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NGNP Reactor Type Comparison Study

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LIST OF EFFECTIVE PAGES

Page Number	Page Count	Revision
Cover page	1	0
ii through vii	6	0
1 through 62	63	0
Back page	1	0
Total Pages	71	

TABLE OF CONTENTS

ACRONYMS AND ABBREVIATIONS vi

1. SUMMARY 1

2. INTRODUCTION 7

2.2 Background 7

3. ASSUMPTIONS FOR DESIGN SELECTIONS 10

3.1.1 Utility/User Requirements 10
3.1.2 Gen-IV Goals 11
3.1.3 Design Definition for Reasonable Assessments 12
3.1.4 NRC Design Certification 13
3.1.5 High Efficiency Electricity Generation and Hydrogen Production Capability 13
3.1.6 Use of Alternate Fuel Cycles 14

4. SELECTED DESIGNS 15

5. COMPARISON CRITERIA 25

6. COMPARISON OF DESIGNS 29

6.2 Economics 31
6.3 Technology Development Risks 36
6.4 Plant Availability 38
6.5 Proliferation Resistance and Material Accountability 40
6.6 Reactor Thermal/Hydraulic and Nuclear Design 42
6.7 Impact of Reactor Concept on Other Plant Systems 43
6.8 Fuel Design 45
6.9 NRC Licensing and Design Certification 46
6.10 Life Cycle and Fuel Disposal Issues 49
6.11 Reactor Vessel and Component Fabrication 50
6.12 Safety Performance under Accident Conditions 51
6.13 Flexibility of Design to Handle Different Fuel Cycles 52
6.14 Plant Operation and Potential Problems 53
6.15 NGNP 2016-2018 Startup Schedule Impact on Choice 54

7. CONCLUSIONS 56

8. REFERENCES 61

LIST OF FIGURES

Figure 4-1. GT-MHR core and vessel isometric 16
Figure 4-2. Direct cycle GT-MHR plant isometric 16
Figure 4-3. PBMR-400 design vessel cross section [Ref. 5] 17
Figure 4-4. PBMR-400 design plant layout isometric [Ref. 34] 17
Figure 6-1. Evolution of the PMR core design 30
Figure 6-2. PBMR-400 fuel handling and storage system [Ref. 34] 40

LIST OF TABLES

Table 4-1. Plant Level Parameters for the GT-MHR and PBMR-400 Reactor Designs 18
Table 4-2. Core and Fuel Cycle Data for the GT-MHR and PBMR-400 Designs 19
Table 4-3. GT-MHR and PBMR-400 Vessel and Reflector Design Data 20
Table 4-4. GT-MHR and PBMR-400 Reactor Coated Particle Design Data 21
Table 4-5. GT-MHR and PBMR-400 Physics and Thermal/Hydraulic Performance Data 22
Table 4-6. GT-MHR and PBMR-400 Economic Data 23
Table 4-7. GT-MHR and PBMR-400 Other Safety Parameters 24
Table 5-1. List of Comparison Criteria 26
Table 6-1. Comparison of Capital Costs for PMR, PBR, and Coal Steam Cycle Systems 32
Table 6-2. Levelized Cost of Product for PMR, PBR, and Coal Steam Cycle Systems 33
Table 6-3. Summary of Estimated Busbar Costs (1992 dollars) 34
Table 7-1. Summary of the Comparison of the GT-MHR and PBMR-400 Designs 60

ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
AGR	Advanced Gas Reactor
AVR	Arbeitsgemeinschaft Versuchsreaktor
DCC	Depressurized Conduction Cooldown
DOE	Department of Energy
EAB	Exclusion Area Boundary
EC	Equilibrium Cycle
EPZ	Emergency Planning Zone
FBP	Fixed Burnable Poison
FSV	Fort St. Vrain
GA	General Atomics
GNEP	Global Nuclear Energy Partnership
GT-MHR	Gas Turbine Modular Helium Reactor
HTE	High Temperature Electrolysis
HTGR	High Temperature Gas Reactor
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
KAERI	Korean Atomic Energy Research Institute
LEU	Low Enriched Uranium
MHR	Modular Helium Reactor
N/A	Not Applicable
NERAC	Nuclear Energy Research Advisory Committee
NGNP	Next Generation Nuclear Plant
NRC	Nuclear Regulatory Commission
O&M	Operation and Maintenance
PBR	Pebble Bed Modular Reactor
PCRV	Pre-Stressed Concrete Reactor Vessel
PMR	Prismatic Block Modular Reactor
PRA	Probabilistic Risk Assessment
RCCS	Reactor Cavity Cooling System
RCS	Reserve Shutdown Control
RPV	Reactor Pressure Vessel

SA	South Africa
TDP	Technology Demonstration Program
THTR	Thorium High Temperature Reactor
T/H	Thermal/Hydraulic
TRISO	TRi-ISOtropic coated fuel particle design consisting of three materials (low-density PyC, high-density PyC, and SiC)
TRU	Transuranics
UAB	Utility Advisory Board
UCO	A mixture of uranium oxide and uranium carbide phases
V&V	Verification and Validation
VHTR	Very High Temperature Reactor
VLPC	Vented Low Pressure Containment
WPu	Weapons-Grade Plutonium

1. SUMMARY

Two high-temperature gas cooled reactor (HTGR) concepts were developed and demonstrated in commercial-size plants in the 1970's and 1980's. The prismatic block concept was demonstrated in the Fort St. Vrain nuclear power station in the U.S. The pebble bed concept was demonstrated in the AVR and THTR in Germany. Current designs of both of these HTGR concepts use TRISO-coated fuel particles, but the fuel particles are contained in fuel elements having quite different configurations. In a prismatic block reactor, the fuel particles are formed into cylindrical compacts and loaded into fuel holes in hexagonal-shaped graphite fuel blocks that are about 80 cm in height and 36 cm across flats. The fuel is cooled by helium that flows downward through vertical coolant channels in the graphite blocks. In a pebble bed reactor, the fuel particles are contained in billiard-ball sized spherical fuel elements (i.e., pebbles). The fuel is cooled by helium flowing downward through a close-packed bed of the spherical fuel elements. In prismatic block reactors, spent fuel blocks are removed and replaced with fresh fuel blocks during periodic refueling outages. In pebble bed reactors, fuel elements are removed continuously from the core during reactor operation, measured for radionuclide content, and returned to the core or replaced with a fresh fuel element depending on the amount of fuel depletion. With this continuous on-line refueling approach, there is no need for refueling outages.

In 1986, a task force consisting of General Atomics (GA), Bechtel, Combustion Engineering, EG&G Idaho, Gas-Cooled Reactor Associates, General Electric, Oak Ridge National Laboratory, and Stone and Webster Engineering performed an evaluation of two passively safe modular helium reactor (MHR) concepts, a prismatic block modular reactor (PMR) and a pebble bed reactor (PBR), to determine which of the concepts could best meet the requirements of potential commercial users in the United States. At that time, commercial interest in the MHR was focused on highly efficient production of electricity and cogeneration of electricity and process steam. The strategy was to develop a standard passively-safe MHR design that was amenable to serial production and to design certification by the U.S. Nuclear Regulatory Commission (NRC). The PBR plant considered in the study comprised four 250 MW(t) PBRs with cylindrical down-flow cores. The PMR plant considered in the study comprised three 350 MW(t) PMRs with annular down-flow cores. In both the PBR and PMR plants, each modular reactor was contained in a steel reactor vessel configured in a side-by-side arrangement with a steam generator within a below-ground vented low-pressure containment (VLPC). These designs were selected because they were judged to be capable of meeting the overall Utility/user plant requirements that had been developed by Gas Cooled Reactor Associates (GCRA) and reviewed by the Program Requirements Management task force, which was chaired by the Department of Energy and had representation from all of the MHR program participants.

The ranking of the two concepts in the 1986 evaluation was close, but plant economics (i.e., the overall electricity generation busbar cost) favored the PMR, which resulted in selection of a 4 x 350 MW(t) PMR as the reference plant design to be developed by the U.S. MHR Program. The task force recommended the four module layout over the three module layout considered in the study because it provided a more efficient and economical arrangement of the supporting and ancillary facilities. The utilities represented by GCRA concurred with this selection, which was approved by the DOE.

Both the PMR and PBR concepts have gone through considerable design evolution since 1986. The motivation for this evolution has been to reach higher power levels within the constraint of passive safety, and to achieve greater thermal energy conversion efficiency in order to improve the economics of the reactors relative to other options for electricity production. For the PMR, the reactor core diameter was first enlarged to increase the power level from 350 MW(t) to 450 MW(t). The power level was then increased to 550 MW(t) by moving the annular rings of fuel elements radially outward and reducing the width of the outer reflector to maintain the same core outer diameter. A further increase in the design power to 600 MW(t) was obtained by increasing the core power density of the 550 MW(t) design. The core outer diameter that GA selected for the 450 MW(t), 550 MW(t), and 600 MW(t) PMR designs was based on the results of a GA vendor survey that was performed to determine the largest diameter reactor vessel that could be fabricated using available commercial vessel manufacturing capability. Starting with the 450 MW(t) design, the steam generator was replaced with a gas turbine to obtain the higher efficiency available from a Brayton power conversion cycle. GA's 550/600 MW(t) PMR design is called the Gas Turbine – Modular Helium Reactor (GT-MHR).

The latest commercial-size PBR design is the ESKOM 400 MW(t) PBMR-400. This design includes an annular core with a fixed central graphite reflector. The annular core configuration is necessary for both PMRs and PBRs to obtain higher power levels while keeping maximum fuel temperatures below the 1600°C design guideline for depressurized core conduction cooldown accidents. The core power density is 6.6 W/cm^3 for the 600 MW(t) GT-MHR and 4.8 W/cm^3 for the PBMR-400. A fundamental consideration in setting the limit on core power density is the peak temperatures reached under core heatup conditions. Because PMR cores have considerably smaller void volumes than PBR cores (~20% vs. ~40%), the effective thermal conductance of a PMR core is higher than for a PBR core during a depressurized core heat-up accident. For a given accident condition peak fuel temperature limit (e.g., 1600°C) and a given core volume, this allows for a higher core power density in a PMR.

This report presents a systematic comparison of the 600 MW(t) GT-MHR design and the 400 MW(t) PBMR-400 design (as described in the open literature) against a set of evaluation criteria selected by GA based on the requirements for a commercial VHTR and the Next Generation Nuclear Plant (NGNP), and the perceived capability of the criteria to discriminate between the designs. The objective of the comparison was to identify the reactor type (PMR or PBR) that is best suited for the Very High Temperature Reactor (VHTR) commercial mission of cogeneration of electricity and very high-temperature process heat for production of hydrogen using advanced, highly-efficient processes such as thermochemical water splitting and high-temperature electrolysis. These specific designs have been compared in lieu of a design-independent comparison of the inherent capabilities of PMRs and PBRs because such a comparison, while conceptually ideal, would have been impossible to perform within the time and funding constraints of this study given the large number of design variables and the economic and performance tradeoffs associated with these variables. Thus, a basic assumption of this comparison study is that both the GT-MHR and the PBMR-400 designs have been sufficiently optimized by their respective designers to provide a basis for a valid comparison of the two reactor types.

Regardless of the specificity of the comparison, some conclusions about the inherent differences between the PMR and PBR that favor one reactor concept or the other are possible, and are noted below. It is also important to emphasize that the objective of this comparison study was to identify the best choice for a commercial VHTR as opposed to identifying the design that best fits into the current preliminary schedule for the Next Generation Nuclear Plant (NGNP) Project. This is because GA believes that the best design for the commercial VHTR should drive the selection of the NGNP design and, hence, the NGNP project schedule, as opposed to the NGNP schedule driving selection of the NGNP design and, hence, the commercial VHTR design.

Based on the detailed evaluation described in Section 6 of this report, differences between the PMR and PBR designs that significantly favor the PMR are as follows.

- The effective thermal conductance of a PBR core is inherently lower than the effective thermal conductance of a PMR core, so the core power density in PBRs must be lower to limit peak fuel temperatures during core conduction cooldown accidents. Thus, for equal core volumes, PBRs must have lower power ratings than PMRs.

- The overall coolant flow resistance of a PBR core is inherently greater than the overall coolant flow resistance of a PMR core. Thus, the core pressure drop will be higher in a PBR than a PMR for designs having the same core height and coolant flow rates. Consequently, a PBR requires more energy per unit of thermal power output to circulate the coolant, which results in lower PBR plant efficiency.

- The inherently higher operating power level and efficiency of PMRs relative to PBRs equates to an estimated electricity generation busbar cost for a GT-MHR plant that is 10% to 20% lower than for a PBMR-400 plant having the same electrical power output. This economic advantage in electricity generation cost translates to an approximately equivalent advantage for the PMR in electricity/process heat cogeneration applications given that a cost measure of the thermal energy utilized as process heat is the value of the electricity that could have been produced had the thermal energy been used for electricity production.

- The PMR designs include an annular core to achieve a high power rating while maintaining passive safety. A PBR annular core design makes the PBR more competitive economically with a PMR, but the need to periodically replace the central and outer graphite reflectors poses potential problems for the PBR. Specifically, it is estimated that the fast neutron exposure of the PBMR-400 graphite reflectors over their projected design lifetime of 20 years would be about 3×10^{22} n/cm^2 ($E > 0.18$ MeV). Acceptable graphite performance to a fast neutron fluence of this magnitude has not been demonstrated, and qualification of graphite to such high fast neutron fluence will be problematic. Consequently, the graphite reflectors in a PBR annular core design represent a significant design risk. More frequent reflector replacement, should this be necessary, would have a significant impact on PBR plant availability because replacement of the PBR reflectors is estimated to require an approximate 6 month outage. (In contrast, the non-permanent reflector blocks in a PMR can be replaced during the normal periodic refueling outages.)

- As demonstrated by operating experience in the Fort St. Vrain HTGR and in the AVR, there is much more graphite dust formation in PBRs than in PMRs. The circulation of large quantities of graphite dust in the primary coolant loop of PBRs has the potential to adversely affect the operation of a direct-cycle power conversion system (PCS) and/or an intermediate heat exchanger (IHX), and could potentially preclude use of printed circuit heat exchangers for the IHX and PCS recuperator. This would be a significant disadvantage for the PBR.
  Also, the dust is an excellent medium for enhanced release of fission products during accidents involving depressurization of the primary coolant loop. Indeed, the quantity of graphite dust that would be expected in the primary circuit of the PBMR-400 based on AVR experience raises a question as to whether a PBMR-400 with a VLPC can meet off-site dose limits (assuming a 425-m plant exclusionary boundary) during a rapid depressurization accident.

- Uncertainties associated with PBR core thermal/hydraulic performance could adversely impact PBR licensing and design certification. Although fuel temperatures during normal operation should be lower in a PBR than in a PMR because of the lower core power density and better pebble-to-coolant heat transfer, coolant and fuel temperatures in the AVR were much higher than predicted based on temperature measurements in the core and the results of post-irradiation examination (PIE) of AVR fuel[1]. The reasons for these higher-than-expected temperatures are not well understood, but they were likely related to power peaking and thermal/hydraulic irregularities at core – reflector boundaries or adjacent to the graphite "noses" in the AVR core; effects that could be enhanced in a PBR annular core. One such anomaly that has been observed experimentally is that pebble flow along reflector surfaces can be two to three times slower than in the interior of the pebble bed core.

- The PMR refueling approach and fuel element design makes fuel element accountability substantially simpler in a PMR than in a PBR, and diversion of nuclear material more difficult.

Based on the detailed evaluation described in Section 6 of this report, differences between the PMR and PBR that may favor the PBR are as follows:

- On-line refueling in the PBR eliminates the need for refueling outages, which may give the PBR a small advantage over the PMR with respect to availability, but only if the lifetime of the graphite reflectors in the PBR is very long (i.e. of the order of 20 years). A significantly shorter reflector lifetime and/or unreliable operation of equipment such as the on-line fuel handling system in the PBR would partially or completely eliminate this advantage. Also, pebble bridging, which was observed in the AVR, could cause pebble flow perturbations that disrupt on-line refueling and adversely impact reactor availability.

- The inherently lower core power density and better pebble-to-coolant heat transfer in PBRs should result in lower fuel temperatures in PBRs during normal operation, which could translate to better fuel performance in PBRs than in PMRs. However, as noted above, coolant temperatures and fuel temperatures in the AVR were much higher than predicted, and the reason for these higher-than-expected temperatures is not known with certainty. Higher-than-expected peak fuel temperatures in PBRs could have an adverse impact on expected PBR fuel performance, particularly for UO_2 fuel having relatively high burnup

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[1] Temperature measurements made with dummy (non-fueled) pebbles containing melt wires indicated local coolant temperatures in excess of 1280°C in the AVR core, and postirradiation examination of AVR pebbles suggested peak in-service fuel temperatures approaching 1600°C. These temperatures are hundreds of degrees higher than the temperatures predicted for the AVR.

