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NGNP with Hydrogen Production Reactor Type Comparison Study

March 2007

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BEA Contract No. 000 60209



AREVA NP Inc.

Record of Revisions

Revision	Date	Pages/Sections Changed	Brief Description
000	3/14/2007	None.	Original Issue

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1.0 INTRODUCTION

The Reactor Comparison Type Study is one of the four special studies which the AREVA NGNP Team is performing for INL. This study will compare the pebble bed reactor concept to the prismatic reactor concept as specified in Section 6.3.1 of the Statement of Work [1]. The report identifies the most important discriminating criteria between the two concepts and provides an assessment of the important technical, operational and maintenance differences and the important developmental risks for each.

2.0 STUDY OBJECTIVES

This study provides an answer to the main question posed by the study, namely:

What type of reactor should NGNP be?

The answer depends on which concept best fulfills the NGNP mission [2]; namely, to develop and demonstrate:

- A commercial-scale prototype Generation IV HTR
- Commercial-scale high-efficiency electricity production
- Hydrogen production
- Process heat delivery for industrial applications
- The licensing process with the USNRC and the commercial licensing protocol for future HTR commercialization
- The inherent safety characteristics via special testing of the HTR.
- The economics of the HTR
- New technologies, i.e., high temperature capability, advanced fuel design, advanced energy conversion systems.

The main question can only be answered after appropriate comparisons have been made for each option with respect to the relevant NGNP functions and requirements [2] and a detailed assessment of the key discriminating criteria.

Furthermore, consideration must be given to the future commercialization aspects of the chosen type of reactor. Commercialization of HTR technology is the real NGNP success criterion that can only be measured by the extent of HTR deployment in the decade following NGNP startup and operation.

Industry Acceptance of HTR Technology

Industry acceptance of the chosen reactor concept and the subsequent deployment of a fleet of NGNP-based HTRs is the true measure of success for the NGNP program. The NGNP program plays a key part in the successful commercialization of an advanced reactor concept especially with respect to the developing those essential elements that are critical to success.

The essential elements [3] for the successful commercialization of a new reactor concept are as follows:

Certifiable design Regulatory certainty Competitive plant financials Capital, O&M, cost of product Risk mitigation & financing (i.e., similar legislation to EPAC of 2005) Successful demonstration plant (NGNP) Public acceptance Predictability

It is beyond the scope of this report to provide a detailed explanation of how each these tenets promote commercialization, nevertheless, it can be safely said that if an advanced reactor concept can successfully satisfy each of the above tenets, it will have a high probability of acceptance in the market place.

These are important considerations to keep in mind as the comparison of key discriminators are presented.

3.0 ASSUMPTIONS

For the purposes of this study, it is assumed that the NGNP plant is a full-sized demonstration plant. This is consistent with the finding of the Power Level Trade Study Report.

Furthermore, this study does not assume a fixed power level; rather, it assumes that each reactor pebble bed or prismatic – has been optimized for its mission at its maximum achievable power level.

Also, the comparison between pebble bed and prismatic options in this study does not assume a given design for each technology. Granted, the pebble bed offering of PBMR and AREVA's prismatic offering (ANTARES) offer good starting points and information, nevertheless, they should be viewed as examples of available HTR technology. Hence, the comparison should be more accurately considered as more a "generic" comparison of pebble and prismatic technology. Furthermore, this assessment is limited to reactor type and confined to the envelope defined by the reactor vessel. Hence, the reactor as viewed herein is considered a "universal" heat source that can be connected to the application of choice.

4.0 ASSESSMENT APPROACH

Figure 1 below shows the general process followed in performing the study. The selection of reactor type will be based on appropriate comparisons made for each option with respect to the relevant NGNP functions and requirements [2] and a detailed assessment of the key discriminators presented in Section 6.0.

First, the NGNP functions and requirements are reviewed to assess the ability of each option to fulfill the function or requirement. The purpose the review is simply to ensure that there are no "showstopper" functions or requirements at this level for a given option. Also, to determine if there is any advantage or disadvantage that is sufficiently remarkable.

Second, key discriminators are compared for each option. This was done in several steps. First, a list of key, toplevel discriminators was compiled via an expert panel. Then, the list was prioritized by a ranking scheme which combined relative discriminator importance and degree of prismatic-pebble difference. This ranking serves only to present the results in order of impact of reactor type choice. Finally, the top-level discriminator list was expanded by adding subordinating items, as appropriate for assessment. The assessments provide the bases for the selection of reactor type. The following main discriminators (ordered by degree of importance and option difference) serves as the basis for ordering the detailed assessments provided in Section 6.0:

- 1. Performance Capabilities
- 2. Fuel Design, Performance, & Development Issues
- 3. Fuel Handling & Refueling Issues
- 4. Economics Factors
- 5. Research & Development
- 6. Core Design Issues
- 7. Maintenance issues
- 8. Operational Considerations
- 9. Safety & Licensability
- 10. Level Of Difficulty Of Key Mechanical Hardware Design And Fabrication
- 11. Schedule Risk
- 12. Non-Proliferation, Safeguards, SNM Accountability
- 13. Behavior of reactor systems and fuel during and after key accident conditions
- 14. Plant Layout and Construction
- 15. Plant Security





5.0 NGNP REQUIREMENTS REVIEW

5.1 Top Level Requirements

The following top level requirements are taken from the NGNP High-Level Functions and Requirements Document [2]. The NGNP Functions and Requirements document is technology neutral to the extent specified in Section 3.1.3, "Reactor Type – Prismatic or Pebble Bed" which states:

The reactor shall be either prismatic or pebble bed.

The reason for limiting the choice is that in the Generation IV technology roadmap selection process both the prismatic and pebble bed reactor concepts were highly rated as potential VHTR systems. Both concepts received high scores in economics because of their high efficiency and also in safety and reliability due to the inherent safety features of the fuel and reactor.

In the following matrix, each top level requirement is reviewed with respect to the impact that choice of reactor type may have upon the ability to meet the requirement. If there is a discernable difference arising from the choice of reactor, commentary is provided. Conversely, the requirement is 'Assumed Equivalent' if both options would appear able to meet the requirement, discounting the degree of difficulty (unknown at this time) that may be encountered.

Top Level NGNP Requirement		Impact of Reactor Type Rating/Comments		
1.	NGNP prototype shall be designed, constructed, licensed, and operating by 2020 with initial operations in 2018.	Meeting the 2018 schedule date is mission critical. Pebble technology may have a schedule advantage with the potentially earlier (i.e., before 2018) startup of the PBMR prototype in South Africa. 2018 should be achievable with prismatic technology. In either case, the design of critical components (fuel, IHX) will govern.		
2.	NGNP prototype design configuration shall consider cost and risk profiles to ensure that NGNP establishes a sound foundation for future commercial deployment.[1]	Gas reactor technology represents a paradigm shift for prospective plant owners. Prismatic reactor technology may present less of a paradigm shift than do pebble bed reactors and can achieve a higher power level. There is less perceived risk with concepts that have a high element of familiarity/similarity to current day practice. Public and investor confidence needs to be demonstrated.		
3.	NGNP prototype shall produce high efficiency electricity and generate hydrogen on a scale that sets a foundation for future commercial deployment.[1]	Assumed Equivalent – Both prismatic and pebble bed reactors should be able to meet this requirement.		
4.	NGNP prototype shall be licensed by the NRC as a commercial cogeneration facility producing electricity and hydrogen.[1]	Assumed Equivalent –Both prismatic and pebble bed reactors should be able meet this requirement.		

Table 5-1: Top Level NGNP Requirements Review

5.	NGNP prototype shall include provisions for future testing. [1]	Assumed Equivalent –Both prismatic and pebble bed reactors should be able meet this requirement.
6.	NGNP prototype shall enable demonstration of energy product and processes utilizing its nuclear heat source. [1]	Assumed Equivalent –Both prismatic and pebble bed reactors should be able meet this requirement.
7.	The project shall include identification of necessary and sufficient R&D technical scope and priorities. [1]	Assumed Equivalent –Both prismatic and pebble bed reactors should be able meet this requirement.

5.2 Plant Level Requirements

The top level plant requirements include restraints based on commercial considerations, customer specific requirements, any design constraints placed on the project, safety considerations and regulatory considerations. The top level requirements are listed below:

Top Level Plant Requirement	Impact of Reactor Type Rating/Comments
The electric plant shall demonstrate high efficiency electricity production [>44%]	Prismatic reactors have a significant efficiency advantage over pebble bed reactors because its substantially lower core pressure drop translates into less parasitic power loss.
The plant shall meet the NRC commercial power plant licensing requirements and be licensed for commercial operation supporting creation of regulatory requirements and acceptance criteria for future plant licensing similar to NGNP design.	Both prismatic and pebble bed reactors should be able to meet this requirement; however, the licensing basis for HTR technology has not yet been established. Integrated test and acceptance criteria (ITACC) may lead to differentiation. Prismatic reactors have past licensing history (Ft. St. Vrain, GT-MHR) with the NRC that may be helpful.
Fuel burn-up shall be such that it maximizes uranium utilization, minimizes proliferation risks, minimizes waste streams for open fuel cycle, and optimizes fuel economics.	Prismatic reactors have a 3-4% advantage with respect to fuel utilization (higher burn-up and plant efficiency). Diversion of pebbles may be easier than fuel assembly compacts. Non proliferation fuel surveillance is less difficult with the prismatic core.
The plant shall be designed such that the Nth of a kind plant costs will result in an economically competitive plant.	Nth of a kind cost differences between prismatic and pebble bed reactors will be a key determinant. The prismatic reactor's 50% higher power level translates into a significant economic advantage.
Fuel Qualification	Pebble bed reactors without advanced fuel may have a schedule advantage. PBMR, with its reliance on German particle fuel experience, may be able to qualify its fuel in a shorter time frame as compared to the time needed to qualify an advance fuel type. However, this downside of this strategy is significant should PBMR not be able to

Table 5-2: Plant Level NGNP Requirements Review

	demonstrate the ability to make fuel commensurate with the quality of the German fuel.
Fuel Performance	A pebble bed reactor with is less limiting fuel service conditions may be easier to demonstrate compliance with requirements. Prismatic reactors with advanced fuel and more limiting service conditions may have more difficulty with compliance.
The electric plant shall feed an outside commercial electrical grid system	Assumed Equivalent – Both prismatic and pebble bed reactors should be able meet this requirement.
The hydrogen production plant shall demonstrate commercial scale production and economics	Assumed Equivalent – Both prismatic and pebble bed reactors should be able meet this requirement.
The NGNP hydrogen product shall be sent to (TBD) for commercial usage.	Assumed Equivalent – Both prismatic and pebble bed reactors should be able meet this requirement.
No provisions shall be made for onsite produced hydrogen storage.	Assumed Equivalent – Both prismatic and pebble bed reactors should be able meet this requirement.
The NGNP shall be designed in accordance with defense-in-depth principles and philosophy with the intent to eliminate the need for evacuation beyond the plant site boundary of 450 meters.	Assumed Equivalent – Both prismatic and pebble bed reactors should be able meet this requirement.
The nuclear heat source shall use TRISO- coated particle fuel	Assumed Equivalent – Both prismatic and pebble bed reactors should be able meet this requirement.
The reactor shall be graphite moderated.	Assumed Equivalent – Both prismatic and pebble bed reactors should be able meet this requirement.
The nuclear heat source shall use once through uranium fuel cycle with uranium enrichment less than 20% 235U.	Assumed Equivalent –Both prismatic and pebble bed reactors should be able meet this requirement.
The primary nuclear heat source shall utilize an indirect cycle heat transport system (although a study will be performed addressing alternatives).	Assumed Equivalent –Both prismatic and pebble bed reactors should be able meet this requirement.
Hydrogen production plant will requires high temperature (~ 900°C range) process heat from the nuclear plant.	Assumed Equivalent –Both prismatic and pebble bed reactors should be able meet this requirement.
The plant shall be designed to the USA industrial Codes and Standards as necessary to meet the USA industrial and regulatory requirements.	Assumed Equivalent –Both prismatic and pebble bed reactors should be able meet this requirement.
The nuclear heat source shall be inherently safe and passively cooled in case of loss of all off-site and on-site motive power.	Assumed Equivalent –Both prismatic and pebble bed reactors should be able meet this requirement.
The plant design shall result in ease of	Assumed Equivalent – Both prismatic and pebble bed

required maintenance activities with appropriate considerations for layout space, access, and maintenance equipment.	reactors should be able meet this requirement.
The nuclear plant refueling outage shall allow 18 months operation between refuelings.	Assumed Equivalent – The prismatic reactor should be able meet this requirement. The requirement is not applicable to the pebble bed reactor with on-line refueling.
The nuclear plant shall be designed for 60 year life and with fifteen year onsite used fuel storage capacity within the plant boundary fence.	Assumed Equivalent – Both prismatic and pebble bed reactors should be able meet this requirement.
The nuclear plant shall be designed for an availability of greater than 90%.	Assumed Equivalent – Both prismatic and pebble bed reactors should be able meet this requirement.
Public safety due to any accident at the nuclear plant shall not depend on public or personnel beyond site boundary.	Assumed Equivalent –Both prismatic and pebble bed reactors should be able meet this requirement.
The nuclear plant design bases accidents shall not lead to nuclear plant write-off.	Assumed Equivalent –Both prismatic and pebble bed reactors should be able meet this requirement.
The plant shall be located at the NPR site at the Idaho National Laboratory, Idaho USA, approximately 3.5 miles northeast from the INTEC facilities.	Assumed Equivalent – Both prismatic and pebble bed reactors should be able meet this requirement.
The reactor shall be built to commercial scale with a power level consistent with passive safety features.	Assumed Equivalent – Both prismatic and pebble bed reactors should be able meet this requirement.
The NGNP shall have adequate passive safety systems to cool the core down from full power to safe shutdown mode and limit the fuel temperatures under accident conditions to levels consistent with fuel performance requirements.	Assumed Equivalent – Both prismatic and pebble bed reactors should be able meet this requirement.

5.3 Top /Plant Level Requirements Review Summary

Based upon the above discussion, most high level requirements are neutral (i.e., assumed equivalent) with respect to "reactor type." For those requirements that are remarkable, the review reveals no real "show stoppers," i.e., a requirement that would be impossible to meet. These are simply requirements for which one type of reactor has a greater level of difficulty meeting the requirement versus the other. Nevertheless, to summarize, the pebble reactor may have an edge in schedule but the prismatic reactor will always have an economic advantage due to its higher power capability and the added power is needed and can be used.

