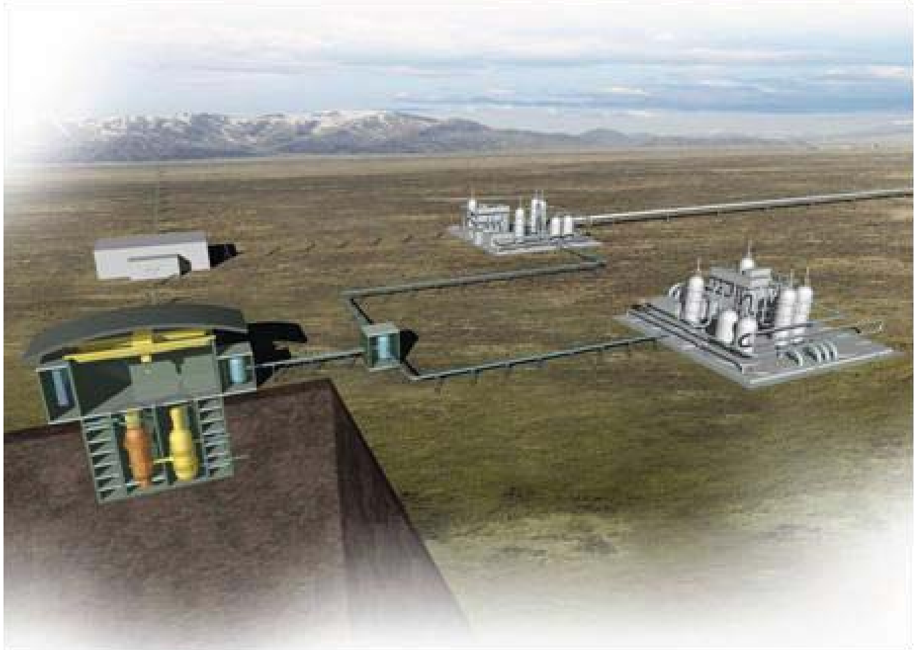
INL/EXT-07-12967
Revision 1

Next Generation Nuclear Plant

Pre-Conceptual Design Report

November 2007



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Next Generation Nuclear Plant Pre-Conceptual Design Report

November 2007

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

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Next Generation Nuclear Plant Project

Next Generation Nuclear Plant Pre-Conceptual Design Report

INL/EXT-07-12967

Revision 1

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EXECUTIVE SUMMARY OF RESULTS, RECOMMENDATIONS, AND CONCLUSIONS

Introduction

The Next Generation Nuclear Plant (NGNP) will be a demonstration of the technical, licensing, operational, and commercial viability of High Temperature Gas-Cooled Reactor (HTGR) technology for the production of process heat, electricity, and hydrogen. This nuclear based technology can provide high-temperature process heat (up to 950°C) that can be used as a substitute for the burning of fossil fuels for a wide range of commercial applications. The substitution of the HTGR for burning fossil fuels conserves these hydrocarbon resources for other uses, reduces uncertainty in the cost and supply of natural gas and oil, and eliminates the emissions of greenhouse gases attendant with the burning of these fuels. The HTGR is a passively[1] safe nuclear reactor concept with an easily understood safety basis that permits substantially reduced emergency planning requirements and improved siting flexibility compared to current and advanced light water reactors (LWRs).

In the *Energy Policy Act of 2005* (EPAct), the Department of Energy (DOE) was tasked with providing a demonstration of this HTGR technology to economically and reliably produce electricity and hydrogen by the year 2021. As the lead nuclear technology development laboratory of the DOE, the Idaho National Laboratory (INL) has initiated the work necessary to complete this task. The EPAct also stipulated that the task should be undertaken in partnership with the industrial end users of the technology. To that end, a working group has been assembled consisting of suppliers of the technology, nuclear plant owner/operators, other supportive technology companies, and potential end users. The objective of the working group is to form an Alliance that would provide the private sector perspective and direction for completion of the NGNP in partnership with the DOE. The Alliance will support the selection of the specific operating conditions and configuration for NGNP to ensure it meets private sector expectations, commence management of the project using commercial processes, share the cost of design and construction with the government, and secure a commercial nuclear operating company to operate the plant.

