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A STRATEGY FOR THE PRACTICAL UTILIZATION OF THORIUM FUEL CYCLES*

Paul R. Kasten

Oak Ridge National Laboratory
Oak Ridge, Tennessee

SUMMARY**

There has been increasing interest in the utilization of thorium fuel cycles in nuclear power reactors for the past few years. This is due to a number of factors, the chief being the recent emphasis given to increasing the proliferation resistance of reactor fuel cycles and the thorium cycle characteristic that bred ^{233}U can be denatured with ^{238}U (further, a high radioactivity is associated with recycle ^{233}U, which increases fuel diversion resistance). Another important factor influencing interest in thorium fuel cycles is the increasing cost of U_3O_8 ores leading to more emphasis being placed on obtaining higher fuel conversion ratios in thermal reactor systems, and the fact that thorium fuel cycles have higher fuel conversion ratios in thermal reactors than do uranium fuel cycles. Finally, there is increasing information which indicates that fast breeder reactors have significantly higher capital costs than do thermal reactors, such that there is an economic advantage in the long term to have combinations of fast breeder reactors and high-conversion thermal reactors operating together. Further, from a proliferation resistance viewpoint, it appears desirable to maintain the ratio of

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thermal reactors to fast reactors at a high value, which reinforces the influence of the capital cost factor and also leads to interest in the generation of ^{233}U in the blanket region of fast breeder reactors. Thorium blankets in fast breeder reactors would then generate fissile fuel for use in high-conversion-ratio thermal reactors operating on thorium fuel cycles. Thus, a strategy is implicit in the above which indicates that there should be commercial introduction of advanced converter reactors followed by introduction of fast breeder reactors. Further, use of the stowaway fuel cycle initially in advanced converters permits fuel recycle technology to be developed without requiring a large expenditure of funds for demonstration facilities at the time of initial introduction of thorium fuel cycles in reactors. Once thorium-fueled reactors are established, fuel recycle demonstration should proceed for thermal reactors. Fast breeder reactors (FBRs) are also important, and should be developed as soon as practical, but economic and other issues may delay their commercial introduction. However, fuel recycle is needed at the time of their introduction. In the above strategy, FBRs would operate most effectively with U/Pu cores (with recycle of plutonium), and with thorium blankets.

The above scenario considers advanced converter use in a general way; however, specific reactor types need to be evaluated since the results are influenced by the reactor systems which are utilized. In particular, while use of the thorium fuel cycle rather than the uranium cycle improves fuel utilization in all thermal reactors, it does not follow that the thorium fuel cycle is always less expensive than the uranium fuel cycle in such reactors. Another factor involves the ability to bring a new reactor system into commercial use. The more distant the practical commercialization of an advanced converter reactor system, the less important is that system in resolving problems which the new system is to overcome. Only those systems which, with strong government support, might be commercialized within the period 1990-2000 are considered here, with those systems being Advanced Light Water Reactors (ALWRs), Spectral Shift Converter Reactors (SSCRs), Heavy Water Reactors (HWRs), and High-Temperature

Gas-Cooled Reactors (HTGRs). Of these systems, the water reactors as a class are more heterogeneous in a nuclear sense than are HTGRs. As a result, for water reactors the uranium fuel cycle tends to be more attractive economically than does the thorium fuel cycle; the converse is true for the HTGR. Further, the fuel exposures which are practical in water reactors are about a factor of three less than those attainable in HTGR fuel systems. Thus, on stowaway fuel cycles the water reactors as a class have relatively poor economic and fuel utilization performance with the thorium fuel cycle compared with the uranium cycle, whereas in the HTGR the thorium cycle has both better economic and fuel utilization performance. With fuel recycle, the competitive position of the thorium fuel cycle improves relative to the uranium cycle, but based on present estimates of unit fuel recycle costs, water reactors in general perform better economically on the uranium cycle up to uranium prices of about \$200/lb, whereas the thorium cycle in HTGRs appears economically attractive at present U_3O_8 prices and higher. Thus, the strategy for early introduction of thorium fuel cycles basically revolves about the introduction of HTGRs into the nuclear economy. If HTGRs are successfully introduced, they show promise of economic operation initially on stowaway cycles, followed by improvements with fuel recycle. In addition, HTGRs are attractive systems in combination with fast breeder reactors which produce ^{233}U in thorium blankets, since the HTGR shows promise of having economic conversion ratios above 0.9 when externally fueled with makeup ^{233}U; the above permits the thermal-to-fast reactor ratio to be relatively high in the long term.

Overall, it appears that the practical, early utilization of thorium fuel cycles in power reactors requires commercialization of HTGRs operating first on stowaway fuel cycles, followed by thorium fuel recycle. In the longer term, thorium utilization involves use of thorium blankets in fast breeder reactors, in combination with recycling the bred ^{233}U to HTGRs (preferably), or to other thermal reactors.

1. INTRODUCTION

Proliferation concerns of the nuclear fuel cycles in both fast and thermal reactors has increased as a result of the nuclear policy statement as articulated by President Carter on April 7, 1977. That policy statement has led to an emphasis on alternate fuel cycles not involving access to materials directly useful for weapons production. Since the thorium fuel cycle breeds ^{233}U from thorium, and since ^{233}U can be mixed with ^{238}U to produce a fuel material useful in reactors not directly applicable to weapons, thorium fuel cycles have received increased attention. Further, ^{233}U will contain ^{232}U and associated daughter products which make fuel handling difficult because of intense radioactivity; plutonium production from thorium fuel cycles is relatively low. Independent of the above, there is also increasing interest in the use of thorium in thermal power reactors as the cost of uranium and separative work increases; this latter interest is due to the improved fuel utilization that thorium cycles provide over uranium fuel cycles in thermal reactors, leading to a potential for improved economic performance. Also, thorium use would add to the world's nuclear resource base.

