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Abstract

Thorium utilization appears to permit development of an advanced technology involving fuel handling, processing, and refabricating on an economic basis. Based on U. S. cost rules, countercurrent fueling, and a throw-away cycle, heavy-water reactors fueled with Th-U^{235} had fuel costs as low as natural-uranium-fueled systems. The spent fuel from the thorium system contained four times as much fissionable fuel as that from the natural-uranium system, and so processing costs and/or refabrication costs for the thorium fuel could be relatively high and still be economical. With fuel processing, U. S. processing charges, and uniform-batch fueling, light-water reactors fueled with Th-U^{235} had lower fuel costs than slightly-enriched-uranium reactors; for higher neutron-economy systems, the uranium reactors had lower fuel costs in the initial uniform-batch cycle, but recycle of thorium fuel was generally more economic than recycle of uranium fuel. Based on the existence of an economic, advanced technology, calculated fuel-cycle costs for thorium-breeder reactors (including special-materials inventory charges) were less than 1 mill/kwh. The aqueous-homogeneous breeder reactor studied had a fuel cost of about 0.9 mill/kwh at a fuel yield of 7% per year, while a molten-salt-breeder reactor had a fuel cost of about 0.6 mill/kwh at a fuel yield of 1% per year.

ECONOMICS OF THORIUM FUEL CYCLES*

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1. Introduction

The essential justification for civilian nuclear energy development is associated with the development of a power source which is economic generally in the near future and for long periods of time. Thus, reactor development should point toward those systems which have low power costs, and which show promise for lower power costs in the future.

The utilization of the fission process requires the ability to handle safety and cheaply huge amounts of radioactivity, and this involves a technology which is only now being developed. Because of the necessity of an advanced technology in order to obtain low-cost nuclear power, reactor development should support those systems which advance nuclear technology at the fastest pace, consistent with the economic conditions which exist during the time of development, and the future usefulness of the development. It is the thesis of this paper that thorium utilization will advance nuclear technology at the fastest pace at this time, that power costs of thorium reactors during the initial period of reactor development can be as low as those of other nuclear systems, and that an advanced technology permits low power costs in thorium breeders and also other reactors.

Availability of Thorium---- If we consider thorium utilization as an economic stepping stone for advancing reactor technology, it is not too important whether we have enough thorium for tens of years or for thousands of years. However, if a thorium technology is developed, it would be desirable

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to apply it economically to thorium for long periods of time. Let us therefore examine what periods of time are pertinent to thorium utilization.

Although there has been no intensive search as yet for thorium ores, the known reserves of low-cost thorium oxide (less than $10/lb) in the free world are 500,000 tons, and the conjectured low-cost reserves in the free world amount to 1,000,000 tons.[1] Based on an inventory requirement of 1 ton thorium per Mw(e) and a fuel exposure of 30,000 MwD/ton, even the 500,000 tons of known low-cost thoria are sufficient to supply thorium inventory and burnup requirements for an installed electrical capacity of 200 million kilowatts for over 40 years. Thus, free-world thorium reserves appear capable of establishing an electrical industry greater than that presently in the U.S. for a period of 40 years, based on relatively low burnup of the thorium. In addition, if high-performance thorium breeders are developed, the United States and Canada alone have enough low-priced thorium to supply the inventory for an electrical capacity of 750 million kilowatts;[2] also, the supply of thorium raw materials required for this system at prices which increase fuel costs but slightly (less than 0.1 mill/kwh(e)) appears virtually inexhaustible.[3] Thus, from both the short term and long term view, the supply of thorium (and also uranium) appears adequate, and the success of thorium (as well as uranium) systems depends primarily upon the economic success of reactor technology.

Technology Considerations---- A large fraction of nuclear power costs appears to be associated with capital investment; in fact, it is generally agreed that capital costs of nuclear plants will be higher than those for fossil-fuel plants. Thus, the major economic advantage of nuclear fuel is the potentially low fuel cost associated with its use. However, the nuclear power plants built to date correspond to systems which have relatively poor

neutron economy and which do not have particularly low fuel costs. This apparently is due to the present influence which fuel cycles have on capital and operating costs, either directly or indirectly.

The many studies which emphasize the potentially low power costs attainable in future nuclear plants use as a common basis the existence of an advanced technology. In particular, a technology is required which can economically move, process, and fabricate radioactive fuel during various times of the fuel cycle. These operations are directly concerned with fuel-cycle costs. While it is appreciated that fuel cycle costs do not constitute the major costs in an advanced nuclear technology, it is important that these costs be low, or nuclear power cannot compete except at prices which are higher than present-day power costs. In addition, a technology which permits very low fuel costs will probably permit capital and other costs to be relatively low; under such conditions reactor development will be guided by fuel-cycle development. This paper deals primarily with the fuel cycle and conditions necessary for low fuel costs. Although neutron economy will not be an objective in itself, it will affect fuel and power costs; or, stated differently, changes in economic conditions will influence the neutron economy of a minimum-power-cost system.

2. General Considerations of Thorium Fuel Cycles

Thorium, just as uranium, can be utilized in either fast or thermal reactors; the nuclear characteristics of a thorium system relative to a uranium system, however, are quite different for the two reactor types. We will consider thermal reactors first.

Since natural thorium contains no fissionable materials, it must first be converted to U^{233} before it can be used as a nuclear energy source. This requires that highly enriched fissionable fuel be supplied to a reactor system

utilizing thorium, and so such systems depend upon relatively expensive fuel for criticality. While this is in itself an economic disadvantage when compared with natural uranium systems, the initial-loading cost does not give the complete picture. With no processing of the spent fuel, it is the attainable exposure in combination with the initial fuel cost which determines fuel-burnup costs; with processing, the costs of processing and refabrication influence the effective cost of the fuel.

The attainable fuel exposure* is a function of neutron economy and the value of eta, the average number of neutrons produced per neutron absorbed in fuel. The conversion of thorium into U^{233} results in a fuel having a superior value of eta, and it is this characteristic which is primarily responsible for the interest in thorium.

The average value of eta in a thermal reactor varies with the specific neutron-energy spectrum, and with the fuel. In a typical thermal spectrum, effective eta values for the three principal fuel isotopes may be: U^{233}, 2.27; U^{235}, 2.03; Pu^{239}, 1.90. Thus, in thermal reactors it is easier to attain a higher conversion (or breeding) ratio in thorium systems, and so thorium-U^{233} fuels can have relatively long reactivity lifetimes. With high conversion ratios and long fuel exposures, fuel-burnup and fabrication costs can be so low that spent fuel can be discarded without undue economic penalty. Under such circumstances, a single-region reactor with fissionable fuel mixed with thorium can operate economically in much the same manner as proposed for the CANDU reactor.[4] However, if fuel-processing and refabrication costs are low, long fuel exposure during a fuel cycle is no longer a prerequisite for low fuel costs. In fact, under such conditions, it appears more economical to go to two-region-type systems which have improved neutron economy.

*Oxide fuels have the physical ability to withstand very high burnups, and so reactivity lifetime was taken as the limiting exposure condition.

Using fuel cost as the criterion of merit, the advantages of a two-region reactor (in which a thorium region surrounds a fissionable-fuel region) over a single-region system (with fuel and thorium intimately mixed) are due to the lower critical mass, lower neutron leakage, and lower Pa^{233} losses associated with the two-region system. However, use of such a system implies an advanced technology, inasmuch as low-cost fuel processing, fuel handling, and refabrication are required.

Thorium can also be utilized in a fast reactor, although most studies consider its use in thermal reactors. Here again, thorium has to compete with uranium, and at high energies it does not have a nuclear advantage over uranium systems. In a fast reactor based on the U^{238}-Pu^{239} cycle, the effective value of eta in a metallic-fueled core is estimated to be about 2.7, while the corresponding value is about 2.4 for a Th-U^{233} cycle.[5] If oxide fuels are considered, the neutron-spectrum is degraded relative to that in a metallic system, and the effective eta is lower for both uranium and thorium reactors,[6,7,8] with uranium systems still having superior eta values. However, if power-removal considerations degrade the neutron spectrum into the kilovolt region (below about 100 kev), thorium systems can have higher effective etas than do uranium systems.[8]

Fast power-reactor concepts which have been studied consist of two-region systems, with fertile-material blankets surrounding a core region.[9-11] Such systems imply recycle of the fissionable fuel produced in the blanket to the core region. As mentioned previously, this will require an advanced technology, wherein fuel is handled, processed and refabricated safely and economically.

