.S. contractors(10) for the AEC as a base point. Hence, typical fabrication and reprocessing charges reported for oxide fuel elements have been used in these evaluations, and a conversion ratio of 1.30, a specific power of 800 kw/kg, and a fuel exposure of 100,000 Mwd/T have been assumed. These estimates appear to be optimistic objectives for the fast-spectrum, sodium-cooled reactor. Assuming that the value of fissionable plutonium is 10/12 that of U^{235} (possibly an overly optimistic low value if there is a strong demand for Pu) and assuming private financing, the fuel cycle cost as a function of uranium ore cost is shown by Curve A in Fig. 4.3. Under these favorable conditions, the fuel cycle cost is about 0.1 mill/kw-hr lower than that of the HTGR for ore at $6 per pound and about 0.2 mill/kw-hr lower for ore at $20 per pound. Hence, under these favorable conditions, the fast breeder reactor would be competitive with the HTGR if the capital cost of the FBR does not exceed that of the HTGR by more than about $10/kw(e).

Curve B in Fig. 4.3 indicates the fuel cycle cost for the same reactor if the conversion ratio and fuel exposure time must be degraded in order to satisfy safety and materials problems. In this case, it is seen that the fuel cycle cost for the fast breeder reactor is significantly poorer than that for the HTGR.

Curve C indicates the fuel cycle cost data for the case where the conversion ratio is 1.5 and the other performance characteristics are the same as assumed for Case A. These characteristics are typical of the objectives for the fast gas-cooled reactor using oxide-type fuel elements. This case clearly has the potential for showing a significant improvement over the HTGR in the long range and would seem to warrant a continuing development effort.

In the fuel cycle cost data presented for the HTGR, we have, until now, shown only the results of one set of core design conditions and economic assumptions. The detailed design specifications for an HTGR core would, of course, depend on many technical and economic considerations. A very large number of survey calculations have been done on the 1000-Mw(e) HTGR to define the range of interest for the various design parameters. Some of the results of these studies will be illustrated.

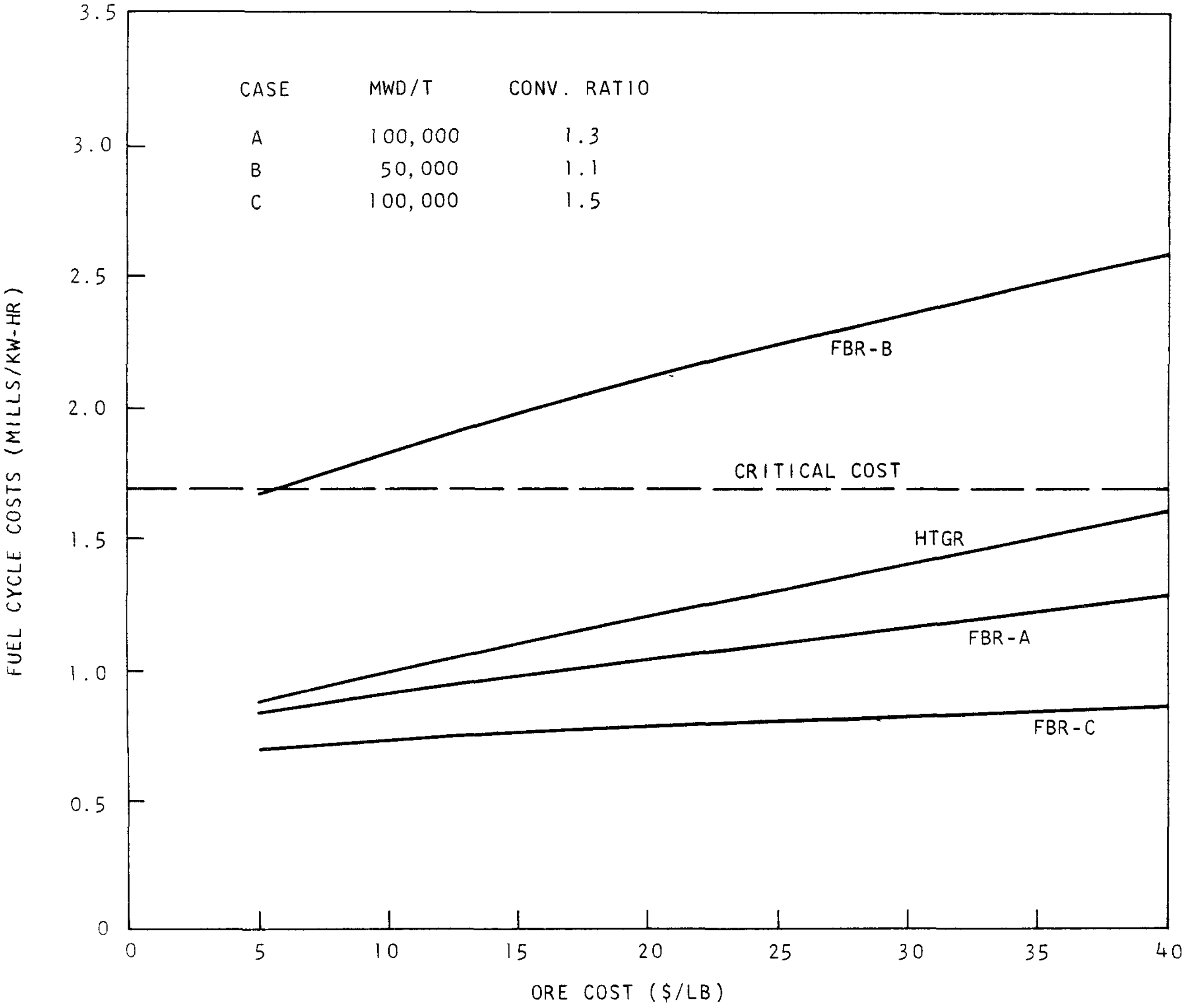

Fig. 4.3--Effect of uranium ore cost on fuel cycle cost for various fast breeder reactor conditions relative to fuel cycle cost for HTGR