An important factor in the long-term use of nuclear energy is the amount of natural uranium resources which exist at economic costs of recovery. If very large amounts of uranium exist at low cost, there is less need to have high fuel utilization performance in power reactors. Further, if nuclear power growth is very restricted, the demands on uranium use are much less than if nuclear growth is rapid. It is presently expected that nuclear energy capacity installed in the United States by the year 2000 will be in the range of 300 to 450 GW(e). Uranium resources recoverable at reasonable costs are estimated to be in the range of 2-4 million tons U_3O_8 in the U.S. Under such circumstances, continued use of present-day LWRs operating on the stowaway uranium fuel cycle would lead to limited use of nuclear energy from a long-term viewpoint. As a result, considerable emphasis has been placed on the development of systems which have improved fuel utilization characteristics, with most emphasis having been placed on the development of the Liquid Metal Cooled Fast Breeder Reactor (LMFBR) operating on the uranium/plutonium fuel cycle. However, the recent decision by President Carter to defer commercialization of plutonium recycle and of Fast Breeder Reactors (FBRs), along with recent cost estimates indicating that LMFBRs will have capital costs 25-75% higher than those of LWRs, implies that the introduction date of FBRs will be delayed which, along with continued use of LWRs over the next decades, makes it important to quickly commercialize reactors which have improved fuel utilization over that of present LWRs. With regard to the above, the preferred fuel for thermal spectrum reactors is ^{233}U, the fissile material bred from thorium. Thermal spectrum reactors with conversion ratios close to unity can be developed with ^{233}U as the fuel; thus, advanced converters based on the U/Th cycle can give much more energy per pound of uranium mined than corresponding thermal reactors based on the U/Pu cycle. Finally, in the long term it appears desirable from economic, proliferation resistance, and licensing viewpoints to have a high ratio of thermal to fast reactors; symbiotic combinations of breeders and advanced converters utilizing thorium cycles could permit such ratios. Thus, there are several reasons for exploiting the thorium fuel cycle.

There are only a limited number of advanced reactor types which might be considered in the above context. These are: (1) Advanced Light Water Reactors [ALWRs; these are improved LWRs which will give improved fuel utilization; includes thorium use], Spectral Shift Converter Reactors [SSCRs; basically LWRs utilizing a mixture of light and heavy water as moderator/coolant], High-Temperature Gas-Cooled Reactors [HTGRs], and Heavy Water Reactors [HWRs]. All these reactors can operate on either the uranium, thorium, or mixed thorium-uranium cycle, and might be reasonably introduced within the next 10-15 years. In the sections that follow, emphasis will be on the relative performance of thorium and uranium fuel cycles in the different reactor types since they represent the extremes in nuclear performance one might obtain between available fuel cycles. The effect of utilizing mixed thorium-uranium fuel cycles (associated with use of denatured-uranium thorium fuel) are discussed later.

2. THORIUM CYCLE IN THERMAL CONVERTER REACTORS

Resource considerations and nuclear energy demand determine the need for improved reactor performance from the viewpoint of fuel utilization requirements. Specific reactor types and nuclear power growth scenarios will be considered here, in order to give understanding of how thorium fuel cycles can contribute to improved uranium utilization, and how they influence power costs. As indicated above, the standard thorium cycle is compared with the uranium cycle in this section. Results obtained previously[1,2] will be first reviewed and form a basis for further evaluations given here.

The nuclear power growth scenario considered first is that indicated in Fig. 1 and assumes a nuclear power growth of 15-GW(e)/yr during the period 1970-2000. After the nuclear power capacity reaches 450 GW, it is maintained at that level until reduction is necessary because of limitations in U_3O_8 resources, consistent with a 30-yr lifetime for all reactors which are built. The available U_3O_8 resource is considered to be either 2.5 or 3.5 million short tons of U_3O_8.

In these studies, reference LWRs operating on the uranium cycle are used initially; these are termed LWR_1s, as given in Fig. 1. Reactors built after the year 2000 are either additional LWRs operating on the uranium cycle (termed LWR_2s for ease of identification), LWRs operating on the thorium cycle [LWR(Th)s], SSCRs, HWRs, or HTGRs. The latter three reactors can be operated on either the thorium or uranium fuel cycle (the best fuel utilization will be obtained on the thorium cycle; the economic performance tends to be better on the thorium cycle for HTGRs, and tends to be better on the uranium cycle for HWRs and SSCRs).[1] After the year 2000, LWR_1s are withdrawn from use as their 30-yr lifetime (21 full power years) is attained and

