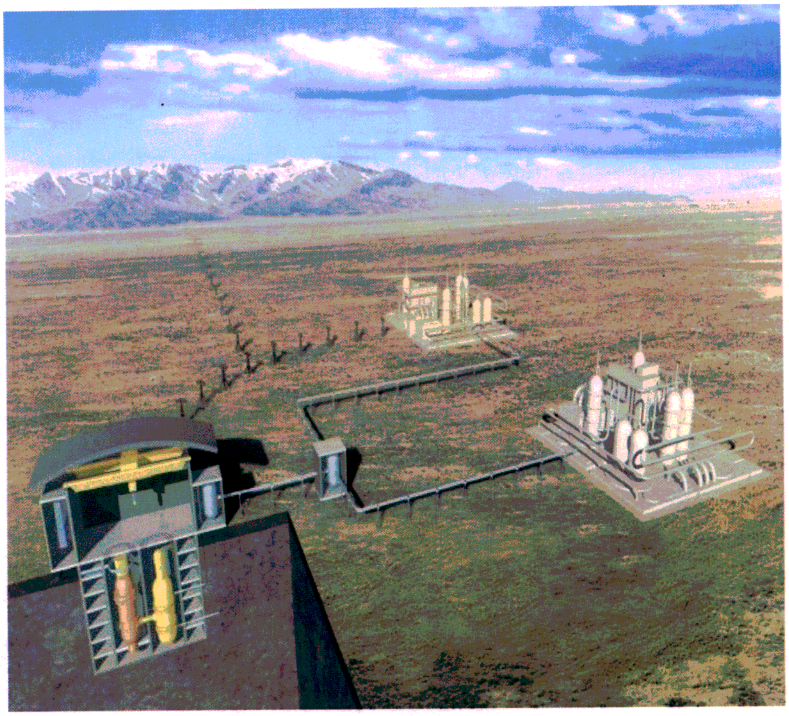
Enclosure 1
May 22, 2007
CCN 209674
Page 1 through 10, inclusive

INL/EXT-07-12729

NGNP Engineering White Paper: Reactor Type Trade Study

Kevan D. Weaver

April 2007



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NGNP Engineering White Paper: Reactor Type Trade Study

Kevan D. Weaver

April 2007

Idaho National Laboratory
Next Generation Nuclear Plant Project
Idaho Falls, Idaho 83415

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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Executive Summary

Preconceptual design studies for the Next Generation Nuclear Plant (NGNP) were initiated by three teams led by the following companies: AREVA, General Atomics, and Westinghouse Electric Company. The Statement of Work for the preconceptual design (under Section 6.3.1) requires that a special study be performed for the choice of reactor type (i.e., the choice between pebble bed and prismatic block cores), and each of the three teams were asked to develop discriminating criteria for each design, and compare the relative merits of the pebble bed and prismatic reactor designs to produce electricity and/or process heat. The three teams independently proposed prioritized lists of criteria based on design details that each considered important. While several of the criteria were common, their relative rankings were not. One of the highest ranked items was the core performance (power density/level, core pressure drop, outlet temperature, etc.) criterion, where it was rated as high/important by all three teams. However, the resulting choice was different: AREVA and General Atomics gave the advantage to their prismatic designs, while Westinghouse gave the advantage to their pebble bed design. Economics was also ranked high by all three teams, but AREVA and General Atomics give the advantage to the prismatic design, while Westinghouse considers the pebble bed and prismatic designs to be comparable. Some of those criteria that were ranked differently by each team include safety, R&D needs/design maturity, and project schedule.

Based on each of the separate criteria and ranking lists, AREVA and General Atomics recommended the prismatic block core concept, and Westinghouse recommended the pebble bed core concept. However, as the criteria priority were not equal among the teams, and conflicted in some cases, a final recommendation will only be possible after the priority differences are reconciled, and concurrence on the priorities is reached. As such, a recommendation on reactor type cannot be made from the special studies alone. Further studies should be performed that allow each design to be optimized, and discriminating criteria developed that can be jointly used by each design.