In FY-07, Pre-Conceptual Design (PCD) work was completed by the NGNP Project at the INL with the objective of developing a framework in which the design and technology development of the NGNP could progress and to begin to develop bases for selection of the specific design and operational characteristics of NGNP. This work was completed by three contractor teams with extensive experience in HTGR technology, nuclear power applications, and hydrogen production. The teams were led by Westinghouse Electric Company, LLC; AREVA NP, Inc.; and General Atomics. The scope of work included completion of special studies to address key aspects of the NGNP (e.g., reactor type, power levels, power conversion system [PCS] and heat transfer / transport system [HTS] designs, licensing and end product disposition). The results of these special studies were applied to the development by each contractor of a recommended design for NGNP and a commercial version of the HTGR. These were then used to estimate costs and schedule for design; construction; licensing; startup and testing; operation; and deactivation, decontamination, and decommissioning (DD&D) of the NGNP and an economic assessment for an Nth of a kind (NOAK) commercial plant. A primary objective of this work is to identify research

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[1] "Passive," as used here, means that the performance of engineered systems (e.g., the reactor cavity cooling system) 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.

and development (R&D), data needs, and future studies required to support selection of key characteristics of and to support the design and licensing processes for the NGNP.

The Preliminary Project Management Plan (PPMP) for the NGNP identifies two planning options that weigh a range of programmatic risks and approaches to mitigating risk. The two options are compliant with the EPAct, but emphasize different approaches to technology development risks, design and construction risks, and the extent of demonstration in support of commercialization. Option 1, labeled the Milestone Compliant option, establishes an overall schedule based on the milestone dates in the EPAct for Phase I and Phase II, and emphasizes extended R&D activities before proceeding with design and construction activities. Start of operations and project completion for this option is scheduled for 2021.

Option 2, labeled the Balanced Risk option, assesses the overall project risk with the objective of balancing technology development risk against design, licensing, and construction risk. Emphasis is on initiating design and licensing work as early as practical to reduce the uncertainties in the scope and focus of R&D activities. The expected date for initial operations (following the test program) is 2018. This option allows for a two- to three-year period of operation (prior to 2021) simulating a commercial power reactor operating cycle that is followed by an extensive outage, during which the equipment performance is confirmed by detailed disassembly and inspection. This proof-of-principle operating period provides support for commercialization decisions by industry.

Option 2 was chosen by the NGNP Project as the reference schedule for preconceptual design activities. Discussions with the private sector indicate a strong preference for the Option 2 schedule, which will support commercialization at the earliest date practical. Setting the Option 2 schedule as the goal for the NGNP Project provides margin to and supports the objectives of the EPAct for demonstration of the technology by 2021 while addressing the needs and expectations of the private sector.

A brief discussion of HTGR technology and the extension of the current state-of-the-art of this technology required to meet NGNP performance objectives is provided in Appendix A.

Pre-Conceptual Design Work and Report Objectives

There were several objectives for the FY-07 Pre-Conceptual Design work:

- Initiate development of the functional and operational requirements (F&ORs) and the configuration of the NGNP
- Provide direction to the NGNP Project R&D programs to ensure they support design development, licensing, construction, and deployment of the NGNP by 2018
- Support development of the licensing strategy for the NGNP with the objective that the strategy should support operation of the NGNP in 2018 and, ultimately, development of a Certification of Design for the use of the HTGR technology in the private sector
- Develop pre-conceptual designs with sufficient detail to provide credible estimates of the schedule and costs for NGNP and a NOAK plant
- Perform economic assessments for the NOAK plant to confirm the economic viability of the HTGR technology in production of electricity and hydrogen.

To meet these objectives, the contractor teams were tasked to define the state-of-the-art in HTGR technology in FY-07 and the advancements that could be made in that technology assuming deployment of the NGNP in 2018. This work was based on prior work of each reactor vendor on development of

HTGR technology and the experience and capabilities of their team members. These tasks defined design values and configurations of the reactor (e.g., reactor design, power level, gas temperatures and gas pressures), the HTS (e.g., type, heat exchanger effectiveness, operating temperatures), the PCS (e.g., configuration, power level and efficiency), and the hydrogen production processes for potential application in the NGNP. The capability and availability of materials, fabrication technologies, licensing issues, and development requirements to support effective use of the technology in private sector process heat applications (e.g., electricity, steam and hydrogen production) were focus issues.