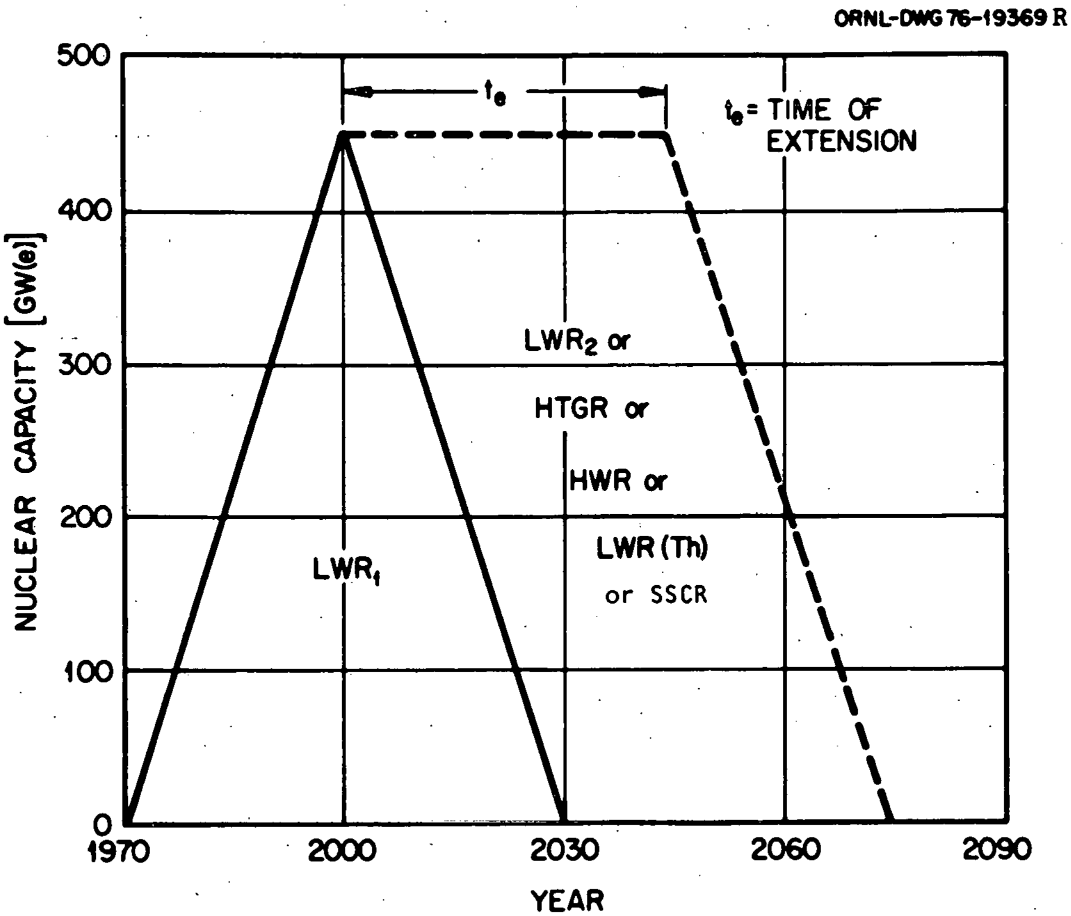

FIG. 1. THERMAL REACTOR POWER GROWTH SCENARIO [INITIAL GROWTH OF 15 GW(e)/YEAR; LWR_2, LWR(Th), SSCR, HWR, OR HTGR INTRODUCED IN 2000]. The t_e time shown is illustrative only, and varies with different cases.

replaced with a second type reactor chosen from the available types considered above. The power capacity is maintained at 450-GW(e) for a period of time, t_e, defined as the time of extension associated with maintaining the power capacity at 450-GW(e). After time t_e, no new reactors are built and those in use operate until the end of their 30-yr lifetime. Figure 1 serves as an illustration of what t_e signifies and the time given should not be taken literally.

The power growth scenario of Fig. 1, along with the estimated lifetime U_3O_8 requirements of the various reactors, is used to calculate the energy that can be generated as a function of new reactors used. In performing this calculation, a given reactor is considered to operate for 21 full power years over its lifetime and the uranium tails from enrichment plants were considered to be 0.2% ^{235}U. It is further assummed that 1200 tons of fissile plutonium generated by LWR_1s is stored for future use in FBRs. That amount of plutonium permits a significant breeder economy to develop eventually as discussed later.

In measuring the improved fuel utilization of a new reactor, it is important to factor in the time of introduction of the new reactor and the amount of U_3O_8 resource available to it. This is done here by measuring the energy generation of combined reactor systems against the energy which could be generated if no new reactors were introduced. Thus, the energy generated by LWR_1s plus LWR_2s is the reference energy generation, based on the use of LWRs with uranium and plutonium recycle in which the entire ore resource is utilized (except for the plutonium stored for FBRs). The corresponding energy generation when new reactors are introduced after the year 2000 is also calculated and compared with the reference energy generation. The resulting comparisons are termed the Relative Energy Generation (REG), and are given in Table 1 for various reactor combinations and U_3O_8 resource levels.[1-4] Table 1 results are based on thorium cycle use in the second reactor, on reference designs, and on fuel conversion ratios which correspond to economic operation based on estimated unit fuel recycle costs for the above reactors.[1] The fuel utilization results also consider the reactor thermal efficiencies as given in Table 1.

Table 1. Relative Energy Generation and Extension Time for Assumed Power Growth Scenario as a Function of Reactor Use and U_3O_8 Resource

Reactor Use	Fuel CR for Second Reactor	Second Reactor Thermal Efficiency (%)	Relative Energy Generation (REG) and Extension Time (t_e) for Two U_3O_8 Resource Levels			
			2.5×10^6 tons		3.5×10^6 tons	
			REG	t_e, years	REG	t_e, years
LWR_1 + LWR_2	0.60	33	1	8.6	1	25
LWR_1 + LWR(Th)	0.68	33	1.12	13.4	1.16	34
LWR_1 + SSCR(Th)	0.74	33	1.14	14.2	1.25	40
LWR_1 + HTGR(Th)	0.82	39	1.20	16.5	1.42	48
LWR_1 + HWR(Th)	0.82	30	1.15	14.7	1.31	43

In the power growth scenario of Fig. 1 and up to time t_e, new reactors are always being built at 15 GW(e)/yr (including replacement reactors); thus, the higher the value of t_e, the longer the time available for FBR development without a closeout of the nuclear power industry.

