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PRACTICAL INTRODUCTION OF THORIUM FUEL CYCLES

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The practical introduction of thorium fuel cycles implies that thorium fuel cycles compete economically with uranium fuel cycles in economic nuclear power plants. In this study the reactor types under consideration are light water reactors (LWRs), heavy water reactors (HWRs), high-temperature gas-cooled reactors (HTGRs), and fast breeder reactors (FBRs). On the basis that once-through fuel cycles will be used almost exclusively for the next 20 or 25 years, introduction of economic thorium fuel cycles appears best accomplished by commercial introduction of HTGRs. As the price of natural uranium increases, along with commercialization of fuel recycle, there will be increasing incentive to utilize thorium fuel cycles in heavy water reactors and light water reactors as well as in HTGRs. After FBRs and fuel recycle are commercialized, use of thorium fuel cycles in the blanket of FBRs appears advantageous when fast breeder reactors and thermal reactors operate in a symbiosis mode (i.e., where ^{233}U bred in the blanket of a fast breeder reactor is utilized as fissile fuel in thermal converter reactors). If HTGRs are not developed as economic reactors on once-through fuel cycles, it is doubtful whether thorium cycles would be utilized commercially prior to FBR introduction along with symbiosis interactions between fast and thermal reactors. The ability to initiate thorium fuel cycles prior to the introduction of FBRs leads to a marked decrease in natural uranium requirements relative to that associated with introduction of thorium fuel cycles after fast breeder reactors are introduced.

Introduction

Interest in thorium fuel cycles has existed for many years.[1-4] Thorium is a fertile material whose bred fissile material, ^{233}U, has superior nuclear characteristics in thermal reactors when compared with ^{235}U and plutonium; the associated better fuel utilization of thorium cycles can also reduce power costs, although that is not assured.[3] Further, during the past few years there has been emphasis on decreasing the enrichment of uranium used in the thorium cycle, leading to use of mixed thorium-uranium fuel cycles rather than the standard thorium cycle. The mixed thorium-uranium fuel cycle utilizes uranium of about 20% enrichment plus thorium as the initial fuel, and is termed here as the "denatured uranium-thorium" or DUTH fuel cycle. The standard thorium fuel cycle employs highly enriched uranium plus thorium as the initial fuel. DUTH cycles, the standard thorium cycle, and uranium cycles were studied extensively in the Nonproliferation Alternative Systems Assessment Program (NASAP) carried out in the U.S. during 1977-79, and in the International Nuclear Fuel Cycle Evaluation (INFCE) studies carried out in the same period.

While the results of the INFCE studies showed that institutional factors were more important than technical factors in controlling proliferation aspects of commercial nuclear power, emphasis is still placed on use of uranium of less than 20% enrichment for the initial fueling of reactors. At the same time, once reprocessing technology is utilized commercially, the recycle of bred ^{233}U with thorium should receive emphasis since acceptance of reprocessing implies institutional control of the "highly fissile" material which is handled in the process ("highly fissile" is used here to refer to fuel having a fissile enrichment of more than 90%).

Another factor supporting acceptance of recycle of highly fissile ^{233}U is the presence of radioactivity due to the ^{232}U inherently associated with the ^{233}U; ^{232}U is generated along with ^{233}U when thorium is exposed to a neutron flux, and the daughter products resulting from ^{232}U decay produce a high energy gamma field which increases the difficulty of handling ^{233}U.

On the above bases, this paper considers thorium cycle use as follows: in the initial fueling of reactors, ^{235}U is the fissile material and the enrichment of the uranium is 20%, with thorium utilized with the uranium (DUTH) fuel; after fuel recycle is established, recycle fuel consists of ^{233}U and thorium; further, after fuel recycle is established, makeup fuel will utilize ^{235}U-Th based on establishment of institutional controls (alternatively, makeup ^{235}U can be

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added to the ^{233}U in the reprocessing plant such that all fuel contains inherently high radiation levels because of the ^{232}U daughter products).

