Gas-Cooled Reactors—The Importance of Their Development

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GAS-COOLED REACTOR PROGRAMS

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CONTENTS

ABSTRACT	1
SUMMARY	1
INTRODUCTION	6
GAS-COOLED FAST BREEDER REACTORS (GCFRs)	6
HIGH-TEMPERATURE GAS-COOLED REACTORS (HTGRs)	10
SC-HTGR AND GT-HTGR	12
SC-HTGR and Thorium Cycles in Thermal Converter Reactors	12
Denatured-Uranium-Thorium (DUTH) Fuel Cycles	20
Comparison of GT-HTGR and SC-HTGR	21
PRACTICAL INTRODUCTION OF THORIUM FUEL CYCLES	23
USE OF HEAVY WATER REACTORS	31
VERY HIGH-TEMPERATURE REACTORS	32
CONCLUDING REMARKS	33
REFERENCES	38

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Paul R. Kasten

ABSTRACT

The various kinds of gas-cooled reactors are important to develop because of their ability to serve different purposes and needs while sharing major component technology. Hence their timely development and commercialization not only provides early economic and fuel utilization benefits but also accelerates the development of future advanced reactors.

The nearest term GCR is the steam-cycle HTGR, which can be used for both power and process steam production. Use of SC-HTGRs permits timely introduction of thorium fuel cycles and of high-thermal-efficiency reactors, decreasing the need for mined U_3O_8 before arrival of symbiotic fueling of fast-thermal reactor systems. Under symbiotic fueling conditions, the greater fuel economy of HTGRs relative to light-water reactors will permit a higher ratio of thermal reactors to FBRs. However, uncertain capital costs of SC-HTGRs lead to uncertainties in their commercialization.

The gas-turbine HTGR offers prospects of lower capital costs than other nuclear reactors, but it appears to require longer and more costly development than the SC-HTGR. Accelerated development of the GT-HTGR is needed to gain the advantages of timely introduction. Added advantages of this reactor are high thermal efficiency, usability at sites requiring dry cooling towers, and provision of materials technology for the Very-High-Temperature Process Heat Reactor (VHTR).

The Gas-Cooled Fast Breeder Reactor (GCFR) offers the possibility of fast breeder reactors with lower capital costs and with higher breeding ratios from oxide fuels. This permits earlier attainment of economic symbiotic fast-thermal reactor operation and a higher ratio of thermal to fast reactors under symbiotic conditions.

The VHTR provides high-temperature heat for hydrogen production.

SUMMARY

Gas-Cooled Reactors (GCRs) can have a significant impact on the future application of fission energy. The specific reactor types are

the steam-cycle High-Temperature Gas-Cooled Reactor (SC-HTGR), the gas-turbine HTGR (GT-HTGR), the Gas-Cooled Fast Breeder Reactor (GCFR), and the Very High-Temperature Process Heat Reactor (VHTR). The importance of developing the above systems is discussed relative to alternative fission power systems involving light-water reactors (LWRs), advanced light-water reactors (ALWRs), heavy-water reactors (HWRs), spectral-shift-controlled reactors (SSCRs), and liquid-metal-cooled fast breeder reactors (LMFBRs). A primary advantage of developing GCRs as a class lies in the technology and cost interrelations, which permit cost-effective development of systems having diverse applications. In addition, HTGR-type systems have fuel proliferation and diversion-resistant characteristics and attractive safety features. Finally, HTGR systems and fast breeder reactors (FBRs) operate advantageously in a symbiotic mode (i.e., ^{233}U from FBR blankets is used to fuel HTGRs). Overall, GCRs provide interrelated systems that serve different purposes and needs while utilizing interrelated component systems; their development can proceed in stages that provide early benefits while meeting future needs.

GCFRs have no intermediate coolant circuit and use HTGR-type component technology; thus they have the potential of lower capital costs than LMFBRs. Also, since the helium coolant is gaseous and inert, GCFR maintenance costs may be relatively low. GCFRs also have a relatively high breeding gain while utilizing oxide-based uranium-plutonium fuel in the core region and permit efficient generation of ^{233}U in their blankets. Their lower capital costs, if achievable, would permit FBRs to be economic at an earlier date than if only LMFBRs are used; that is an important advantage because it permits more energy to be recovered economically from a given U_3O_8 resource up to the time of steady-state operation of symbiotic fast and thermal reactor systems. Since FBR capital costs are probably higher than those of thermal reactors, high-performance thermal reactors are desirable for the interim and in the long term in conjunction with FBRs. This follows from the above economic consideration as well as from the viewpoint that the number of FBRs should be relatively low to decrease the amount of plutonium that is

used to fuel reactors. Further, since the component technology of GCFRs is similar to that for HTGRs, the vendor industry for producing primary GCFR components could be developed rapidly if HTGRs were commercial systems. This factor is important relative to the rate at which GCFRs could be introduced into the economy once they were commercialized. Use of GCFRs inside energy centers with production of ^{233}U in their blankets for use in HTGRs outside energy centers permits a high ratio of "outside" to "inside" reactors. This also implies that mixed uranium-thorium fuel cycles in FBRs permit long-term use of slightly enriched uranium in some reactors.

The SC-HTGR is in a more advanced state of development than the other GCRs. These reactors operate efficiently on the thorium fuel cycle, and that cycle in HTGRs appears to provide economic, improved fuel utilization over the thorium or uranium cycle in thermal reactors that might be commercialized in the U.S. within the next approximately 20 years (reactors in this category are ALWRs, HWRs, SSCRs, and HTGRs). Further, of the above reactor types (including HWRs), the HTGR is the only one that operates more economically on thorium-based fuel cycles than on uranium cycles for reasonable U_3O_8 prices. As a result, commercialization of thorium fuel cycles before the introduction of FBRs depends upon commercialization of HTGRs. Introduction of SC-HTGRs on thorium fuel cycles before commercialization of FBRs provides a high-thermal-efficiency system with advantageous safety and fuel utilization features, which by timely introduction also reduces significantly the amount of mined U_3O_8 required to convert thermal and fast reactor systems to self-supporting symbiotic systems. Thus, installing HTGRs before FBR introduction also assists eventual FBR development. With timely SC-HTGR introduction (and replacing LWRs) the overall savings in U_3O_8 after FBRs start to realize a net production of fissile fuel can be greater than the U_3O_8 savings before FBR introductions. Up to the time of net fissile fuel production by FBRs, using HWRs on the low-enrichment uranium cycle instead of HTGRs on the thorium cycle provides about the same fuel utilization; however, HWR capital costs appear higher than those of HTGRs, and conversion of the LEU HWRs to the ^{233}U -Th fuel cycle requires significantly more mined U_3O_8 than conversion of HTGRs from the ^{235}U - ^{238}U -Th- ^{233}U cycle to the ^{233}U -Th cycle. The SC-HTGR also results in an

advantageous system for process steam generation ("cogeneration" or "HTGR steamer"). Finally, the use of denatured uranium-thorium (DUTH) fuel cycles in HTGRs appears to have attractive proliferation- and diversion-resistance features; the spent fuel from HTGRs contains relatively small amounts of plutonium, and HTGRs have fuel in such a form that high-fissile-content material is difficult to recover; also, the bred ^{233}U inherently contains ^{232}U , whose decay products are very detectable, and ^{233}U can be denatured with ^{238}U . In the case of a policy prohibiting fuel recycle, HTGRs have the advantage of a fuel design that allows long exposure; thus, the economics of once-through fuel cycles on the thorium cycle can be attractive. However, in the long term, the HTGR is most economic (in terms of fuel utilization and power costs) when the fuel is recycled and the amount of ^{238}U in the fuel is low. Finally, early introduction of HTGRs permits relatively high ratios of HTGRs to FBRs to be established in a timely manner and to be maintained in the long term.

