INL/EXT-08-14395

Summary of Bounding Requirements for the NGNP Demonstration Plant F&ORs

June 2008

Idaho National Laboratory

DISCLAIMER

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

INL/EXT-08-14395

Summary of Bounding Requirements for the NGNP Demonstration Plant F&ORs

June 2008

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

Next Generation Nuclear Plant Project

Summary of Bounding Requirements for the NGNP Demonstration Plant F&ORs

INL/EXT-08-14395

June 2008

Approved by:

Richard Garrett NGNP Engineering Director	6/27/08 Date
Greg Gibbs NGNP Project Director	6/27/08 Date

ABSTRACT

This report documents bounding design, functional and operating requirements (F&ORs) for the Next Generation Nuclear Plant (NGNP) Project to support selection of the nuclear system design and specification of the operating conditions and configuration of NGNP once the nuclear system design is selected. These requirements derive from the conceptual design work completed for NGNP during FY 2008 to the date of this report, including full consideration of the expectations and needs of the private sector, and are judged by the NGNP Project to be important considerations affecting the selection and development of specific requirements for NGNP. These do not replace but rather supplement the detailed F&ORs for NGNP developed by the three contractor teams in the FY 2007 NGNP Pre-conceptual design work, which are summarized in Appendix A. These requirements will inform the ongoing processes that will eventually result in finalization of the requirements for NGNP. These processes include the Request for Information and Expression of Interest, issued by the DOE in April 2008 [Ref. 1]; the Request for Proposals for NGNP that will be issued later in 2008, and the actions of the Public-Private Partnership that will ultimately manage the NGNP Project.

CONTENTS

FIGURES

ACRONYMS

AVR	Arbeitsgemeinschaft Versuchsreaktor
CFR	Code of Federal Regulations
CTF	Component Test Facility
DOE	U.S. Department of Energy
EAB	Exclusion Area Boundary
EPA	Environmental Protection Agency
F&OR	Functional and Operating Requirements
FHSS	fuel handling and storage system
FY	fiscal year
GA	General Atomics
HTE	high-temperature electrolysis
HTGR	High Temperature Gas Reactor
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
LOCA	loss of coolant accident
LWR	light water reactor
NGNP	Next Generation Nuclear Plant
NRC	Nuclear Regulatory Commission
PCS	power conversion system
R&D	research and development
RFI/EOI	Request for Information/Expression of Interest
RPV	reactor pressure vessel
SRM	System Requirements Manual
THTR	Thorium Hochtemperatur Reaktor
W/PBMR	Westinghouse/Pebble Bed Modular Reactor, LLC

Summary of Bounding Requirements for the NGNP Demonstration Plant F&ORs

1. PURPOSE

This report documents bounding design, functional and operating requirements (F&ORs) for the Next Generation Nuclear Plant (NGNP) Project to support selection of the nuclear system design and specification of the operating conditions and configuration of NGNP once the nuclear system design is selected. These requirements derive from the conceptual design work completed for NGNP during FY 2008 to the date of this report, including full consideration of the expectations and needs of the private sector, and are judged by the NGNP Project to be important considerations affecting the selection and development of specific requirements for NGNP. These do not replace but rather supplement the detailed F&ORs for NGNP developed by the three contractor teams in the FY 2007 NGNP pre-conceptual design work, which are summarized in Appendix A. These bounding requirements will inform the ongoing processes that will eventually result in finalization of the requirements for NGNP. These processes include the Request for Information and Expression of Interest (RFI/EOI) issued by the U.S. Department of Energy (DOE) in April 2008 [Ref. 1][a], the Request for Proposals for NGNP that will be issued later in 2008, and the actions of the Public-Private Partnership that will ultimately manage the NGNP Project.

2. BACKGROUND

2.1 NGNP Functional & Operational Requirements

As part of the pre-conceptual design work in FY 2007, the three reactor vendor teams provided detailed design F&ORs for the plant designs proposed for NGNP [Ref. 2, 3, 4, 5]. These are comprehensive, generically addressing general requirements for the NGNP Project and the demonstration plant, and for each of the plant facilities, consistent with the work breakdown structure provided by the Project [Ref. 6]. The plant facilities include the nuclear system, heat transport and transfer system, power conversion system (PCS), hydrogen plant, balance of plant, and the overall site and infrastructure supporting NGNP. The F&ORs provided by each team were similar for all three recommended designs. The areas specific to the design recommended by each team are easily separated from the larger population of those generically applicable. These F&ORs continue to be generally applicable to the NGNP Project.