(because of high CO pressure within the coated particles). Also, recent studies have shown that it should be possible to further optimize the PMR core design to reduce power peaking factors, bypass flows, and boundary-layer temperature gradients, all of which would contribute to reducing peak fuel temperatures and potentially improving overall fuel performance.

- Both PMRs and PBRs can use UCO fuel, and by doing so would benefit from lower fuel costs because of the higher fuel burnup obtainable with UCO fuel relative to UO_2 fuel[2]. However, the economic penalty associated with use of UO_2 fuel would be greater for a PMR than a PBR because this would necessitate a shorter refueling cycle, thereby reducing reactor availability. Also, it is not clear that a PMR loaded with UO_2 fuel could operate for an extended period of time with a core outlet coolant temperature of 950°C because of the potential for kernel migration in UO_2 fuel exposed to high thermal gradients. The capability of PBRs to use UO_2 fuel, which has a more extensive irradiation and safety testing data base than UCO fuel, could potentially make licensing a pebble bed NGNP somewhat less difficult than licensing a prismatic block NGNP. However, this advantage would not extend to a follow-on commercial pebble bed VHTR because it is expected that UCO fuel will have been qualified and be available for use by the time a commercial VHTR is built.

The overall conclusion of the current PMR vs. PBR comparison is that the PMR has a clear advantage over the PBR as the modular helium reactor type best suited for a commercial VHTR for electricity production and various high-temperature process heat applications, including hydrogen production. Consequently, a PMR is also the clear choice for the NGNP. This conclusion is consistent with the result of the aforementioned 1986 study that resulted in selection of a PMR as the concept to be developed by the U.S. MHR Program for commercial applications in the U.S.

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[2] Because the inclusion of carbon as uranium carbide phases in the UCO kernel suppresses CO formation.

2. INTRODUCTION

2.1 Purpose and Scope

This report describes a trade study performed by General Atomics (GA) to compare a Prismatic Block Modular Reactor (PMR) design and a Pebble Bed Modular Reactor (PBR) design. The objective of the comparison was to identify the reactor type (PMR or PBR) that is best suited for the Very High Temperature Reactor (VHTR) commercial mission of cogeneration of electricity and very high-temperature process heat for production of hydrogen using advanced, highly-efficient processes such as thermochemical water splitting and high-temperature electrolysis. Because the Next Generation Nuclear Plant (NGNP) is to be a prototype for a commercial VHTR, the reactor type that is best suited for a commercial VHTR should also be the best choice for the NGNP.

Many different PMR and PBR designs have been developed, and specific designs (e.g., power level, operating temperatures, fuel cycle, etc.) must be selected before the reactor concepts can be compared using any set of comparison criteria. The designs selected for comparison must be relevant to Utility/user requirements for a commercial VHTR and to requirements for the Next Generation Nuclear Plant (NGNP). The assumptions used as a basis for selection of the PMR and PBR designs to be compared in this study are listed and discussed in Section 3, and the PMR and PBR designs selected based on these assumptions are discussed in Section 4.

Clearly there is a large set of potential comparison criteria for the study, but the important criteria are those that can discriminate between the designs. Based on this premise, a limited set of criteria was selected for the study. These criteria are reviewed and discussed in Section 5, and the set chosen for the evaluation are listed. The comparison of the PMR and PBR designs against the evaluation criteria defined in Section 5 is presented in Section 6. The conclusions from this study are discussed in Section 7.

2.2 Background

In 1986, a task force consisting of General Atomics (GA), Bechtel, Combustion Engineering, EG&G Idaho, Gas-Cooled Reactor Associates, General Electric, Oak Ridge National Laboratory, and Stone and Webster Engineering performed an evaluation of two passively safe modular helium reactor (MHR) concepts, a prismatic block modular reactor (PMR) and a pebble bed reactor (PBR), to determine which of the concepts could best meet the requirements of potential commercial users in the United States [Ref. 7]. At that time, commercial interest in the MHR was focused on highly efficient production of electricity and cogeneration of electricity and process steam. The strategy was to develop a standard passively-safe MHR design that was amenable to serial production and to design certification by the U.S. Nuclear Regulatory Commission (NRC). In the longer term, it was planned to develop advanced MHR designs for non-electric applications such as coal liquefaction and gasification, and for high efficiency electricity generation or cogeneration using direct cycle gas turbines.

Two candidate MHR concepts, neither of which was fully optimized at the time, were selected for the evaluation:

- 4 x 250 MW(t) PBR modular reactors with side-by-side steel reactor vessel and steam generator in a below-ground vented low-pressure containment (VLPC), using pebble bed fuel in a cylindrical down-flow core. Reactivity control was provided by control rods in four in-core control structures (graphite noses from the outer reflector).
- 3 x 350 MW(t) PMR modular reactors with side-by-side steel reactor pressure vessel and steam generator in a below-ground VLPC, using a prismatic fuel design in an annular down-flow core. Reactivity control was provided by control rods located in the outer reflector, with a reserve shutdown system that allowed for the insertion of neutron poison into selected core fuel blocks.

These two concepts were selected because they met overall Utility/user plant requirements that had been developed by Gas Cooled Reactor Associates (GCRA) and reviewed by the Program Requirements Management task force, which was chaired by the Department of Energy and had representation from all of the MHR program participants. The concept evaluation plan developed for the study defined the evaluation criteria in terms of minimum requirements called "musts" and desirable attributes called "wants".

The major conclusions from this evaluation were as follow.

- Neither the 3 x 350 MW(t) PMR nor the 4 x 250 MW(t) PBR plants met the availability goal of greater than 80% over the plant lifetime.
- The 350 MW(t) PMR plant met the forced outage goal of less than 10% per year.
- Both plants met the risk aversion goal with margin.
- Both plants met the goal to preclude necessity for planned evacuation of the public outside the plant exclusion area boundary.
- The 3 x 350 MW(t) PMR plant met the criteria of being at least 10% below the levelized electricity generation busbar cost of the best coal alternative; the 4 x 250 MW(t) PBR plant option did not meet this goal.
- Both plants met the requirements for total energy output, for capability to startup by the mid 1990's, and for standardization suitability.
- Both plants met the requirement that the development be completed by the required delivery date at a reasonable cost.

The numerical ranking of the two concepts was close, but the cost comparison results (see Section 6.2), and concerns about access to German PBR information were the deciding factors that led the evaluation task force to recommend that a 4 x 350 MW(t) prismatic fuel, annular core reactor design be selected for further development. The task force recommended a four module layout of this PMR over the three module layout because it provided an efficient and economical arrangement of the supporting and ancillary facilities. The Utilities that were represented by GCRA concurred with this selection, which was approved by the Department of Energy.

3. ASSUMPTIONS FOR DESIGN SELECTIONS

3.1 Assumptions

The selection of specific PMR and PBR designs for this comparison study was based on a set of assumptions relevant to commercial VHTR and NGNP requirements. For this study the following assumptions were chosen:

1.0 The reactor design should meet U.S. Utility/User commercial reactor requirements

2.0 The reactor design should meet stated Gen-IV goals

3.0 The designs should be defined well enough to:

- Allow a reasonable assessment of technology risks, and the technology development required.
- Allow a reasonable economic comparison using accepted methods.
- Allow an assessment of design effects on other plant systems.

4.0 The reactor design should be capable of providing a basis for design certification of a commercial VHTR by the Nuclear Regulatory Commission (NRC) for an electric utility power producing plant

5.0 The reactor design should be capable of generating electricity at high efficiency, and of providing process heat to demonstrate efficient hydrogen production capability

6.0 The reactor design should be capable of utilizing alternative fuels

These assumptions were used in selecting the specific PMR and PBR designs for the comparison based on the evaluation criteria listed in Section 5. A more detailed discussion of these assumptions is given below.

3.1.1 Utility/User Requirements

A major objective of the NGNP Project is to demonstrate a nuclear plant design that can meet the requirements of potential future users in the U.S. for electricity and hydrogen production. As part of the Gas Turbine Modular Helium Reactor (GT-MHR) development program, General Atomics (GA) organized a Utility Advisory Board (UAB) with representatives from many of the U.S. nuclear plant operators to guide its selection of design requirements for the High-Temperature Gas-Cooled reactor. The UAB has provided GA with a set of key Utility/user requirements [Ref. 1] specifically for a commercial modular helium reactor plant. Key requirements include:

- The plant should consist of four standard reactor modules.
- The plant should have a Brayton power conversion system with > 40% efficiency.

- The plant should have an overnight plant capital cost <$1500/kWe.
- The reactor should be capable of operating on a once-through uranium fuel cycle (<20% U-235 enrichment) with $\geq$18 months between refueling.
- The standard power unit design should have an NRC design certification.
- The plant should not need an evacuation zone, i.e. EAB=EPZ.
- The probability of exposure exceeding the protective action guidelines should be $<5\text{x}10^{-7}$ per plant year.
- The maximum accident should result in <1 rem effective whole body radiation dose equivalent, and <5 rem thyroid dose.
- Inherent response to satisfy NRC design basis accident limits and requirements, i.e., no reliance on operator or control room action or any AC – powered equipment.
- The plant service life should be $\geq$ 60 years.
- The plant should be capable of automatic load following over 50% to 100% of full power.
- The plant should be capable of rapid load changes of +5%/minute over 50% - 100% of full power.
- The plant should be capable of a 100% - 0% step change without trip.
- The plant should be capable of reaching hot critical within 24 hours after a cold shutdown.
- The design capacity factor (breaker-to-breaker) should be $\geq$ 94%.

These Utility/User requirements combine the evolving capabilities for current light water reactors in terms of fuel cycle length, capacity factor, system lifetime, and operational capability, with the Gen-IV requirements for inherent operational safety, a site-only evacuation zone, and high operation efficiency.

3.1.2 Gen-IV Goals

The Generation IV International forum (Gen-IV) explored and evaluated 4th Generation reactor concepts against a set of goals designed to meet future safety, cost, proliferation risk, and environmental impact concerns [Ref. 2]. The NGNP as a next generation nuclear plant must satisfy these Gen-IV goals [Ref. 3], which are:

- Achieve improved sustainability and enhance the fuel supply.
- Reduce environmental impact and improve nuclear waste management.
- Improve economics by reducing cost and financial risk.
- Improve safety and reliability as compared to current nuclear plants.

- Eliminate the requirement for off-site response.
- Reduce proliferation risk, make nuclear materials unattractive for diversion, and increase physical protection for nuclear materials.

3.1.3 Design Definition for Reasonable Assessments

Technology Risks and Technology Development Needs

The NGNP will demonstrate the operation of high-temperature technology including high reactor coolant temperatures, high efficiency electricity generation, and hydrogen production capability. Any new technologies for these applications must be developed prior to design and fabrication of the relevant NGNP systems. The technology development needs for both reactor types, the development schedule, and the potential development risks need to be compared to assess their impact on the NGNP design and schedule, and on the commercial costs and construction schedule. The lowest risk technology development necessary for demonstration of economic commercial operation is desired. Any significant difference in technology risks between the plant designs could impact the NGNP choice in addition to commercial reactor development.

The NGNP balanced risk option [Ref. 3] assesses the overall project risk with the objective of balancing technology development risk against design, licensing and construction risk. Emphasis is on initiating design work as early as practical to reduce the uncertainties in the scope and focus of research and development activities. Critical Decision-1 is scheduled for 2008, with the expected date for initial operations (following the test program) in 2018. This option allows for a two-to-three year period of operation (prior to 2021) simulating a commercial power reactor operating cycle that is followed by an extensive outage, during which the equipment performance is confirmed by detailed disassembly and inspection. This proof-of-principle operating period provides the basis for commercialization decisions by industry. The balanced risk option provides for an early plant demonstration while minimizing development risks that could seriously affect future plant commercial success.

Assessment of Plant Economics using Acceptable Methods

The cost to produce electricity or other products is key to the commercial feasibility of a reactor plant. The designs must be sufficiently well defined and the technology development risks sufficiently understood for a reasonable cost estimate of plant construction costs, fuel cycle costs, operating costs, and lifetime and disposal costs to be developed. These cost estimates can be based on DOE standards or accepted commercial costing methods for the U.S. utility market.

Assessment of Design Effects on Other Plant Systems

Modular High-Temperature Gas-Cooled reactors are viewed as having multiple future applications, including generation of electricity at very high efficiencies, production of hydrogen, and process heat applications. Reactor design parameters such as coolant pressure drop and temperature, coolant flow rates, fission product release and plate out, and graphite dust formation and circulation can have significant impact on the plant systems designed for these applications. These impacts need to be assessed to determine their effect on system availability, and operating efficiency.

3.1.4 NRC Design Certification

It is anticipated that the NGNP demonstration plant will be licensed under 10CFR 50 rules because of time and schedule constraints. The NGNP will then be used to develop the necessary information for NRC design certification of follow-on commercial plants under 10 CFR 52, and eventually under 10 CFR 53 rules when completed.

The licensing basis is expected to be risk-informed and to use a mechanistic source term for accident consequence evaluation consistent with the concepts used in the proposed licensing approaches for the Modular High Temperature Gas Reactor and the Pebble Bed Modular Reactor. Any pre-application discussions with NRC will address these and other topics (e.g., approach to defining control interactions between the nuclear system and hydrogen production facility) to reach formal agreement on the overall licensing approach and NRC review criteria. These pre-application discussions will also be required to ensure NRC and public familiarity with the NGNP prototype licensing methodologies before application for the construction permit and the subsequent operating license. NRC licensing for the demonstration unit under these conditions should ensure that the follow-on commercial units can be certified for operation as utility power producing plants. An assessment of the potential impact of NRC requirements on the reactor and plant designs is needed to determine if they result in any major differences in the two designs.

3.1.5 High Efficiency Electricity Generation and Hydrogen Production Capability

While the utility/user requirements described in Section 3.1.1 call for the demonstration of a Brayton power conversion system with at least 40% efficiency, clearly the next generation plants should have the highest possible electricity generation efficiency to compete economically with current and future, high-temperature, natural gas-fired units. These units can produce electricity with conversion efficiencies close to 50%. The reactor design should have the capability to operate at $\geq$900°C gas outlet temperature for highly efficient hydrogen production and multiple high temperature process heat applications.

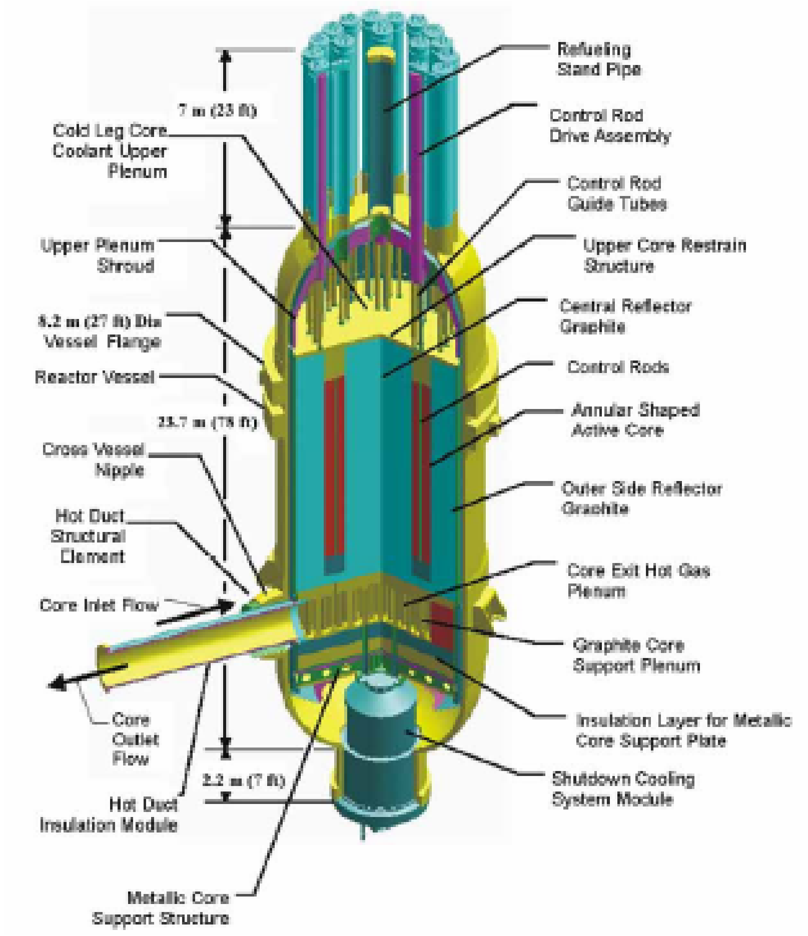
3.1.6 Use of Alternate Fuel Cycles

A utility/user requirement specific to the NGNP is that the reactor should have the capability to use alternate fuel cycles [Ref. 1], a goal shared with both Gen-IV and the Global Nuclear Energy Partnership (GNEP). It implies that future reactors should be capable of operating on many different fuel cycles. This capability, important for extending fuel resources, minimizing proliferation risks, and reducing the high-level waste disposal problem, is included in the reactor comparison.