The GT-HTGR has general characteristics similar to the SC-HTGR, except it has the potential for having lower capital costs and improved fuel utilization; also, GT-HTGRs are well suited for sites requiring dry cooling towers, or where reject heat can be utilized in district heating, desalination, or similar applications. The highest thermal efficiencies are attained with combined use of a bottoming cycle (ammonia cycle or possibly a steam cycle) in conjunction with the helium turbine topping cycle, leading to potential thermal efficiencies in the 45 to 50% range. Overall, GT-HTGRs have potentially the lowest capital costs of all nuclear power plants; however, their commercialization date appears delayed 5 to 10 years relative to that possible with the SC-HTGR. As a result, the discounted benefits to be derived from GT-HTGR introduction appear more limited than benefits obtainable from SC-HTGRs followed by GT-HTGRs if the capital costs of SC-HTGRs are about the same as LWRs. Other factors that tend to improve the relative benefit from GT-HTGRs are: (1) a low nuclear power growth [less than 30C GW(e) capacity in year 2000]; (2) a high U_3O_8 resource level at reasonable costs [greater than 3.2 Tg (3.5 million tons) U_3O_8]; and (3) a low discount factor [significantly less than 7.5%/year]. Early SC-HTGR

introduction (relative to delayed GT-HTGR introduction) can lead to lower mined U_3O_8 requirements during the period of converting reactors to self-sufficient symbiotic systems based on combined use of FBRs and HTGRs. If emphasis is placed on GT-HTGRs as the first commercial HTGRs, it is important that the associated development program has as an objective the introduction of GT-HTGRs with a minimum of delay.

The VHTR is the only fission reactor that appears to be able to directly provide energy for high-temperature processes operating at 850 to 1000°C, thus expanding the application of nuclear energy to processes for hydrogen production, coal liquifaction and/or gasification, and long-distance transport of chemical energy (chemical heat pipes). Commercialization of the VHTR logically follows GT-HTGR commercialization, since the primary problems are associated with developing practical materials for very high-temperature operation. Because of the long development time required, work on VHTRs should proceed in parallel with GT-HTGR development. In the long term, VHTRs probably will depend upon the commercialization of FBRs to assure an economic fissile fuel resource.

Overall, the long-term importance of the various GCRs is as follows: (1) SC-HTGR - providing early economic and timely fuel utilization benefits (both before and during conversion to symbiotic systems) in a system pertinent to electricity and/or industrial steam production and having a proliferation- and diversion-resistant fuel, while also providing component technology for economic GT-HTGRs and GCFRs; (2) GT-HTGR - providing a low-capital-cost system having a high thermal efficiency, which is well suited for use in areas requiring dry cooling towers or "low" temperature process heat applications, while also providing technology pertinent to VHTRs; (3) CC-HTGR (combined cycle system, which is a variant of the GT-HTGR) - providing a very high thermal efficiency system having low capital costs, improved fuel utilization, and technology pertinent to VHTRs; (4) GCFR - providing an FBR with capital costs lower than those for an LMFBR, leading to lower power costs; further, the higher breeding gain obtained in GCFRs based on use of U-Pu oxide fuels increases the ratio of thermal to fast

reactors in symbiotic systems, providing improved economics and flexibility in reactor siting; and (5) VHTR - providing a high-temperature heat source for hydrogen production processes.

INTRODUCTION

The importance of gas-cooled reactors (GCRs) lies in their ability to meet perceived needs of energy generation in unique and comprehensive ways. The interrelated reactor systems that can do this are the steam-cycle High-Temperature Gas-Cooled Reactor (SC-HTGR), the gas-turbine HTGR (GT-HTGR), the Very High-Temperature Process Heat Reactor (VHTR), and the Gas-Cooled Fast Breeder Reactor (GCFR). The potential contribution of these reactor types and of various fuel cycles to future energy needs is discussed in terms of power cost and the availability and effective utilization of uranium resources. Comparison is made with other commercial and developmental reactor types: light-water reactors (LWRs), advanced LWRs (ALWRs), heavy-water reactors (HWRs), spectral-shift-controlled reactors (SSCRs), and liquid-metal-cooled fast breeder reactors (LMFBRs). The discussion will focus first on the GCFR and then on the HTGR types.

GAS-COOLED FAST BREEDER REACTORS (GCFRs)

It is generally recognized that fast breeder reactors (FBRs) are needed to provide fissile fuel and energy in the long term. Introduction of an economic high-performance breeder has a major impact on mined fuel and uranium enrichment requirements, reducing such needs markedly. Utilization of FBRs, however, requires fuel recycle, and this is true of both LMFBRs and GCFRs. While development of the GCFR per se has been limited (about \$100 million on a world-wide basis), this reactor concept benefits significantly from the LMFBR fuel and fuel recycle development efforts, from the absence of an intermediate coolant circuit, and from HTGR component technology development. It is also recognized that if the economic performance of FBRs is improved, they

will compete sooner commercially with thermal reactors and thus better assure that fissile fuel requirements are met in a timely manner. It is the aspect of economic introduction that points to the importance of GCFRs. In particular, GCFR component technology is similar to that associated with HTGRs, namely, prestressed concrete reactor vessels (PCRVs), liners, insulation, ducting, heat exchangers, steam generators, circulators, and associated equipment and systems. Thus, it is anticipated that the unit capital costs of the GCFR are closely allied to HTGR capital costs and are relatively low. Capital cost estimates made by United Engineers and Constructors (UE&C)^{1,2} indicate that GCFRs would have capital costs about 10% lower than those of LMFBRs based on a specific design concept. This would permit GCFRs to compete economically earlier than would LMFBRs, since GCFRs would compete with thermal reactors at lower U_3O_8 costs. This is illustrated in Fig. 1, which shows

Fig. 1. Power Costs as Influenced by Fuel Recycle, Reactor Type, and FBR Capital Cost. Δ is the incremental unit capital cost of FBRs above LWRs and HTGRs. Note: \$100/lb = \$220/kg. (Numbers in parentheses are the fuel conversion ratios).

the variation in LWR (uranium cycle) and HTGR (thorium cycle) costs as a function of ore price and fuel cycle (once-through or recycle), treats incremental FBR capital costs above those for the thermal reactors as a parameter, and considers that the fuel cycle cost of FBRs would remain essentially constant independent of ore price. (It should be noted that in general the power cost of FBRs would vary with U_3O_8 price with generating costs tending to decrease as more credit is given for bred fuel; however, that variation is relatively small compared with the changes due to the differences in capital costs considered here, and was not treated.)