The results and conclusions of the PCD define key technical risks and specific requirements that will govern the evaluations and design development required to be completed in continuing NGNP design progression. It was not an objective of the PCD work to make a final decision on the operating conditions and configuration of NGNP, but to provide the foundation for making the decisions. The decision process will depend on results from:

- Completion of additional evaluations on key issues (e.g., power levels, gas temperatures and pressures, IHX design, and materials)
- Planning for the development and acquisition of fuel, graphite, high temperature materials, and analysis methods
- Coordination with the Nuclear Hydrogen Initiative (NHI) program
- Licensing strategy development
- Due diligence to establish the technical completeness and credibility of work already completed by the contractor teams
- Further characterization of the marketplace for the HTGR technology by the potential end users and input from the commercial Alliance.

The NGNP Project schedule currently assumes that the key decisions will begin to be made in mid CY-08 as part of conceptual design. It is anticipated that the Alliance will be able to support making these decisions at that time.

This report summarizes the scope, results, and conclusions of the work completed during the PCD Phase for the NGNP. This includes the operating conditions, plant configuration, data, and development needs, including required future studies, cost and schedule estimates, and the economic assessments of the three contractor teams. This report also identifies the key technical risks for completion of the NGNP and the steps that need to be taken to resolve these risks. This report provides a part of the foundation for advancing the design progression of the NGNP, identifying the next steps in the design progression, and providing bases for interfacing with potential end-users and for obtaining necessary support from the Alliance in making the final decisions on the operating conditions and configuration of the NGNP. This report, however, is only one document of many documents and programs that support establishing NGNP requirements and planning. The others include:

- *Energy Policy Act of 2005*
- *Next Generation Nuclear Plant High Level Functions and Requirements*, INEEL/EXT-03-01163
- *Design Features and Technology Uncertainties for the Next Generation Nuclear Plant*, INL/EXT-04-01816

- *Next Generation Nuclear Plant Preliminary Project Management Plan*, INL/EXT-05-00952
- R&D program plans
- NHI program plans
- Licensing Strategy Development Program and plans
- Alliance working group white papers and end-user requirements.

The following sections first summarize the results, conclusions, and recommendations of the contractor teams. Second, they summarize the path forward for NGNP design development that is indicated from evaluation of the results, conclusions, and recommendations of the contractor teams.

Pre-Conceptual Design Team Recommendations

Plant Operating Conditions and Configuration

Table ES-1 summarizes the key results of each contractor teams' evaluations and recommendations for the NGNP operating conditions and configuration.

Table ES-1 Summary of Results

Item	**Recommended Operating Conditions & Plant Configuration**		
	Westinghouse	**AREVA**	**General Atomics**
Power Level, MWt	500 MWt	565 MWt	550 – 600 MWt
Reactor Outlet Temperature, °C	950°C	900°C	Up to 950°C
Reactor Inlet Temperature, °C	350°C	500°C	490°C
Cycle Configuration	Indirect – Series hydrogen process and power conversion	Indirect – Parallel hydrogen process and power conversion	Direct PCS Parallel indirect hydrogen process
Secondary Fluid	He	He-Nitrogen to PCS He to H_2 Process	He
Power Conversion Power	100% of reactor power	100% of reactor power	100% of Reactor Power
Hydrogen Plant Power	10% of reactor power	10% of reactor power	5 MWt – HTE 60 MWt – S-I
Reactor Core Design	Pebble Bed	Prismatic	Prismatic
Fuel	TRISO UO_2 1st and subsequent cores	TRISO UCO – 1st and subsequent cores	TRISO UO_2 1st Core Variable subsequent cores
Graphite	PCEA & NBG-18	NGG-17 and NBG-18	IG-110 & NBG-18
RPV Design	Exposed to the gas inlet temperature	Exposed to the gas inlet temperature; insulation and vessel cooling options may be pursued	Exposed to the gas inlet temperature
RPV Material	SA508/533	9Cr -- 1Mo	2-1/4 Cr – 1Mo 9 Cr – 1 Mo