Also, as part of the pre-conceptual design work in FY 2007, the three reactor vendor teams provided detailed System Requirements Manuals (SRM) for the plant designs proposed for NGNP [Ref. 2, 3, 4]. The SRM defines the requirements hierarchy for the NGNP Plant with Hydrogen Production and Electricity Production and includes initial requirements based on the current maturity state of the NGNP project. A typical SRM for NGNP was included as Appendix D of the *NGNP Pre-Conceptual Design Report* [Ref. 22]. Subsequent to issuing this report, the SRM was updated to reconcile the submittals of the three reactor vendor teams. This revision of the *NGNP System Requirements Manual* [Ref. 26] is included as Appendix A to this document. Once the Public-Private Partnership is constituted and the specific requirements for NGNP are developed, the requirements summarized in this manual, including the F&ORs, will be revised and augmented.

---

[a] Items in brackets refer to references listed in the last section of this report.

2.2 FY 2008 Conceptual Design Trade Studies

As part of the FY 2007 pre-conceptual design work, the three reactor vendor teams identified critical technical and programmatic issues that affect the selection of the F&ORs and design requirements for NGNP. Several conceptual design trade studies were completed early in FY 2008 to address critical issues. Specifically, these studies addressed:

- The impacts of plant operating conditions on material selections of key components (e.g., reactor pressure vessel [RPV], intermediate heat exchanger [IHX]) as they affect risk to plant completion cost and schedule [Ref. 7, 8, 9, 10, 11]
- Configuration and design of the plant heat transfer and transport systems [Ref. 12, 13, 14]
- Potential end user requirements for application of High Temperature Gas Reactor (HTGR) technology [Ref. 15]
- Public and plant worker exposure criteria for normal operating and accident conditions of the plant and methods for control of radionuclide and dust contaminants in the helium coolant to satisfy those criteria [Ref. 16, 17]
- Licensing strategy [Ref. 18]
- Hydrogen process development [Ref. 19, 23]
- Concepts and preliminary F&ORs for the Component Test Facility (CTF) [Ref. 20, 21].

The objective of these studies was to provide insight into the impact of these issues on the ultimately selected design(s) functional and operating conditions and configuration. Accordingly, the results provide a structure, framework, and bounding conditions in which key characteristics of the plant can be finalized once the nuclear system design(s) is selected for NGNP.

2.3 DOE RFI/EOI

A significant factor that is expected to also affect the determination of the F&ORs of the selected design(s) for NGNP is the responses to the DOE RFI/EOI for the NGNP Project issued in April 2008 [Ref. 1]:

> *"The Department of Energy (DOE or Department) is requesting comments and expressions of interest from all interested parties on its Next Generation Nuclear Plant (NGNP) Project. DOE is soliciting comments on two aspects of the NGNP Project: (1) the strategy to proceed with the technology research and development; and the design, construction, licensing and operation of the proposed NGNP prototype demonstration plant; and (2) the structure, management, and funding of the public/private cost-share agreements that are necessary to proceed with the NGNP Project."*

The responses to this RFI/EOI, and more importantly to the Request for Proposal that will be issued after review and consideration of these responses, are expected to have an impact on how the F&ORs and other facets of the project that are addressed herein, including the selection of the nuclear system for NGNP, are ultimately configured. The bounding requirements cited herein are intended to provide information necessary to support this process.

3. OBJECTIVE OF THIS REPORT

This report defines bounding conditions within which the F&ORs for the selected NGNP design(s) are developed. These are presented as Bounding Conditions in the several areas addressed in the FY 2008 conceptual design trade studies. This document also provides the bases for these conditions. The following subsections discuss the specific objectives in defining these bounding conditions.

3.1 Operating Conditions

The objective in selecting the bounding operating conditions for NGNP was to balance the need to maximize the translation of the NGNP design; licensing; cost; construction; operating; and reliability, availability, and maintainability experience to the private sector against the need to minimize technical, cost, and schedule risks to bringing the NGNP on-line while retaining the long-term development capabilities of NGNP. The expectations and the needs of the private sector in specific applications of the HTGR technology have continuing influence on meeting this objective and will continue to be explored throughout development of the NGNP requirements.

Expanding the discussion of this objective, the three factors that combine to influence the selection of the bounding operating conditions for NGNP are as follows:

1. The effectiveness of NGNP to demonstrate the technical, licensing, reliability, and economic viability of the HTGR technology at conditions that meet the energy needs of the private sector. In this regard, the short- and long-term energy needs of potential end users were identified through NGNP Project discussions with selected end users (e.g., refining and petrochemical companies), potential end users (e.g., current owner/operators of nuclear power plants), and through prior contractor reviews of market surveys completed by the HTGR suppliers.