In the following sections, emphasis will first be placed on conditions and fuel costs associated with no fuel processing and refabrication. Comparison

of thorium and uranium systems will then be made on the basis of the processing-and/or-refabrication costs which are economically permissible in the two systems. Following this, an advanced technology is assumed in which fuel processing and refabrication costs are low, and which permits breeder reactors to have low fuel costs.

3. Near-Term Potential of Thorium Fuel Cycles

In the current decade reactor technology may not advance to the point where breeder-reactor fuel cycles are economically attractive; however, advances in technology should improve the relative position of breeder systems. For the moment, let us consider processing and/or fuel refabrication to be relatively expensive. This immediately imposes a penalty on two-region systems, such that both fast- and thermal-breeder reactors would be relatively uneconomical. Not all situations have been examined; nonetheless, it appears reasonable that thermal reactors which do not depend upon low fuel-processing and fuel-fabrication costs will develop during this period. We wish to examine the relative fuel costs of thorium and uranium systems under such conditions.

The simplest fuel cycle during this period would correspond to mixing thorium and U^{233} such that the conversion of fertile to fissile material has an immediate effect in maintaining the reactivity of the reactor. Any loss of neutrons to Pa^{233} is accepted, and the fission products are allowed to build up to the point where criticality can no longer be maintained.

Examples of fuel exposures which are possible from the standpoint of reactivity are indicated in Fig. 1. The conditions of the calculation were: an equilibrium fuel cycle with fresh-fuel elements consisting of U^{235} and thorium, a core neutron-leakage fraction of 0.05, fraction absorptions in structure of 0.01, a moderator temperature of 1000°K, and graphite as moderator

with a feed-fuel moderator-to-uranium ratio of 4000. As shown, there is an optimum thorium-to-uranium ratio for a given specific power. At low thorium-to-uranium ratios the conversion ratio is relatively low, resulting in short reactivity lifetimes; increasing the thorium concentration increases the conversion ratio and initially increases the lifetime, but eventually the reactivity importance of fission-product buildup is greater than that associated with the increase in conversion ratio, resulting in the maxima shown in Fig. 1. The lifetimes are less at higher specific powers due to greater absorptions in Pa^{233}, Xe^{135}, and due to the necessity of providing greater reserve reactivity for overriding peak Sm^{149} poisoning after shutdown.

The results of similar calculations at different moderator-to-fuel ratios are shown in Fig. 2. In this case only the results at optimum thorium-to-uranium concentrations are plotted. It can be seen that a moderator-to-fuel ratio of about 4000 gives generally the highest fissions per initial fissile atom under the stated conditions. At carbon-to-uranium ratios greater than 4000 there are generally more absorptions in the moderator, leading to lower conversion ratios and shorter reactivity lifetimes. At ratios less than 4000 the corresponding increase in thorium concentration leads to a relative increase in the importance of fission-product poisons with respect to criticality and shorter reactivity lifetimes.

The above calculations indicate that practical reactor systems fueled with thorium and U^{235} may obtain about 2 fissions per initial fissile atom; reactors with lower leakage than that specified above can obtain greater exposures. Thus, fuel-burnup costs of about 1 mill/kwh can be obtained based on a throw-away fuel cycle; the possibility of low fuel costs in thorium systems employing a throw-away cycle has also been pointed out by Lewis.[12]

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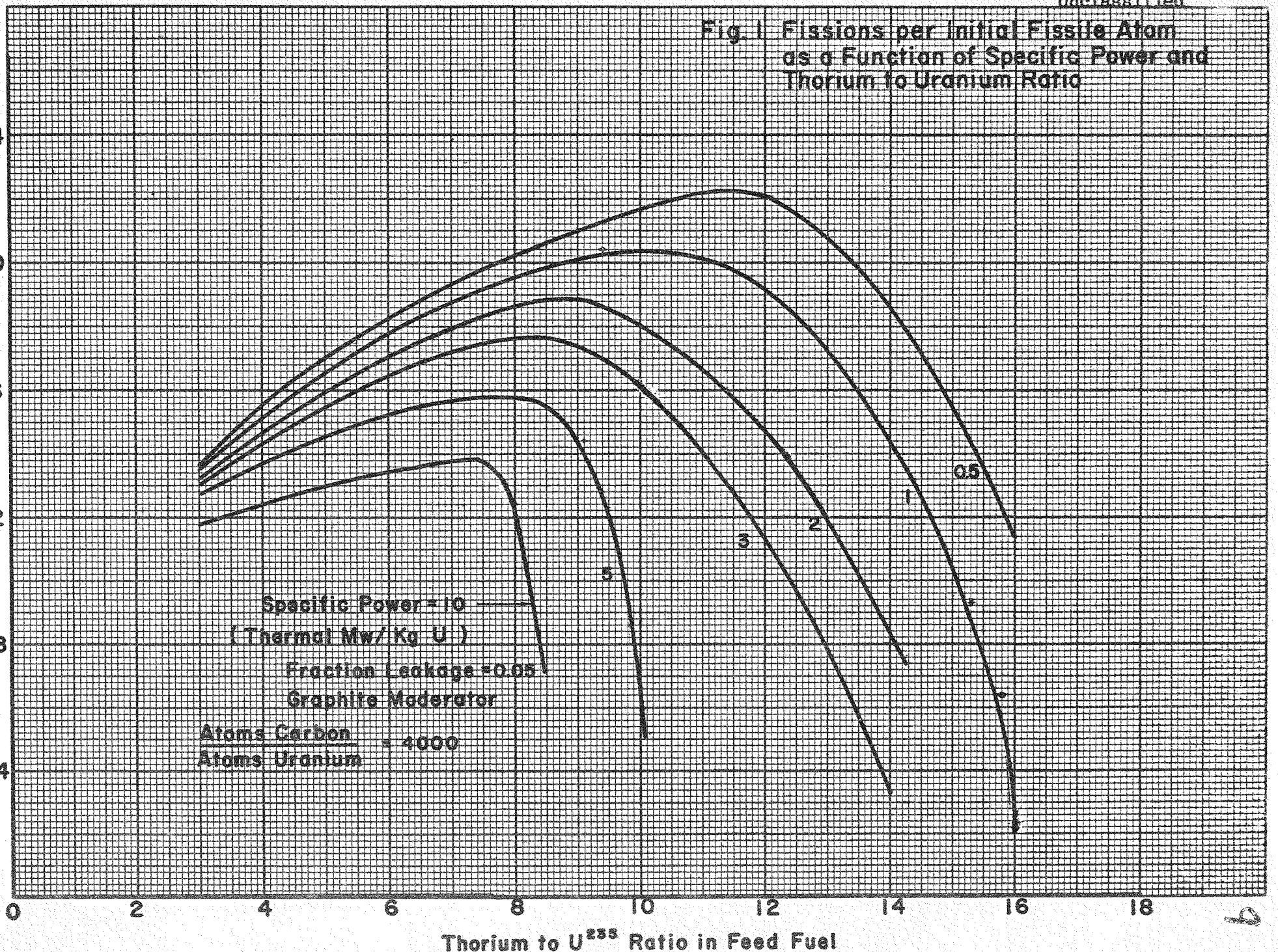

