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THE ECONOMIC INCENTIVE FOR THORIUM REACTOR DEVELOPMENT

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The Energy Supply Problem

Throughout the nuclear power industry, people have in recent years become increasingly aware of the fact that mining uranium for its fissile content can at best be only a temporary solution to the energy supply problem. There is just not enough low cost uranium ore to sustain mankind's power needs for long, especially in view of the rapid growth of these needs. Although the vast quantity of high cost fissile uranium existing in the earth's crust can conceivably be considered a source of energy, to utilize this source as such would entail expenditures far greater than could be tolerated by our expanding civilization. The solution to the long term energy supply problem therefore, as everyone well recognizes is to produce all future fissile needs by breeding rather than by mining U-235. Since an abundant supply of bred fissile material means an abundant supply of neutrons, which in turn can be used to produce more fissile material from U-238 or thorium, breeding is effectively a "renewable" source of energy whose costs are no longer sensitive to the costs of mined source material. Latent energy sources such as fossil fuels and mined (and separated) U-235, on the other hand, even though they may be "relatively inexhaustible" will always be confronted by the problem of rising production costs. When application by application, these costs become prohibitive, the use of such latent sources must necessarily dwindle and the renewable sources take over.

Of the many possible renewable energy sources that exist in the world such as wind, tides, solar energy, farm wastes, etc., only the breeding of fissile material appears to be sufficiently economic, adequate and adaptable to serve as an overall long term energy source. Thus the question to be answered for each individual needs is not "Must we develop nuclear power breeders?", but rather, "When must we develop nuclear power breeders?". In this context, the word "develop" should be taken to mean "develop to the point where they are economically competitive with alternative power sources" because regardless of their state of technical development no breeders will be exploited commercially unless they are economically competitive. It is obvious that the answer to the above question is "As soon as possible" merely because renewable

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energy sources are economically stable over a long period whereas latent energy sources are not. The main problem then is to find the optimum, shortest path to follow to develop such breeders. It is the purpose of this paper to show how thorium fits into this overall picture.

Economics and Fuel Utilization

The development of any power system whether it be nuclear or conventional is complicated because of the many opposing forces which influence the path taken. In general, economic factors such as investment and operating costs, costs of money and anticipated profits dictate the direction to go; however, for any new unit being considered, these are tempered by an assessment of the reliability and performance of the unit and the overall risk involved. Because most power systems are developing very rapidly, gross changes in technology and particularly in the fuel supply picture are likely to occur during the life span of any individual plant. In spite of this, most decisions are based mainly on prevailing conditions rather than on future possibilities even though these latter might indicate a different direction to take.

The nuclear industry, in particular, is characterized by such an approach. Present lines of development are based almost entirely on historical origins rather than on future outlooks. These historical lines of development unfortunately involve reactor designs and systems, such as the light water moderated reactors, which have been optimized for minimum power costs in an era of cheap and abundant uranium. For this reason, most present day reactors are wasteful of neutrons and thereby have very poor fissile production characteristics. Because of this, they consume rather than produce fissile material and in order to produce cheap power are more or less completely dependent on a continuing supply of low cost uranium from the ground. Fortunately, present estimates indicate that resources of cheap uranium are relatively plentiful compared to present and near-future needs. Thus, current technology light water reactors appear to be an acceptable short term solution to the energy supply problem even though they may be inadequate as a long term energy source. The question now becomes - "How can the gap between present day reactors and breeders best be bridged?"

One obvious approach, of course, is to start with present day reactors and gradually improve their neutron utilization characteristics (measured in terms of fissile material produced) with the hope that they might evolve into breeders. Although this approach may result in reactors with very good fuel utilization characteristics, the disparity between neutron utilization in current reactor types and what is needed for the reactors to be efficient breeders seems too great to overcome. It is not enough for reactors to eliminate the consumption of fissile material, they must go beyond this point and produce excess fissile material at a rate adequate to meet all needs.

A second approach to the establishment of a breeder industry, which is the one generally being pursued, is to support an independent line of fast reactor development leading hopefully to commerically exploitable fast breeders. The chances of success in this direction are very good; however, the technology of sodium cooled fast breeders on which most hopes are based, is radically different from that of current technology water reactors. Unknown problems and uncertain economics confront the fast breeder line of development, as a result of which, the time required for complete success is quite uncertain. Thus, a considerable time might elapse during which a large amount of uranium must be mined to support the U-235 consuming industry. If too long a time is allowed to elapse before bringing fast breeders on the line, the amount of money spent on mining uranium and separating the U-235 in diffusion plants will reach astronomical proportions.