Reactor Use of Thorium Fuel Cycles

The practical importance of thorium fuel cycles will be largely determined by the relative economic performance of those cycles compared with alternative choices. Items such as fuel utilization, available fuel resources, capital requirements, and technology development needs are all a part of the overall economic picture. Only those thermal reactor types which appear to be commercially available over the next 20 years will be considered in this paper, and these include LWRs, HWRs, and gas-cooled reactors (GCRs). In addition, FBRs are considered to be commercially available in 2020. All the above reactors can operate on either uranium, mixed uranium-thorium, or thorium fuel cycles. Further, all the thermal reactors can have good fuel utilization performance and even operate as break-even breeders under conditions which are not economic. Without consideration of economic limitations, a wide range of fuel utilization performances can be obtained and this is reflected in the wide range of values found in the literature for thorium fuel cycles. In this paper, reactor economics is considered to be the bases for fuel cycle application and so DUTH and standard thorium fuel cycles have to compete economically with uranium-based fuel cycles in order for them to be applied. This follows since mined uranium is the essential source of initial fissile fuel for both thorium and uranium fuel cycles.

An important consideration in the practical utilization of thorium fuel cycles is the availability of economic fuel recycle. Thorium fuel cycles in thermal reactors give improved fuel utilization over uranium cycles only if bred fuel is recycled, or if the fuel exposure is very high in once-through cycles. FBRs require fuel recycle to be economic on either uranium or thorium fuel cycles. Other important factors are the unit cost of fissile fuel, unit capital costs of reactors, costs of fuel fabrication and recycle, costs of fuel storage and waste disposal, and the economic ground rules associated with reactor inventory charges and capital charge rates.

The unit cost of initial fissile material increases as the uranium enrichment increases because the overall cost of separative work increases with enrichment. The capital costs of power plants vary with reactor type, which influences their economic performance. A high cost of money is detrimental to the use of high fuel inventory levels, which influences the nuclear performance of a given fuel cycle. The cost of fuel recycle generally is high relative to fresh fuel fabrication costs, which tends to favor use of once-through cycles; these costs are also highly dependent upon the status of technology and the size of the industry. Thus, while economic factors are very important, their future values are also very uncertain. Thus, results obtained under certain economic conditions may not always be cited with confidence, and estimates of future applications do have significant uncertainties; nonetheless, planning is still required based on the best estimates which can be made.

Additional features of fuel cycle use in specific reactor types are given here. LWRs (pressurized water reactors or boiling water reactors) are operating commercially on once-through uranium fuel cycles. While thorium cycles can also be used, the uranium cycle is clearly the present choice. The primary reason for that is the unavailability of fuel recycle; however, even with fuel reprocessing, the uranium cycle tends to be more economic than thorium cycles because the unit cost of fissile fuel in the uranium cycle is relatively low. Recycle of plutonium with thorium rather than uranium appears to be more economic,[5] but the amount of plutonium available for this situation would be limited, and such fuel recycle is not specifically considered here. Factors which favor use of thorium fuel cycles are fuel recycle, low costs for fuel recycle, low fuel inventory charge rates, low cost for separative work units, and high costs for mined U_3O_8.

The HWRs considered here are the pressure-tube heavy water reactors of the CANDU (Canadian-Deuterium-Uranium) type which utilize heavy water as both coolant and moderator. These reactors are commercially available and a relatively large number are in operation. While pressure-vessel heavy-water reactors have also been built and are operating, their number is few, and it is not clear that they provide an advantage in thorium use not provided by CANDUs.[3] HWRs using natural uranium fuel have a very low cost for the initial fissile material, such that thorium cycles will find it difficult to compete economically with the natural-uranium once-through cycle. HWRs have very good fuel economy; if thorium cycles are used in HWRs, their fuel utilization performance would be greater than that for thorium cycles in LWRs. As for LWRs, economic fuel recycle is required for practical use of thorium cycles in HWRs. Factors which favor use of the thorium cycle in HWRs are the same as for LWRs.