4. SELECTED DESIGNS

Based on the assumptions developed and discussed in Section 3, the PMR design selected for the study is the 600 MW(t) GT-MHR developed by GA [Ref. 4] and the selected PBR design is the PBMR-400 developed by Pebble Bed Modular Reactor (Pty) Ltd of South Africa for the ESKOM utility [Ref. 5]. This selection was based on the amount of detail available for these designs and the potential of the selected designs to satisfy the assumptions discussed in Section 3. In this report, the selected PMR design will be referred to as the GT-MHR and the selected PBR design will be referred to as the PBMR-400. An isometric layout of the GT-MHR reactor vessel and core is shown in Figure 4-1, and the plant layout for electricity production using the direct Brayton cycle is shown in Figure 4-2. A cross-section view of the PBMR-400 reactor vessel and core is shown in Figure 4-3, and an isometric view of the plant layout is shown in Figure 4-4.

The parameters for these two designs were extracted from several sources and are listed in Tables 4-1 through 4-7. Table 4-1 summarizes the plant level data for the two designs; Table 4-2 summarizes the core and fuel cycle designs; Table 4-3 provides the vessel and reflector design; Table 4-4 lists the coated particle designs; Table 4-5 summarizes the physics and thermal/hydraulic (T/H) performance data; Table 4-6 summarizes the available economic data; and Table 4-7 provides basic safety parameters. The source of the data is also indicated in the tables (using the reference list in Section 8), followed by the page number within the reference, separated by a colon. Parameters that have been calculated from other data presented in the tables are denoted by “calc”.



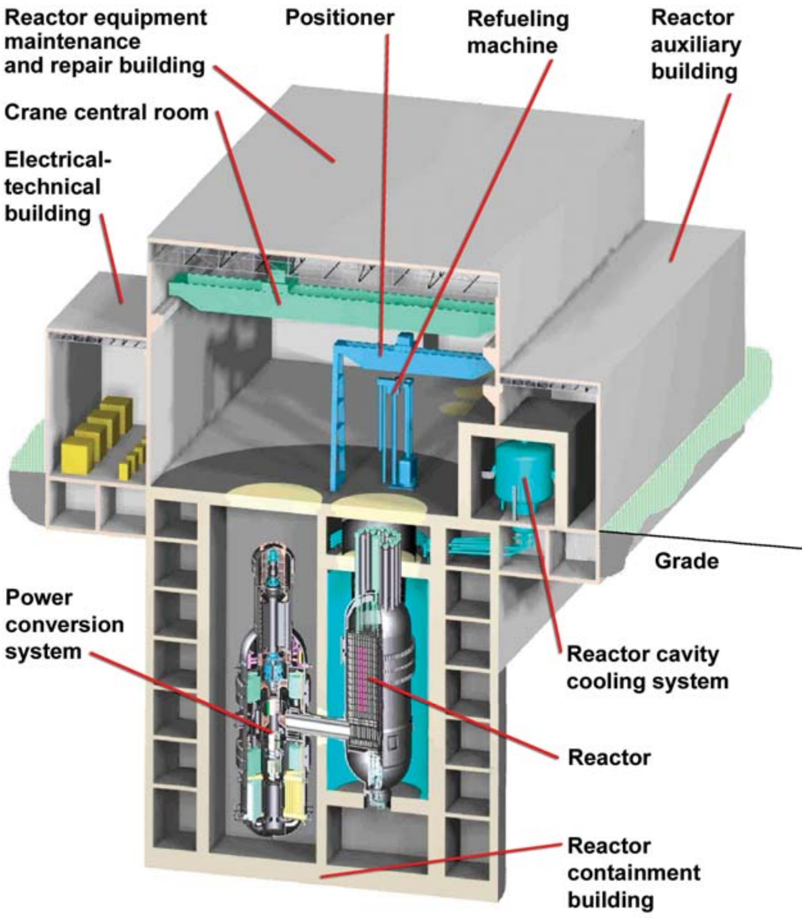
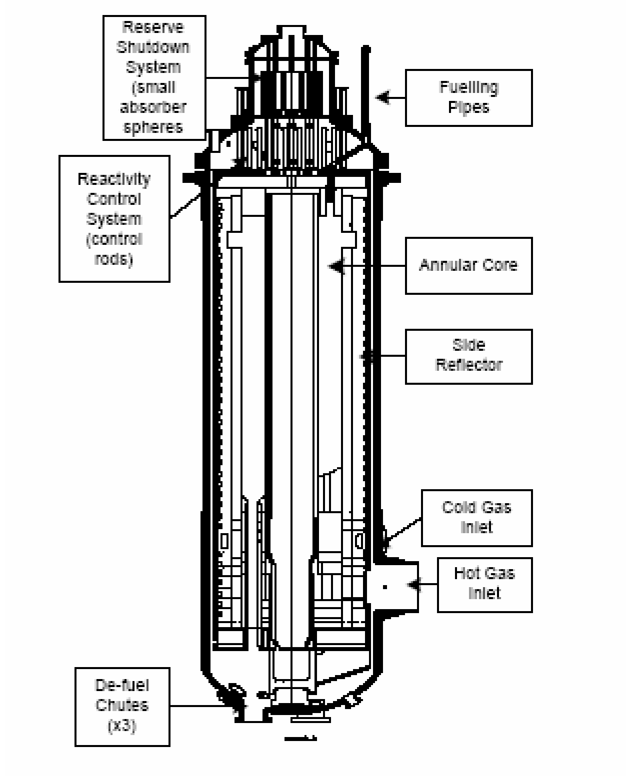


Figure 4-1. GT-MHR core and vessel isometric

Figure 4-2. Direct cycle GT-MHR plant isometric



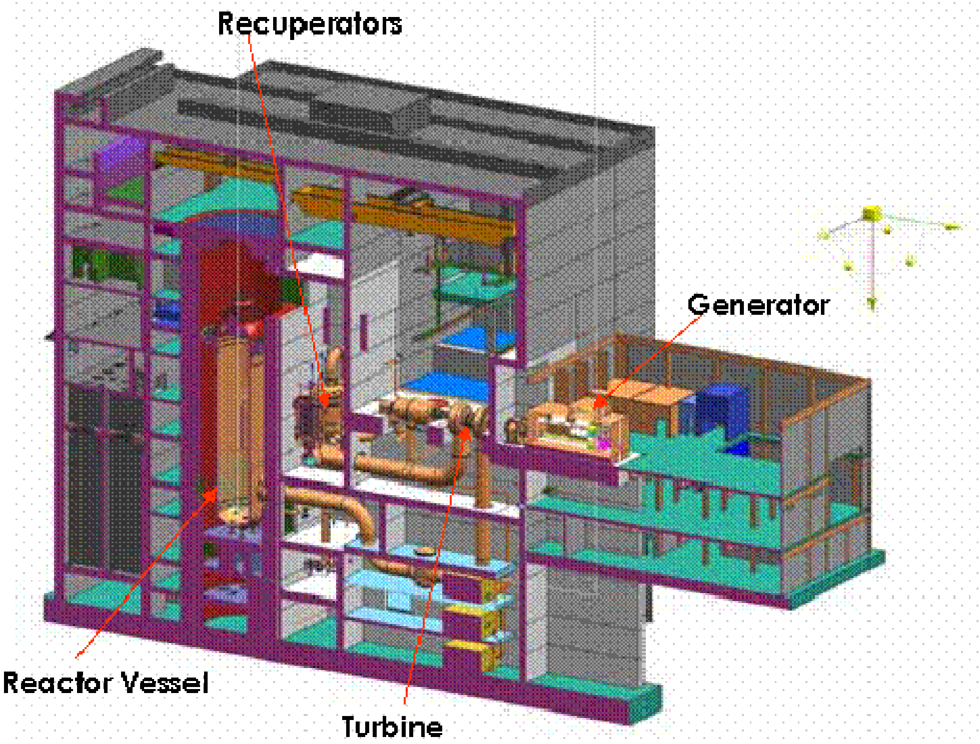


Figure 4-4. PBMR-400 design plant layout isometric [Ref. 34]

Figure 4-3. PBMR-400 design vessel cross section [Ref. 5]

TABLE 4-1. PLANT LEVEL PARAMETERS FOR THE GT-MHR AND PBMR-400 REACTOR DESIGNS

Reactor Parameters	**Value [reference:page]**	
	GT-MHR Design	**PBMR-400 Design**
Plant Level Data - Power Ratings		
Thermal Power per Module (MWt)	600 [6:3-9]	400 [11:8]
Heat Transfer to Power Conversion	Direct Brayton Cycle [6:1-1]	Direct Brayton Cycle
Net Plant Thermal Efficiency (%)	47.7 [6:1-15]	41 [34:118]
Net Electrical Output (MWe)	286 [6:3-9]	165 [11:8]
Number of Modules per 1100 MWe Plant	4 [6:1-1]	7 [calc]
Plant Level Data - Normal Operation		
Design Life of Plant (years)	60 [6:4-35]	60 [11:18]
Plant Availability (Capacity Factor) (%)	≥87 [9:4-14]	≥95 [34:118]
Automatic Load Following Over 50-100% of Full Power?	Yes (100-15-100%) [6:5-12]	Yes (100-20-100%) [34:118]
Rapid Load Changes of ±5%/minute Over 50-100% of Full Power?	Yes (15-100%) [6:5-12]	Yes (100-20-100%) [34:118]

* Comparison criteria are discussed in Section 5, and listed in Table 5-1

Table 4-2. Core and Fuel Cycle Data for the GT-MHR and PBMR-400 Designs

Reactor Parameters	Value [reference:page]	
	GT-MHR Design	PBMR-400 Design
Core Dimensions		
Outside Diameter (m)	4.83 [6:4-6]	3.7 [12:3]
Inside Diameter (m)	2.96 [6:4-6]	2 [12:3]
Height (m)	7.93 [6:4-6]	10.12 [34:121]
Effective Annulus (cm)	93 [26:3]	85 [12:3]
Fuel Pebble Diameter (cm)	N/A	6 [11:17]
Fuel Compact Outer Radius (cm)	0.6225 [6:4-10]	N/A
Fuel Compact Height (cm)	4.928 [6:4-10]	N/A
Fuel Block Height (cm)	79.3 [6:4-10]	N/A
Fuel Block Distance Across Flats (cm)	36 [6:4-10]	N/A
Core Materials		
U-235 EC Loading (kg)	349.75 [39:6]	348.5
U-238 EC Loading (kg)	1912.49 [39:6]	3751.5
Total Uranium EC Loading (kg)	2262.24 [39:6]	4100 [11:17]
FBP Composition / Density (g/cm^3) (kg)	B_4C / 2.47 [6:4-18]	N/A
Refueling Scheme		
Refueling Type	Open and Replace [6:4-6]	Continuous [11:15]
Fraction of Core Replaced	0.5 [6:4-6]	N/A
Fuel Lifetime (years)	3 [39:4]	2.6 [34:121,122]
Fuel Cycle Flexibility		
Design Capable of Utilizing LWR Spent Fuel?	Yes	unknown
Design Capable of Utilizing Weapons Grade Plutonium?	Yes	Difficult (no fixed burnable poison)
Design Capable of Utilizing Thorium Fuels?	Yes (FSV was Th/HEU)	Yes (THTR was Th/U MOX) [12:7]

* Comparison criteria are discussed in Section 5, and listed in Table 5-1

TABLE 4-3. GT-MHR AND PBMR-400 VESSEL AND REFLECTOR DESIGN DATA

Reactor Parameters	Value [reference:page]	
	GT-MHR Design	PBMR-400 Design
Dimensions - Reactor Vessel		
Inside Diameter (m)	7.22 [35]	6.20 [12:3]
Wall Thickness (cm)	21.59 [6:4-38]	18 [12:3]
Dimensions - Reflectors		
Outer Permanent Reflector Thickness (cm)	30 (est)	60 (est)
Outer Replaceable Reflector Thickness (cm)	61.08 (est)	40 (est)
Inner Reflector Diameter (m)	2.96 [6:4-6]	2 [12:3]
Materials		
Reactor Vessel	9Cr1Mo or 2¼Cr1Mo	SA508
Reflectors	Graphite	Graphite
Replaceable Reflector Lifetime (years)	8 (est)	20 (est)

* Comparison criteria are discussed in Section 5, and listed in Table 5-1

TABLE 4-4. GT-MHR AND PBMR-400 REACTOR COATED PARTICLE DESIGN DATA

Reactor Parameters	Value [reference:page]		
	GT-MHR Design		PBMR-400 Design
Fuel Kernel			
Composition	$UC_{0.5}O_{1.5}$ [6:4-14]		UO_2 [34:121]
Effective U-235 EC Enrichment (%)	15.5 [6:4-6]		9.6 [34:121]
TRISO Dimensions	**Fissile [6:4-14]**	**Fertile [6:4-14]**	
Fuel Kernel Radius (µm)	175	250	250 [27:57]
Buffer Thickness (µm)	103	68	91.5 [27:57]
Inner PyC Thickness (µm)	50	50	40 [27:57]
SiC Thickness (µm)	35	35	35 [27:57]
Outer PyC Thickness (µm)	43	43	40 [27:57]
TRISO Diameter (µm)	812	892	920 [27:57]
TRISO Densities			
Fuel Kernel Density (g/cm^3)	10.5 [6:4-14]		10.4 [27:57]
Buffer Density (g/cm^3)	1 [6:4-14]		1.05 [27:57]
Inner PyC Density (g/cm^3)	1.87 [6:4-14]		1.9 [27:57]
SiC Density (g/cm^3)	3.2 [6:4-14]		3.18 [27:57]
Outer PyC Density (g/cm^3)	1.83 [6:4-14]		1.9 [27:57]

* Comparison criteria are discussed in Section 5, and listed in Table 5-1

TABLE 4-5. GT-MHR AND PBMR-400 PHYSICS AND THERMAL/HYDRAULIC PERFORMANCE DATA

Reactor Parameters	Value [reference:page]	
	GT-MHR Design	PBMR-400 Design
Normal Core Physics Performance		
Avg. Core Power Density (W/cm^3)	6.5 [26:3]	4.78 [12:3]
Max. Core Power Density (W/cm^3)	9 [26:3]	10.99 [12:3]
EOC Negative Temperature Coefficient of Reactivity?	Yes [9:4-5]	Yes [12:3]
Avg. Fuel Burnup (MWD/MTIHM)	112,742 [10:6]	90,000 [34:121]
Normal T/H Performance		
Coolant Type	Helium [6:3-9]	Helium [11:13]
Coolant Pressure (MPa)	7.13 [6:3-9]	9.0 [34:118]
Core Coolant Flow Rate (kg/s)	320 [6:3-9]	185 [12:3]
Core Inlet/Outlet Pressures (MPa)	7.07/7.02 [6:3-9]	8.9/8.6 [12:3]
Core Inlet/Outlet Temperatures (°C)	491/850 [6:3-9]	487/900 [12:3]
Vessel Avg. Wall Temperature @ Design MWt (°C)	446 [26:2]	350 [12:3]
Avg. Fuel Temperature (°C)	821 [26:3]	800 [12:3]
Max. Fuel Temperature (°C)	1218 [26:3]	1057 [12:3]
Accident Performance		
Depressurized Conduction Cooldown:		
Maximum fuel temperature (°C)	1521 [6:6-20]	1590 [11:20,21]
Percent of core involved	<5% [6:6-21]	<6.9% [11:20,21]
Duration of high temperature (hours)	20 [6:6-22]	20 [11:20,21]

* Comparison criteria are discussed in Section 5, and listed in Table 5-1

TABLE 4-6. GT-MHR AND PBMR-400 ECONOMIC DATA

Reactor Parameters	Value [reference:page]			
	GT-MHR Design		PBMR-400 Design	
Plant Level Data - Economics Input	[6]		[34]	
Reactor Thermal Power (MWt)	600		400	
Net Plant Thermal Efficiency (%)	47.7		41.25	
Number of Power Units per Plant	4		7	
Plant Electrical Output (MWe)	1145		1155	
Plant Level Data - Economics Costs (1992-$'s)				
Overnight Plant Cost of NOAK Plant (M$)	1,549 [28:8]		2,046 [41:22]	
Overnight Unit Cost of NOAK Plant ($/kWe)	1,353 [28:8]		1860 [41:22]	
Total Capital Cost (M$)	1,740 [28:8]		2,296 [41:22]	
BUSBAR COSTS	**Value**	**% of Busbar**	**Value**	**% of Busbar**
Capital (mills/kWhr)	19.0 [28:8]	57.5	26.0 [calc]	65.5
O&M (mills/kWhr)	4.1 [28:8]	12.4	4.1 [est]	10.3
Fuel (mills/kWhr)	9.3 [28:8]	28.2	9.0 [est]	22.7
Decommissioning (mills/kWhr)	0.6 [28:8]	1.9	0.6 [est]	1.5
Total Busbar Generation Cost (mills/kWhr)	33.0	100.0	39.7	100.0