   These needs were characterized as power level (e.g., MWt or MWe), temperatures and pressures, form of the energy transfer (e.g., hot gas, steam, hydrogen), the quantities of energy required (i.e., rates, annual), redundancy requirements for assured availability, costs and economics, numbers of units, locations, and time frame of needs.

2. The impact of the bounding operating conditions on the risk to completion of the NGNP Project on schedule and within budget. The principal concerns are the qualification, availability, and performance of fuel, graphite, materials for the reactor pressure vessel and other primary pressure vessels, and the intermediate heat exchanger. Other factors considered included transportation of large vessels, on-site fabrication, cost, affect on licensing, technical readiness of critical components, requirements of test facilities to support progressing the technical readiness of critical components to ensure their performance, reliability when installed in NGNP (e.g., heat exchangers, circulators, valves), and control of radionuclides.

   Several of the conceptual design trade studies performed by the three contractor teams in the first half of FY 2008 investigated these factors in detail. The reports of these studies are included in the References section. Figure 1 provides a pictorial representation of the relationships among the results of several of these studies and their impact on selection of the NGNP operating conditions.

3. The third factor is the objective that NGNP continue to support the development of HTGR technology over the long term. For example, it is anticipated that at initial startup and

operation NGNP will be operated at a lower gas outlet temperature than would be needed to achieve maximum efficiency in hydrogen production. Based on the survey of potential end user energy needs this is acceptable to address current requirements. However, it should be an objective to attain the higher gas outlet temperatures over the long term as the technology and material performance and availability evolve. Accordingly, the design of NGNP should not preclude an increase in gas temperature over the long term.

3.2 Design Selections and Programmatic Issues

Additional work performed early in FY 2008 addressed other issues affecting the design selections and programs for NGNP. These included licensing risk reduction, specific prismatic fuel design [Ref. 24] and setting requirements and developing concepts for a CTF. The reports for these studies are, also listed in the References section for completeness.