A third approach which represents the middle ground between the two approaches previously described may be the answer. This approach involves the development of reactor systems whose technology is not appreciably different from that of present day reactors but which offer the possibility of developing into efficient breeders. Such reactors can not only reduce the consumption of uranium in the interim period but without drastic changes in technology can also solve the long range problem of providing a new source of fissile material by breeding. It is in this category of reactors that thorium fueled reactors belong.

The Future Role of Thorium Converters and Breeders

The role of thorium reactors may be twofold; first, as recycle converters which make better use of mined U-235 than U-238 based converters; and second, as high performance thermal breeders playing a primary or secondary role to fast breeders. Implementation of the first role, namely the development of advanced thorium converters, may achieve the following three objectives:

a) reduction in nuclear fuel cycle costs.

b) reduction in the requirement for mined uranium and associated U-235 separation in diffusion plants.

c) development of a technology which might result in high performance thermal breeders.

The justification for pursuing these objectives, however, depends on what it costs to attain them compared to future savings that might result. In the last section of this paper, a quantitative assessment of this aspect is given which indicates that the present worth of future savings achievable through the successful development of advanced thorium converters followed by thermal breeders may far exceed presently planned expenditures for the development of such reactors.

The primary incentive for pursuing the longer range goal of establishing a thermal breeder complex of significant size is that such breeders have lower specific inventories (kg fissile/Mwe) than fast breeders and comparably low doubling times (~ 10 yrs to double fissile inventory). Thus thermal breeders would require a smaller total investment in fissile material to reach the point at which the system can be sustained on bred material only. The economics of this aspect of thermal breeders is also analyzed in the last section of this paper.

The Economics of Fuel Utilization

The two nuclear characteristics of a reactor which are important from the standpoint of the economics fuel utilization are a) fuel inventory and b) net fuel burnup. The first of these, the fuel inventory, is the amount of fuel in the reactor and associated fuel processing plants required to supply a given electrical capacity. This is usually expressed as kilograms of fissile material per megawatt of electrical

capacity (kg/Mwe) since in most reactor designs, costs associated with the inventory of fertile material are relatively unimportant. The second fuel utilization characteristic, net fuel burnup, represents the net loss (or gain) of fissile material associated with the production of a given amount of electrical energy. Because this is such a small unit in terms of kilograms per megawatt hour of electricity, it is convenient to express net burnup in terms of kilograms fissile per megawatt year of electricity (1 Mw Yr = 8760 Mw hr = 8.76×10^6 kwhr). The actual annual consumption or production of fissile material, of course, depends on the load factor of the reactor and the net burnup figure must be corrected accordingly.

The two fuel utilization characteristics just described are important when comparing the economics of various future nuclear power systems because first of all, only these two factors will be influenced by changes in the cost or value of fissile material. Secondly, as nuclear power systems grow and the individual plants become very large, construction costs of various types of plants tend to approach one another. This means that capital costs will not greatly influence the choice of what kind of system to build. Finally, in large scale fabrication and processing plants, (i.e. plants handling 5-10 tons per day of nuclear fuels) unit fuel costs become very low and relatively insensitive to the type of fuel being handled. Thus, as a first approximation, an analysis of the economics of fuel utilization should provide a good indication of the probable long term competitiveness of various nuclear power systems.

Before considering the fuel utilization of various systems, however, a few words of caution should be introduced. Although the fuel utilization characteristics of a reactor type may be a good measure of its long term merit, reactor designers can vary these characteristics over a wide range to optimize their system for prevailing or anticipated economic conditions. Thus, any single measure of the inventory and net burnup characteristics of a reactor type is not necessarily representative of that type optimized under other economic ground rules. The following analysis, therefore, is subject to this limitation.

Fuel Utilization Characteristics of Various Reactor Types

The fuel utilization characteristics of current technology light water reactors are compared with those of more advanced systems in Table 1. These data may be converted into short tons of U_3O_8 on the basis of 3.77 kg U-235 extractable/short ton U_3O_8. Corresponding separative work requirements of course depend on the degree of enrichment of the fuel loading. In the case of the light water reactors which use slightly enriched U-235, 110 kg separative work are required per kg fissile to supply the initial inventory and 180 kg separative work per kg fissile are required for U-235 makeup. In the case of the remaining reactors which are fueled with highly enriched U-235 or recycled fissile material, 240 kg separative work per kg fissile are required.