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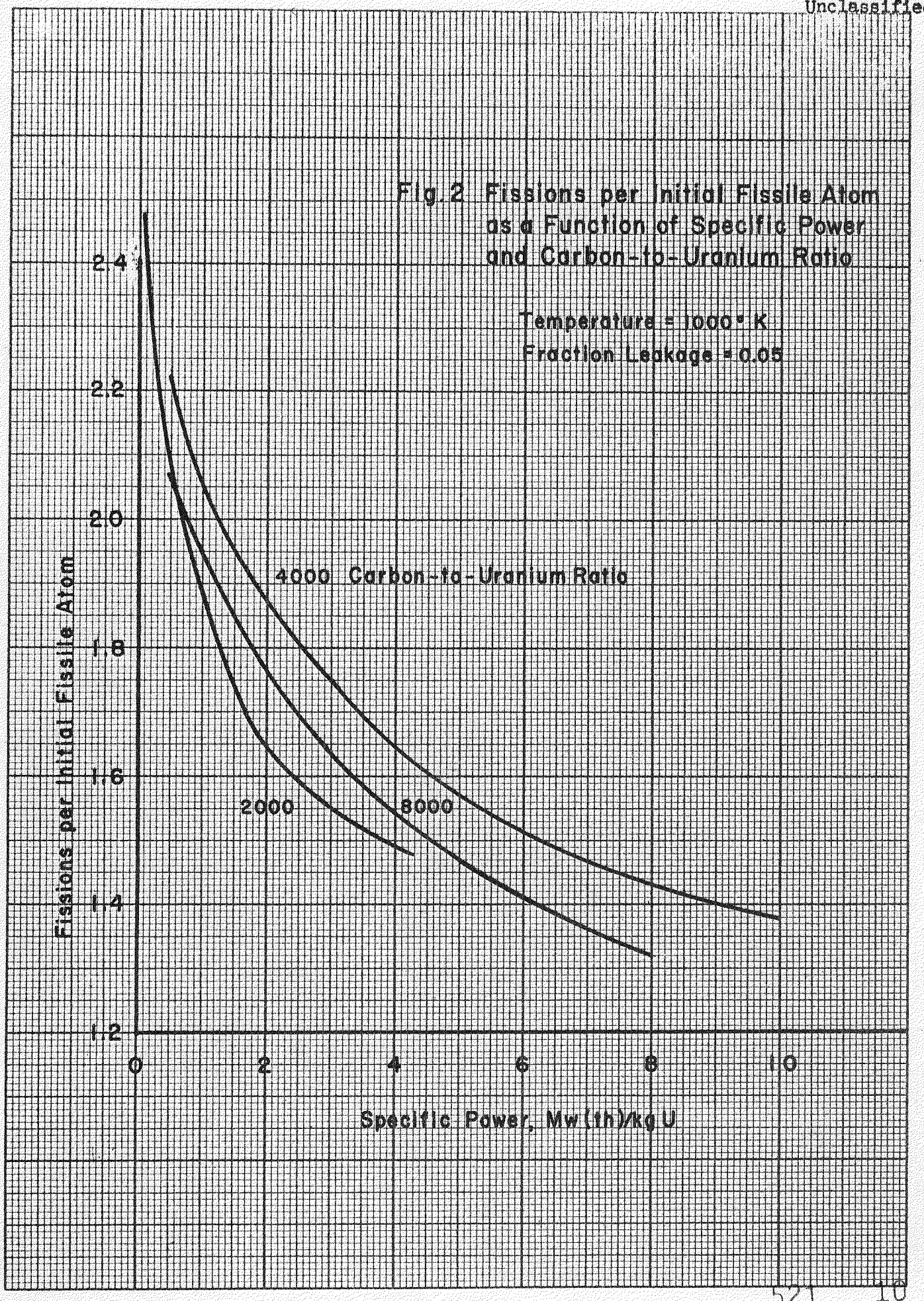

In order to explore this point in more detail, a specific reactor system was investigated. The reactor chosen was a heavy-water moderated and cooled system, since this type appears to have relatively low fuel costs for a throw-away cycle when fueled with natural uranium.[4,13] Both thorium-U^{235} and natural uranium were considered as fuels, so the results of this study permit evaluation of the relative merits of thorium and uranium fuel cycles.

Comparison of Thorium-U^{235} Fuel with Natural Uranium (Throw-away Cycle)----

The Canadians have been working intensively for a number of years specifying the design characteristics of an optimum power reactor utilizing natural uranium and heavy water, and so their work formed a base for the comparison considered here. Specifically, we will model our reactor after their 200 Mw(e) CANDU (CANadian-Deuterium-Uranium) reactor,[4] which is fueled with natural-uranium dioxide clad with Zircaloy, moderated with low-temperature heavy water (80°C), and cooled with heavy water contained in Zircaloy pressure tubes. It is assumed that countercurrent fueling (addition of fresh fuel bundles to adjacent fuel channels at opposite ends of the reactor) occurs on a semicontinuous basis, leading to relatively high fuel exposures and spent fuel of low value. The general design of the CANDU reactor was utilized for both thorium-U^{235} fuel and natural-uranium fuel; in all cases the geometry of the fuel bundles, pressure tubes and calandria tubes were the same. The maximum-permissible heat rating was that associated with a temperature-integrated thermal conductivity of 40 watts/cm; the average heat rating was 0.5 times the maximum-permissible value.

In order to obtain valid comparisons between thorium and uranium systems, consistent nuclear-design optimizations based on total fuel-cycle costs were performed for both systems,[14-16] using United States economic ground rules.

Thus, fuel costs were calculated for various thicknesses of heavy-water reflectors, different fuel-rod diameters, and several lattice spacings; in addition, the U^{235}/Th ratio was varied in the thorium system. The natural-uranium reactor was termed a CANDU type, while the thorium reactor was called a CANDUTH type.

The cost bases utilized in this study are given in Table 1. The "USAEC" values correspond primarily to present USAEC economic ground rules, the "low" values correspond to possible future conditions. In all cases the spent fuel was assumed to be stored indefinitely. The calculated fuel cycle costs include charges for the burnup of U^{235} and thorium (or natural uranium), fabrication of fuel, inventory of U^{235} and thorium (or natural uranium), and heavy-water inventory and losses.

Fuel costs obtained for CANDUTH-type reactors are given in Fig. 3. As shown, the minimum fuel cost based on "USAEC" costs was about 2.8 mills/kwh, and occurred at a lattice spacing of 7-8 inches and a U^{235}/Th ratio of about 0.036. On the basis of the "low" cost assumptions, the minimum fuel cost was about 1.83 mills/kwh, and occurred at a 7-inch lattice spacing and a fuel "enrichment" of about 3.6%. The fuel exposures corresponding to these minimum costs were in the neighborhood of 60-70,000 MwD/ton.

In the above calculations the maximum heat rating was assumed to be the same as in CANDU, namely, a temperature-integrated thermal conductivity of 40 watts/cm $\left[\int_{\text{surface}}^{\text{center}} k \, d\theta = 40 \text{ watts/cm} \right]$. Since the thermal conductivity of thoria at 600°C is about 20% lower than that of urania, release of fission gases may occur more readily in thoria systems. Thus, it may be more reasonable to assume a maximum heat rating of 35 watts/cm when thoria is used. The results[16] of calculations based on the lower heat rating, an average-to-maximum heat rating of 0.43 (instead of 0.5), and "USAEC" costs are given in Fig. 4,

Table 1. Cost Bases Employed

Unit Costs	"USAEC"		"low"
Natural U, \$/lb U_3O_8		8	
Thorium, \$/lb ThO_2		10	
D_2O (0.14% H_2O), \$/lb	28		17[a]
Fuel fabrication, \$/kg U	88[b]		44[c]
Fuel fabrication, \$/kg U + Th	88		44
Enriched uranium, \$/gm U^{235}	17		12
Annual Charges, %/yr			
Fabricated fuel or fertile material[d]		12.7	
Enriched uranium		4	
Heavy water		12.7	
Heavy water replacement		2	
Plant Utilization, %/yr		80	
Station Net Efficiency, %		29.1	

a. Based on possible future cost of heavy water.[13]

b. Obtained from value of 20/D, where this gives \$/lb UO_2 when D is the pellet diameter in inches; this expression fits fairly well the lower line given in the plot of fabrication cost versus rod diameter given in USAEC Cost Handbook.[17]

c. Conforms more with predicted fabrication costs.[13,18]

d. Applies to natural uranium and thorium; the annual charge of 12.7% was applied to one-half the value of the natural-uranium fabricated fuel, since spent fuel was assumed to be discarded.