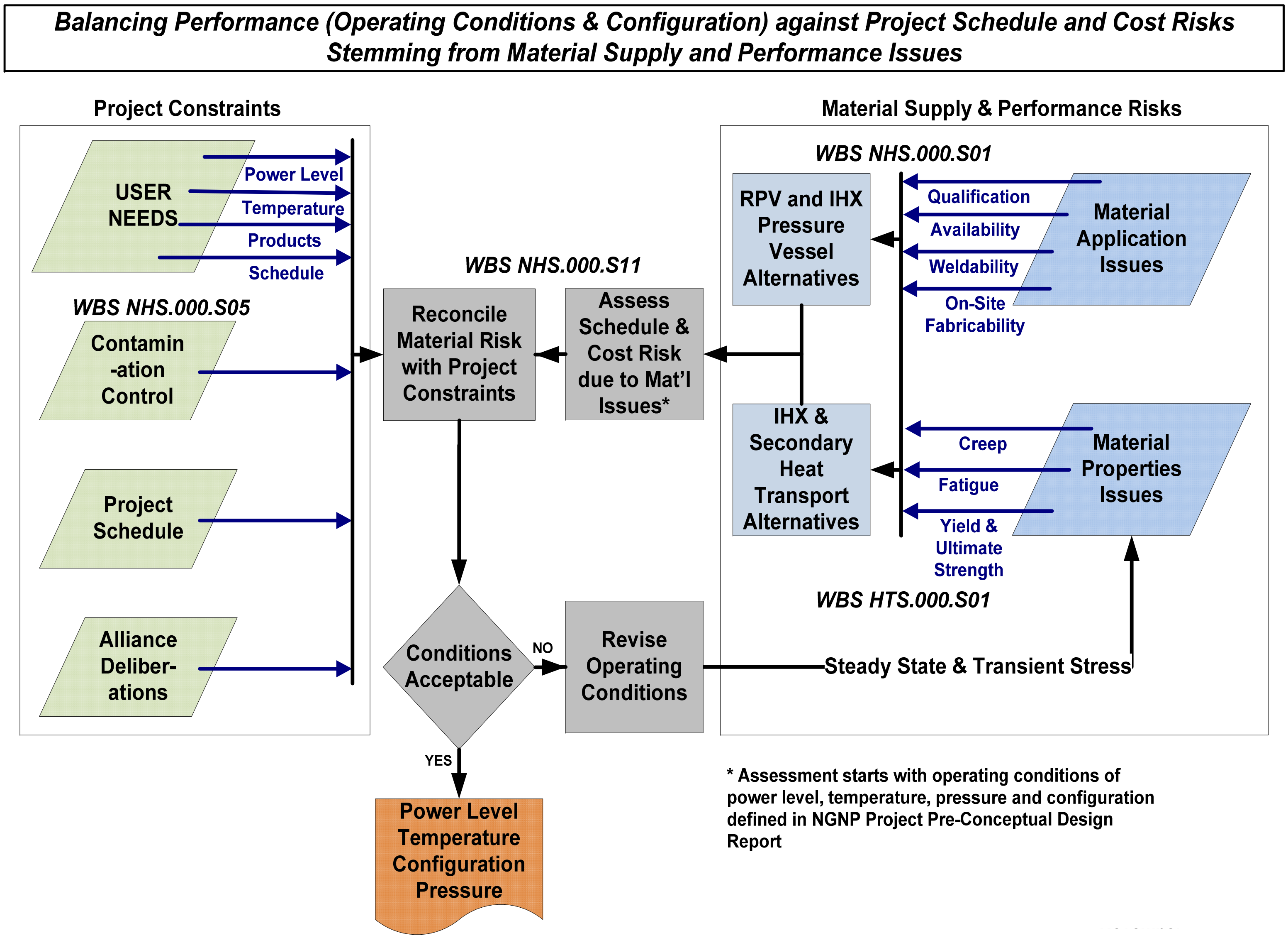

Figure 1. Conceptual Design Technical Selection Studies Integration

4. SUMMARY OF RECOMMENDATIONS AND BASES

The following section of the report summarizes the bounding conditions and their bases for the NGNP Demonstration Plant.

4.1 Reactor Type

4.1.1 Bounding Condition – 001

The prismatic and pebble bed designs shall continue as alternatives for NGNP until the strategy for the Project is formulated by the Public-Private Partnership(s). At present the alternatives include:

- Westinghouse/Pebble Bed Modular Reactor, LLC (W/PBMR) – Pebble Bed Design
- AREVA – Prismatic Design
- General Atomics – Prismatic Design.

Summary of Basis:

There are no discriminating technical factors among the designs that suggest one has an advantage either in the NGNP demonstration plant or in commercial applications [Ref. 22]. Additionally, there is no strategic path in development of the HTGR technology that has been defined either by the government or the private sector that favors one design over the other. This strategy must be developed before a clear preferred reactor design can be identified for the demonstration plant. The responses to the DOE RFI/EOI [Ref. 1] and the strategy developed by the DOE for the NGNP Project based on these responses is expected to have a significant influence on the selection of the reactor type for NGNP.

4.2 Reactor Design Power Level

4.2.1 Bounding Condition – 002

The NGNP shall be capable of operation at power levels up to 600 Mwt, depending on the core design, and core power densities that will demonstrate the technical and economic feasibility of commercial HTGRs with a passive[b] safety basis such that maximum fuel temperatures under normal and abnormal conditions are acceptable. Specifically, the reactor shall be designed for the maximum power level achievable for the core (pebble and prismatic) that ensures the peak time average fuel temperature under normal operating conditions and the time at temperature of the fuel under calculated accident conditions are sufficient to reduce radionuclide release rates to levels necessary to support meeting the specified public and worker exposure limits (see below under Exposure Limits). Based on currently available data and analyses, this requirement results in the following limits on fuel temperatures:

- The peak time averaged fuel temperature does not exceed 1250°C under normal operating conditions.
- The peak fuel temperature does not exceed 1600°C under accident conditions.

---

[b] "Passive," as used here, means that the performance of engineered systems are relied upon in the safety analyses, but without requiring any component in those systems to maintain or change state to satisfy the safety functions.

In addition, the core design shall result in a self-consistent set of operating parameters (e.g., power density, core delta T) and material choices (e.g., fuel, graphite, core barrel, reactor vessel) that demonstrate adequate safety margin when uncertainties in operating parameters and in the associated calculation methods (typically at 95% confidence) are explicitly accounted. At present, the contractor teams have proposed that the NGNP be designed, licensed, constructed, and operated at the maximum power level for their designs, as follows [Ref. 22]:

- W/PBMR – 500 Mwt
- AREVA – 565 Mwt
- General Atomics – 550 Mwt – 600 Mwt.