Regarding GCRs, there are several types of graphite-moderated thermal reactors which are in operation; however, the high-temperature gas-cooled reactor (HTGR) type using helium as the coolant is the most attractive for thorium fuel cycle application, appears to provide a more economic power plant, and has a greater market potential in the process heat field. As a result, only the HTGR is considered in this study.

In general, thorium fuel cycles tend to be more economic in those thermal reactors which are homogeneous in a nuclear sense, since this leads to relatively high uranium enrichments for the uranium cycle as well as for the thorium cycle. The HTGR is a relatively homogeneous system from a reactor physics viewpoint. Also, it has a relatively "hard" thermal nenutron spectrum, which tends to give thorium cycles an advantage. Further, HTGR fuel fabrication costs are relatively high, which makes it economically important to have long fuel exposures; since HTGRs fuels have excellent high exposure behavior, and can economically attain higher reactivity lifetimes than uranium cycles, thorium cycles are again favored in HTGRs. Because of the high fuel exposures which are practical, once-through thorium fuel cycles can be economic in HTGRs. At the same time, fuel recycle improves the relative advantage of thorium cycles, as does low costs for fuel recycle, low fuel inventory charge rates, low cost for separative work units, and high cost for mined U_3O_8. Use of plutonium from LWRs with thorium appears attractive in HTGRs,[5] but the amount of such plutonium would be limited, and such cycles were not specifically considered.

FBRs can operate on the various fuel cycles considered above, but economic fuel recycle is required to have practical FBRs. The fuel breeding ratio is highest for the uranium cycle, being substantially greater than for the standard thorium fuel cycle . Thus, there is not much incentive to operate FBRs on the standard thorium fuel cycle per se. However, if FBRs are used as fissile fuel production units with excess bred fuel being used to fuel thermal reactors, a mixed uranium-thorium cycle can be advantageous. By placing thorium in the blanket of FBRs and using the bred ^{233}U from the blanket region as fissile feed to thermal reactors, a combined symbiosis between thermal and fast reactors can take place. The nuclear performance of an FBR under the above conditions (with U-Pu in the core region) is nearly the same as use of the standard U-Pu cycle (U-Pu in the core, U in the blanket).

The advantage of fast-thermal reactor symbiosis as given above is that it permits a higher ratio of thermal to fast reactors. This is economically important if the capital costs of FBRs are significantly higher than those of thermal reactors; present estimates indicate that the above conditional situation will be the case.

Economic Conversion Ratios

Based on earlier studies[5] and other information, the economic fuel conversion ratios in the reactors under consideration are estimated to be those given in Table 1. The fuel conversion ratios given are the average in-reactor fuel conversion ratios, and do not consider the fuel "losses" in spent fuel for once-through cycles. Also, the economic ground rules are those given in Ref. 5, which include a fuel inventory charge rate of about 15%, and a mined U_3O_8 cost of

Table 1. Economic Conversion Ratios as Utilized in this Study

Reactor Type	Economic Fuel Conversion Ratio			
	Uranium Cycle		Thorium Cycle	
	Once-through	Recycle	Once-through	Recycle
LWR	0.6	0.6	*	0.7
HWR	0.75	0.75	*	0.8
HTGR	0.6	0.6	0.6	0.8
FBR	*	1.3	*	1.3†

* Not an economic cycle.

† Based on thorium use in radial blanket only.

$220/kg (representing U_3O_8 costs about the year 2000). DUTH fuel is considered as the initial fuel in the thorium reactors, but the standard thorium cycle is considered for recycle. In the case of FBRs, thorium without fissile material is used as feed to the radial blanket region of the reactor. In all cases, oxide fuel is considered to be utilized. Also, under recycle conditions, the effective inventory of the total fuel cycle was included when estimating economic fuel conversion ratios.