Table 1

Fuel Utilization Characteristics of Various Reactor Types

Reactor Type	Inventory kg fissile/Mwe	Net Burnup kg fissile/Mwyr
Current Technology Light Water	3.8	0.38
High Temperature Gas Cooled	3.2	0.11
Thorium Fueled Heavy Water	2.1	0.25
Seed Blanket	4.8	0.073
Molten Salt Converter	2.0	0.073
"Westinghouse" Type Fast Breeder	5.0	- 0.31
Molten Salt Thermal Breeder	1.5	- 0.10

Fuel Requirements of Light Water Reactors

Table 2 gives the amount of uranium required to support a nuclear industry based solely on light water reactors with the fuel utilization characteristics given in Table 1. The results are also based on the recent growth of the nuclear industry projected by the AEC in December 1964 but rounded off so that the incremental additions to the system during any given five year period follow a smooth curve. Also shown in Table 2 are the possible costs of the uranium based on (1) use of

Table 2

Uranium Requirements of Water Reactors

Year	Installed Nuclear Electricity Capacity Thousands of Mwe	Thousands of Short Tons of U_3O_8	Required Separative Work Capacity Million kg/yr	Cost of U_3O_8 $/lb	
				U.S. Only	U.S. + Canada
1970	7	7	2	8.00	5.00
1975	28	30	6	8.00	5.00
1980	75	90	12	8.00	5.00
1985	175	230	20	8.00	5.00
1990	320	460	34	10.00	5.00
1995	510	810	53	10.00	5.00
2000	745	1300	75	10.00	10.00
2005	1030	1960	100	30.00	20.00
2010	1360	2790	125	30.00	30.00
2015	1740	3830	144	30.00	30.00
2020	2165	5070	163	30.00	30.00
2025	2645	6550	200	30.00	30.00

Table 3

U.S. and Canadian Resources of Uranium

Price Range Per Pound U_3O_8	U.S. Resources Thousands of Short Tons U_3O_8	Canadian Resources Thousands of Short Tons U_3O_8
5 - 10	300 - 350	650
10 - 15		460
15 - 20		430
10 - 30	700	
30 - 50	8000	

References: R. L. Faulkner "Fuel Resources and Availability for Civilian Nuclear Power 1964-200," Geneva Conference P/256 Aug. 1964.

J. W. Griffith and S. M. Roscoe, "Canadian Resources of Uranium and Thorium," Geneva Conference P/24 Aug. 1964.

U.S. resources only or (2) U.S. plus Canadian resources respectively as shown in Table 3. It is seen that with light water reactors only, the price of natural uranium would rise to about $30/lb by about 2010. What increased uranium costs would do to the price of fully enriched U-235 and to the corresponding cost of electric power is shown in Table 4.

Applying the data in Tables 2 and 4 to the cumulative nuclear power generation anticipated during the next 50 years results in added power costs of many $ billions as shown in Table 5.

The increased power costs shown in Table 5 are based on the assumption that separative work costs (i.e., the cost of U-235 enrichment) will remain unchanged. The separative work capacity of the existing diffusion plant complex, however, is only about 20 million kg per year according to unclassified estimates, (Nucleonics, Sept. 1964). On this basis, three new diffusion plants of about the same capacity as existing plants will have to be built by the year 2000 and at least one new plant every five years after that time. If this were done with private capital, increased costs of money might well cause the cost of separative work to increase which would make the incremental cost of power even higher than shown in Table 5.

Table 4

Cost of U_3O_8 $/lb	U-235 Cost* 2/gram	Incremental Added Power Cost, Mills/kwhr
10	10	0.3
30	20	1.6
50	30	3.0

*Based on separative work costs of $22.50/kg.

Table 5

Incremental U.S. Nuclear Power Cost
With Light Water Reactors Only

Year	Cumulative Power Generation - 103 Mwyrs	Added Power Cost, $ Billions*
1970	16	-
1980	290	-
1990	1610	-
2000	5250	10
2010	12800	100
2020	25600	300

*Assuming use of U.S. plus Canadian Resources.

Reduction in Uranium and Seoparative Work Requirements Through the Introduction of Fast Breeders

It is obvious from the foregoing that because of the added cost of power which would be experienced by light water type nuclear plants if low cost sources of uranium become exhausted, there is a tremendous economic incentive to develop breeders to the point where they can provide needed fissile material. To really meet the fissile requirement problem, moreover, such breeders must produce excess fuel at a rate sufficient to supply fissile inventories for new plants being added to the system and also to make up for the fissile material consumed in non-breeders. Indications are that to do this job, breeders should produce new fuel at an annual rate of about 5% to 10% of their total fissile inventory (i.e., 20 to 10 year inventory doubling times). Achievement of the lower doubling time, moreover, has the added attribute that if annual interest charges on fissile inventories are 10%, sale of bred fuel at its purchased price would just balance these charges. In other words, the value or price of fissile material would remain constant. It is apparent, therefore, that if breeders are inventoried with low cost fissile material, they can sell bred fuel cheaply, whereas, if they are inventoried with high cost fissile material they must get high prices for their bred fuel. Thus the long term price of fissile material

hinges on what it will cost to supply inventories for the breeders to the point where they become self sustaining on bred fuel.