Summary of Bases:

While a small power prototype reactor (e.g., 25-30 Mwt) may be able to meet some of the goals for NGNP, it is recommended that NGNP be designed, licensed, and constructed at approximately commercial scale with respect to power output. This will ensure that uncertainties and technical challenges associated with fuel performance, code verification and validation, large component manufacturing and fabrication, materials issues at full scale, etc. will be addressed by NGNP to support future HTGR commercialization.

The vendor recommendations that NGNP power level should be the maximum achievable are based on their assessments, in part, of the following [Ref. 2, 3, 4]:

- The economies of scale – Standard scaling factors on cost versus size would predict that two nuclear island modules of half power would be estimated to cost about 23% more than one module of full power (applying a 0.7 exponent to account for the lower cost for the 50% reduction in power then multiplied by 2 to obtain the same total power). Therefore, it is judged by the contractors that the private sector will prefer the largest power module because of this cost factor (as expressed in private conversations during project review meetings).
- The preference for power levels in the private sector as high as attainable for specific applications (e.g., specific oil sands and oil shale recovery, some co-generation and hydrogen production applications) [Ref. 15].
- The need to establish a bounding licensing position that will facilitate transference of the NGNP experience to the private sector.

Other results of NGNP Project discussions with potential end users indicate that a one-size-fits-all power level for HTGR is not necessarily consistent with all of the end user needs and preferences for HTGR. The use of multiple lower power modules is considered to have potential advantages in siting, fabrication, and transportation to landlocked sites of large vessels and in addressing N-1 and N-2 reliability and availability requirements (e.g., the ability to continue to satisfy the process energy needs upon loss of one or two energy supplies). The flexibility of a modular approach in the adaptation of the HTGR technology (e.g., varying power, temperature, and product among multiple modules) to address efficiency and availability factors for each energy delivery component of a process is a unique strength of the technology. Having high and low power levels in the stable of reactor designs improves this flexibility.

The reactor vendor reports completed in FY 2007 and FY 2008 indicate that the power levels recommended by the three reactor vendors for NGNP are the maximum power levels attainable while retaining completely passive safety characteristics and fuel temperatures within the specified ranges [Ref. 2, 3, 4, 7, 8, 9]. Final design work is required to verify that the calculated fuel temperatures meet the specified ranges under all conditions after appropriately accounting for uncertainties in the calculations.

The design of the nuclear island for the nuclear system selected for NGNP needs to be completed along with the research and development (R&D) supporting the qualification of fuel, graphite, materials, and methods required to support the licensing basis of the plant. Additional work is required to develop the characteristics of the nuclear system with a lower power rating (e.g., one half the maximum power design) in conjunction with an evaluation of design and any additional R&D that would be required to include or evolve certification of this lower-power design under that for the higher-power design. It is judged that completing the design, licensing, construction, and operation at maximum power and certification of the commercial version of the NGNP nuclear system should facilitate receiving the certification of the lower-power design (i.e., scaling down should be more straightforward than scaling up; for example, if NGNP were a half-power design and the commercial need was for a full-power design).

In prior work, General Atomics (GA) has developed lower-power HTGR designs than they are currently proposing for NGNP, such as the Gas Turbine-Modular Helium Reactor. These are not necessarily the designs, however, that best fit the lower power requirements of the private sector. In summary, the additional work required is to:

- Clearly identify the lower-power design requirements in further evaluations with the private sector and through evaluation of other factors (e.g., availability of components, transportation of large vessels and components, potential for mass production, licensing)
- Develop the lower-power designs by the vendors through scaling, where possible, of the current designs to meet the private sector needs
- Process these designs through Nuclear Regulatory Commission (NRC) design certification. It is anticipated that the licensing of the lower-power designs should be facilitated by the certification of and scaling down from the higher-power designs.

4.3 Reactor Gas Outlet Temperature

4.3.1 Bounding Condition – 003

The reactor island shall be designed for operation at the highest temperature achievable for the reactor core design (i.e., pebble bed, the prismatic cores) and the maximum power level (see specific fuel temperature requirements above). However, NGNP shall be capable of operating at lower power and temperature to accommodate a period of plant operation below design conditions. This phase-in of operating temperature may be due to the following:

- Requirements to address open issues identified during licensing. These conditions will be established during the licensing process and are expected to be included as provisions in the operating license
- Limitations on operating conditions that derive from incomplete phases of qualification at the time the plant initiates operation (e.g., for fuel, graphite, materials or methods)

- Limitations on the capabilities of materials to operate at sustained periods at elevated temperatures (e.g., intermediate heat exchanger).