The influence of using DUTH initial cycles in the thermal reactors is primarily on the amount of bred fissile fuel in the spent fuel elements, and not on the mined U_3O_8 requirements of the first cycle. For either DUTH or standard thorium cycles (the latter uses high enriched uranium and thorium, and is termed HEUTH), use of the once-through cycle requires about 8300 standard tons of U_3O_8/GW(e) over a 30-year life for either LWRs or HWRs.[6] This value can be compared with 3800 and 6000 standard tons U_3O_8/GW(e) for HWRs and LWRs respectively for once-through uranium cycles, indicating that the once-through uranium cycle is more economic than the once-through thorium cycle. The influence of DUTH versus HEUTH cycles is greater in HTGRs, but even there both the once-through cycles have about the same uranium requirements. Calculations for pebble-bed-fueled HTGRs gave 4200 tons U_3O_8/GW(e) over 30 years for the DUTH cycle, 4000 tons for the HEUTH cycle and 4500 tons for the low-enriched-uranium (LEU) cycle; with prismatic fuel elements, the HTGRs required 4500 tons for the DUTH cycle, 4400 tons for the HEUTH cycle, and 4600 for the LEU cycle.[5] The above also indicates that once-through thorium cycles are preferable to the once-through uranium cycle in HTGRs, although the differences are small. With recycle, however, use of the DUTH cycle in HTGRs required 3700 tons U_3O_8, while the HEUTH cycle only required 2300 tons.[6] Thus, it is important to use HEUTH rather than DUTH cycles in HTGRs under recycle conditions from economic and fuel utilization viewpoints, but not too important for once-through cycles.

Extensive calculations under detailed economic conditions have been carried out covering the various fuel cycles and different reactor types; these were performed during the 1977-79 time period and reported in References 6-8. While these calculations generally did not optimize the economic performance of thorium fuel cycles, the results obtained are reasonably consistent with the estimates given in Table 1 for economic fuel conversion ratios of the reactor types of interest here, when the fissile inventory of the total fuel cycle and fuel recycle costs are considered.

Practical Introduction of Thorium Fuel Cycles

In examining the virtues of thorium fuel cycles, certain reactor-use scenarios will be employed,[9] with reactors having the conversion ratios given in Table 1. Under these conditions, the mined U_3O_8 requirements will be estimated. This approach basically considers operation of reactors under the economic factors and ground rules used in Ref. 5, and the fuel conversion ratios of Table 1; under these conditions, the estimated mined U_3O_8 requirement is a measure of the desirability of specific reactor use.

The first reactor use scenario is given in Figure 1, in which only LWRs and FBRs are assumed. LWRs operating on the uranium fuel cycle are considered to be installed at a rate of 10 GW(e)/year up to a level of 500 GW(e) in the year 2020. After that time LWR capacity remains constant at 500 GW(e). Recycle of uranium and plutonium starts in 2000, with operation on the once-through cycle previously, and with the plutonium in the previously stored fuel from once-through cycle operations available for FBRs at the time of FBR introduction. Starting in 2020, FBRs are introduced into the economy at 10 GW(e)/year until 2050, after which time the total nuclear capacity remains at 800 GW(e). Fuel recycle in FBRs is available at the time of FBR introduction.

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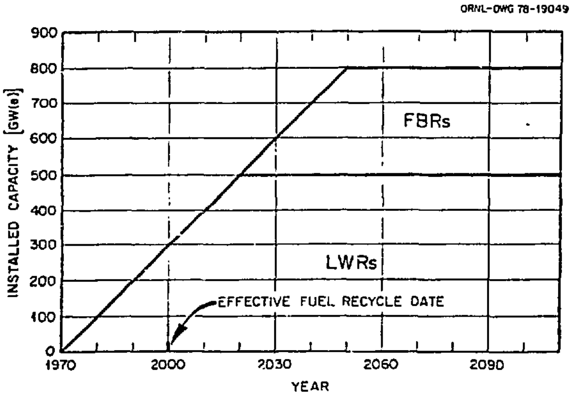