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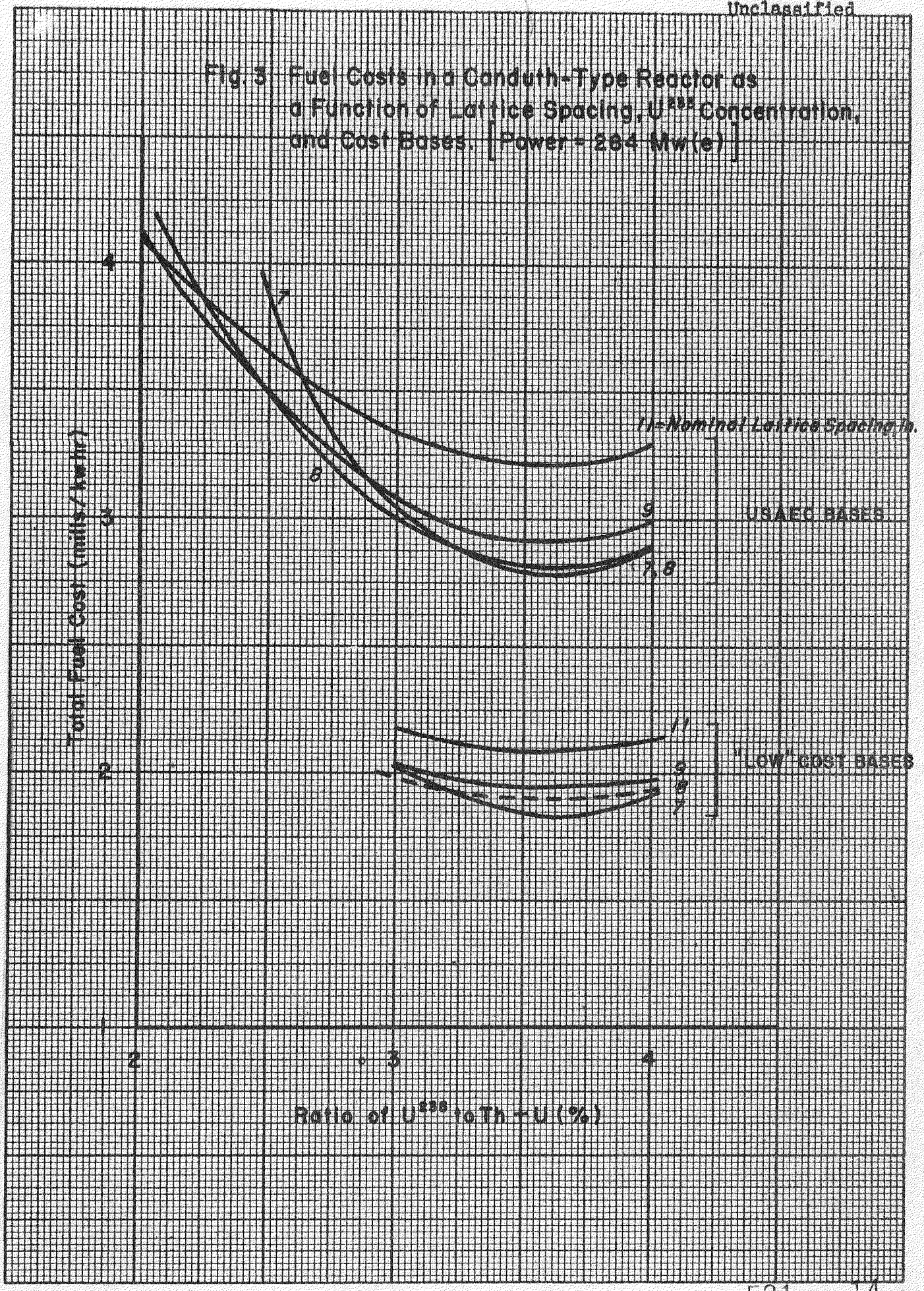
Fig. 3 Fuel Costs in a Conduth-Type Reactor as a Function of Lattice Spacing, U^{235} Concentration, and Cost Bases. [Power = 284 Mw(e)]



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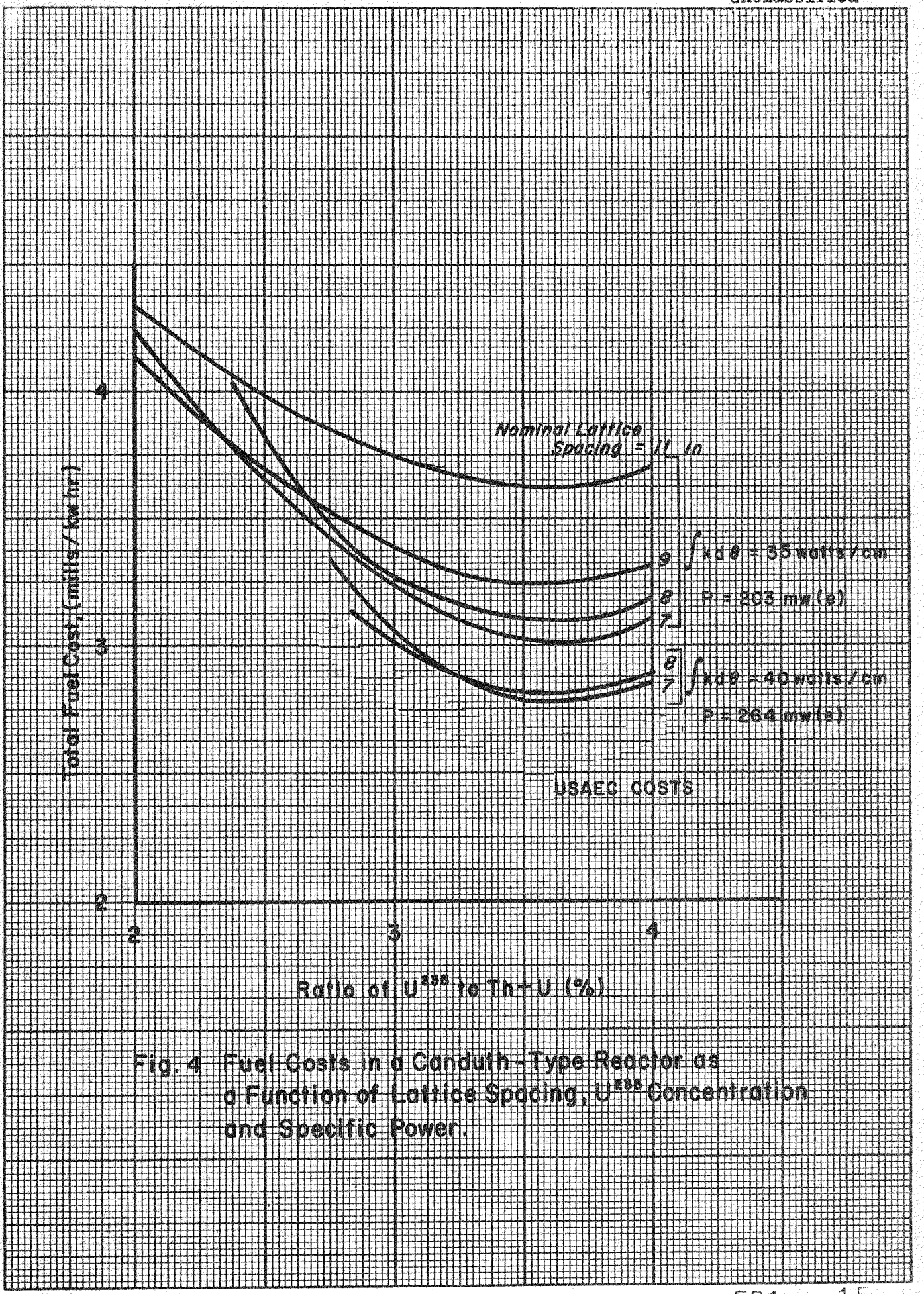

Fig. 4 Fuel Costs in a Canduth-Type Reactor as a Function of Lattice Spacing, U^{235} Concentration and Specific Power.

along with some of the previous results. As shown, the minimum fuel costs occurred at about the same lattice spacing and fuel "enrichment" independently of heat rating, with the fuel costs about 0.25 mill/kwh higher at the lower rating. This difference was obtained at different total reactor powers (the higher power was associated with the higher heat rating) and different average-to-maximum heat ratings, and so does not represent the effect of specific power alone. For the CANDUTH sizes considered, there appeared to be little influence of power level on attainable fuel exposures. It is estimated that decreasing the heat rating from 40 to 35 watts/cm (at a given power level) and decreasing the flux "flatness" from 0.5 to 0.43 would increase the fuel cost by about 0.20 mill/kwh. At an average-to-maximum heat rating of 0.5, decreasing the rating from 40 to 35 watts/cm would increase the fuel cost by about 0.1 mill/kwh.