It is generally considered that the unit capital costs [$\$/kW(e)$] of LMFBRs will be between 1.25 and 1.75 times that of LWRs, with the factor probably being in the 1.25-1.50 range. (Recently the French have estimated the capital costs of LMFBRs to be 1.35 to 1.50 times that of LWRs.³) If LMFBRs have capital costs 1.35 times that of LWRs, GCFRs might have capital costs about 1.25 times that of LWRs, according to the UE&C relative estimates. Thus, for an LWR having a unit capital cost of $\$800/kW(e)$, the LMFBR capital cost would be about $\$1080/kW(e)$, and the GCFR would be about $\$1000/kW(e)$. According to Fig. 1, this would imply that the GCFR would compete economically at a lower U_3O_8 price than would the LMFBR, with power costs about 2 mills/ $kWh(e)$ lower. On the basis of Fig. 1 and the above capital costs, the LMFBR would compete economically with LWRs at U_3O_8 costs of approximately $\$220/kg$ ($\$100/lb$), or with HTGRs at costs of $\$330$ to $485/kg$ ($\$150-220/lb$) U_3O_8 , depending on the fuel cycle mode. On the above bases, GCFRs would compete with LWRs at U_3O_8 costs of approximately $\$175/kg$ ($\$80/lb$), or with HTGRs at costs of $\$265$ to $375/kg$ ($\$120-170/lb$) U_3O_8 . Under symbiotic conditions where FBRs fuel thermal reactors, the above implies that more energy could be obtained from a given ore resource when GCFRs are utilized rather than LMFBRs because symbiotic fueling would occur earlier. Also, based on capital costs indicated above, the power costs from symbiotic FBR and thermal reactor systems utilizing GCFRs would be lower than if the symbiotic systems utilized LMFBRs. This is seen in Table 1, where power costs are estimated on the above capital cost bases, a reasonable set of economic ground rules,⁴ reactor operating costs of

Table 1. Relative Power Costs for Symbiotic Operation of Fast and Thermal Reactors

Thermal to Fast Reactor Ratio	Thermal to Fast Reactor Capital Cost Ratio	Relative Power Costs [mills/kWh(e)]
LWR/LMFBR = 1.5:1	1:1.35	30.5
HTGR/LMFBR = 3:1	1:1.35	28.5
HTGR/LMFBR = 3:1	1.05:1.35	29.3
LWR/GCFR = 1.5:1	1:1.25	29.8
HTGR/GCFR = 3:1	1:1.25	28.0
HTGR/GCFR = 3:1	1.05:1.35	28.7
LWR/GCFR = 1.7:1	1:1.25	29.1
HTGR/GCFR = 3.4:1	1:1.25	27.9
HTGR/GCFR = 3.4:1	1.05:1.25	28.6

2 mills/kWh(e), reasonable thermal/fast reactor ratios, and fuel cycle costs corresponding to symbiotic operation of fast and thermal reactors in which ^{233}U from the blanket of fast reactors is used to fuel thermal reactors with makeup fissile fuel. The relative fuel cycle costs for symbiotic operation of reactors were taken to be 4.5 mills/kWh(e) for the FBRs (having a breeding ratio of 1.3), 7.5 mills/kWh(e) for LWRs (with a fuel conversion ratio of 0.8), and 5.5 mills/kWh(e) for HTGRs (with a fuel conversion ratio of 0.9). (If the relative fuel cycle cost for FBRs were higher than that used, there would be economic advantages to increase the number of thermal reactors.)

Table 1 considers that symbiotic operation of FBRs (U-Pu in core, Th in blanket) and LWRs (operating on the thorium fuel cycle) permits about 1.5 LWRs for each FBR, and that use of HTGRs with FBRs permits about 3 HTGRs for each FBR. The above assumes that the breeding gain of GCFRs and LMFBRs would be the same; however, using oxide-based fuel and uranium-plutonium in the core region, GCFRs would have breeding gains 10 to 20% higher than those of LMFBRs, which would increase the number of LWRs supported by GCFRs from 1.5 to about 1.7 and the number of HTGRs from 3 to about 3.4. Finally, the capital costs of HTGRs are considered to be either the same as or 5% higher than those of LWRs. Using

the above symbiotic reactor ratios and specified reactor capital cost ratios, relative power costs were calculated considering the relative fuel cycle costs given above for the different reactors. According to the results given in Table 1, use of GCFRs leads to lower power costs than use of LMFBRs under symbiotic fueling conditions, and FBR-HTGR combinations have lower power costs than FBR-LWR combinations.

Rather than looking at differences in power costs as is done in Table 1, it is instructive to assume that the power cost from FBR-thermal reactor systems is permitted to rise to that for FBRs. Under this scenario, it is evident that more U_3O_8 is available for GCFR-thermal reactor systems than for LMFBR-thermal reactor systems, since less U_3O_8 has been mined at the time GCFR symbiotic systems are introduced. This implies that for many years (associated with a given U_3O_8 resource) the thermal reactor/GCFR ratio could be higher than that associated with only symbiosis conditions, and this appears desirable for power growth; the same degree of flexibility would not exist with LMFBRs.

Overall, a major advantage of the GCFR is that its component technology is closely allied with HTGR component technology, permitting relatively low capital costs. Also important is that a GCFR vendor industry can be established readily if an HTGR vendor industry exists, thus permitting GCFRs to be introduced relatively rapidly into the power economy on early and timely bases. The above capital cost advantage also permits more energy to be recovered economically from a given U_3O_8 resource up to the time of steady-state operation of symbiotic fast and thermal reactor systems. Further, the GCFR permits a higher ratio of thermal/fast reactors under symbiotic fueling.

HIGH-TEMPERATURE GAS-COOLED REACTORS (HTGRs)

The term "HTGR" applies to the various fueled-graphite reactor designs (SC-HTGR, GHTGR, VHTR) with prismatic or pebble-bed cores. By far most of the development effort has been expended on the SC-HTGR; however, the concept can also be utilized in gas-turbine systems

(including combined cycles involving topping and bottoming cycles), as well as in high-temperature process heat systems. At present the SC-HTGR is the most developed of the HTGRs. The GT-HTGR is a logical near-term extension of the SC-HTGR, and when used with combined cycles has improved fuel utilization characteristics and potentially lower costs for power production. The VHTR, in turn, is a logical extension of the GT-HTGR as the core outlet coolant temperature is increased, with important potential benefits regarding long-term fossil fuel utilization and conservation. However, the practical timing of VHTR introduction would be such that widespread VHTR use appears dependent upon successful breeder introduction, or on obtaining sufficient amounts of U_3O_8 at reasonable prices.

Because of their high thermal efficiency, advantageous safety features (associated with a low reactor power density, a core having a high thermal heat capacity, and a high temperature capability), and improved fuel utilization, HTGRs can meet a number of needs. At the same time, there is uncertainty in the capital costs. However, under mature industry conditions, UE&C has estimated² the unit capital costs of SC-HTGRs to be about the same as to about 4% higher than those of LWRs. There would, of course, be substantial first-of-a-kind costs. Analogous unit costs for GT-HTGRs have been estimated to be approximately 15% lower than those for SC-HTGRs if the GT-HTGR had 40% thermal efficiency and were used at sites where cooling towers are needed. Also, the GT-HTGR would be well suited for sites where low-temperature process heat would be utilized. However, until new or modified structural metals are developed, the thermal efficiency of the GT-HTGR would be lower than that of the SC-HTGR when cooling water is available at the plant site. However, use of combined cycles at such locations might attain thermal efficiencies of 45 to 50% in the long term. At the same time, considerably more development effort is required to commercialize GT-HTGRs (and combined cycles) than to commercialize SC-HTGRs, so GT-HTGRs appear to be 5 to 10 years behind SC-HTGR in commercialization (assuming that SC-HTGR capital costs are comparable to those for LWRs). A delay in introduction of an HTGR means that additional LWRs, which consume additional U_3O_8 , would be built and benefits from the HTGR

would be decreased. Thus, it is not obvious that the GT-HTGR would lead to greater benefits than the SC-HTGR. The section below evaluates some economic and fuel utilization features associated with SC-HTGR and GT-HTGR introduction and gives perspective to the above. Further, the importance of HTGRs is related to their ability to compete with other reactor systems; therefore the following sections also compare HTGRs with competing reactors.