* Comparison criteria are discussed in Section 5, and listed in Table 5-1

TABLE 4-7. GT-MHR AND PBMR-400 OTHER SAFETY PARAMETERS

Reactor Parameters	**Value [reference:page]**	
	GT-MHR Design	**PBMR-400 Design**
Active Core Void Fraction (%)	20	40
Core Thermal Conductance During DCC Accidents	Higher	Lower
Risk of Pebble "Hang-up" at Core/Reflector Interface	N/A	Yes
Risk of Pebble "Bridging" Leading to Loss of Flow	N/A	Yes
Design Capable of Controlling Coolant Flow Distribution	Yes	No
Design Capable of Fuel and Burnable Poison Zoning	Yes	No
Excess Reactivity (%ΔK)	4.5	1.4
Design Allows for In-Core Control Rods	Yes [6:4-3]	No
Volume of Graphite Dust in Primary Loop	Low	High
Core Oxidation Resistance	High	Lower than PMR
Plant Level Data - Accident Operation		
Evacuation Zone (Exclusion Area Boundary) (m)	425 [9:7-17]	400 [34:118]
Probability of Exceeding PAG Exposure (per plant year)	$2x10^{-8}$ (EPRI), $7x10^{-7}$ (EPRI, @95% truncated source term) [9:7-18]	*unknown*
Max. Accident Thyroid Dose (rem)	10.5 (EPRI), 1.5 (EPRI, @95% truncated source term) [9:7-18]	*unknown*

* Comparison criteria are discussed in Section 5, and listed in Table 5-1

5. COMPARISON CRITERIA

5.1 Comparison Criteria Evaluation

Many comparison criteria were considered for inclusion in this study, and the set developed for further evaluation is listed below:

- Core nuclear design, including power density, power distributions, power level, fuel zoning, excess reactivity and its control requirements, temperature coefficients, use and zoning of burnable poison, fuel cycle requirements, and fuel cycle flexibility
- Fuel element design, including coated-particle design, oxidation resistance, graphite impurities, and stationary vs. flowing element considerations
- Reactor thermal hydraulic design, including internal reactor heat transfer, core pressure drop, and flow stability
- Reactor vessel and internal components, including neutron fluence and temperature limits
- Fuel performance and fission-product transport, including circulating and plate-out activity. Proliferation resistance and material accountability
- Impact of reactor concept type on other systems, including power conversion system, hydrogen production system, heat transport system, refueling and fuel handling system, and balance-of-plant systems
- Component fabrication feasibility
- Plant operation
- Plant maintenance and worker safety
- Safety performance during accident conditions, including loss of flow, loss of coolant, reactivity insertion via control rods or moisture ingress, and seismic events
- Plant availability
- Design methods development considerations, including code verification and validation
- Licensing considerations
- Economics, including capital costs, operating costs, and life-cycle costs
- Commercial applications, including electricity production, hydrogen production, other process heat applications, and commercial scalability
- NGNP schedule for startup by mid-2017
- Date for on-line operation by a U.S. Utility
- Technology development requirements and schedule

- Flexibility of design to handle different fuel cycles
- Use for GNEP application, specifically for high level waste reduction and proliferation resistance
- Overall risk of each type for successful operation including potential problem areas based on past experience

Because it is not possible in this study to review all possible comparisons, the above criteria were reviewed and the subset listed in Table 5-1 was selected based on the important of these criteria to the reactor application (Utility/User, Gen-IV, etc.) and the potential of the criteria to discriminate between the PMR and PBR designs. The comparisons of the PMR and PBR against these criteria are discussed in subsections of Section 6 as indicated in Table 5-1.

Table 5-1. List of Comparison Criteria

Section	Comparison Criteria	Comment
6.1	Core power level and plant scalability	Impacts plant economics, utility acceptance, inherent safety, technology development.
6.2	Plant economics, including capital costs, operating costs, and life-cycle costs.	Key criteria for commercial acceptance
6.3	Technology development risks	Are there any show stoppers? Any high risks for application? Impacts engineering costs and testing requirements.
6.4	Plant availability.	Utilities want ≥ 94% availability
6.5	Proliferation resistance and material accountability	Gen-IV criteria and application to world markets
6.6	Reactor thermal hydraulic and nuclear design, design methods development	Design and operation impacts of core pressure drop, bypass flow, power distribution, fuel temperatures, etc.
6.7	Impact of reactor concept on other plant systems	e.g., core pressure drop and graphite dust affects
6.8	Fuel element design - stationary vs. flowing elements, fuel performance, oxidation resistance, etc.	Impact on plant operation, cost and availability
6.9	NRC design certification	NRC issues e.g.,confinement vs. containment may affect costs.
6.10	Life cycle and fuel disposal issues	High level waste volumes, container design and costs.
6.11	Reactor vessel, fabrication, fuel handling and other components	Vessel dimensions, material selection, Component fabrication, Brayton cycle layout, etc.
6.12	Safety performance and fission-product transport during accident conditions, plant maintenance and worker	Needs evaluation, possibly a discriminator
6.13	Flexibility of design to handle different fuel cycles.	Impact on fuel cycle cost and economics.
6.14	Plant operation and potential problems	Discriminator based on past reactor operation history?
6.15	NGNP 2016-2018 startup schedule impact on choice	This schedule should not force the selection

In evaluating these criteria, plant power level is a major consideration given that the economics of scale always drive designs to larger power outputs. On the other hand, Gen-IV inherent safety goals, coupled with reactivity control and peak fuel temperature concerns, put a limit on reactor size and power density, and thus power output.

Plant economics are clearly of primary importance to future users, and a careful comparison needs to be made between the two designs (commercial application schedule, interest rates, ground rules, etc.). Technology development risks are also a key consideration. There should be no “show stoppers” in the designs from a development standpoint, thus the probability for successful technology demonstration needs to be evaluated.

Plant availability is a potential discriminator because of the differences in refueling between the prismatic and pebble designs and the Utility/user desire to have the highest possible on-line availability. The refueling differences may also affect proliferation resistance and material accountability requirements, which will be important in future reactor designs, especially for international markets.

Reactor thermal/hydraulic and nuclear design differences may be discriminators when considering the impact of parameters such as core pressure drop; core bypass flow; dust formation, circulation, and deposition; core power distribution; fuel performance; and fuel temperatures. These design differences may also have an effect on other plant system designs and costs, for example, on a direct Brayton cycle or a high temperature heat exchanger.

Stationary fuel elements vs. flowing fuel elements may have different impacts on plant operation, cost, and availability, and need to be considered. The reactor designs can impact component materials and costs, for example, in the size and composition of the reactor vessel and in the design of the fuel handling equipment. These design choices can also be discriminators and need to be considered.

Given that both designs have inherent safety, the performance under accident conditions may not be a discriminator, but this needs to be evaluated.

NRC design certification may be an issue if licensing concerns require different design approaches (e.g., confinement vs. containment) and result in major impacts on plant costs. This issue needs to be evaluated.

The overall fuel life cycle and fuel disposal issues from a high level waste standpoint need to be considered to determine if the prismatic and pebble fuel have different cost impacts; for example, in the amount of high-level waste generated and in the design and certification of high-level waste containers.

Past performance and operation concerns of both designs should be evaluated along with design solutions to these problems to determine if there is any cost impact.

The order-of-magnitude increase in uranium ore prices over the last eight years and the growing world wide demand for nuclear power place an increased emphasis on the ability of the Gen-IV reactor types to accommodate different fuel cycles (e.g., Low Enriched Uranium, LEU/Th, Pu/Th, transuranics, etc.) so as to maximize the flexibility that the operating Utility/user has in minimizing fuel costs. Thus, the GT-MHR and PBMR-400 reactors need to be compared with respect to their flexibility to use different fuel cycles.

The INL NGNP Project schedule calls for startup of the NGNP in the 2016 - 2018 time frame, and this needs to be considered in any comparison, as do the technology development requirements and associated development schedule. However, these considerations should not drive selection of the reactor type for the NGNP. Rather, if the evaluation of the designs against the high-priority criteria shows a significant advantage of one design over the other, the results of the evaluation should drive NGNP design selection and, hence, the NGNP Project schedule.

6. COMPARISON OF DESIGNS

This section presents a comparison of the GT-MHR and the PBMR-400 against each of the 15 evaluation criteria listed in Table 5-1. Each subsection evaluates these designs against a specific criterion and provides a conclusion as to whether or not there is a significant difference between the designs with respect to the criterion.

6.1 Core Power Level and Plant Scalability

As discussed in Section 2.2, the PMR design initially selected for development by the U.S. HTGR Program had a power rating of 350 MW(t). The core had 68 fuel columns in an annular configuration with a central graphite reflector and was designed to meet a requirement that the reactor be inherently safety. The specific passive safety criterion that GA used was that fuel temperatures must not exceed damage limits under accident conditions, including loss of coolant flow and/or pressure, with a generous safety margin; in this case, a 400°C margin below the damage limit of 2000°C, or a maximum temperature of 1600°C. To provide further design margin, the reactor was designed to be placed underground and was sized to allow conduction to ground in the event of a loss of the passive heat sink.

The PMR has since gone through considerable design evolution. The motivation for this evolution has been to reach higher power levels, within the constraint of passive safety, and to achieve greater thermal energy conversion efficiency in order to improve the economics of the PMR relative to other options for electricity production. The reactor core diameter was first enlarged to increase the power level from 350 MW(t) to 450 MW(t). The power level was then increased to 550 MW(t) by moving the annular rings of fuel elements radially outward and reducing the width of the outer reflector to maintain the same core outer diameter. A further increase in the design power to 600 MW(t) was obtained by increasing the core power density of the 550 MW(t) design. These size and power increases were carefully selected to maintain the same inherent safety characteristics of the original 350 MW(t) design. Figure 6-1 shows an isometric view of the 350 MW(t), 450 MW(t), and 550/600 MW(t) designs. The core outer diameter that GA selected for the 450 MW(t) and 550/600 MW(t) designs was based on the results of a GA vendor survey that was performed to determine the largest diameter reactor vessel that could be fabricated using available commercial vessel manufacturing capability. Starting with the 450 MW(t) design, the steam generator was replaced with a gas turbine to obtain the higher efficiency available from a Brayton power conversion cycle. GA's 550/600 MW(t) PMR design is called the Gas Turbine – Modular Helium Reactor (GT-MHR).

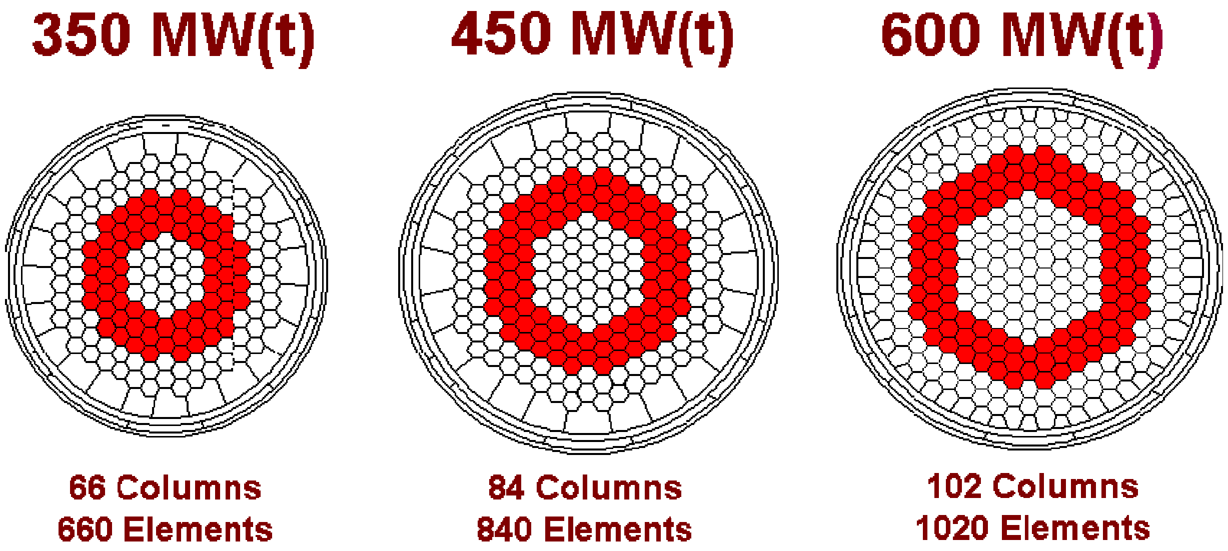


Figure 6-1. Evolution of the PMR core design

The annular core in these PMR designs is 10 fuel blocks, or 7.93 m, high. This height could be increased to increase total core power, while still meeting radial heat removal and reflector control requirements. However, a thermal spectrum reactor can be subject to xenon-induced power oscillations, which can become un-damped as a core dimension such as height is increased. For the GT-MHR, conservative calculations have shown that the 10-block high core is stable against these power oscillations, i.e. they are self-damped. This analysis also showed that the core height could be increased to at least 12 blocks while still meeting the self-damped power oscillation criteria [Ref. 36]. This would allow operation at up to 720 MW(t) with the core power density and annular core configuration of the 600 MW(t) GT-MHR. A 12-high block core would be 9.5 m tall, which is less than the 10.2 m effective core height of the PBMR-400 design, so core-height-related issues such as the design of control rods with a very long reach and increased core coolant pressure drop, which reduces net power production efficiency, should not be significant concerns for the GT-MHR at this height.

PBR designs have also been chosen to meet the inherent safety requirement. However, because PMR cores have considerably smaller void volumes than PBR cores (~20% vs. ~40%), the effective thermal conductance of a PBR core is lower than the effective thermal conductance of a PMR core during a depressurized core heat-up accident. Consequently, the core power density in PBRs must be lower to limit peak fuel temperatures during core conduction cooldown accidents. Thus, for equal core volumes, PBRs must have lower power ratings than PMRs. The heat transfer path could be shortened in a PBR core by increasing its core height and reducing the radius to compensate for the lower thermal conductance, but the penalty would be a higher core pressure drop during normal operation, which would reduce plant electricity generation efficiency. The initial PBR core designs were cylindrical and limited to 250MW(t). An annular core design similar to that of the PMR was adopted for the PBMR-400 and the core power rating was increased to 400MW(t). However, the core power density for the PBMR-400 is limited to 4.8 w/cc.

Because the core response to xenon-induced power oscillations is a function of the neutron spectrum, power density, and the temperature coefficient of reactivity, a PBR core will have a response to xenon power oscillations that is similar to a PMR core, but a PBR core can be somewhat taller due to the lower power density. However, other core-height-related considerations such as control rod reach and core pressure drop probably limit the PBMR-400 core height to about the current 10.2 m. The annular thickness of the pebble bed in a PBR is constrained by reflector-only control; which is necessary for PBRs because insertion of control rods into a pebble bed is difficult and could potentially damage pebbles, as was observed during operation of the German Thorium High Temperature Reactor (THTR) [Ref. 16]. However, the power rating of the PBMR-400 could potentially be increased by moving the annular pebble bed radially outward to increase its volume while maintaining its thickness, which would require an increase in the diameter of the reactor pressure vessel (RPV).

In summary, both PMRs and PBRs can be built over a range of power levels, but a passively safe PMR can operate at a higher power rating than a passively safe PBR. This is a major economic advantage for the PMR for most commercial applications.

6.2 Economics

An economic comparison of a 350 MW(t) PMR annular core and a 250 MW(t) PBR cylindrical core was performed as part of the 1986 design selection study discussed in Section 2.2, and is documented in the concept evaluation report [Ref. 7]. A 3-module PMR steam-cycle plant and a 4-module PBR steam-cycle plant were analyzed for consistency of total plant electricity output. The reactor designs were chosen such that both provided the same level of inherent safety. As discussed in Section 6.1, the selected PBR design had a lower power rating than the PMR design because of the inherently lower power density of the PBR core (3.8 W/cm^3 vs. 5.9 W/cm^3). The PBR design had a higher core outlet temperature than the PMR design, but also a higher core pressure drop (which requires use of more of the reactor's power output to circulate the coolant, thereby reducing plant efficiency).