Similar calculations involving fuel-cycle optimization were performed[14] for CANDU-type reactors; the minimum fuel costs, lattice spacing, and power level are given in Table 2, along with the values obtained for the CANDUTH-type reactors considered above. The results show that under "USAEC" ground rules and with reactor power levels in the range from 200 to 250 Mw(e), the thorium-fueled reactors had lower fuel costs than the natural-uranium systems (3.02 vs 3.09 mills/kwh if a heat rating of 35 watts/cm and an average-to-maximum value of 0.43 is taken for the thorium reactors). If the same heat rating (40 watts/cm) and same average-to-maximum value can be applied to both systems, then the thorium reactor had lower fuel costs on both cost bases at a power level of about 250 Mw(e). At higher reactor power levels (and larger reactor sizes), the natural-uranium systems gained relatively more in fuel-cost reduction, because reactor size had a greater influence on attainable exposure in such systems; conversely, at lower power levels, the thorium systems would gain in a relative manner.

Table 2. Minimum Fuel Costs in CANDU and CANDUTH Reactor Types and Associated Conditions

Reactor Type			CANDUTH		CANDU	
Nominal Lattice Spacing, in.			7		9	
Nominal Ratio of Fissile-to-Fertile Atoms, %			3.6		Natural uranium	
Cost Bases			"USAEC"	"Low"	"USAEC"	"Low"
Fuel Costs, mills/kwh						
Heat Rating watts/cm	ave/max	Power Level Mw(e)				
35	0.43	203	3.02			
40	0.5	250			3.09	1.85
40	0.5	264	2.78	1.83		
40	0.5	333			2.82	1.69

Value of Spent Fuel from Th-U^{235} and Natural-Uranium Reactors----The amount of fissile material present in the spent fuel from the above reactors is significantly different for the two fuels; for the reactors specified in Table 2, typical amounts of fissile fuel remaining after exposure are 3 kg/ton in uranium systems and 14 kg/ton in thorium systems. If the processing costs are those associated with the USAEC cost schedule, and one reactor loading is processed in a batch, processing costs (based on initial enrichments) amount to $19,500 per ton of uranium fuel and $32,500 per ton of thorium fuel. This cost is equivalent to paying about $6.5 per gram of fissile plutonium, and about $2.3 per gram of fissile uranium. Clearly, in terms of recycle, there is an advantage in processing the thorium reactors rather than the natural uranium ones. Considering USAEC suggested charges for shipping spent fuel of $16,000 per ton, the costs for recovering fissile plutonium and uranium would increase to about $11.8/gram and $3.5/gram, respectively. Under these conditions and with a fissile-plutonium value of $12/gram, there would be little incentive for processing natural-uranium fuel. Further, if fissile uranium were sold at $15/gram, the thorium reactors could obtain a fuel credit of about 0.3 mill/kwh. Thus, processing costs of thorium reactors could be significantly higher than those assumed here and still be economical.

Studies were also made in which recycle fuel obtained from thorium reactors was mixed with highly enriched U^{235} plus thorium. If recycle uranium were available at about $3.5 per gram of fissile material, the fuel fabrication cost could be appreciably higher than that associated with the use of high-purity U^{235}. If fabrication costs for fresh fuel were $88 per kg of U^{235}-Th, recycle fuel could be refabricated at $130 per kg without increasing the fuel cost; if base fabrication costs were $44 per kg, recycle-material fabrication could cost $90 per kg without increasing fuel cost.

Although not considered here, highly enriched uranium could be utilized in thorium reactors without being mixed with the thorium. Use of enriched uranium in separate fuel rods would permit fission products from burned U^{235} to be removed without removing thorium,[12] leading to greater equivalent thorium exposures than those calculated here.

Another use for thorium is in combination with recycle plutonium from natural-uranium reactors. Because of the buildup of higher isotopes, this fuel composition does not have very much reactivity, but at the same time it does not lose very much reactivity upon additional exposure. Combining this material with thorium (about 4% Pu) gave fuel exposures of about 40,000 MwD/ton, with relatively little reactivity change in the fuel as it passed through the reactor. Although such a system does not appear economic when applied to large power reactors, there may be special applications in which long, batch exposures are desired having relatively little reactivity change.

Comparison of Thorium-U^{235} Fuel with Slightly Enriched Uranium---- In the United States much reactor development has been associated with systems utilizing slightly enriched uranium, and this development has encompassed a number of reactor types. A study of the relative virtues of thorium and uranium fuels should therefore consider several specific reactor designs, with fuel-processing costs specified by the USAEC schedule. Fortunately, a comparison of fuel costs for thorium and uranium fuels under such conditions can be obtained from the studies of Jaye et al[19,20] concerning the fuel values of plutonium and U^{233}. In these studies the calculated fuel cost in a given reactor was the criterion for fuel value, with U^{235}, U^{233}, and plutonium considered as the fissile materials. The value of fuel was found relative to that of U^{235}, with the latter fuel assigned the value given in the USAEC price schedule of 1960.

The reactors considered are types of power reactors presently in operation, under construction, or considered for construction. The specific types were: the Dresden boiling water reactor (Zircaloy-clad fuel); the Yankee pressurized-water reactor (stainless-steel clad fuel); the Carolinas-Virginia heavy-water reactor (Zircaloy cladding and pressure tube); the Hallam sodium-graphite reactor (stainless-steel-clad fuel); and the GCR-2 gas-cooled, graphite-moderated reactor (stainless-steel-clad fuel).

For all reactors, the fuel was assumed to be in oxide form, with reactivity lifetime the only limitation on fuel exposure. For a given reactor, the reactivity lifetime was calculated as a function of fissile enrichment for the several fuels. The fuel costs were then calculated as a function of fissile enrichment, considering the value of U^{233} (or fissile plutonium) as a parameter.

In obtaining the fuel value of recycle material in thorium cycles, fuel product from the previous cycle was mixed in various amounts with thorium and the above-indicated calculations repeated; this procedure was followed for both once- and twice-recycled uranium. An analogous procedure was used in determining the fuel value of recycle plutonium in uranium systems, with recycle material mixed with natural uranium.

The general results obtained from the above studies indicated that the fuel value of U^{233} was significantly more than that of plutonium, and that the fuel value of recycle material in thorium systems did not vary greatly through the second recycle, whereas in uranium systems the value of recycle material tended to decrease markedly with increasing recycle. These studies in themselves did not compare uranium and thorium systems. However, a comparison can be made using the above results, and this is given here, based on assumed values of \$15/g and \$12/g for U^{233} and fissile plutonium, respectively.

The absolute value of the fuel cost will be influenced considerably by the fuel-management scheme and by the fabrication charges as a function of fuel material. The reactivity lifetime was based on uniform-exposure in a batch cycle, and so the fuel costs given are greater than those associated with countercurrent fueling. Use of fuel-management schemes which approximated countercurrent fueling would tend to lower the fuel costs of the thorium reactors more than those of the uranium reactors.