Item	Recommended Operating Conditions & Plant Configuration		
	Westinghouse	**AREVA**	**General Atomics**
IHX	2- Stage Printed Circuit Heat Exchanger (PCHE), In 617 material	PCS – 3 - Helical Coil Shell & Tube, In 617 Process – PCHE or Fin-Plate, In 617	Process – single stage PCHE, In 617
Hydrogen Plant	Hybrid thermo-chemical plus electrolysis	Initial –High Temperature Electrolysis Longer Term – Sulfur-Iodine	Initial –High Temperature Electrolysis Longer Term – Sulfur-Iodine
Power Conversion	Rankine; standard fossil power turbine generator set	Rankine; standard fossil power turbine generator set	Direct gas turbine Option -- Direct Combined Cycle

These recommendations represent the judgment of the reactor vendors on what can be achieved for use in NGNP assuming an operational date of 2018. These are based on the current state of the design work related to HTGR by each contractor and prior commercial applications of gas-cooled reactor technology (see Appendix A). The reactor vendors note that achieving the recommended operating conditions requires significant design, licensing, and development effort.

Completing this effort to support operation of the plant in 2018, requires balancing the selection of initial operating conditions and the plant configuration for NGNP against the schedule and cost risks associated with design, licensing, R&D and construction. This balance must also consider the impact of technology selections and operating conditions on the viability of translating the NGNP experience to private sector applications. Later sections of this Executive Summary discuss how this balance can be struck in the progression of the NGNP design.

Licensing Strategies

As requested in the PCD Statement of Work (SOW), the contractor teams provided several potential strategies for obtaining a Nuclear Regulatory Commission (NRC) license for the NGNP. These strategies reflected the very preliminary nature of the NGNP design and the uncertainty in the approach the NRC will take in addressing the license applications for the NGNP. As required by EPAct, the approach for licensing the NGNP is being developed through a joint effort between DOE and the NRC. The PCD work, particularly that identifying the R&D and code committee work that will be needed to support the licensing process, will support this development. This effort is scheduled to be completed in FY-08 and will establish the basis for the detailed NGNP licensing strategy.

Cost Estimate

All three contractor teams prepared pre-conceptual level cost estimates and schedules as part of the PCD work for the NGNP. The cost estimates were developed using different methodologies that included parametric modeling, vendor quotes, actual costs, and proprietary costing databases. NGNP Project Engineering reviewed the assumptions and bases of estimate that supported the cost estimates for credibility and performed multiple studies to reconcile the variations in scope and assumptions among the three cost estimates. This effort resulted in an estimated range of \$3.8B to \$4.3B for completion of the NGNP. This range is based on the information and evaluations available to date and reflects possible contingency requirements. Figure ES-1 depicts the funding profile that would be required based on this estimate to meet the 2018 operational date for the NGNP. These costs estimates will be updated with higher confidence levels as design development progresses.

The cost estimates provided by the contractor teams for the NOAK commercial plant were all in the same range. All contractor teams proposed 4-unit plants with thermal power levels between 2000 MWt and 2400 MWt at a cost of about $4B, including owners cost. This value was used in the economic assessments.

