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NGNP and Hydrogen Production Preconceptual Design Report

SPECIAL STUDY 20.1: REACTOR TYPE COMPARISON

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ACRONYMS

Acronyms	Definition
ASME	American Society of Mechanical Engineers
AVR	Arbeitsgemeinschaft Versuchsreaktor (Jointly-operated Prototype Reactor)
BOEC	Beginning of Equilibrium Cycle
DBE	Design Basis Event
DLOFC	Depressurized Loss of Forced Cooling
DPP	Demonstration Power Plant
FHS	Fuel Handling System
FOAKE	First-Of-A-Kind Engineering
FSV	Fort Saint Vrain
H2-MHR	Hydrogen Production - Modular Helium Reactor
HEU	Highly Enriched Uranium
HPB	Helium Pressure Boundary
HTGR	High-Temperature Gas-Cooled Reactor
HTR	High-Temperature Reactor
IHX	Intermediate Heat Exchanger
LEU	Low-Enriched Uranium
LWR	Light Water Reactor
NGNP	Next Generation Nuclear Plant
NHS	Nuclear Heat Source
NRC	Nuclear Regulatory Commission
PBMR	Pebble Bed Modular Reactor
PHP	Process Heat Plant
PLOFC	Pressurized Loss of Forced Cooling
QA	Quality Assurance
R&D	Research and Development
RSA	Republic of South Africa
RSS	Reserve Shutdown System
THTR	Thorium High-Temperature Reactor
U	Uranium

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20.1 REACTOR TYPE COMPARISON

SUMMARY AND CONCLUSIONS

The objective of this special study is to provide a comparative assessment of the relative merits of the pebble and prismatic modular HTGR core designs. Both fundamentals and design specifics are addressed with the latter based on process heat delivery at 950^0C.

The fundamental differences between the pebble and prismatic fuel designs can be grouped into those related to fuel-graphite geometry in the fuel elements, the fuel element-coolant geometry, core refueling, and equilibrium core conditions. The major fundamental differences between the pebble and the prismatic cores can be summarized as follows.

- The pebble core has a higher outlet temperature for a given normal operation maximum fuel temperature limit. Although there is a lower power density within the fueled region of the fuel element, there is lower resistance for heat transfer from the fuel to the fuel element surface, and greater heat transfer from the fuel element surface to the coolant.
- Because of its lower coolant volume, the prismatic core can achieve greater power within a given core volume and geometry, for a given fuel element (solid) power density, and a given DLOFC maximum fuel temperature limit.
- The pebble core can be taller than the prismatic core because it is not as limited by axial neutronic stability.
- Because of greater coolant mixing in the pebble core, hot streaks downstream from the core are a non-issue versus a major issue for the prismatic – particularly for core outlet mean temperatures greater than 900^0C.
- Because the pebble core has a higher resistance to flow, it requires a relatively larger circulator/compressor.
- The pebble core on-line refueling offers the basis for a higher capacity factor and simplifies fuel manufacturing, reload complexity, and QA, plus it is compatible with continuous process heat applications.

For process heat applications and specifically for hydrogen production, Reactor designs are optimized that take advantage of the above fundamentals of the fuel technology. There are significant differences in selections made for the pebble and prismatic reference process heat designs described in References 20.1-1 and 20.1-2. These include reactor dimensions and power level, reactor operating parameters, fuel and structural (core barrel and reactor vessel) materials, and fuel maximum temperature limits. Specific differences are illustrated in Table 20.1.1. As an example of the first factor above, the pebble core has a power level of 500 MWt as opposed to 600 MWt for the prismatic core. Although the core outlet temperatures specified for both systems are identical (950^0C), both the core inlet temperatures and helium pressure are different. The fuel materials for the two systems are different - fissile UO_2 for the pebble versus fissile/fertile UCO for the prismatic. Another significant difference in the designs is that different maximum fuel temperature limits, both for normal operation and for DLOFC events, have been selected. Any comparison of specific reference designs is strongly influenced both by the pebble/prismatic fundamental differences discussed earlier and the vendor-specific design selections themselves.

Table 20.1.1 Reference Process Heat Design Selections

Parameter	PBMR PHP	H2-MHR
Inner/outer active core diameter (m)	2.0/3.7	2.96/4.83
Active core effective height (m)	11.0	7.93
Fueled region power density (w/cc)	16.9	32
Fuel element (solid) power density (w/cc)	9.8	8.3
Core power density (w/cc)	6.0	6.6
Core inlet/outlet coolant temperature (^oC)	350/950	590/950
Normal operation max. fuel temp. (^oC)	~1150	1250-1350
Off-normal max. fuel temperature (^oC)	~1670	<1600
Module power rating (MWt)	500	600
Primary He coolant inlet pressure (MPa)	9.0	7.1
Primary He flow rate (kg/s)	160	320
Core pressure drop (KPa)	202	58
Fuel composition	UO_2	$UC_{0.5}O_{1.5}$
Fuel enrichment (%)	5.0 startup 9.6 equilibrium	19.8 fissile 14.5 avg with fertile
Fuel burnup (GWd/mt U)	90	120

The comparison of the merits of these pebble and prismatic reference process heat designs requires that the designs be compared on the basis of specific and relevant discriminating criteria. The following criteria and their relative weight (WEIGHT) were selected:

- Readiness
  - Design maturity and limited enabling technology R&D required (HIGH)
  - Vendor/supplier infrastructure (MEDIUM)
- Performance
  - Process heat delivery (HIGH)
  - Capacity factor/investment protection (MEDIUM)
  - Public safety (HIGH)
  - Safeguards (MEDIUM)

- Wastes and other environmental impact minimization (MEDIUM)
- Cost competitiveness (HIGH)

- Enhancement Potential
  - Fuel cycle flexibility and enhancement opportunities (LOW).

The results of the comparison against these discriminating criteria led to the following conclusions:

- The pebble fuel PBMR PHP has a clear advantage over the prismatic block H2-MHR relative to R&D needs for fuel because of the German experience with UO2 fuels in the AVR and THTR and because of the pebble's fundamental lower normal fuel operation temperatures. DPP experience, especially the selection of LWR reactor vessel steels and other code-qualified materials, also results in much reduced R&D needs for the PBMR PHP.
- The advantage for process heat delivery also goes to the PBMR PHP because of the much lower risk for achieving the desired very high core outlet temperature (950^0C). Capacity factor for the PBMR PHP should also be superior to that for the H2-MHR because of on-line refueling. Safety in terms of potential radionuclide releases should also be better for the PBMR PHP because of the demonstrated superior performance of the fuel and its lower normal temperature of operation.
- The estimated unit capital cost for mature, multi-module plants is lower for the H2-MHR than for the PBMR PHP given identical assumptions. This is primarily because of the lower power level of the latter. However, resultant process heat or H2 costs should be lower for the PBMR PHP because of its higher capacity factor, simpler fuel cycle and lower O&M costs. Altogether, the PBMR PHP is competitive with the H2 MHR concept at much lower overall risks.

Table 20.1.2 provides the evaluation of the PBMR PHP relative to the H2-MHR in terms of the discriminating criteria. The comparison illustrates that for all of the discriminating criteria the PBMR PHP is better than or comparable to the H2-MHR.

In closing, pebble core technology offers many fundamental advantages over the prismatic core for high temperature process heat applications and adapts well qualified and demonstrated German-based fuel and on-line refueling experience. The PBMR PHP is superior in essentially all respects to the H2-MHR for the high temperature process heat/H_2 production NGNP. This is true primarily because of lower development costs and risks for the pebble fuel, minimization of development costs and risks because of the DPP baseline, a much stronger vendor/supplier infrastructure, and a higher performance capability. Lower fuel temperatures and normal operation radionuclide releases result for the same required process heat temperature and on-line refueling is consistent with continuous process industries. Finally, the PBMR PHP is attainable at lower overall forward costs and risks.

Table 20.1.2 Reactor Type Summary Relative to the Discriminating Criteria

Criteria	Weight	PBMR PHP versus H2-MHR	Basis
Readiness			
Design maturity and limited enabling technology R&D required	High	PBMR PHP Better	• German fuel experience • DPP design selections focused on near-term implementation
Vendor/supplier infrastructure	Medium	PBMR PHP Better	• Builds on DPP international team, including WEC/Shaw in the US
Performance			
Process heat delivery	High	PBMR PHP Better	• Pebble lower fuel temperatures for 950^0C core outlet
Capacity factor/ investment protection	Medium	PBMR PHP Better	• Pebble on-line fueling
Safety	High	PBMR PHP Better	• Pebble lower normal operation temperatures with demonstrated fuel
Safeguards	Medium	Comparable	• Both can meet requirements
Wastes and other environmental impact minimization	Medium	PBMR PHP Better	• Pebble lower releases and less fuel element and control rod volume
Cost competitiveness	High	Comparable	• Prismatic power level advantage but pebble utilizes available materials & on-line refueling
Enhancement Potential			
Fuel cycle flexibility and enhancement opportunities	Low	PBMR PHP Better	• Pebble more upside potential for advanced fuels and more margin for higher core outlet temperatures

INTRODUCTION

The purpose of this study is to provide a comparative assessment of the relative merits of the pebble and prismatic modular HTGR core designs. Both fundamentals and design specifics are addressed with the latter based on process heat delivery at 950^0C.

The collection and examination of information in specific design and performance related areas are necessary to permit this assessment to be conducted objectively. First, background information relative to the modular HTGR safety design approach is presented, with special emphasis on the importance of fuel performance. In this regard, the pebble and prismatic block fuel element designs and core concepts are discussed.

As a next step in the assessment, a number of fundamental differences between the pebble and prismatic core designs are discussed. These include fuel-graphite geometry within the fuel elements, fuel element-coolant geometry influences, refueling, and equilibrium core conditions.

Details of the reference PBMR PHP and prismatic process heat designs are then given in terms of design optimization, influences on normal operation fuel performance, influences on Depressurized Loss of Forced Cooling (DLOFC) events on radionuclide release, and influences on core power. The PBMR Process Heat Plant reference design (PBMR PHP) is based on a 500 MWt core with an outlet temperature of 950^0C; the prismatic reference design (H2-MHR) is based on a 600 MWt core, also with an exit temperature of 950^0C (Reference 20.1-1).

Discriminating criteria for the pebble and prismatic designs are then presented and discussed as the critical tools to permit the desired comparative assessment. These criteria include "readiness" of technology and necessary infrastructure and "performance" in terms of normal operation Nuclear Heat Source (NHS) effectiveness, capacity factor/investment protection, public safety, safeguards/security, and waste and other environmental impact minimization. "Enhancement potential" is also included as one of the discriminating criteria.

These discriminating criteria are exercised to provide summary conclusions relative to R&D needs, performance, and cost competitiveness and to give a direct comparison of the pebble and prismatic designs for all of these factors.

20.1.1 FUEL PERFORMANCE AND SAFETY APPROACH

The safety design approach for both the pebble and prismatic core modular HTGR designs is based on the inherent properties and characteristics of the particle fuel, the graphite moderator, and the reactor coolant. The fuel is the primary and most important barrier to radionuclide release. The pebble spherical fuel element design is illustrated in Figure 20.1.1.

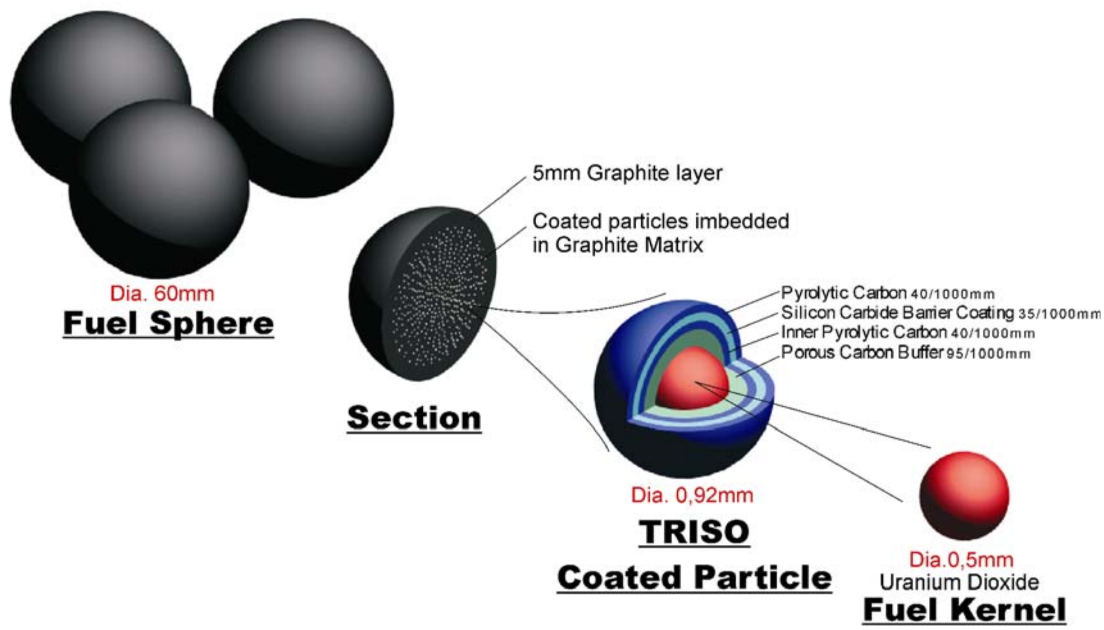
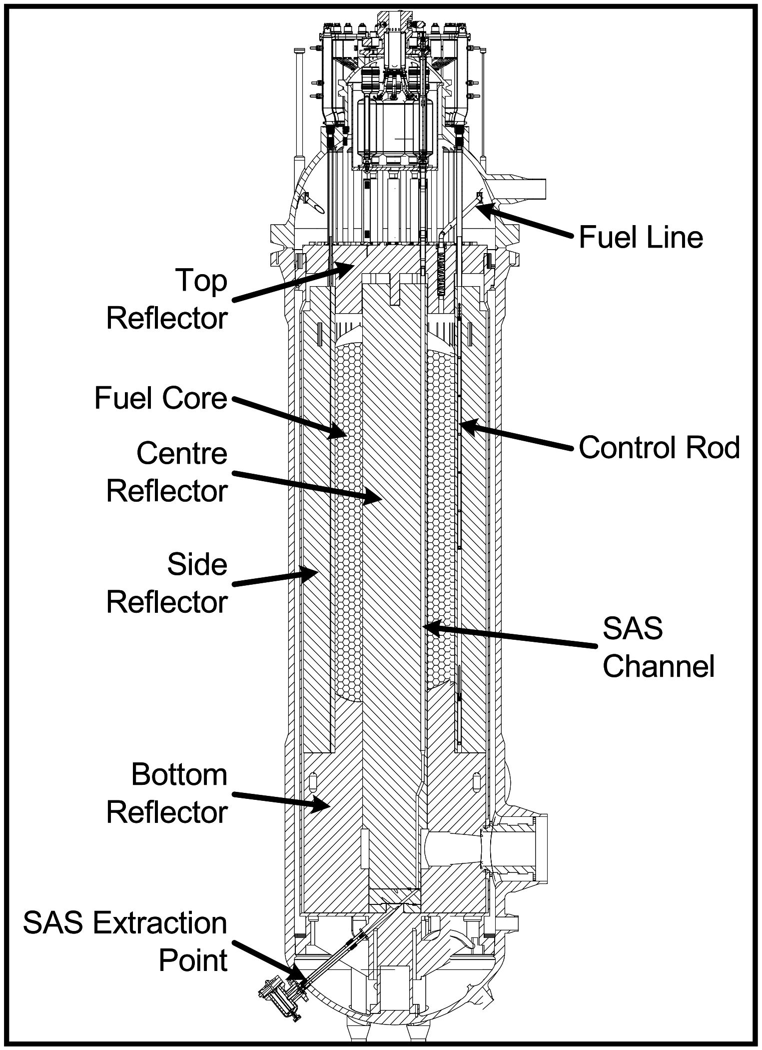