The fabrication costs are based on estimates[21] in which the specific fuel elements and fuel materials were considered; values used are given in Table 3:

Table 3. Fuel Element Fabrication Charges, $/kg

Reactor \ Fuel Cycle	Initial	Recycle
Dresden	155	215
Yankee	52	110
Carolinas-Virginia	130	200
Hallam	25	90
GCR-2	22	85

Using USAEC economic ground rules and processing-cost schedule, the fuel-cycle cost was calculated as a function of fuel material. The results are listed in Table 4; these show that for the initial cycle the thorium systems give lower fuel costs in the light-water reactors, while the better-neutron-economy systems have lower costs when using uranium. This result is associated with the fuel enrichments required in the different reactor types. In the light-water uranium reactors, relatively high fuel enrichments were

required, leading to unit U^{235} costs which approached the unit cost of U^{235} in the thorium systems; this in combination with the increased reactivity lifetime associated with U^{233} systems led to lower fuel costs with thorium. In the better neutron-economy systems, however, there was a greater difference in initial-loading cost between the thorium and uranium reactors, which was not entirely compensated by the longer reactivity lifetimes obtained in the thorium systems. Use of countercurrent fueling would tend to lower thorium-fuel-cycle costs more than uranium-fuel-cycle costs.

With recycle material, thorium systems generally tended to have lower fuel costs than did uranium systems, since the recycle U^{233} is a much better nuclear fuel than is recycle plutonium in thermal reactors. As shown in Table 4, the fuel cost in the thorium systems stayed relatively constant during recycle, whereas in uranium systems the fuel cost tends to increase with recycle (this was not true in the first recycle with the Carolinas-Virginia and Hallam reactor types).

Rather than compare differences in fuel costs, we can consider the fuel-processing charge which gives the same fuel cycle cost for both thorium and uranium systems. This is done in Table 5, relative to the USAEC price schedule. As shown, the light-water thorium reactors permit fuel processing costs to be substantially higher than the USAEC schedule without imposing an economic penalty on thorium systems, but this was not true of the other reactors for uniform-batch fueling. In terms of a recycle technology, thorium systems had a clear economic advantage past the first recycle for all reactors studied.

Table 4. Fuel Costs in Thorium and Uranium Systems*

	Fuel Costs in mills/kwh(e)					
	Thorium System			Uranium System		
Reactor Type/Cycle	Initial	1st Recycle	2nd Recycle	Initial	1st Recycle	2nd Recycle
Dresden	4.30	4.37	4.48	4.54	5.09	7.5
Yankee	3.98	4.02	4.13	4.27	8.01	> 10
Carolinas-Virginia	4.77	5.16	5.95	4.70	3.92	7.48
Hallam	4.53	4.50	4.54	4.19	3.96	4.95
GCR-2	3.06	3.32	3.27	2.78	~ 4	> 4

*Based on fissile plutonium value of $12/gram, and a U^{233} value of $15/gram; uniform-batch cycle; fabrication charges listed in Table 3.

Table 5. Fuel-Processing Charges, Relative to USAEC Schedule, which give Same Fuel Cycle Cost in Thorium and Uranium Reactors

Reactor Type	Fuel-Processing Charge Relative to USAEC Schedule		
Cycle	Initial	1st Recycle	2nd Recycle
Dresden	2.6	5.8	19
Yankee	2.45	19	26
Carolinas-Virginia	0.8	-3.8	4.6
Hallam	-1.4	-6.4	2.7
GCR-2	-1.9	6.4	> 6.4

The above results indicate that thorium utilization is economically superior to uranium utilization in poor neutron-economy systems if fuel processing is to be performed. In terms of fuel recycle in thermal reactors, thorium systems generally appear to permit more-economic development of a recycle technology than do uranium systems.

Use of Thorium in Single-Region Homogeneous Reactors---- Thorium utilization in aqueous-homogeneous systems appears to give lower fuel cycle costs than does use of uranium in the same type of reactor.[22] Low fuel costs in thoria-heavy water slurry reactors result from the long fuel exposures which are possible without processing, high specific power, and the relatively high conversion ratio over the fuel cycle. If system corrosion rates are low, and slurries can withstand long periods of exposure, fuel costs in aqueous slurry systems can be less than 2 mills/kwh, based on zero processing for 10 or more years. At the end of that exposure, fuel-processing costs can be much greater than those specified in the USAEC schedule and still be economical.

4. Long-Term Potential of Thorium Fuel Cycles

As nuclear technology develops, it is expected that the costs of fuel handling, fabrication, refabrication, and processing will become relatively low. This will probably come about through a gradual expansion of nuclear-power stations and an associated growth in facilities serving these power stations; eventually, large-scale facilities should develop which will permit further advances in economic nuclear technology.

Once the costs of handling large amounts of radioactivity become low, power reactors will tend to operate on a breeding cycle. The actual value of the breeding (or conversion) ratio will depend on the relative worth of the fuel produced, inventory charges, the reactor type, and the cost of processing and refabricating the fuel in question. Under the circumstances postulated, both fast and thermal reactors should have low fuel costs, and it is difficult to know which of these reactor types will first overcome the technical problems which exist today. The point here is that breeder reactors in an era of advanced technology can have lower fuel costs than nonbreeders which do not use fuel processing and refabrication. It is only necessary to show that this is true for a certain class of reactors; thus, we will restrict our studies to thermal, thorium breeder reactors. If these reactors have very low fuel costs, then there are advantages in developing an advanced, fuel-handling technology utilizing thorium.

Because of superior nuclear properties, U^{233}-thorium systems have more potential as breeders, with potentially low fuel costs. However, in attempting to maintain good neutron economy the designer of a U^{233}-Th reactor is faced with a problem which does not occur to the same degree when U^{238} is used as the fertile material. The conversion of Th to U^{233} proceeds through the

intermediate, Pa^{233} which decays with a 27-day half life. There is some uncertainty about the cross sections of Pa^{233}, but they do not appear to be above 70 barns for the thermal cross section and 1200 barns for the resonance integral[23] (recent measurements[24] indicate these values may be about 40 barns and 900 barns, respectively). Based on the higher cross section values, Fig. 5 illustrates how seriously the absorptions in Pa^{233} can reduce the breeding (or conversion) ratio. Several methods of circumventing the Pa^{233} losses have been proposed, each of which has some undesirable economic features. From the graph it can be seen that one method of minimizing the Pa^{233} absorptions in single-region reactors is to have a low specific power in the core. If the specific power is kept down to 500 w/gm, the absorptions in Pa^{233} will be only 1 to 2% of those in U^{233}. Single-region reactors with such low specific power have relatively high fuel inventory charges if interest rates are high; conversely, less economic penalty is paid for low specific power if interest rates are low.

A second method of avoiding Pa^{233} losses, and the one most commonly suggested for thermal breeders, is to segregate the thorium in a separate region outside the core (referred to as a two-region reactor), where the flux is low enough to avoid excessive neutron captures in the protactinium. In a solid-fuel reactor, the core must be reprocessed relatively frequently, since the maximum fuel burnup that can be achieved without conversion is somewhat less than 1.0 absorptions per initial fissile atom. Two-region fluid-fuel reactors avoid this disadvantage since it is possible to increase enrichment without reprocessing the fuel. Another limitation associated with good neutron economy, and affecting all two-region systems, is that the net leakage from the fissile region to the fertile region must be almost 50% of the neutrons produced. At least one dimension of the core must be small to achieve this much leakage.