NGNP Engineering White Paper: Reactor Type Trade Study

Introduction – Scope and Participants

The Energy Policy Act of 2005 authorizes the Next Generation Nuclear Plant (NGNP) as a project to demonstrate a first-of-a-kind, very-high-temperature gas-cooled nuclear system with the capability to generate electrical power and produce hydrogen using process heat. In order to focus the research and fulfill the requirements of DOE Order 413.3, preconceptual design studies were initiated by three teams led by the following companies: AREVA, General Atomics, and Westinghouse Electric Company. The Statement of Work (under Section 6.3.1) requires that a special study be performed for the choice of reactor type:

"Prepare a trade study based on currently available information supplemented as required by this work scope comparing the pebble bed reactor concept to the prismatic block reactor concept. Identify the most important discriminating criteria between the two concepts and provide an assessment of the important technical, operational and maintenance differences, including the important development risks for each. Discriminating criteria may include: thermal power rating, commercial scalability, licensability, design and operational considerations (e.g., fabricability, fuel handling systems and material accountability systems), development risks, life cycle cost, nuclear safety, non--proliferation, etc."

Each of the three teams made a recommendation on which design would best accomplish the goals of producing electricity and/or process heat based on discriminating criteria that each identified. As the discriminating criteria for the selection of reactor type were formulated independently by each preconceptual design team, the criteria differed between teams based on their own assessments of priority and importance. It is important to note that the selection criteria and recommendations from each team will help to form the final criteria for a future down selection of reactor type.

Summary of the Results

There are many criteria that can be used to differentiate the pebble and prismatic reactor types. However, the most important requirement for the NGNP is the ability to produce process heat for both efficient electricity and hydrogen production. In addition to the high outlet temperature, the NGNP is to demonstrate the exceptional passive safety features cited as a principal advantage by the designers and operators of gas-cooled reactors, and by obtaining an NRC license to demonstrate commercial viability of such a reactor.

Historically, both reactor types have been capable of producing temperatures that approach 850-950°C, and both reactor types have the capability to overcome some of the most severe accidents without intervention, (i.e., the fuel and core structure due not fail under all potential operating and accident conditions). Additionally, the time constants for changes in fuel and core conditions in response to accidents are measured in hours or days that allow for long lead times to take action. As such, the choice between either type, pebble or prismatic, will most likely be based on design details that give a technical, schedule and cost advantage to one design, and/or end-user preferences that will influence a decision on the design.

All three teams have designs in various stages of maturity with design details that each considers important. These details manifest themselves in the prioritized criteria developed by each team, where each team has ranked their criteria. The criteria and their rankings/ratings can be found below.

AREVA discriminating criteria and rankings

AREVA compared the prismatic reactor based on the ANTARES design (600MWt), to the PBMR-DPP pebble bed reactor (400MWt). The AREVA rating scheme for each criterion is as follows:

- o No clear advantage or disadvantage
- + Weak or small advantage
- ++ Moderate advantage
- +++ Strong advantage

In addition, the criteria are ordered based on the difference between options and the relative importance of each criterion. For seven of the criteria, both options are shown as equivalent or the prismatic option has a small advantage. However, for six of the top nine criteria, the prismatic reactor is considered to have a moderate advantage, and the top criterion is considered to have a strong advantage. This criterion includes the higher power density and lower pressure drop, leading to higher power capabilities and higher thermal efficiencies for the prismatic core. The pebble bed is considered to have a moderate schedule advantage based on the PBMR schedule status.

Discriminating Criteria	Prismatic Reactor	Pebble Bed Reactor
Performance Capability (power level, outlet temperature, pressure drop, etc.)	+ + +	-
Fuel Service Conditions	+ +	-
Fuel Qualification & Fabrication	o	o
Spent Fuel Disposal & Reprocessing	+ +	-
Fuel Handling and Refueling	+ +	-
Economic Factors	+ +	-
Research and Development Difficulty	o	o
Core Design Issues	+ +	-
Maintenance Issues	+ +	-
Operational Considerations	+	-
Safety and Licensing	+	-
Mechanical Components	o	o
Plant Layout/Schedule	o	+ +
Non-Proliferation, Safeguards, SNM Accountability	+	-
Post-Accident Behavior	o	o

Based on the rankings and ratings, AREVA has chosen the prismatic design.

General Atomics discriminating criteria and rankings

General Atomics compared the prismatic reactor based on the GT-MHR design (550-600MWt), to the PBMR-DPP pebble bed reactor (400MWt). Additionally, the criteria are rated based on whether they are considered an important discriminator, and which design has the advantage if they are a discriminator. The top two criteria appear as the first two items in the table, where the advantage is given to the prismatic design based on the higher power density and higher efficiency of the prismatic design. Of the remaining discriminating criteria, the pebble bed has the design advantage in only two areas: plant availability and fuel design/performance. The pebble bed is given the advantage in plant availability due to the continuous refueling of the pebble bed, i.e., planned outages are on 20-year intervals allowing for high capacity factors. The fuel design/performance advantage is given to the pebble bed due to the large amount of data and experience, and the fuel temperatures during normal/steady-state operation remain lower than for prismatic block fuel.