Figure 20.1.1 Pebble Sphere Fuel Element Design

The 0.5 mm UO_2 fuel kernel (lower right) is first coated with a buffer layer of porous carbon and then an inner layer of pyrolytic carbon. A barrier layer of SiC and an outer layer of pyrolytic carbon follow. These TRISO coated fuel particles (~0.92 mm diameter) are incorporated into a graphite matrix to form a 60 mm diameter fuel sphere that includes a 5 mm thick outer layer of graphite. These fuel spheres fill the annulus between the center and side reflectors (see left side of 0) to form the pebble reactor core (Reference 20.1-1)



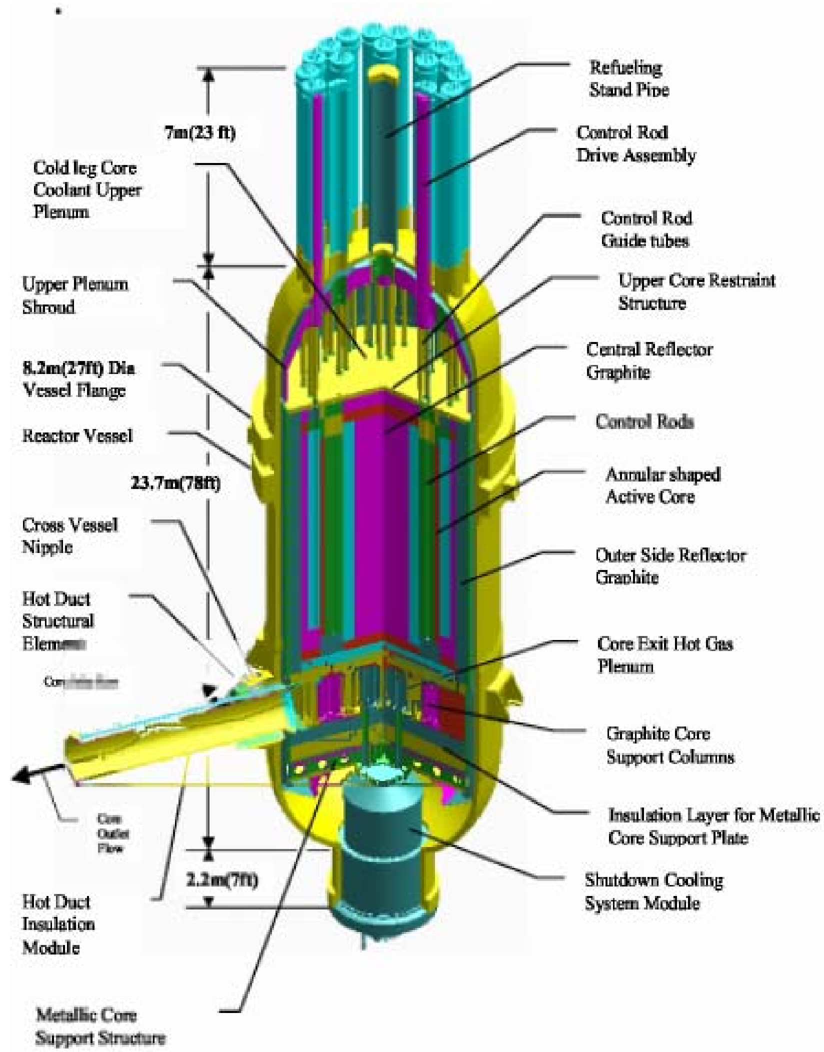


Figure 20.1.2 Pebble and Prismatic Core Concept Cross-Sections

Figure 20.1.3 describes the main features of the UCO fuel for the prismatic block design. There are both fissile and fertile fuel particles involved with diameters of 0.35 mm and 0.50 mm, respectively. As in the pebble fuel case, these fuel kernels are coated with the same layers of porous carbon, pyrolytic carbons, and SiC. These particles are incorporated into a carbonaceous material to form cylindrical compacts of 12.45 mm diameter by 49.3 mm in length. Approximately 15 compacts are loaded into each blind fuel hole in each hexagonal graphite block (360 mm across flats, 794 mm in length). Parallel coolant channels are drilled all the way through the graphite blocks on a triangular pitch to the fuel holes. One fuel compact plus several of the fuel holes and coolant channels are shown in the two views in Figure 20.1.3. The blocks are stacked to form the annular core shown on the right of Figure 20.1.2.

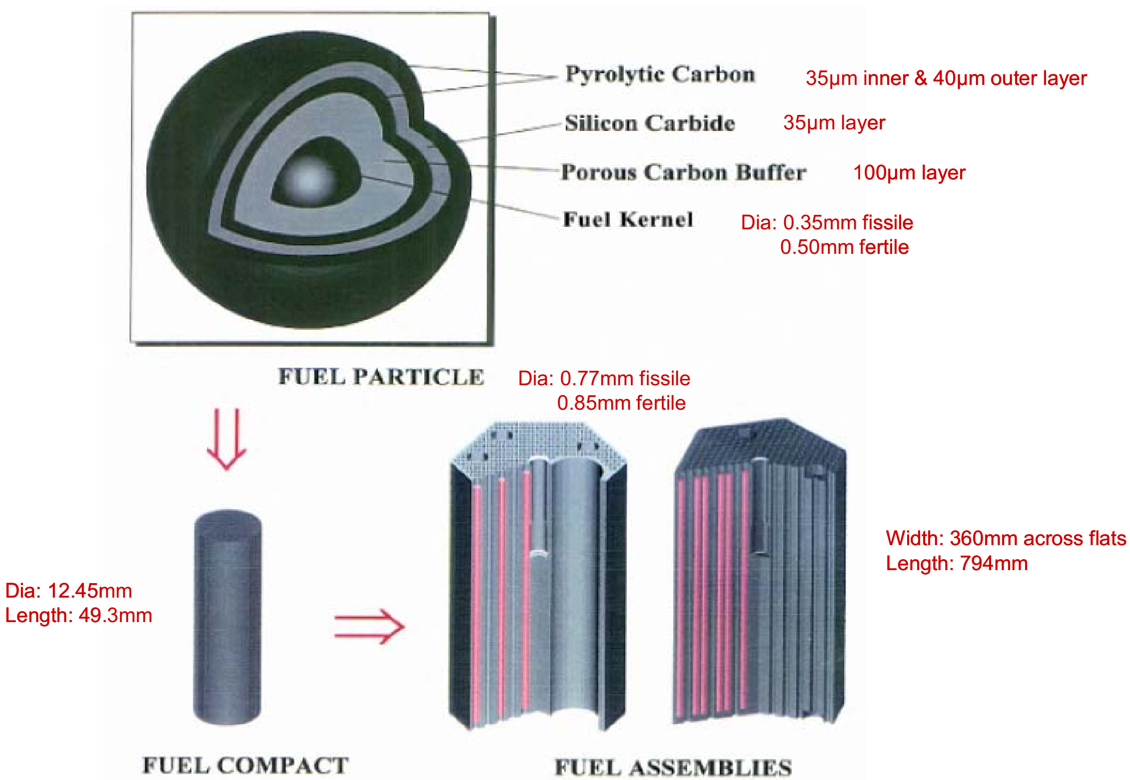


Figure 20.1.3 Prismatic Block Fuel Element Design

As stated earlier, fuel performance is key to the safety design approach. This demands a very high quality of the manufactured fuel. This high quality will be the major feature in the normal operation limitation of the sources of prompt releases of radionuclides should leaks/breaks occur in the Helium Pressure Boundary (HPB). In other words, the better the fuel retains radionuclides during normal operation, which is directly related to fuel quality, the fewer the radionuclides that will be available for prompt release should an HPB leak occur. Similarly, high radionuclide retention potential for the fuel under off-normal conditions will help to limit delayed releases from the HPB resulting from long-term heatup of the fuel.

In modular HTGR systems, there is emphasis on relying on passive design features to remove core heat, to control heat generation, to control chemical attack, and to maintain core geometry to maximize radionuclide retention within the fuel. However, there are additional concentric and independent barriers (the HPB and the reactor building) to provide for defense-in-depth and safety margins.

20.1.2 FUNDAMENTAL DIFFERENCES BETWEEN PEBBLE AND PRISMATIC CORE DESIGNS

The fundamental differences between the pebble and prismatic fuel designs can be grouped into those related to fuel-graphite geometry in the fuel elements, the fuel element-coolant geometry, core refueling, and equilibrium core conditions.

Fuel-Graphite Geometry within Fuel Elements - The fuel spheres in the pebble core contain a lower packing fraction of fuel particles than do the fuel compacts in the prismatic core design. In the manufacturing of the fuel spheres, the fuel particles are distributed within the carbonaceous material within the mold. In the manufacturing of the fuel compacts in the prismatic fuel element, care must be taken that the more densely packed fuel particles will not be damaged during the compaction. All other things being equal, there is a lower probability of processing/compacting-induced fuel particle damage/failure in the pebble fuel spheres than in the prismatic compacts. This, in turn, is a positive influence on overall fuel performance during both normal operation and off-normal events.

Further, since the fueled region of the pebble design has a lower particle density than the prismatic fuel compacts, the pebble core has both lower average and maximum fuel temperatures during normal operation.

Fuel Element-Coolant Geometry Influences - Fuel element-coolant geometry differences contribute to factors related to normal operation fuel temperatures, axial neutronic stability, power level, downstream conditions, circulator/compressor power, Pressurized Loss of Forced Cooling (PLOFC) event response, and support of the center reflector of the annular core.

Since the pebble fuel is closer to the coolant stream compared to the prismatic design in which the fuel compacts are separated from the coolant channels in the graphite blocks, the pebble fuel can achieve a higher core outlet temperature for the same normal operation maximum fuel temperature limit. Another important difference is that the prismatic core has greater bypass flow between the blocks and in control rod channels that are even further removed from the fuel compacts. This requires higher fuel temperatures to achieve a given average helium core outlet temperature. Stated in another way, for identical pebble and prismatic core outlet temperatures, the pebble core will have a lower normal operation maximum and average fuel temperature.

The pebble core has a greater coolant volume than does the prismatic core. This influences axial neutronic stability such that, for the same core height, the pebble core has greater axial neutronic stability and is, therefore, not as limited in height. However, the prismatic core has the advantage in that it can achieve a higher power level for the same fuel element (solid) power density, core volume and geometry, and peak fuel temperature limit during DLOFC events.

Because of the channeled flow of the coolant holes top to bottom in the stacked blocks of the prismatic design, the prismatic core has less resistance to flow. However, this also results in a lower degree of mixing of the coolant between core regions. Unlike channeled flow reactors, the pebble bed is less susceptible to negative feedbacks that could lead to starved flow regions. Because of the greater resistance to flow, the pebble core has better heat transfer from the fuel elements to the coolant. Another positive from the greater resistance to flow in the pebble core is that there is less natural convection to transfer heat to challenge the upper core metallic components and the reactor vessel during PLOFC events. However, a negative resulting from the higher resistance to flow in the pebble core is that, relative to identical core heights and He pressures, the pressure drop through the pebble core is greater than in the prismatic core and thus requires more circulator/compressor power. The greater degree of coolant mixing for the pebble core results in reduction in hot streaks at the core outlet and to downstream components. This translates to more reliable component operation and performance.

A positive for the prismatic design is the less demanding structural design of the center reflector compared to that of the pebble core's support of its center reflector.

Core Refueling – Scheduled, off-line refueling is required for the prismatic system, typically every 18 months. Since the pebble core is fueled on-line, it has no scheduled outages for refueling. This is compatible with continuous operation of process heat based industries. Process plants require periodic maintenance in addition to the minor maintenance during unplanned brief shutdowns. Depending on the process, typical schedules are major shutdowns of one to four weeks scheduled every one to three years. The issues for integration with a reactor requiring a refueling shutdown are how accurately can it be forecast and scheduled, how much flexibility is there in doing it sooner or later if market circumstances call for it, and whether its duration is comparable to that needed for the process plant maintenance? These are not issues with the on-line fueling of the pebble core. Further, most unplanned outages associated with the pebble core fuel handling system can be handled without impacting the continued operation and availability of the reactor.

The pebble core has more flexibility than the prismatic core in choosing optimum burnup for fuel performance. There is less flexibility in the prismatic core case because burnup must be adjusted to achieve an economic refueling interval each refueling cycle. Also, the pebble core has a continuous measurement of burnup for each fuel sphere; thus no core physics analyses are required or margins added to account for analytic uncertainties.

The pebble core has less excess reactivity than the prismatic core. This results in a requirement for control rod and reserve shutdown worths that are smaller for the pebble than the prismatic core. Safety analyses of rod withdrawal events are less challenging for the pebble core.

A relative disadvantage of the pebble core is that a core unload will be needed every 15-20 years to allow for replacement of the reflectors. In the prismatic system, a fraction of the reflectors is replaced as part of each off-line refueling outage.

Equilibrium Core Conditions – The pebble core is at equilibrium conditions for >90% of its lifetime. This minimizes fuel manufacturing, reload complexity, and QA. For example, the pebble core uses fuel particles of a single enrichment in the initial core and particles of a single (but different) enrichment after initial startup. In contrast, the prismatic core has zones of fissile and fertile fuel particles and uses burnable poisons within the hexagonal fuel blocks. The fuel blocks are re-arranged during every refueling outage. Because the pebble core is in general much more homogeneous, there are fewer extremes in fuel performance demands.