SC-HTGR AND GT-HTGR

In comparing HTGRs with other advanced reactor types that might be commercialized relatively quickly, only a limited number might be considered. These are: (1) ALWRs (these are improved LWRs which will give improved fuel utilization; thorium use in LWRs is included); (2) SSCRs (basically LWRs cooled and moderated by a mixture of light and heavy water); (3) HTGRs; and (4) HWRs. All these reactors can operate on either the uranium, thorium, or mixed thorium-uranium fuel cycle and might reasonably be first introduced within the next 10 to 15 years. The sections that follow will emphasize the relative performance of thorium and uranium fuel cycles in the different reactor types. The effects of using mixed thorium-uranium fuel cycles (associated with use of denatured uranium-thorium fuel) are discussed later. Also, since SC-HTGRs could be available before GT-HTGRs, the initial emphasis is on SC-HTGRs in this comparison with other reactor types. Further, since fuel utilization advantages are associated with thorium fuel cycle use in thermal reactors, emphasis is on use of that cycle.⁵

SC-HTGR and Thorium Cycles 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 fuel cycle is compared with the uranium cycle in this section. Results obtained previously^{4,6} will be reviewed first and form a basis for further evaluations.

The nuclear power growth scenario considered first is that indicated in Fig. 2. It assumes a nuclear power growth of 15 GW(e)/year during the period 1970 to 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-year lifetime for all reactors that are built. The available U_3O_8 resource is considered to be either 2.3 or 3.2 Tg (2.5 or 3.5 million short tons) U_3O_8 .

Fig. 2. Thermal Reactor Power Growth Scenario [initial growth of 15 GW(e)/year; LWR₂, LWR(Th), HWR, or HTGR introduced in 2000]. The t_e time shown is illustrative only and varies with different reactor types introduced.

In these studies, reference LWRs operating on the uranium fuel cycle are used initially; these are termed LWR₁s, as given in Fig. 2. Reactors built after the year 2000 are either additional LWRs operating on the uranium cycle (termed LWR₂s for ease of identification), LWRs operating on the thorium cycle [LWR(Th)s], SSCRs, HWRs, or SC-HTGRs. The latter three reactors use the thorium fuel cycle in these studies. (These reactors can be operated on either the thorium or uranium fuel cycle; however, the best fuel utilization will be obtained with 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).⁴ After the year 2000, LWR₁s are withdrawn from use as their 30-year lifetime (21 full-power years) is attained and 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-year lifetime. (Figure 2 serves as an illustration of what t_e signifies, and the time given should not be taken literally.)

The power growth scenario of Fig. 2, along with the estimated lifetime U₃O₈ requirements of the various reactors, is used to calculate the energy that can be generated for each type of new reactor used. This calculation assumes that a given reactor operates 21 full-power years over its lifetime, the uranium tails from enrichment plants are 0.2% ²³⁵U, and 1.1 Gg (1200 tons) of fissile plutonium generated by LWR₁s 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 U₃O₈ resource available to it. This is done here by measuring the energy generation of combined reactor systems against the energy that could be generated if no new reactors were introduced. Thus, the energy generated by LWR₁s plus LWR₂s 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 2 for the various reactor combinations and U_3O_8 resource levels.⁴⁻⁷ Table 2 results are based on thorium fuel cycle use in the second reactor, on reference designs, and on fuel conversion ratios that correspond to economic operation based on estimated unit fuel recycle costs for the above reactors.⁴ The fuel utilization results also consider the reactor thermal efficiencies as given in Table 2.

In the power growth scenario of Fig. 2 and up to time t_e , new reactors are always being built at 15 GW(e)/year (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.

Table 2. Relative Energy Generation and Extension Time for Assumed Power Growth Scenario as a Function of Reactor Use and U_3O_8 Resource
(HTGR is SC-HTGR)^{4,6,7}

Reactor Use	Fuel Conversion Ratio for Second Reactor	Second Reactor Thermal Efficiency (%)	Relative Energy Generation (REG) and Extension Time (t_e) for two U_3O_8 Resource Levels in Tg (tons)			
			2.3 (2.5×10^6)		3.2 (3.5×10^6)	
			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

The results in Table 2 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 and the greater the relative energy contribution of advanced converters.

Table 3 gives the economic benefits associated with the various combinations of reactors for the assumed power growth scenario, the economic and cost bases given in ref. 4, a 7.5%/year discount factor on benefits, a U_3O_8 price of \$220/kg (\$100/lb), and a uranium enrichment (separative work) price of \$150/SWU. The economic benefits were calculated relative to the power cost of the LWR (U-Pu recycle) system for designs with economic fuel conversion ratios. Fuel recycle was assumed after the year 2000. The specific unit reactor and fuel recycle costs

Table 3. Discounted Benefits of Various Thorium-Fueled Reactors Relative to LWR (U-Pu Recycle) Systems⁴⁻⁸

Reactor System	Discounted Benefits, $\$10^9$ for each U_3O_8 Resource in Tg (tons)	
	2.3 (2.5×10^6)	3.2 (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 + SC-HTGR(Th)	6.4	8.7

considered are given in Tables 4 and 5; the capital costs of HTGRs were considered to be the same as those of LWRs based on estimates by UE&C.

For the specific designs and economic bases considered, the SC-HTGR gave the best fuel utilization and economic performance of the thorium-fueled reactors. Use of different bases, however, could change the

Table 4. Power Cost Factors⁴⁻⁸

Capital Charge Rate: 16%/year (15%/year for fuel cycle)					
H ₂ O Cost: \$120/kg					
H ₂ O Inventory: ~0.8 kg/MWh(e)					
H ₂ O Losses: 2%/year					
Reactor Type	Capital Cost		Load Factor, (%)	Cost, mills/MWh(e)	
	\$/kW(e)	mills/MWh(e)		Operating and Maintenance	H ₂ O
LMR	800	19.5	75	2.0	
HR(U)	853	19.5	80	2.0	2.26
HR(Th)	843	19.3	80	2.0	2.0
HTGR-SC	800	19.5	75	2.0	

Table 5. Fuel Cycle Cost Factors⁴⁻⁸ Used in Cost and Benefit Calculations

Ore and Separative Work Factors				
ThO ₂ \$30/kg (no recycle considered)				
U ₃ O ₈ and enrichment costs ^a				
		U ₃ O ₈		SWU
		(\$/kg)	(\$/lb)	(\$/kg)
		55	25	75
		88	40	100
		220	100	150
		640	300	200
Unit Fuel Cycle Costs				
Reactor	Fuel Cycle	Cost, \$/kg		
		Fabrication	Reprocessing	Refabrication
LMR	235 _g -238 _g	114	221	
	Pu-U		221	500
	235 _g -Th	152	250	
	233 _g -Th		250	570
	Pu-Th		260	510
HR	Natural U	50	150	
	Enriched U	80	160	
	Pu-U		160	310
	235 _g -Th	100	210	
	233 _g -Th		210	390
HTGR	Pu-Th		220	320
	22 ⁵ g	400	750	
	2 ³⁵ g-Th		750	1030
	235 _g -238 _g	360	730	
	Pu-Th		750	1030
Effective Fuel Storage Costs				
Reactor	Fuel	Storage Cost, \$/kg		
HR	(natural U)	25		
HR	(enriched)	100		
LMR		100		
HTGR		400		

^aFour cases are considered; as the cost of U₃O₈ rises, the cost of enrichment (separative work) is assumed to rise also.

relative results. If the HTGR capital costs were increased to \$900/kW(e) (~12% increase), the discounted benefits shown in Table 3 would largely disappear. Alternatively, there would still be benefits even if the HTGR had capital costs 10% higher than LWRs.