6.0 ASSESSMENTS

This section presents assessment of the key discriminator topics listed in Section 4. Each discriminator topic area has been further subdivided into the key parameters comprising the discriminator topic area. These parameters are then evaluated with respect to reactor type and the results summarized in a table for each discriminator topic area. A simple rating scheme is applied to the comparison results. For each parameter compared; a simple score is assigned depending whether the reactor type displays a weal advantage (+), a moderate advantage (++) or a strong advantage (+++) or not advantage over the other (o). Some parameters are listed for information. The bases for the evaluations are discussed following each table.

While each performance parameter is viewed independently, the reader must be aware of the strong interdependence between certain parameters. Furthermore, it assumed for comparison purposes, that each option is designed to produce the maximum power level that can be supported by the design and still achieve inherent safety goals.

As mentioned in Section 4, the discriminators topic areas have been prioritized and are presented in that order in the following sub-sections.

6.1 **Performance Capabilities**

The performance capabilities of the pebble bed reactor and prismatic reactor are compared in this section as shown in Table 6-1.

PERFORMANCE PARAMETER	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Power Level (MWT _{thermal})	600	+++	400	-
Electric Output (MWe)	284	+++	165	-
Modules per 1200 MWe site	4.2	+++	7.3	-
Capacity Factor, %	92	-	95	+ +
Efficiency	>44	+ +	42	-
Core Outlet Temperature, °C	900	-	950	+ +
Core Pressure Drop	low	+++	high	-
Fuel Enrichment, %	14	-	9.6	+
Fuel Burnup, GWD/MTU	120	++	91	-
Uranium Requirements, Tonnes/Gwe-Year	192	0	198	0
Plant Lifetime/License, Years	60/60	0	60/40	0
Overall Performance Capability Rating		+++		

Table 6-1: Performance Capability Comparison

6.1.1 Power Level

The achievable thermal power in the prismatic core is about 50% greater than the thermal power achievable in the pebble bed core. The main reason for this is geometry. Because pebble cores have a lower void fraction (19% versus 40%), the prismatic core can achieve a higher power rating for a given gross core volume while still retaining the passive safety attributes. Hence, 81% of the gross core volume has fuel in the prismatic case while only 60% of the pebble bed gross core volume contains fuel.

The key to the prismatic reactor's power level advantage lies in its performance during the limiting design basis event (i.e., depressurized conduction cool down). The additional mass in the prismatic core behaves as a heat sink for decay heat energy that serves to buffer the internal core and fuel temperature rise. Hence, for a fixed maximum post-accident fuel temperature (i.e., 1600 °C) limit, the prismatic core is able to meet this requirement at a higher power level.

Hence, as the designs have evolved over the past several years, the maximum achievable core power is approximately 600 MWth for the prismatic core versus 400 MWth for the pebble bed core. Clearly, the higher power capability of the prismatic core is a strong advantage that the option possesses over the pebble bed option and is rated accordingly.

6.1.2 Electrical Output and Modularity

Both reactor types can be matched with similar energy conversion systems, whether it be for electricity generation or process heat. The higher power capability for the prismatic reactor simply translates into more useable power. Furthermore, when considering a multi-unit site, the prismatic reactor has almost a 3:2 advantage in terms of the number of unit required to supply the total plant output.

6.1.3 Capacity Factor

Capacity factor is the ratio of the actual energy produced by the facility to the maximum amount of energy that the facility could have produced in a given period.

With on-line refueling, the pebble bed reactor can potentially achieve a nominally higher capacity factor than the prismatic option which must shut down periodically for refueling. PBMR claims a 95% capacity factor is achievable whereas this prismatic vendor (i.e., AREVA) supports a 92% capacity factor which includes a 22-day refueling every 18 months.

The theoretical advantages of online refueling have not been realized over the long term in other commercial designs. AREVA believes that this will be the pebble bed reactor experience as well. Additionally, the PBMR pebble bed design supports an outage every 5-years. Conventional wisdom questions the ability to continuously operate mechanical equipment for such a lengthy period without maintenance and maintenance requires downtime (preferably scheduled downtime). It also could promote a "run-to-failure" plant philosophy that is detrimental to overall plant safety. This, in turn, could result in a higher forced-outage rate for the pebble bed option, negating any benefit from continuous operation with online refueling

The potentially higher capacity factor of the pebble bed reactor with on line refueling is not a strong advantage of this reactor type over the capacity factor of the prismatic reactor.

6.1.4 Plant Efficiency

Plant efficiency is simply the ratio of useful energy produced to the amount of energy used by a power generation facility. For the case of electricity production only, the plant efficiency the net electrical output produced divided by the plants thermal power rating. Furthermore, plant efficiency in the case of electrical production is strongly dependent on the choice of power production cycle (Brayton, Rankine, combinations etc.).

Regardless of the cycle match to the plant, the prismatic core offers a significant advantage in achievable plant efficiency (>44% versus 42% for pebble bed using comparable Brayton cycles). The main reason for this is again core geometry. In this case, the pressure drop across the prismatic core is a factor of 2 to 3 less than the pressure drop across the pebble bed core. This translates into significantly less power being consumed by the prime mover for primary coolant flow (i.e., helium circulators in an indirect cycle or compressors in a direct cycle). Hence, more net power is available in the prismatic case.

The higher achievable plant efficiency of the prismatic core reactor is a strong advantage over the pebble bed core. Note also that the current plant efficiency for PBMR (42%) is slightly less than the plant efficiency requirement specified in the NGNP functions and requirements document [2].

6.1.5 Maximum Core Outlet Temperature

The maximum core outlet temperature that can be achieved by either option is a function of the temperature difference between the fuel and the coolant and the maximum allowable post-accident fuel temperature (approximately 1600 °C). In the pebble bed reactor, the average fuel particle-to-coolant temperature drop is 50-70 °C as opposed to 150-200 °C in the prismatic design. Several phenomena are responsible for this, primarily, better core flow mixing. This translates into an advantage for the pebble bed design because the core outlet coolant temperature can be higher for the same maximum fuel temperature. Conversely, for the same coolant outlet temperature, the pebble bed design has more margins.

The pebble bed reactor type does have an advantage of having a slightly higher temperature capability than the prismatic reactor.

6.1.6 Core Pressure Drop

The core pressure drop can significantly affect the power required to either compress or circulate primary helium. The higher the core pressure drop the more energy is required to circulate a given amount of helium flow. The pebble bed reactor is significantly disadvantaged in this regard because the torturous flow path helium must follow through the pebbled bed. This results in a relatively high core pressure differential as compared to the prismatic core. For, example, the pressure drop in the PBMR core demands approximately 40-60 MWe (estimated) to circulate primary helium as opposed to only 15 MWe for the ANTARES prismatic reactor. Note that while these are electric power requirements, a similar ratio of compressor power requirements is expected in the case of a direct power conversion system.

Hence, the prismatic reactor is judged to have a significant advantage due to its relatively low core pressure drop and the attendant power savings that this realizes.

6.1.7 Fuel Enrichment

Because of continuous refueling, the pebble bed core requires only a nominal amount of excess reactivity above that necessary to maintain criticality at power. As a result, the fuel enrichment requirement for pebble fuel is approximately 8-9%. Conversely, the prismatic core requires additional fuel material to remain critical through out its 18 month cycle. This translates into an enrichment requirement of approximately 14-16%. The excess reactivity that the additional fuel represents is readily offset by the use of burnable poisons.

The pebble bed fuel, because of the lower enrichment requirement, will therefore bear a cost advantage over the prismatic reactor for this element of fuel costs. However, on an overall basis, this is not a strong advantage considering that HTR fuel costs are estimated to be about 26% [4] of the overall plant production costs and that a significant portion of the cost of particle fuel is in its fabrication.

6.1.8 Fuel Burnup

The burnup capability of the TRISO particle fuel is independent of the reactor type but is wholly dependent on the fuel qualification program and the conditions at which it is qualified.

For PBMR, the fuel has a target burnup of approximately 90 GWD/MTU, this translates into about 9 overall core passes. For the prismatic core, the fuel must achieve an average burnup of 120 -140 GWD/Mtu in order to achieve an 18-month cycle length (36-month residence time for each element). Should prismatic fuel be successfully qualified to this burnup level, it will clearly be an advantage over pebble fuel performance because of the higher fuel utilization. Attaining similar burnup performance with pebble fuel may be possible but the additional fissile material (i.e., more enrichment) required to take advantage of the higher burnup capability will have to be accommodated in the core design. Conversely, should prismatic fuel not achieve target burnups, the result is a reduced cycle length and should pebble fuel suffer the same, pebbles will simply be passed through the core fewer times; however, this will result in using more fuel.

The prismatic core is seen to have an advantage over the pebble bed core due to its higher burnup capability. This advantage results in better fuel utilization.

6.1.9 Uranium Requirements

Plant uranium requirements are function of initial fuel loading of U-235 (i.e., enrichment), power level, and burnup capability. How efficiently the uranium is used is also a function of the plant efficiency. Despite the significant difference in initial enrichment between the pebble reactor and the prismatic reactor (8% versus 14%), natural uranium requirements on a unit energy basis for each option are approximately the same. Uranium consumption is estimated at 192 T/GWe-Year the prismatic reactor versus 198 T/GWe-Year for the pebble bed reactor assuming published data for the each option.

As approximations, the above uranium requirements are judged to be roughly equal; hence, neither the prismatic reactor nor the pebble reactor has a clear advantage over the other with respect to natural uranium requirements.

6.1.10 Plant Lifetime

Based on the Atomic Energy Act, the Nuclear Regulatory Commission (NRC) issues licenses for commercial power reactors to operate for up to 40 years and allows these licenses to be renewed for up to another 20 years. A 40-year license term was selected based on economic and antitrust considerations, not technical limitations (source - NRC website).

Currently, PBMR is designing for 40-year plant lifetime whereas ANTARES is being designed for a 60-year plant life for prismatic. These choices are arbitrary. There is no reason you could not design a pebble reactor for 60 years. PBMR simply made a design decision to go with 40 years. Clearly, the 60-year lifetime and license of the prismatic reactor is advantageous; however, it is unlikely that the NRC will license a reactor for 60 years. Nevertheless, by designing for 60 years, the life extension process is simplified.

6.2 Fuel Design and Fuel Performance Issues

The safety case for the HTR relies heavily on TRISO-coated particle fuel technology with its high temperature capability and high fission product retention capability. Both the pebble bed and prismatic reactors rely on this technology. The similarity in required performance and reliance on fuel to hold together during accidents is effectively identical; however, the fuel development strategy taken by PBMR to demonstrate required performance is very different from the strategy taken for ANTARES. The extent to which fuel strategy differences matter will depend on one's perspective with respect to the NGNP mission relative to fuel development

6.2.1 Fuel Service Conditions

In this section, the fuel service conditions of the pebble bed reactor as represented by PBMR and the prismatic reactor as represented by the potential baseline design for NGNP (i.e., AFCI program) are reviewed. A comparison of fuel service conditions is presented in Table 6-2 below. These data were compiled from various publicly available sources (e.g., material from reference[5]).

Fuel Service Conditions	Prismatic Reactor	Prismatic Rating	Pebble Reactor	+ or -
Service Conditions - Normal Operations:				
Avg. Fuel-Coolant Temp. Difference, ºC	100-200	-	50-70	++
Avg. Fuel Temperature, °C	1250	+	1100	-
Fluence, 10 ²⁵ n/m ²	4.7	++	3.5	-
Burnup, % FIMA	15	++	10	-
Power Density, W/cc	6.6	+++	4.7	-
Packing Fraction	30	+	10	-
Operational Fuel Performance Target, failure rate	1.00E-05	о	1.00E-05	о
Service Conditions - Post Accident	<1600 °C	0	<1600 °C	0
Overall Fuel Service Conditions Rating		++		

 Table 6-2: Fuel Service Condition Comparison

6.2.1.1 Fuel Service Conditions – Normal Operation

As shown in the preceding table, the target fuel service conditions found in the pebble bed reactor design are less challenging than those found in the prismatic design. Note, however, both designs must meet similar fuel performance targets.

First, the pebble reactor does benefit from a lower average fuel temperature during operation because conditions support a much lower fuel-to-coolant temperature difference. This is attributed to lower core power density, more heat transfer surface area and, perhaps more importantly, a significantly higher degree of coolant mixing in the pebble core. This is obviously an advantage. The lower average fuel temperature is also below the silver "cliff"

region with respect to silver release. The other parameters (fluence, burnup, power density, packing fraction) are, to some extent, variables that can be controlled through design as dictated by fuel qualification results.

6.2.1.2 Fuel Development Strategy

However, the fuel development strategy being followed by PBMR relies heavily on its fuel operating near or within the German fuel operating envelope (inner green circle) as shown below in Figure 6-1 (from reference [5]). Because PBMR is adapting the German fuel design, PBMR may be able to credit pas German fuel qualification work in licensing and qualification, thereby reducing the scope of fuel qualification. It is not all clear, however, that this strategy will ultimately be successful. Reliance on this strategy presents a significant schedule risk given the uncertainty in regulatory response to the issue. In contrast, the fuel operating envelope proposed for ANTARES and, potentially NGNP, is similar to that of the AGR program (outer, brown circle) which is very aggressive. Hence, the qualification and licensing of ANTARES fuel must meet the demands of a much more challenging design envelope.

Figure 6-1: Normal Operation Fuel Service Conditions: AGR versus German Fuel Development Programs



The service conditions for pebble fuel - lower average operating temperature, burnup, power density etc. - may translate into less licensing risk and research and development risk. The reverse is true for the advanced fuel design. However, the PBMR fuel strategy is wholly dependent on their being able to demonstrate the applicability of the German data set to their current or to be developed fuel process. Should this demonstration not succeed, PBMR will be faced with a fuel development challenge similar to that of the advanced fuel design but at a much later stage in their overall plant development after a significant amount of investment.

Regarding the advanced fuel strategy, there is significant benefit to be gained by developing an advanced particle fuel capable of meeting the more stringent requirements represented by the outer envelope above. The higher burnup results in greater fuel efficiency and longer fuel cycles while the higher temperature capability permits extending the range of applications to which the plant can be marketed. Hence, the advanced fuel design endorsed by ANTARES is clearly an advantage and, moreover, is fully compatible with the objective of the NGNP program to develop advanced technology.

Note that in the foregoing discussion, the focus is fuel development strategy which is independent of reactor type. There is no reason to believe that fuel for a prismatic reactor could not be designed to stay within the German fuel envelope. Obviously, that would have operational implications because of the lower burnup. Conversely, there is nothing that would prevent PBMR from expanding its operating envelope to that of the AGR program as well; however, this would not be in line with PBMR's current low risk fuel qualification strategy. The point is that either fuel stratagem has its advantages and disadvantages but, albeit with some difficulty, fuel strategy decisions are reversible. New fuel strategies can be introduced as newer designs evolve or, more importantly, as chosen designs lose favor due to unfavorable operational experience.