The capital costs and the levelized cost of product in 1985 dollars for both plants are given in Table 6-1 and Table 6-2, respectively. These costs were developed using a consistent approach. The electricity generation busbar costs listed in Table 6-2 include plant capital costs, O&M costs, and fuel costs. A fuel disposal cost of 1.0 mills/kw(e)hr is included in the fuel cycle cost. The higher capital cost for the PBR plant is primarily a result of the larger number of units (4 vs. 3) needed to obtain the same power output as the PMR plant. Also, the PBR core design included control rods that moved in In-Core Control Structures (ICCS). The ICCS had to be replaced on a frequent basis due to neutron radiation damage, which had a significant negative impact on PBR plant availability. In fact, neither plant met the lifetime availability goal of ≥80%, although the PMR plant value was slightly higher. The fuel components of the busbar costs were essentially the same for both designs, 11.2 mills/kw(e)hr for the PMR and 11.0 mills/kw(e)hr for the PBR. The total busbar costs were about 11% lower for the PMR plant as compared to the PBR plant. As discussed in Section 2.2, the PMR design was selected as the reference design for further development by the U.S. HTGR Program.

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Table 6-1. Comparison of Capital Costs for PMR, PBR, and Coal Steam Cycle Systems

ITEM	**Plant Capital Costs (1985 Dollars), M$**		
	3x350 MWt PMR	**4x250MWt PBR**	**Coal Fired Plant**
Net electric Output, MWe	404 MWe	385 MWe	406 MWe
Direct Costs:			
Structures and Improvements	87	105	50
Reactor Plant Equipment	187	236	207
Turbine Plant Equipment	90	90	78
Electric Plant Equipment	39	42	31
Misc. Plant Equipment	13	14	9
Heat Rejection System	14	14	17
Subtotal	**430**	**501**	**392**
Indirect Costs:			
Construction Services	81	93	59
Home Office Engineering and Services	43	50	32
Field Office and Services	Inc.	Inc.	Inc.
Owner's Services	55	64	49
Subtotal	**179**	**207**	**140**
Total Direct and Indirect Costs	609	708	532
Contingency	100	120	53
AFUDC	30	42	32
Total Investment Cost	**739**	**870**	**617**
Unit Capital Cost, $/KWe	**1,829**	**2,260**	**1,520**

Table 6-2. Levelized Cost of Product for PMR, PBR, and Coal Steam Cycle Systems

ITEM		Levelized Cost of Product (1985 Dollars - Plant Startup 2005) M$		
		3x350 MWt PMR	4x250MWt PBR	Coal Fired Plant
Plant Operating Characteristics				
Thermal Rate	**MWt**	1,050	1,000	1,200
Electric Rate	**Mwe**	404	385	406
Capacity Factor	**%**	78	75	80
Plant Investment and Capital Charges				
Overnight Capital Investment	**M$**	709	828	585
Capital Investment with AFUDC	**M$**	739	870	617
Unit Capital Cost	**$/KW(e)**	1,829	2,260	1,520
Fuel Cycle Cost				
Fuel Fab	**mills/KW(e)hr**	2.7	3.9	
Uranium and Enrichment	**mills/KW(e)hr**	7.5	6.1	
NWPS Disposal	**mills/KW(e)hr**	1.0	1.0	
Total	**mills/KW(e)hr**	**11.2**	**11.0**	
Busbar Cost of Product				
Plant	**mills/KW(e)hr**	24	30	20
O&M	**mills/KW(e)hr**	13	13	7
Fuel	**mills/KW(e)hr**	11	11	30
Total	**mills/KW(e)hr**	**48**	**54**	**57**

Both the PMR and PBR designs have been improved considerably since the 1986 evaluation was performed. The current PMR and PBR designs being compared herein have higher core power densities and power ratings, and greater efficiencies as a result of the use of a Brayton power conversion cycle in place of the steam-cycle used in the earlier designs. A rigorous comparison of the new PMR and PBR designs similar to the 1986 evaluation is beyond the scope of the current study, but an economic comparison has been performed based on data available in the literature. The GT-MHR data for this comparison was obtained from a commercialization study for an nth-of-a-kind (NOAK) unit consisting of four 600 MW(t) modules (1,145 MWe) [Ref. 24]. Table 6-3 gives the levelized capital cost, annual operation and maintenance (O&M) cost, levelized fuel cost, and decommissioning cost in terms of mills/kw(e)hr in 1992 dollars.

Table 6-3. Summary of Estimated Busbar Costs (1992 dollars)

BUSBAR COSTS - mills/kwhr(e)	GT-MHR Estimate		PBMR-400 Design Estimate	
	Value	% of Busbar	Value	% of Busbar
Capital	19	57.6%	26	65.5%
O&M	4.1	12.4%	4.1	10.3%
Fuel	9.3	28.2%	9	22.7%
Decommissioning	0.6	1.8%	0.6	1.5%
Total Busbar Generation Cost	**33**	100.0%	**40**	100.0%

Based on the GT-MHR busbar cost data in Table 6-3, estimates were made for the corresponding busbar cost components for the PBMR-400 and are also included in Table 6-3. For the capital cost component, the scaling rule for large process systems such as chemical plants and nuclear plants was used. This rule states that the capital cost per unit of output increases with the size of the unit as the ratio of the overall outputs to the 0.6 power {i.e., [MWe(larger unit)/MWe(smaller unit)]$^{0.6}$}[Ref. 30]. Based on this rule, the capital cost of the 600 MW(t) GT-MHR would be 27.5 % higher than the capital cost of a PBMR-400. However, each GT-MHR module produces 50% more thermal power, thus for the same thermal power the GT-MHR capital cost would be about 85% of the PBMR-400 capital cost. This advantage is further enhanced by the higher thermal efficiency of the GT-MHR (47.7%) compared to the PBMR-400 (41.2%). When the greater efficiency of the GT-MHR is also accounted for, the capital cost component of the GT-MHR busbar cost [19 mills/kw(e)hr] should be only about 73% of the capital cost component of the PBMR-400 busbar cost, so this gives 26 mills/kw(e)hr as the estimated capital cost component of the PBMR-400 busbar cost.

From a MWe standpoint, the 4-unit 600 MW(t) GT-MHR plant is equivalent to a 7-unit PBMR-400 plant. For the current comparison, the O&M costs for both plants are assumed to be the same, [4.1 mills/kw(e)hr], although it is likely that the O&M cost for the PBR plant would be somewhat higher because of the larger number of reactor modules. The decommissioning components of the busbar costs were also assumed to be the same for both plants.

The fuel component of the GT-MHR busbar cost was estimated to be 9.3 mills/kW(e)hr in the GT-MHR commercialization study. This estimate is somewhat lower than the estimate of 10.2 mills/kW(e) from the 1986 evaluation of a 350 MW(t) steam-cycle plant. It is reasonable that the estimate from the GT-MHR commercialization study is lower given the increased efficiency of the GT-MHR relative to the earlier steam-cycle plant. The fuel cost for the PBMR-400 would be expected to be somewhat lower than the fuel cost estimated for the earlier 250 MW(t) PBR design for the same reason. Thus, the fuel component of the PBMR-400 busbar cost is estimated to be about 9 mills/kw(e)hr by assuming the same ratio between PBR and PMR fuel costs as in the 1986 evaluation. However, it should be noted that the combined fuel and O&M busbar cost for the PBMR-400 is given in Ref. 34 as 9 mills/kw(e)hr. If the O&M costs for the GT-MHR and PBR-400 are assumed to be about the same, the fuel component of the busbar cost for the PBMR-400 is only 4.9 mills/kw(e)hr. The authors do not know the basis for this cost, but do not believe it is credible that the PBMR-400 fuel cost could be nearly a factor of two lower than the GT-MHR fuel cost.

The overall result of the comparison as shown in Table 6-3 is that the estimated electricity generation busbar cost is about 18% lower for the GT-MHR relative to the PBMR-400. Given the uncertainties in these estimates (including the uncertainty associated with the PBMR-400 combined O&M and fuel cost from Ref. 34), the GT-MHR is concluded to have a 10% to 20% cost advantage over the PBMR-400.

Process heat applications, including hydrogen production, are considered very important for the VHTR. Two advanced high-efficiency hydrogen production technologies under development are high temperature electrolysis (HTE), and thermo-chemical water splitting using the sulfur iodine (SI) process. HTE and SI production of hydrogen require both electricity and very-high-temperature process heat. A VHTR based on the GT-MHR design (with the core outlet coolant temperature increased from 850ºC to 950ºC) should have an economic advantage over a VHTR based on the PBMR-400 design (with the core outlet coolant temperature increased from 900ºC to 950ºC) for these hydrogen production applications due to its higher thermal energy output and greater efficiency. This advantage would also apply to the use of a VHTR for coal liquefaction or gasification because these plants can be designed to handle thousands of tons of coal per day. The same conclusion applies to other applications such as steel or aluminum production.

The advantage of a prismatic block VHTR is not as clear for oil extraction applications, such as from tar sands, oil shale, or old non-producing oil wells because the steam temperature and pressure requirements are fairly low for these applications and could be supplied by other nuclear options such as small LWRs. However, use of a VHTR as the process heat source would provide for highly-efficient production of the hydrogen needed for initial refining of the heavy oil product, with process steam supplied by a bottoming cycle. Again, economy of scale for hydrogen production would give the PMR an advantage over a PBR for this application.

In summary, the inherently higher operating power level and efficiency of PMRs relative to PBRs equates to an estimated electricity generation busbar cost for a GT-MHR plant that is

10% to 20% lower than for a PBMR-400 plant having the same electrical power output. This significant economic advantage in electricity generation cost translates to an approximately equivalent advantage for the PMR in process heat or electricity/process heat cogeneration applications given that a cost measure of the thermal energy utilized as process heat is the value of the electricity that could have been produced had the thermal energy been used for electricity production.

6.3 Technology Development Risks

The technology development needs for both reactor types and the development risks must be compared to assess their potential impact on the costs and construction schedule for a commercial VHTR. For the NGNP, the lowest risk technology development necessary for demonstration of economic commercial operation is desired.

The reference fuel particle for the PBMR-400 is TRISO-coated UO_2 and the reference fuel particle for the GT-MHR is TRISO-coated UCO. As discussed in Section 6.8, UCO was selected as the reference fuel for the GT-MHR because it allows the fuel to be irradiated to higher burnup (% FIMA), which permits longer refueling cycles. However, while there is an extensive irradiation and safety testing data base for German-fabricated TRISO-coated UO_2 fuel that qualifies UO_2 fuel for the PBMR-400 fuel service conditions envelope, there is relatively little irradiation performance and safety testing data for high-quality UCO fuel. Thus, there is some technical risk associated with qualification of UCO for GT-MHR service conditions even though the case for UCO fuel is theoretically compelling. It should also be noted that regardless of the qualification status of the fuel form, the acceptable performance of either LEU TRISO-coated UO_2 or TRISO-coated UCO commercially fabricated fuel will have to be satisfactorily demonstrated under expected commercial plant operating conditions in order to obtain an operating license from the NRC.

Development of nuclear grade graphite is required for both reactor types. For PMRs, the graphite needs to be qualified for use as fuel blocks, and impurity levels must be minimized to reduce parasitic neutron absorption and minimize the potential for chemical attack by impurities on fuel particle coatings. For PBRs, the design lifetime for the central and outer reflector graphite is a key issue with respect to reactor availability. Nuclear grade graphite undergoes fast-neutron irradiation damage that results in dimensional changes that are a function of the type of graphite, the fast-neutron fluence, and irradiation temperature. In the radial direction, the graphite initially shrinks with increasing fast neutron fluence and then expands with further irradiation. The graphite will eventually undergo a net expansion if the fast neutron fluence is sufficiently high. Such graphite behavior could lead to expansion and lockup of the blocks comprising the PBMR-400 central and outer reflectors such that that the blocks cannot easily be removed [Ref. 13].

The PBMR-400 design calls for reflector replacement, which is a 6-month operation, once every 20 years. Analysis indicates [Ref. 32] that the PBMR-400 central reflector could see a neutron fluence of about 1.5 x 10^{21} n/cm^2 (E>0.18MeV) every year at an operating temperature of about 500^{o}C. Over 20 years, the central reflector graphite would experience a fast neutron fluence of about 3 x 10^{22} n/cm^2. The outer reflector is estimated to see a fast neutron fluence of about 1.2 x 10^{21} n/cm^2 every year at the same operating temperature, or about 2.4 x 10^{22} n/cm^2 over 20 years. Any graphite selected for the reflectors will require extensive irradiation testing to determine if it can meet such stringent performance requirements. Demonstration of graphite behavior to these fluence levels requires long irradiations and represents a significant technology risk. More frequent reflector replacement, should it be necessary, would have a significant effect on PBR plant availability.

The fuel blocks in the GT-MHR are not subject to this potential problem because of their relatively short irradiation time, but the design lifetime of graphite reflector blocks is longer, thus they will be exposed to higher fast neutron fluence. It is planned to replace the graphite reflector blocks adjacent to the core in the GT-MHR on a staggered schedule during a normal core refueling outage, which takes less than 30 days. The maximum service lifetime for the GT-MHR reflector blocks is limited to 8 years such that they are removed from the reactor before the turnaround point in the dimensional change vs. fast neutron fluence curve is reached. In 8 years of irradiation, the reflector graphite should see a fast neutron fluence of only about 5.5 x 10^{21} n/cm^2 (E > 0.18 MeV)[3] [Ref. 32]. If necessary, the graphite reflector blocks could be replaced on a shorter schedule in the GT-MHR without affecting plant availability, but this is not anticipated based on their relatively low fast neutron exposure.

The GT-MHR is designed for an 850ºC reactor coolant outlet temperature, while the PBMR-400 design calls for a 900ºC coolant outlet temperature. For operation at 900^{o}C coolant outlet temperature and above, the GT-MHR may require additional design work to reduce coolant bypass flow and improve fuel zoning to reduce peak fuel temperatures. A prismatic NGNP plant would serve to demonstrate this high temperature operational capability.

In summary, both reactor types have some technology development risks. Qualification of UCO fuel is an issue for the GT-MHR, while qualification of reflector graphite capable of withstanding

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[3] Fast neutron flux levels at the GT-MHR reflectors are somewhat lower than in the PBMR-400 because the core neutron flux spectrum in the GT-MHR is more thermalized due to its higher graphite content.

very high fast neutron fluence is an issue for the PBMR-400. However, qualification of UCO fuel is considered to be more a schedule and cost issue than a technical issue, and is not considered to be a significant risk for a commercial prismatic block VHTR because it is expected that UCO fuel will have been qualified in time for use in the first commercial prismatic block VHTR[4]. On the other hand, it is not at all certain that graphite can be qualified to the very high fast neutron fluence corresponding to a 20-year design lifetime for the PBMR-400 reflectors. This is a considerable risk for the PBMR-400 because more frequent reflector replacement would have a significant impact on plant availability. Overall, the technical risk criterion is judged to moderately favor the PMR over the PBR, but the risks are difficult to assess at this time.

6.4 Plant Availability

GA's Utility Advisory Board has advised GA that the member Utilities want a high plant capacity factor (≥94% breaker-to-breaker), at least 18 months between refueling outages, and a refueling outage period of ≤ 30 days for the GT-MHR [Ref. 1]. The GT-MHR shuts down on a regular basis for refueling and has been evaluated to have an overall plant capacity factor of 87% [Ref. 4] based on an 18-month refueling cycle, with the potential to achieve a capacity factor of >90% with experience gained during operation. The design 87% capacity factor is based on an estimated 6% downtime for scheduled maintenance and refueling and an estimated 7% downtime for unscheduled maintenance. The 87% capacity factor therefore corresponds to a 92% to 93% breaker-to-breaker capacity factor. For an overall capacity factor of 90% and with the same allowance for scheduled maintenance and refueling, the breaker-to-breaker capacity factor would increase to about 95%. Based on refueling experience in the Fort St. Vrain reactor, refueling times of less than 30 days for the GT-MHR appear to be feasible.

The PBMR-400 design assumes that the reactor runs continuously for six years followed by a one month shutdown for general equipment inspection and replacement [Ref. 34]. In addition, the inner reflectors are assumed to be replaced once every 20 years, which is a 6-month operation. The outer reflector immediately adjacent to the core may also have to be replaced at that time. These scheduled maintenance and reflector replacement outages equate to a plant availability[5] of about 97% with no allowance for unscheduled shutdowns. The stated availability of the PBMR-400 is ≥95% [Ref. 34], but it is not known what allowance this includes for unscheduled maintenance. If the same allowance for unscheduled maintenance downtime is

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[4] UCO fuel is currently being developed and qualified for anticipated prismatic block VHTR service conditions by the DOE sponsored Advanced Gas Reactor Fuel and Qualification Program.