Summary of Pebble-Prismatic Core Fundamental Differences – The major fundamental differences between the pebble and the prismatic cores can be summarized as follows.

- The pebble core has a higher outlet temperature for a given normal operation maximum fuel temperature limit. Although there is a lower power density within the fueled region of the fuel element, there is lower resistance for heat transfer from the fuel to the fuel element surface, and greater heat transfer from the fuel element surface to the coolant.
- Because of its lower coolant volume, the prismatic core can achieve greater power within a given core volume and geometry, a given fuel element (solid) power density, and a given DLOFC maximum fuel temperature limit.
- The pebble core can be taller than the prismatic core because it is not limited by axial neutronic stability.
- Because of greater coolant mixing in the pebble core, hot streaks downstream from the core are a non-issue versus a major issue for the prismatic, particularly for core outlet mean temperatures greater than 900^{0}C.
- Because the pebble core has a higher resistance to flow, it requires a relatively larger circulator/compressor.
- The pebble core on-line refueling offers the basis for a higher capacity factor and simplifies fuel manufacturing, reload complexity, and QA, plus it is compatible with continuous process heat applications.

20.1.3 REFERENCE PBMR AND PRISMATIC PROCESS HEAT DESIGNS

Given the fundamentals discussed in the preceding section, the reactor designs are optimized that take advantage of the core technology's strengths. The resulting design selections have influences on a number of key performance parameters.

Design Optimization - Reactor designs for both the pebble and prismatic core process heat designs (PBMR PHP and H2-MHR, respectively) are optimized to meet application-based design requirements as well as schedule and economics, and required technology and R&D. There are significant differences in selections made for the pebble and prismatic reference process heat designs described in References 20.1-1 and 20.1-2. These include reactor dimensions and power level, reactor operating parameters, fuel and structural (core barrel and reactor vessel) materials, and fuel maximum temperature limits. Specific differences are illustrated in Table 20.1.3.

Table 20.1.3 Reference Process Heat Design Selections

Parameter	PBMR PHP	H2-MHR
Inner/outer active core diameter (m)	2.0/3.7	2.96/4.83
Active core effective height (m)	11.0	7.93
Fueled region power density (w/cc)	16.9	32
Fuel element (solid) power density (w/cc)	9.8	8.3
Core power density (w/cc)	6.0	6.6
Core inlet/outlet coolant temperature (^{o}C)	350/950	590/950
Normal operation maximum fuel temp. (^{o}C)	~1150	1250-1350
Off-normal max. fuel temperature (^{o}C)	~1670	<1600
Module power rating (MWt)	500	600
Primary He coolant inlet pressure (MPa)	9.0	7.1
Primary He flow rate (kg/s)	160	320
Core pressure drop (KPa)	202	58
Fuel composition	UO_2	$UC_{0.5}O_{1.5}$
Fuel enrichment (%)	5.0 startup 9.6 equilibrium	19.8 fissile 14.5 avg with fertile
Fuel burnup (GWd/mt U)	90	120

As an example of the first factor above, the pebble core has a power level of 500 MWt as opposed to 600 MWt for the prismatic core. Although the core outlet temperatures specified for both systems are identical (950^{0}C), both the core inlet temperatures and helium pressure are different. The fuel materials for the two systems are different - fissile UO_2 for the pebble versus fissile/fertile UCO for the prismatic. Another significant difference in the designs is that different maximum fuel temperature limits, both for normal operation and for DLOFC events, have been selected. Any comparison of specific reference designs is strongly influenced both by the pebble/prismatic fundamental differences discussed earlier and the vendor-specific design selections themselves.

Design Selections Influencing Normal Operation Fuel Performance – There are a large number of fuel-related design selections that will influence fuel performance during normal operation. These include the fuel design specification itself, manufactured fuel quality, and fuel temperatures and irradiation conditions. Included in the fuel specification factor are the fuel material (UO_2 versus UCO or other), fissile and fertile fuel loadings, fuel kernel size, and coating layer thicknesses and compositions. As-manufactured fuel quality is described by factors such as the fraction of missing buffers, cracked or missing coating layers, other out-of-specification defects, and U contamination. Operational parameters such as average and maximum burnup, average and maximum fluence, average and maximum fuel temperatures and time-at-temperature, and temperature gradients within the fuel also influence normal operation fuel performance.

Design Selections Influencing DLOFC Radionuclide Releases – A number of design selections can also have strong influences on the early and delayed releases of radionuclides during DLOFC events and their transport from the fuel to the offsite environment. Early release of radionuclides in the form of circulating activity, dust, or plateout liftoff in the event of a DLOFC is influenced both by normal operation fuel performance and the size and location of the leak or break in the HPB. Delayed releases of radionuclides can occur both from heatup of initially failed fuel particles (normal operation fuel performance related) and from incremental failures resulting from the heatup. In both instances, the releases are also related to the fraction of the core with temperatures above normal operation levels, peak fuel time-at-temperature, and the fraction of the core with peak temperatures. Beyond this, the offsite release is influenced by the size of the leak or break in the HPB and any chemical attack by water or air. Release can also be reduced by retention within the core, the HPB, and the reactor building.

Design Selections Influencing Core Power – There are a number of design selections relative to normal operation and to restrictions relative to PLOFC and DLOFC conditions that influence the level of core power. Mass flow rate, maximum and average fuel temperatures, and core temperature rise impact core power. The temperatures and time-at-temperature of the metallic reactor internals and the reactor vessel during both a PLOFC and a DLOFC also limit the core power. The maximum fuel temperature and time-at-temperature during a DLOFC also influence core power and these temperatures and times are, in turn, influenced by a large number of factors related to effective outer core diameter, effective core height, annular active core thickness, power density, and normal operation average fuel temperature. Effective outer core diameter includes consideration of vessel diameter, vessel shipping weight, and supplier infrastructure while effective core height involves core pressure drop (pebble), axial neutronic stability (prismatic), fuel handling (prismatic), and center structure reflector design (pebble). The annular active core thickness in the pebble core is strongly influenced by control rod effectiveness.

The remainder of this report is based on a comparative evaluation of the two reference designs summarized in Table 20.1.3. It is important to understand that the results of this evaluation are impacted by the design approaches and specific design selections taken by the two respective design teams. Two examples may help to illustrate this point.

If rather than both teams selecting the same core outlet temperature of 950 ^{o}C, both had used the same criteria for maximum fuel temperature limit of 1250 ^{o}C during normal operation, the evaluation would flip from the pebble core having superior normal operation fuel performance to having superior process heat delivery. The advantage would stay with the pebble core technology, but for different reasons.

If both teams had selected the German UO_2 fuel particle design, both would have a much smaller fuel development program within the NGNP schedule, but the prismatic core refueling interval would be shortened to stay within the burnup envelope of that fuel type, further aggravating its disadvantage relative to capacity factor.

20.1.4 DISCRIMINATING CRITERIA FOR PEBBLE AND PRISMATIC DESIGNS

A direct comparison of the merits of the reference pebble and prismatic process heat designs requires that the designs be compared on the basis of specific and relevant discriminating criteria. The following criteria and their relative weight (WEIGHT) have been selected to permit the desired comparative evaluation:

- Readiness
  - Design maturity and limited enabling technology R&D required (HIGH)
  - Vendor/supplier infrastructure (MEDIUM)
- Performance
  - Process heat delivery (HIGH)
  - Capacity factor/investment protection (MEDIUM)
  - Public safety (HIGH)
  - Safeguards (MEDIUM)
  - Wastes and other environmental impact minimization (MEDIUM)
  - Cost competitiveness (HIGH)
- Enhancement Potential
  - Fuel cycle flexibility and enhancement opportunities (LOW).

These criteria are judged to be sufficiently broad as to apply to the important differences between the reference designs for the pebble and prismatic cores proposed for hydrogen/process application. The grouping into readiness, performance, and enhancement potential is consistent with the aims of the NGNP. The criteria themselves are weighted by their perceived importance to the commercialization of the NGNP. It is understood that some of these criteria may be impacted more by other systems, structures, and components within the plant than the reactor, for example, capacity factor. The focus here though is limited to the comparison of the fuel element and the corresponding reference reactor designs. In some cases, both fuel element technologies are comparable, for example, with respect to process heat delivery, both are typically designed to operate at part power compatible with the operational needs of the process industry.

Readiness and Design Maturity – Readiness of the pebble and prismatic core designs can be evaluated in terms of the maturity of technologies related to fuel manufacturing and testing, component and material availabilities, and circulators. Table 20.1.4 compares the status of fuel manufacturing and experience for PBMR PHP (pebble) and H2-MHR (prismatic) fuels. The table illustrates that the PBMR PHP clearly has the advantage in terms of confirmed fuel quality, irradiation test data, heatup testing, need for fuel qualification, and supplier options.

Material availabilities for the PBMR PHP and H2-MHR process heat systems can be compared as another measure of readiness. The reference graphite selected for the PBMR is SGL grade NBG-18 and it is commercially available in the billet sizes needed. As yet, reference grades of graphite for the reflectors, fuel blocks, etc. for the H2-MHR have not been selected. The PMBR utilizes LWR reactor vessel steels (SA-533 Grade B, Class 1 plates and SA-508 Class 3 forgings) as its reactor vessel material while, because of the much higher vessel temperatures chosen for the H2-MHR, modified 9Cr-1Mo ferritic/martenitic steel has been selected. Although such 9Cr materials have been used extensively in fossil and chemical application, they have not seen service as reactor pressure vessel steels. It can be expected that a modified 9Cr reactor pressure vessel would receive considerable regulatory scrutiny. The 6.5 m diameter of the PBMR PHP is amenable to fabrication by multiple suppliers, including ENSA, MHI, AREVA, Doosan, and Japan Steel. Only Japan Steel may be able to fabricate the 7.2 m diameter of Modified 9Cr-1Mo and even this capability has not been demonstrated. The core barrel materials for the PBMR PHP are lower temperature materials (SA-336/SA-387) fully ASME qualified for the conditions needed; the H2-MHR utilizes Alloy 800H which may require

Table 20.1.4 Fuel Manufacturing Experience and Testing

Parameter	PBMR PHP	H2-MHR	Comments
Confirmed fuel quality in production scale facility	NUKEM/FZJ proved high quality	GA demonstrated requisite quality	PBMR PHP fuel quality will meet or exceed German fuel quality; PBMR PHP will demonstrate quality in pilot fuel plant for DPP
Irradiation test data on manufactured fuel	Extensive capsule tests meet performance criteria up to 1250^{0}C	Limited capsule tests showed higher failure rate than required	PBMR-German fuel performance data base is much stronger than for prismatic fuel; PBMR PHP to demonstrate irradiation performance of manufactured fuel
DLOFC heatup testing	Extensive heatup testing in excess of 1600^{0}C	Limited heatup testing	As above
Need for qualifying fuel from new production facility	Confirmation of earlier German performance required	Qualification and confirmation required	Prismatic lack of proven fuel production is a major development risk
Supplier options	PBMR pilot fuel plant in RSA for initial core and early reloads; joint venture in the US to follow	Expand BWXT or NFI for initial core and early reloads	Pebble fuel supply infrastructure much more advanced than prismatic

further qualification under DLOFC conditions. Clearly, the PBMR PHP uses state-of-the-art structural materials and this reduces development risks and costs.

Primary circulator conditions related to both the PBMR PHP and H2-MHR are shown in Table 20.1.5. Note that the PBMR PHP circulator has lower power requirements and is within the temperature range of demonstrated circulators.

Table 20.1.5 PBMR PHP and H2-MHR Circulator Conditions

Parameter	PBMR PHP	H2-MHR	Comments
Core thermal power (MW)	500	600	PBMR PHP selected lower thermal output
Coolant inlet temperature (°C)	350	590	PBMR PHP circulator temperature within experience
Core mass flow (kg/s)	160	320	PBMR PHP lower flow rate due to higher temperature rise and lower power
Core inlet pressure (MPa)	9.0	7.1	PBMR PHP selected higher pressure
Core pressure drop (%dP/P)	2.2	0.8	PBMR PHP has greater resistance and taller core
IHX pressure drop (%dP/P)	0.6	0.4	PBMR PHP has greater temperature decrease due to the hydrogen production process selected
Ducting pressure drop (%dP/P)	0.6	0.1	PBMR PHP has conservative losses, and more ducting
Total primary pressure drop (kPa)	307	100	PBMR PHP has greater overall pressure drop
Circulator compressor power (MWt)	8.9	10.2	PBMR PHP needs less circulator power

Readiness and Vendor/Supplier/Regulatory Infrastructure – The plant and fuel vendor/supplier team for the PBMR PHP builds on PBMR's established international supply teams for the DPP and ongoing PHP project initiatives plus the Westinghouse-led NGNP team. Development of the H2-MHR vendor/supplier team is expected to evolve from the GA/Russian GT-MHR program for weapons Pu disposition and/or the AREVA-led ANTARES studies as well as both of their NGNP related developments. The fuel supply team for the PBMR PHP builds on a full transfer of German (NUKEM) know-how for pebble fuel manufacture and there is a joint venture under development with NFS for a US supply base. Initial core supply options for the H2-MHR are limited to NFI and possibly BWXT. In addition, an AREVA-based company for gas reactor fuel supply is in an early stage of development.

Related to the fuel system is the equipment for refueling. PBMR has a full-scale, operating temperature test facility for the DPP pebble core recirculation system. The block fuel refueling and handling technology is limited to experience concluded approximately 25 years ago.

All things considered, there is a clear advantage for the PBMR PHP with regard to vendor/supplier infrastructure.

Performance and Process Heat Delivery – Normal operation NHS effectiveness relative to PBMR and H2-MHR process heat delivery can be evaluated considering normal operation fuel temperature and fuel performance, fuel enrichment and burnup, and as-manufactured fuel. Various normal operation fuel temperature parameters are shown and commented on in Table 20.1.6. It is obvious from the PBMR PHP versus H2-MHR comparisons that, for the same core outlet temperature, the PBMR PHP has lower average and maximum fuel temperatures. IHX metallic materials limit the core outlet temperature in both cases.

Table 20.1.6 Comparison of Normal Operation Fuel Temperatures

Parameter	PBMR PHP	H2-MHR	Comments
Core inlet temperature (°C)	350	590	H2-MHR will require high temperature circulator R&D
Fuel element-coolant temperature rise (°C)	~50-70	~100-200	Pebble core fundamental advantage
Core outlet temperature (°C)	950	950	Prismatic fuel experience limited to 750°C in FSV; AVR fuel operated at 950°C for 900 days
Average fuel temperature (°C)	819	>900?*	Pebble fuel lower temperature
He mixing & cross flow between high & low power fuel	Extensive	Minimal	Pebble core fundamental advantage
Normal operation maximum fuel temperature limit (°C)	1250	1350	The higher limit selected by the H2-MHR will require additional fuel development
Normal operation maximum fuel temperature (°C)	~1150	1250-1350	PBMR PHP has margin relative to the selected limit

*Question marks indicate that this parameter is not provided in the reference description.