Using the projected nuclear power growth figures given in Table 2 and the performance characteristics of a "Westinghouse" type (Geneva paper P/August 1964) fast breeder as a basis, the natural uranium required to support the industry was determined as a function of the time the breeders are introduced into the system. The results shown in Figure 1 indicate that introduction of breeders of the given type by 2000 AD (assume one constructs only breeders after that time) would limit the total amount of uranium mined for its U-235 content to about 3.6 million tons. But under such conditions, the price of fissile material would rise to about $20 per gram which is undesirable. Switching over to this type of breeders by 1990 would not alleviate the situation as the total amount of mined uranium would still be more than 2 million tons which exceeds the estimated low cost ($5-10/lb U_3O_8) resources by a factor of two. Introducing the fast breeders by 1980, however, does limit the uranium requirement to approximately the amount that might be available at low cost.

The corresponding separative work capacity to enrich the U-235 that is mined is shown by Figure 2. It is seen that only by introducing the given type of fast breeder as early as 1980 can one limit the needed capacity to that which might be satisfied by existing diffusion plants.

The Natural Uranium - D_2O - Fast Breeder Complex

An alternative to the early introduction of fast breeders has been suggested; namely, to build natural uranium heavy water reactors prior to breeders. This would not only save on the consumption of U-235 but also provide the plutonium needed to inventory the fast breeders. Figure 3 shows the influence on ore requirements of replacing light water reactors with natural uranium heavy water reactors during the period 1975 to 1990. Two types of fast breeders are considered: (1) a 16-year doubling time, 5 kg fissile per Mwe design and (2) a 10-year doubling time, 4 kg fissile per Mwe breeder. It is seen in Figure 3, that the introduction of heavy water reactors saves about 400,000/short tons of mined U_3O_8; however, a more important saving