6.2.1.3 Fuel Operational Performance

Actual fuel performance during operation must be consistent with established fuel performance limits which include:

- 1. As-manufactured quality requirements:
 - a. Allowable failure of fuel particle coatings at the time of manufacture,
 - b. Free uranium contamination in fabricated fuel.
- 2. In-service fuel performances requirements:
 - a. Fission product retention capabilities during normal operation (accounting for the failure of fuel particle coatings and, if significant, for the radionuclide diffusion out of the fuel particles).
 - b. Fission product retention capabilities during off-normal events (accounting for any incremental failure of fuel particle coatings and, for any increased diffusion of radionuclides out of the fuel particles).

Currently, the operational fuel performance target for both reactor types is the same: 1.00E-05 or 1 failure for each 100,000 particles.

The actual limits are established to meet acceptable dose consequences for normal operation and as a result of a design basis accident. Though the acceptable dose consequence is the same for both reactor types, the resulting fuel performance limits may be different for a number of reasons:

- Accident severity/duration
- Core radionuclide inventory (source term)
- Fission product retention capability (fuel, filtering)
- FP retention within primary system (plateout)
- Degree of Graphite Oxidation
- Release of non-fuel radio-contaminants (e.g., dust)
- Distance to site boundary

Hence, given the above, it is premature to acknowledge one reactor type as having a significant advantage over the other with respect to operational fuel performance. There a too many variables that can be adjusted to achieve acceptable results. However, the fact that the pebble bed reactor is more prone to creating dust that could potentially be released is remarkable. Furthermore, should the pebble bed reactor be coupled to a direct cycle, dust transport into sensitive turbo-machinery and heat exchange equipment could be problematic. Also remarkable is the fact that the prismatic core is more resistant to graphite oxidation than the pebble bed core. Due to the presence of the fuel kernels and to assure the integrity of the SiC coating, neither the pebble fuel spheres nor the fuel compacts can be fully graphitized. However, in the prismatic core, the fuel compacts are completely sealed in a fully graphitized matrix. Hence, the result is significantly less graphite oxidation in post-accident heat-up scenarios.

6.2.1.4 Fuel Service Conditions – Post-Accident

It is not clear if either reactor type option has an advantage with respect to post accident fuel performance. In the pebble bed case, the more favorable normal operational environment would challenge the fuel less because fuel performance is heavily dependent on burn-up and temperature resulting in the fuel being in "better" condition prior to an operational event. However, the prismatic fuel, even running at a higher temperature and burn-up, may perform better post accident (i.e., less release) due to its quality being higher as a result of having to meet a more stringent qualification process due to its more aggressive operational envelope. In either case, the maximum post accident fuel temperature will need to be maintained at or below the maximum allowed post accident temperature of 1600°C, dependent on the fraction of fuel experiencing this temperature. Under the assumption that this fraction is very low (<1%), even a potentially higher accident temperature may be justified.

6.2.2 Fuel Qualification and Fabrication

Fuel qualification and fabrication issues are summarized in Table 6-3 below and discussed.

Fuel Qualification & Fabrication	Prismatic Reactor	Prismatic Rating	Pebble Reactor	+ or -
Fuel Qualification Program	Harder	-	Easier	++
Fuel Fabrication				
Fuel Quality Requirements	Higher	-	Lower	++
Unitized Material Burden				
Natural Uranium (Tonnes/GWe-Year)	192	0	198	0
*Graphite (Tonnes/GWe-Year)	156	++	218	-
Process Complexity	Similar	0	Similar	0
TRISO Particles/GWe-Year	1.2x10 ¹⁰	++	1.6x10 ¹⁰	-
Fuel Compacts/GWe-Year	3.9x10 ⁶	о	N/A	
Fuel Elements/Gwe-Year (prisms or pebbles)	1396	о	1,084,717	о
Fabrication Cost	TBD	0	TBD	0
Overall Fuel Qualification & Fabrication Rating		ο		0

 Table 6-3: Fuel Qualification and Fabrication

*Includes fuel block and compact graphite for prismatic fuel and graphite portion of pebble fuel.

6.2.2.1 Fuel Qualification Program

Due to adhering to the German fuel service conditions as shown above, PBMR fuel qualification appears to be less challenging than that faced by ANTARES. By effectively replicating the German fuel manufacturing process,

PBMR may effectively reduce the scope of fuel qualification, relying heavily on the applicability of existing data. Furthermore, PBMR fuel program relies on a step-wise burn-up escalation program whereby burn-up levels are increased only after satisfactory fuel performance has been demonstrated in-reactor. This permits PBMR to introduce fuel improvements and higher burn-up gradually in a fashion similar to that seen in commercial LWRs.

Conversely, ANTARES fuel qualification is more challenging than that faced by PBMR because its fuel service conditions significantly exceed the German fuel service conditions for the major parameters. Hence, the scope of fuel qualification is greater because of the research and development that is involved (i.e., significant fuel irradiation program is required to obtain the data necessary to demonstrate the desired level of fuel performance.

Based on the above, it currently appears that pebble bed fuel development presents less risk than prismatic fuel development. This less risk, however, comes at a price – limited fuel performance capability. By adopting 25-year old, UO_2 based German particle fuel technology; PBMR is sacrificing the prospective benefits of an advanced fuel design for less licensing risk and less fuel R&D.

It remains to be seen if the PBMR fuel development strategy will work. The excellent performance of German particle fuel is well known; however, the reasons why it performed so well are not fully understood. Nevertheless, the PBMR strategy hinges on replicating the German fuel fabrication to maximum extent possible and then demonstrating similar fuel performance. This allows PBMR to present a reasonable licensing case based on past German fuel development and at the same time significantly reduce R&D requirements. PBMR is confident that this approach will be successful; and, is willing to accept the risk that failing to demonstrate fuel performance similar to German fuel represents.

In comparison, ANTARES, by virtue of its more severe fuel service conditions, must pursue an advanced fuel design to accomplish its mission. ANTARES is not limited to UO2 based fuel and is highly likely to adopt UCO or another advanced fuel type in order to achieve satisfactory performance levels. This aspect of ANTARES and prismatic fuel development is more fully in line with NGNP's mission to develop and demonstrate new technologies.

6.2.2.2 Fuel Fabrication

Given that both pebble bed and prismatic reactor fuel is based on TRISO-particle technology, the main question to be answered with respect to fuel fabrication is this: "Is the manufacturing burden and cost greater for one option than the other?"

First, fuel quality requirements for the prismatic fuel will be more restrictive than for pebble reactor fuel because the prismatic fuel must meet similar operational and post-accident failure targets but while being qualified to the more severe service conditions. This will add to fuel costs.

With respect to natural uranium usage, ANTARES requires 192 Tonnes/GWe-year versus PBMR requiring 198 Tonnes/GWe-year. Or, on an annual basis, ANTARES requires 54 Tonnes/year versus 33 Tonnes/year for PBMR. ANTARES requirement is higher due to its higher power capability.

Graphite requirements for fuel manufacturing must also be considered. PBMR requires approximately 218 Tonnes/GWe-year versus 156 Tonnes/GWe-year that ANTARES requires. However, on a yearly basis, again due to its higher power output capability, ANTARES requires 44 Tonnes/year versus PBMR's 36 Tonnes per year. Clearly, the lower graphite requirement for the prismatic reactor is an advantage.

The process to make particle fuel for either the pebble or prismatic reactor is of comparable complexity. The basic process is based on particle formation by the sol-gel process followed by the application of the successive particle layers via the chemical vapor deposition process. Obviously, the procedures and technologies involved are fundamental elements, including 'art-of-the-trade' considerations. Once particles are fabricated, they then must be fabricated into pebbles or compacts and prisms.

Based on advertised conditions [9.6% enrichment and 90.7 GWD/MTU], PBMR requires an estimated 1,100,000 pebbles per gigawatt-year of electrical energy output or 179,000 pebbles per year (490 pebbles/day). On a particle basis, PBMR requires about 16 Billion particles per gigawatt-year of electric energy output or about 3 billion particles per year. Conversely, ANTARES [14% enrichment, 120 GWD/MTU] requires 1397 prismatic fuel elements per gigawatt-year of electrical output or about 400 prismatic fuel elements per year. On a particle basis, this translates into 12 billion particles/GWe-year or 3 billion particles per year. Hence, the prismatic reactor produces approximately 50% more energy per particle than the pebble reactor.

From the perspective of manufacturing burden, ANTARES and PBMR have remarkably similar annual material flows – each must process relatively the same amount of fuel particles and process similar amounts of graphite. Hence, any real differences must arise in the fabrication process. Because of its more demanding service condition envelope, ANTARES fuel will be required to meet more stringent quality requirements and, therefore, will be subject tighter fabrication controls. However, that is not to say PBMR fuel will be subject to lesser fabrication controls. It does mean that the ANTARES fuel qualification program requires fuel that performs in its service envelope to the required quality level.

In summary, it is premature at this point to make a judgment on fuel fabrication cost. The fuel for the prismatic reactor has an advantage due to requiring less material; however, it is not clear, despite requiring 33% less particles that the costs associated with particles, compacts and prisms will be less than the cost of particles and pebbles. More detailed data is required to assess fuel cost; however, the availability of such data is limited due to its proprietary nature.

6.2.2.3 Fuel Design Options

In the foregoing discussion, we have focused on PBMR and ANTARES fuel programs as they are currently known; hence, it must be viewed in "snapshot" fashion. Furthermore, one needs to acknowledge the many degrees of freedom that are possible in fuel and reactor design. Thus, caution is advised when extrapolating comparison results of ANTARES and PBMR on the fuel utilization question.

Assuming that a pebble bed reactor uses UO_2 and only has a burnup of 60% of the prismatic (possibly using UCO or other advanced fuel), then clearly the pebble bed reactor will require 70% more particles for the same energy output. However, it is not a requirement that pebble bed reactors be limited to UO_2 . Pebble bed reactors are flexible in that they can operate with lower particle burnups, but they are not required to. With a successful UCO fuel qualification program, there is no reason they could not go to higher enrichments and run their pebbles through 12-15 times instead of 8-10. This would take them to burnup levels similar to that of the prismatic reactor fuel.

With online refueling, the pebble bed reactors have less need to pursue higher burnup, but there is no reason that they could not do it. PBMR has opted to build upon the German experience with respect to fuel qualification, but they could go farther if the value of fuel utilization and spent fuel charges became significant enough to justify UCO qualification.

6.2.3 Waste Disposal and Reprocessing

Table 6-4 below compares the back end material flow for ANTARES and PBMR, respectively. These data have been assembled based on published information.

SPENT FUEL DISPOSAL- REPROCESSING	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Spent Fuel Disposal				
Fuel Units/Gwe-Year compacts (prisms) or pebbles)	4.265x10 ⁶ (1396)	0	1.085x10 ⁶	0
Fuel Unit Volume, M ³ /GWe-Year	124	0	123	0
Fuel Unit Stored Volume, M ³ /GWe-Year	124	++	204	-
Heavy Metal Waste, Tonnes/Gwe-Year	6.4	+	9.8	-
Non-Heavy Metal Waste, Tonnes/Gwe-Year	156	+	218	-
High Level Waste, M ³ /Gwe-Year	26	++	204	-
High Level Waste, Tonnes/Gwe-Year	53	++	228	-
Non-Compact Graphite, Tonnes/Gwe-Year	109	0	Na	0
Residual Uranium-235 content, %	~5		<1	+
Reprocessing Considerations	Easier	+	Harder	-
Overall Rating for Spent Fuel Dipsosal & Reprocessing		++		

Table 6-4: Spent Fuel Disposal and Reprocessing

6.2.3.1 Spent Fuel Disposal

The prismatic reactor has a significant advantage over the pebble bed reactor with respect to spent fuel:

- 1. First, as seen in the preceding table, the discharged volume of spent fuel is, remarkable, almost identical. However, the similarity ends when considering stored volume – pebble fuel, due to packing efficiency, requires nearly twice its volume for storage.
- 2. Second, the actual amount of heavy metal waste and fission products is less in the prismatic case than for the pebble case due better fuel utilization.
- 3. Third, the non-heavy metal portion (i.e., fuel block graphite plus compact graphite) of the waste is also less (156 vs 218). Furthermore, about 1/3 (47 tonnes) of the non-heavy metal waste by weight for the prismatic fuel is compact graphite. Conversely, 100% (i.e., 218) of the value for the pebble reactor represents the graphite portion of the pebble sphere.
- 4. Assuming the compacts are separated from the bulk fuel block, and amount combined with the heavy metal waste yields 53 tonnes/GWe-Year of high level waste. This is a significant advantage when compared to the pebble waste of 228 tonnes/GWe-year (which is simply the spent fuel pebble mass)

Whether or not compacts are separated from the prismatic blocks, the above data show the prismatic advantage with respect to spent fuel management. It is very important to know that for prismatic designs spent fuel waste can be segregated and dispositioned via to most economical path.

6.2.3.2 Graphite Waste

Finally, a word about fuel-related graphite waste is in order. The balance of the fuel-related graphite waste or approximately 110 Tonnes/GWe-Year is attributed to the prismatic block. Because the fuel compacts can be removed, this graphite could most likely be disposed of as low level waste; however, its radioactivity content may challenge Class C limits. Because it is unlikely to be performed on-site, the benefit of compact removal in terms of high level waste volume reduction will not be realized until a suitable infrastructure exists that will support the required processing. This infrastructure, of course, will require a sufficient population of reactors to support its viability.

Graphite lifetime is an essential consideration and there is a significant amount of graphite in the core structures, and reflectors. In the prismatic design, reflectors are routinely replaced as part of the refueling process. Current thinking is that a replacement frequency on the order of 6-years will be appropriate for reflectors directly adjacent to fuel.

In a pebble bed design, there is not a convenient opportunity to replace the massive central fixed reflector. It is highly likely that the central reflector will have to be replaced at least once. A dedicated or extended scheduled outage will be required to replace it.

There is considerable amount of uncertainty in core structure and reflector graphite lifetime material requirements. AREVA estimates that ANTARES will require approximately 124 Tonnes/GWe-year of graphite over its lifetime. PBMR appears to have a slight advantage here in that it requires approximately 103 Tonnes/GWe-year of graphite over its life. (Note that these are rough estimates and that actual graphite lifetimes need to be determined through appropriate material qualification programs.)

6.2.3.3 Waste Storage / Reprocessing

Spent fuel (i.e., fuel + moderator graphite) and reflector graphite comprise the majority waste flow for either the pebble or the prismatic option. ANTARES is estimated to produce 162 Tonnes of spent fuel elements per GWe-Year versus an estimated 228 Tonnes of spent pebbles/GWe-year for PBMR. This is clearly an advantage for ANTARES. On an annual basis, the values are 46 Tonnes and 38 tonnes, respectively for ANTARES and PBMR, acknowledging ANTARE/s higher power level as the reason for the higher annual material flow.