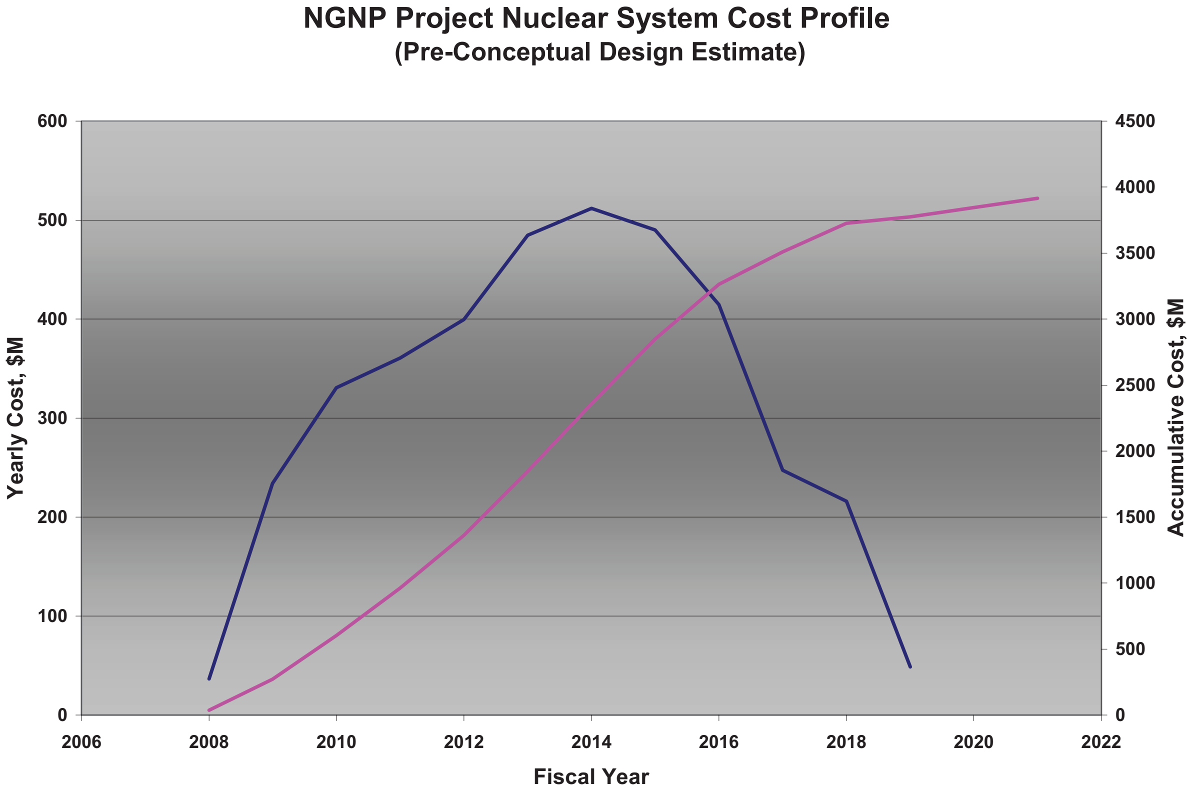

Figure ES-1. NGNP Project funding profile (based on pre-conceptual design cost estimates and operational date of 2018)

Schedule

The three contractor teams prepared pre-conceptual level schedules highlighting critical paths for initial operation of the NGNP in 2018. The NGNP Project reconciled these schedules in extensive reviews by cognizant Battelle Energy Alliance (BEA) / INL personnel to prepare an initial project schedule. The schedule was prepared consistent with the Work Breakdown Structure (WBS) for the project. Both this schedule and the WBS are presented in Section 8 and related Appendices of this report.

The schedule identifies the key milestones that must be met to achieve the objective of operation in 2018. Key milestones include the Critical Decision points for completion of design, long lead procurement initiation, start of construction, and approval for operation. They also include the submittal and receipt of critical regulatory documentation – Limited Work Authorization (LWA), Permit to Construct (PTC), and receipt of an Operating License from the NRC. The current critical paths for meeting the 2018 operational date are tied to completion of fuel qualification and completing the NRC licensing process.

As the licensing strategy matures (e.g., potentially adopting the one-step licensing process currently being used for licensing of light water power reactors versus the two-step process on which the current schedule is based) and the selection of NGNP operating conditions and configuration progresses, the schedule will be updated with the goal of establishing critical paths that support initial operation in 2018.

Economic Assessment

Each of the contractor teams prepared an economic assessment using their recommended design for a NOAK commercial plant producing hydrogen and, in one case, electricity. The contractor teams did not use the same economic assessment methodology, nor did they assume the same values for key economic parameters. For these reasons, the NGNP Project included a review of the contractor teams' methods and results and then revised each team's assessment using, in general, more conservative but consistent assumptions for key parameters and a consistent methodology. These revised assessments were performed using the costs (e.g., capital, operations, DD&D) estimated by each contractor team. A fourth assessment was then performed using the costs that were developed by the NGNP Project in reconciling the cost estimates provided by the three contractor teams.

The results of these analyses confirm the economic viability of the HTGR technology in two markets when compared with current technologies and prices of natural gas. Internal rates of return (IRR) in the 10% range were calculated for hydrogen and electricity production using conservative assumptions in an inflationary market. Accordingly, these results support the continued development of the NGNP and fostering the private sector application of the HTGR technology.

Technology Selection and Design Development Studies

The PCD work identified a number of areas that require further study to support the final selection of NGNP operational and physical characteristics (addressed herein as Technology Selection Studies) and to support design development of the NGNP (addressed herein as Design Development Studies). These were identified as "future studies" during the performance of PCD work by the contractor teams and in the review of this work by the NGNP Project. Several of these studies will be performed in the initial phase of conceptual design in FY-08.