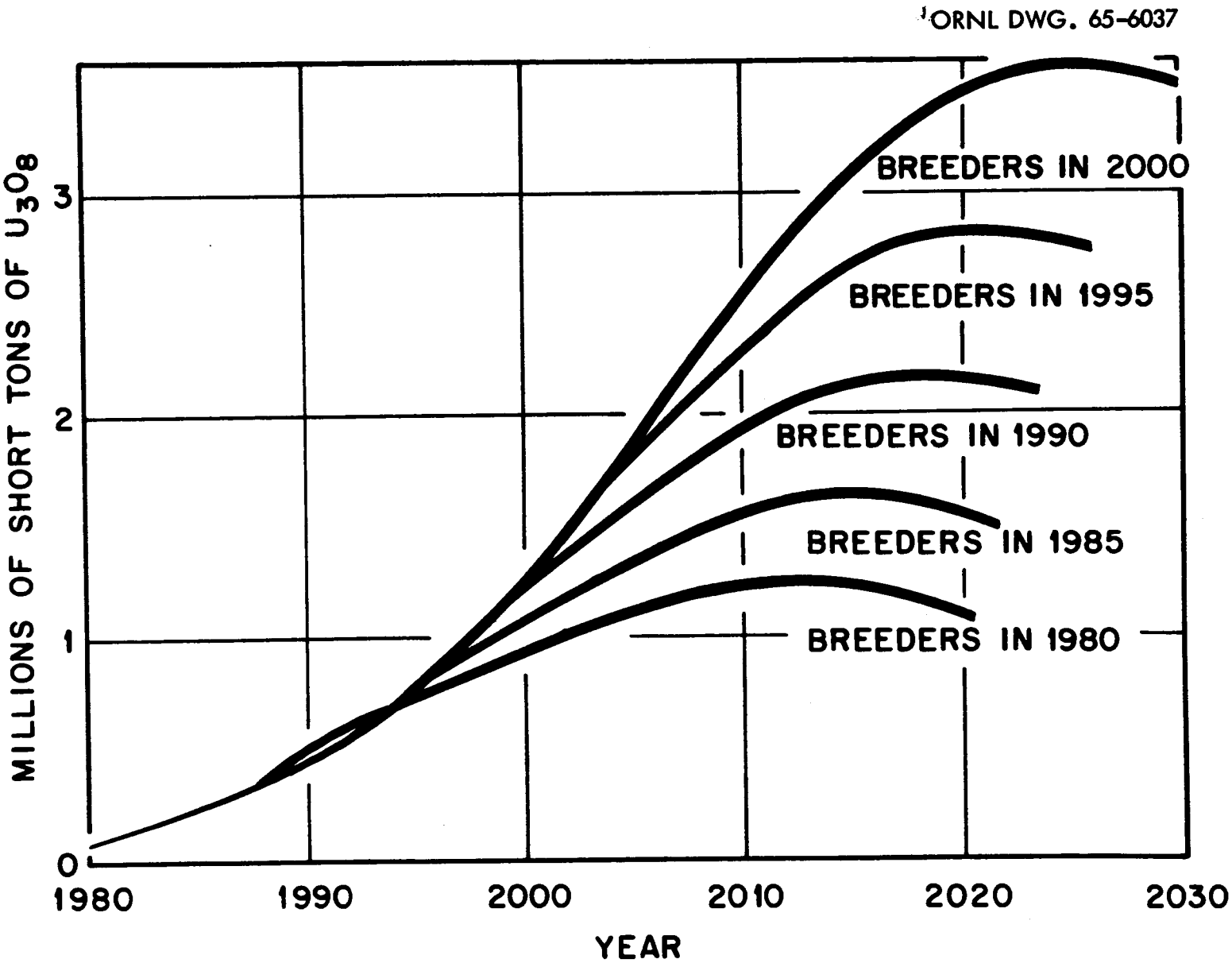

FIG. 1. ORE REQUIREMENTS FOR WATER REACTORS PLUS WESTINGHOUSE OR LOW TEMPERATURE FAST BREEDERS (5 kg FISSILE/MWE, 16 yr D.T.)

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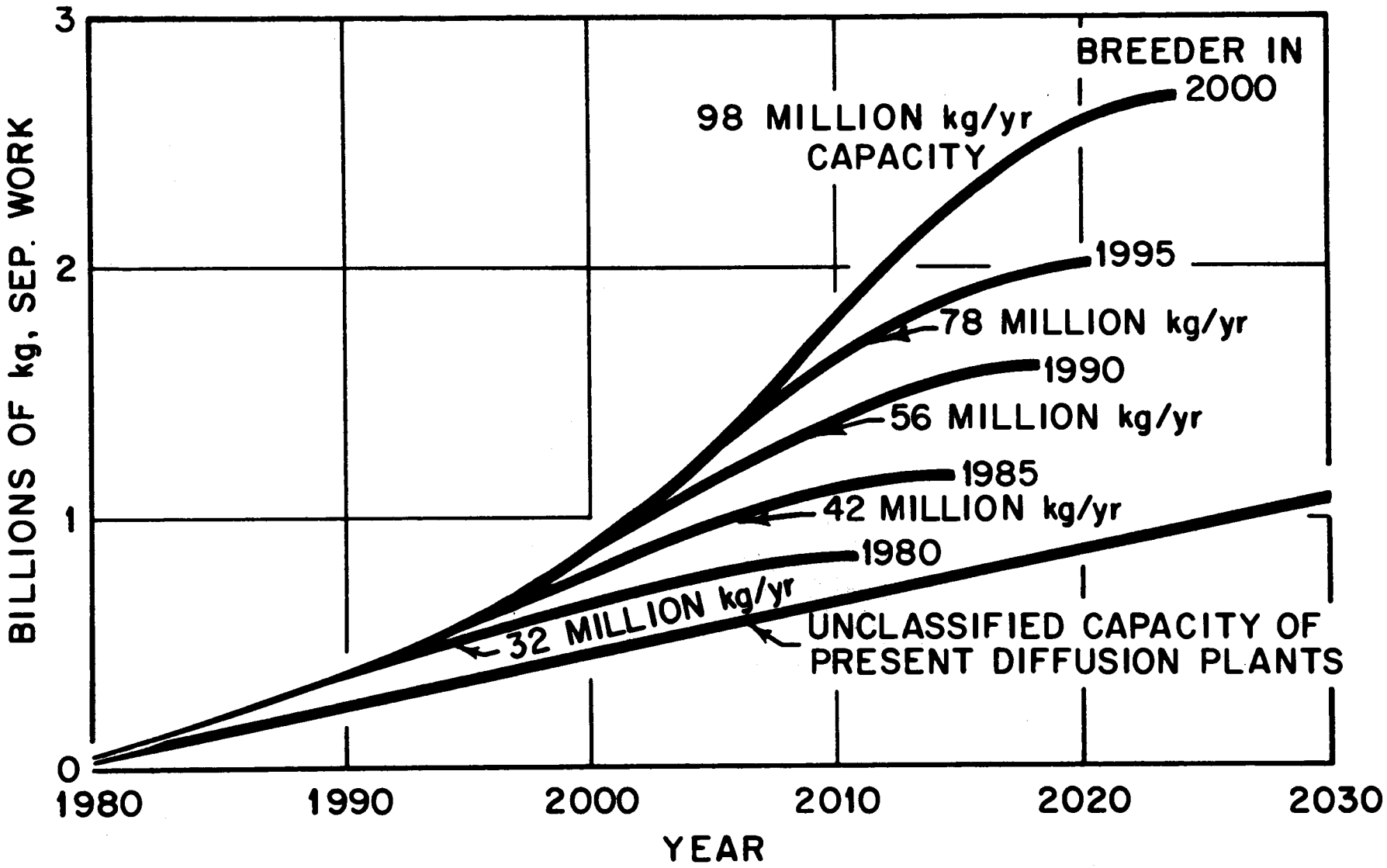