The results in Table 1 illustrate that use of the thorium fuel cycle rather than the uranium cycle permits a significant increase in energy generation, even though thorium reactors are not introduced until the year 2000. At the same time, there is a difference in the relative energy generation associated with the different reactor types, and also with the U_3O_8 resource base. The higher the U_3O_8 base, the more ore is available for fueling advanced converters, which increases their relative energy contribution.

Table 2 gives the economic benefits associated with the various combinations of reactors for the assumed power growth scenario based on the economic bases given in Ref. 1, a 7.5%/yr discount factor on benefits, a U_3O_8 price of \$100/lb, and a separative work price of \$150/SWU; the economic benefits were calculated relative to the power cost of the LWR (U/Pu recycle) system, using designs with economic fuel conversion ratios. Fuel recycle was assumed after the year 2000.

Table 2. Discounted Benefits of Various Thorium-Fueled Reactors Relative to LWR (U/Pu Recycle) Systems[1]

Reactor System	Discounted Benefits, $\$10^9$ for each U_3O_8 Resource (tons)	
	2.5×10^6	3.5×10^6
$LWR_1 + LWR_2$	reference value = 0	
LWR_1 + LWR(Th)	negative benefit	
LWR_1 + SSCR(Th)*	∿0.5	∿1.0
LWR_1 + HWR(Th)	1.1	1.5
LWR_1 + HTGR(Th)	6.4	8.7

*SSCR capital cost assumed to be 5% higher than that of LWR.

Based on the specific designs and economic bases considered[1], the HTGR gave the best fuel utilization and economic performance of the thorium fueled reactors. Use of different bases, however, could change the relative results.

The above was based on fuel recycle after the year 2000, such that fuel recycle occurred in all thorium-based reactors. Use of stowaway thorium fuel cycles would accentuate the advantage that HTGRs have in practical application of thorium fuel cycles. This is illustrated in Table 3, which gives estimated relative power costs of LWRs, HWRs, and HTGRs based on stowaway uranium cycles, stowaway thorium cycles, and recycle thorium cycles. Table 3 and previous results show that the uranium cycle is more economic than thorium cycles in water reactors, and that the thorium cycle is more economic in HTGRs; further, for stowaway thorium fuel cycles, the

HTGR is economically much superior to water reactors. This is due to the higher fuel utilization associated with high fuel exposures and relatively low fuel inventories in HTGR systems.

Table 3. Power Costs of LWRs, HWRs, and HTGRs for Once-Through and Fuel Recycle Cases

Reactor Type/(Fertile Fuel)/Type Cycle	Power Cost/Mills/kWh(e)* U_3O_8 Cost (\$/lb)/Separative Work Cost (\$/kg SWU) 40/100	 100/150
PWR/(U)/Stowaway	27.8	33.8
LWR/(Th)/Stowaway	32.8	41.8
LWR/(Th)/Fuel recycle	29.0	32.0
HWR/(U)/Stowaway	27.5	30.8
HWR/(Th)/Stowaway	30.6	36.6
HWR/(Th)/Fuel recycle	28.6	31.6
HTGR/(U)/Stowaway	27.0	32.0
HTGR/(Th)/Stowaway	26.4	30.0
HTGR/(Th)/Fuel recycle	26.1	29.0

*Based on economic bases given in Ref. 1.

The nuclear power capacity in the year 2000 is not known accurately at this time, and could be substantially lower than the 450 GW(e) shown in Fig. 1. Reducing the 450 GW(e) value to 300 GW(e) could have a significant effect on the time available for commercializing breeder reactors, and would also permit advanced converters to have a greater impact on improved fuel utilization. For example, if Fig. 1 were altered so that the linear power growth were an average of 10 GW(e)/yr up to the year 2000, followed by a constant capacity of 300 GW(e) until a decline were required because of limitations in U_3O_8 resources, the relative energy generation provided by advanced converters would be increased. This is shown in Table 4, which is based on a linear power growth rate of 10 GW(e)/yr to a level of 300 GW in the year 2000 as discussed above; further, the advanced converter reactor is considered to be the HTGR, since it is the preferred thorium-fueled reactor based on results given previously. The HTGRs are introduced in the year 2000 in a manner analogous to that given in Fig. 1; Table 4 gives the relative energy generation for ore resource levels of 1.7 million, 2.5 million, 3.5 million, and 5.1 million tons of U_3O_8. Compared with cases considered previously, the relative energy generation value of 1.2 based on a power level of 450 GW(e) in the year 2000 (and a 2.5 million ton U_3O_8 resource) increases to 1.4 if the power level in 2000 is only 300 GW(e); similarly, with a 3.5 million ton U_3O_8 resource, the relative energy generation increases from 1.4 to 1.6. Thus, increasing the U_3O_8 resource level and/or decreasing the nuclear power capacity in the year 2000 permits HTGRs operating on the thorium cycle to have increased influence on improving fuel utilization.

3. DENATURED-URANIUM-THORIUM FUEL CYCLES

The above considered the standard thorium cycle which utilizes recycle of bred ^{233}U. The present U.S. emphasis on maintaining high proliferation resistance in nuclear fuel cycles would indicate that the ^{235}U in thorium fuel cycles could be replaced by denatured uranium, i.e., uranium having an enrichment low enough that effective weapons could not be made directly from such material. Under such circumstances, <u>d</u>enatured-<u>u</u>ranium-<u>th</u>orium (DUTH) fuels would be employed rather than <u>h</u>igh-<u>e</u>nriched-<u>u</u>ranium-<u>th</u>orium (HEUTH) fuels, with the enrichment of the denatured uranium being about 20% ^{235}U. The ^{233}U bred in such systems could be denatured in situ by the appropriate presence of ^{238}U along with the thorium. However, there will be high levels of radioactivity associated with the daughter products of ^{232}U which will be generated along with the ^{233}U, and this activity may be sufficient to permit recycle of ^{233}U (along with attendant ^{232}U) without denaturing under certain circumstances. If all uranium has to be denatured, use of the DUTH cycle rather than the HEUTH cycle will degrade the fuel utilization of the reactor;