The characteristics of the 1000-Mw(e) reactor are summarized in Table 4.3. Among the reactor characteristics that can be classified as independent variables are the following:

1. Fuel Cycle. The $U^{235}/Th^{232}/U^{233}$ cycle and the $U^{233}/Th^{232}/U^{233}$ recycle are of greatest interest for the HTGR. Studies have been made for the low-enrichment fuel cycle and for a recycle operation using Pu as makeup fuel. These cycles are the subject of a different paper.
2. Fuel Element Design. Two fuel element designs have been considered in the large HTGR studies. In one case, the fuel element incorporates a BeO spine whereas in the second, the entire moderator consists of graphite.
3. Initial Fuel Loading. The initial fuel loading is generally characterized by the ratio of moderator to fertile atoms, i.e., Be/Th or C/Th atom ratios.
4. Fuel Residence Time. Fuel residence times from three to ten years have been examined. In all cases it has been assumed that the reactor is refueled semiannually, with a fraction $1/2\tau$ of the fuel elements being replaced, where τ is the residence time.

For the studies reported here, the reactor power density has been chosen at 7 w/cm^3 and the core reflector has been chosen to be 61 cm thick. Some consideration has also been given to the use of thorium blankets at the edge of the core, and to the possible use of fuel elements designed to purge the volatile fission products. The use of thorium blankets would enhance the conversion ratio by about 0.02 over the values reported in this paper.

An HTGR using fuel elements with BeO spines and a thorium blanket would be able to achieve a conversion ratio greater than unity. This mode of operation might be economically attractive when the cost of uranium ore becomes sufficiently large or under circumstances where it might be desirable to be independent of an enriched uranium supply. The use of fuel elements designed to remove the volatile fission products might be justified when more experience is available on the control of fission products.

Table 4.4 illustrates some typical conversion ratios calculated under various HTGR operating conditions. Thus, for a 1000-Mw(e) HTGR with an all-graphite moderator, a conversion ratio of 0.75 is calculated for the case where U^{235} is used as the initial fuel charge. If the discharged U^{233} is stored for the first 6 years and subsequent cores are loaded with the first generation U^{233}, a conversion ratio of 0.99 could be achieved in the second core using an all-graphite-moderated core and a thorium blanket. With fuel elements containing BeO spines the conversion ratio could be as high as 1.05 under similar circumstances.

Table 4.3

SUMMARY OF THE PHYSICAL CHARACTERISTICS OF THE TARGET CORE

Power, Mw(t)	2340
Power, Mw(e)	1050
Coolant	Helium
Coolant inlet temperature, °F	720
Coolant outlet temperature, °F	1470
Fuel element diameter, in.	4.65
Fuel element pitch, in.	4.7
Fuel element array	Triangular
Fuel element length, ft	20
Core diameter, ft	31.1
Core length, ft	15.5
Number of fuel elements per core	5489

Table 4.4

NEUTRON BALANCES FOR VARIOUS HTGR CONDITIONS

Initial fuel	U^{235}	U^{233} (1st cycle)	U^{233} Recycle - (Equilibrium) (U^{235} makeup)		
Moderator	C	C	C	C/BeO	C/BeO
Fuel lifetime, years	4	3	4	4	4
Volatile fission product control	← Retained →				Withdrawn
η	2.06	2.22	2.16	2.17	2.22
$\epsilon\eta$	2.06	2.22	2.16	2.24	2.29
Losses					
Leakage	0.05	0.02	0.05	0.04	0.04
Moderator	0.03	0.03	0.03	0.04	0.06
Pa^{233} (× 2)	0.03	0.03	0.03	0.03	0.04
$U^{236} + Np^{237}$	0.02	--	0.01	--	--
Xe^{135}	0.04	0.04	0.04	0.04	--
Other F. P. P.	0.11	0.08	0.10	0.08	0.07
Control	0.03	0.03	0.03	0.02	0.02
Total losses, L	0.31	0.23	0.29	0.25	0.23
$\epsilon\eta-1-L$	0.75	0.99	0.87	0.99	1.06

Normally, it has been the custom at General Atomic to calculate the neutron balances for equilibrium conditions, i.e., after the fuel has been recycled through the reactor a very large number of times and the heavy element isotopes have reached an equilibrium atomic distribution. The buildup of some of the undesirable heavy element isotopes can be controlled by a fuel management program that either recycles the bred U^{233} only one cycle with the feed fuel (the once-through recycle), or keeps the makeup fuel distinct from other fuel and uses it for only one cycle, but continuously recycles the bred fuel (the bred-fuel recycle). The third column in Table 4.4 shows the neutron balance for an equilibrium cycle using the once-through-recycle fuel management program. The fourth column shows a similar cycle, but with fuel elements containing BeO spines. With a thorium blanket, a conversion ratio of about 1.01 could be achieved for this case even for the equilibrium condition. The final column indicates the conversion ratio that might be achieved if the volatile fission products are withdrawn from the fuel elements.