Comparison Criteria	Discriminator?	Design Advantage
Core power level and plant scalability	Yes	Prismatic block
Plant economics, including capital costs, operating costs, and life-cycle costs	Yes	Prismatic block
Technology development risks and development schedule	Difficult to judge at this stage	-
Plant availability	Yes	Pebble bed
Proliferation resistance and material accountability	Slight	Prismatic block
Reactor thermal hydraulic and nuclear design, design method development	Small	Prismatic block
Impact of reactor concept on other plant systems	Yes	Prismatic block
Fuel element design - stationary vs. flowing elements, fuel performance, oxidation resistance, etc.	Yes	Pebble bed
NRC design certification	Possible	Prismatic block
Life cycle and fuel disposal issues	Not significant	-
Reactor vessel, fabrication, fuel handling and other components	No	-
Safety performance and fission-product transport during accident conditions, plant maintenance and worker safety	Yes	Prismatic block
Flexibility of design to handle different fuel cycles	Possible	Prismatic block
Plant operation and potential problems	No	-
NGNP 2016-2018 startup schedule impact on choice	No	-

Based on the rankings and ratings, General Atomics has chosen the prismatic design.

Westinghouse discriminating criteria and rankings

Westinghouse compared a variation on the PBMR-DPP pebble bed reactor (the PBMR-PHP: 500MWt) to the prismatic reactor based on the H2-MHR design (600MWt). The discriminating criteria are grouped into three areas: Readiness, Performance, and Enhancement Potential. Of the nine criteria, four are weighted as high, and all but one of these shows that the pebble bed has the advantage. The remaining criterion weighted as high (cost competitiveness) is considered comparable with the prismatic design.

Criteria	Weight	PBMR-PHP versus H2-MHR
Readiness		
Design maturity and limited enabling technology R&D required	High	PBMR-PHP better
Vendor/supplier infrastructure	Medium	PBMR-PHP better
Performance		
Process heat delivery	High	PBMR-PHP better
Capacity factor/ investment protection	Medium	PBMR-PHP better
Safety	High	PBMR-PHP better
Safeguards	Medium	Comparable
Wastes and other environmental impact minimization	Medium	PBMR-PHP better
Cost competitiveness	High	Comparable
Enhancement Potential		
Fuel cycle flexibility and enhancement opportunities	Low	PBMR-PHP better

Based on the rankings and ratings, Westinghouse has chosen the pebble bed design.

Comparison of the Results

Several of the criteria are common to all three design studies, but their relative rankings are not. It is important to note that in comparing the designs, each team chose different base designs to compare. AREVA compared the ANTARES design to the PBMR-DPP, General Atomics compared the GT-MHR to the PBMR-DPP, and Westinghouse compared the PBMR-PHP (a variation on the PBMR-DPP with higher core power and outlet temperature) to the H2-MHR. While in some cases the differences are minimal, there are other factors that might change the relative ranking or weighting. For example, the PBMR-DPP is a 400 MWt plant, and has a power level that is 50% less than any of the prismatic designs. Whereas the PBMR-PHP is a 500 MWt plant, and only has a power level that is 20% less than the prismatic designs. This power level difference is important for both performance and economics of the plant.

One of the highest ranked items was the core performance (power density/level, core pressure drop, outlet temperature, etc.) criterion, where it was rated as high/important by all three teams. However, the resulting choice was different: AREVA and General Atomics gave the advantage to their prismatic designs, while Westinghouse gave the advantage to their pebble bed design. The differences lie mainly in which sub-criteria were considered more important, where the prismatic designs consider power density/level of high importance, and pebble bed designs consider core outlet temperature of higher importance. Economics was also ranked high by all three teams, but AREVA and General Atomics give the advantage to the prismatic design, while Westinghouse considers the pebble bed and prismatic designs to be comparable.