TABLE 4. RELATIVE ENERGY GENERATION FOR POWER GROWTH LEADING TO 300 GW(e) in 2000

POWER LEVEL IN 2000 [GW(e)]		RELATIVE ENERGY GENERATION: HTGR INTRODUCED IN YEAR 2000			
	ORE RESOURCE, S.T. U_3O_8:	1.7×10^6	2.5×10^6	3.5×10^6	5.1×10^6
450		1.0	1.2	1.4	1.6
300		1.2	1.4	1.6	1.8

however, the decrease in performance is inherently small in water reactors, and can be made relatively small in HTGRs with proper reactor physics design.[5] Thus, the results for the DUTH cycles are reasonably close to the fuel utilization performances associated with the previous results, so long as plutonium produced in the DUTH cycles is also recycled. However, as discussed later, use of DUTH cycles in thermal reactors does have implications relative to the ratio of thermal to fast reactors in the long term. In the section below, it is assumed that highly fissile fuel can be recycled so long as high activity is inherently associated with it. Thus, the thorium cycles would utilize DUTH fuel for the initial and makeup fuel, but recycle fuel would primarily be ^{233}U and thorium. Since small quantities of Pu would be discarded from such HTGRs, the fuel utilization performance would be close to that for the HEUTH cycle (mined U_3O_8 requirements would be less than 10% more than the requirements for the HEUTH cycle), based on fuel conversion ratios of about 0.8. The appropriate requirements are considered below.

The above considered only thermal reactors. In fast breeder reactors, use of the DUTH cycle leads to significantly lower nuclear performance than the U/Pu cycle.[6] However, incorporating thorium only in the blanket of a fast reactor does not lead to significant changes in nuclear performance, and the ^{233}U which is produced is the most efficient fissile material for thermal reactors, thus leading to good fueling interactions between fast and thermal reactors. Further, the ^{233}U produced could be denatured if desired, which permits fast breeder reactors to provide a long-term source of low-enriched uranium for a limited number of reactors.

4. PRACTICAL INTRODUCTION OF THORIUM FUEL CYCLES

The above results indicate that early introduction of economic thorium fuel cycles is best accomplished by commercial introduction of HTGRs. Further, from the viewpoint of minimizing funding requirements associated with the introduction of new reactor systems as well as from the viewpoint of maintaining high fuel proliferation resistance, it is desirable that the thorium fuel cycle use DUTH fuel and be introduced on the basis of a once-through cycle. Initial use of such fuel cycles would substantially decrease the monies required for fuel recycle demonstration prior to the commercialization of HTGRs, and would also decrease the amount of highly fissile fuel which is associated with spent fuel. Because of their high fuel exposure, HTGRs can operate economically initially on once-through fuel cycles, and still provide economic incentive to initiate fuel recycle at a later date. A practical scenario for such HTGR introduction is given below.

Consider LWRs operating on the uranium fuel cycle to be installed at a rate of 10 GW(e)/yr up to a level of 300 GW(e) in the year 2000; after that time LWR capacity remains level for 10 years and then decreases in accordance with a 30-yr life and no more LWR construction. LWR fuel recycle (U/Pu) starts in 2000. In the year 2000, HTGRs are introduced at a rate of 10 GW(e)/yr, using a once-through DUTH fuel cycle. This continues for 10 years, after which time HTGRs are introduced at a rate of 10 GW(e)/yr, using a once-through DUTH fuel cycle. This continues for 10 years, after which time HTGRs are introduced at a rate of 20 GW(e)/yr to maintain an overall growth rate of 10 GW(e)/yr. Further, HTGR ^{233}U recycle is started in the year 2010. Nuclear power continues to grow through HTGR additions until a level of 500 GW(e) is attained in 2020. Fast breeder reactors (FBRs) are then introduced commercially, making use of Pu from previously stored LWR fuels to inventory the FBRs. The FBRs contain thorium in the blanket, and the bred ^{233}U is recycled to the HTGRs as makeup fissile feed. The FBRs are introduced at 10 GW(e)/yr until 200 GW(e) of FBR capacity is reached; from 2020 to 2050, HTGRs are added at a rate of 10 GW(e)/yr. After 2050 the nuclear capacity remains at 800 GW(e).

The above power growth scenario is illustrated in Fig. 2, and considers that the nuclear power capacity will eventually level off. Whether 800 GW(e) is the appropriate assymtotic power level is not certain; it may be higher if nuclear power is to make a significant long-term contribution to energy generation. A level of 300 GW(e) in the year 2000 is probably realistic, even though it may be desirable to have a higher level at that time. The abrupt introduction of HTGRs and of FBRs at relatively