Limiting normal operation fuel performance parameters are compared in Table 20.1.7. Average and peak fuel temperatures and the fractions of fuel at temperatures above 1000^0C through 1300^0C are lower for the PBMR PHP than for the H2-MHR; peak burnup is also lower. As a result, much lower normal operation radionuclide releases can be expected for the pebble system. The last row in the table is a judgment of the cumulative impact of these factors on the normal operation fuel performance for the two cores. Both are assumed to have the same fuel quality from the manufacturer (~6 x 10^{-5}), but primarily because of the higher core temperatures, the pebble core releases will be lower. (Recall that as discussed in Section 20.1.3 if both designs had assumed the same normal operation core temperature limit, the releases would be more comparable, but then the pebble core advantage would show up in a higher core outlet temperature for the process.) The lower releases mean a lower circulating activity of noble gases and other volatiles that are a potential source term in the event of small leaks in the HPB. Additionally, lower halogen, silver, and cesium releases mean less personnel doses during scheduled and unscheduled maintenance. This is particularly important to direct cycle designs with turbomachinery in the primary circuit and for the prismatic designs that require opening the HPB for frequent refueling.

There are significant differences in fuel enrichment loadings and burnup between the PBMR PHP and the H2-MHR. For the PBMR PHP, enrichment is about 5% for the initial startup core and 9.6% at equilibrium. This is consistent with the German fuel experience base. The prismatic core adapts an enrichment of 19.8% for fissile particles, which translates to about a 14% average including natural U fertile particles. US enrichment capability for LWRs is limited to ~5%. This will need to be extended to higher values for the PBMR PHP and even

Table 20.1.7 Comparison of Limiting Fuel Performance Parameters

Parameter	PBMR PHP	H2-MHR	Comments
Average fuel temperature (°C)	~835	>900?*	PBMR PHP temperature lower
Volume of fuel >1000°C (%)	~10	>15?	PBMR PHP temperature lower
Volume of fuel >1100°C (%)	~1	>10?	PBMR PHP temperature lower
Volume of fuel >1200°C (%)	0	>5?	PBMR PHP temperature lower
Volume of fuel >1300°C (%)	0	2	PBMR PHP temperature lower
Peak fuel temperature (°C)	~1155	1250-1350	Distinct PBMR PHP advantage
Peak burnup (MWd/mt U)	104,000	135,000	PBMR PHP advantage relative to fuel performance
Duration of fuel in high fluence and high temperature locations	Pebbles pass through full range of conditions	Fuel in same position throughout refueling interval	Pebbles also rotate so there is not a constant temperature gradient on an element
Location of high burnup fuel	Passes thru high temperature region	Can be placed in lower temperature regions during refueling	Potential H2-MHR advantage
Expected fraction of normal operation fuel failure	~10^{-4}	10^{-3}?*	PBMR PHP overall advantage

*Question marks indicate that this parameter is not provided in the reference description.

further for the H2-MHR. Both systems would probably utilize a blend-down of HEU until market conditions warrant enrichment supply capability. Average and peak burnups in the pebble fuel will be on the order of 90,000 and 104,000 MWd/mt U, respectively. Values of average and peak burnup for the prismatic fuel are about 120,000 and 135,000 MWd/mt U, respectively. Hence, the PBMR PHP requires more U-235, but at a lower enrichment which offsets the cost impact. In either case, the level of burnup results from the economic optimization of the costs of uranium, enrichment, and fabrication.

A final advantage of pebble versus prismatic fuel is the volume fraction of coated particles in the fueled region of the pebbles vs. the fuel compacts of the prismatic blocks. In the pebble spheres it is about 8.5 % (9 g per sphere), while in the prismatic fuel the average loading is 15% with a 30% maximum. This difference provides a distinct advantage in that the risk for damage of particles during the fuel form manufacturing process is much less and, consequently, meeting as-manufactured fuel quality specifications should be much easier for the pebble concept.

Consideration of reactivity, reactivity control systems, and shutdown margins are also important to the question of performance in delivering process heat. The PBMR PHP has a requirement for 1.4% excess reactivity during normal operation at hot conditions and the control rods alone provide the requisite reactivity control. (This is addressed further below in connection with shutdown margins and reactivity control systems.) In comparison, excess reactivity of 3.9-4.5% is needed for the H2-MHR prismatic core and is provided by a combination of control rods and lumped burnable poisons. Given the above, reactivity control is simplified for the PBMR PHP versus the H2-MHR.

Table 20.1.8 describes the shutdown margin requirements and capabilities for the PBMR PHP and the H2-MHR. The information given in the table shows that reactivity requirements for shutdown of the PBMR PHP are considerably less than those for the H2-MHR and that the PBMR PHP shutdown margin is greater. The PBMR PHP can achieve cold shutdown with either the control rods or the RSS at anytime during its life. Note that the H2-MHR cannot achieve cold shutdown at the beginning of the equilibrium cycle (BOEC) on the RSS alone. Twenty-four control rods in the side reflector and 8 RSS channels in the center reflector provide reactivity requirements for the PBMR PHP. The larger reactivity requirement for shutdown of the H2-MHR is provided by 48 control rods (36 in the side reflector and 12 in the core) and by 18 RSS channels (all in the core). In short, the PBMR PHP needs less and simpler reactivity control throughout its lifetime.

Table 20.1.8 Shutdown Margins for the PBMR PHP and the H2-MHR

Parameter	PBMR PHP	H2-MHR
Requirement		
Operation hot-to-cold (20°C) (%dk/k)	~4.0	5.2-7.2 BOEC*
Xenon decay (%)	~3.0	3.8-3.9 BOEC
Burnup (%)	Negligible	3.6-4.5 BOEC
Uncertainty/margin (%)	1.0	1.2-1.0 BOEC
Total (%)	~8.0	13.8-16.0 BOEC
Capabilities		
Worth of all control rods, cold (%)	~8.4	18.9-18.7 BOEC
Worth of all RSS (%)	~12.0	11.9-11.0 BOEC

*BOEC = Beginning of Equilibrium Cycle

Performance and Capacity Factor/Investment Protection – Capacity factor and investment protection as related to performance is evaluated here in terms of fuel handling outages, graphite mechanical stresses, graphite dust, and replacement of the graphite reflectors.

Fuel handling is the primary reactor auxiliary system that is impacted by the choice of fuel element and associated reactor core. By comparison, impacts on the helium inventory and purification system, the auxiliary shutdown forced cooling system, the reactivity control systems, and the reactor cavity cooling system are secondary. The fuel-handling rate for the PBMR PHP is proposed as 1111 spheres/day/fuel train over a 12-hour day. The rate in the AVR was 500 spheres/day/train and for the THTR it was 3700 spheres/day/train. Therefore, the fuel-handling rate for the PBMR PHP is certainly within the experience base. Total experience for reactor on-line refueling was some 28 years between the AVR and the THTR. It is recognized that the portions of the FHS form part of the HPB and will receive special treatment commensurate with their risk-significance. The South African DPP fuel handling experience will also be factored in as it becomes available. The H2-MHR will require the replacement of ~100 fuel blocks/day with the reactor down and depressurized during each refueling outage. During operation of FSV, the handling rate was ~17 blocks/day and included three refuelings over a period of 5 years. Scheduled outages for refueling are 0% for the PBMR PHP and 4.4% (~16 days/year) for the prismatic system. Frequent usage of the PBMR core FHS may increase its failure frequency. However, the PBMR PHP can continue to operate at power without the circulation of spheres for up to 20 days. Therefore, most Fuel Handling System (FHS) failures can be accessed without downtime. The unscheduled outage rates associated with refueling of the AVR and the THTR were ~3% and ~6.3%, respectively. Unscheduled outages associated with the refueling of FSV amounted to 4%. One positive factor for the prismatic FHS is that equipment maintenance is performed off-line. However, on the whole, the pebble core has the potential for a significant capacity factor advantage over the prismatic core.

Stresses in the graphite fuel components of the PBMR PHP and the H2-MHR as well as graphite dust generated in both systems are important performance questions relative to capacity factor and investment protection. There is no issue with respect to stresses in the pebble fuel spheres but there will be high internal stresses in the prismatic fuel blocks. This gives rise to the potential for broken fuel blocks and possible resulting core and circuit blockage. However, it is worth noting that, although cracks were found in some FSV blocks, this led to no serious problems. Even so, the advantage here goes to the pebble core. On the other hand, repeated impacts to the irradiated pebble fuel spheres as they exit the core add to the risk of forced outages as a result of FHS stoppage. The only potential impacts to the irradiated prismatic fuel blocks and reflectors would be as a result of seismic activity. The PBMR PHP reflectors also need to resist seismic loads.

Graphite dust will be generated in the PBMR PHP as a result of the rubbing of the fuel spheres within the FHS and the reflector wall. In the H2-MHR, dust can result from rubbing between fuel blocks, for example during refueling, and from fuel block machining debris. Experience with the AVR indicated a graphite dust generation rate of ~3 Kg/year. This was attributed to abrasion within the FHS. The AVR had a dust filter in the FHS. The PBMR PHP estimate for dust is ~6 Kg/yr, primarily within the FHS which has a dust filter as well. Very little graphite dust was generated in FSV. The FSV dust filter was in the helium purification side stream of the primary circuit.

There should be little if any effect of graphite dust on maintenance or radionuclide release during an HPB leak for either the PBMR PHP or H2-MHR; both incorporate dust filters. The IHX will have some dust deposits in stagnant and quiescent places, but the flow velocity as well as the small size of the dust particles makes it unlikely that there will be clogging or loss of effectiveness of the IHX. This will have to be confirmed during the design of the IHX. However, the level of circulating activity associated with graphite dust should be lower for the PBMR PHP than for the H2-MHR because of the lower normal operation fuel temperatures for the 950C core outlet reference design. Overall, however, the effects of graphite dust on the performance of both process heat systems should be negligible and meet requirements.

Another factor relating to capacity factor and performance is reflector lifetime and replacement. The plan for the PBMR PHP is to replace the replaceable center and side reflectors after 15 to 20 years while the H2-MHR would replace these reflectors during scheduled refueling outages at an average of every 6 years. The 6-year replacement lifetime is based on bowing and cracking predictions but would be dependent on the graphite grade utilized. The duration for the replacement of the PBMR PHP reflectors would be ~190 days. There are only limited provisions provided for the replacement of the PBMR PHP large permanent reflectors and core support blocks; provisions are provided for these replacements in the case of the H2-MHR. The irradiation and other service duties on these components are substantially less than for the replaceable components. Relative to reflector replacement, the prismatic system has the advantage.

Performance and Public Safety – The public safety aspects of performance can be analyzed as functions of core thermal power and temperature, fuel behavior during DLOFC events, graphite oxidation, and licensing acceptability criteria. Table 20.1.9 lists fuel and fuel temperature parameters for both the PBMR PHP and the H2-MHR and provides comparative

Table 20.1.9 Core Parameters for the PBMR PHP and H2-MHR

Parameter	PBMR PHP	H2-MHR	Comments
Radially fueled core thickness (m)	.85	.935	PBMR limited by reflector control rod effectiveness
Radially fueled core effective height (m)	11.0	7.93	H2-MHR approaching the limit for axial neutronic stability
Core volume (m^3)	84	92	H2-MHR higher
Fuel element power density (MWt/m^3)	9.8	8.26	PBMR PHP greater
Core packing fraction	0.61	0.80	Pebble-prismatic fundamental difference
Core power (MWt)	500	600	H2-MHR higher
Initial average fuel temperature (^0C)	~835	>900?*	PBMR PHP less
Peak DLOFC fuel temperature (^0C)	<1670	<1600	PBMR PHP selected higher temperature limit
Reactor vessel temperature limit (^0C)	371 to 482 for 3000 hr, 482-538 for 1000 hr	495?	H2-MHR selected a higher temperature material but it has not yet been used for reactor vessels
Peak DLOFC reactor vessel temperature (^0C)	~455, >371 for 65 hrs	420?	Comparable, but H2-MHR not limited in time at elevated temperature

*Question marks indicate that this parameter is not provided in the reference description.

comments. Note that the H2-MHR has selected a larger reactor vessel to provide more fuel volume radially, but is more limited in the axial direction by neutronic stability concerns. The resultant greater core volume of the H2-MHR together with the respective fuel element power densities and the fundamental core packing fraction difference nets out to an advantage for the H2-MHR in terms of power rating and peak fuel temperature during a Depressurized Loss of Forced Cooling (DLOFC).

Table 20.1.10 addresses fuel performance and radionuclide release in a DLOFC event. With respect to fuel performance and public safety, comparison of the PBMR PHP and the H2-MHR involves a balancing of the presumed fraction of initially failed fuel from normal operation (judged to be an order of magnitude less for the pebble fuel) against peak fuel temperatures during a DLOFC (slightly higher for the PBMR PHP) and the small fraction of PBMR PHP fuel at >1600^{0}C. Radionuclide release from initially failed fuel will certainly be less for the PBMR PHP but release resulting from heatup during the DLOFC could be slightly higher. Overall, total release from the PBMR PHP fuel will likely be lower.

Table 20.1.10 DLOFC Fuel Performance Comparison

Parameter	PBMR PHP	H2-MHR
Expected fraction of failed fuel during normal operation	~10^{-4}	10^{-3}?*
Average fuel temperature (^{0}C)	~835	>900?
Volume of fuel >1400^{0}C (%)	~12	>10?
Volume of fuel >1500^{0}C (%)	~15	>10?
Volume of fuel >1600^{0}C (%)	~7	0
Peak fuel temperature in DLOFC (^{0}C)	<1670	<1600
Radionuclide release from initially failed fuel	Less than H2-MHR	>PBMR PHP
Radionuclide release from fuel failed during DLOFC	Slightly more than H2-MHR	<PBMR PHP

*Question marks indicate that this parameter is not provided in the reference description.

The question of graphite oxidation due to ingress of air or water (particularly in steam cycle systems) is a longstanding, but largely overblown, concern for HTGR concepts during events such as the DLOFC. In the present comparison, the higher flow resistance of the pebble core helps to limit the air supply relative to the prismatic core. However, fuel element surface area exposed to air is greater for the pebble core. Both systems should be acceptable for air ingress licensing basis events.