The C/Th and Be/Th atom ratios are very important parameters. It is generally found that the optimum C/Th or Be/Th ratios depend on other factors, such as the cost of fuel, the cost of fuel fabrication and reprocessing, and temperature limitations on the fuel elements. We will not attempt to present a detailed description of the effect of this particular variable on reactor performance characteristics. Hence, in the following discussion, the C/Th and Be/Th ratios will be chosen to be typical values pertinent to a particular set of cost assumptions.

The optimum fuel exposure lifetime in the HTGR depends on the cost of the fuel fabrication and reprocessing and, to some extent, on the cost of the uranium fuel. For the next decade, for example, while fuel manufacturing technology is still being improved and while the volume of production is expected to be relatively small, the cost of fuel fabrication will be sufficiently high to encourage a relatively long fuel lifetime in the reactor. Since a shorter fuel lifetime results in a better conversion ratio and therefore a lower depletion cost component, it is economically beneficial to decrease the fuel lifetime, within limits, when the fabrication and reprocessing costs justify such a decrease.

Since it is too early to estimate the future cost trends accurately for fuel processing, we have prepared fuel cycle costs for several possible processing cost patterns. The assumptions are as follows:

Fabrication Cost ($/kg)	Shipping and Reprocessing Costs ($/kg)
300	150
200	100
100	50

In each case, an additional \$500 per fuel element is assumed for the cost of the finished graphite pieces. There is no particular basis for the specific choice of the numbers, except that the range is expected to cover future costs and the fabrication cost should certainly decrease with time and experience. The lowest cost shown on the figure corresponds approximately to the fabrication cost estimated by the Oak Ridge analysis.(9)

Figure 4.4 illustrates the fuel cycle costs as a function of fuel lifetime for the above three different assumptions on fabrication and reprocessing costs. The data assume recycle operations with U^{235} makeup and with fuel elements containing only graphite as a moderator material. It can be seen that the optimum fuel lifetime is 4 to 5 years if the fabrication cost becomes \$100 per kg, or less. However, with the higher fabrication cost the optimum fuel lifetime is larger.

Figure 4.5 shows the calculated conversion ratio as a function of fuel burnup time. In this figure results are shown both for the graphite fuel element and the graphite/BeO fuel element. As would be expected, the conversion ratio improves significantly as the fuel exposure time (and consequently the fission product inventory) is reduced. Remembering that the conversion ratio is improved by about 0.02 when a thorium blanket is included, it can be seen that a conversion ratio greater than unity can be achieved with the graphite/BeO fuel element and a fuel life of 3 years.