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 HWRs have in practical application of thorium fuel cycles. This is illustrated in Table 6, which gives estimated relative power costs for LWRs, HWRs, and HTGRs based on once-through and recycle-uranium fuel cycles, and once-through and recycle thorium cycles. Table 6 shows that the uranium fuel cycle is more economic than thorium cycles in water reactors, that the thorium cycle is more economic in HTGRs, and further that 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 6. Power Costs of LWRs, HWRs, and HTGRs for Once-Through and Fuel Recycle Cases^a

Reactor Type	Fertile Fuel	Type Fuel Cycle	Power Cost, mills/kWh(e), for Two Uranium Cost Cases ^a	
			Case 1	Case 2
LWR	U	Recycle	28.2	32.3
LWR	U	Stowaway	27.5	33.0
LWR	Th	Stowaway	32.8	41.8
LWR	Th	Recycle	29.0	32.0
HWR	U	Recycle	28.0	31.0
HWR	U	Stowaway	27.5	30.8
HWR	Th	Stowaway	30.6	36.6
HWR	Th	Recycle	28.6	31.6
HTGR	U	Recycle	28.0	33.0
HTGR	U	Stowaway	27.0	32.0
HTGR	Th	Stowaway	26.4	30.0
HTGR	Th	Recycle	26.1	29.0

^aCase 1: U₃O₈ \$88/kg (\$40/lb); \$100/kg SWU. Case 2: U₃O₈ \$220/kg (\$100/lb); \$150/kg SWU.

The nuclear power capacity in the year 2000 is not known accurately at this time. It could be substantially lower than the 450 GW(e) shown in Fig. 2. Reducing the 450 GW(e) value to 300 GW(e) could significantly affect 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. 2 were altered so that the linear power growth was an average of 10 GW(e)/year up to the year 2000 followed by a constant capacity of 300 GW(e) until limitations in U_3O_8 resources required a decline, the relative energy generation provided by advanced converters would be increased. This is shown in Table 7, which includes a linear power growth rate of 10 GW(e)/year to a level of 300 GW in the year 2000, as discussed above; further, the advanced converter reactor is considered to be the SC-HTGR, since it is the preferred thorium-fueled reactor on the basis of results given previously.

Table 7. Relative Energy Generation for Power Growths Leading to 300 GW(e) or 450 GW(e) in Year 2000, and with SC-HTGRs Introduced in Year 2000

Ore Resource		Relative Energy Generation for Each Power Level in Year 2000	
(Tg U_3O_8)	(tons U_3O_8)	450 GW(e)	300 GW(e)
1.4	1.7×10^6	1.0	1.2
2.3	2.5	1.2	1.4
3.2	3.5	1.4	1.6
4.6	5.1	1.6	1.8

The SC-HTGRs are introduced in the year 2000 in a manner analogous to that given in Fig. 2. Table 7 gives the relative energy generation for four ore resource levels. 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 2.3 Tg (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 3.2 Tg (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 or decreasing the nuclear power capacity in the year 2000 increases the influence of thorium cycle HTGRs on improving fuel utilization.

Denatured-Uranium-Thorium (DUTH) Fuel Cycles

The above considered the standard thorium cycle, which recycles bred ^{233}U . The present U.S. emphasis on maintaining high proliferation resistance in nuclear fuel cycles indicates that the ^{235}U in thorium cycles would be replaced by denatured uranium; that is, uranium having an enrichment low enough that effective weapons could not be made directly from such material. Under such circumstances, DUTH fuels would be employed rather than highly enriched uranium-thorium (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, high levels of radioactivity will be associated with the decay 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) under certain circumstances without denaturing. If all uranium has to be denatured, use of the DUTH fuel cycle rather than the HEUTH cycle will degrade the fuel utilization of the reactor. However, the decrease in performance is inherently small in water reactors, and it can be made relatively small in HTGRs with proper reactor physics design.⁹ Thus, the results for the DUTH fuel 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 fuel cycles in thermal reactors does have implications relative to the ratio of thermal to fast reactors in the long term. The discussion below assumes that highly concentrated fissile fuel can be recycled so long as high activity is inherently

associated with it. Thus, the thorium fuel cycles would utilize DUTH fuel for the initial and makeup fuel, but recycle fuel would primarily be ^{233}U and thorium. Since only small quantities of plutonium 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 core designs that give 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 fuel cycle leads to significantly lower nuclear performance than the U-Pu cycle.¹⁰ However, incorporating thorium only in the blanket of a fast reactor does not lead to significant changes in nuclear performance, and the ^{233}U that 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.

Comparison of GT-HTGR and SC-HTGR

Based on a UE&C estimate,² the capital cost of a GT-HTGR with 40% thermal efficiency and using dry cooling towers would be approximately 15% less than that of an SC-HTGR using wet cooling towers. If such a GT-HTGR could be introduced on the same schedule considered in Fig. 2, the discounted benefits given in Table 3 for the HTGR would increase substantially (fuel utilization benefits plus capital cost benefits would increase total benefits by about a factor of 2.25). However, such a GT-HTGR would probably be commercialized about 10 years later than an SC-HTGR, which would about halve the discounted benefits at a 7.5%/year discount factor, if the same amount of energy were generated by the HTGRs (relative benefits would be $2.25 \times 0.46 = 1.04$). However, a delay in HTGR introduction would limit the amount of energy generated by the HTGR, and for the case of an available resource of

2.3 Tg (2.5×10^6 tons) U_3O_8 , a 10-year delay would leave no U_3O_8 for the HTGR, and thus zero benefits for the GT-HTGR. For the case of an available resource of 3.2 Tg (3.5×10^6 tons) U_3O_8 , a 10-year delay would decrease the fraction of U_3O_8 available to the GT-HTGR from unity to about 0.63 (relative to no delay), which would lead to net benefits about 70% those of the SC-HTGR (\$6.1 billion vs \$8.7 billion).

A GT-HTGR with a thermal efficiency of about 35% could probably be available about 5 years earlier than one with a 40% thermal efficiency, since the material development requirements associated with a lower core outlet temperature (and a lower plant thermal efficiency) could be significantly less. Such a system would then be only 5 years later than an SC-HTGR. In that case the GT-HTGR unit capital costs would probably be about 5% less than those of an SC-HTGR. The discounted benefits under the above circumstances (assuming the same amount of energy to be generated by the different HTGRs) would be about the same for the GT-HTGRs as for the SC-HTGR (fuel utilization benefits plus capital cost benefits would give a factor of about 1.42; discounted benefits factor would be $1.42 \times 0.68 = 0.97$). However, for the case of an available resource of 2.3 Tg (2.5×10^6 tons) U_3O_8 , a 5-year delay would leave only about half as much U_3O_8 for the GT-HTGR relative to no delay; for a resource of 3.2 Tg (3.5×10^6 tons) U_3O_8 , a 5-year delay would decrease the fraction of U_3O_8 available to the GT-HTGR from unity to about 0.8. Thus, for the above, and based on a 7.5%/year discount factor, the benefits from a GT-HTGR would be less than from the SC-HTGR. Therefore, while the GT-HTGR could provide substantial benefits and be worthwhile, it does not appear to have advantages in discounted benefits over the SC-HTGR according to the above analyses and cost factors. However, changing the discount factor to a smaller value or increasing the U_3O_8 resource available would increase the relative benefits of the GT-HTGR. Also, no credit is given above to the GT-HTGR because of site advantages that might apply.

If a combined cycle HTGR [CC-HTGR (GT plus bottoming cycle - ammonia or steam)] were deployed, the unit capital costs would probably be about the same as those of an SC-HTGR, but the thermal efficiency could be about 47%. A CC-HTGR would probably not be available commercially

until 10 years after an SC-HTGR. If both SC-HTGRs and CC-HTGRs were utilized, with introduction of CC-HTGRs 10 years after SC-HTGR introduction, the total benefits would increase to \$6.8 billion and \$9.0 billion, respectively, instead of the \$6.4 billion and \$8.7 billion listed in Table 3 for HTGRs. (If the CC-HTGR had unit capital costs 10% lower than the SC-HTGR, the above total benefits would increase to \$8.3 billion and \$12.8 billion, respectively). Thus, it appears that introduction of SC-HTGRs followed by GT-HTGRs and/or CC-HTGRs would lead to a desirable order of HTGR introduction based on the above benefit analyses and parameter values employed, if SC-HTGRs have capital costs about the same as those for LWRs.