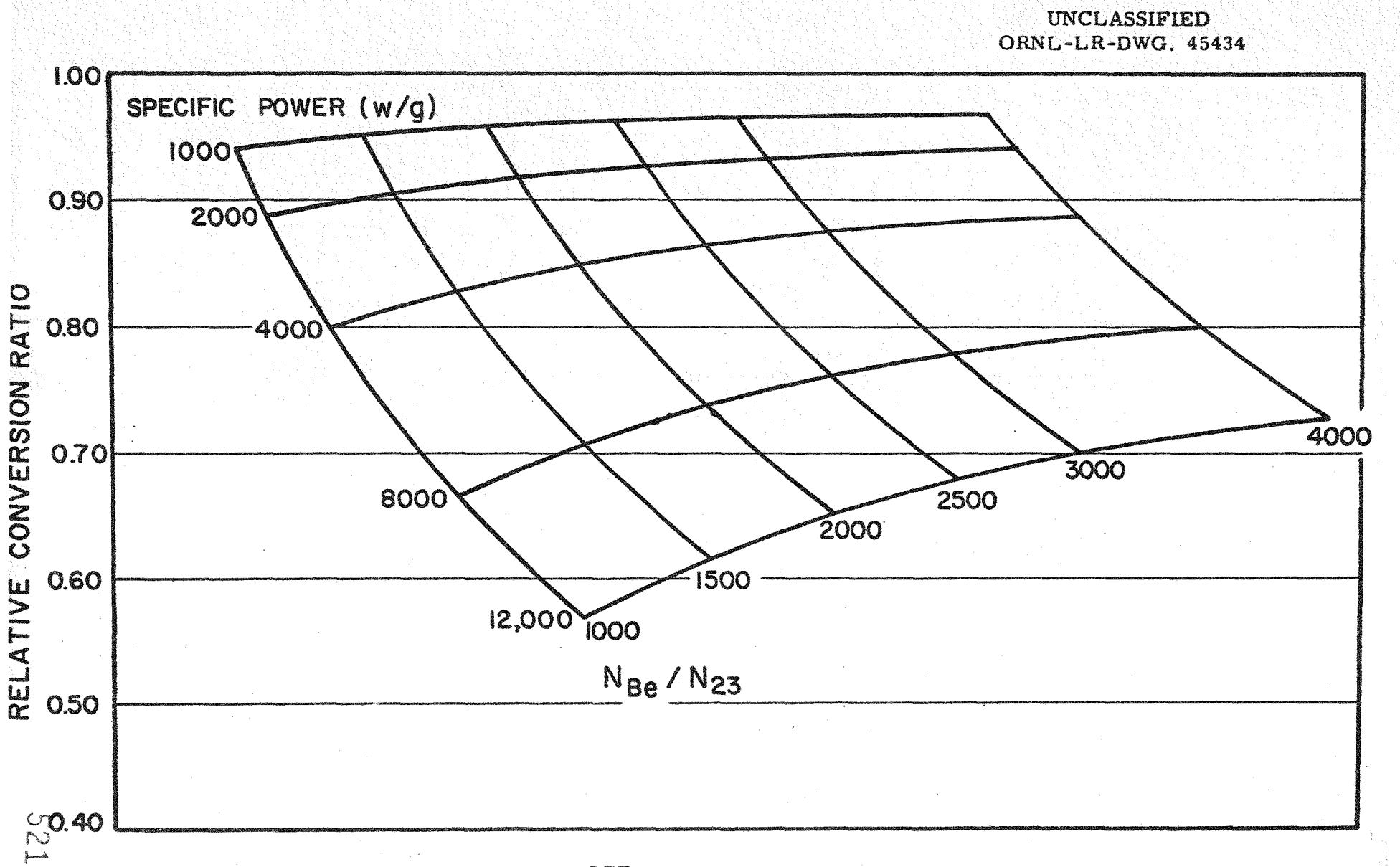

FIG 5 CONVERSION RATIO $U^{233}O_2$ - BeO - ThO_2 SYSTEMS COMPARED TO THE CONVERSION RATIO AT ZERO SPECIFIC POWER

When other aspects of the design (such as heat transfer requirements) are taken into account, it is often found that the total power output from the reactor is smaller than desired. Thus, Perry et al[25] studied a two-region graphite-moderated reactor with a 51-cm core radius in which 300 Mw(th) power could be generated. Studies of a BeO-moderated two-region system, however, have indicated[26] that 140 Mw(th) is a probable maximum for this system (31-cm core radius and a 610-cm core length). Limitations on total power can, of course, be avoided by multiple-region arrangements having more than one blanket region. Such designs are more complex mechanically but could prove worthwhile in some cases.

A third type of proposal for limiting the Pa^{233} losses involves moving the thorium (either with or separately from the fuel) through the core on a time scale which is short compared to the 27-day half life of protactinium. In the case of solid-fuel-element reactors this proposal would require the development of on-stream fuel handling equipment with a high degree of reliability and a moderate cost.

An economic disadvantage of reactors designed to breed is that a relatively short fuel lifetime is imposed by the requirements of maximum neutron economy. The fuel-movement and geometry requirements imposed by separating the thorium and uranium into two regions has been mentioned above. A more stringent and inescapable limitation is the need to remove fission products from a breeding system before they accumulate and absorb an excessive fraction of the neutrons. From an economical viewpoint, this removal is practical only if fuel processing costs are low. However, under such circumstance, breeder reactors have fuel-cost potentials lower than other systems.

Rather than speak in generalities, let us consider some specific reactor designs and methods of operation. In particular, five thermal, thorium breeder reactors will be considered for which a detailed analysis was made[14] of the relations between fuel cycle cost, breeding ratio, inventory requirement, and fuel-processing rate. Each reactor had a core region containing fissionable fuel, and a blanket region containing thorium; in general, U.S. cost bases were applied. Each reactor type was considered to generate energy for a large reactor station. Some major postulates were: (a) that each station have a net electrical capacity of 1000 Mw provided by at least two reactors, (b) that all processing be carried out in an on-site processing plant, (c) that the reactors are continuously fueled and processed and have reached equilibrium with respect to fission product poisoning and uranium isotopic concentration; and (d) the isotopic composition of new fuel produced is the same as the average composition of the entire system. A general, brief description of the five reactor systems and their operating conditions are given in Table 6. Further details are given in reference 14. The fuel cycle cost was composed of inventory and replacement charges for nuclear materials (fertile and fissionable isotopes, moderators, special coolants, carriers, or structural materials), processing costs, and breeding credit. The components of the fuel cost are a complex function of the reactor concept, its mode of operation, and the value of nuclear materials. The breeding credit is a direct function of the fuel inventory, the value of fuel, and the fuel yield; this latter quantity is defined as the annual net amount of fuel produced divided by the fuel inventory of the reactor system. The optimum fractional burnup of thorium in the blanket per cycle was determined principally by balancing the cost of blanket reprocessing, which tends to be high for low burnup, against the U^{233} inventory cost, which tends to be high for high thorium exposure.

Table 6. Characteristics of Five Thermal, Thorium Breeder Reactors

AHBR: Aqueous-Homogeneous Breeder Reactor. Four cores per station. Fuel was UO_2SO_4 in D_2O (473-554°F at 2000 psi). Processed by hydroclones and Thorex. Station efficiency was 27%. Zircaloy core vessel. ThO_2 pellets in blanket cooled by D_2O; processed by Thorex. Key variables were thorium cycle time and inventory. Fuel specific power was 0.7-1.1 Mw(e)/kg; thorium specific power was 6-7 Mw(e)/ton.

MSBR: Molten-Salt Breeder Reactor. Two cores per station. Fuel was UF_4 in $LiF-BeF_2$ (1100-1300°F, 100 psi) in direct contact with graphite moderator. Processed by F_2 volatility, HF dissolution, with salt discard. Station efficiency was 42%. Heat exchanger and reactor vessel constructed of INOR-8. Blanket contained ThF_4 solution in $LiF-BeF_2$; processed by F_2 volatility with salt discard. Key variables were process and discard cycle times, and thorium inventory. Fuel specific power was 0.8-1.2 Mw(e)/kg; thorium specific power was 4-5 Mw(e)/ton.

LBBR: Liquid-Bismuth Breeder Reactor. Two cores per station. Fuel was solution of U metal in Bi (1000-1300°F, 100 psi) in direct contact with graphite moderator. Fuel processed by molten-salt extraction. Station efficiency was 42%. Tantalum heat exchanger. ThO_2 slurry in blanket; processed by Thorex. Key variables were thorium cycle time and inventory. Fuel specific power was 0.5-0.7 Mw(e)/kg; thorium specific power was 6-11 Mw(e)/ton.