Some of those criteria that were ranked differently include safety, R&D needs/design maturity, and project schedule. Safety was considered of low importance by AREVA and General Atomics, but high by Westinghouse. R&D was considered of moderate importance by AREVA, hard to judge by General Atomics, and high by Westinghouse. Of particular interest is the ability to meet the 2016-2018 schedule: Westinghouse ranked this criterion as high; General Atomics did not consider it a discriminating criterion, and stated that it should not be a deciding factor; and AREVA ranked it as low.

Conclusions

Not all comparisons made were equal due to the lack of fully optimized designs, or lack of information by all teams. It is clear that more work is needed in order to make an equivalent comparison of the prismatic and pebble bed designs. In particular, an identical set of criteria should be used, and optimized designs should be compared.

AREVA evaluations show the prismatic concept is more advantageous than the pebble bed concept in all but the following criteria:

- Prismatic and pebble are equal in fuel fabrication and qualification, R&D, key components, and post accident behavior.
- The pebble bed design has an advantage over the prismatic design in plant layout and schedule.

General Atomics evaluations show the prismatic concept is more advantageous than the pebble bed concept in all but the following criteria:

- The pebble bed's ability to more easily supply a higher core coolant temperature outlet, for VHTR applications, and its online refueling capability, which contributes to a superior capacity factor potential.
- The pebble bed design has an advantage over the prismatic design in schedule, but this is not/should not be considered a discriminating criteria.

Both the AREVA and General Atomics studies found that the main advantage of the prismatic design is its higher power density, resulting in greater economic potential. In addition, fuel temperatures during accident conditions are lower in the prismatic fuel, which is considered important for fission product release and defining the boundaries for the emergency planning zone.

Westinghouse evaluations show the prismatic concept is more advantageous than the pebble bed concept in all but the following criteria:

- The prismatic design is capable of higher power densities, and lower pumping power (due to the lower pressure drop across the prismatic core), resulting in higher power levels and higher efficiency.

The Westinghouse study found that the main advantages of the pebble bed concept were the ability to produce process heat at the required temperature, and the reduced R&D needs for fuel (due to the German experience) and the reactor pressure vessel. Although fuel temperatures during accident conditions are higher in a pebble bed, fuel temperatures during normal/steady-state conditions are lower. Based on historical data, Westinghouse claims that since most fuel failure and thus fission product release occurs during normal operations, the lower fuel temperatures during normal conditions give the advantage to the pebble bed. Additionally, the superior economic potential of the prismatic design is refuted by the Westinghouse study due to the above pebble bed advantages, and based on the higher capacity factor potential.

Recommendations

Given the conclusions by the teams, AREVA and General Atomics recommend the prismatic design, and Westinghouse recommends the pebble bed design.

However, as stated earlier, the criteria priority for the studies was not equal among the teams, and conflicted in some cases. A final recommendation will only be possible after the priority differences are reconciled, and concurrence on the priorities is reached. As such, a recommendation on reactor type cannot be made from the special studies alone. Further studies should be performed that allow each design to be optimized, and discriminating criteria developed that can be jointly used by each design.

May 22, 2007 CCN 209674

Mr. T. L. Cook
NGNP Project Manager
NE- 33
U.S. Department of Energy
19901 Germantown Road
Germantown, MD 20874

SUBJECT: Contract No. DE-AC07-05ID14517 – Milestone Completion for G-IN07NG0701, "Issue Summary Report on Next Generation Nuclear Plant Project Special Studies"

Dear Mr. Cook:

This letter submits seven white papers (enclosed) that summarize the results of Special Studies performed as part of the Next Generation Nuclear Plant (NGNP) Pre-Conceptual Design work. This submittal satisfies the requirements of NGNP Project M1 Milestone ID 6356: "Issue Completed Special Studies" under Work Package: G-IN07NG07, "NGNP Pre-Conceptual Design Studies."

If you have any questions, please contact me at (208) 526-4250 or Larry Demick, NGNP Director, Engineering (208) 526-9344.