The licensing acceptability/public safety aspects of the pebble and prismatic core designs can be further examined as a function of a number of factors related to shutdown and to off-normal events. Shutdown margins with control rods and RSS are significantly better for the PBMR PHP than the H2-MHR. This is true also for beyond DBE rod withdrawal incidents. Normal operation radionuclide releases are deemed acceptable for the PBMR PHP but only marginal for the H2-MHR and the latter will have to deal with higher maintenance doses. Releases resulting from a HPB leak or break should also be acceptable for the PBMR PHP but the H2-MHR may have to provide active filters and/or other active mitigation systems to limit releases. The PBMR PHP has selected a reactor design that results in a DLOFC peak fuel temperature of ~1670^{0}C. Regulators will certainly require additional justification for higher temperatures. Even so, radionuclide releases from the pebble core as a result of a DLOFC should be acceptable. There is a concern during normal operation for the H2-MHR fuel performance due to the higher temperatures for the 950^{0}C core outlet that will lead to higher releases from the initially failed fuel during DLOFC events. Overall, the PBMR PHP appears to have a safety/licensing advantage over the H2-MHR during normal operation and possibly during off-normal events.

Safeguards –Table 20.1.11 describes specific safeguards parameters and how they compare between the PBMR PHP and the H2-MHR. As a positive for the PBMR PHP, it requires a lesser fissile material inventory and has a lower enrichment than the H2-MHR. However, the potential for diversion of the fuel spheres is greater than that for the prismatic fuel blocks because of the relative size/weight of the fuel forms. The pebble and prismatic fuels have different pros and cons but both provide adequate safeguard assurances.

Table 20.1.11 Comparison of Safeguards Factors for the PBMR PHP and the H2-MHR

Parameter	PBMR PHP	H2-MHR	Comments
Front-End Enrichment and Inventory	9.6% LEU reloads utilized, ~0.9 kg/MWt fissile material loading	19.8% LEU utilized, ~1.1 kg/MWt fissile material loading	PBMR PHP has lower enrichment
Operational Diversion and Misuse Potential	On-line refueling increases potential	Batch fuel loads limit such potential	The PBMR PHP will require added surveillance; the IAEA is familiar with refueling in the THTR and with the DPP
Detection of U-238 Target Material	Readily detectable with one fuel cycle pass	Easily hidden	PBMR PHP advantage
Back-end Diversion and Misuse Potential	Pebble size and weight increase such potential, pebble has more Pu/GWd because of lower enrichment	The fuel block size and weight deter back-end diversion	PBMR PHP will require added surveillance to maintain control of the burned pebbles

Performance and Waste and Environmental Impact Minimization – The spent fuel storage volumes needed for the PBMR PHP and the H2-MHR are ~0.14 m^3/GWe-day and ~0.19 m^3/GWe-day, respectively. However, there is potential for spent fuel volume reduction for the PBMR PHP which is being researched. Similarly, push-out of the fuel compacts from the prismatic fuel blocks could also dramatically reduce the volume needed for spent fuel storage. Most importantly, the low power density of both fuel technologies translates into large volumes of fuel that is required for safeguard concerns, plus the isotopic mix is not conducive to proliferation. On the down side, volume reduction for either system would increase safeguards concerns and require added waste disposal. Storage volume and disposal will also be required for replaced reflectors and control rods. The PBMR PHP will need ~0.01 m^3/GWe-day for the reflectors and ~0.0002 m^3/GWe-day for control rods. This is less than the storage volumes required for the H2-MHR reflectors and control rods (~0.07 and ~0.001 m^3/GWe-day).

Performance and Cost Competitiveness – Cost competitiveness can be evaluated in terms of capital cost, efficiency, capacity factor, fuel cost, and O&M. With respect to capital cost, the PBMR PHP will be able to build on the experience with the DPP while the H2-MHR will experience the full FOAK costs and will have more expensive components (e.g., circulator, reactor vessel, and core barrel). The PBMR PHP should certainly have a capital cost advantage for early plants but the advantage will likely shift to the H2-MHR for equally mature plants, due to the higher power rating. The PBMR PHP should be superior to the H2-MHR in efficiency since there is less risk relating to achieving the 950^{0}C core outlet temperature. Capacity factor for the PBMR PHP should also be better, primarily because of on-line refueling and lower fuel temperatures. O&M costs should also be lower for the PBMR PHP because of lower levels of radionuclide release during normal operation from lower reactor operating temperature; and lower quantities of waste to be stored. Fuel costs for the PBMR PHP will be based on the experience with DPP and follow-on plants. The higher burnup to be achieved in the H2-MHR will tend to lower fuel cost but will be counterbalanced by the cost of higher enrichment, multiple fuel and poison loadings, and greater costs due to fuel reload complexity and QA. In summary, the PBMR PHP is comparably competitive in terms of cost to the H2-MHR and has lower risks.

Enhancement Potential and Fuel Cycle Flexibility – Based on the German experience, the PBMR PHP has an advantage in that the AVR plant has demonstrated the potential for operation with both HEU and various LEU spheres. However, the PBMR PHP has a disadvantage when it comes to enrichment changes within a modest reactivity domain. In this regard, the H2-MHR is superior because different burnable poison designs can be utilized in different batch loadings. The H2-MHR also has the advantage in terms of fuel changes (e.g., Pu/transuranic burning) within the major reactivity domain because of the option for burnable poisons and the potential to burn Pu/transuranic elements more fully with its softer neutron spectrum. There is only limited reactivity control flexibility for the PBMR PHP, but both systems would require major fuel development programs for such applications.

Enhancement Potential with Advanced Fuels, Materials, and Components – The PBMR PHP could go with higher temperature fuels, e.g. utilizing UCO, but also others such as ZrC coatings, if and when they are developed and demonstrated. In contrast, prior prismatic designs have assumed that UCO is available for core outlet temperatures of 700 to 850^{0}C and the H2-MHR assumes such advanced fuels will be developed in order to achieve a 950^{0}C core outlet temperature. In terms of materials and components, there is margin in the PBMR fuel and core to go to higher core outlet temperatures when higher temperature materials become available and code-qualified. This is also true relative to materials for the IHX (e.g., ceramics), the core barrel, and the reactor vessel. By contrast, the H2-MHR is predicated on a core barrel material that needs code qualification for the higher temperatures predicted during core heatup events and on a material that needs R&D for first-time use as a nuclear reactor vessel. As such, the pebble core has the advantage as higher capability materials become available, whereas the prismatic is already counting on them.

20.1.5 COMPARISONS RELATIVE TO DISCRIMINATING CRITERIA AND CONCLUSIONS

The pebble fuel PBMR PHP has a clear advantage over the prismatic block H2-MHR relative to R&D needs for fuel because of the German experience with UO_2 fuels development for and in the AVR and THTR and because of its lower normal fuel operation temperatures. DPP experience, especially the selection of LWR reactor vessel steels and other code-qualified materials, also results in much reduced R&D needs for the PBMR PHP.

The advantage for process heat delivery also goes to the PBMR PHP because of the much lower risk for achieving the desired very high core outlet temperature (950^0C). Prior prismatic designs with acceptable fuel performance during normal operation have had lower core outlet temperatures up to 850^0C. The capacity factor for the PBMR PHP should also be superior to that for the H2-MHR because of on-line refueling. Safety in terms of potential radionuclide releases should also be better for the PBMR PHP because of the demonstrated superior performance of the fuel and its lower normal temperature of operation.

The estimated unit capital cost for mature, multi-module plants is lower for the H2-MHR than for the PBMR PHP given identical assumptions. This is primarily because of the lower power level of the latter. However, resultant process heat or H_2 costs should be lower for the PBMR PHP because of its higher capacity factor, simpler fuel cycle and lower O&M costs. Altogether, the PBMR PHP is competitive with the H2 MHR concept at much lower overall risks.

Table 20.1.12 provides an evaluation of the PBMR PHP relative to the H2-MHR in terms of the discriminating criteria presented and discussed earlier. The comparison illustrates that for all of the discriminating criteria the PBMR PHP is better than or comparable to the H2-MHR.

In closing, pebble core technology offers many fundamental advantages over the prismatic core for high temperature process heat applications and adapts well qualified and demonstrated German-based fuel and on-line refueling experience. The PBMR PHP is superior in essentially all respects to the H2-MHR for the high temperature process heat/H_2 production NGNP. This is true primarily because of lower development costs and risks for the pebble fuel, minimization of development costs and risks because of the DPP baseline, a much stronger vendor/supplier infrastructure, and a higher performance capability. Lower fuel temperatures and normal operation radionuclide releases result for the same required process heat temperature and on-line refueling is consistent with continuous process industries. Finally, the PBMR PHP is attainable at lower overall forward costs and risks.

Table 20.1.12 Reactor Type Summary Relative to the Discriminating Criteria

Criteria	Weight	PBMR PHP versus H2-MHR	Basis
Readiness			
Design maturity and limited enabling technology R&D required	High	PBMR PHP Better	• German fuel experience • DPP design selections focused on near-term implementation
Vendor/supplier infrastructure	Medium	PBMR PHP Better	• Builds on DPP international team, including WEC/Shaw in the US
Performance			
Process heat delivery	High	PBMR PHP Better	• Pebble lower fuel temperatures for 950^{0}C core outlet
Capacity factor/ investment protection	Medium	PBMR PHP Better	• Pebble on-line fueling
Safety	High	PBMR PHP Better	• Pebble lower normal operation temperatures with demonstrated fuel
Safeguards	Medium	Comparable	• Both can meet requirements
Wastes and other environmental impact minimization	Medium	PBMR PHP Better	• Pebble lower releases and less fuel element and control rod volume
Cost competitiveness	High	Comparable	• Prismatic power level advantage but pebble utilizes available materials & on-line refueling
Enhancement Potential			
Fuel cycle flexibility and enhancement opportunities	Low	PBMR PHP Better	• Pebble more upside potential for advanced fuels and more margin for higher core temperatures

REFERENCES

20.1-1 ”Technical Description of the PBMR Demonstration Power Plant,” Pebble Bed Modular Reactor Pty. Ltd. document number 016956, Rev. 4, February 14, 2006.

20.1-2 “H2-MHR Conceptual Design Report SI-Based Plant,” General Atomics, Idaho National Laboratory, and Texas A&M University, GA A25401, April 2006.

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1. Gilbert Melese and Robert Katz, *Thermal and Flow Design of Helium-Cooled Reactors*, American Nuclear Society for the Department of Energy, La Grange Park, IL 1984.

2. Baumer, R et.al., *AVR – Experimental High-Temperature Reactor*, Association of German Engineers (VDI) – The Society for Energy Technologies (Publ.), VDI-Verlag GmbH, Dusseldorf 1990.

3. Karl Winnacker and Karl Wirtz, *Nuclear Energy in Germany*, American Nuclear Society, La Grange Park, IL 1979.

DEFINITIONS

None.

REQUIREMENTS

None.

LIST OF ASSUMPTIONS

General assumptions for this study include:

1. The respective fuel element designs compared are those described in References 20.1-1 and 20.1-2.

2. The reference process heat design for the prismatic fuel element (Reference 20.1-2) is representative of those under consideration for the NGNP.

3. The PBMR DPP reactor rated at 400 MWt with a helium core outlet temperature of 900^0C is essentially identical to the PBMR PHP reactor rated at 500 MWt with a helium core outlet temperature of 950^0C achieved by lowering the core inlet temperature.

4. The comparisons are based on a core outlet temperature of 950^0C, which is compatible with the NGNP priority on hydrogen production applications.

TECHNOLOGY DEVELOPMENT

None.

APPENDICES

APPENDIX 20.1.1 PRESENTATION SLIDES, "20.1 REACTOR TYPE SPECIAL STUDY," DECEMBER 6, 2006

The slides presented on this special study at the December 2006 monthly meeting at the Shaw Group offices in Stoughton, MA are attached.

APPENDIX 20.1.1: PRESENTATION SLIDES,"20.1 REACTOR TYPE SPECIAL STUDY," DECEMBER 6, 2006

20.1 Reactor Type Special Study

December 6, 2006

Objectives

- **Identify discriminating criteria for reactor type evaluation with emphasis on process heat and hydrogen production applications**
- **Comparatively assess the relative merits (pros and cons) of the pebble bed and prismatic modular HTGR core concepts**
  - Pebble bed based on 500MWt 950C core outlet temperature
  - Prismatic based on 600MWt 950C core outlet temperature (reference: H2-MHR Conceptual Design Report SI-Based Plant, GA, INL, Texas A&M, GA-A25401 April 2006; AREVA prismatic design assumed to be very similar)
- **Provide basis for reactor concept for NGNP**

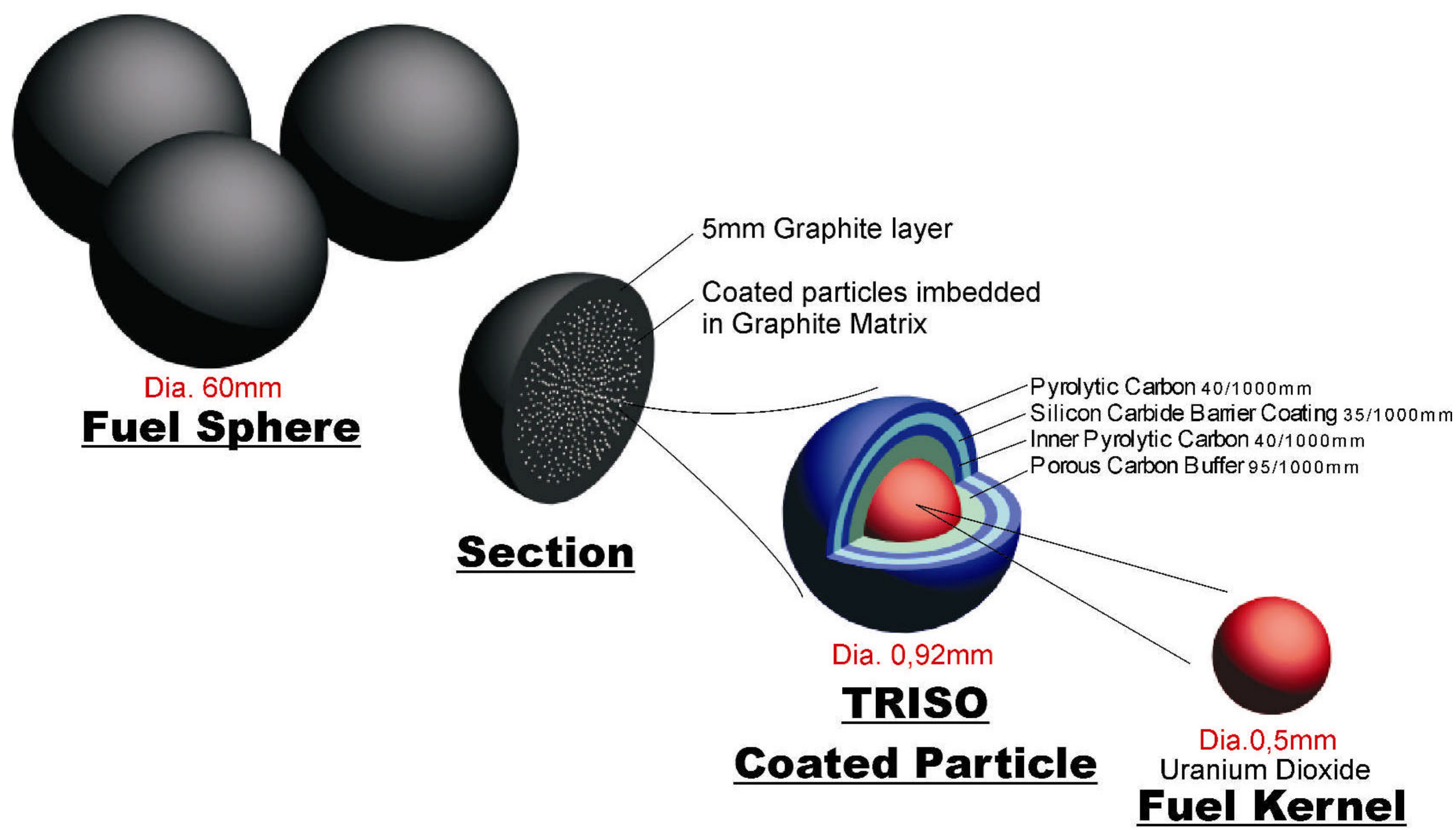
Presentation Outline

- ➔ Background
- Fundamental pebble-prismatic fuel element and core differences
- Reference PBMR and prismatic process heat reactor designs
- Discriminating criteria
- Comparative evaluation
- Summary