[5] Capacity factor = availability x power level, so capacity factor is equal to availability if the reactor is operated continuously at 100% power.

made for the PBMR-400 as for the GT-MHR (7%), then the overall plant availability for the PBMR-400 would be about 90%.

For the PBMR-400, the design service lifetime for the reflector graphite is an issue because it determines the frequency with which these reflectors need to be replaced. If the graphite reflector blocks in the PBMR-400 have to be replaced more frequently than every 20 years, the availability advantage that the PBMR-400 has over the GT-MHR would be reduced, and this advantage would disappear completely if the graphite reflector blocks have to be replaced every eight years, which is the reflector block design replacement frequency for the GT-MHR. In this context, it is interesting to note that the Chinese HTGR demonstration plant, the HTR-PM, which is a PBR design, initially had a 450 MW(t) annular core. This design has since been replaced with two 250 MW(t) cylindrical cores because of concerns about the central reflector and operation of the annular pebble bed design [Ref. 17].

Fuel handling system performance is another uncertainty that could adversely impact PBMR-400 availability. This fuel handling system is shown in Figure 6-2. Given the complexity of this system, it could be a source of frequent unscheduled outages as well as a source of pipe leaks or breaks, blockages, and worker exposure to radiation (during maintenance of the system).

In summary, The PBR may have a small advantage over the PMR with respect to availability, but only if the lifetime of the graphite reflectors in the PBR is very long (i.e. of the order of 20 years). A significantly shorter reflector lifetime and/or unreliable operation of equipment such as the on-line fuel handling system in the PBR would partially or completely eliminate this advantage.

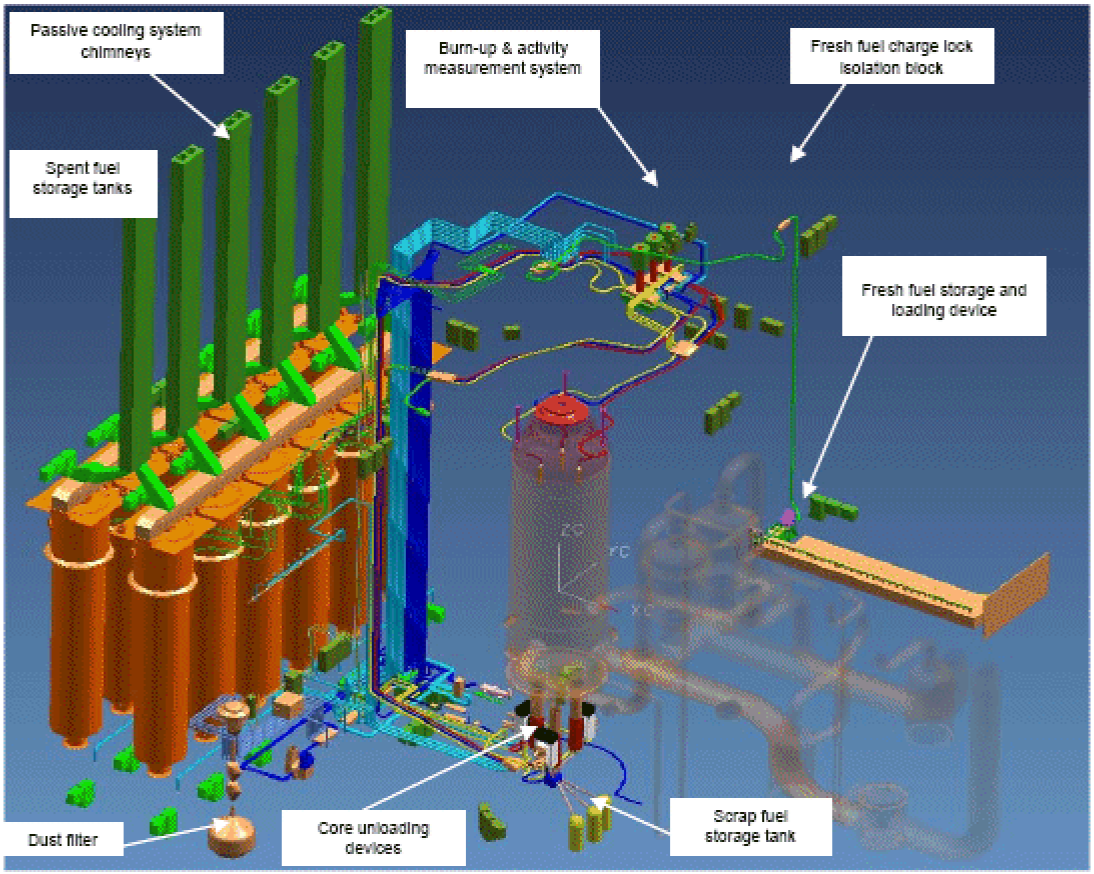

Figure 6-2. PBMR-400 fuel handling and storage system [Ref. 34]

6.5 Proliferation Resistance and Material Accountability

For the GT-MHR, the Fuel Handling System is the only system needed to manipulate and account for fuel material. All the refueling functions performed by this system are normally performed under remote automatic control, although manual intervention is allowed at all times. Regardless of how it is controlled, system computers monitor and electronically log every motion and control action to keep track of all fuel and reflector element transfers. The large fuel elements make tracking and accountability relatively straightforward. Each prismatic fuel element will carry a unique identification number engraved on the block that is easily readable by the fuel handling equipment. A similar system was used successfully for the FSV fuel blocks. Thus the block movements are easily accounted for, which simplifies licensing and safeguard procedures.

The key proliferation-resistant attributes of the GT-MHR are:

- The capability to use proliferation resistant fuel cycles such as low enriched uranium (LEU) fuel, $\leq$19.9% enriched in U-235, or LEU-thorium fuel
- The highly dilute fuel form of TRISO (ceramic) coated particles in large graphite blocks (less than 3 grams of Pu-239 in a discharge block)
- Off-line refueling
- The very high burnup capability of the TRISO fuel (>120,000 MWD/T), which results in unfavorable isotopics in the plutonium at discharge, with very low concentrations of fissile nuclides, which means that a large number of fuel blocks would have to be diverted to provide a significant quantity of weapons-useful material
- The radiation barrier provided by the discharged fuel elements

The proliferation resistance of the GT-MHR was evaluated by the NERAC TOPS[6] task force using their formal “barrier framework” methodology. It was concluded that the GT-MHR is highly proliferation-resistant.

For the PBMR-400 design, there are three separate systems involved in manipulating, and therefore accounting for, the fuel. These include a Fuel Handling and Storage System, a Fuel Circulation System, and a Fuel Burn-up Measurement System. Successful operation of the PBMR-400 design relies on the capability of these three fuel systems to run continuously while the reactor is on-line, although the Fuel Handling and Storage System can be out of service for several days without affecting the reactor availability. More systems imply that more components are necessary to manipulate the fuel, making accountability more complex, and increasing licensing and safeguards concerns. An example of this complexity is the six separate entry and exit points (three at each end), along with their associated separate bins, entry chutes, and unloading devices (see Figure 6-2 above). Pebble flow is difficult to trace and it may be difficult to provide the NRC with adequate assurance of material accountability for the PBR case. Also, there is a higher risk of personnel radiation exposure from refueling operations in the PBR than in the GT-MHR because the refueling system must be continuously maintained.

However, the pebble bed core has many of the same proliferation-resistant attributes of the prismatic core, including the use of proliferation-resistant fuel cycles, the same highly dilute TRISO fuel particles, and high burnup with low concentrations of useful fissile nuclides. There is only about 0.045 grams of Pu-239 in a discharged pebble, even after a single pass, so a very large number of pebbles would have to be diverted to recover useful amounts of weapons material. It is interesting to note that on-line refueling has been the method most commonly

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[6] NERAC Task Force on Technology Opportunities for Increasing the Proliferation Resistance of Global Civilian Nuclear Power Systems

used for weapons Pu production. India used the on-line refueling feature of the CANDU design to make WPu.

In summary, both reactor types have low proliferation and diversion risk, but the PBR has less simplicity and greater uncertainty with respect to fuel accountability, and provides a relatively easier diversion path for nuclear material. These safeguards issues could potentially result in a somewhat more difficult licensing case for the PBR relative to the PMR. However, the proliferation-resistance and material accountability criterion is not considered to be a significant discriminator between the two reactor types provided that adequate material accountability and control procedures are defined and carefully followed during plant operation.

6.6 Reactor Thermal/Hydraulic and Nuclear Design

For a given vessel diameter and fuel temperature limit, a PMR can have a higher core power density – hence a higher thermal power rating - than a PBR core because of its lower core void fraction, which gives the PMR core a higher effective thermal conductance (see Section 6.1). The GT-MHR utilizes UCO fuel as opposed to UO_2 fuel, which is used in the PBMR-400 design. The UCO fuel permits higher burnup and allows for a larger temperature gradient through the fuel. PBR cores have inherently higher core coolant pressure drops than PMR cores as a result of flow around the pebbles. A lower core pressure drop results in better electric power production efficiency for the GT-MHR. Nuclear design of PMR cores is very flexible because a single fuel element can contain a variable amount of fuel and fixed burnable poison (FBP) or fuel having different uranium enrichments, which provides many zoning (axial and radial) options. The extent to which PBR cores can be effectively zoned is more limited. Potentially, pebbles with different fuel loadings could be preferentially located within the core by selective use of the various loading chutes.

PBR cores have a lower TRISO particle packing fraction and an increased overall heat exchange surface area compared to PMR cores. Also, power peaking in PBR cores occurs at the top of the core where the cold helium enters. This results in lower nominal fuel temperatures in the PBMR-400 (relative to the GT-MHR) during normal reactor operation, even with the PBMR-400 operating with a higher coolant outlet temperature than the GT-MHR (i.e., 900°C in the PBMR-400 [Ref. 32] vs. 850°C in the GT-MHR). However, peak fuel temperatures in the AVR were much higher than predicted based on melt-wire temperature measurements in unfueled graphite pebbles that revealed coolant temperatures as high as 1280ºC [Ref. 25]. Also, all fuel pebbles, including high-burnup pebbles, will be exposed to high core exit coolant temperatures, and flow tests [Ref. 40] show wide variations (i.e., up to a factor of two) in the pebble transit time through the core.

Peak fuel temperatures are also a concern in PMR cores. This is a particular concern for a prismatic block VHTR operating with a core outlet coolant temperature of 950ºC (vs. 850ºC for the GT-MHR). However, recent studies have shown that it should be possible to further optimize the PMR core design to reduce power peaking factors, bypass flows, and boundary-layer temperature gradients, all of which would contribute to reducing peak fuel temperatures and potentially improving overall fuel performance [Ref. 42]. A combination of these design improvements should allow core coolant outlet temperatures to be increased above 900°C in PMRs without exceeding the maximum time-averaged temperature design guideline of 1250°C.

PBR cores require less excess reactivity due to on-line refueling, which lowers the required hot-to-cold shutdown margin and reduces potential reactivity transients. Control rods and RSS channels are provided in both the central and outer reflectors of the PBMR-400. However, the GT-MHR has more reactivity control options and can provide sufficient negative reactivity during all modes of operations to meet cold shutdown requirements, with stuck rod and calculation uncertainties included. Reactivity control is available from in-core control rods and reserve shutdown control (RSC) channels, as well as control rods in the outer reflector.

In summary, the inherently lower core power density and better pebble-to-coolant heat transfer in a PBR should result in lower fuel temperatures (than in a PMR) during normal operation, which could translate to better fuel performance in PBRs than in PMRs. However, coolant and fuel temperatures in the AVR were much higher than predicted. The reasons for these higher-than-expected temperatures are not well understood, but they were likely related to power peaking and thermal/hydraulic irregularities at core – reflector boundaries or adjacent to the graphite “noses” in the AVR core; effects that could be enhanced in a PBR annular core. Consequently, it is not entirely clear that PBRs will have lower peak fuel temperatures and potentially better fuel performance than PMRs. With respect to the nuclear design criterion, PBRs require less excess reactivity, which is often cited as an advantage for PBRs over PMRs. However, the authors believe that the flexibility provided by the available design options for PMR cores actually represents an advantage for the PMR.

6.7 Impact of Reactor Concept on Other Plant Systems

As high temperature heat sources, both the GT-MHR and PBMR-400 designs are ideally suited to support multiple commercial applications, in particular the generation of electricity and hydrogen at high efficiencies (up to 50%). Other applications include the generation of high temperature process steam to replace coal, oil, and natural gas in petrochemical plants, refineries, steel mills, etc. These applications all require different plant systems attached to the reactor system; for example, a direct Brayton cycle for high efficiency electricity generation, a high temperature intermediate heat exchanger (IHX) for use with a hydrogen production plant, etc. Therefore, a natural question is whether the reactor type affects the design or performance of these different systems and components.

One major issue is the dust inventory in the primary coolant loop. Because of the constant motion of the graphite pebbles through the core and handling of pebbles by the on-line refueling system, significantly more graphite dust will be produced in the PBMR-400 than in the GT-MHR. This assumption is consistent with dust measurements at AVR [Ref. 31] and FSV [Ref. 33]. It is estimated that about 100 kg of dust, mainly small particles < 1μm in diameter, was produced during the operation of AVR [Ref. 31]. This dust was highly radioactive, mainly from Cs-137, Cs-134, Sr-90, Sr-89, and Ag-110m. (The Sr-90 activity, for example, ranged between 19 and 363 GBq/kg). Based on measurements in the AVR and THTR, the PBMR-400 will produce an estimated 2,000 kg of dust over the life of the reactor. About 210 kg of this dust will not be retained by the filters of the fuel handling system, and will be present in the primary coolant loop [Ref. 33]. Similar estimates are not available for the GT-MHR, but the amount of dust in the primary coolant loop should be orders of magnitude lower based on FSV experience. The FSV primary loop contained extremely little circulating particulate matter, and the small quantities of dust in FSV contained less than 10% carbon, being primarily metal-oxide rather than carbonaceous aerosols [Ref. 33]. Indeed, the circulators in the FSV primary loop were removed for maintenance and were easily decontaminated for hands-on work.

The dust in the primary coolant loop of a PBR may have an adverse effect on certain plant components. One effect is the potential for the dust to accumulate in the IHX, particularly in advanced printed circuit heat exchanger designs having small flow paths. The dust could have a similar adverse effect on the recuperator in a direct-cycle power conversion system (PCS). The potential for plugging of the heat exchangers due to agglomeration of the graphite dust, especially at directional changes in flow paths, needs to be assessed. Indeed, the potential for significant plugging could preclude the use of printed circuit heat exchangers in PBRs, which would be a significant disadvantage, or could require design changes such as the use of larger IHX units, which would increase costs. The potential for dust-related damage to the seals and turbine blades in a direct-cycle PCS must also be considered.

In summary, graphite dust production and circulation in the primary coolant loop could have a significant design and cost impact on other plant systems. The quantity of dust circulating in the primary coolant loop will be much higher in PBRs than in PMRs. This is a very significant issue for PBRs. Consequently, this criterion is a significant discriminator between the two reactor types.

6.8 Fuel Design

The use of prismatic block fuel elements versus fuel pebbles is the most distinguishing characteristic between the PMR and PBR designs. A summary of the fuel element designs is given in Table 4-2 and the designs of the TRISO fuel particles used in both designs is provided in Table 4-4. This basic difference between PMRs and PBRs is responsible for substantial differences with respect to thermal power rating, plant economics, core thermal/hydraulic performance, and other evaluation criteria that are discussed elsewhere in this report; consequently, the discussion below is limited graphite oxidation resistance and fuel type (i.e., UO_2 vs. UCO) to avoid redundancy.

The nuclear-grade graphite fuel blocks used in the GT-MHR have significantly higher oxidation resistance than the less graphitized matrix material of the PBMR-400 pebbles. Under water or air ingress accident conditions, the pebble matrix would be more reactive than the fuel block graphite. However, if the accident scenarios are realistically assessed, the accident condition performance of the fuel elements would probably not be a discriminator between the two designs [Ref. 37].

The reference fuel particle for the PBMR-400 is TRISO-coated UO_2 and the reference fuel particle for the GT-MHR is TRISO-coated UCO. UO_2 fuel is subject to various failure mechanisms as a result of CO buildup within the coated particle at high fuel burnup. High CO pressure can potentially result in failure of the SiC coating layer (i.e., pressure vessel failure) or can cause the UO_2 kernel to migrate through the coating layers in fuel particles exposed to a large thermal gradient (i.e., the amoeba effect). In UCO fuel, the addition of carbon as carbide phases in the UCO kernel precludes CO pressure buildup within the fuel particles, thereby minimizing the potential for the CO-related fuel particle failure mechanisms. UCO was selected as the reference fuel for the GT-MHR because the design fuel burnup and the fuel temperatures and thermal gradients are well outside the qualified performance envelop for UO_2 fuel.