NUCLEAR POWER GROWTH SCENARIO WITH LWRs AND FBRs

The FBRs have a breeding ratio of about 1.3 and a system specific inventory of about 6 kg fissile Pu/MW(e); the fuel doubling time is about 20 years. The total fissile plutonium requirement at an FBR growth rate of 10 GW/year is about 600 MG of fissile plutonium. Further, this maximum need occurs 20 years after FBR introduction for the above conditions. Since the amount of fissile plutonium in spent LWR fuel generated up to the year 2000 would be about 700 Mg, saving LWR plutonium up to the year 2000 will provide sufficient plutonium for the start-up of the FBRs. In order to limit the fissile plutonium requirements to 600 Mg, the FBRs are operated on the U-Pu fuel cycle with recycle of plutonium for 20 years. After 2040, however, the FBR operates with a radial thorium blanket and produces ^{233}U for use in thermal reactors; for such circumstances, an effective conversion ratio of unity applies to the U-Pu cycle in the core, with an excess bred fuel ratio of 0.3 associated with the thorium in the radial blanket. On the above basis, LWRs can be converted to the thorium cycle using ^{233}U obtained from FBRs starting in 2040; after converting to ^{233}U fueling, the LWR thorium cycle conversion ratio is about 0.8. Under these conditions, two FBRs can fuel about three LWRs under equilibrium fueling conditions, which is approximately the equilibrium conditions given in Fig. 1 (as given in Fig. 1, the LWR fuel conversion ratio for the thorium cycle is 0.82).

The mined fuel requirements for the Fig. 1 scenario up to the year 2040 is 3 Tg U_3O_8 (3.3 million tons) based on U_3O_8 requirements/GW(e)-lifetime of 5.4 Gg (6000 short tons) U_3O_8 for LWR once-through LEU cycles and 3.5 Gg (3900 short tons) U_3O_8 for LWRs with U-Pu recycle. After 2040, FBRs would start contributing to the fissile needs of LWRs, and in the steady state would meet them. However, mined U_3O_8 is needed while the LWRs are being converted to ^{233}U fueling. The thorium cycle LWR with a conversion ratio of about 0.8 will require an effective fissile inventory of about 6 kg ^{233}U/MW(e). Converting 500 GW(e) of LWRs to ^{233}U/Th fueling will require about 2 Gg ^{233}U, and an additional 1.2 Gg ^{233}U is needed to provide makeup fuel and raise the conversion ratio from 0.6 to 0.8 over the period 2040 to 2050. Thus, the total ^{233}U need is about 3.2 Gg ^{233}U, of which 750 Mg ^{233}U is produced by FBRs during the same period. The above leaves a net need of 2.5 Gg ^{233}U, which is estimated to be equivalent to about 5.5 Gg ^{235}U, taking into account the relatively long time to reach equilibrium fueling. Thus, converting LWRs to the thorium cycle will require about 1.0 Tg (1.1 million tons) of mined U_3O_8. The total mined U_3O_8 requirements for the Fig. 1 scenario is then 4 Tg (4.4 million tons) U_3O_8.

The next scenario is given in Figure 2, and considers use of LWRs, HWRs, and FBRs. In this scenario, LWRs are again initially introduced at 10 GW(e)/year, but introduction is stopped in

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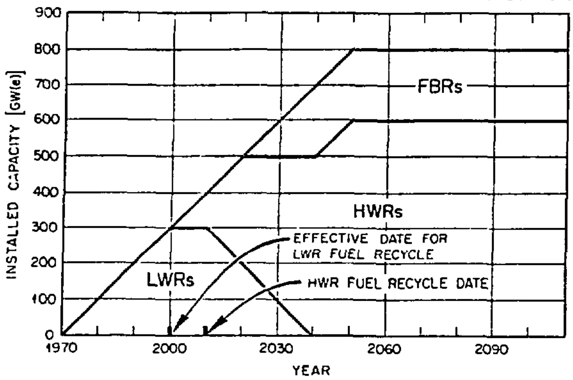