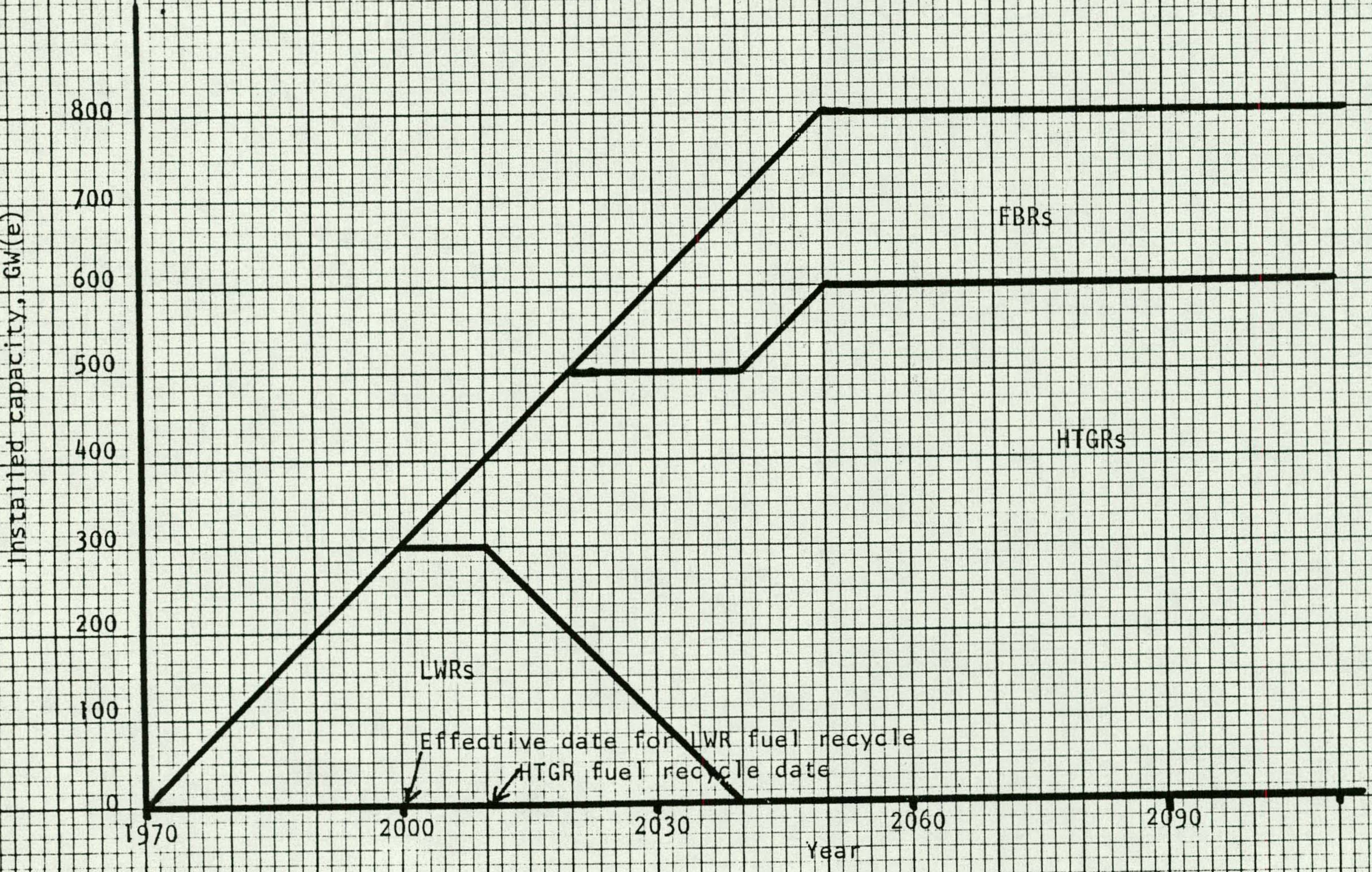

Fig. ③. Nuclear Power Growth Scenario with LWRs, HTGRs, and FBRs.
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high rates as given in Fig. 2 is utilized as a convenience in calculating U_3O_8 requirements, and is not meant to imply that actual introduction rates would be that way. Thus, the power growth scenario for HTGRs does not imply that the first HTGR would be built in the year 2000, but rather implies that 2000 is the year at which commercial introduction at a substantial rate is possible. Similarly, the year 2020 is the time at which FBRs are introduced commercially at a substantial rate. The increase in HTGR capacity from 500 GW(e) to 600 GW(e) after the year 2040 is associated with the ability of FBRs to maintain an HTGR/FBR ratio of 3 on an equilibrium basis when product ^{233}U from FBRs is used to feed HTGRs. More will be said of this below. The LWRs are operated on the once-through uranium fuel cycle until the year 2000, with spent fuel stored so as to provide Pu inventory for future FBRs. After the year 2000, LWRs utilize fuel recycle for all spent fuel generated after that date (the above basically provides a fixed amount of Pu for FBRs; whether the Pu comes from reactors before 2000 or after 2000 is not important so long as it is available).

The fissile fueling requirements of FBRs are determined by the doubling time of the system, the specific fissile inventory, and the nuclear power growth rate associated with FBRs. This relationship is given in equations 1 and 2 below.

$$F(t) = \text{Inventory minus net bred fuel at time } t = SP - \int_0^t \frac{SP}{D} dt \qquad (1)$$

where

$F(t)$ = fissile Pu required to be furnished at time t, kg

S = specific inventory, kg fissile Pu/MW(e)

D = fuel doubling time, yrs

P = nuclear power capacity, MW(e) .

For $P = at$,

where

a = linear power growth coefficient, MW(e)/yr

$$F_{(max)} = \text{maximum fissile Pu requirements} = \frac{aSD}{2} \quad . \qquad (2)$$

Assuming an FBR breeding ratio of about 1.3 and a system specific inventory of about 6 kg fillile Pu/MW(e), the fuel doubling time will be about 20 years. On that basis, the total fissile Pu requirements at an FBR growth rate of 10 GW/yr is about 600 000 kg of fissile Pu based on equation (2). Further, this maximum need would have occurred D years (20 years in this case) after FBR introduction. Since the amount of fissile Pu in spent LWR fuel generated up to the year 2000 would be about 700 000 kg, saving the Pu up to the year 2000 will provide sufficient Pu for the startup of FBRs having the above characteristics, considering the above power growth scenario. [In order to limit the fissile Pu requirements to 600 000 kg, the FBRs need to operate on the U/Pu cycle with recycle of Pu. If FBR Pu recycle were only associated with reactor cores having a breeding ratio of unity, then the fissile Pu requirements 20 years after FBR introduction would be 1.2 million kg of fissile Pu. Here it is assumed that the FBRs operate on the U/Pu cycle for 20 years, which limits the amount of fissile Pu the FBR system needs. After that time, the FBR operates with a thorium blanket producing ^{233}U for use in thermal reactors.]