From an order of magnitude perspective, these numbers are similar and, even though one may be higher or lower, these differences would not, by themselves, be significantly influential with respect to reactor type. However, some key basic differences between pebbles and prisms now must be considered.

First, consider storage implications. ANTARES produces 124 m3 of fuel elements per GWe-year versus 123 m3 of pebbles per GWe/year. Assuming a 60% packing fraction, the required storage volume for pebbles is nearly doubled at 205 m3 per GWe-year. Furthermore, because of the homogeneous nature of the pebble fuel, volume reduction is not practical. For prismatic fuel, the case is markedly different. Fuel compacts comprise 20% of the fuel element waste volume. Separating the fuel compacts from the balance of the fuel element is possible and can reduce the high level waste volume by 80%. The balance of the fuel element graphite can be disposed of as low level waste.

Second, there are fuel handling implications to consider as well. Pebble fuel is easier to move than prismatic fuel blocks because, as in the PBMR design, they pneumatically transferred into storage tanks that serve as both short term and long term storage. Prismatic blocks need equivalent storage as well; but, at least initially, they must be handled individually. In the ANTARES design, on-site storage will be provided that is sufficient to hold the spent fuel output of 10-years of a 4-module plant's operation.

Third, reprocessing is the essential element in the closure of any nuclear fuel cycle. The following points demonstrate a strong case for reprocessing:

- 1. It allows the recovery of valuable residual fissile (U-235, Pu-239) and fertile fuel (U-238), which may be recycled for further energy production.
- 2. It permits more efficient management of the remaining waste, allowing for waste reduction and waste conditioning (in which waste volume and radiotoxicity are significantly reduced)
- 3. These achievements (1 and 2, above) are consistent with Generation IV goals of sustainability and waste reduction.
- 4. With the exception of head-end processing, it is wholly compatible with the existing reprocessing technology
- 5. It allows for the potential customization of the waste for final disposal (i.e., a waste form that is specially designed and qualified to optimize characteristics for long term disposal).

Because of its robustness, reprocessing TRISO-fuel is a challenge that is borne by both pebble and prismatic choices. However, the first phase of reprocessing consists of separating fuel particles from graphite moderator. This phase is easier for prismatic fuel than for pebble fuel. In prismatic fuel, the fuel particles are concentrated in the fuel compacts which can be readily separated from the bulk graphite of the fuel element. Conversely, in the case of pebble bed fuel, the fuel particles are homogeneously mixed throughout the pebble. Hence, all of the graphite moderator must be separated from the particles in pebble reactor fuel as opposed to only a much smaller amount of graphite contained in the compact. While the prismatic fuel has an advantage in this regard, it is not out of the question to crush pebble fuel and separate out the fuel particles; however, the issue of failed particles and their presence in the bulk graphite would have to be addressed.

In countries where reprocessing is available (e.g., France, Russia, United Kingdom, Japan), spent fuel is shipped to the reprocessor after an acceptable cooling period. It is the ideal situation because the availability of reprocessing eliminates the need for large and costly on-site fuel storage facilities. This is certainly not the case currently in the US. Nevertheless, with the advent of the GNEP program and the initiative to re-establish reprocessing in the US, the prismatic reactor is wholly compatible with this mission.

6.3 Fuel Handling and Refueling Issues

Geometry drives the choice of refueling method in the pebble-bed reactor. The basic fact that fuel in a pebble bed reactor is in the form a billiard ball-sized sphere and can roll makes this option a natural candidate for some form of an on-line refueling system. Geometry and reactor physics also pose difficulties for the alternate form - a batch-type pebble bed reactor (i.e., if one could manage the required excess reactivity required for a batch core, the pebbles would still need to be recirculated within the core to assure even burnup). The geometry of the prismatic reactor naturally leads to the choice of periodic refueling.

Given preceding primer, one can readily see that, realistically, the selection of the refueling option is a defacto decision inherent to selection of reactor type. Hence, the pebble bed reactor choice implies on-line refueling while the prismatic reactor choice implies periodic refueling. A comparison of the attendant fuel handling and refueling issues is provided in Table 6-5 and discussion provided thereafter.

Fuel Handling and Refueling Issues	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Fuel Elements in Core	1020	0	460,000	0
Refueling Method	Batch, 50%	ο	Continuous	ο
Refueling Interval, Months	18	ο	na	ο
Refueling Duration, Days	22	ο	Continuous	ο
Fuel Moves/Day During Refueling or Pebbles handled per day, continuously.	100-200	++	3000-5000	-
Reflector Replacement (i.e., during refueling)	Yes	+++	No	-
Special Equipment for Reflector Removal	No	+	Yes	-
Complexity of Refuel Equipment	High	+	Very High	-
Module Sharing of Refuel Equipment	Yes	++	No	-
Other Maintenance Opportunity	High	++	Limited	-
Planned Major Outage	Not Req'd	++	Req'd	-
Major Outage Frequency, Years	Not Req'd	ο	5	ο
Impact of Refuel Equipment Breakdown	Extended Refueling Outage	++	Unplanned Outage	-
Ability to Maintain/Repair Refuel Equipment During Normal Operation	Yes	+	Limited	-
Overall Rating for Fuel Handling and Refueling		++		

Table 6-5: Fuel Handling and Refueling Issues

6.3.1 Fuel Handling Benefits, Risks and Tradeoffs

The benefits, risks and tradeoffs associated with online vs. offline refueling is therefore an important consideration in choosing the reactor type.

6.3.1.1 Pebble-bed reactor

In the pebble bed reactor, the on-line refueling equipment is constantly operating and the impact of potential down time is a strong concern on plant availability. Furthermore, continuous operational pressure arising from online refueling presents less opportunity for planned maintenance which could possibly result in deferred maintenance of other plant systems

The pebble handling system is shown conceptually in Figure 6-2 [6]. Because it must operate continuously, the pebble handling system must highly reliable. It is also a complex system. These combined attributes may make it relatively costly to build and maintain. Furthermore, the pebble handling system build cost is repeated for every module needed.



Figure 6-2: Conceptual Pebble Handling System

The prospective advantage of online refueling is an increase in plant availability. PBMR claims that a 98% availability is possible with a maintenance outage every 5-years. However, the theoretical advantages of online refueling have not been realized over the longer term in other commercial power reactor designs (e.g., CANDU reactors). For pebble reactor, pebble handling equipment reliability is the key consideration. The pebble handling system at AVR worked well after improvements but did account for 3% generator unavailability [7]. PBMR's target unavailability for their pebble handling system appears possible in light of AVR experience.

On-line refueling demands that approximately 3000-5000 fuel spheres be processed each day. While refueling equipment problems of up to approximately a week in duration may be tolerable, longer term problems will force shutdown and reduce plant availability. Personnel access to refueling equipment to effect repairs may also be limited. Furthermore, extremely long operational runs will place increased demands on mechanical equipment and could result in higher forced outage rates, thereby further negating the advertised benefit of online refueling.

The negative impact of the higher forced outage potential cannot be understated. It is not simply the prospect of the plant being forced to shutdown to fix a problem. It is the unpredictability of the timing of the forced outage. The resources to do major maintenance work at a nuclear plant are not instantaneously available, making unplanned outages more costly simply because they are unplanned. Furthermore, the timing is critical because of the extremely costly prospect of having to buy replacement power to meet generation commitments, especially when the power demand is high. When normal generation costs approximately \$50/Mw-hr and replacement power on the spot market is running \$500/MW-Hr, the economic advantage of continuous refueling can erode very quickly.

An additional concern with the continuous refueling system is that of the potential to introduce another source of contamination in to the primary coolant system. Each pebble will make up to 8 or 10 trips through the fuel handling system before being discharged as spent fuel. In those transits, the pebbles will erode fuel handling system and could potential be a carrier of erosion products (e.g., iron, nickel) into the core for activation.

Finally, reflector replacement in the pebble reactor is problematic because there is no opportunity to do so with the on-line refueling equipment. PBMR will require a special mid-life outage to replace reflectors. It will also need special equipment to perform the replacement and, moreover, removal of the reactor vessel head (a major evolution for an HTR) is required.

6.3.1.2 Prismatic Reactor

The prismatic reactor (e.g., ANTARES) is refueled every 18-months. Refueling takes approximately 22 days. The reliability of the refueling equipment must be commensurate with meeting this refueling window. The prismatic core is refueled in 1/6 radial segments. With a 50% fuel management scheme, approximately 1500-2000 fuel blocks must be moved each refueling. This includes the complement of 510 fresh elements being introduced and the same number of spent elements being removed. The balance of the fuel moves are necessary to configure the core to the desired loading scheme. Additionally, refueling also offers the opportunity to replace graphite reflector blocks on a periodic basis. Typically, a reflector block adjacent to fuel will be replaced every 6 years or every 4-cycles.

The question of refueling equipment reliability is very important for the prismatic. Its design is also challenging. The system must be able to accurately move over three axes bearing a 150 Kg at the end of a long reach and perform many manipulations. Such prismatic fuel handling equipment has been successfully demonstrated (at Fort St. Vrain). It is reasonable to expect that this technology, update appropriately, can be readily developed for moderns HTRs.

An added advantage of periodic refueling of the prismatic reactor is that maintenance of the refueling equipment itself can be accomplished when the plant is operating. Furthermore, once commercialized and in a multi-module setting, maintenance of refueling equipment can be accomplished for all modules during non-refueling periods, optimizing use of the both the equipment and the refueling staff.

Finally, the refueling window is very advantageous to the prismatic option since it represents an opportunity to perform scheduled maintenance on other plant equipment, thereby lessening the chances of forced outages during operation. While this does not completely eliminate the potential for forced outages during plant operation, it certainly will contribute to reducing the frequency of forced outages.

6.3.2 Perspectives on Fuel Handling/Refueling Method

In conclusion to the foregoing discussion, it is difficult to declare one option having a clear advantage with respect to fuel handling and refueling issues. A significant difference in availability with online vs. offline refueling, as previously stated, is not strongly supported through prior experience; however, it must be recognized that mature commercial scale designs have not yet evolved for either approach to HTRs. In the end, the determining factor will be whether the unplanned unavailability associated with the more complex operational configuration of online refueling exceeds the marginal evaluated advantage of that approach versus periodic refueling. Effectively, this also represents a tradeoff between overall planned unavailability, which can be optimally timed to power generation requirements and unplanned unavailability, which is random.

The prismatic reactor periodic refueling approach is more advantageous and consistent with current operating philosophy (i.e., consistent with current day LWRs). This reasoning is supported by AREVA NP's choice of reactor type whereby the selection of the prismatic form for ANTARES was based on four key perceptions regarding the associated tradeoffs:

- 1. The prospective availability advantage associated with online refueling is remains to be demonstrated
- 2. The potential economic benefits associated with prospective availability advantages are outweighed by the higher power capability of the prismatic core (if high power is needed)
- 3. Planned maintenance can be schedule more uniformly throughout the life of the plant and timed more appropriately to utility planned outage requirements.

Finally, power level aside, it must be recognized that the end user requirements may impact the selection of reactor type. The details of specific process heat requirements of the systems supplied by the reactor may make the choice of refueling concept either vitally important or unimportant. That is to say that continuous refueling

may be more amenable to certain process heat users than others and vice versa for period refueling. The point is that the plant can be used in other modes than the standard supply electricity only mode.

6.4 Economic Factors

The key economic discriminators are compared in the below table and discussed in detail afterwards.

ECONOMICS	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Capital Cost	Lower	++	Higher	-
O&M Cost	Lower	++	Higher	-
Fuel Cost	Similar	ο	Similar	ο
Waste Costs	Lower	++	Higher	-
Decommissioning Costs	Similar	ο	Similar	ο
Overall Rating for Economic Factors		++		

 Table 6-6:
 Economic Factors

6.4.1 Capital Cost

Both the prismatic and pebble bed reactors can be designed with similar secondary systems; hence, the only discriminators for the purpose of this study are those cost items comprising the envelope of the nuclear core. These are core, initial fuel and reflector elements, core internals, control rod systems, fuel handling and storage equipment, reactor vessel and related equipment.

A major cost item in the preceding list is the reactor vessel. The following table compares some of the key data for the prismatic and pebble reactor vessels:

Reactor Vessel Parameter	Prismatic Reactor	Pebble Reactor
Overall Height, Meters	25	30
Internal Diameter, Meters	7.2	6.2
Operating Pressure, MPa	5	9
Weight, Tonnes	965*	1000**
Material (design option)	9 Cr 1 Mo	SA508

Table 6-7: Reactor Vessel Data

*ANTARES vessel at 6 MPA; **PBMR vessel

Note that the prismatic reactor vessel is somewhat similar in geometric size to the pebble reactor vessel but almost identical in weight. A key discriminator is the choice of material. Hence, assuming the same material, the cost of these reactor vessels will be similar as well; however, cost of the prismatic reactor vessel per unit of energy

produced will be less (if higher power is needed). However, the prismatic reactor needs to use an advanced vessel material which will serve to reduce the advantage of the prismatic reactor's larger power output.

Of the remaining cost items introduced above, the fuel handling and storage system is perhaps the most remarkable with respect to cost differential. Items such as core internals, control rods, reflector elements will bear similar costs in each option.

The pebble bed reactor has a very complex pebble handling system as shown previously in Figure 6-2. It will be very costly to design and build a system with the requisite high reliability that will continuously circulate the highly radioactive pebbles for the life of the plant. Furthermore, in a multi-module setting, the build cost is repeated in how ever many modules as needed.

The additional complexity shown in the PBMR design will add significant costs as well (fuel handling system). Significant additional storage capacity for pebbles not in the core will be needed, adding to cost. In conjunction with storage for pebbles not in use, a complex radiation measuring system will need to be created that can determine the needed information about each pebble that is removed from the reactor at 30-second intervals. All of these measuring and storage systems will need to be safety rated and operating at all times in order to prevent an unscheduled outage – further increasing costs

The pebble bed design will also likely require a large number of extra pebbles to be ready to circulate in the core when the plant first reaches criticality. While it is not an overall extra cost, it is an additional upfront cost that will need to be paid sooner than other reactor designs require.

6.4.2 Fuel Cost

Fuel fabrication costs are not readily available, but the main cost component of both designs is expected to be that of the TRISO fuel particles. Considering that the pebble reactor requires more particles per unit energy produced may be a cost discriminator; however, it is premature to judge this one way or the other without hard fabrication cost data. Additionally, the cost of fabrication of the fuel particles into the final fuel form (i.e., either fuel compacts/blocks or pebbles) is not expected to be much different for pebble or prismatic options.