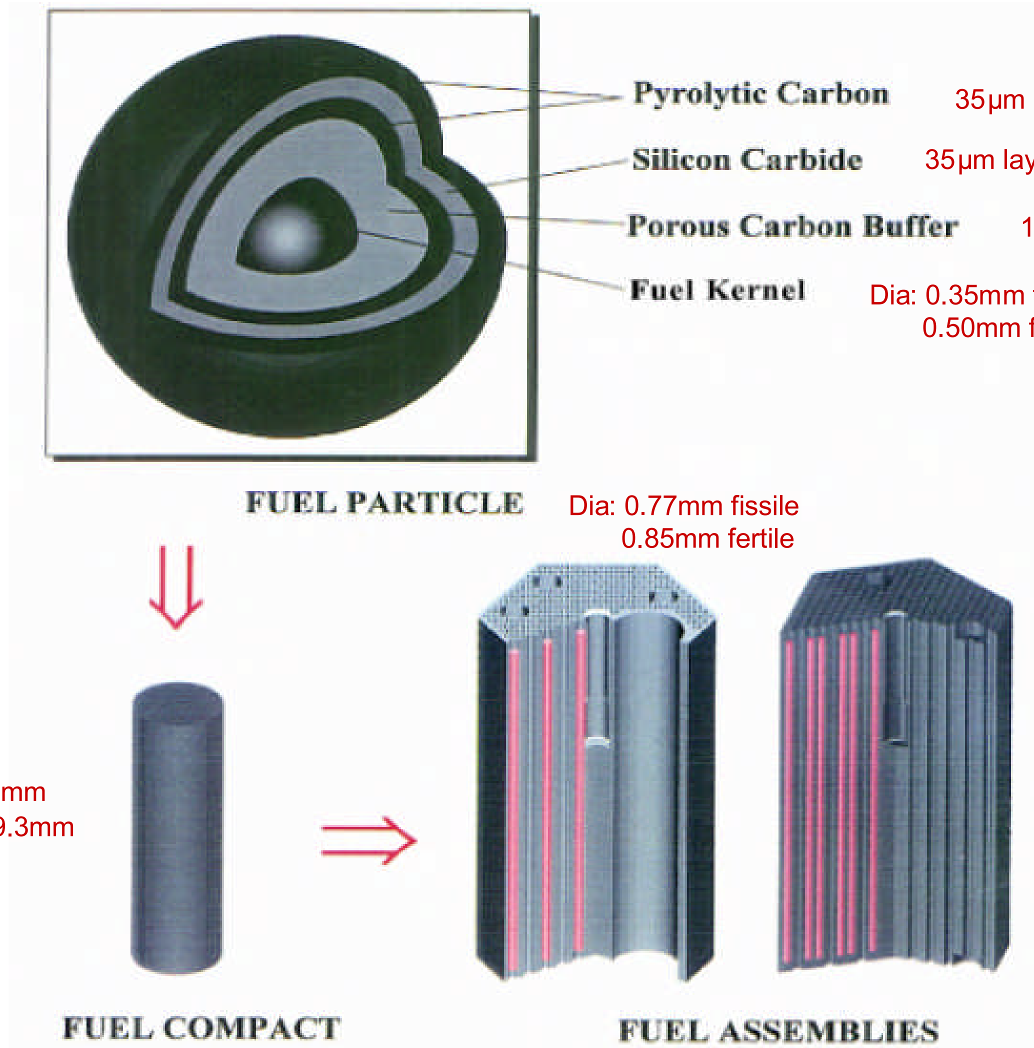
Fuel Performance is Key to Modular HTGR Safety Design Approach

- **Based on inherent properties of fuel, moderator, and coolant**
- **Fuel is primary barrier for radionuclide retention**
  - High quality manufacturing
  - **Normal operation performance to limit sources of prompt releases from potential leaks/breaks in the Helium Pressure Boundary (HPB)**
  - **Off-normal performance to limit delayed releases from long-term heatup of the fuel from potential leaks/breaks in the HPB**
- **Emphasis on passive design features to perform safety functions for radionuclide retention within the fuel**
  - Remove core heat
  - Control heat generation
  - Control chemical attack
  - Maintain core geometry
- **Additional concentric, independent barriers (HPB and reactor building) provide defense-in-depth and safety-margins**

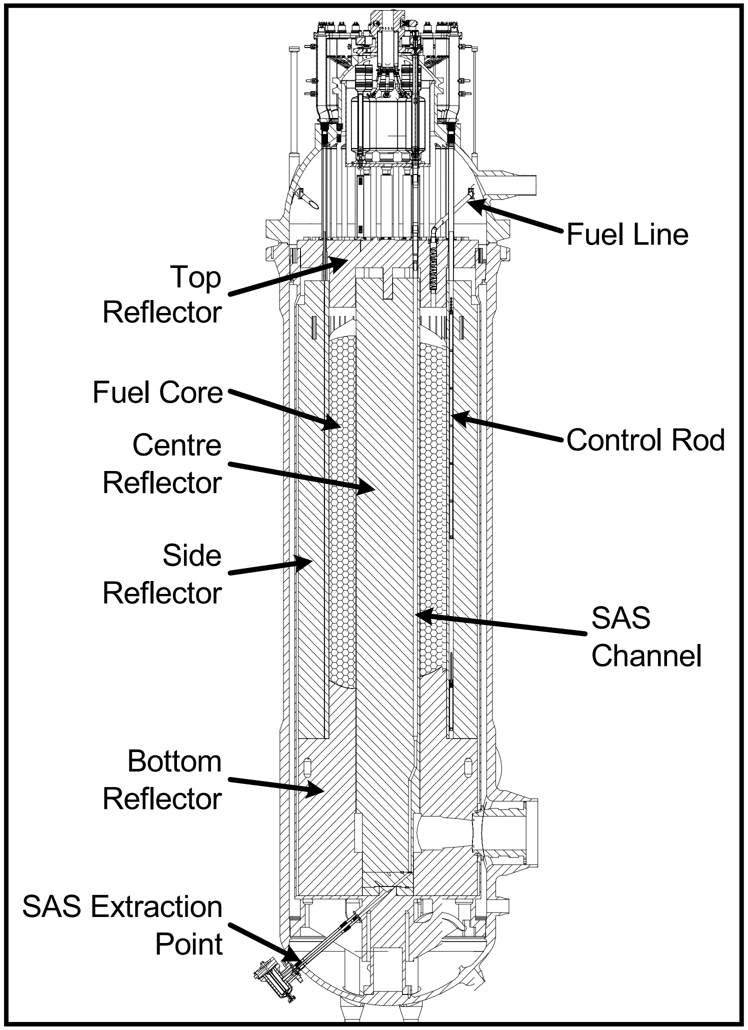
Pebble Sphere Fuel Element Designs

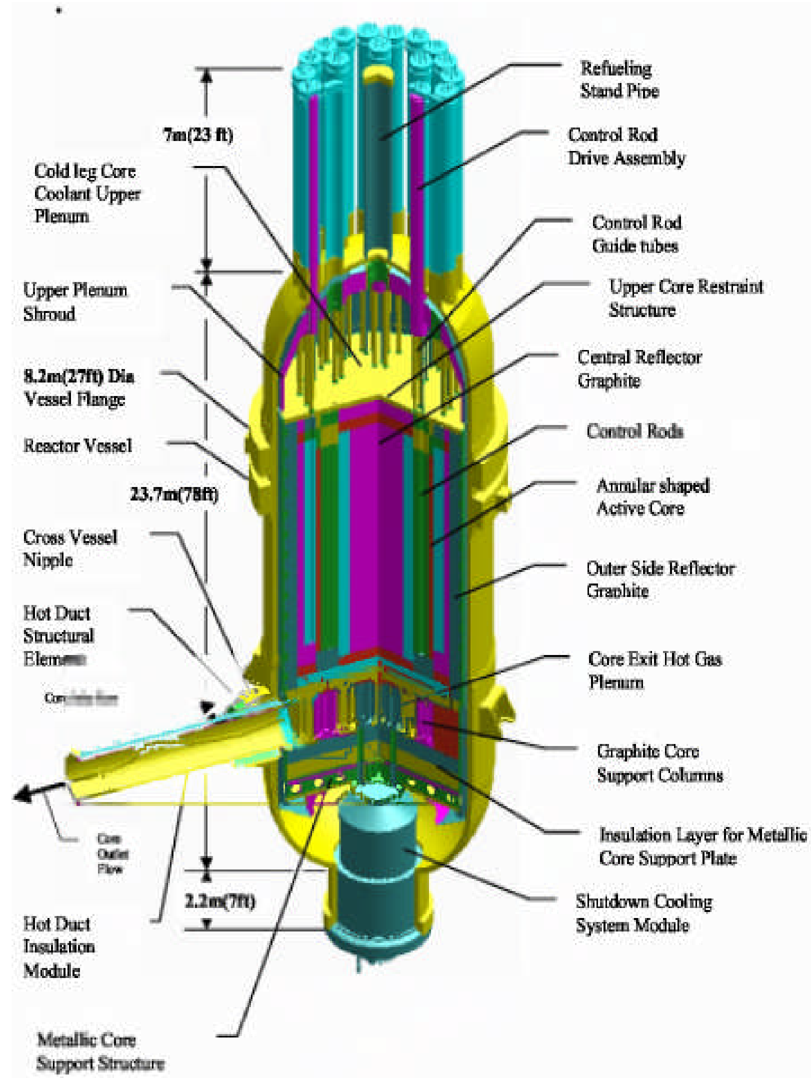


Prismatic Block Fuel Element Design



Comparison of Pebble Bed and Prismatic Core Concepts





Presentation Outline

- Background
- ➔Fundamental pebble-prismatic fuel element and core differences
- Reference PBMR and prismatic process heat reactor designs
- Discriminating criteria
- Comparative evaluation
- Summary

Fundamental Difference: Fuel Arrangement within Fuel Element

Fundamental: fueled region of pebble has lower packing fraction of fuel particles than prismatic fuel compacts

- **Influence: fuel performance**
  - pebble fuel particles have less chance of compacting process-induced failures

Fundamental: fueled region of pebble has lower particle density than prismatic fuel compacts

- **Influence: fuel performance**
  - pebble has lower maximum and average fuel temperatures during normal operation

Fundamental Differences: Fuel Element-Coolant Geometry

Fundamental: pebble fuel overall closer to the coolant

- **Influence: normal operation fuel temperatures**
  - for the same normal operation maximum fuel temperature limit, the pebble core can achieve a higher core outlet temperature

  or

  - for the same core outlet temperature, the pebble core has lower normal operation maximum fuel temperatures

Fundamental Differences: Fuel Element-Coolant Core Geometry

Fundamental: pebble core has more coolant volume

- **Influence: axial neutronic stability**
  - for the same core height, pebble bed has greater axial neutronic stability

  or
  - pebble core not as limited in height
- **Influence: power level**
  - for the same fuel element (solid) power density, core volume and geometry & peak fuel temperature limit during Depressurized Loss of Forced Cooling (DLOFC) events, the prismatic core can achieve a higher power level

Fundamental Differences: Fuel Element-Coolant Core Geometry (cont)

Fundamental: pebble core has greater resistance to flow

- **Influence: heat transfer**
  - pebble core has better heat transfer from fuel element to coolant
- **Influence: circulator/compressor power**
  - for the same core height & helium pressure, the prismatic core has a smaller pressure drop through the core
- **Influence: natural convection during Pressurized Loss of Forced Cooling (PLOFC)**
  - pebble core design has less natural convection to transfer heat to challenge the upper core metallic components and to the reactor vessel

Fundamental: pebble core has greater mixing of coolant

- **Influence: core outlet components and IHX/turbine performance**
  - pebble core has reduced hot streaks

Fundamental Difference: Core Refueling

Fundamental: pebble core refueled on-line

- **Influence: scheduled outages for refueling**
  - pebble core has no scheduled outage for refueling – better suited for continuous process heat based industries
- **Influence: fuel burnup**
  - pebble core has more flexibility in choosing optimum burnup for fuel performance; prismatic design has less flexibility in order to achieve economic refueling interval
  - pebble core has continuous measure of each fuel elements burnup; no analyses or margin needed to cover range of conditions
- **Influence: forced outages associated with fuel handling**
  - most unplanned outages of pebble fuel handling system can be repaired without impacting reactor availability
- **Influence: excess reactivity**
  - pebble core has less excess reactivity so that required control rod and reserve shutdown worths are smaller
- **Influence: reflector replacement during plant lifetime**
  - pebble core requires core unload every 15-20 years for replacement of the reflector; prismatic core replaces a fraction of the reflector as part of the off-line refueling