FIG. 2. CUMULATIVE SEPARATIVE WORK REQUIREMENTS FOR WATER REACTORS PLUS WESTINGHOUSE FAST BREEDERS

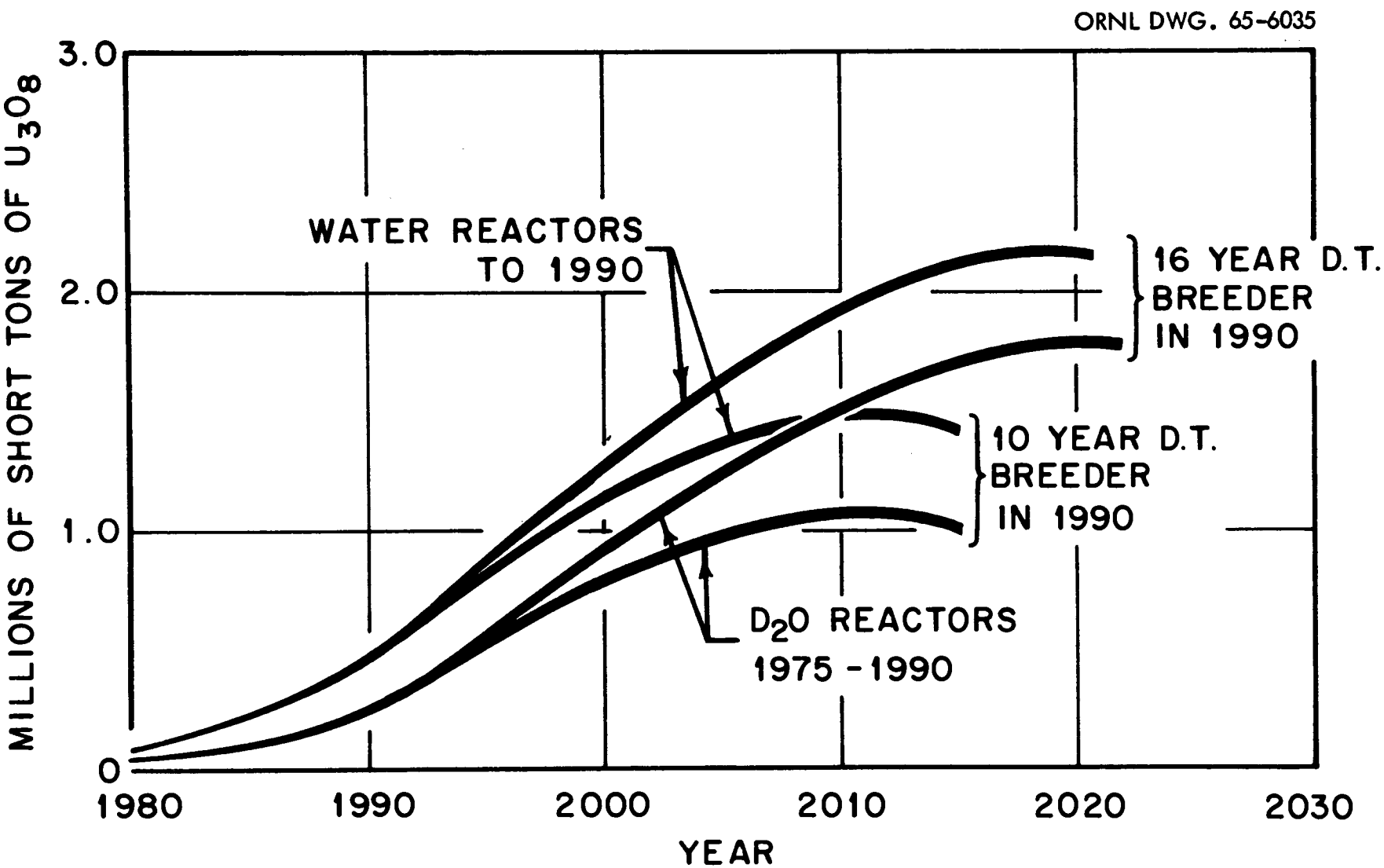

FIG. 3. ORE REQUIREMENTS FOR NATURAL U-D_2O - FAST BREEDER COMPLEX

(i.e., 700,000 short tons of U_3O_8) is achieved by improving the performance of the fast breeder. The combination of heavy water reactors followed in 1990 by 10-year-doubling-time fast breeders does, however, appear to limit the mined re-requirement to that which might be available at low cost.