In enrichment costs, there will be a difference because the prismatic reactor requires 14% enriched fuel while the pebble core requires 9.6% enriched fuel. Hence, more separative work units will be required for the prismatic fuel (enrichment factor of 30 versus 20). Nevertheless, on a unit energy basis, the natural uranium requirements are remarkably similar between prismatic and pebble bed fuel as shown in Table 6-3.

Enrichment costs are only one component of the cost of fuel fabrication, and it is generally agreed that the bulk of the cost of fuel will lie in the manufacture of the particles themselves. Hence, as shown previously in Table 6-3, the pebble reactor requires 33% more particles to be fabricated per unit of energy delivered than the prismatic reactor. This is an advantage for the prismatic reactor; however, given the more severe service conditions, this advantage may be offset by higher costs due to stricter quality requirements.

While enrichment costs may be higher, the prismatic offers significantly more capacity per module. Assuming a 47% electric conversion efficiency for the prismatic, a 600 MWt prismatic module offers 264 MWe. The PBMR module is designed for 400 MWt with a 41% electric conversion efficiency, offering 164 MWe. Therefore, a similar sized prismatic module offers 61% more power then the PBMR design. Assuming a 600 MWt for the PBMR, mentioned in the NGNP Point Design study [8],there would be 246 MWe produced, or still 11% more power in the prismatic design. The point here is simply that even with the same power capability, the prismatic reactor will still realize a fuel economy benefit.

The pebble bed design will also likely require a large number of extra pebbles to be ready to circulate in the core when the plant first reaches criticality. While it is not an overall extra cost, it is an additional upfront cost that will need to be paid sooner than other reactor designs require.

Enrichment differences, number of particles required and fuel utilization comprise key fuel cost components as discussed above; however, there are many other factors to be considered such fuel fabrication costs, cost impact of required quality control requirements, graphite costs, etc. must also be considered. At this time, there are simply too many parameters, many with offsetting cost components, and too many unknowns with respect to overall fuel cost to be able to declare that one reactor type has a fuel cost advantage over the other. The correct judgment is that fuel costs will be similar given that both the prismatic and pebble reactors face similar situations with respect to their fuel, its qualification, and its fabrication.

6.4.3 Operation and Maintenance Cost

The operation and maintenance of an HTR require fewer personnel than do light water reactors for the following reasons:

- Simpler, more compact design
- Fewer systems and components
- Smaller staff sizes

Considering that the scope of this study encompasses only the reactor vessel and its contents, any differential with respect to cost must addressed within that context. The main discriminator is the fuel handling system. In the pebble bed reactor (i.e., PBMR), the fuel handling system is a large and complex system and continuously operates (which requires that much maintenance be performed on it while "hot"). The fuel handling system in the prismatic reactor, on the other hand, is somewhat smaller and, while complex, it is not on the same level of complexity compared to the pebble handling system. Additionally, it is decoupled from the spent fuel storage mission which is an integral part of the pebble system. Hence, the prismatic reactor is considered as having the advantage of "less complexity" that will require less resources to operate and maintain.

6.4.4 Waste Costs

Because it does not have extensive water purification systems to maintain, it is expected that the low-level waste generate by an HTR would be lower than that of light water reactors. This expectation applies equally to both reactor types.

However, as discussed previously in Section 6.2.3, the prismatic reactor will have a waste cost advantage over the pebble core primarily due the ability to separate fuel related waste into constituent parts and lower storage volume requirements.

6.4.5 Decommissioning Cost

The smaller, simpler core of the pebble bed reactor appears to be easier to decommission, but the pebble circulation system adds significantly more complexity and cost. The decommissioning costs for the prismatic reactor core should therefore be significantly less because it does not have the additional radioactive systems. Since the rest of the reactor systems can be designed in similar ways for either reactor type, there does not appear to be any additional decommissioning cost distinctions.

6.5 Research and Development

Research and development risks are present in Table 6-8 below followed by explanatory discussion.

DEVELOPMENT & R&D	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Fuel Development	Higher	-	Lower	++
High Temperature Materials (e.g., core internals)	Similar	ο	Similar	ο
Reactor Vessel	Higher	-	Lower	++
Graphite	Lower	+	Higher	-
Licensing Methods, Computer Code Development, and Qualification	Lower	++	Higher	-
Refueling Equipment	Similar	ο	Similar	ο
Overall Rating for R&D Difficulty		ο		ο

 Table 6-8:
 R&D Difficulty

6.5.1 Fuel Development

The safety case for HTR technology wholly depends on the performance of TRISO particle fuel. Successful development of TRISO particle fuel technology requires a combination of knowledge and skill in order to establish an acceptable fuel particle design, develop a cost-effective fuel fabrication process, and demonstrate that the resultant fuel meets the required performance objectives. It is critical that any fuel development program obtain a detailed knowledge and understanding of each step of the process. Both "know how" and "know why" must be equally obtained before a valid basis for fuel design and fabrication specifications can be established.

As previously mentioned in Section 6.2.1.1, two different fuel development strategies are being followed. PBMR is qualifying their fuel to the previously qualified German fuel. Prismatic reactor proponents are developing an advanced fuel design to accommodate the large performance envelope shown in Figure 6-1. Each program, given enough time, should be successful.

The main risk, therefore, associated with fuel development for NGNP is primarily a schedule risk. Namely, will the advanced fuel design be available in time to meet the initial operation target date of 2018? The ongoing DOEsponsored Advanced Gas Reactor (AGR) Fuel Development and Qualification Program is working to reestablish coated-particle fuel fabrication capability in the U.S. and to qualify a coated-particle fuel design for use in advanced gas reactors. However, the current AGR Program schedule does not match the NGNP need for fuel by 2018 and would have to be accelerated significantly to do so. To this end, AREVA and BWXT have jointly stated it is feasible to provide either UO_2 or UCO fuel on a schedule that is consistent with NGNP requirements.

Based on the above, it appears PBMR and the pebble technology has an advantage with respect to fuel R&D. This is not to say their strategy is not without risk because PBMR must successfully demonstrate the ability to manufacture fuel to the quality of the past German fuel but they also must demonstrate that they have mastered their understanding of its behavior.

6.5.2 High temperature materials

The Next Generation Nuclear Plant (NGNP) HTR will demonstrate the use of nuclear power for electricity, hydrogen production, and process heat applications. The HTR will have an average reactor outlet temperature of approximately 900 °C° - 1000 °C°. The design service life of the NGNP is 60 years.

The thermal, environmental, and service life conditions of the NGNP will make selection and qualification of some high-temperature materials a significant challenge. High temperature metallic materials, graphite, and SiC-SiC and C-C composites are being considered for use. Important materials issues that must be addressed include:

- High-temperature mechanical properties (e.g., tensile, creep, creep fatigue, stress-rupture, high and lowcycle fatigue, fracture toughness) in air and impure helium environments
- Environmental degradation processes from exposure to high-temperature helium with contaminants such as CO, CO₂, H₂, H₂O, and CH₄
- Long-term irradiation effects on mechanical properties (e.g., tensile, creep, creep fatigue, stress-rupture, high and low cycle fatigue, fracture toughness)
- High-temperature metallurgical stability (thermal aging effects)
- Development and validation of new sources of graphite materials
- Extension of ASME Code approval for metallic materials at the higher NGNP operating temperatures
- Development and ASME Code approval for 9 Cr-1 Mo steel, graphite, composite, and ceramic materials
- Development of component fabrication technologies for critical components such as the reactor pressure vessel (RPV) and control rods
- Emissivity of the RPV surfaces for cool-down under accident conditions

Because the average reactor outlet temperatures of either the pebble or the prismatic reactor are not significantly different, the R&D risk associated with the necessary high temperature materials for core internals, control rods, fuel handling equipment etc. is considered to be similar for both options.

More discussion relative to reactor vessel material is presented later in Section 6.10.

6.5.3 Graphite

Graphite is the foundation for HTR technology. Both reactor types, pebble bed or prismatic, need qualified grades of graphite for the key component in the reactor core: fuel, reflectors, core support structures. Significant R&D will be required to qualify the different grades of graphite that will be used. Does one option have an R&D advantage relative to graphite over the other?

The prismatic reactor has an advantage in this regard due to the fact that in the prismatic reactor, both inner and outer reflector blocks can be routinely replaced (target 6-year replacement frequency). In the pebble bed reactor, the outer and central reflectors will be replaced every 20-years during a special outage. Hence, the R&D for the pebble reactor must qualify their reflectors for significantly greater neutron fluence.

6.5.4 Licensing Methods, Computer Code Development, and Qualification

Both prismatic and pebble bed reactor technologies will require significant effort in the area of methods development and qualification. The spectrum to be covered is quite broad since every facet of the technology requires attention in this regard.

Again, as in the previous section, the question "Does one option have an advantage over the other?" needs to be addressed. In this case, the answer is clear – the prismatic reactor option, due to its static core geometry, has a significant advantage.

The stochastic nature of the pebble core simply adds another dimension of complexity on top of already complex issue area. This has not gone unnoticed – witness below the concerns raised in Reference [9] as paraphrased below:

"Core physics will be constantly changing as the pebbles flow through the core, necessitating some statistical bounding of key parameters. Differences between the center of mass and the center of gravity for individual pebbles, and surface defects and irregularities may result in non-linear conditions governing pebble flow through the core which can make it impossible to reliably predict the transit time for any particular fuel pebble, or even the fuel pebble packing density within the core."

"Design analyses will require development of appropriate thermal-hydraulic codes to deal with the complex geometries and uncertain core configurations of the pebble bed design."

"At present, there are gaps in the spectrum of internationally accepted codes and standards dealing with nuclear grade graphite and the fabrication of graphite components for use in HTGRs; with thermalhydraulic codes for use in the complex geometries of a Pebble Bed Modular Reactor (PBMR); nucleonic codes that can accurately predict the transient and accident response of a loosely coupled, statistically bounded pebble bed core configuration."

"The statistical nature of the distribution of the PBMR fuel could also conspire to make one section of the spent fuel array particularly reactive. Criticality control events at fuel fabrication facilities have shown that processes in place to exclude moderator from an area occasionally fail, as do geometry and quantity controls, thus, care will need to be exercised in the management of criticality during the storage, transportation, and disposal of the PBMR spent fuel pebbles."

Both technologies need to develop their respective licensing and analytical methods and secure regulatory approval for them as a prerequisite for licensure; however, the main point is the pebble reactor faces a much more difficult challenge due to the stochastic nature of the pebble core. This not to say it cannot be done, which it can; but, it will probably be at the expense of having to provide additional margins the prismatic option would not have to give away.

6.5.5 Refueling Equipment

Both prismatic and pebble bed reactor technologies depend on highly reliable fuel handling equipment. The pebble bed reactor has its pebble handling system which has to work continuously whereas the prismatic reactor depends on its fuel handling system to work flawlessly during its refueling outage. Both systems are complex and require significant development work; however, this is not so much an R&D problem but more of an engineering problem. Hence, with respect to R&D, the associated risks are considered similar.

6.6 Core Design Issues

In this section, core design and capability differences are examined. The section is divided into three subsections; namely, general considerations, central reflector, and core stochastic subsections.

6.6.1 General Considerations

The performance capabilities of the pebble bed reactor and prismatic reactor are compared in this section as shown in Table 6-8.

CORE DESIGN ISSUES – 1	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Core Power Density, KW/liter	6.6	+++	4.7	-
Reactivity Control				
Excess Reactivity, %∆k/k	3-5	-	1-2	+
Control Rods in Fuel Region	Yes	++	No	-
Control Rods in Reflector Region	Yes	0	Yes	0
Alternate Shutdown Capability	Yes	ο	Yes	0
Xenon Defect Override Capability	Yes	ο	Yes	0
Xenon Stability/Oscillation Control	Yes	0	Yes	0
Flexibility/Adaptability				
Fuel Zoning	Yes	++	No	-
Burnable Poisons	Yes	0	Yes	0
Axial/Radial Shuffling	Yes	+	Limited	-
Pu & Actinide Burning Capabilities	Yes	+	Limited	-
Deep Burn Capabilities	Yes	+	Limited	-
Traceable limiting fuel location	Yes	+	No	-
Mis-loaded Fuel Possibility	Yes	0	Yes	0
Overall Rating for Core Design Issues -1		++		

Table 6-9: Principal Core Design Features

6.6.1.1 Power Density

Prismatic cores can have higher power densities than pebble reactors. Compare ANTARES power density of 6.5 KW/L versus PBMR's 4.7 KW/L – approximately 50% higher. The maximum power density each option can achieve is a function of that option's acceptable performance in the limiting design basis event (i.e., depressurized conduction cool down) and thus demonstrating inherent safety.

6.6.1.2 Reactivity Control

Pebble cores, due to continuous refueling, require only a minimal amount of excess reactivity. This reactivity is managed with control rods that, by necessity, are located in the outer reflector region. As a result of THTR experience, control rod insertion directly into the pebble core is not considered a design option. While minimum excess reactivity is considered an advantage by pebble reactor advocates, its management becomes more difficult as the pebble core power is increased. Hence, increases in the pebble core power are usually accompanied by increased height rather than increased radial dimension. This is done to maintain the effectiveness of the control rods.

The pebble reactor core, due to its low reactivity margin, may have difficulty in performing load follow maneuvers or difficulty in overriding post-shutdown Xenon defect. Control rods would need to be able to add sufficient compensating reactivity in order to maintain power or restart the reactor. The situation could also be exacerbated by the unavailability of the pebble handling system which would preclude addition of fresh fuel and removal of spent fuel.

Prismatic cores require additional fuel material in order to be able to maintain full power throughout its cycle. The additional reactivity that this represents can be readily managed. First, the prismatic core can readily accommodate control rods or alternate shutdown channels directly in the fueled zone. Second, additional control rods can be located in the reflector region for further control. Third, prismatic fuel elements can accommodate fuel zoning and burnable poisons for long term reactivity control in a manner similar to current day LWR cores. Furthermore, the axial and radial shuffling of fuel elements is possible which facilitates core management. Finally, increases in both radial and axial dimensions can be considered in increasing core power level since control rods can be located within the fueled region.

The prismatic core's excess reactivity capability is an asset with respect to being able to override the effects of xenon, either following load follow operations or a full shutdown. The post-shutdown maximum Xenon defect is on the order of 4-5% $\Delta k/k$ (similar to LWR behavior). Sufficient excess reactivity is available to override this level of defect; hence no restart issues are envisioned. (This result has been confirmed by preliminary analysis results for ANTARES.) Further more, at the currently envisioned height, the prismatic core is not anticipated to be susceptible to xenon oscillations; however, the prismatic core does have many design options through which compensatory measures can be implemented should it become necessary.