NUCLEAR POWER GROWTH SCENARIO WITH LWRs, HWRs, AND FBRs

2000, after which LWRs are retired in accordance with a 30-year plant life. Recycle of LWR fuel (U and Pu) again starts in 2000. In the year 2000, HWRs are introduced at a rate of 10 GW(e)/year, using a once-through uranium fuel cycle. This continues for 10 years; then HWRs are introduced at a rate of 20 GW(e)/year to maintain an overall nuclear power growth rate of 10 GW(e)/year. Recycle of U-Pu from HWRs is started in the year 2010. Nuclear power continues to grow through HWR additions until a level of 500 GW(e) is attained in 2020. Then FBRs are introduced commercially, fueled with plutonium from previously stored LWR fuels. The FBRs again contain uranium in their blanket, but 20 years after FBR introduction, thorium is used in the blanket, and the bred ^{233}U is recycled to the HWRs as makeup fissile feed, at which time the HWRs are converted to thorium fuel cycles. The FBRs are introduced at 10 GW(e)/year until 200 GW(e) of FBR capacity is reached. From 2020 to 2050, HWRs are added at a rate of 10 GW(e)/year. After 2050 the nuclear capacity remains at 800 GW(e).

Twenty years after their introduction, the FBRs start contributing excess fissile fuel for use in HWRs. This excess fissile fuel would be ^{233}U for the above scenario, and its use would increase the HWR fuel conversion ratio from 0.75 to 0.9. This increase permits one FBR to fuel three HWRs under equilibrium conditions. Thus, in 2040, the number of HWRs start to increase up to a level of 600 GW(e), giving a total of 800 GW(e) from about 2050 onward.

On once-through LEU cycles, HWRs provide relatively good fuel utilization, with the mined fuel requirement being about 3.4 Gg (3800 tons) U_3O_8/GW(e)-lifetime. With fuel recycle, the mined fuel requirement would be about 2.7 Gg (3000 tons) U_3O_8/GW(e)-lifetime. This leads to mined U_3O_8 requirements up to 2040 of about 2.6 Tg (2.9 million tons) of U_3O_8. After 2040, the HWRs on ^{233}U equilibrium fueling would have a conversion ratio of 0.9, and a fuel cycle inventory of 5 kg fissile/GW(e). In converting the HWR to ^{233}U/Th fueling after the year 2040, the HWR is estimated to require about 3.2 Gg of ^{233}U [500 mg for the "new" 100 GW(e) of HWRs after 2040, 2 Gg for converting 500 GW(e) of HWRs from U to Th cycles, and 700 Mg for makeup over 10 years], of which 600 Mg would be provided by FBRs; for these HWRs, this is estimated to be an equivalent need of about 5.2 Gg of ^{235}U, or about 0.9 Tg (1.0 million tons) U_3O_8. The total mined fuel requirement for the Fig. 2 scenario would then be 3.5 Tg (3.9 million tons) of U_3O_8.

The third scenario is given in Figure 3. It is analogous to Fig. 2, except that HTGRs are utilized instead of HWRs, with HTGR introduction in 2000 and HTGR fuel recycle occurring in 2010. The LWR use is the same as in Fig. 2. HTGRs are introduced in 2000 operating on the once-through DUTH cycle. Starting in 2010, the HEUTH fuel cycle is utilized in the HTGRs. Again, FBRs are introduced in 2020, initially operating on the U-Pu fuel cycle; starting in 2040, thorium is placed in the radial blankets of the FBRs, and the bred ^{233}U is recycled to the HTGRs. With ^{233}U fueling, the fuel conversion ratio of the HTGRs increases to 0.9 under equilibrium conditions, so that one FBR can fuel three HTGRs. Thus, in 2040, the number of HTGRs start to increase up to a subsequent level of 600 GW(e), with the FBR capacity remaining at 200 GW(e). This gives a total of 800 GW(e) from about 2050 onward.