Influence of High Performance Thermal Breeders on Ore and Separative Work Requirements

A similar situation exists for developing a self-sustaining breeder industry based on high performance thermal breeders rather than fast breeders. In contrast to the high inventory—high breeding gain characteristics of fast breeders, however, thermal breeders have lower inventory—lower breeding gain characteristics but approximately the same doubling times. A switch from water reactors to 15-year-doubling-time thermal breeders in 1990, however, would alleviate, but not solve, the fissile shortage problem. As shown in Figure 4, the required amount of mined uranium would still be about 1.4 million tons. It is doubtful that such thermal breeders could be developed before 1990, therefore, earlier cases have not been considered.

The Role of Advanced Thorium Converters

There is some indication that advanced thorium converters now being developed as part of the U.S. Civilian Nuclear Power Program may be a possible answer to the fissile shortage problem. Such reactors make considerably better use of mined U-235 than the light water reactors and if they can be introduced into the industry at an early enough date can save on fissile consumption to the point where the high cost U-235 need never be used. Figure 4 illustrates this point for four advanced thorium converters; namely, thorium-fueled heavy water, large seed-blanket, high temperature gas cooled and molten salt converter. It is seen that replacement of the water reactors with any one of these reactor types during the period 1975 to 1990 would limit the requirement for mined U-235 to that available in low cost ore. Thus, the role of advanced converters may be that of conserving low cost U-235 such that enough remains to inventory a self-sustaining breeder industry.

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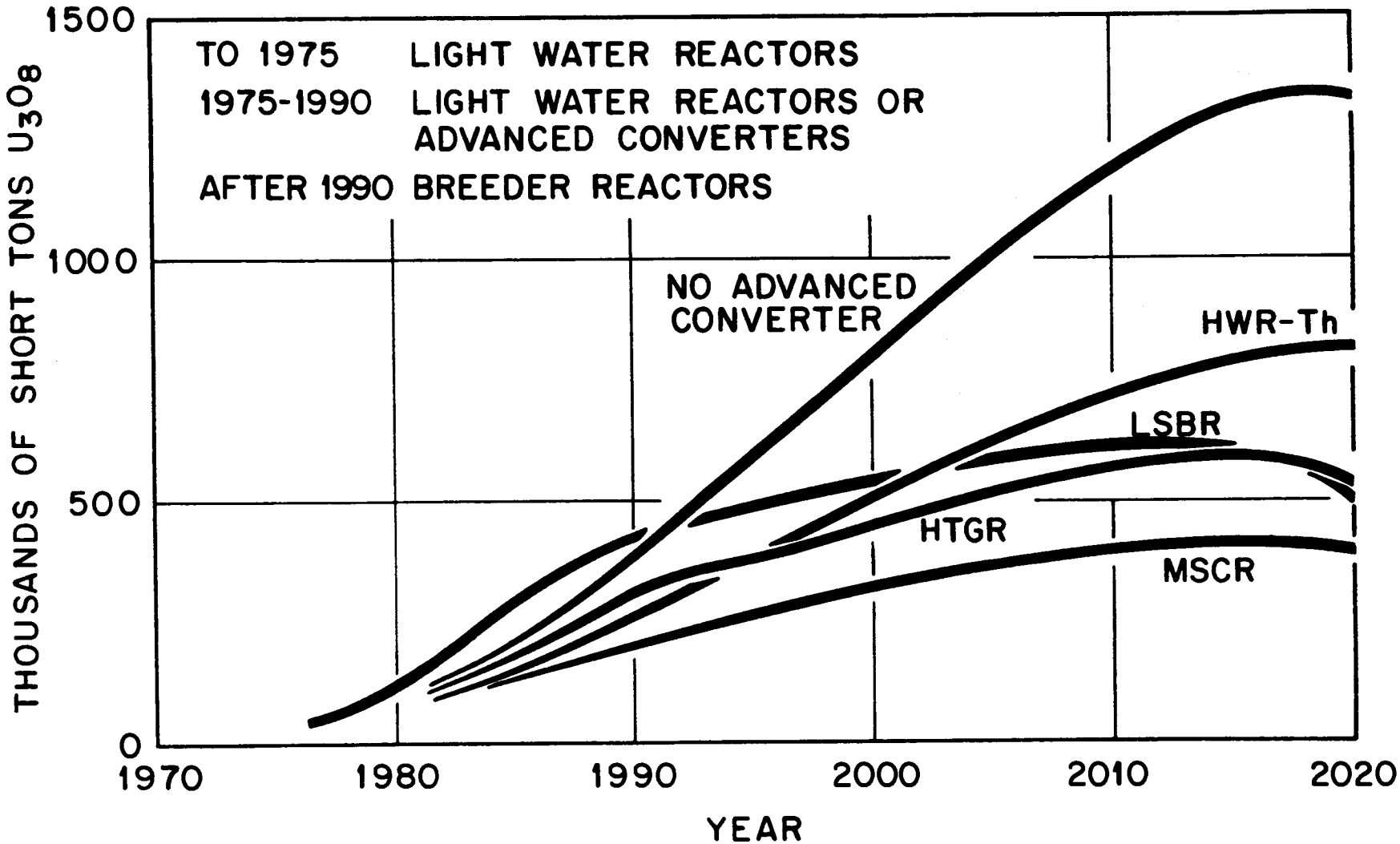