Fundamental Difference: Equilibrium Core Conditions

Fundamental: pebble core at equilibrium conditions >90% of its lifetime;

- **Influence: fuel manufacturing and reload complexity and QA**
  - Pebble core has a one particle with single enrichment in initial core and single (but different) enrichment after initial startup; whereas, the prismatic core zones fissile and fertile fuel loadings and uses burnable poisons within fuel elements rearranged every refueling outage
- **Influence: fuel performance**
  - pebble core is more homogeneous - less extremes in fuel performance demands

Pebble - Prismatic
Summary of Fundamentals

- **Pebble core has higher outlet temperature for a given normal operation maximum fuel temperature limit**
  - lower power density within fueled region of fuel element
  - lower heat transfer resistance from fuel to fuel element surface
  - greater heat transfer from surface of fuel to coolant
- **Prismatic core can achieve greater power within a given core volume & geometry, a given fuel element (solid) power density, and a given DLOFC maximum fuel temperature limit**
  - lower coolant void fraction
- **Pebble core can be taller**
  - Not limited by axial neutronic stability
- **Pebble core reduces hot streak potential to core outlet components**
  - greater coolant mixing
- **Pebble core requires larger circulator/compressor**
  - higher resistance to flow
- **Pebble on-line refueling offers basis for higher capacity factor and simplifies fuel manufacturing and reload complexity and QA**

Presentation Outline

- **Background**
- **Fundamental pebble-prismatic fuel element and core differences**
- ➔ **Reference PBMR and prismatic process heat reactor designs**
- **Discriminating criteria**
- **Comparative evaluation**
- **Summary**

Pebble and Prismatic Core Process Heat Designs
(denoted PBMR PHP and H2-MHR)

- **Given the pebble and prismatic core fundamentals, reactor designs are optimized to meet**
  - application-based design requirements and schedule
  - economics
  - technology and planned R&D
- **Pebble & prismatic reference designs**
  - have not selected the same reactor dimensions
  - have not selected the same operating parameters
    - *core inlet temperature*
    - *helium pressure*
  - have not selected the same materials
    - *UO_2 vs UCO fuel*
    - *core barrel material*
    - *reactor vessel material*
  - have not chosen the same limits for
    - ***normal operation maximum fuel temperature limit***
    - ***DLOFC maximum fuel temperature limit***
- **A comparison of specific reference designs is influenced by both the fundamentals and the design selections**

Design Selections that Influence Normal Operation Fuel Performance

- Fuel design specification
  - UO_2 vs UCO or other
  - Fissile or both fissile and fertile fuel loadings
  - Kernel size
  - Layer thicknesses
- As-manufactured fuel quality
  - Fraction of missing buffers, cracked layers, or other out-of-spec defects
  - Uranium contamination
- Average and maximum burnup
- Average and maximum temperature and time-at-temperature
- Average and maximum fluence
- Temperature gradient within fuel particles

Design Selections that Influence DLOFC Radionuclide Releases

- **Early release from circulating, dust, and plateout liftoff**
  - Normal operation fuel performance
  - Size of leak or break in HPB
- **Delayed release from heatup of initially failed particles**
  - Normal operation fuel performance
  - Amount of core with temperatures above normal operation levels
  - Peak fuel time-at-temperature
- **Delayed release from incremental fuel particle failures due to heatup**
  - Peak fuel time-at-temperature
  - Amount of core with peak temperatures
- **Transport of release from fuel to offsite**
  - Size of leak of break in Helium Pressure Boundary
  - Chemical attack by water or air if any
  - Retention within core, HPB, and reactor building

Design Selections that Influence Core Power

- **During normal operation:**
  - Mass flow rate
  - Core temperature rise
  - Maximum and average fuel temperatures
- **During PLOFC:**
  - Metallic reactor internals time-at-temperature
  - Reactor vessel time-at-temperature
- **During DLOFC:**
  - Maximum fuel time-at-temperature which is influenced by
    - *Effective outer core diameter*
      - Vessel diameter, shipping weight, and supplier infrastructure
    - *Effective core height*
      - Core pressure drop (pebble)
      - Axial neutronic stability (prismatic)
      - Fuel handling (prismatic)
      - Center reflector structural design (pebble)
    - *Annular active core thickness*
      - Control rod effectiveness (pebble)
    - *Power density*
    - *Normal operation average fuel temperatures*
  - Metallic reactor internals time-at-temperature
  - Reactor vessel time-at-temperature

Reference Process Heat Design Selections

Parameter	PBMR PHP	H2-MHR
Inner/outer active core diameter (m)	2.0/3.7	2.96/4.83
Active core effective height (m)	11.0	7.93
Fueled region power density (w/cc)	16.9	32
Fuel element (solid) power density (w/cc)	9.8	8.3
Core power density (w/cc)	6.0	6.6
Core inlet/outlet helium temperature (C)	350/950	590/950
Normal operation maximum fuel temperature (C)	~1150	1250-1350
Off-normal maximum fuel temperature (C)	~1670	<1600
Module power rating (MWt)	500	600
Primary helium coolant inlet pressure (MPa)	9.0	7.1
Primary helium flow rate (kg/s)	160	320
Core pressure drop (KPa)	202	58
Fuel composition	UO_2	$UC_{0.5}O_{1.5}$
Fuel enrichment (%)	5.0 startup 9.6 equilibrium	19.8 fissile 14.5 avg w/fertile
Fuel burnup (GWd/mtU)	90	120

Presentation Outline

- Background
- Fundamental pebble-prismatic fuel element and core differences
- Reference PBMR and prismatic process heat reactor designs

→ Discriminating criteria

- Comparative evaluation
- Summary

Discriminating Criteria

Criteria	Relative Weight
Readiness	
➢ **Design maturity and limited enabling technology R&D required**	**High**
➢ Vendor / supplier / regulatory infrastructure	Medium
Performance	
➢ **Process heat delivery**	**High**
➢ Capacity factor / investment protection	Medium
➢ **Public safety**	**High**
➢ Safeguards	Medium
➢ Wastes & other environmental impact minimization	Medium
➢ **Cost Competitiveness**	**High**
Enhancement Potential	
➢ Fuel cycle flexibility & enhancement opportunities	Low

Presentation Outline

- Background
- Fundamental pebble-prismatic fuel element and core differences
- Reference PBMR and prismatic process heat reactor designs
- Discriminating Criteria
- ➔ Comparative Assessment
- Summary

Discriminating Criteria

Criteria	Relative Weight
• **Readiness**	
➔ **Design maturity and limited enabling technology R&D required**	**High**
➢ Vendor / supplier / regulatory infrastructure	Medium
• **Performance**	
➢ **Process heat delivery**	**High**
➢ Capacity factor / investment protection	Medium
➢ **Public safety**	**High**
➢ Safeguards	Medium
➢ Wastes & other environmental impact minimization	Medium
➢ **Cost Competitiveness**	**High**
• **Enhancement Potential**	
➢ Fuel cycle flexibility & enhancement opportunities	Low

Design Maturity – Limited R&D:
Fuel Manufacturing and Performance

	PBMR PHP UO_2	H2-MHR UCO/ other advanced	Comment
Confirmed fuel quality in production scale facility	Nukem/FZJ proved high quality	GA demonstrated requisite quality	PBMR to meet or exceed German quality PBMR demonstrating quality in fuel pilot plant for DPP
Irradiation test data on manufactured fuel	Extensive capsule tests meet performance criteria up to 1250C	Limited capsule tests showed higher failures than required	PBMR-German fuel performance data base is much stronger PBMR to demonstrate performance in irradiation of manufactured fuel
DLOFC heatup testing	Extensive heat up testing in excess of 1600C	Limited heatup testing	PBMR-German fuel performance data base is much stronger PBMR to demonstrate performance in irradiation of manufactured fuel
Need for qualifying fuel from a new production facility	Confirmation of earlier performance required	Qualification and confirmation required	Prismatic lack of proven fuel is major development risk
Supplier options	PBMR pilot plant in RSA for initial core and early reloads; Joint Venture in US to follow	Expand BWXT or NFI for initial core and early reloads	Pebble supply infrastructure much more advanced

Conclusion: Primary PBMR advantage

Design Maturity – Limited R&D: Component & Material Availability

	PBMR PHP pebble	H2-MHR prismatic	Comment
Graphite	SGL NBG-18 reference	TBD reference	PBMR reference is commercially available; DPP billets ordered
Reactor vessel material	SA508:SA533	9Cr1Mo	PBMR utilizes LWR material; DPP order placed with ENSA
Reactor vessel inner diameter (m)	6.5	7.2	PBMR can choose from multiple suppliers: ENSA, MHI, AREVA, Doosan, Japan Steel; H2-MHR limited to Japan Steel
Core barrel material	SA336/SA387	Alloy 800H	PBMR utilizes lower temperature materials that are ASME code qualified for the conditions needed
Primary circulator temperature (C)	350	590	H2-MHR requires high temperature circulator development

Conclusion: PBMR PHP uses state-of-the-art components and materials– reduces development costs and risks

Design Maturity – Limited R&D: Circulator

	PBMR PHP	H2-MHR	Comment
Core thermal power (MW)	500	600	PBMR selected lower thermal output
Coolant inlet temperature (C)	350	590	PBMR circulator temp within experience
Core mass flow (kg/s)	160	320	PBMR lower flow rate due to higher temperature rise & lower power
Core inlet pressure (MPa)	9	7.1	PBMR selected higher pressure
Core pressure drop (% dP/P)	2.2	.8	PBMR has greater resistance & taller core
IHX pressure drop (% dP/P)	.6	.4	PBMR has greater temperature decrease
Ducting pressure drop (% dP/P)	.6	.1	PBMR has conservative losses
Total primary pressure drop (kPa)	307	100	PBMR has greater overall pressure drop
Circulator Compressor Power (MWt)	8.9	10.2	PBMR has lower circulator requirement

Conclusion: PBMR PHP circulator smaller and within temperature range of demonstrated circulators

Vendor / Supplier / Regulatory Infrastructure

	PBMR PHP	H2-MHR	Comment
Plant vendor / supplier team	Builds on established PBMR Pty Ltd and international supply team for DPP and Westinghouse-led NGNP team	GA-led team development with Russian GT-MHR program for WPu disposition AREVA-led ANTARES studies	PBMR vendor / supplier infrastructure more advanced
Fuel supply team	Builds on full German (NUKEM) know-how transfer Joint venture with NFS under development for US supply base	Initial core supply options limited to NFI and possibly BWXT AREVA-based company at early stage	PBMR fuel supply infrastructure more advanced with DPP fuel pilot plant and performance testing
Modular HTGR regulatory experience	Builds on HTR Modul concept license in Germany, DPP licensing in SA, plus Exelon and PBMR ongoing pre-application design certification with NRC	Builds on past GA-led pre-application programs with NRC AREVA yet to make formal submittals or initiate interactions	PBMR regulatory experience and infrastructure more advanced

Conclusion: Clear advantage for the PBMR

Discriminating Criteria

Criteria	Relative Weight
Readiness	
➢ **Design maturity and limited enabling technology R&D required**	**High**
➢ Vendor / supplier / regulatory infrastructure	Medium
Performance	
➔ **Process heat delivery**	**High**
➢ Capacity factor / investment protection	Medium
➢ **Public safety**	**High**
➢ Safeguards	Medium
➢ Wastes & other environmental impact minimization	Medium
➢ **Cost Competitiveness**	**High**
Enhancement Potential	
➢ Fuel cycle flexibility & enhancement opportunities	Low

Process Heat Delivery:
Normal Operation Fuel Temperatures

	PBMR PHP	H2-MHR	Comment
Core Inlet Temperature (C)	350	590	PBMR selected lower core inlet; H2-MHR will require high temperature circulator R&D
Fuel Element-Coolant Temp Rise (C)	~50 - 70	~100 - 200	Pebble fundamental
Core Outlet Temperature (C)	950	950	Prismatic limited by fuel temperatures; FSV experience at 750C for ___ days AVR operated for 900days at 950C Both limited by IHX metallic materials
Average Fuel Temperature (C)	~835	>900?	PBMR fuel lower
Helium mixing & cross flow (between high & low power fuel)	Extensive	Minimal	Pebble fundamental
Normal operation maximum fuel temperature limit (C)	1250	1350	H2-MHR prismatic selected a higher limit requiring fuel development
Normal operation maximum fuel temperature (C)	~1150	1350	PBMR has margin to selected limit

Conclusion: Pebble has lower average and maximum fuel temperature advantage for the same core outlet temperature

Process Heat Delivery:
Normal Operation Fuel Performance

	PBMR PHP	H2-MHR	Comment
Average fuel temperature (C)	~835	>900?	PBMR temperatures lower
Volume >1000C, <1100C (%)	~10	>15?	PBMR lower
Volume >1100C , <1200C (%)	~!	>10?	PBMR lower
Volume >1200C , <1300C (%)	0	>5?	PBMR lower
Volume >1300C , <1400C (%)	0	?	PBMR lower
Peak fuel temperature (C)	~1150	1250-1350	PBMR temperatures lower
Peak burnup (MWd/mtU)	104,000	135,000	PBMR advantage
Duration of fuel in high fluence and temperature locations	pebbles pass thru full range of conditions	prismatic fuel in same position throughout refueling interval	Pebbles also rotate so that there is not a constant temperature gradient
Location of high burnup fuel	passes thru high temp region	can be placed in lower temp regions	

Conclusion: Pebble can expect much lower normal operation radionuclide releases

Process Heat Delivery: Enrichment / Burnup

	PBMR PHP	H2-MHR	Comment
Enrichment loadings (%)	~5 initial core 9.6 equilibrium	19.8 fissile particles ~14 average w/ natural U particles	PBMR based on German fuel experience base Prismatic based on US fuel experience base
Supply	Commercial enrichment to be extended for higher enrichment	Further extension required for higher enrichment	Both use blend down of HEU until market conditions warrant supply capability PBMR requires less topping enrichment
Burnup (MWd/mtU)	~90,000 avg ~104,000 peak*	~120,000 average ~135,000 peak*	PBMR requires more enriched U, but less enrichment. .