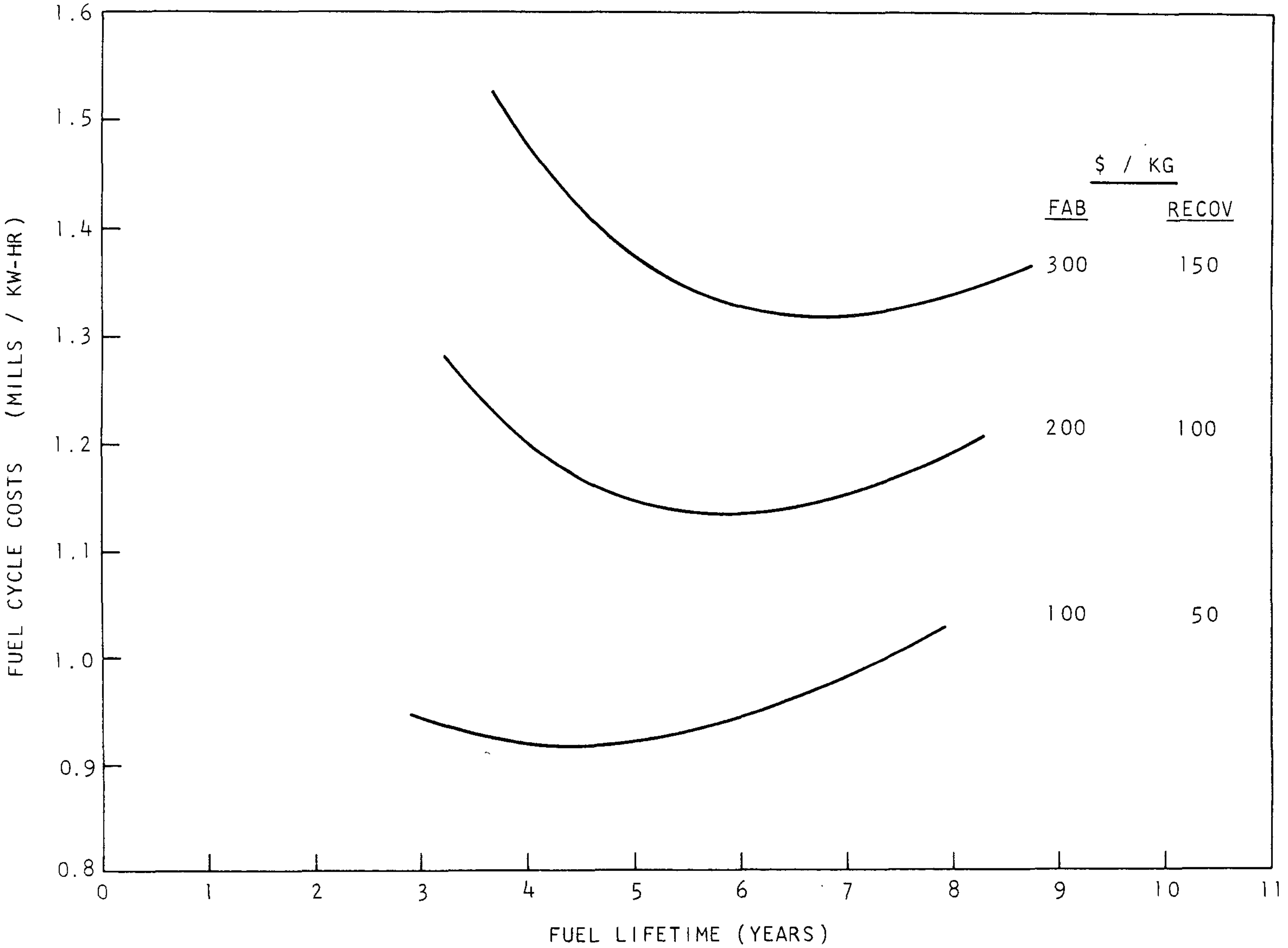

Fig. 4.4--Effect of fuel exposure lifetime on HTGR fuel cycle cost for various assumed fabrication and recovery costs

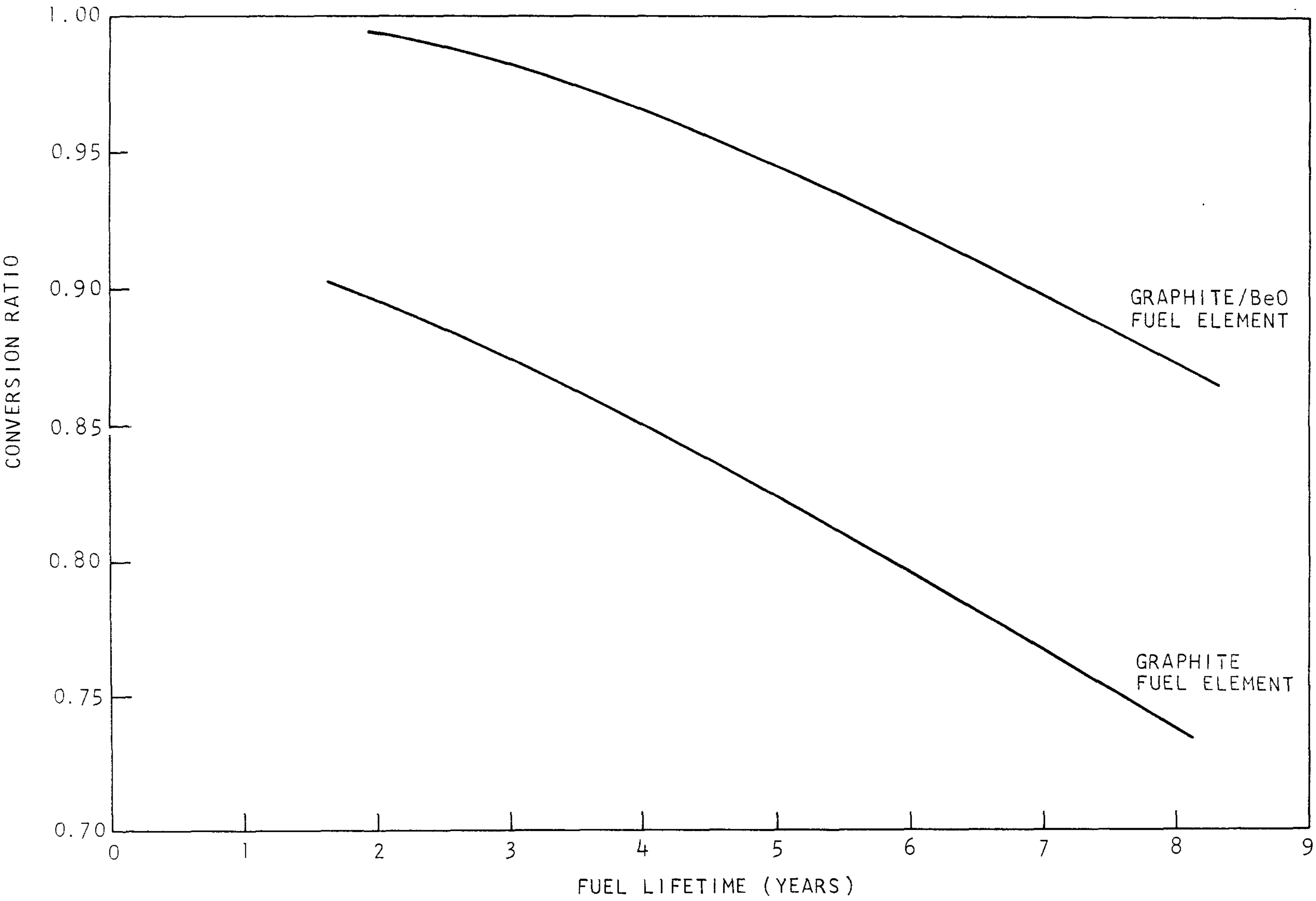

Fig. 4.5--Effect of fuel exposure lifetime on HTGR conversion ratio for two fuel element designs