The reactor vendors have proposed reactor gas outlet design temperatures in the range of 900°C to 950°C, depending on the reactor design [Ref. 22]. However, based on evaluations of user needs and potential limitations on the availability and performance of materials in this temperature range, it is considered likely that the initial reactor island gas outlet operating temperature for NGNP may be in the 750°C to 800°C range [Ref. 15].

Summary of Bases:

In FY 2007 pre-conceptual design work and in FY 2008 Conceptual Design Trade Studies completed as of the date of this writing, the reactor vendors proposed reactor island designs for NGNP with gas outlet temperatures in the range of 900°C to 950°C and power levels in the range 500 Mwt to 565 Mwt [Ref. 2, 3, 4, 7, 8, 9]. The risk assessments performed by the reactor vendors in FY 2008, however, indicate that a gas outlet temperature higher than 750°C to 800°C significantly increases the risk of not meeting the schedule for deployment of NGNP because of concerns with the performance, codification, and availability of materials capable of sustained operation above these temperatures (e.g., in the higher temperature sections of the intermediate heat exchanger) [Ref. 7, 8, 9].

Evaluations of potential user needs show that a gas outlet temperature range of 900°C to 950°C bounds requirements of the potential commercial applications that have been identified for the HTGR technology. The majority of the applications that have been identified for initial use of the HTGR technology can be met with temperatures below 800°C. These include oil sands steam for well injections and co-generation applications in petro-chemical and refining plants [Ref. 15]. The 800°C gas outlet temperature is, however, not sufficient to operate the candidate hydrogen processes that are being developed for use with the HTGR technology at maximum efficiency. These include high temperature electrolysis (HTE), sulfur-iodine, and hybrid sulfur processes. It is possible that these processes can be demonstrated at lower efficiency or at the higher efficiency using supplementary heat sources (e.g., electric heaters at the sulfur-iodine and hybrid sulfur process sulfuric acid de-composer) until the plant can be operated at the higher temperatures. Accordingly, operation at a lower temperature in the initial phases of NGNP deployment is not a detriment to translation of that experience to the private sector.

Depending on the ultimate strategy developed for completion of the Project, it appears likely that initial operation of the NGNP will be at lower than design temperature. The plant may continue to operate at lower than design temperature for considerable time until technical and licensing issues are resolved for operation at the design temperature. It is judged important, however, that the reactor island be designed to accommodate the higher temperatures, particularly for those components that cannot be replaced in the future, so that the plant can be operated at the higher temperatures to support demonstration of advanced and evolving HTGR technologies and applications in the future.

At the time of this writing, tasks are being established with the reactor vendors to provide reactor temperature (inlet and outlet) and power envelopes within which their plants can be operated. The objective of this effort is to identify any design feature changes needed to facilitate operating at other than full design temperature and power. This work will also be used to identify advantages or disadvantages attendant to operating at the lower temperatures and potentially lower power levels (e.g., effects on cycle time, replaceable component lifetime, overall plant efficiency).

4.4 Reactor Gas Inlet Temperature

4.4.1 Bounding Condition – 004

The reactor gas inlet temperature shall be compatible with the maximum reactor power, gas outlet temperature, and required gas flow rate to achieve acceptable fuel operating temperatures (see design limits in Section 4.2.1,) and material choices, particularly the RPV.

Summary of Bases:

The pre-conceptual designs provided by the reactor vendors in FY 2007 have inlet temperatures in the range 350°C to 500°C [Ref. 22]. For all of the reactor designs proposed for NGNP, the RPV is exposed to the gas inlet temperature. The maximum inlet temperature during normal operation, therefore, affects the material that can be used for the RPV:

- Typical material used in light water reactor (LWR) RPVs (e.g., SA 508/533) can be used without modification at inlet temperatures of 350°C.
- SA 508/533 material may also be acceptable up to inlet temperatures of 490°C with modification of the cooling path and without a separate active vessel cooling system. [Ref. 11].
- Either modified 9Cr material or an active vessel cooling system would be required for inlet temperatures above 490°C if SA 508 material is used [Ref. 10, 11].

The optimum reactor inlet temperature will be reactor specific and affected by the process (e.g., return temperature of gas, condensate). Inlet temperature will also affect the size of the circulator for a given power level (e.g., the higher the inlet temperature, the higher the mass flow rate for a given power level and outlet temperature). To promote use of the NGNP to demonstrate the ability to supply a wide range of processes, it should be possible to operate NGNP with varying inlet temperatures. Thus, there is a need to characterize the acceptable operating regime for the plant as a function of inlet and outlet temperature, power level, and mass flow rate.