The PBMR-400 can use UO_2 fuel because the design fuel burnup is limited to 9.6% FIMA and the design fuel temperatures and thermal gradients are lower than in the GT-MHR. However, the PBMR-400 could also use UCO fuel, and by doing so should benefit from a somewhat lower fuel cost because the cost of manufacturing UCO and UO_2 fuel are about the same and higher fuel burnup can be obtained with UCO fuel relative to UO_2 fuel. Similarly, the GT-MHR could also use UO_2 fuel, but the economic penalty associated with use of UO_2 fuel would be greater for the GT-MHR than for the PBMR-400 because this would necessitate a shorter refueling cycle, thereby reducing reactor availability. Also, it is not clear that a GT-MHR loaded with UO_2 fuel could operate for an extended period of time with a core outlet coolant temperature of

950°C because of the potential for kernel migration in UO_2 fuel exposed to high thermal gradients.

In summary, the authors consider PBRs to have a modest advantage over PMRs with respect to the fuel design criterion because of the capability of PBRs to better utilize UO_2 fuel, which is currently more qualified by irradiation and safety testing than is UCO. As discussed in Section 6.3, UCO is considered to represent somewhat of a risk for the GT-MHR, although this risk is considered minor.

6.9 NRC Licensing and Design Certification

Both the GT-MHR and PBMR-400 designs will have to meet the requirements and standards that the NRC is currently developing for the licensing of new generation, non-LWR reactors. The NRC's design certification rules in 10 CFR 52 make general provision for certifying an advanced reactor design "which differs significantly" from currently operating light water reactors ("LWRs") or "utilizes simplified, inherent, passive, or other innovative means to accomplish its safety functions". For the design of such a reactor to be certified, the applicant must show that:

- "Interdependent effects among the safety features of the design have been found acceptable through either analysis, appropriate test programs, experience, or a combination thereof"
- "Sufficient data exist on the safety features of the design to assess the analytical tools used for safety analyses over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions"
- "The scope of the design is complete except for site-specific elements such as the service water intake structure and the ultimate heat sink."

Alternatively, an advanced reactor design can be based on "acceptable testing of an appropriately sited, full-size, prototype of the design over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences including equilibrium core conditions." 10 C.F.R. § 52.47(b)(2)(i)(B).

GA has previously obtained NRC licenses for both the Peach Bottom unit one and Fort St. Vrain HTGRs. FSV used TRISO coated fuel, but was licensed under older ground rules, including a deterministic approach to accident evaluations. Peach Bottom had full containment, but FSV was licensed with a Pre-Stressed Concrete Reactor Vessel (PCRV) as opposed to a pressure-retaining containment building. In the mid 1980s, General Atomics, with support from other vendors, architect engineers, national laboratories, and utilities under DOE funding, developed the conceptual design of a steam-cycle MHR. Several years of pre-application interactions with the NRC culminated in the submittal of licensing approach and assessment documents, including a "pre-application SAR" and a probabilistic risk assessment (PRA) [Ref. 19].

In 2001, GA initiated a pre-application process with the NRC on the licensing of the GT-MHR. A licensing plan was developed [Ref. 19] and presentations were made to the NRC on the MHR fuel design and performance; however, this process is currently on hold pending further development of the MHR program. A licensing plan for the GT-MHR in Russia is also being prepared.

Pebble Bed Modular Reactor (Pty) Ltd intends both to seek a license from South Africa's National Nuclear Regulator (under the National Nuclear Regulator Act of 1999) for a single module PBMR demonstration plant capable of generating 165 MWe and to pursue design certification for the PBMR from the U.S. NRC. It has initiated pre-application review activities with the NRC and plans to file a design certification application with the NRC in early 2008 [Ref. 20]. The pre-application review process has identified a preliminary set of issues that would need to be addressed and resolved before the granting of a design certification for the PBMR design. Pebble Bed Modular Reactor (Pty) Ltd is in the process of submitting four white papers to the NRC covering various technical and licensing issues associated with licensing their PBMR-400 design. These papers are "Licensing Basis Event Selection," "System Structure and Component Classification," "Defense in Depth," and "Probabilistic Risk Assessment Approach".

In a presentation to the 2004 International Congress on Advances in Nuclear Power Plants, the NRC identified a number of challenges specific to its technical review of a modular high temperature gas reactor, such as the PBMR-400 and GT-MHR [Ref. 18]. These challenges include:

- New licensing basis approach
- Different materials; higher temperatures
- Passive safety systems and structures
- Fuel performance role in the safety case
- Use of a mechanistic source term
- Non-conventional containment design
- Limited operational or PRA experience
- Foreign codes and standards
- Limited NRC analytical tools, data, and expertise

Of these, the new licensing basis approach, different materials and higher temperatures, and passive safety systems are issues that are similar for both designs and unlikely to differentiate them from a licensing standpoint.

Fuel performance, especially in the safety case, is an important issue. The reference fuel particle for the PBMR-400 is TRISO-coated UO_2 and the reference fuel particle for the GT-MHR is TRISO-coated UCO. As discussed in Section 6.8, UCO was selected as the reference fuel for the GT-MHR because it allows the fuel to be irradiated to higher burnup (% FIMA), which permits longer refueling cycles. This is because UCO is not subject to certain CO-related fuel failure mechanisms that could degrade UO_2 fuel performance at fuel burnup greater than about 10% FIMA. Although the service conditions envelop for the PBMR-400 is designed to preclude them, these UO_2 failure mechanisms could potentially be a licensing issue for the PBMR-400. Some of the uncertainties with respect to fuel temperatures and the thermal/hydraulics in PBR cores discussed in Section 6.6 and the implications of these uncertainties on fuel performance might also be of concern to the NRC and complicate PBMR licensing and design certification.

The use of a mechanistic source term for accident evaluations may pose different issues for the GT-MHR and PBMR-400 designs. For the GT-MHR, the fuel is fixed and its prior irradiation history can be well characterized. However, the PBMR-400 core consists of fueled pebbles with widely different burnup histories and exposures that are relatively randomly distributed throughout the core. This may lead to a different licensing approach in this area for the PBMR-400 design.

Fuel movement in the core is also an area where the two designs differ from a licensing standpoint. The GT-MHR uses a refueling system similar to that licensed and used successfully in FSV. The PBMR-400 design uses an on-line refueling system for which there is limited operational performance data and limited expertise available to the NRC. Diversion and proliferation issues may become important in licensing considerations in this area for the PBMR-400 design because, in general, cores that are refueled on-line are more reliant on administrative controls for resistance to proliferation. The additional systems and components required to measure the discharged spent fuel from the core with respect to burnup, to store or recycle the discharged pebbles, and to add new pebbles to the core are unique to the PBMR-400 design and will all require additional licensing review and approval by the NRC.

The codes used for PMR nuclear analysis have been verified and validated for design use in the U.S. although they will probably be subject to re-review in any future NRC licensing process. The PBR codes have been used for design studies in Germany, South Africa and China, but will have to be validated for use in any U.S. reactor design. This may be an additional delay in the PBR licensing process.

With a 950°C core outlet temperature, issues related to high temperature materials under high pressure are common for both gas reactor designs. Qualified vessel materials do, however, exist for the estimated vessel operating conditions, although without a conceptual design it is not known whether those materials can satisfy all of the system requirements. There is currently a prototype reactor vessel, the HTTR in Japan, constructed from applicable qualified materials and operating at representative conditions.

In summary, the design certification process for the PBR under the new NRC ground rules for licensing of next generation, non-LWR reactors is currently ahead of that for the PMR. However, licensing and design certification of the PBMR-400 design could be complicated by a number of issues including the limited operational performance data for the on-line refueling system, the NRC's unfamiliarity with the on-line refueling approach, and the uncertainties with respect to the thermal/hydraulic performance of PBR cores and the impact of these uncertainties on predicted fuel performance. These issues could potentially result in a more difficult licensing and design certification process for the PBMR-400 than for the GT-MHR. On the other hand, the capability of PBRs to use UO_2 fuel, which has a more extensive irradiation and safety testing data base than UCO fuel, could potentially make licensing a pebble bed NGNP somewhat less difficult than licensing a prismatic block NGNP. However, this advantage would not extend to a follow-on commercial pebble bed VHTR because, as discussed in Section 6.3, it is expected that UCO fuel will have been qualified and be available for use by the time a commercial VHTR is built. Furthermore, GA proposes to use UO_2 fuel for the initial core fuel load for a prismatic block NGNP, which would mitigate any NGNP schedule risk associated with qualification of UCO fuel. Overall, the NRC licensing and design certification criterion in not considered a discriminator between the two reactor types.

6.10 Life Cycle and Fuel Disposal Issues

On average, the GT-MHR design achieves 25% higher fuel burnup compared to the PBMR-400 design (see Table 4-5). This leads to an extension of the fuel supply and improved sustainability – one of the GEN-IV goals. The power-normalized mass discharge of key uranium and plutonium isotopes shows the expectedly higher U-235 discharge associated with the GT-MHR design and higher Pu-239 discharge associated with the PBMR-400 design. This is directly due to the higher initial uranium enrichment of the GT-MHR.

If whole blocks are sent to the repository, then the prismatic core has about twice the volume of waste as the pebble core for the same burnup, since it has only half the in-core void volume. On a MWe generation basis and considering the higher burnup of the PMR fuel, the annual spent fuel volume is almost 30% more for the GT-MHR as compared to the PBMR-400. However, the PMR fuel block makes an excellent, stand alone, high-level waste storage container, and the TRISO fuel particles have shown excellent corrosion resistance in tests in a repository environment [Ref. 14].

In summary, the higher fuel burnup achievable in the PMRs relative to PBRs would extend the fuel supply and provide for better sustainability. The as-discharged PMR fuel block volumes for high level waste disposal are greater than those for the pebble fuel, but the fuel blocks are excellent, stand alone, high-level waste storage containers. On balance, the life cycle and fuel disposal criterion is not considered a significant discriminator between the two reactor types.

6.11 Reactor Vessel and Component Fabrication

With core outlet coolant temperatures of up to 950°C, issues related to high temperature materials for the reactor vessel under high pressure and for internal components are common to both the PBMR-400 and GT-MHR designs.

The PBMR-400 design RPV uses SA508 material and is 6.38 m in outer diameter and 0.18 m thick. The desired operating temperature is around 325^{o}C, and the maximum permitted temperature is 371^{o}C. An ASME code case permits temperatures to exceed 371°C for short periods of time, but in no case should the RPV exceed the peak temperature limit (410^{o}C for 48 hours). An analysis performed by KAERI [Ref. 32] indicates that this temperature limit can be exceeded in the PBMR-400 RPV during a pressurized cooldown event so that cooling of the vessel would be required to limit investment risk.

GT-MHR RPV designs have been prepared for both 9Cr-1MoV and 2¼Cr-1Mo materials of construction. The RPV designed to be constructed from 9Cr-1MoV has a 7.22-m inner diameter and is 0.216 m thick. The RPV designed to be constructed from 2¼Cr-1Mo has a 7.2-m inner diameter and is 0.19 m thick. 9Cr-1MoV has a maximum permitted temperature under ASME Code Section III of 650^{o}C, and 2¼Cr-1Mo has a maximum permitted temperature of 590^{o}C, so both materials could be used for VHTR passively safe applications and stay within their respective temperature limits during conduction cooldown events without external cooling [Ref. 32]. A reactor vessel of the size required by the GT-MHR using these materials has not been previously constructed. The HTTR in Japan uses a smaller prototype reactor vessel constructed from 2¼Cr-1Mo, and is currently operating at representative conditions. The expected size of the vessel in both overall dimensions and weight creates challenges in construction of the vessel on-site, or transportation of the vessel from a distant construction site.

The GT-MHR for VHTR applications could also use SA508 steel with vessel cooling similar to the PBMR-400 plant for investment protection purposes. Similarly, if the high temperature materials are developed for use, both the GT-MHR and PBMR-400 designs could employ them, so that there is no difference between the designs in this area.

The other non-core components that are internal to the pressure vessel are exposed to the same basic temperature conditions during operation in both the GT-MHR and PBMR-400 and hence should not serve as discriminators between the two concepts (graphite reflector replacement due to fast neutron damage was considered in Section 6.4).

In summary, while the use of SA508 for either the PBMR-400 or the GT-MHR RPV will require vessel cooling to keep vessel temperatures below the allowable limits, both the GT-MHR and PBMR designs can use this or other higher temperature materials. Thus, the reactor vessel criterion is not a discriminator between the two reactor types.

6.12 Safety Performance under Accident Conditions

The overriding concern in accident analysis for high-temperature graphite-moderated reactors (HTRs) is the release of radionuclides to the environment. Graphite has an excellent sorption capability for fission and activation products, and due to its mobility, graphite dust is an excellent vehicle for radioactive releases from the primary coolant loop in HTRs during depressurization accidents. Because of the constant motion and attendant abrasion of the graphite pebbles through the core and subsequent handling in the on-line refueling system, significantly more graphite dust will be produced in the PBMR-400 than in the GT-MHR (see Section 6.7). Indeed, the quantity of graphite dust that would be expected in the primary coolant loop of the PBMR-400 based on AVR experience raises a question as to whether the PBMR-400 can meet off-site dose limits (assuming a 425-m plant exclusionary boundary) during a rapid depressurization accident.

Because of the multiplicity of piping for handling on-line refueling and the complexity of the systems that are inter-connected with these pipes, the potential for pipe breaks is considerably higher in PBRs than in PMRs.

PMRs and PBRs have different heat transfer characteristics due to their different fuel designs. In a PBR during normal operation, fuel particle temperatures are slightly lower than in a PMR for the same coolant outlet temperatures. However, because PMR cores have considerably smaller void volumes than the PBR cores (~20% vs. ~40%), the effective thermal conductance of the PMR core is significantly higher than that of a PBR core during a core heat-up accident, and can result in lower accident fuel temperatures. Indeed, a primary consideration in setting the limit on core power density is the peak temperatures reached under accident conditions. Consequently, for a given peak accident-condition fuel temperature limit (e.g., 1600°C) and a given vessel diameter, the higher thermal conductance permits a substantially higher core power density in the PMR cores. (As discussed in Sections 6.1 and 6.2, this gives the PBR a significant advantage over the PBR with respect to thermal power rating, and, therefore, reactor economics.)

In summary, the quantity of graphite dust that would be expected in the primary circuit of the PBMR-400 based on AVR experience raises a question as to whether a PBMR-400 with a VLPC can meet off-site dose limits (assuming a 425-m plant exclusionary boundary) during a rapid depressurization accident. This is a very significant issue for the PBMR-400, and for PBRs in general. Also, the potential for a pipe break leading to a release of primary coolant is higher in a PBR than a PMR due to the extensive piping of the on-line refueling system. Thus, PMRs are considered to have a significant advantage over PBRs with respect to the safety performance under accident conditions criterion.

6.13 Flexibility of Design to Handle Different Fuel Cycles

Many studies have been performed on the use of different fuel cycles in HTGRs. To date, the U/Th fuel cycle has been used in almost all reactors of this type (Peach Bottom, FSV, AVR, and THTR). Current designs for commercial applications use the LEU fuel cycle. For the GT-MHR, the LEU fuel cycle uses a combination of LEU enriched to 19.9% U-235 plus natural uranium in two TRISO-particle designs, with an average reload segment enrichment of about 15%. An alternative to the use of these two fuel particle designs is to use a single particle design and multiple uranium enrichments. NFI in Japan has fabricated TRISO-coated fuel having multiple uranium enrichments for the HTTR reactor.

The PBMR-400 design uses a single LEU TRISO particle enriched to 9.6% in U-235. The lower enrichment (relative to the GT-MHR) is due to the lower excess reactivity requirement for PBRs, which have continuous on-line refueling. Other fuel cycles that have been evaluated for HTGR applications include Pu-Th, Weapons Grade Plutonium (WPu), and the TRU waste from LWR discharged fuel. In particular the WPu fuel cycle has been the subject of a significant jointly funded effort between the US-DOE and Rosatom in the Russian Federation.

Both the GT-MHR and PBMR-400 cores have very similar neutron spectra, hence if one design can utilize a given fuel cycle, in principle both can. Differences in the application would arise from core reactivity requirements, the need for burnable poisons, and differences in temperature feedback effects on reactivity. For most cycles, there is little difference in overall utilization. The higher enrichment requirements for the GT-MHR are offset to some extent by the lower fuel burnup for the PBMR-400 design (90,000 MWD/MT vs. 113,000 MWD/MT for the GT-MHR for the LEU cycle). However, the GT-MHR can use burnable poison at fixed core locations, which is not possible in the PBMR-400 design. This offers greater flexibility in the use of some alternate fuel cycles. For example, the WPu fuel cycle being designed for the Russian WPu-burning GT-MHR (i.e., the "International GT-MHR") utilizes Er-167 as a burnable poison to provide control of excess reactivity and to ensure a negative temperature coefficient of reactivity over life. A WPu fuel cycle could be used in the PBMR-400 design, but it would be much more difficult to ensure negative reactivity feedback [Ref. 21].