V. RESOURCE UTILIZATION IN REACTOR COMBINATIONS

The importance of the reactor performance characteristics on uranium conservation and uranium utilization has been examined in Sections III and IV. It was tacitly assumed in the previous sections that U^{233} would be available for starting up thermal spectrum advanced converter reactors and Pu would likewise be available for starting up fast breeder reactors in whatever quantity was required. In practice, both of these fuels must, of course, come from the discharge of previous reactor cycles, since neither exists in nature. The rate of introduction of the recycle reactors is, then, limited by the production rate of U^{233} or Pu in nonrecycle reactors. A complete analysis of the utilization of nuclear resources must then include an evaluation of reactor systems involving some reactors that produce the desired fuels (i.e., feeder reactors) and reactors that use the bred fuels (i.e., fed or recycle reactors). A complete evaluation of these symbiotic systems represents a rather complicated operations research study, since it depends on detailed information of future nuclear fuel values, fuel supply and demand, and reactor operating characteristics and economics. Such an analysis is probably impractical at this time because of the limited amount of reliable information available. However, some general conclusions regarding the practicality of various symbiotic reactor combinations can be seen by some rather simple analyses of the uranium consumption and the fuel cycle economics for these combinations. The results of some of these studies will be presented in this section.

The startup of new reactor plants and the approach to recycle equilibrium of the new plants can be accomplished in several ways, two of which are:

1. Each reactor is initially fueled with U^{235} and either U^{238} or Th^{232}. The bred fuel is stored, kept separate from the fed fuel, and subsequently reused in the same reactor, with U^{235} makeup if necessary.

2. A symbiotic reactor system can be assumed in which some of the reactors are always fed with U^{235} and either U^{238} or Th^{232}. The bred fuel from these converter or feeder reactors is then used only in the fed or recycle reactors. New fed reactors can be started up only when fuel is available either from their own excess production or from the nonrecycle feeder reactors. If

more capacity is required than the fed reactors can provide, additional feeder reactors must be installed.

In this analysis, the second approach has been used, since it allows greater flexibility in optimizing the feeder—fed reactor system and indicates how current reactors can be used to produce the desired fuels. The growth curves for the installed capacity of nuclear power and the cumulative energy generated were covered in detail in Section II.

Two symbiotic systems involving HTGR feeders and HTGR recycle reactors were studied. The first of these, which resulted in a particularly small demand on nuclear resources, was a system consisting of

1. HTGR feeder plants using U^{235}/Th nonrecycle, a fuel element design that incorporates BeO in the spines, a Be/Th atom ratio of 28, and a fuel residence time of three years.
2. HTGR fed plants using the U^{233}/Th recycle, fuel elements with BeO spines, a Be/Th ratio of 40, and a fuel residence time of three years.

The ratio of recycle to feeder reactors and the net resource requirements for this complex are shown in Fig. 5.1. When the capacity is growing very rapidly, about 60% of it can be accommodated with recycle reactors. However, when the doubling time stretches out to ten years or more after year 2000, the recycle reactors account for about 80% of the capacity. The net uranium resource requirement by the year 2020 is 1.1×10^6 metric tons, which is only slightly above that estimated to be available at $5 to $10 per pound.

A second HTGR system was considered that exhibits a somewhat larger nuclear resource commitment but probably operates with lower fuel cycle costs. This system is composed of

1. HTGR feeder plants using U^{235}/Th nonrecycle, a fuel element design that uses only graphite as moderator, a C/Th ratio of 200, and a fuel residence time of four years.
2. HTGR fed plants using U^{233}/Th recycle, all-graphite fuel elements, a C/Th ratio of 200, and a fuel residence time of four years.

The ratio of recycle to feeder reactors and the net resource requirements for this system are also shown in Fig. 5.1. During the period of rapid growth, the recycle reactors can accommodate only about 30% of the required capacity. When the growth rate slows down, roughly 50% of the capacity can be accommodated by the recycle reactors. By the year 2020, this reactor system requires roughly 1.9×10^6 metric tons of