Another factor favoring SC-HTGRs is the timely introduction of symbiotic systems. It is desirable to build up a large thermal reactor capacity operating on thorium fuel cycles before the fueling of such systems with ^{233}U from FBRs, since that reduces the mined U_3O_8 requirement in the long term. Thus, the earlier commercial introduction possible with SC-HTGRs reduces the amount of mined U_3O_8 needed to convert to ^{233}U fueling. The above factor is discussed at the ends of the next two sections.

The above considers that SC-HTGRs are economic relative to LWRs. If SC-HTGRs have capital costs too high to compete economically (i.e., greater than 10% higher than those of LWRs), then, of course, there is advantage in emphasizing the development of GT-HTGRs. Factors helping GT-HTGR benefits are a lower discount factor, higher U_3O_8 resources, a lower nuclear power level in 2000, delayed FBR introduction, and water-restricted siting locations.

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. At the same time, HWRs on the uranium fuel cycle also have good fuel utilization; thus, introducing such HWRs should also be given consideration and is discussed in the next section. To minimize funding

requirements associated with the introduction of new reactor systems as well as to maintain high fuel proliferation resistance, it is desirable that the thorium fuel cycle be introduced on the basis of a once-through cycle and use DUTH fuel. Initial use of a once-through fuel cycle would substantially decrease the funds required for fuel recycle demonstration before the commercialization of HTGRs, and would also decrease the amount of high-fissile-content fuel associated with spent fuel. Because of their high fuel exposure, HTGRs can operate economically initially on a once-through fuel cycle and still provide economic incentive to initiate fuel recycle at a later date. A practical scenario for such HTGR introduction is given below. The discussion pertains to either the SC-HTGR or GT-HTGR, so long as either can meet the implied commercialization schedule.

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 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-year life and no more LWR construction. Recycle of LWR fuel (U and Pu) starts in 2000. In the year 2000, HTGRs are introduced at a rate of 10 GW(e)/year, using a once-through DUTH fuel cycle. This continues for 10 years; then HTGRs are introduced at a rate of 20 GW(e)/year to maintain an overall growth rate of 10 GW(e)/year. Recycle of HTGR ^{233}U 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. Then FBRs are introduced commercially, fueled with plutonium from previously stored LWR fuels. 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)/year until 200 GW(e) of FBR capacity is reached. From 2020 to 2050, HTGRs are added at a rate of 10 GW(e)/year. After 2050 the nuclear capacity remains at 800 GW(e).

The above power growth scenario is illustrated in Fig. 3. It considers that the nuclear power capacity will eventually level off. Whether 800 GW(e) is the appropriate asymptotic 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 high rates as given in Fig. 3 is used 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 to 600 GW(e)

Fig. 3. Nuclear Power Growth Scenario with LWRs, HTGRs, and FBRs.

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 to provide plutonium 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 plutonium for FBRs; whether the plutonium comes from reactors before 2000 or after 2000 is not important so long as it is available in a timely manner).

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. The relationship is given in Eqs. (1) and (2) below.

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

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, years
- P = nuclear power capacity, MW(e).

For $P = at$,

where

- a = linear power growth coefficient, MW(e)/year
- $F_{\max} = \text{maximum fissile Pu requirements} = \frac{aSD}{2}. (2)$

Assuming an FBR breeding ratio of about 1.3 and a system specific inventory of about 6 kg fissile Pu/MW(e), the fuel doubling time will be about 20 years. On that basis, the total fissile plutonium requirement at an FBR growth rate of 10 GW/year is about 600 Mg of fissile plutonium, according to Eq. (2). Further, this maximum need would occur D years (20 years in this case) after FBR introduction. Since the amount of fissile plutonium in spent fuel generated up to the year 2000 would be about 700 Mg, saving the plutonium up to the year 2000 will provide sufficient plutonium for the start-up of FBRs having the above characteristics, considering the above power growth scenario. In order to limit the fissile plutonium requirements to 600 Mg, the FBRs need to operate on the U-Pu fuel cycle with recycle of plutonium. If FBR

plutonium recycle were associated only with reactor cores having a core breeding ratio of unity, then the fissile plutonium requirements 20 years after FBR introduction would be 1.2 Gg. Here it is assumed that the FBRs operate on the above U-Pu fuel cycle for 20 years, which limits the amount of fissile plutonium 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. This excess fissile fuel would be ^{233}U for the above scenario, and its use would increase 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 up to 2040 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.

To put the above results in perspective, we consider below a corresponding scenario in which only LWRs and FBRs are utilized. This is shown in Fig. 4. LWRs are installed up to the year 2020; then their

Fig. 4. Nuclear Power Growth Scenario with LWRs and FBRs.

capacity level is maintained constant at 500 GW(e). 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 LWRs is introduced in the year 2000, with LWRs operating on the once-through cycle previously, and with the plutonium in the previously stored fuel effectively 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; however, the FBR excess fissile production does not fuel as many LWRs as HTGRs. The LWRs are converted to the thorium fuel cycle with a fuel conversion ratio of 0.8 (based on ^{233}U fueling and economic operation), so that two FBRs can fuel three LWRs under equilibrium fueling conditions (the ratio of FBRs to LWRs would be greater than unity for the case of plutonium use in LWRs). Figure 4 assumes LWR conversion to thorium fuel cycles after 2040, with makeup ^{233}U being obtained from FBRs. The total mined U_3O_8 required up to 2040 for the scenario in Fig. 4 is about 3.0 Tg (3.3 million tons).

If only once-through fuel cycles were employed up to the year 2020, with fuel recycle after that date, the Fig. 3 scenario would require 3.6 Tg (4.0 million tons) U_3O_8 up to 2040, and the Fig. 4 scenario would require 4.1 Tg (4.5 million tons) U_3O_8 . If improved once-through fuel cycles were employed, such that HTGRs required 3.6 Gg (4000 tons) $\text{U}_3\text{O}_8/\text{GW(e)}\text{-lifetime}$ and LWRs required 4.5 Gg (5000 tons) $\text{U}_3\text{O}_8/\text{GW(e)}\text{-lifetime}$, the U_3O_8 requirements would be 3.1 Tg (3.4 million tons) for the Fig. 3 scenario and 3.4 Tg (3.8 million tons) for Fig. 4 up to the year 2040.

While the fuel utilization of LWRs can and should be improved, the improvement should have a practical quality and be economic. Increasing the average fuel exposure from 30 MW(th)/kg to 50 MW(th)/kg increases the fuel utilization performance for a given refueling interval; further, the present standard refueling interval is 12 months. However, utilities appear to be choosing 18-month refueling periods on the recognition that the longer periods will lead to higher plant availabilities and lowered power production costs. If that change were to occur,

along with an increase in fuel exposure to 50 MW(th)/kg, the net improvement in fuel utilization would be 4 or 5%. Other core design changes can also be made to improve fuel utilization, but these also have compensating features, such that their practical attainment is not certain. Under the best of circumstances it appears unlikely that fuel utilization improvement of once-through fuel cycles in LWRs can exceed 20%, and that is about the improvement considered above. At the same time, it appears more likely that about 10% is a more practical value to be expected from present-type LWRs.

By going to ALWRs (having major changes in core design relative to present LWRs), more significant improvements in fuel utilization can be achieved. The major core design change to improve performance corresponds to effective removal of neutron poisons from the core region during the fuel exposure cycle. Proposals for doing this invariably involve seed-blanket type control, in which relative neutron absorptions in fertile material are varied during the cycle. However, use of seed-blanket core designs leads to lower average core power densities, larger reactor vessels for a given power capacity, and thus higher capital costs. Further, the seed-blanket fuel elements would have higher unit fuel fabrication costs because they require more complex fuel loading, and the cost of recovering the ^{233}U in the blanket rods does not justify that recovery. As a result, it is not assured that the envisioned improved fuel utilization performance associated with control-poison removal corresponds to practical core designs.