The tasks identified above for establishing the temperature power envelopes for each design will establish the required inlet temperature conditions for a range of outlet temperatures and reactor powers.

4.5 Public and Worker Exposure Limits

4.5.1 Bounding Condition – 005

Fuel specifications, operating conditions, and plant shielding shall be sufficient to meet NRC and Environmental Protection Agency (EPA) exposure limits for the public and workers under normal operation and calculated accident conditions. Tritium concentration control shall be sufficient to meet NRC and EPA limits on tritium concentrations in plant gaseous and liquid effluents and products. These limits are as follows:

- Under accident conditions, the release rates shall be limited to meet the EPA Protective Action Guidelines limits and 10% of the 10 CFR 100 limit at the exclusion area boundary (EAB; 400+ meters).
- Exposure to the public under normal plant operation shall not exceed 0.1 rem in a year, exclusive of the dose contributions from background radiation.

- The occupational dose to individual adults shall be limited on an annual basis to 10% of the 10 CFR 20 limits.

Tritium concentration control shall be sufficient to meet activity limits in the products of the plant. Note that investigations performed to date have not defined these limits for products. As such, they will need to be developed by the end users on a product-specific basis. The contractor teams performed work in FY 2007 and FY 2008 on contamination control in the primary and secondary loops of the plant, and in that work recommended the following limits for tritium concentrations in plant gaseous and liquid effluents and products. These are based on EPA and NRC requirements [Ref. 16, 17].

- Tritium concentrations in liquid effluents and products shall not exceed 100 Bq/liter (~10% of the EPA limit for drinking water, 740 Bq/liter).

- Tritium concentrations in gaseous effluents and products shall not exceed 3.7 Bq/liter (the NRC limit for air).

Summary of Bases:

The principal impact of the exposure requirements on the plant design is to set specifications for as-built fuel quality and failure rates during normal operation and under accident conditions. FY 2008 studies by the W/PBMR and GA vendor teams applied similar requirements. From these, W/PBMR and GA established preliminary fuel specifications and plant shielding requirements that result in acceptable radionuclide release rates and exposure levels that meet the specified limits [Ref. 16, 17].

A key characteristic and advantage of the HTGR technology is that the fuel, as the primary and effective barrier to radionuclide release, results in calculated source terms low enough that these exposure requirements can be met at the site boundary. The ability to meet the requirements at the EAB provides support for establishing the Emergency Planning Zone at the EAB rather than at the 10 mile radius point currently mandated by the NRC for LWRs. This provides significant flexibility in siting the HTGR plant for co-generation and other commercial applications.

The W/PBMR and GA reports identified potential approaches for meeting the tritium concentration limits. These are summarized under Bounding Condition – 007, below. Tritium generation and transport studies were performed in FY 2007 in a joint effort between the Idaho National Laboratory (INL) and the Japan Atomic Energy Agency [Ref. 23]. This study also identified methods for controlling tritium concentrations. The results of this study were included in this review and are discussed below.

The calculations performed by the reactor vendor teams to support the conclusions are preliminary and in some cases (e.g., the GA calculations) were performed with codes that need to be updated and validated. Work is required to develop, verify, and validate codes covering the following:

- Generation, depletion, and release from the fuel of radionuclides, including tritium

- Transport and plate out of radionuclides

- Tritium transport, sorption in graphite, and permeation through heat exchanger tubes and plates

- Cleanup system effectiveness.

The validation of these codes will require completing fuel R&D, including radionuclide release rates under normal and accident conditions, tritium generation, and characterizing the permeability of the materials of construction anticipated for use in the NGNP heat exchange equipment.

4.5.2 Bounding Condition – 006

Methods shall be developed and implemented to control the concentrations of tritium sufficient to meet or exceed the activity concentration limits for the products using the HTGR technology and the NRC and EPA limits on plant gaseous and liquid effluents, as defined above.