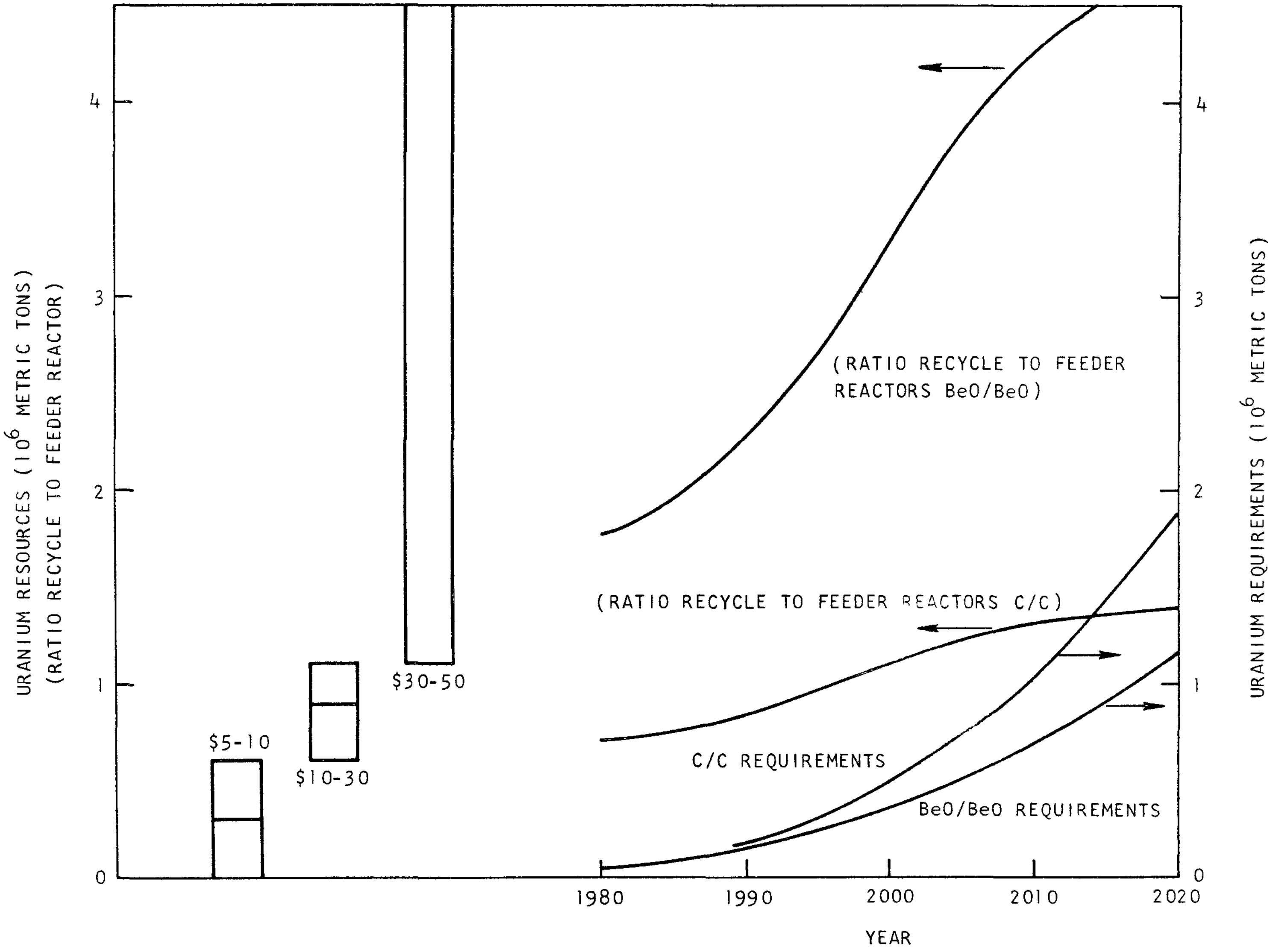

Fig. 5.1--Uranium requirements and relative number of recycle to feeder reactors for two HTGR symbiotic systems

uranium resources. As a point of comparison, it is recalled that a light water reactor would require in excess of 5 × 10^6 metric tons of uranium.

The fuel cycle characteristics of these symbiotic reactors are shown in Table 5.1. In the case of the system using reactors with fuel elements having BeO spines, about 80% of the energy up to the year 2020, is generated in the very high conversion ratio, recycle reactors. Therefore, the average conversion ratio for the system is about 0.98, which is quite close to the equilibrium cycle value of 0.97 with U^{235} feed. For the system with all-graphite fuel elements, about 50% of the energy up to the year 2020 is generated in the recycle reactors. Therefore, the average conversion ratio for this system is roughly 0.86, which again, is quite close to the equilibrium cycle value of 0.83 with U^{235} feed.

For comparative purposes, several other symbiotic systems have been considered in which plutonium was manufactured in thermal or fast reactors from U^{235} and subsequently used to provide the initial fuel to fast breeders. The plutonium-fueled fast reactors were allowed to pick up as much new capacity as they could accommodate. These systems are characterized in Table 5.2. The nuclear resource requirements for these reactor systems are shown in Fig. 5.2, together with the HTGR systems. It is clear that, from the point of view of resource conservation only, the best way to start up the plutonium-fueled fast reactor is to use U^{235}-fueled fast reactors. The thermal reactors provide plutonium at too slow a rate. It is found that the HWR/FBR system requires about the same resources as the LWR/FBR system. The HWR uses the resources quite well, but produces very little Pu, since most of the Pu made is burned in situ. This behavior could be modified, but probably at a significant increase in fuel cycle costs.

The HTGR system is competitive with the U^{235} fast reactor system until the doubling time stretches out to ten years. Beyond this point the installed plutonium-fueled reactors can meet the new capacity with their own excess production of plutonium. However, it should be noted that the uranium requirements for the systems involving the FBR assume that the previously stated objectives of the FBR will be met. If, for example, the conversion ratios for these reactors should be, say, 1.1 and/or the system specific power about 400 kw/kg, because of safety and materials limitations, then all of the systems using the FBR would require in excess of 2 × 10^6 metric tons of uranium resources by the year 2020. Since all of the systems involving the HTGR or the FBR show uranium requirements very close to the probable division point between low-cost and higher-cost uranium ore supplies, it is difficult to state reliable conclusions, particularly in view of the large uncertainties in available resources, nuclear energy buildup, and actual reactor performance characteristics. In any

Table 5.1

FUEL CYCLE CHARACTERISTICS OF SYMBIOTIC, 1000-MW(e) HTGR COMPLEXES

C/Th (Be/Th)	(28)→(40)		200→200	
Fuel residence time, years	3	3	4	4
Fuel management	Non-recycle	Once-through	Non-recycle	Once-through
Conversion ratio	0.85	1.01	0.73	0.90
Eta	2.00	2.22	2.08	2.22
Burnup, fifa	0.7	1.6	1.4	2.0
Initial specific power, kw/kg	700	1700	1100	1600
Initial fissile loading, kg	3300	1400	2100	1460
Net fissile requirements, kg/yr	630	0	480	90
Fissile available to fuel recycle reactors, kg/yr	480	--	220	--