Twenty years after their introduction, FBRs start contributing excess fissile fuel for use in HTGRs. Further, this excess fissile fuel would be ^{233}U for the above scenario, leading to an increase in the HTGR fuel conversion ratio from 0.8 to 0.9. This increase permits one FBR to fuel three HTGRs under equilibrium conditions. Thus, in 2040, the number of HTGRs can start to increase up to a level of 600 GW(e), giving a total of 800 GW(e) from about 2050 onward.

The total mined U_3O_8 requirements associated with the above scenario are about 2.8 million tons of U_3O_8, based on GW(e) lifetime requirements of

6000 short tons U_3O_8 for LWRs on once-through cycles,
3900 short tons U_3O_8 for LWRs with fuel recycle,
4500 short tons U_3O_8 for HTGRs on once-through cycles, and
2400 short tons U_3O_8 for HTGRs with fuel recycle.

To put the above results in perspective, a corresponding scenario is considered below where only LWRs and FBRs are utilized. This is shown in Fig. 3, which shows LWRs installed up to the year

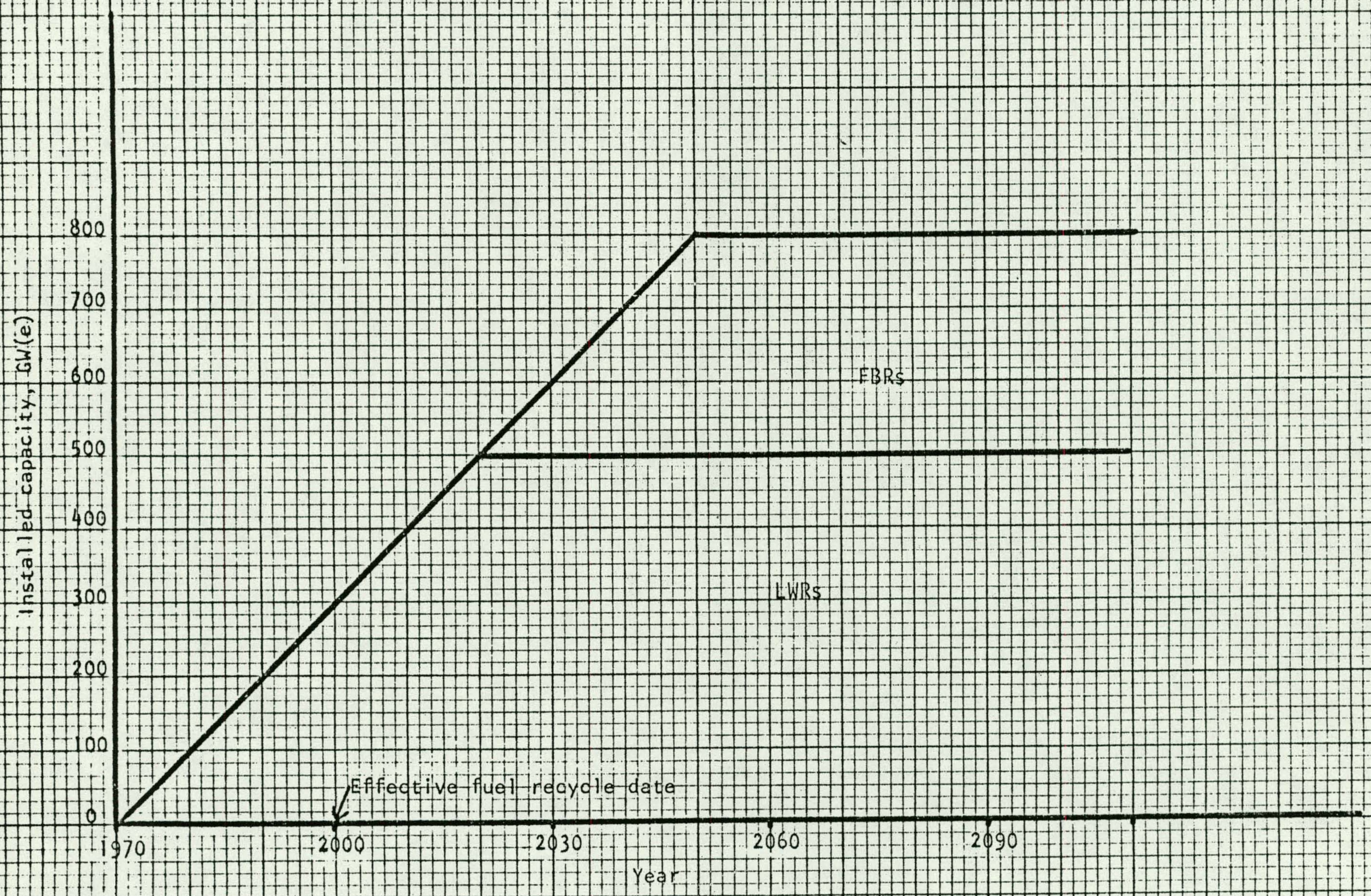

Fig. 2 Nuclear Power Growth Scenario with LWRs and FBRs

2020, after which time their capacity level is maintained constant at 500 GW(e); starting in 2020, FBRs are introduced into the economy at 10 GW(e)/yr until 2050, after which the total nuclear capacity remains at 800 GW(e). Fuel recycle for LWRs is introduced in the year 2000, with LWRs operating on the once-through cycle prior to that time, and with the Pu in the stored fuel available for FBRs at the time of FBR introduction; fuel recycle, of course, takes place in FBRs. The characteristics of the FBR are the same as given above, except the FBR excess fissile production does not fuel as many LWRs as HTGRs. If the LWRs are converted to the thorium cycle, the economic operation of those reactors would correspond to about three LWRs to two FBRs; the number of FBRs to LWRs would be greater than unity for the case of Pu use in LWRs. Fig. 3 assumes LWR conversion to thorium cycles after 2040, with makeup ^{233}U being obtained from FBRs. The total mined U_3O_8 required for the scenario in Fig. 3 is about 3.3 million tons U_3O_8.

If only once-through fuel cycles were employed up to the year 2020, with fuel recycle after that date, the Fig. 2 scenario would require 4.0 million tons U_3O_8 and the Fig. 3 scenario would require 4.5 million tons U_3O_8. If improved once-through fuel cycles were employed, such that HTGRs required 4000 tons U_3O_8/GW(e)-lifetime and LWRs required 5000 tons U_3O_8/GW(e)-lifetime, the U_3O_8 requirements would be 3.4 million tons for Fig. 2 and 3.8 million tons for Fig. 3.

Thus, use of HTGRs under the above conditions would lead to a 10-15% reduction in mined U_3O_8 requirement; further, the economic impact of HTGR use could be significant, since the U_3O_8 saved would be the highest cost resource. Finally, the ratio of thermal to fast reactors could be significantly higher if HTGRs were utilized rather than LWRs in the long term.

5. CONCLUSIONS AND CONCLUDING REMARKS

It appears that the most practical early utilization of thorium in nuclear reactors is associated with HTGR use. In the long term, thorium use in the blankets of fast reactors provides a source of