The above indicates the small economic leverage associated with improved fuel utilization performance at reasonable U_3O_8 prices. What is needed is an economic reactor concept that operates under conditions inherently providing improved fuel utilization. The HTGR can provide such features because it has a high thermal efficiency and uses core moderator and fuel cladding materials with a low absorption cross section. Further, use of pebble-bed reactor cores (or advanced prismatic cores) can achieve on-line refueling, which effectively removes control poisons during the fuel exposure cycle.

Another type ALWR that has improved fuel utilization performance involves core designs that effectively remove water from the LWR core region and increase the neutron energy spectrum of the core, leading to a high-energy spectrum reactor. Such reactors require fuel recycle to be effective in fuel utilization, and operating conditions (e.g., increased core power density) lead to safety concerns under accident conditions. It is preferable to develop a reactor that has improved safety characteristics, as exemplified by HTGRs.

Finally, mention should be made of the LWBR, which operates on the thorium fuel cycle. This reactor is of the seed-blanket design and has the same advantageous and disadvantageous features discussed above for that type core design. Further, it needs fuel recycle at a relatively high rate, which, along with the high unit cost for fuel recycle (associated with the LWBR core design), leads to uneconomic operation as a break-even breeder reactor. Both HTGRs and HWRs can also operate as break-even breeders, but such operation is uneconomic in these systems too.

Returning again to Figs. 3 and 4, the year 2040 corresponds to the time at which FBRs would start contributing to net fissile needs of the thermal reactors. While in the steady state, the FBRs could fuel the long-term ratio of reactors shown in Figs. 3 and 4; however, mined U_3O_8 is needed while the thermal reactors are converted to ^{233}U fueling. For a conversion ratio of 0.9, we estimate that the HTGR will need a system inventory of about 5 kg $^{233}U/MW(e)$, while the LWR with a CR of 0.8 will need a system inventory of about 6 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 CR of 0.8 to systems with a CR of 0.9, plus makeup of 550 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 .

For the case shown in Fig. 4, converting 500 GW(e) of LWRs to $^{233}\text{U}/\text{Th}$ 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 CR 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, leading to a mined fuel need of about 1.0 Tg (1.1 million tons) U_3O_8 .

Thus, in converting to a symbiotic system of fast and thermal reactors, the HTGR would require about 0.45 Tg (0.5 million tons) U_3O_8 , and the LWR would need about 1.0 Tg (1.1 million tons); the savings of 0.55 Tg (600,00 tons) during the conversion period is greater than the savings accumulated before that period.

Overall, use of HTGRs under the above conditions would lead to a 20 to 30% reduction in mined U_3O_8 requirements, and 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 used rather than LWRs in the long term.

In the above, no mention is made of thorium requirements, although there is an obvious requirement when thorium fuel cycles are used. 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.

USE OF HEAVY WATER REACTORS

The above scenarios did not include HWRs since they do not economically use the thorium fuel cycle at reasonable U_3O_8 prices. However,

HWRs make efficient and economic use of U_3O_8 on the uranium fuel cycle. The key factor influencing HWR use is the capital cost under U.S. conditions. UE&C has estimated¹¹ the unit capital cost of a "dry" HWR to be about 18% higher than that of an LWR. If that cost factor is employed, HWRs would not compete economically with LWRs in the U.S. for many decades, and they would not compete with HTGRs having capital costs about 15% higher than those of LWRs. At the same time, there is a large uncertainty in what the HWR capital costs would be in the U.S. Assuming that HWRs did compete economically, they would first be utilized on the LEU fuel cycle in the U.S., and they could be converted to the thorium cycle when ^{233}U is provided by FBRs.

In about the year 2000 and thereafter HWRs with LEU fueling could be introduced in the U.S. in the same ways as HTGRs are introduced in Fig. 3. 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. Thus, the HWR on uranium fueling would provide only slightly less fuel utilization than the HTGR (using thorium) up to the year 2040 in the scenario given in Fig. 3, if the HWR replaced the HTGR. However, 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, leading to an equivalent need of about 5.2 Gg of ^{235}U , or about 0.9 Tg (1.0 million tons) U_3O_8 . Thus, the potential advantages of the HTGR over the HWR are its better economic performance (due to capital cost and fuel utilization factors), its smaller amount of U_3O_8 needed to convert to ^{233}U fueling in symbiotic systems, its higher thermal efficiency, and the versatile application of HTGR component technology.

VERY HIGH-TEMPERATURE REACTORS¹²

The VHTR would operate at temperature levels higher than those required for the steam-cycle or gas-turbine HTGR. A number of large

industrial process heat applications could utilize the VHTR. These include processes for conversion of coal to synthetic gas or liquid fuels and hydrogen production for use in direct reduction of iron ore, refining of petroleum, and refining of liquids derived from oil shale and tar sands. The VHTR could also produce electricity by use of a helium turbine for part of the high-temperature energy produced or by combining a steam power cycle with the process heat cycle. It could also be used in chemical heat pipes, where chemical energy would be piped to dispersed locations for conversion to heat energy for use in power or heat producing facilities. The VHTR is the only type of fission reactor with the potential for directly attaining desired process temperatures in the range from 850 to 1000°C or slightly above. The major advantages of the VHTR over competing fossil energy sources would be the conservation of fossil fuels, the reduced atmospheric and environmental impacts, and associated economic benefits. The basic problems that need to be addressed in the development of VHTRs are materials problems, which limit the outlet gas temperature, and those associated with high-temperature process development.

Many years will be needed to overcome the materials problems, and VHTRs would logically follow GT-HTGR development. The economic incentives for VHTR development will increase as oil and gas reserves are depleted and the costs of using coal increase. Because of the long-term nature of VHTR application, it is important that adequate U_3O_8 be available to fuel them. This probably means that the economic performance of VHTRs depends substantially upon the commercialization of FBRs in the long term.

CONCLUDING REMARKS

On the bases presented above, perceived HTGR capital costs are clearly a very important factor influencing the development and support for GCRs. So long as SC-HTGR capital costs are no more than 10% higher than those of LWRs, the above analyses indicate the SC-HTGR development to be worthwhile. Obviously, General Atomic Company estimated SC-HTGR capital costs to be competitive when they offered them for sale in the

early 1970s and made a number of sale contracts; however, subsequent events proved that estimate to involve more risks than Gulf-Shell was willing to underwrite. Cost estimates made by UE&C¹³ indicated that for a mature HTGR industry, the total direct construction costs of an SC-HTGR are comparable to those for the same size LWR plant (detailed distributions of costs were different for the two plants, however). More recent estimates have also indicated that SC-HTGR capital costs are about the same as those of LWRs. In 1976 UE&C estimated the capital costs of LWRs and HTGRs (under mature industry conditions) to be about the same for approximately 1150 MW(e) twin units.¹⁴ In 1977, RAMCO estimated SC-HTGR capital costs for a 3800 MW(th) unit and a mature industry.¹⁵ In that study, Bechtel estimated the balance-of-plant costs [using the 4100 MW(th) Vidol plant study as a base], while the nuclear steam supply cost estimate was coordinated by RAMCO. The unescalated total plant cost was estimated to be about \$990 million. Then RAMCO utilized UE&C cost estimates for 1300 MW(e) SC-HTGRs and LWRs (in which the HTGR had a unit capital cost 2 to 3% higher than did the LWR), extrapolated to 3800 MW(th) units for both reactor types, and obtained parity in unit costs. Thus, RAMCO concluded¹⁵ that under favorable conditions the SC-HTGR can achieve parity in capital costs with LWRs. [The above also implies that 900 MW(e) unit SC-HTGRs would have capital costs 7 to 8% higher than 900 MW(e) unit LWRs.]