Table 5.2

FUEL CYCLE CHARACTERISTICS OF SYMBIOTIC, 1000-MW(e) REACTOR COMPLEXES

Reactor Type	Light Water	Fast Breeder	Heavy Water	Fast Breeder	Fast Converter	Fast Breeder
Fissile material	U^{235}	Pu^{239}	U^{235}	Pu^{239}	U^{235}	Pu^{239}
Fuel management	Non-Recycle	Recycle	Non-Recycle	Recycle	Non-Recycle	Recycle
Burnup, Mwd/t	20,000	100,000	15,000	100,000	-	100,000
Conversion ratio	0.6	1.3	0.7	1.3	0.93	1.3
Initial specific power, kw/kg	1000	800	3600	800	500	800
Initial fissile requirements, *kg	3900	3700	1040	3700	6100	3700
Net U^{235} requirements, kg/yr	730	0	660	0	~800	0
Fissile Pu available, kg/yr	230	200	205	200	~800	200

*Includes requirements to accommodate one year external to the reactor.

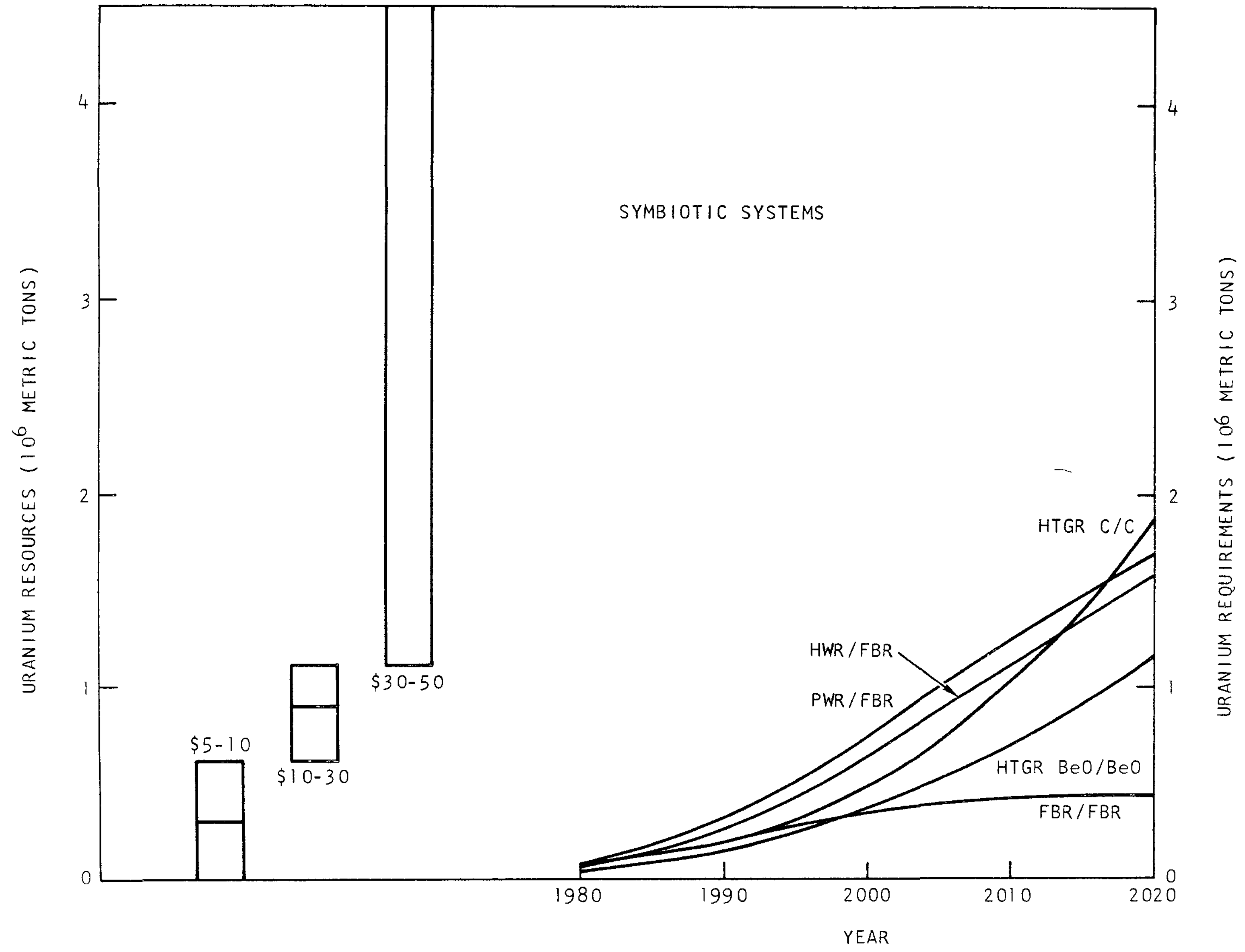

Fig. 5.2--Uranium requirements of various reactor symbiotic systems

case, it is probably more significant to examine the economic performance of the various systems under various assumptions on uranium ore costs.

Tables 5.3 and 5.4 summarize the approximate fuel cycle economics calculated for the various symbiotic systems under two different assumptions on uranium ore cost. The fast breeder reactor characteristics have been chosen to be consistent with the data previously presented. For the FBR fueled with U^{235}, we have used a core that is physically similar to the Pu-fueled FBR, i.e., the fuel is oxide with about equal fuel element dimensions and volume fractions of cladding and coolant. The specific power and conversion ratio for the fast-spectrum reactor are substantially degraded for the case where the initial fuel is U^{235}, since the spectrum-averaged fission cross section and eta values for U^{235} are considerably poorer than the values for plutonium. Consequently, the fuel cycle costs for the fast feeder reactor are significantly higher than the costs for the fast recycle reactor.