6.6.1.3 Fuel Flexibility/Adaptability

The prismatic core design affords excellent fuel cycle flexibility whereas the pebble bed design, due to its stochastic core, is much more constrained both spatially and temporally. The reasons for the prismatic core advantages are as follows:

- 1. A fixed-core geometry allows for fuel zoning and burnable poison capabilities, both important to efficient fuel management
- 2. Axial and radial shuffling of fresh and exposed fuel elements also contributes fuel management flexibility
- 3. Due to finer control of core geometry, the prismatic core is more adaptable to other fuel types and (PuO, actinide burning, deep burn etc.)
- 4. Limiting core locations with respect to maximum fuel burn-up and maximum fuel temperatures are traceable throughout the cycle and, by inherent design, would never be concurrent.

The pebble bed core may offer a degree of fuel cycle flexibility as well; however, it will be difficult for it to achieve the same level of flexibility as the prismatic core because of the larger operating margins it must have to accommodate an ever changing core configuration. Furthermore, in the pebble bed core, the limiting core

location is not as traceable, and given the random paths the pebbles take, the possibility of the maximum burn-up pebble being at the maximum temperature location is distinctly real.

6.6.1.4 Mis-Loaded Fuel

Refueling of prismatic cores requires the placement/replacement of many prismatic fuel elements to replenish the core with fresh elements. The possibility of a miss-loaded fuel element, though unlikely, cannot be ignored. The probability of mis-loading a fuel element is low because refueling is computer controlled and refueling algorithms are thoroughly verified on an element-by-element basis prior to refueling operations. Nevertheless, this unlikely event must be anticipated and its impact be demonstrated to be acceptable within operational limits.

The pebble bed core is not susceptible to fuel mis-loading in the same sense as in a prismatic reactor because the fuel is all the same. However, there is the potential to overcharge the pebble core with fresh fuel; however, this is very improbable and, given the individual worth of a pebble, probably of little impact. Hence, for the pebble reactor, this is judged as a non-event.

6.6.2 Core Physical Features

The prismatic and pebble core physical features are examined in this section as shown in Table 6-9 below.

CORE DESIGN ISSUES-2	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Annular Core	Yes	ο	Yes	ο
Top Axial Reflector	Integral / Regularly Replaced	++	Permanent	-
Central Reflector	Integral / Regularly Replaced	++	Semi-Permanent Free Standing Column	-
Outer Reflector	Integral / Regularly Replaced	++	Permanent	-
Bottom Axial Reflector	Integral / Regularly Replaced	++	Permanent	-
Overall Rating for Core Design Issues-2		++		

Table 6-10: Core Physical Features

Both prismatic and pebble cores at the referenced power levels are designed as annular cores with a central reflector. However, the central reflector represents more of a design challenge for the pebble core versus the prismatic core.

In the prismatic core, prismatic reflector elements are essentially identical to prismatic fuel elements except they do not have fuel or coolant channels. Moreover, they are designed to be handled in similar fashion to the prismatic fuel element and do not require special handling equipment. Furthermore, prismatic reflectors in the central region, along with the annular core and outer reflector elements are all constrained within the core barrel and upper core constraints. Finally, reflector elements are periodically replaced including those located in the central reflector region.

In a pebble reactor with an annular core similar to PBMR, the central reflector is a 9-meter high column of graphite freestanding in a sea of fuel pebbles. The column consists of inter-locking graphite blocks. These blocks will need to be replaced at least once during the life of the pebble reactor. Separate handling equipment will need to be provided and, more importantly, a prolonged outage will be required to perform the replacement because the

evolution will require removal of the reactor vessel head. Furthermore, demonstration of the seismic adequacy of this tall columnar design may prove very challenging.

6.6.3 Core State Issues

A major difference between the prismatic and pebble bed reactor is the latter's stochastic core (versus the static nature of the prismatic core). In the pebble core, the fuel pebbles are continuously removed from the bottom and replaced at the top; hence, the fuel pebbles flow down through the core. The key aspects of core state issues are summarized in Table 6-10 below and discussed thereafter.

CORE STATE ISSUES	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Core Geometry State	Fixed	+++	Random	-
Statistical Core Design Req'd	No	++	Yes	-
Add'l Margin to Accommodate	No	++	Yes	-
Packing Fraction, Bridging Issues	No	+	Yes	-
Pebble flow path predictions	na	++	Difficult	-
Validation of Max Conditions (Temp, Bu, Power)	Easier	++	Harder	-
Overall Rating Core State Issues		++		

 Table 6-11: Core State Issues

Pebble flow is difficult to predict. Even more so is the prediction of the spatial distribution of fresh and burnt pebbles and the corresponding power profiles and temperatures. Given this behavior, bounding core analysis techniques (physics plus thermo-hydraulics) must be used in assessing safety margins to ensure operational limits are not exceeded. This approach was thought adequate, however, testing at AVR [Test HTA-8] revealed unexpected hot spots that were significantly hotter than expected maximum coolant temperatures (i.e., > 1280 °C). Furthermore, THTR experienced pebble flow distributions that were significantly different than predicted. Pebble flow distributions, temperature distributions, nuclear shutdown margins).

USNRC staff involved with HTR licensing is well aware of flow distribution issues in the pebble reactor and will need to be ensured that flow distribution anomalies are adequately addressed in design and safety analyses. Additionally, the IAEA has prepared a report [9] identifying key issues relating to the safety and licensing of an HTR. With respect to the pebble reactor core, the report highlighted issues related to the stochastic nature of the pebble core. A synopsis of their concerns is summarized in the following points:

- The statistical distribution of PBMR spherical fuel results in additional uncertainties in the character of the core, uncertainties that will vary over time. These additional uncertainties will need to be addressed in the nucleonic, thermal hydraulic, and fuel performance codes in licensing the PBMR design.
- The statistical nature of the distribution of the PBMR fuel could also conspire to make one section of the spent fuel array particularly reactive. Criticality control events at fuel fabrication facilities have shown that processes in place to exclude moderator from an area occasionally fail, as do geometry and quantity controls, thus, care will need to be exercised in the management of criticality during the storage, transportation, and disposal of the PBMR spent fuel pebbles.

• Core physics will be constantly changing as the pebbles flow through the core, necessitating some statistical bounding of key parameters. Differences between the center of mass and the center of gravity for individual pebbles, and surface defects and irregularities may result in non-linear conditions governing pebble flow through the core which can make it impossible to reliably predict the transit time for any particular fuel pebble, or even the fuel pebble packing density within the core.

While both reactor types will certainly have a learning curve to follow upon initial start-up, the pebble core with its random core configuration has an additional level of complexity to deal with in ferreting out problems. Consider the following "teething" experiences at THTR: broken pebbles, higher than predicted core bypass flows, uneven pebble flow distribution between center and periphery, and larger than predicted temperature gradients at core exit.

This is not to say the prismatic core will not have its share of growing pains; however, it is easier to address problems in a static situation as opposed to a constantly changing one. Take for example the solution of core flow fluctuations which occurred during initial operations at Fort St. Vrain. The flow fluctuations were caused by the prismatic blocks shifting slightly. The problem was solved by the addition of core restraint devices know as "Lucy Locks" which prevented any further block movement [10].

Another issue faced by the pebble core is concerned with fuel pebble bridging. This phenomena occurs when a section of pebbles literally locks it self in place, allowing other pebbles to flow around it or, if severe, hold a part of the core stationary.

Finally, to ensure operational limits are adequately met, the pebble core has to operate with larger margins than the prismatic core. Hence, this has implications for the extent to which the pebble design can be optimized.

In summary, the fixed state of the prismatic reactor core is a significant advantage relative to licensing the technology and analytically demonstrating its safety case. The stochastic nature of the pebble core will serve as a "lightening rod" to regulators and will require a significant level of effort above that required for the prismatic reactor for the proponents of pebble technology to demonstrate its safety case. This is also likely to be a "confidence issue" with both likely end-users and the public in general.

6.7 Maintenance Issues

Both reactor types, prismatic and pebble, must be not only be designed to facilitate maintenance but must also be designed to be ALARA (as low as reasonably achievable) with respect to the potential radiation dose imparted to maintenance workers. Issues related to core component accessibility and replacement capability are judged to be roughly equivalent between the reactor types for items such as control rods, in-core instrumentation, ex-core instrumentation etc. from both maintenance ease and ALARA perspectives. However, there are several maintenance areas where the prismatic reactor has a clear advantage over the pebble reactor. These are summarized in the table below:

MAINTENANCE ISSUES	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Dust & Particulate Generation Impacts				
Quantity	Lower	++	Higher	-
Erosion	Lower	++	Higher	-
Blockages of passageways	Lower	++	Higher	-
Spread of Contamination	Lower	++	Higher	-
Impact of flow control/Pressure Control	Lower	++	Higher	-
Release Potential	Lower	++	Higher	-
Dust Control Measures	Lower	++	Higher	-
Mechanical Failure	Lower	+	Higher	-
Defueling/Refueling Capability	Yes	ο	Yes	ο
Reflector Replacement	Easier	++	Harder (if required)	-
Component Replacement capabilities	Yes	ο	Yes	ο
Component Accessibility (refueling systems)	Easier/Low Dose	+	Harder/High Dose	-
ISI Requirements	Easier	++	Harder	-
Overall Rating Maintenance Issues		++		

 Table 6-12:
 Maintenance Issues

Dust generation in the pebble core is a major concern. As the pebbles flow down through the core, they are constantly rubbing against themselves and against the inner and outer reflectors. The resulting abrasion produces graphite dust that will be dispersed throughout the system. THTR experienced graphite dust deposition of about 1 mg/cm² which correlates to the expected weight loss due to abrasion. Nevertheless, it did require the addition of an enhanced filtering arrangement [11] [12]. Furthermore, THTR experienced an off-site radiological release involving graphite dust.

The main problems arising from dust generation are identified in the preceding table. Circulating graphite dust acts as an abrasive on the pebbles and core internals, and, in direct cycles, the turbo-machinery. The higher turbulence of the flow regime in the core may also exacerbate the level abrasion experienced. Furthermore, critical flow passageways may become blocked. This is of special concern if more advanced heat transfer technology is used where passageways, with dimensions in millimeters, will be prone to blockage. The spatial distribution of the dust may also be unpredictable especially if the reactor is coupled directly to the power conversion system and core flow varies with power level. Fluctuating flow fields will relocate stagnation points and correspondingly, the dust will relocate as well. Finally, and perhaps most importantly, the dust inventory represents an additional radionuclide inventory that could potentially be released in accident.

Given the foregoing dust related issue, the pebble reactor must implement dust control measures to eliminate the problem. It also should be noted that the prismatic reactor also is susceptible to dust generation; however, the magnitude of the dust problem in the prismatic core is significantly less.

While reflector replacement is a core management activity, it does have maintenance impacts. In the prismatic reactor, the reflectors are moved using the fuel handling equipment which can be removed for maintenance. On the other the hand, PBMR requires a special plant shutdown to replace the central reflector.

Regarding ISI requirements, there is concern [9] with the pebble bed reactor that given its on-line refueling capability, the amount of shut down time to perform NDE and ISI will be reduced, and with fewer periods of time with the entire core off-loaded, the accessibility of some components (for inspection and repair) will be more restricted. This may require in-service inspection and techniques to shift to on-line, real time monitoring. To address this concern PBMR is developing on-line ISI methods. Also, NDE techniques for nuclear grade graphite will need to be developed and improved, as well as remote methods to assess the surface condition and structural integrity of pebbles as they are examined before permitting additional passes through the reactor.

With respect to ISI and subsequent NDE examinations, the prismatic reactor is in better standing. The prismatic reactor's regular refueling interval permits opportunity to perform inspections. The fuel handling equipment access ports on the vessel head permit the insertion of inspection equipment. Granted the inspection equipment remains to be designed, tested etc., nevertheless, the prismatic reactor has the potential to better accommodate ISI requirements.

6.8 Operational Considerations

Operational considerations are summarized in Table 6-13 below and followed by explanatory discussion.

OPERATIONAL CONSIDERATIONS	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Past Reactor Experience (AVR, THTR, FSV) (with respect to core only)	Similar	ο	Similar	ο
Operational Core Management	Easier	+	Harder	-
Plant Staffing	Lower	++	Higher	-
Overall Rating – Operational Considerations		+		

Table 6-13: Operational Considerations

6.8.1 Past Reactor Experience

Past experience relative to pebble reactor and prismatic reactor technology within the boundary of the reactor (i.e., core only) has been positive. The Ft. Saint Vrain prismatic reactor in the US and the AVR and THTR in pebble bed reactors in Germany experienced "teething" problems upon initial operation that required resolution. As mentioned previously, FSV experience core flow fluctuations that were eliminated by the installation of a core restraint system. AVR core was very successful but its fuel handling system did require frequent maintenance during its initial years of operation. The system worked well after undergoing a series of improvements. Perhaps THTR operational experience was more remarkable – broken pebbles caused by the direct insertion of the control rods into the pebble bed, larger than expected core bypass flows, uneven pebble transit times, and a significant amount of dust generation. Each one of these problems was addressed and satisfactorily resolved. Nevertheless, THTR operation was considered a success.

The lessons learned from this past experience are very important. It is interesting to note that the scale up in size from AVR (49 MWth) to THTR (700 MWth) was significant – more than a factor of ten! It is not surprising then level of difficulty encountered initially in THTR's larger core. On the other hand, Fort St. Vrain (842 MWth) had no comparable prototype yet, from a core perspective, operated remarkably well after the flow fluctuation problem was solved.

Consideration should then be given to the "leap" in technology the HTR/NGNP core will represent. The prismatic annular core will be about 25% smaller than FSV, excluding reflectors; and based on FSV experience, the annular configuration should pose no difficulties. On the other hand, the annular pebble core will be smaller than THTR as well; however, there is the potential to encounter difficulties due to the annular configuration (e.g., pebble flow behavior, bypass flow).

Overall then, based on the above discussion, the past experience with both types of reactor cores is viewed as similar.

6.8.2 Operational Core Management

Prismatic core management should be similar to the core management of current day LWRs. Loading patterns are developed and implemented during refueling. Upon startup, reactor operations staff track core behavior through monitoring to verify/validate core performance.

Pebble core management is distinctly different. There are no loading plans because of continuous refueling. However, assuring acceptable core parameters will be a continuous job. Pebbles will need to be monitored for burn-up and structural integrity. Pebble flow patterns will need to be established. Periodic reactor physics testing to confirm core nuclear characteristics will be required. Witness the difficulty THTR encountered with pebble flow distribution which has to be constantly monitored.

Hence, the prismatic reactor is viewed as being more operational friendly which is a definite advantage.

6.8.3 Plant Staffing

A prismatic plant facility consisting of 4 x 600 MWth prismatic reactor modules requires an operating plant staff of 225 people on-site[13]. Approximately 25% of the staff is licensed operators (60) with the balance being attributable to remaining standard departments (Administration, technical support, maintenance, radiological protection, radwaste, QA/QC, and security). Of the standard departments, another 25% or 60 people will be required for continuous support coverage for all four modules on a 24hr/day, 7-day per week basis.