^{233}U which can advantageously be utilized in thermal reactors, leading to a relatively high ratio of thermal to fast reactors, which may be desirable for several reasons. The use of HTGRs in the scenarios considered permits more energy to be extracted from a given ore resource or, alternatively, for a given power growth scenario requires less mined ore requirements; further, power costs are reduced through HTGR introduction, on the basis of the cost factors employed here. At the same time, introduction of an advanced converter does not replace the long-term need for a high-performance breeder. Introduction of break-even thermal breeders (based on HTGRs or on water reactors) was not considered because they do not provide long-term flexibility with regard to use of reactor combinations, and appear uneconomic in operation. Further, so long as fissile plutonium is available for future use, FBRs will be able to be fueled; the primary concern, then, is that of timely FBR introduction.

If the fuel utilization performance of LWRs were improved, then the U_3O_8 resource needed in the above LWR-FBR scenario would decrease. There are ways of increasing fuel utilization, and these should be investigated since the U_3O_8 resource available is not known accurately. However, the most dramatic changes in fuel utilization in LWRs would be associated with removal of neutron poisons from the system, and in recycle systems with removing the amount of water and increasing the neutron energy spectrum. The practicality of such changes from the viewpoint of power costs and licensing needs to be addressed. At the same time, HTGR performance can be improved; use of gas-turbine HTGRs along with bottoming cycles can improve thermal efficiencies and associated fuel utilization performance by 15-20%. Also, use of pebble-bed-fueled HTGRs permits more flexibility in performance because of their on-line refueling feature which reduces the neutron poisons present during operation. Further, pebble-bed reactors (PBRs) have fuels amenable for use in tandem fuel cycles, i.e., placement of pebble-bed fuel in the blanket of fast reactors for breeding in ^{233}U with subsequent use in PBRs (without fuel refabrication). Overall, the fuel utilization performance of the HTGR is basically better than that of LWRs, and the uncertainty in getting improved fuel utilization is not so much in the fuel cycle as it is in the capital costs of the HTGR.

If the nuclear power level were to increase more rapidly with time than considered here, additional mined U_3O_8 resources would be needed; alternatively, more rapid commercialization of FBRs would be needed. Since the resource limitation is fissile uranium rather than fertile material, lowering the tails of fuel enrichment plants from 0.2 to 0.1 % ^{235}U would also be beneficial in extending resources. Because of the large uncertainty in the amount of U_3O_8 available at reasonable prices, all the various options available for practical extension of energy generation from U_3O_8 should be pursued, including commercialization of HTGRs on thorium fuel cycles.

REFERENCES

1. Kasten, P. R., Homan, F. J., et al., Assessment of the Thorium Fuel Cycle in Power Reactors," report ORNL/TM-5565, Oak Ridge National Laboratory, January 1977.

2. Kasten, P. R., McNeese, L. E., and Bartine, D. E., "Use of Thorium in Power Reactors," paper 77-JPGC-NE-24, American Society of Mechanical Engineers, September 1977.

3. Rosenthal, M. W., et al., "A Comparative Evaluation of Advanced Converters," report ORNL-3686, Oak Ridge National Laboratory, January 1965.

4. Shapiro, N. L., Rec, J. R., and Matzie, R. A., "Assessment of Thorium Fuel Cycles in Pressurized-Water Reactors," report EPRI NP-359, Combustion Engineering, Inc., February 1977.

5. Turner, R. F., General Atomic Company, personal communication, August 1978.

6. Burns, T. J., and Bartine, D. E., "Feasibility of Denatured LMFBRs," Trans. Am. Nucl. Soc. 26, 285-6, June 1977.