Summary of Bases:

The W/PBMR, GA, and INL reports [Ref. 16, 17, 23] conclude that specific methods will be required for control of tritium concentrations in the secondary helium loops and in the permeation rates through heat exchange equipment to meet the specified limits on plant gaseous and liquid effluents and products. These studies note that the normally developed oxide layers that form on the heat exchanger surfaces, if maintained, will provide some reduction in permeation rates through these surfaces. It is noted that maintenance of these barriers is dependent on close control of coolant chemistry; upsets in that chemistry or rapid transients in the plant may cause loss of the barriers. In any event, the contractor teams concluded that the reductions in permeation rates that would be expected, even if these barriers were effectively maintained, would not be sufficient to limit the concentrations to meet the activity levels specified. Adequate control of tritium activity levels in the plant effluents and in products will require a combination of several features. Each report identified several methods that need to be explored for application to NGNP to meet these limits. The principal methods included:

- Providing a significant secondary loop cleanup system. This is considered an effective but expensive alternative.
- Reducing the permeability of the heat transfer surfaces to tritium by adding coatings (e.g., aluminum oxides) on the surfaces. This would be a partially effective alternative that is developmental and could be combined with an upgraded cleanup system.

It is likely that a combination of these approaches will be required to achieve the specified limits.

Additional work is required to characterize the potential methods for reducing the concentrations of tritium in plant gaseous and liquid effluents and products to values that meet regulatory limits. This will require validation of codes used to track generation, transport, and permeation of the tritium and the impact of the control methods. R&D is also required to confirm tritium generation rates, permeability of heat transfer surfaces, sorption coefficients for graphite, effectiveness of barriers on reducing permeability of heat transfer surfaces, effectiveness of cleanup systems, and oxidant and hydrogen injection.

4.5.3 Bounding Condition – 007

Characterization and control of dust circulation in the primary system shall be required to ensure acceptable levels of dust-borne activity in the system and to minimize the impact on operability of primary system components (e.g., the control rods and circulators) and abrasion of primary system components.

Summary of Bases:

Radionuclide absorption on dust is one of the principal components of activity distribution in the primary loop and, therefore, a potentially significant contributor to radionuclide release in loss of coolant accidents (LOCAs) [Ref. 16, 17]. Significant dust concentrations in the primary coolant can also affect the operability and lifetime of primary system components. Areas of specific concern raised in reactor vendor evaluations of this issue include deposition within the control rod drive sleeves, which could affect rod insertion times and circulator performance and potentially bearing reliability. Erosion of components in high velocity areas is also a concern.

The dust generation rates in the PBMR reactor are higher than in the prismatic design. The W/PBMR report [Ref. 17] establishes expected generation rates in the core and as injected from the fuel handling and storage system (FHSS) and calculates the coolant activity expected from activation of the dust through sorption of fission products. The calculated activity levels are several orders of magnitude lower than attributed to radionuclide concentrations in the coolant and plated out on the metallic surfaces. The effectiveness of the filtration systems in maintaining dust levels in the coolant at acceptable levels are based on experience in the Arbeitsgemeinschaft Versuchsreaktor (AVR) and Thorium Hochtemperatur Reaktor (THTR). These systems are judged by W/PBMR to be effective in obtaining acceptable equipment performance and component lifetimes in the primary loop.

One of the principal reasons for the low estimate of dust activity in the primary loop is that the transport models indicate that the majority of the dust falls out and deposits in the RPV and on the heat exchange surfaces. The impact of these accumulations of dust, particularly on the heat exchange surfaces, and on re-entrainment during depressurized accident scenarios, needs further analysis. The dust transport and settling (re-entrainment) calculations are based on the SPECTRA code [Ref. 17], which needs further validation for application to NGNP.

The GA report concludes that dust generation in the prismatic reactor design is not a concern either as it affects coolant activity or component operability. Additional work is needed to fully characterize the generation rates of dust in the core and FHSS of the PBMR design, validate transport and activation models, and validate transport and deposition models. Further evaluation is required to assess the impact of dust depositions on the performance and reliability of the heat exchangers (e.g., effect on fouling and clogging of gas passages). W/PBMR anticipates obtaining data from the Demonstration Pilot Plant to confirm calculation results of SPECTRA.

The role of cobalt activation and distribution on the activity levels in the primary coolant loop was discussed briefly in the contractor reports on contamination control. Additional work is required to characterize this issue and establish design guidelines for its control.

5. CONCLUSIONS

This report has documented the bounding conditions on F&ORs for the NGNP Project to support selection of the nuclear system design and specification of the operating conditions and configuration of NGNP once the nuclear system design is selected. These bounding conditions supplement the detailed F&ORs for the NGNP developed in the FY 2007 pre-conceptual design work (as summarized in Appendix A) and to inform the ongoing processes (i.e., the RFI/EOI), the Request for Proposal that will be issued later in 2008, and the actions of the Public-Private Partnership that will eventually result in finalizing the requirements for the NGNP.

Appendix A

Next Generation Nuclear Plant System Requirements Manual

INL/EXT-07-12999, Rev. 1