FIG. 4. EFFECT OF ADVANCED CONVERTER CONSTRUCTION ON URANIUM ORE REQUIREMENTS

In order to achieve this role, however, the advance thorium converters must be able to produce energy more cheaply than light water reactors. This may seem to be a formidable barrier to their introduction into the industry. However, because of the more favorable fuel utilization characteristics of advanced thorium converters, they should be able to generate electricity around half a mill per kilowatt hour cheaper than the present types of light water reactors. If no serious technical problems are encountered in their development, advanced thorium converters offer the potential of being an economical solution to the U-235 conservation problem.

The Economic Incentive for the Early Development and Introduction of Breeders and Advanced Converters

By applying ore costs and separative work costs to the previously derived requirements it is now possible to determine the dollar requirement for mining and for U-235 separation for the various approaches to a self-sustaining breeder industry. These costs can then be put on a present worth basis to establish the present economic incentive for the early introduction of breeders and the earlier introduction of advanced converters.

Table 6 gives the present worth of future savings in mining uranium and separating U-235 for a system based solely on advanced converters followed by thermal breeders. Costs of uranium were taken as $20/kg and separative work as $25/kg. It is seen in this table that the present worth (calculated using a 5% discount factor) of introducing thermal breeders in 1990 compared to 2000 is $6.2 billion. Replacing water reactors with advanced converters in the period 1975 to 1990 would increase the present worth of future savings to $9.2 billion. It is apparent on this basis, that a very sizable development program is justified as a means of achieving these two goals.

Table 6

Economic Incentive for Early Introduction of Advanced Converters and Thermal Breeders

Year Advanced Converter Introduced	Year Thermal Breeder Introduced		
	2000	1995	1990
	Present Worth of Future Savings $ Billions		
	base case	3.1	6.2
1990	3.3	4.8	—
1985	4.9	6.4	7.8
1980	6.3	7.8	9.2

The Importance of Thorium Resources

In considering the development of thorium fueled converters and breeders, a question that is often raised is "Are thorium resources adequate to support a large scale industry based on the use of thorium?"

In answering this question it is important to point out that thorium does not in itself constitute a nuclear fuel but merely an indirect source of such fuel. Thus, thorium is not mined for its fissile content as is natural uranium and future requirements will be considerably lower. Existing designs of thorium converters and thorium breeders require between 100 kg and 200 kg of thorium per Mwe for initial inventory of such reactors and an additional 50 kg/Mwe for thorium consumed during a 30 year plant life. Using these data and the previously mentioned projected growth of the U.S. nuclear industry as a basis, and assuming all reactors in the industry are thorium fueled, the future thorium requirements might be as much as shown in Table 7.

Table 7

Projected Growth of U.S. Nuclear Industry
and Corresponding Thorium Requirements

Year Ending	Mwe x 10^3	ThO_2 Required (Thousands of Short Tons)
1980	75	20
1990	335	86
2000	730	194
2010	1380	375
2020	2200	660

These projected requirements may be compared with estimated U.S. resources of thorium shown in Table 8.

It is seen that the low cost domestic reserves of thorium would not be exhausted before the year 2010 even though the U.S. nulcear power system consisted solely of thorium based reactors. Using higher cost thorium, moreover, would not greatly influence the economics of thorium reactors.

Since world reserves of low cost thorium ore are many times greater than U.S. resources, it is unlikely that any pressing demand for higher cost material will be encountered in other parts of the world during the next half century.

Table 8

U.S. Thorium Resources - 1981
(Thousand Short Tons ThO_2)

Price Range Per Pound ThO_2	Reasonably Assured Resources	Possible Additional Resources	Total Resources
\$ 5 - \$ 10	100	300[a]	400
10 - 30	100	100[a]	200
30 - 50	3,000	7,000[b]	10,000
50 - 100	8,000	17,000[b]	25,000
100 - 500	1,000,000	2,000,000[b]	3,000,000

[a]Depends on new discoveries which may yield smaller or larger reserves than indicated.

[b]Extensions of known uraniferous (thoraniferous) formations

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