The FBR-A, it will be recalled, assumed a conversion ratio of 1.3 and a reactor specific power of 800 kw/kg for the plutonium-fueled core. The FBR-C was a higher-performance fast-spectrum reactor having a conversion ratio of 1.5. The compromise case, i.e., FBR-B, is not shown, since it was clear that it could not compete with the HTGR in the simple recycle mode.

It can be seen from the data in the tables that the thermal-spectrum reactors associated with the fast reactors all lead to poorer average fuel cycle costs than those for either the HTGR/HTGR system or the FBR/FBR systems. In addition, the fuel cycle costs individually for the LWR and HWR do not appear to be as attractive as those for the HTGR, as has been pointed out previously. Hence, in the long range, it appears that the LWR and HWR do not offer advantages as sources of plutonium for the FBR.

The fuel cycle cost for the FBR feeder using U^{235} fuel is quite high relative to the recycle case, but with the conversion ratio and specific power we have assumed for the Pu-fueled FBR, the integrated energy from the FBR feeder reactor over a 30—50-year period is quite small relative to that of the recycle reactor. Therefore, the high feeder fuel cycle cost in the U^{235}-fueled FBR can probably be justified in the long range on the basis of the average fuel cycle cost for the system. This argument does not apply to the thermal/fast systems since the productivity of plutonium from the thermal reactors is considerably smaller.

In conclusion, we believe that the most promising symbiotic systems are the HTGR/HTGR and the FBR/FBR systems. Looking only at the uranium conservation aspects of the various possibilities, it is apparent that the HTGR is clearly superior in performance to the other thermal-spectrum reactors by themselves, and would probably be superior to the

Table 5.3

FUEL CYCLE COSTS FOR SYMBIOTIC SYSTEMS ASSUMING FUEL VALUES BASED ON URANIUM ORE AT $8 PER POUND

Reactor System	U^{235} Cost (\$/g)	(Pu^{239} + Pu^{241}) or U^{233} Value (\$/g)	Fuel Cycle Cost (mills/kw-hr)		
			Feeder Reactor	Recycle Reactor	Energy-weighted Average to 2020
HTGR/HTGR	12	14	1.1	0.95	1.0
BWR/FBR-A	12	(10)	1.6	0.90	1.2
HWR/FBR-A	12	(10)	1.4	0.90	1.1
FBR-A/FBR-A	12	(10)	1.6	0.90	1.0
FBR-C/FBR-C	12	(10)	1.5	0.70	0.7

Table 5.4

FUEL CYCLE COSTS FOR SYMBIOTIC SYSTEMS ASSUMING FUEL VALUES BASED ON URANIUM ORE AT $20 PER POUND

Reactor System	U^{235} Cost (\$/g)	(Pu^{239} + Pu^{241}) or U^{233} Value (\$/g)	Fuel Cycle Cost (mills/kw-hr)		
			Feeder Reactor	Recycle Reactor	Energy-weighted Average to 2020
HTGR/HTGR	18	21	1.4	1.2	1.3
BWR/FBR-A	18	(15)	2.3	1.05	1.5
HWR/FBR-A	18	(15)	1.9	1.05	1.4
FBR-A/FBR-A	18	(15)	2.1	1.05	1.1
FBR-C/FBR-C	18	(15)	1.9	0.80	0.8

LWR/FBR and HWR/FBR systems for the next 50 years. On the basis of resource conservation alone, the FBR/FBR system could offer advantages over all the other possibilities providing the recycle FBR is able to achieve a conversion ratio in the range of 1.3, a specific power of 800 kw/kg and a fuel burnup of 100,000 Mwd/T.

Turning to the more important question of economic performance, the HTGR promises substantially lower fuel cycle costs than the LWR or HWR in the long range, and the HTGR/HTGR system can apparently offer better fuel cycle cost performance than the LWR/FBR or BWR/FBR systems for the next 50 years or more, assuming the FBR would have, on the average, performance characteristics typified by the FBR-A objectives. Although the initial operation of the FBR with U^{235} fuel would result in a relatively high fuel cycle cost, the most economic symbiotic system involving the fast breeder reactors would be the FBR/FBR.

Primarily on the basis of development status and economic potential, it would appear that the HTGR/HTGR system would gain acceptance over the other thermal reactors when the performance potential of the HTGR becomes generally accepted. If the FBR is developed to the point where the recycle reactor operation has performance characteristics typified by the FBR-A objectives, then this reactor could gain acceptance by the utility industry, providing the capital cost of the FBR plant does not exceed that of the HTGR by more than about $10/Kw(e).

In summary, considering the small potential margin of improvement accomplished by the FBR-A plant over the HTGR plant, we believe that the FBR must set higher objectives. It is partly for this reason that General Atomic has focused its attention on the gas-cooled, fast breeder reactor as a long-range development concept.

We believe that it is much too early to predict the trend in future reactor acceptance with any certainty Clearly, however, it is important that advanced nuclear power plants be available in the next few decades, particularly if the uranium ore costs should increase significantly. The HTGR has the potential for supplying the long-range energy needs of the world at economically attractive prices, even in the face of rising costs for uranium ore.

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