* Peak values due to flux peaking and location uncertainties

Conclusion: PBMR lower burnup has advantage for fuel performance

Process Heat Delivery: Excess Reactivity

	PBMR PHP	H2-MHR	Comment
Excess reactivity during normal operation at hot conditions	1.4%	3.9-4.5%	Pebble fundamental
Mechanism for controlling excess reactivity	Control rods	Control rods and lumped burnable poison	Pebble fundamental

Conclusion: PBMR requires less excess reactivity which simplifies reactivity control

Process Heat Delivery: Shutdown Margins

	PBMR PHP	H2-MHR	Comment
Requirement			
Operation hot-to-cold (20C) (% dk/k)	4.0	5.2-7.2 BOC*	Pebble fundamental
Xenon decay (%)	3.0	3.8-3.9 BOC	PBMR advantage
Burnup (%)	negligible	3.6-4.5 BOC	Pebble fundamental
Uncertainty / Margin (%)	1.0	1.2-1.0	PBMR requires less margin
Total (%)	8.0	13.8-16.0 BOC	Pebble requires lower margin
Capabilities			
Worth of all CR, cold (%)	8.4	18.9-18.7 BOC	Pebble has fewer and shorter CR, all in reflector
Worth of all RSS (%)	12.0	11.9-11.0 BOC	H2-MHR cannot shut down cold at BOC with RSS

*BOC = Beginning of equilibrium Cycle

Conclusion: Pebble can shutdown cold with either CRs or RSS throughout the lifetime

Process Heat Delivery: Reactivity Control Systems

	PBMR PHP	H2-MHR	Comment
Reactivity Requirement	8.2	13.8-16.0	Pebble has less demanding requirement
Number of CR	24 in side reflector	36 in side reflector 12 in core	PBMR has fewer for smaller core annulus, lower core power & less excess reactivity
Number of RSS Channels	8 in center reflector	18 in core	PBMR has fewer for smaller core annulus, lower core power & less excess reactivity

Conclusion: PBMR needs less reactivity control

Capacity Factor / Investment Protection: Graphite Dust

	PBMR PHP	H2-MHR	Comment
Mechanism for generating graphite dust	Fuel handling and rubbing of pebbles within FHS and core reflector walls	Contact & rubbing between blocks, especially during refueling, plus machining debris	Imponderable comparison
Dust generation rate experience	AVR: 3 Kg/yr – most attributed to abrasion in FHS	FSV: very little	Pebble has measured dust in the primary coolant for longer operation time AVR had dust filter in FHS; FSV had filter in primary circuit
Impact of dust on maintenance and release during a HPB leak	negligible	negligible	PBMR PHP has dust filter in FHS; both have filter in primary circuit
Amount of circulating activity released	lower	base	PBMR has much lower core temperatures

Conclusion: Both are negligible and both will meet requirements

Capacity Factor / Investment Protection: Fuel Handling Outages

	PBMR PHP	H2-MHR	Comment
Fuel handling design rate	1111spheres/d/train, 12 hr/day AVR: 500spheres/d/train THTR:3700spheres/d /train	~100blocks/d, during outage FSV: ~17blocks/d	PBMR within experience base
System O&M environment	Reactor on-line	Reactor depressurized	Pebble fundamental
Refueling system experience	28 years (AVR & THTR)	3 refuelings in 5 years (FSV)	PBMR has more overall experience
Scheduled outage due to refueling (%)	0	4.4	Fundamental pebble advantage
Forced outage influence	Up to 20 days to restore on-line fuel handling	Refueling outage may be extended	PBMR PHP can continue to run while repairing most FHS failures
Unscheduled outage due to refueling (%)	Continuous usage increases failure frequency AVR: <3; THTR: ~6.3	Equipment can be maintained off line FSV: 4	PBMR failure rate comparable Pebble on-line fueling advantage not fully realized in early plants

Conclusion: Clear Pebble advantage

Capacity Factor / Investment Protection: Reflector Replacement

	PBMR PHP	H2-MHR	Comment
Replaceable reflector lifetime	15-20 yr	6yr on average	Pebble center and side reflector require non-routine replacement 6yr life for prismatic was based on bowing and cracking predictions; PBMR may have comparable effects.
Duration of replacement	190 days	Included in refueling outages	Pebble estimate longer for entire removal at once
Permanent reflector	Limited provisions provided	Provisions provided	PBMR does not plan replacement or have planned provisions for larger reflector and core support blocks

Conclusion: H2-MHR prismatic has less impact if fuel handling is reliable

Public Safety: Core Thermal Power

Parameter	PBMR PHP	H2-MHR	Comment
Core volume (m^3)	84	92	H2-MHR greater
Fuel element power density (MWt/m^3)	9.8	8.26	PBMR greater
Core packing fraction	.61	.8	Pebble-prismatic fundamental
Core power (MWt)	500	600	H2-MHR greater
Initial average core fuel temp (C)	~835	>900?	PBMR less
Peak DLOFC fuel temperatures (C)	~1670	<1600	PBMR selected higher temperature fuel limit
Reactor vessel temp limit (C)	Between 371 and 428 for 3000hrs Between 428 and 538 1000hrs	495?	H2-MHR selected higher temp material not currently used for reactor vessels
Peak DLOFC reactor vessel temp (C)	~455 >371 for ~65hrs	420?	comparable

Conclusion: Prismatic has core thermal power advantage due to core packing fraction fundamental and bigger volume

Public Safety:
DLOFC Fuel Performance

Parameter	PBMR PHP	H2-MHR	Comment
Normal operation initially failed fuel	10^{-4}	10^{-3}?	PBMR has superior normal operation performance
Average fuel temperature (C)	~835	>900	PBMR
Volume >1400C , <1500C (%)	~12	>10?	
Volume >1500C , <1600C (%)	~15	>10?	
Volume >1600C , <1700C (%)	~7	0?	
Peak fuel Temperature (C)	~1670	<1600	H2-MHR has advantage
Radionuclide release from initially failed fuel	less	greater	H2-MHR has more initial failure core-wide
Radionuclide release from fuel failed during DLOFC	slightly more	less	PBMR has a small percentage of the core with higher temps

Conclusion: PBMR normal operation fuel performance may outweigh higher temperatures during event since releases from initially failed particles has traditionally been the dominant release source

Public Safety: Graphite Oxidation

	PBMR PHP	H2-MHR	Comment
Core Flow Resistance	greater	base	Pebble has higher core pressure drop to limit air supply
Fuel Element Oxidation	greater	base	Pebble has higher surface area next to coolant Pebble shell is not graphitized

Conclusion: Both acceptable for air ingress licensing basis events

Public Safety & Licensing

	PBMR PHP	H2-MHR	Comment
Shutdown margins with CRS / RSS (%dk/k)	.8 / 1.0	2.0 to 4.1/ -3.9 to -5.7	PBMR can shut down cold with either system
Normal operation releases	Acceptable	Marginal	H2-MHR will have higher maintenance doses
HPB leaks and breaks	Acceptable	Marginal	H2-MHR accidents may need active filters and active mitigation systems
DLOFC peak fuel temps	Higher	Within conventional limit	PBMR needs additional fuel capsules to confirm performance up to 1700C
DLOFC releases	Acceptable	Acceptable?	H2-MHR accidents may need active filters and active mitigation systems
Beyond DBE rod withdrawal	More margin	Acceptable	Both acceptable
Beyond DBE graphite oxidation	Acceptable	More margin	Both acceptable

Conclusion: PBMR PHP has advantage during normal operation and possibly during off-normal events

Discriminating Criteria

Criteria	Relative Weight
• **Readiness**	
➢ **Design maturity and limited enabling technology R&D required**	**High**
➢ Vendor / supplier / regulatory infrastructure	Medium
• **Performance**	
➢ **Normal operation NHS effectiveness** `	**High**
➢ Capacity factor / investment protection	Medium
➢ **Public safety**	**High**
➔ Safeguards	Medium
➢ Wastes & other environmental impact minimization	Medium
➢ **Cost Competitiveness**	**High**
• **Enhancement Potential**	
➢ Fuel cycle flexibility & enhancement opportunities	Low

Safeguards / Security: Fuel Fissile Material Loading

	PBMR PHP	H2-MHR	Comment
Average enrichment	9.6%	14%	PBMR design choice
Burnup control	On-line refueling	Burnable poison and control rods	Pebble fundamental
Neutron Leakage	Higher-- tall, slender core	Lower	PBMR design choice, but offset by better fuel utilization without loss to burnable poisons
Uranium to Carbon ratio (in core)	0.04	0.03	PBMR has slightly lower moderation
Excess Reactivity Required	1.4%	4.5%	Pebble fundamental
Fissile Material Loading (kg/MWt)	~0.9	~1.1	PBMR requires less fissile material inventory

Conclusion: PBMR has slight advantage.

Safeguards

	PBMR PHP	H2-MHR	Comment
Front-end diversion and misuse potential	9.6% LEU utilized	19.8% LEU utilized	Eventual enrichment upgrades close to SNM for prismatic
Operational diversion and misuse potential	On-line refueling increases such potential	Batch fuel reloads limit such potential	PBMR requires added surveillance IAEA familiar with THTR and has approved DPP plans
Detection of U-238 target material	Readily detectable with one FS pass	Easy to hide	PBMR advantage – assuming access to fuel monitoring system
Back-end diversion and misuse potential	Pebble size/weight increases such potential, Pebble has more PU/GW-day due to lower enrichment	Block size/weight deter such potential	PBMR requires added surveillance – requires ~100,000 spheres to collect 1 Significant Quantity of Pu

Conclusion: Prismatic and pebble have different pros and cons – both provide safeguard assurances

Wastes & Other Environ. Impact Minimization

	PBMR PHP	H2-MHR	Comment
Spent Fuel Storage Volume (m^3/GWe-day)	~.14	~.19	PBMR advantage due to greater power density per fuel element
Potential for Spent Fuel Volume Reduction	Limited	Potential for push out of fuel compacts, but increases safeguards and block disposal is uncertain	PBMR disadvantage
Reflector Storage Volume (m^3/GWe-day)	~.01	~.07	PBMR advantage due to longer replacement interval
Control Rod Volume (m^3/GWe-day)	~.0002	~.001	PBMR advantage due to fewer rods

Conclusion: PBMR has advantage in all areas except in spent fuel where prismatic may have potential for compact push out

Cost Competitiveness

	PBMR PHP	H2-MHR	Comment
Capital Cost	Base with DPP and follow-on plant experience	Higher for NGNP with full FOAK costs and more expensive component materials, e.g. 9Cr1Mo; Lower per higher output	PBMR advantage for NGNP and early plants; Slight H2-MHR advantage for equally mature plants
Efficiency	Base	Much higher risks related to providing ~950C ROT	PBMR advantage
Capacity Factor	Base	Lower due to off-line refueling; otherwise dueling offsets with reflector replacements but lower fuel temperature/release impacts, etc	PBMR advantage
Fuel	Base with DPP and follow-on plant experience	Lower due to higher burnup; Higher due to more enrichment required; Higher due to fuel mfg and reload complexity and QA requirements	Even
O&M	Base	Higher due to higher fuel releases and attendant contamination impacts, plus higher waste quantities	PBMR advantage

Conclusion: PBMR PHP advantage or even in all areas except for output – comparably competitive with less risks

Enhancement Potential: Fuel Cycle Flexibility

	PBMR PHP	H2-MHR	Comment
Range demonstrated	HEU core transition to various partial LEU cores at AVR	NA	PBMR advantage
Changes within modest reactivity domain	On-line transition capability, but within reactivity control limits	Batch or core reloads that may require different burnable poison designs	PBMR disadvantage
Changes within major reactivity domain, e.g. PU/Transuranic burning	Limited reactivity control flexibility	More flexibility with burnable poisons, potential to burn PU/TU more fully due to softer neutron spectrum	PBMR disadvantage, but major fuel development program required for either

Conclusion: H2-MHR prismatic slight advantage

Enhancement Potential: Advanced Materials & Components

	PBMR PHP	H2-MHR	Comment
Advanced Fuels	Could go to higher temperature fuels (e.g., ZrC, UO_2*) when developed and demonstrated	Currently assuming availability to achieve 950C core outlet	PBMR advantage
Core outlet components and ceramic IHX	Have margin on fuel temperatures to raise core outlet when higher temperature materials become available	At limit	PBMR advantage
Core Barrel	Could go to higher temperature materials when code-qualified	Currently assuming availability	PBMR advantage
Reactor Vessel	Could go to higher temperature materials and larger diameter when commercially available	Currently assuming availability	PBMR advantage

Conclusion: PBMR PHP advantage

Presentation Outline

- **Background**
  - ➢ Common modular HTGR safety design approach
  - ➢ Pebble bed and prismatic core and reactor design basics
- **Fundamental pebble-prismatic differences**
- **Reference PBMR and prismatic process heat designs**
- **Discriminating criteria**
- **Comparative evaluation**
  - ➢ Readiness
  - ➢ Performance
  - ➢ Enhancement Potential

➔ **Summary**

Summary Conclusions

- **R&D Needs**
  - PBMR clear advantage due to German UO_2 fuel and design baseline, lower operational temperatures, and DPP experience, including selection of LWR reactor vessel and other available code-qualified materials
  - PBMR meets NGNP schedule
- **Performance**
  - Process heat delivery
    - *PBMR advantage due to lower risks of achieving very high core outlet temperatures*
  - Capacity factor
    - *PBMR advantage (2-4%) attributed to on-line refueling*
  - Safety
    - *PBMR has superior fuel performance due to lower normal operation temperatures, and hence lower releases*
- **Cost Competitiveness**
  - Unit capital cost (with same mature, multi-module plant output, assumptions, etc.)
    - *PBMR disadvantage due to lower power level layout, quantities, etc.*
  - Resultant process heat or H_2 cost
    - *PBMR advantage with DPP baseline, higher capacity factor, simpler fuel cycle and lower overall risks with offset from higher capital costs*

Reactor Type Summary Relative to Criteria

Criteria	Weight	PBMR PHP
Readiness		
➢ **Design maturity and limited enabling technology R&D required**	**High**	**Better**
➢ Vendor / supplier / regulatory infrastructure	Medium	Better
Performance		
➢ **Process heat delivery**	**High**	**Better**
➢ Capacity factor / investment protection	Medium	Better
➢ **Safety**	**High**	**Better**
➢ Safeguards / security `	Medium	Comparable
➢ Wastes & other environmental impact minimization	Medium	Comparable
➢ **Cost Competitiveness**	**High**	Comparable
Enhancement Potential		
➢ Fuel cycle flexibility & enhancement opportunities	Low	**Better**

Closing

- **Pebble core technology offers many fundamental advantages over the prismatic core**
  - Lower operational fuel temperatures leading to superior fuel performance
  - On-line fueling leading to superior capacity factor
- **For the high temperature process heat / hydrogen production NGNP, the PBMR PHP is superior to the H2-MHR**
  - Lower development costs and risks due to German-based fuel technology
  - Lower development costs and risks due to DPP baseline
  - Stronger vendor/supplier/regulatory infrastructure
  - Higher performance capability
    - *Lower fuel temperatures/releases for same required process heat temperature*
    - *On-line refueling compatible with continuous process industries*
  - Competitive with lower risks