If the above estimates are valid, and since the larger size units would probably be the preferred power units in the long term, the analyses performed in the previous sections support proceeding with the commercialization of SC-HTGRs. At the same time, "mature industry" costs are lower than "initial industry" costs, HTGR cost estimates are uncertain, and there is a propensity to underestimate costs for units not yet built. Nonetheless, there may also be compensating factors; HTGRs have advantageous safety features associated with low power densities, high core heat capacities, high core temperature capabilities, and prestressed concrete pressure vessel containment, such that licensing times may be advantageously reduced and indirect construction costs lowered. Further, although there has been perception that the capital costs have been high for other thermal GCRs such as the Magnox and

Advanced Gas-Cooled Reactors in the UK, such costs have decreased in going from the Magnox (core power density of approximately 2 MW/m^3) to the higher core power density AGRs (approximately 4 MW/m^3), and additional reductions should be expected in going to the yet higher power density HTGRs (approximately 7 MW/m^3). Also, it appears that the UK is still planning to build additional AGRs instead of LWRs, while still keeping the LWR option open for the future.

Interest in GT-HTGRs has been associated with the low capital costs that might be attained in such systems and with their unique siting abilities associated with economic dry cooling. The helium gas turbine has much smaller volume than the steam turbine, leading to space and cost savings.¹⁶ Because of the above, A. D. Little in its 1976 assessment report¹⁷ essentially stated the following: "The GT-HTGR is a promising reactor concept in an early state of development that can profit greatly in a technical sense from the early commercialization of the SC-HTGR. The GT-HTGR is potentially the lowest cost converter reactor — sufficiently promising that its development should be continued even if the SC-HTGR cannot be commercialized in the near future."

The A. D. Little report estimated the capital costs of GT-HTGRs (40% thermal efficiency, 850°C core outlet gas temperature, natural draft cooling towers) to be approximately 15% less than those of an SC-HTGR using mechanical draft wet cooling towers. Further, there is the general perception by many utilities that GT-HTGRs will indeed be economically advantageous because of their siting flexibility and the extra assurance that such HTGRs will indeed have capital costs as low or lower than those of LWRs. At the same time, as pointed out previously, the technology of GT-HTGRs is not as advanced as that for SC-HTGRs, such that the research, development, and demonstration schedules and costs will be inherently longer and thus more costly than for the SC-HTGR. However, if a crash development program were mounted for the GT-HTGR vs a relatively weak program for the SC-HTGR, the GT-HTGR could probably be brought in sooner than the SC-HTGR, but it is important to recognize that timely introduction of HTGRs will require strong support by government, utilities, and vendors. The government will have to take the lead role initially because of the large financial risks associated with

commercializing a reactor technology having high and uncertain front end costs and uncertain licensing requirements, which lead to uncertain benefits in the short term.

The uncertainty of HTGR capital costs also leads to uncertainty in GCFR capital costs; however, once HTGRs are commercialized their capital costs would be known and could form the basis for expanded GCFR development, if that had not yet occurred. At the same time, it is of interest to note that the Gas Breeder Reactor Associates estimated the capital costs of GCFRs relative to SC-HTGRs by performing item-by-item differential cost studies. Their results¹⁸ indicated that GCFR capital costs are about 5% higher than those of HTGRs. If that estimate is correct, HTGRs could cost significantly more than LWRs and still lead to attractive GCFR capital costs.

Relative to proliferation and diversion resistance, HTGRs operating on the once-through DUTH fuel cycle use denatured uranium on the front end, while the spent fuel contains very low amounts of highly fissile fuel* (about a factor of 5 lower than that of spent fuel from LWRs on the LEU cycle). Further, the mix of the plutonium isotopes in spent HTGR fuel is not favorable for efficient weapons use. The only other reactor that has lower amounts of highly fissile fuel in spent elements is the HWR operating on the DUTH cycle; however, that fuel cycle in HWRs is uneconomic relative to use of the LEU cycle for U_3O_8 prices up to about \$150 to 200/lb U_3O_8 . Further, since HTGRs are the only thermal reactors that appear to be most economic on the thorium fuel cycle before the advent of FBRs, up to that time they provide the only reactor that might economically generate ^{233}U . Since the ^{233}U would contain ^{232}U and associated decay products that would emit highly penetrating gamma radiation, the HTGR-bred fuel will be very detectable and thus diversion resistant; further, if necessary, it could be denatured, making it proliferation resistant. Finally, HTGR fuel elements are bulky and heavy and contain relatively small amounts of fuel per element;

*"Highly fissile fuel" is used here to mean fuel that is useful in weapons without isotopic separation.

recovery of fissile fuel by reprocessing is also complicated because of the unique features of HTGR fuel elements associated with coated fuel microspheres in a graphite element. If other thermal reactors were "forced" to the DUTH fuel cycle, they would be penalized economically for many decades, and this would place the HTGR in a more competitive position.

Overall, the importance of gas-cooled reactor development is due to the ability of gas-cooled reactors to serve different purposes and needs while based on interrelated component systems, providing early benefits while contributing to future needs. From estimates that the SC-HTGR has capital costs comparable with those of LWRs, it appears desirable to proceed first with the SC-HTGR, then with the GT-HTGR, followed by the VHTR. If the SC-HTGR capital costs are at least 10% greater than LWRs, emphasis might be better placed on early introduction of the GT-HTGR, followed by the VHTR. The GCFR should be pursued with increasing support, particularly when it is indicated that its capital costs permit economic systems at an early date.

The primary advantages of GCFRs are associated with their potentially relatively low capital cost and relatively high breeding ratio with oxide fuels. These permit the GCFR to fill a long-term need for fast breeder reactors, which provide fissile fuel economically. The GCFR also provides diversity in FBR development. The primary advantages associated with SC-HTGRs are their potential for relatively early introduction and for lower power costs relative to LWRs (particularly as the cost of U_3O_8 increases). A key item is the capital costs of SC-HTGRs, and this cannot be determined accurately without hard experience. Capital costs appear lower for GT-HTGRs than for SC-HTGRs, thus improving economic performance. Further, very high thermal efficiencies, which give improved fuel utilization, can be attained by combined-cycle HTGRs. The GT-HTGR shows promise for application at sites where dry cooling towers are required, or where rejected energy is utilized in low-temperature processes. The difficulties associated with the GT-HTGR are the significant materials development required to operate at temperatures that will give improved thermal efficiencies and the time required to develop component technology; thus, GT-HTGR introduction

appears 5 to 10 years behind SC-HTGRs if yearly support programs are comparable. Both SC- and GT-HTGRs can operate economically on once-through fuel cycles and with better fuel utilization than do LWRs. Also, HTGR spent fuel can economically have a relatively low content of high-fissile-content material. Finally, and a most important factor, HTGRs operate well in tandem with FBRs in symbiotic systems, with FBRs being able to economically fuel larger numbers of HTGRs than other thermal reactor types for a given U_3O_8 resource. This feature has proliferation resistance advantages by decreasing the number of FBRs and the amount of plutonium fuel that needs to be fabricated into fuel elements. It also appears to improve overall economic performance. Alternatively, for the same number of FBRs and a given nuclear power level, use of HTGRs and FBRs rather than LWRs and FBRs provides more low-enriched uranium for use in other countries. The VHTRs provide a unique generation of high-temperature process heat; however, a large development effort is needed in order to operate at the required conditions, leading to long times before they can be commercialized. Their commercialization logically follows GT-HTGRs, with early emphasis on materials and process development.

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