Sincerely,

Rafael Soto, Deputy Project Director
Next Generation Nuclear Plant Project

LD:cn

Enclosures:
1. NGNP Engineering White Paper: Reactor Type Trade Study
2. NGNP Engineering White Paper: Power Level Trade Study
3. NGNP Engineering White Paper: NGNP Project Pre-Conceptual Heat Transfer and Transport Studies
4. NGNP Engineering White Paper: Power conversion System Trade Study
5. NGNP Engineering White Paper: Primary and Secondary Cycle Trade Study
6. NGNP Engineering White Paper: Licensing and Permitting Special Study
7. NGNP Engineering White Paper: By-Products Trade Study

cc: M. L. Adams, DOE-ID, MS 1221
A. Clark, INL, MS 3695 (w/o Enc.)
C. P. Fineman, DOE-ID, MS 1235
P. Hildebrandt, INL, MS 3780
L. A. Sehlke, INL, MS 3810
R. M. Versluis, DOE-HQ

bcc: S. Bader, MS 3710
V. J. Balls, MS 3760
C. J. Barnard, MS 3779
L. Demick, MS 3780
P. M. Mills, MS 3780
D. A. Petti, MS 3860
D. S. Vandel, MS 3780
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Idaho National Laboratory

Cheryl A Noble/NOB/CC01/INEEL/US

06/04/2007 01:09 PM

To ·Julie S Banks/BANKSJS/CC01/INEEL/US@INEL

cc

bcc

Subject Fw: Milestone Completion for G-IN07NG0701, "Issue Summary Report on Next Generation Nuclear Plant Project Special Studies"

Record

Cheryl Noble
Executive Administrative Assistant to the Project Director for Next Generation Nuclear Plant Project

2525 Fremont Avenue, P.O. Box 1625, Idaho Falls, ID 83415-3780
Voice: (208) 526-0091 + Fax: (208) 526-9683 + Email: cheryl.noble@inl.gov

----- Forwarded by Cheryl A Noble/NOB/CC01/INEEL/US on 06/04/2007 01:09 PM -----

"Cook, Trevor" <TREVOR.COOK@nuclear.energy.gov>

06/04/2007 12:52 PM

To "Rafael Soto" <Rafael.Soto@inl.gov>

cc "Furstenau, Raymond V (NE-ID)" <fursterv@id.doe.gov>, "Henderson, David (NE-ID)" <henderad@id.doe.gov>, "Adams, Michael L (NE-ID)" <adamsml@id.doe.gov>, "Art Clark" <Art.Clark@inl.gov>, "Fineman, Clifford P (NE-ID)" <finemacp@id.doe.gov>, "Phil Hildebrandt" <Phil.Hildebrandt@inl.gov>, "Lisa A Sehlke" <Lisa.Sehlke@inl.gov>, robert.versluis@nuclear.energy.gov, "O'Connor, Tom" <Tom.Oconnor@nuclear.energy.gov>

Subject RE: Milestone Completion for G-IN07NG0701, "Issue Summary Report on Next Generation Nuclear Plant Project Special Studies"

This email acknowledges receipt and acceptance of the referenced report. The milestone *"Issue Summary Report on Next Generation Nuclear Plant Project Special Studies"* is hereby closed.

One important comment, in the future, when the INL places multiple contracts seeking evaluations, a common set of evaluation criteria should be provided to each contractor.

Trevor Cook
NGNP Program Manager
301 903 7046

From: Cheryl A Noble [mailto:Cheryl.Noble@inl.gov] **On Behalf Of** Rafael Soto
Sent: Tuesday, May 22, 2007 6:54 PM
To: Cook, Trevor
Cc: Furstenau, Raymond V (NE-ID); Henderson, David (NE-ID); Adams, Michael L (NE-ID); Art Clark; Fineman, Clifford P (NE-ID); Phil Hildebrandt; Lisa A Sehlke; robert.versluis@nuclear.energy.gov
Subject: Milestone Completion for G-IN07NG0701, "Issue Summary Report on Next Generation Nuclear Plant Project Special Studies"

Trevor,

Attached is the transmittal letter and enclosed white papers for Milestone Completion for G-IN07NG0701 - *"Issue Summary Report on Next Generation Nuclear Plant Project Special Studies."* This letter and enclosed white papers satisfies the Level 1 Milestone and associated deliverables.

Please let me know if you have any questions or comments.

Rafael

Rafael Soto/RS2/CC01/INEEL/US
Sent by: Cheryl A Noble

05/22/2007 04:54 PM

To trevor.cook@nuclear.energy.gov

cc FURSTERV@ID.DOE.GOV, HENDERAD@ID.DOE.GOV, ADAMSML@ID.DOE.GOV, Art Clark/CLARKA/CC01/INEEL/US@INEL,

bcc Julie S Banks/BANKSJS/CC01/INEEL/US

Subject Milestone Completion for G-IN07NG0701, "Issue Summary Report on Next Generation Nuclear Plant Project Special Studies"

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