The pebble bed plant facility consisting of 8 x 400 MWth modules will require similar staffing requirements; however, the total number will be greater due to the 4 additional modules. This means an additional 60 operations staff and an additional 60 support staff. This would increase the total staff required to 345 people.

Hence, the prismatic reactor in a multi-module setting can claim an advantage with respect to staffing.

Note: The pebble bed operations staffing numbers are not in agreement with PBMR staffing estimates which rely on the acceptance of reduced licensed operational staff. The above numbers assume 1 shift-supervisor per 2 modules and 2 reactor operators per module. This is a safe assumption since it matches current staffing requirements.

6.9 Safety and Licensing

Licensing and safety aspects of the impact of reactor type are summarized in Table 6-14 below and discussed thereafter.

LICENSING & SAFETY	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Licensability	Somewhat Easier	+	Somewhat Harder	-
Safety (Overall)	Higher	+	High but more difficult to prove	-
Overall Rating – Safety and Licensing		+		

Table 6-14: Safety and Licensing

Licensability

Since its conception, the very attractive safety aspects of HTR technology have allowed it to remain in various forms of development over the past 40-years or so despite being overshadowed by LWR technology. The key advantages of the HTR design are:

- Low power density (order of magnitude less than typical LWRs)
- High thermal capacity of the moderator (huge mass of graphite)
- Slowly developing accidents (results directly from the combination of low power density and high thermal capacity)
- Single phase coolant (Helium)
- Robust first fission product barrier (coated particle fuel)
- Reliance on passive decay heat removal
- Large negative reactivity temperature coefficient

These attributes culminate in HTR designs that are inherently safe -i.e., they make it highly improbable to have a catastrophic core damage (i.e., meltdown) and a corresponding release of a large amount of radioactivity. Both the prismatic and pebble reactor options share these attributes.

The issues of fuel, materials, safety, security, safeguards, analytical methods, waste, etc. present significant challenges to the licensability of HTR designs. The impact of reactor type on the level of difficulty in resolving these issues varies, understandably, with the given issue:

- fuel qualification (albeit somewhat harder for the advanced fuel design, in either case, the regulator must be satisfied with the level of qualification that assures fuel performance)
- material qualification (similar operational vectors e.g., temperature, fluence, duty)
- safety (both options must meet established safety goals)
- security/safeguards (theft/diversion of material in pebble reactor is a concern see Section 6.12 for a detailed discussion)

- analytical methods (random nature of pebble core adds an additional degree of difficulty)
- waste (relatively similar waste profiles in terms of material and volume)

If there is one thread that runs through several of the above issues, it is the random nature of the pebble core which was previously discussed in detail in Section 6.6.3. Because the fuel spheres in the pebble core are constantly moving, statistical methods need to be used to derive bounding parameters to demonstrate margins. The validity of the statistical methods will need to be demonstrated to the regulator. In particular, the regulator will need to be assured, most likely by direct demonstration, that calculated parameter values will be conservative. For example, the USNRC is well aware of the AVR pebble melt-wire tests which indicated calculated local maximum core temperatures were non-conservative. Hence, regardless of the sophistication of statistical methods and arguments, the fact that pebble core limiting locations cannot be accurately predicted will be problematic.

Source term

The radiological source term is the amount of fission product inventory that is postulated to be released following a design basis accident. The prismatic core (ANTARES) has approximately 4600 Kg U enriched to 14% U235 (644 Kg). The pebble core (PBMR) contains 9 grams U per pebble or 4140 Kg U enriched to 9.5% U235 (393 Kg). Since most of the fissions come from U-235, the prismatic core radionuclide inventory is approximately 60% (i.e., 644/393) greater that of the pebble core; however, on a per megawatt basis, the core radionuclide inventories are equivalent. Nevertheless, the same site boundary dose limits must be met which would favor the lower inventory of the pebble core; however, the release fraction is the critical variable. In this regard, the prismatic reactor would potentially have the lower release fraction because fission products would encounter additional barriers (fuel compact, fuel block) as opposed to the single protective layer on the pebble sphere. In addition, the pebble core dust inventory release has to be included as well.

Safety Overall

As said above, both the prismatic and pebble cores share the same key attributes that all contribute to the HTR's inherent safety case. Both reactor types must be designed to meet all regulatory requirements and be demonstrated to be safe to operate. In this regard, that demonstration will be more complex and difficult for the pebble core option than the prismatic option due to the stochastic nature of the pebble core. This makes the safety case for the pebble option slightly more difficult to prove.

6.10 Key Component Design and Fabrication Issues

The key mechanical components comprise a large share of the plant capital cost and can have major impact on plant construction and operation. The reactor vessel and the prime mover for core flow are the main mechanical components associated with reactor type.

Based on the discussion presented below and summarized in Table 6-15, both options are judged to face a similar level of overall difficulty with respect to these components. On one hand, the level of difficulty associated with the pebble reactor vessel is judged to be easier than that of the prismatic reactor. However, on the other hand, the prismatic reactor does have a significant advantage over the pebble reactor relative to the prime mover for core flow.

MECHANICAL COMPONENTS	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Assessment of Level Of Difficulty Of Key Mechanical Hardware Design And Fabrication		o		0
Reactor Vessel Design	Harder	-	Easier	++
Core Power	600 MWt	n/a	400 MWt	n/a
Material	9 Cr – 1 Mo	-	SA-508	++
Weight	Similar	0	Similar	ο
Design Pressure	Lower	++	Higher	-
Vessel Fabrication	Harder	-	Easier	++
Fabrication Location (for NGNP)	On-site	0	On-site	0
Prime mover for core flow	Easier	+++	Harder	-
Overall Rating for Mechanical Components		0		0

Table 6-15: Key Components

Reactor Vessel – Weight, Design Pressure

As discussed in preceding Section 6.4.1 and shown in Table 6-7, the weight of the prismatic reactor vessel is comparable to that of the pebble reactor vessel. The reason for this, even with a 1-meter larger internal diameter, is that the prismatic reactor vessel design pressure is 5 MPa versus 9MPa for the pebble reactor vessel. This is a significant advantage; especially considering the higher power capability of the prismatic core.

The somewhat smaller pebble reactor vessel dimensions do not provide a significant advantage in terms of transportation issues. Either option's reactor vessel would need to be significantly smaller (around 5 meters OD) to be able to deliver a complete package at INL site. This means that in both cases, on-site fabrication will be required.

Reactor Vessel - Fabrication

Compared in Table 6-16, as examples of potential vessel designs for NGNP, are the basic dimensions of the PBMR and ANTARES reactor vessels (excluding the closure head):

Reactor Vessel Parameter	PBMR	ANTARES
Internal Diameter, M	6.2	7.2
Flange External Diameter, M	7.7 est.	8.3
Thickness, mm @ core beltline	180	170
Thickness, mm @ nozzle ring	285	270
Height, M (lower section, flange to vessel bottom)	25	19

Table 6-16: Reactor Vessel Data – Lower Section

In both cases, issues associated to the fabrication are similar: (1) forgings are required at least for the flanges and the nozzle ring; and (2) due to the overall dimensions, only Japan Steel Works can provide such large forgings.

For the NGNP, we have proposed a multi-loop design with 4 cross vessels instead of one unique one. For such a condition, the thickness of the nozzle will be below 230 mm which means that rolled plate could be used for the nozzle ring instead of a big forging (limit is at 9 inches according to former experience in the US for BWRs).

It is also to be mentioned that for the prismatic design, the fabrication of the forged ring with one unique cross vessel will be difficult (ingot size would be too large). The problem is the same whatever the material is (SA 508 or mod 9 Cr 1 Mo).

Material Selection

What is the reference material for the reactor vessel?

SA 508 Steel

SA 508 grade 3 class 1 is the conventional steel for forgings of PWRs. This material is already covered by ASME. The use of this material at higher temperature than 700oF is covered by Code Case N-499 and can be summarized as follows:

- 3000 h maximum duration between 371 and 427 $^{\circ}$ C
- 1000 h and no more than 3 events between 427 and 538°C

These requirements are quite severe and could be hard to fulfill, depending on the assumption of availability of active or passive systems.

An issue raised during the pre-application phase with PBMR was the interaction between SA 508 and helium. The feedback from experience with the material is primarily with water and R&D is required to demonstrate that corrosion will not be a problem.

In terms of weld qualification, there are no issues related to welding anticipated. In terms of product size, the PBMR vessel is larger than PWRs (EPR ID is 4.9 m) but is comparable with the size of BWRs vessels and it is likely that no detailed qualification will be required.

9- Chrome 1- Molybdenum

For mod 9 Cr 1 Mo, the following issues need to be addressed.

- Welding-1: problems of hot cracking met at the beginning of weldability actions have been fully solved but further optimization of the welding process and welding products is still required
- Welding-2: post-weld heat treatment has to be performed at higher temperature compared to SA 508 and this complicates the fabrication (this is not however considered a major problem by AREVA)
- Corrosion: mod 9 Cr 1 Mo should have a much better behavior than SA 508 in He environment. This will have however to be showed by specific R&D action (but probably program should be very limited)
- Forgings: there is an issue associated to the availability of big forgings. It is expected that ingot sizes up to 200-250 T could be obtained from JSW to be compared to about two times more for SA 508. Not a real problem if the design is based on plates with a limited number of forgings. This is more a problem if it would be required to have a full forging design in which case mod 9 Cr 1 Mo would require more circumferential welds. The forging of the nozzle ring (with one unique cross vessel) is an issue as already discussed above.
- Code qualification: mod 9 Cr 1 Mo is covered by subsection NH since edition 2004 but this subsection has to be extended to heavy section products

- NRC approval: Generally speaking, high temperature sections of the ASME have never been approved by the NRC and the approbation is likely to take some time
- A qualification will have to be performed to qualify the behavior of representative material in the core beltline (irradiation should be performed on base material and weld but irradiation already carried out in Europe already indicate a good behavior and this shall not be an issue). The characterization of the material of the forging will have also to be carried to demonstrate that the material in the bulk of the forging is as good as the material elsewhere.

Based on the above, the fabrication of the prismatic reactor vessel is judged to be harder primarily due to the combination of its larger diameter and the need to use an advanced material (i.e., 9 Cr-1Mo).

Prime Mover for Core Flow

The primer mover for core flow will either be a helium circulator should the NGNP reactor be an indirect cycle plant or the main compressor should a direct cycle power conversion system be selected. It either case, the prismatic reactor has a significant advantage due to the core's relatively low flow resistance (55 kPa @ 264 kg/s). This translates into approximately 15 MWe of circulator power or about 30 MWth . The flow resistance of the pebble core is significantly greater by a factor of 2-3. This pressure drop translates into much greater circulator power requirements (about 30-45 MWe) or 60-90 MWth out of the direct cycle.

Relative to the question posed by this section, the prime mover which has to pump same amount of flow but develop a factor of 2-3 less head is more readily designed. A key factor is the ability to develop the required pressure head with as simple a machine as possible. In a prismatic reactor, citing the ANTARES circulator as example, a one stage machine is feasible. It is not clear if a multi-stage machine would be required for a pebble core circulator (assuming an indirect cycle configuration), nevertheless, the pebble circulator faces harder duty due the high pressure head it must develop. Should a direct cycle be employed, the same concerns remain, except that additional stages of compression will be required in the pebble option in order to overcome the higher core pressure drop.

6.11 Schedule, Plant Layout

Table 6-17 below and the discussion in the subsequent text examine schedule and plant layout aspects of the reactor types.

PLANT LAYOUT/SCHEDULE	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Schedule	Less Advanced (relative to PBMR)	ο	More Advanced (due to PBMR Demo Plant Lead)	++
Plant Layout and Construction	Similar	ο	Similar	ο
Overall Rating Plant Layout/Schedule		0		++

Table 6-17: Schedule /Plant Layout

6.11.1 Schedule

A main objective of the NGNP project is for the demonstration plant to commence initial operations by 2018 and to be fully operating by 2020. The operative question, for the purposes of this study, is this:

Does one reactor type offer a schedular advantage for NGNP over the other?

And, secondly:

Does this advantage apply to the commercial version of the reactor?

On a single unit basis, the pebble reactor plant (400 MWth) is smaller, hence, it should take less time to build than the larger prismatic reactor plant (600 MWth). This is, of course, a much too simplistic view. For example, as previously shown in Table 6-7, the PBMR vessel is comparable in size to the ANTARES vessel. Another differentiator is number of plant systems and, here, the prismatic reactor may have a slight advantage with fewer systems. However, counting systems is not very accurate; there are many factors that affect the schedule, system size and complexity included.

At this juncture, therefore, it is more appropriate to consider those long term items that will be responsible for driving the schedule. It is also important to note again that the scope of this study is limited to "the reactor vessel and within." Hence, the schedule issues discussed are therefore limited as well.

Licensing

The NGNP will by licensed by the US NRC. The corresponding licensing framework is still under consideration but the goal is to ultimately have non-LWR technology such as HTRs be licensed under the technology neutral framework (10 CFR 53). However, the NGNP, as part of licensing demonstration process for Part 53, may be licensed under 10 CFR 50 as a basis for future applicants to use Part 53.

Both the prismatic and pebble technologies are capable of being licensed by NRC; however, the level of difficulty may be more for the pebble reactor than the prismatic; the difficulties arising from the random nature of the core and the qualification of the fuel. However, there are other licensing issues that are common to both options, such as containment versus confinement or reduction in emergency planning requirements. It will be the resolution of these common issues that will drive the licensing part of the overall schedule. Hence, neither reactor type is judged to have a particular schedule benefit or disadvantage on the licensing front.

Fuel Development

As mentioned previously, PBMR's fuel development strategy (i.e., recreate German quality fuel) is perceived to have a schedule benefit; however, the development of prismatic fuel is the required timeframe for NGNP is also possible. Because the safety case for HTR technology is to a large extent, singularly reliant on the performance of TRISO particle fuel, the level of scrutiny to be afforded to the issue of fuel qualification by the regulator that is anticipated will belay any schedule advantage.

Reactor Vessel

The reactor vessel is the component which needs to most lead time in which to design, procure materials, fabricate and install. As seen in Table 6-7, both the prismatic and pebble reactor vessels are of comparable size; and, based on this size, shipment of a fully fabricated vessel to the INL site is not feasible. Hence, on-site fabrication will be required. At least for NGNP, it would appear that neither reactor type as currently envisioned (i.e., with respect to power level) offer neither a clear advantage nor a clear disadvantage.

With respect to commercialization, reactor vessel size does matter. For sites with water access, transporting a fully shop-fabricated vessel is possible; however, the slightly smaller flange diameter of the pebble reactor vessel may offer it access to more sites than the larger diameter prismatic vessel. Nevertheless, this is not viewed as an important differentiator.