In summary, both reactor types can handle multiple fuel cycles. However, the capability to utilize fixed burnable poison (FBP) in the GT-MHR provides greater flexibility in the design and efficient operation of those fuel cycles. Thus, this criterion is considered to be a potential discriminator between the two reactor types.

6.14 Plant Operation and Potential Problems

Both PMR and PBR plants have operated in the past and both have had operational problems, the solutions for which have been factored into the PBMR-400 and GT-MHR designs. In both designs, care has been taken to minimize the risk of water ingress. The GT-MHR core is designed to prevent column shifts during operation and to keep fuel element stresses within acceptable limits[7]. Variable orifices are not used in the GT-MHR design. The PBMR-400 core is designed to operate on reflector control rods only with an RSS system also located in the reflector. The PBMR-400 fuel handling system, as shown in Figure 6-2, will need to be carefully designed for high reliability and to avoid problems such as pebble "bridging" and blockage in the discharge chutes.

Both plants should be able to meet the Utility/User plant operational requirements listed in section 3.1.1. However, the requirement to return to hot critical within 24 hours after a cold shutdown needs evaluation because of the excess reactivity needed to overcome the xenon neutron absorption transient. The PBMR-400 operates with a small amount of excess reactivity and may need additional reactivity (i.e., added fuel) to meet this requirement. The GT-MHR typically has sufficient reactivity throughout most of a cycle, but may be restricted in fast return to full power over the last few days of a cycle. However, if a cold shutdown were to occur during this short interval, it would be more practical to proceed with the normal refueling and maintenance cycle rather than to have a delayed return to full power.

As discussed in Section 6.7, a large quantity of highly-radioactive graphite dust was observed in the AVR primary coolant loop, whereas very little graphite dust was detected in the FSV primary coolant loop. The inherent production of large quantities of graphite dust in PBRs and its

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[7] Column restraint devices were successfully added to the FSV core to prevent coolant temperature variations due to column shifts.

circulation in the primary coolant loop could have a significant design and cost impact on other plant systems.

As discussed in Section 6.6, coolant and fuel temperatures in the AVR were much higher than expected for reasons that are not well understood, but were likely related to power peaking and thermal/hydraulic irregularities at core – reflector boundaries or adjacent to the graphite "noses" in the AVR core; effects that could be enhanced in a PBR annular core. Uncertainties associated with the thermal/hydraulics and fuel temperatures in the PBMR-400 (and in PBRs in general) could somewhat complicate the licensing case for the PBMR-400.

In summary, there are some plant operation issues that could discriminate between the two reactor types, but these have already been accounted for in other comparison criteria. Otherwise, the plant operation and potential problems criterion does not appear to be a significant discriminator between the two reactor types.

6.15 NGNP 2016-2018 Startup Schedule Impact on Choice

The NGNP project mission is to design, build, and operate a prototype Very High Temperature Reactor (VHTR). The project objectives are to develop and implement the technologies important to demonstrate the basis for commercialization and licensing of the nuclear system, and foster the rebuilding of the U.S. nuclear industry. The NGNP schedule balanced risk option selected by INL [Ref. 3] for construction and operation of the prototype emphasizes initiating design work as early as practical to reduce the uncertainties in the scope and focus of research and development activities. Critical Decision-1 is scheduled for 2008, with the expected date for initial operations (following the test program) in 2018. This option allows for a two-to-three year period of operation (prior to 2021) simulating a commercial power reactor operating cycle that is followed by an extensive outage during which the equipment performance is confirmed by detailed disassembly and inspection. This proof-of-principle operating period is intended to provide the basis for commercialization decisions by industry. The balanced risk option provides for an early plant demonstration while minimizing development risks that could seriously affect future plant commercial success.

The PBR PBMR-400 design should be able to meet this schedule based on the current development activities in South Africa where it is planned to build a first-of-a-kind 400 MW(t) PBR with a 900°C core coolant outlet temperature before 2016. Meeting the NGNP schedule assumes that the technology development for the PBMR-400 will be available for the NGNP prototype.

The GT-MHR 600 MW(t) design could also meet the NGNP schedule based on the on-going joint US/RF GT-MHR program for the development of a 600 MW(t) reactor for burning WPu fuel. The preliminary design for this system has been completed and a technology demonstration program (TDP) is underway. The current schedule calls for the TDP to be completed in 5-6 years. However, the fuel being developed and tested is WPu, while the fuel for the NGNP prototype would be LEU. To meet the NGNP schedule with a PMR design, LEU UO_2 fuel fabricated by Nuclear Fuel Industries (NFI) in Japan could be used in the NGNP initial core. NFI UO_2 fuel has been tested, demonstrated and licensed for use in the HTTR in Japan, but would have to be qualified by irradiation testing for use in the NGNP. UO_2 fuel could be used in a prismatic block NGNP until UCO fuel has been qualified and is available from a domestic U.S. fuel supplier.

In summary, the NGNP balanced risk schedule option selected by INL does not appear to be a significant discriminator between the GT-MHR and PBMR-400 designs. Moreover, it is important to emphasis that the best design for the commercial VHTR as identified based on the other criteria considered herein should drive the selection of the NGNP design and, hence, the NGNP project schedule, as opposed to the NGNP schedule driving selection of the NGNP design (and therefore the commercial VHTR design).

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7. CONCLUSIONS

A trade study was performed to compare the NGNP reactor candidates, namely, a prismatic block modular reactor (PMR) and a pebble bed modular reactor (PBR). A set of assumptions was first defined as a basis for selection of the specific PMR and PBR designs to be considered in the study. Based on these assumptions, the PMR selected was the 600 MW(t) GT-MHR developed by GA [Ref. 4] and the PBR design selected was the PBMR-400 developed by Pebble Bed Modular Reactor (Pty) Ltd of South Africa [Ref. 5]. Many comparison criteria were reviewed and a limited set was chosen for the evaluation based primarily on the potential of the criteria to discriminate between the two designs and for their relevance to commercial VHTR and NGNP requirements.

The systematic comparison of the 600 MW(t) GT-MHR design and the 400 MW(t) PBMR-400 design (as described in the open literature) against the selected criteria was presented in Section 6. The objective of the comparison was to identify the reactor type that is best suited for the VHTR commercial mission of cogeneration of electricity and very high-temperature process heat for production of hydrogen using advanced, highly-efficient processes such as thermochemical water splitting and high-temperature electrolysis. It is important to emphasize that the objective of the study was to identify the best choice for a commercial VHTR as opposed to identifying the design that best fits into the current preliminary schedule for the NGNP Project. This is because GA believes that the best design for the commercial VHTR should drive the selection of the NGNP design and, hence, the NGNP project schedule, as opposed to the NGNP schedule driving selection of the NGNP design and, hence, the commercial VHTR design.

The PBR and PMR designs considered in this study were compared in lieu of a design-independent comparison of the inherent capabilities of PMRs and PBRs because such a comparison, while conceptually ideal, would have been impossible to perform within the time and funding constraints of the study given the large number of design variables and the economic and performance tradeoffs associated with these variables. Thus, a basic assumption of the study was that both the GT-MHR and the PBMR-400 designs have been sufficiently optimized by their respective designers to provide a basis for a valid comparison of the two reactor types. Regardless of the specificity of the comparison, some conclusions about the inherent differences between the PMR and PBR concepts are possible, and are summarized below.

Both PMRs and PBRs can be built over a range of power levels, but a passively-safe PMR can operate at a higher power rating than a passively-safe PBR. This is a major economic advantage for the PMR for most commercial applications.

The inherently higher operating power level and efficiency of PMRs relative to PBRs equates to an estimated electricity generation busbar cost for a GT-MHR plant that is 10% to 20% lower than for a PBMR-400 plant having the same electrical power output. This significant economic advantage in electricity generation cost translates to an approximately equivalent advantage for the PMR in process heat or electricity/process heat cogeneration applications given that a cost measure of the thermal energy utilized as process heat is the value of the electricity that could have been produced had the thermal energy been used for electricity production.

Both reactor types have some technology development risks. Qualification of UCO fuel is an issue for the GT-MHR, while qualification of reflector graphite capable of withstanding very high fast neutron fluence is an issue for the PBMR-400. Qualification of UCO fuel is more of a schedule and cost issue than a technical issue, and is not considered to be a significant risk for a commercial prismatic block VHTR. On the other hand, it is not at all certain that graphite can be qualified for the very high fast neutron fluence corresponding to a 20-year design lifetime for the PBMR-400 reflectors. This is a considerable risk for the PBMR-400 because more frequent reflector replacement would have a significant impact on plant availability.

The PBR may have a small advantage over the PMR with respect to availability, but only if the lifetime of the graphite reflectors in the PBR is very long (i.e. of the order of 20 years). A significantly shorter reflector lifetime and/or unreliable operation of equipment such as the on-line fuel handling system in the PBR would partially or completely eliminate this advantage.

Both reactor types have low proliferation and diversion risk, but the PBR has less simplicity and greater uncertainty with respect to fuel accountability, and provides a relatively easier diversion path for nuclear material. These safeguards issues could potentially result in a somewhat more difficult licensing case for the PBR relative to the PMR.

The inherently lower core power density and better pebble-to-coolant heat transfer in a PBR result in lower predicted fuel temperatures (than in a PMR) during normal operation, which could translate to better fuel performance in PBRs than in PMRs. However, coolant and fuel temperatures in the AVR were much higher than predicted. The reasons for these higher-than-expected temperatures are not well understood, but they were likely related to power peaking and thermal/hydraulic irregularities at core – reflector boundaries or adjacent to the graphite “noses” in the AVR core; effects that could be enhanced in a PBR annular core.

PBRs require less excess reactivity, which is often cited as an advantage for PBRs over PMRs. However, the authors believe that the flexibility provided by the available design options for PMR cores actually represents a nuclear design advantage for the PMR.

The formation of much larger quantities of graphite dust in PBRs than in PMRs and the circulation of this dust in the primary coolant loop could have a significant design and cost impact on other plant systems in PBRs. This could be a very significant disadvantage for PBRs.

The capability of PBRs to better use UO_2 fuel, which is currently more qualified by irradiation and safety testing than is UCO fuel, is a modest advantage for PBRs over PMRs. The need for PMRs to utilize UCO to achieve favorable economics is somewhat of a risk for the GT-MHR, although the authors consider this risk to be relatively small.

The design certification process for the PBR under the new NRC ground rules for licensing of next generation, non-LWR reactors is currently ahead of that for the PMR. However, licensing and design certification of the PBMR-400 design could be complicated by a number of issues, including the limited operational performance data for the on-line refueling system, the NRC's unfamiliarity with the on-line refueling approach, and uncertainties with respect to the thermal/hydraulic performance of PBR cores and the impact of these uncertainties on fuel performance. On the other hand, the capability of PBRs to use UO_2 fuel, which has a more extensive irradiation and safety testing data base than UCO fuel, could potentially make licensing a pebble bed NGNP somewhat less difficult than licensing a prismatic block NGNP. However, this advantage would not extend to a follow-on commercial pebble bed VHTR because it is expected that UCO fuel will have been qualified and be available for use by the time a commercial VHTR is built.

The higher fuel burnup achievable in the PMRs relative to PBRs would extend the fuel supply and provide for better sustainability. The as-discharged PMR fuel block volumes for high level waste disposal are greater than those for the pebble fuel, but the fuel blocks are excellent, stand alone, high-level waste storage containers.

While use of SA508 for either the PBMR-400 or the GT-MHR RPV will require vessel cooling to keep vessel temperatures below the allowable limits, both the GT-MHR and PBMR designs can use SA508 or other higher temperature materials.

The quantity of graphite dust expected in the primary circuit of the PBMR-400 based on AVR experience raises a question as to whether or not a PBMR-400 with a VLPC can meet off-site dose limits (assuming a 425-m plant exclusionary boundary) during a rapid depressurization accident. This is a very significant issue for the PBMR-400, and for PBRs in general. Also, the potential for a pipe break leading to a release of primary coolant is higher in a PBR than in a PMR because of the extensive piping of the on-line refueling system.

There are a number of plant operation issues that could discriminate between the two reactor types; these have already been accounted for in other comparison criteria.

Both reactor types can handle multiple fuel cycles. However, the capability to utilize fixed burnable poison (FBP) in the GT-MHR provides greater flexibility in the design and efficient operation of those fuel cycles.

The only PMR vs. PBR issue that appears to have the potential to impact the NGNP schedule is the use of UCO as the reference fuel in PMRs. This is because UCO is currently less qualified by irradiation and safety testing than UO_2 fuel and there is no credible near-term supplier of UCO fuel. However, GA proposes to use UO_2 fuel for the initial core fuel load for a prismatic block NGNP, which would mitigate any NGNP schedule risk associated with the qualification and availability of UCO fuel. Moreover, it is important to emphasis that the best design for the commercial VHTR as identified based on the other criteria considered herein should drive the selection of the NGNP design and, hence, the NGNP project schedule, as opposed to the NGNP schedule driving selection of the NGNP design (and therefore the commercial VHTR design).

The results of the comparison study are further summarized in Table 7-1.

The overall conclusion of the current PMR vs. PBR comparison is that the PMR has a clear advantage over the PBR as the modular helium reactor type best suited for a commercial VHTR for electricity production and various high-temperature process heat applications, including hydrogen production. Consequently, a PMR is also the clear choice for the NGNP. This conclusion is consistent with the result of a 1986 study that resulted in selection of a PMR as the concept to be developed by the U.S. MHR Program for commercial applications in the U.S.

TABLE 7-1
Summary of the Comparison of the GT-MHR and PBMR-400 Designs

Report Section	Comparison Criteria	Comment	Discriminator?	Design Advantage
6.1	Core power level and plant scalability	Both designs can be built over a range of power levels, the PMR core can operate at a higher power (600MWt) than the PBR core (400MWt), while still retaining Gen-IV type inherent safety characteristics. This represents a major economic advantage for large commercial applications.	Yes	PMR
6.2	Plant economics, including capital costs, operating costs, and life-cycle costs.	There is a clear economic advantage for a PMR relative to a PBR for electric power production, because of its higher thermal power rating, This advantage should also apply to process heat applications, and is a clear discriminator.	Yes	PMR
6.3	Technology development risks and development schedule	Both designs have is an issue for the GT-MHR while development of a reflector graphite to meet the long lifetimes required is an issue for the PBMR-400.	difficult to judge at this stage	
6.4	Plant availability.	The PBR can meet the >94% utility avilabilty goal. The PMR will have to demonstrate this with on line experience. Frequent reflector graphite replacement could eliminate the PBR plant advantage.	yes	PBR
6.5	Proliferation resistance and material accountability	Both cores are low diversion and proliferation risks,but the PBR has greater fuel accontability problems which may impact licensing.	slight	PMR
6.6	Reactor thermal hydraulic and nuclear design, design methods development	In summary, the design flexibility options of the GT-MHR provide an advantage for this criterion.	small	PMR
6.7	Impact of reactor concept on other plant systems	The PBR core generates significantly more graphite dust than the PMR core. Graphite dust production and circulation in the primary loop could have a potential design and cost impact on the other plant systems.	yes	PMR
6.8	Fuel element design - stationary vs. flowing elements, fuel performance, oxidation resistance, etc.	The PBR has an advantage with the use of largely qualified UO_2 fuel.	yes	PBR
6.9	NRC design certification	The licensing of the PBR is likely to involve greater uncertainties and potential delays than the licensing of the PMR.	possible	PMR
6.10	Life cycle and fuel disposal issues	The GT-MHR design has higher waste volumes, but the block element can be used for direct high-level waste disposal.	mot significant	
6.11	Reactor vessel, fabrication, fuel handling and other components	A steel RPV requires external cooling under pressurized cooldown accident conditions. Both designs can utilize the same RPV materials.	No	
6.12	Safety performance and fission-product transport during accident conditions, plant maintenance and worker safety.	Higher levels of dust in the PBR primary circuit and more complex piping poses an accident concern durin a rapid depressurization	Yes	PMR
6.13	Flexibility of design to handle different fuel cycles.	both reactor types can handle multiple fuel cycles. However, the capability for a fixed burnable poison in the PMR provides greater flexibility in the design and efficient operation of those fuel cycles.	possible	PMR
6.14	Plant operation and potential problems	At this stage plant operation and potential operational problems do not appear to be discriminators.	No	
6.15	NGNP 2016-2018 startup schedule impact on choice	The NGNP schedule for a balanced risk option does not appear to be a significant discriminator between the PMR and PBR designs.	No	

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