GGBR: Graphite-Moderated Gas-Cooled Breeder Reactor. Four cores per station. Fuel was unclad-graphite fuel plates impregnated with UO_2. Fuel processed by leaching and Thorex. Cooled by helium (500-1500°F, 2000 psi). Station efficiency was 36%. ThO_2 pellets in blanket were cooled by helium, and processed by Thorex. Key variables were processing cycle times and thorium inventory. Fuel specific power was 0.5-1.0 Mw(e)/kg thorium specific power was 5-10 Mw(e)/ton.

DGBR: Deuterium-Moderated Gas-Cooled Breeder Reactor. Four cores per station. Fuel essentially same as GGBR. Station efficiency was 32% (some heat in moderator was not available). Heavy water was contained in Zircaloy calandria. Thoria pellets in blanket were cooled by D_2O and processed by Thorex. Key variables were processing cycle times and thorium inventory. Fuel specific power was 0.4-0.6 Mw(e)/kg; thorium specific power was 5-8 Mw(e)/ton.

Characteristically, each reactor concept will exhibit a minimum fuel cycle cost at some optimum combination of reactor size, fuel inventory, material replacement and fuel processing rates, and power level per reactor. Factors which were considered in obtaining minimum fuel costs included the influence of moderator and fuel concentration on neutron energy spectrum and moderator absorptions; examination of the heat transfer characteristics of the reactor and (for the fluid fuels) of the system external to the reactor; influence of thorium inventory on protactinium losses and fuel inventory; and the influence of processing rates on processing costs, fuel inventory, and fuel yield. The reactor design and operating conditions selected are believed to be practical based on an advanced nuclear technology. Continuous on-site processing of fuel and fertile material was assumed in all cases, with the size of the processing plants and the method of processing varying from system to system. An attempt was made to develop processing costs which accurately reflect the type of process and the amounts and nature of the material being handled.

Using the aforementioned concepts as a basis, multigroup nuclear calculations were performed along with equilibrium-reactor calculations; the constraints imposed on the system were the conservation of mass, criticality, and neutrons. Finally, the nuclear data were used in conjunction with established cost bases to determine fuel cycle costs.

The results of the above calculations are presented graphically in Fig. 6, which shows the relation between total fuel cycle costs and per cent annual fuel yield. As shown, the AHBR and MSBR have the lowest fuel cycle costs, but all of the concepts have relatively low costs, indicating the worth of an advanced technology.

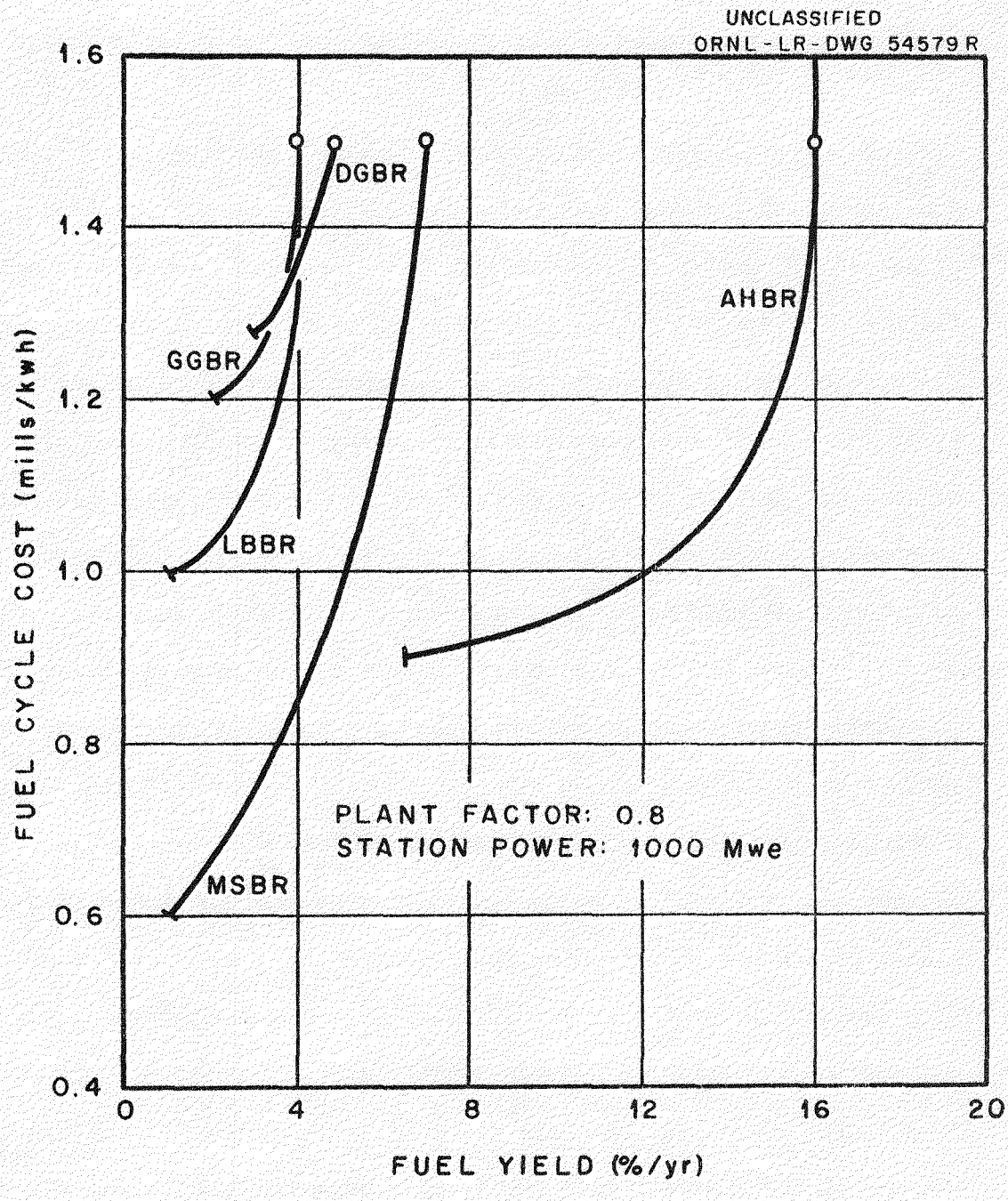

Fig. 6 Fuel Costs in Thermal Breeders

Another factor to be considered is the future cost of nuclear source materials. Eventually, it is expected that these costs will increase. However, reactors with high fuel yield have fuel costs which are least adversely affected by rising costs of fissile material; in fact, for the better breeder systems, increasing the fuel value can lead to fuel costs which are lower[14] than those given in Fig. 6.

5. Discussion

In utilizing nuclear fuels, we start with materials which occur in nature. Since it does not naturally contain fissile material, thorium starts at an economic disadvantage in comparison to natural uranium. However, the U^{233} bred from thorium has nuclear characteristics which are superior to those of the plutonium bred from natural uranium, and so thorium fuels maintain their reactivity for longer periods of exposure. The exposures attainable appear sufficiently long so as to permit economic use of highly enriched uranium in thorium systems; these exposures also permit fuel fabrication costs to be relatively high without increasing fuel cost appreciably. In addition, the value of spent fuel from thorium systems is appreciable, and fuel-processing costs can be several times as great as present USAEC charges and still be economical. In terms of fuel-recycle development, thorium fuels appear to offer economic advantages in thermal reactors.

In this study, reactivity lifetime was considered to be the limiting factor concerning fuel exposure. While tests to date on thoria and urania fuels appear encouraging, much additional information is needed about the effects of temperature and exposure on fission gas release and material properties. Fast reactors require fuel exposures of the same magnitude considered here for thermal thorium reactors, and so development of thorium-reactor technology will help advance reactor technology in general.

Generally, thorium utilization appears to be an economic method for advancing nuclear technology. Once this technology has developed to the point where costs are low for handling large quantities of radioactivity, reactor systems will have low fuel costs and tend to operate as breeders. Eventually, as we deplete inexpensive fuel reserves, breeding will become even more attractive. Thorium utilization appears to be attractive during both of these periods.

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