Previous Licensing/Construction Experience

From a historical perspective, the pebble bed reactor may offer a slight advantage in schedule achievement because other countries (Germany) have more recent building experience (i.e., late 1970s/early 1980s vs early 1970s) that can be drawn on as opposed to Fort St. Vrain, assuming that the age of its construction experience will not probably render most of it moot. Both reactor types will have to rely on the resurgence of nuclear plant

construction and take the appropriate lessons that will evolve from that experience. With respect to licensing, only Fort St. Vrain was licensed by the USNRC; however, because it was issued a Class 104 license (i.e., demonstration reactor), the value of its licensing experience with respect to NGNP is limited.

PBMR Demonstration Project

It would be remiss not to mention PBMR (Pty) Limited's ambitious program in South Africa. Under development since 1993, the PBMR project entails the building of a demonstration reactor project near Cape Town and a pilot fuel plant near Pretoria. PBMR's current schedule is to start construction in 2008 and for the demonstration plant to be completed four years later. The fist commercial PBMR modules are planned for 2016. Furthermore,

Furthermore, PBMR is actively pursuing licensing activities with the NRC and are planning to submit an application for design certification in the 1st quarter of 2008. In support of their project, PBMR has embarked upon a significant series of pre-application licensing interactions with NRC as witnessed by numerous public meetings; especially, the PBMR Technology Familiarization Sessions held with NRC in February and March of 2006.

Clearly, the fact that PBMR's design for its demonstration reactor is far along, its fuel development program well underway, and that actual construction experience may be gained prior to NGNP cannot be ignored. Hence, the pebble reactor option must be credited for the experience that PBMR will gain for it.

Based on the above, it is judged that, due to PBMRs program the pebble reactor option does have a moderate schedule advantage over the prismatic option at this time. That advantage may wax or wane depending on the progress of actual PBMR demonstration plant construction. This advantage applies primarily to NGNP development but does not apply in the commercial case.

6.11.2 Plant Layout and Construction

These following attributes are assessed in terms of impact on Plant Layout and Construction.

- A. Construction Complexity
- B. Constructability
- C. Construction while Operating an Existing Plant

Construction Complexity

Are there features in the plant, which will create transportation issues during construction?

It is assumed that the reactor vessels for either type of reactor will have to be fabricated on site. The pebble bed has a slight advantage due to smaller its smaller diameter vessel. However, the pebble bed also has a disadvantage due to the complexity of the pebble handling system. The prismatic reactor has less equipment, and thus will be the least complex in terms of construction. This may also translate into quicker construction even though it may take longer to place the prismatic core blocks versus filling the pebble bed core with pebbles.

Constructability

Factors that affect constructability include: complexity, and number of pieces, of equipment required for the functioning of the plant; number of units constructed already; operational experience; potential for modular construction; and, estimate of bulk quantities required for construction.

Prismatic type reactors have less equipment, and thus are more likely to have a shorter procurement and construction duration. Since prismatic reactors have less equipment, they will also require less bulk quantities.

Although pebble bed reactors are smaller, they are more complex and an 8-unit pebble bed commercial plant is more likely to have longer construction duration than a 4-unit prismatic commercial plant.

Both the pebble reactor and prismatic vessels are comparably large components, which will require specialty cranes and equipment for transporting at the plant site during final installation. Otherwise, minimal transportation issues are expected during construction.

In general, there will be some difficulty in fabricating the reactor vessels of either type of reactor on site. The materials required to fabricate a vessel to operate at very high temperatures will be expensive and require long lead procurement items regardless of reactor type.

Construction while Operating an Existing Plant

The constructing activities at an operating nuclear plant will have to be analyzed and evaluated with respect to the safety of the operating reactor. The added scrutiny will undoubtedly complicate the work process and lengthen the construction schedule of additional reactors once the first reactor is operational. This difficulty will be present regardless of the type of reactor chosen. However, the pebble bed reactor will be more susceptible to these delays because the first plant will be operational sooner and would require the addition of 7 more units, versus 3 more for the prismatic. Furthermore, for the commercial plant, the prismatic will probably have an advantage because of the reduced complexity in building a 4-unit plant versus a 8-unit plant, assuming the result is the same power output.

Based on the above, with the exception of requiring less units in a multi-unit setting, it is judged that there is no distinct plant layout and construction advantage or disadvantage associated with either the prismatic or pebble bed reactor options.

6.12 Non-Proliferation, Safeguards, SNM Accountability

There are no 100% proliferation-proof nuclear systems but all nuclear systems feature a relatively high resistance to proliferation, provided that comprehensive and efficient international controls can be implemented. Institutional measures to address proliferation resistance are of key importance. Both prismatic and pebble technologies are no exception in this regard because within the context of internal and external controls, they are highly proliferation resistant. Table 6-18 below presents a summary followed by suitable discussion.

NON-PROLIFRATION SAFEGUARDS & SNM ACCOUNTABILITY	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Material Diversion Risk	Lower	+	Low	-
Institutional Diversion Risk	Lower	+	Low	-
Material Tracking	Easier	++	Harder	-
Overall Rating Non-Proliferation etc.		+		

Table 6-18: Non-Proliferation etc

6.12.1 Non-Proliferation

Fuel Cycle Front End

Regardless of the technology, the front end of the fuel cycle is least resistant. The source at the uranium mine appears to be the weakest point largely because it is less difficult for a potential proliferant state to obtain covertly natural uranium as opposed to low enriched uranium (< 20 %) from a facility under international safeguards. In either case, the proliferant state needs anyway an enrichment step (a major obstacle) to obtain weapons grade material. Under these conditions, to start from more or less enriched uranium does not make much difference.

Fuel Cycle - Reactor Operations

Safeguarding fissile material from diversion will provide some different challenges for the PBMR. The small size of a fuel pebble makes theft easier, and the large number of pebbles makes inventorying spent fuel at the fuel pebble level very difficult. Once stolen, a pebble could easily be used as a radiological dispersion device (dirty bomb) or an improvised exposure device.

Theft of fissile material in a prismatic reactor is much more difficult. First, the fuel prisms weigh approximately 120 Kg each; hence, special lifting equipment would be required. Second, shielding the prism, due to its much great radionuclide content, would be very difficult. And, third, refueling is conducted every 18 months which severely limits the theft opportunity.

In a diversion scenario, extracting usable fissile material from fuel pebbles or prisms would be unattractive and very difficult. The initial enrichments are still low and the high burn-ups achieved result in much degraded plutonium concentrations. However, consideration would have to be given to alternate approaches of diverting fissile material such as cycling depleted uranium spheres through the core to breed plutonium. This situation would be unique to the pebble reactor more so than a prismatic reactor. A compensating fact, however, is that a significant number fully irradiated pebbles (~100,000) would be required to amass enough plutonium for a weapon and the time element to collect the diverted pebbles would also be significant. Should depleted uranium pebbles be used, the numbers to divert is much less (~10,000) but the time element factor would be about the same.

Fuel Cycle Back End

One of the main advantages of HTR with regard to the resistance to proliferation, is that there is no operational fuel reprocessing technology available to day. Therefore, a country wanting to proliferate with this kind of reactor fuel (if the plutonium route is chosen by this country) should have to develop a specific technology for that. This does not represent an insurmountable difficulty, but this would need a minimum of skill, knowledge and of course, enough time and money.

It is to be noted that for the case of pebble bed reactors these conclusions could be modified because of very specific characteristics of their fuel and because of the loading / unloading mode of this fuel. However, one can say that the apparent drawback of this on-line refueling mode (from proliferation resistance point of view), could be compensated by the fact that it would be necessary to divert or steal (and reprocess) several hundred thousands of pebbles to obtain enough weapon grade plutonium for the making of a nuclear explosive device.

6.12.2 Safeguards and SNM Accountability

The key differential between prismatic and pebble bed reactors regarding accountability it the level of tracking.

In the prismatic option, individual prisms are numbered and tracked. This also means that its constituent parts, particle fuel and compacts will also be tracked on a lot-wise basis similar to that used today in current LWR fuel manufacturing. Hence, the problem of tracking SNM at a prismatic reactor plant will be one of tracking several thousands of prisms at any given time.

Conversely, the situation for the pebble reactor is much different. Individual pebbles are not uniquely identified which makes tracking individual pebbles extremely difficult. Consider that at any given time, a pebble bed reactor will have 460,000 fuel pebbles in the core and a through-put of about 180,000 pebbles per year. For the envisioned 10-module site proposed by PBMR, this translates to an on-site inventory of nearly 5-million fuel spheres and 4-million pebbles in transit (fresh fuel in, spent fuel out). The logistics associated with tracking pebble inventory and demonstrating SNM accountability will be challenging.

From another perspective, it is also likely that a means of identifying and tracking individual pebbles will be required by the regulator. This is necessary to assure that fuel failures and nonconforming conditions can be tracked back through manufacturing so the extent of condition can be assessed and corrective actions taken.

6.12.3 Plant Security

Both reactor types will need to meet the plant security regulations (10 CFR 73). Normal security (gates, guards, & guns) requirements do not discriminate with respect to reactor type. The maximum credible design basis threat may impact the each option differently; however, without knowing DBT details and considering design status, each option must be viewed as equally capable of meeting survivability requirements.

6.13 Post Accident Behavior

As previously discussed in Section 6.9, HTR have many characteristics that make them inherently safe – i.e., they make it highly improbable to have catastrophic core damage (i.e., meltdown) and a corresponding release of a large amount of radioactivity. Both the prismatic and pebble reactor options share these attributes. It follows, therefore, that both options will display acceptable post-accident behavior with respect to both regulatory requirements and investment protection considerations. Obviously, each option's power level has been optimized to meet these requirements.

Several items worth mentioning are shown in Table 6-19. These are air ingress, water ingress, reactivity excursions, and conduction cool-down response.

In the event of an air ingress event, the pebble bed reactor is more susceptible oxidation issues because of the lower graphitization temperature of the fuel (due to pebble fabrication process limitations). Conversely, the graphite blocks comprising prismatic fuel are fully graphitized because of the absence of fuel kernels at that stage of their fabrication. Hence, the prismatic blocks (which fully encompass the fuel compacts) are more resistant to oxidation.

As configured, neither reactor option as currently envisioned is coupled to a steam cycle; hence, there is little susceptibility to water ingress. This does not preclude coupling the NGNP to a steam cycle. Past experience with water ingress events at AVR, Ft. St. Vrain, and THTR are more of an operational than a safety concern. However, NRC's review of Fort St. Vrain operational experience attributed chronic water ingress and the resulting corrosive atmosphere [10] as a potential cause of partial control rod insertion event.

Prismatic reactors need additional fuel material versus the pebble reactor in order to achieve an 18-month cycle length. The reactivity this additional fuel material represents is managed by the use of burnable poisons such that

the net reactivity in the core is approximately constant through out the cycle. Prismatic reactors may also have control rods directly within the active fuel region; however, inadvertent rod withdrawals and rod ejection accidents are accommodated through design. Furthermore, some excess reactivity will be needed in both reactor types to be able to override post-trip Xenon buildup on restart.

Finally, the depressurized conduction cooldown event is the limiting design basis accident for both reactor types. Each option's power level has been optimized to meet fuel temperature limits following this event. Hence, both prismatic and pebble reactor responses are, by design, similar.

POST ACCIDENT BEHAVIOR	Prismatic Reactor	Prismatic Rating	Pebble Reactor	Pebble Rating
Behavior of reactor systems and fuel during and after key accident conditions				
Air Ingress/Oxidation Issues	Less Susceptible	+	More Susceptible	-
Water Ingress	Low Susceptibility	ο	Low Susceptibility	ο
Reactivity Excursion	Similar	ο	Similar	ο
Conduction Cooldown Events	Similar	ο	Similar	-
Overall Rating Post-Accident Behavior		0		ο

Table 6-19: Post-Accident Behavior

6.14 Comparison Summary Results

The results of the previous sections are summarized in Table 6-20. As previously mentioned, a simple, qualitative rating scheme was applied as follows:

- o No clear advantage or dis-advantage (neutral tone shading)
- + Weak or small advantage (light green shading)
- ++ Moderate advantage (bright green shading)
- +++ Strong advantage (dark green shading)

Additionally, the discriminators are listed in order of the degree of potential difference or remark-ability between options combined with the relative importance of the discriminator itself. The overall results show that for a number of discriminators, both options are perceived as equivalent or that the prismatic option has a small advantage. However, for six of the higher ranked discriminators, the prismatic reactor is considered to have a moderate advantage over the pebble bed option. The pebble bed option, wholly due to PBMR project status, is considered to have a moderate schedule advantage. Finally, for the highest ranked discriminator, Performance Capability, the *prismatic reactor*, due primarily to its power capability, has a *strong advantage* over the pebble bed reactor option.

Table No. / Discriminator	Prismatic Reactor	Pebble Bed Reactor
6-1 Performance Capability	+++	-
6-2 Fuel Service Conditions	++	-
6-3 Fuel Qualification & Fabrication	0	0
6.4 Spent Fuel Disposal & Reprocessing	++	-
6.5 Fuel Handling and Refueling	++	-
6-6 Economic Factors	++	-
6-8 Research and Development Difficulty	0	0
6-9, 10, 11 Core Design Issues	++	-
6-12 Maintenance Issues	++	-
6-13 Operational Considerations	+	-
6-14 Safety and Licensing	+	-
6-15 Mechanical Components	0	0
6-16 Plant Layout/Schedule	0	+ +
6-18 Non-Proliferation, Safeguards, SNM Accountability	+	-
6-19 Post-Accident Behavior	0	0

Table 6-20: Summary Results Comparison

7.0 RECOMMENDATIONS

The DOE should select the *prismatic reactor* for the NGNP because it represents the best technological foundation for a commercially attractive, multi-use high temperature reactor concept.

Furthermore, a commercial GEN-IV HTR based on prismatic reactor technology is more likely to be embraced by the US Nuclear Industry because it represents less of a paradigm shift because it will be operationally familiar to prospective owners. The prismatic HTR is very much analogous to an LWR except that the coolant is helium instead of water.

Past experience in the US with the Fort St. Vrain reactor more that adequately demonstrated the feasibility of the prismatic core concept! The plant was licensed by the USNRC and the core itself operated satisfactorily.

In summary, the prismatic reactor offers the following key advantages over the pebble reactor alternative:

- Greater economic potential
- Higher power level and passive safety
- More useable power
 - i.e., less parasitic power loss
- Greater design flexibility
- Higher degree of license-ability
 - Concept previously licensed (FSV)
- Higher degree of predictability
 - Core performance
 - Scheduled outages
 - Less chance of forced outages

Based upon the above and the assessment provided in Sections 5.0 and 6.0, AREVA recommends the *prismatic reactor* for the NGNP.

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