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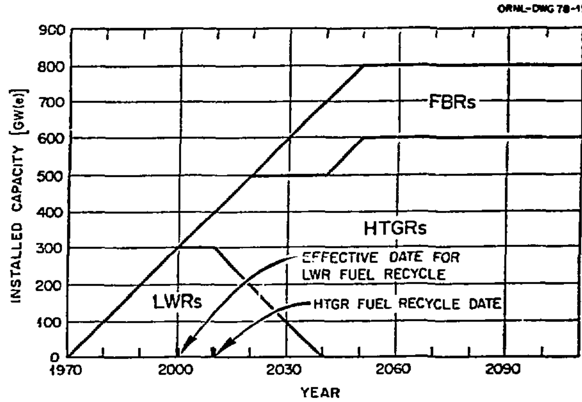

NUCLEAR POWER GROWTH SCENARIO WITH LWRs, HTGRs, AND FBRs

Up to 2040, the mined U_3O_8 requirements associated with the above scenario are about 2.5 Tg (2.8 million tons) of U_3O_8, based on GW(e)-lifetime requirements of:

- 5.4 Gg (6000 short tons) U_3O_8 for LWRs on once-through cycles,
- 3.5 Gg (3900 short tons) U_3O_8 for LWRs with fuel recycle,
- 4.1 Gg (4500 short tons) U_3O_8 for HTGRs on once-through cycles, and
- 2.2 Gg (2400 short tons) U_3O_8 for HTGRs with fuel recycle.

Starting in 2040, the HTGRs would be converted to ^{233}U fueling. For a conversion ratio of 0.9, the HTGR will need a fuel cycle system inventory of about 5 kg ^{233}U/MW(e). Thus, to inventory the "new" 100 GW(e) of HTGRs after 2040 will require 500 Mg ^{233}U, while the inventory of the "old" 500 GW(e) of HTGRs will increase from approximately 4 kg fissile/MW(e) to 5 kg fissile/MW(e), leading to an additional 500 Mg ^{233}U. Further, there will be fuel makeup requirements of about 125 Mg ^{233}U associated with converting systems with a conversion ratio of 0.8 to systems with a conversion ratio of 0.9, plus makeup of 500 Mg ^{233}U over the period 2040 to 2050. The total of the above is 1.675 Gg ^{233}U; however, there is a credit of 600 Mg ^{233}U from the FBRs over the same 10-year period, so that the net ^{233}U need is about 1.1 Gg ^{233}U, which would have to be "obtained" by using an equivalent amount of ^{235}U instead. This "equivalent" amount is estimated to be about 2.2 Gg ^{235}U (taking into consideration the length of time to reach equilibrium fueling conditions), leading to a mined fuel need of about 450 Gg (500,000 tons) U_3O_8. The total mined fuel requirement for the Fig. 3 scenario is then about 3 Tg (3.3 million tons) of U_3O_8.

Summary of Mined U_3O_8 Requirements

On the basis of the above scenarios and the conversion ratios employed for economic reactor operation, the mined U_3O_8 requirements are summarized in Table 2.

Table 2. Summary of Mined U_3O_8 Requirements, Tg (million short tons)

Scenario	Reactors	Up to 2040	For conversion to symbiosis fueling	Total
Figure 1	LWRs, FBRs	3.0 (3.3)	1.0 (1.1)	4.0 (4.4)
Figure 2	LWRs, HWRs, FBRs	2.6 (2.9)	0.9 (1.0)	3.5 (3.9)
Figure 3	LWRs, HTGRs, FBRs	2.5 (2.8)	0.45(0.5)	3.0 (3.3)

Table 2 illustrates that up to 2040, the U_3O_8 savings associated with HWR use (Fig. 2 scenario) or HTGR use (Fig. 3 scenario) relative to LWR use (Fig. 1 scenario) is about 0.5 Tg (0.55 million tons) U_3O_8. However, when converting to symbiosis fueling between fast and thermal reactors, significant savings in mined U_3O_8 occur if the thorium cycle is employed in thermal reactors prior to FBR introduction. Conversion for the Fig. 1 and 2 scenarios required about 1 Tg (1.1 million tons) U_3O_8, whereas conversion for the Fig. 3 scenario required only 0.45 Tg (0.5 million tons). Thus, in converting to the symbiotic system of fast and thermal reactors, use of the HTGR led to savings during the conversion period which were greater than the savings accumulated before that period. The total 20 to 30% reduction in mined U_3O_8 requirements appears significant, since the impact would be on the highest cost ore. Finally, the ratio of thermal to fast reactors could be significantly higher if HTGRs or HWRs were used rather than LWRs in the long term.

In the above, no mention is made of thorium requirements, although there is an obvious thorium requirement. However, the fuel resource limitations are associated with fissile material obtained from natural uranium rather than with fertile material itself. Since there are ample thorium resources (particularly with thorium recycle), thorium requirements are not an issue and are not included here.

Concluding Remarks

The above scenarios are on the basis that LWRs are the initially utilized reator type. While that is true for many countries of the world, it is not true for all. Further, estimates of fuel fabrication costs and fuel recycle costs for the different fuels and different reactor types were used in obtaining economic fuel conversion ratios; these future costs are uncertain and can influence the choice of both fuel cycle and reactor type. The specific unit fuel cycle costs employed are given in Table 3. Also, the capital costs of reactor types are much more controlling of economic performance than the choice of fuel cycle. As a result, uncertainty in capital costs can have an important influence on choice of reactor type. In particular, uncertainty in the capital costs of HTGRs and FBRs influences their development and application. Even where a reactor type is commercially developed, cost uncertainty can be high if licensing requirements vary from country to country. In this study, the power costs of the economic fuel cycles were considered to be competitive.

Table 3. Relative Unit Fuel Cycle Costs Employed

Cost, $/kg

Reactor	Fuel Cycle	Fabrication	Reprocessing	Refabrication	Fuel Storage
LWR	^{235}U-^{238}U	114	221		100
	Pu-U		221	500	
	^{235}U-Th	152	250		
	^{233}U-Th		250	570	
HWR	Natural U	50	150		25
	Enriched U	80	160		100
	Pu-U		160	310	
	^{235}U-Th	100	210		
	^{233}U-Th		210	390	
HTGR	^{235}U-Th	400	750		400
	^{233}U-Th		750	1030	
	^{235}U-^{238}U	360	730		

In spite of the above uncertainties, the analysis performed illustrates the U_3O_8 savings associated with early introduction of thorium fuel cycles if fast-thermal reactor symbiosis as described above is important in the future.* It also indicates that the HTR has the best chance of early introduction of thorium cycles if that reactor type is economically competitive.

The reactor scenarios were chosen to emphasize the effect on mined U_3O_8 requirements of utilizing different thermal reactors prior to FBR introduction, based on estimated economic fuel cycles for specific reactor types. In actual practice, there will undoubtedly be a mix of different reactor types in use throughout the world so long as nuclear power plants are being used.

It should also be remarked that the specific nuclear power development in a country can influence fuel cycle use. For example, in a country such as Canada, perceived overall economics may indicate the development of thorium fuel cycles in thermal reactors at an early date in order to defer the development requirements of FBRs;[10] since Canada is utilizing HWRs which have good fuel utilization requirements, their requirement for FBRs is less compelling than for countries where LWRs are being utilized in large numbers. Also, their U_3O_8 resources relative to nuclear power use are relatively high. As a result, depending on circumstances, a given country may find it overall economically desirable to increase the early cost of a fuel cycle in order to give improved fuel utilization and defer spending large amounts of money for the development of new reactor systems in the future. Such a situation was not considered in the above analysis. Rather, the position taken was that fuel utilization is based on near-term economics, and while it is an adjunct to overall economic performance, it is not a controlling factor. At the same time, because of the uncertainty in the many cost factors and ground rules involved, it is not assurred that the estimated operating conditions will indeed correspond to future economic operating conditions. The final analysis can only be performed after actual reactor and fuel cycle operations are carried out commercially. Nonetheless, planning will continue to be a needed requirement, and has to be based on estimated future costs.

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*Implicit in this presentation is the understanding that symbiosis between fast and thermal reactors as described above for mixed uranium-thorium cycles results in higher ratios of thermal-to-fast reactors than does use of the U-Pu cycle in which the Pu from FBRs is used as feed to thermal reactors. This arises due to the advantageous nuclear properties of ^{233}U relative to those of Pu in thermal reactors.

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