Many of the studies identified by the contractor teams during the PCD work and by the NGNP Project were redundant or had overlapping objectives. NGNP Project Engineering consolidated the studies and classified them using three categories (i.e., Technology Selection, Design Development, and Other). Studies classified as "Other" were captured for later consideration as the design progresses. The Technology Selection and Design Development studies were prioritized to assist in determining which studies will be performed in the initial phases of conceptual design depending on the funding available in FY-08. Within the two categories, the studies were ranked into four levels of priority: highest, high, medium, and low. The last priority was used for those areas that needed to be completed as the design progresses but were not applicable in the initial stages of conceptual design before the key technology selections have been made. For example, establishing the specific reactor building requirements and coolant piping materials will depend on which reactor is selected for the NGNP. Within the two categories, the Technology Selection studies have the highest priority since they should be completed to support development of the final F&ORs and selection of the fundamental configuration of the NGNP.

Section 6.5 of the report provides summary descriptions of each of the studies. The following lists the studies that have the highest priority in the Technical Selection and Design Development categories. (Note: Some of the highest priority studies will be used to resolve key technical risks to support selection of the NGNP operating conditions and configuration. These are referenced in this context in later sections.)

Technical Selection Studies

A total of 12 areas that affect technology selections were identified for further study as part of the initial phase of conceptual design. Seven of these are judged to have the highest priority. (Note: The bracket notation is the WBS designation for the study. This designation is referred to later in the discussion of actions to be taken to resolve technical risks.)

1. Nuclear Heat Supply System F&ORs [WBS NHS.000.S11]

   This study entails an assessment of the appropriate design operating conditions for the NGNP (e.g., maximum reactor power level, reactor inlet and outlet temperatures, and primary pressure), considering cost, technical risk, translation of the NGNP experience to the private sector, and the level of confidence of the private sector that NGNP has effectively demonstrated the technical, licensing, reliability, and economic viability of the HTGR technology. This assessment will be completed by nuclear plant owner/operators, potential end users (e.g., petro-chemical companies, petroleum companies), and subject matter experts. This effort will ensure that the specification of the NGNP operating conditions balances the need to maximize the translation of the NGNP design; licensing; cost; construction; operating; and reliability, availability, and maintainability (RAM) experience to the private sector against the need to minimize technical, cost, and schedule risks to bringing the NGNP on-line.

2. IHX and Secondary Heat Transport Loop Alternatives [WBS HTS.000.S01]

   This study entails characterization and development of the advantages and disadvantages and technical risks of the potential alternatives for the intermediate heat exchanger (IHX) and secondary heat transport loop, including materials, design configuration, fabrication, operation, maintenance, in-service inspection, and means for periodic replacement. This study will be completed by selected members of the contractor teams and subject matter experts, and includes the following:

   - A comparison of the characteristics and development requirements for the candidate IHX designs (e.g., shell and tube, plate-fin, compact and other potential designs as identified). This should include:
     - Maintainability of modules or entire heat exchanger
     - Replaceability of modules or entire heat exchanger
     - Ability to detect material failures and the consequence of material failures during operation
     - The impact of environmental effects on the IHX and HTS (e.g., corrosion potential due to fluid contaminants, potential for dust clogging and erosion)
     - The impact of required in-service-inspection requirements for each design and the practicality in meeting those requirements
     - Required material properties
     - Availability and fabricability of the candidate materials with the requisite properties.

- Evaluation of a “two-stage” IHX design, including a high-temperature module with a limited expected lifetime, but that is easily replaceable, feeding a lower temperature module with longer expected lifetime

- The compatibility or other considerations (e.g., load sharing, outlet temperature variability, heat transfer surface pressure differential) of the candidate designs when included in multiple primary and secondary loop configurations, including expected responses during plant normal and upset transients, such as loss of the PCS and/or of the hydrogen production system (HPS).

The results of this study should include specific recommendations for the IHX design(s), primary and secondary loop configurations, and materials in the following areas:

- All pressure boundaries

- Valves and piping at IHX outlet

- Heat exchange surface.

3. RPV and IHX Pressure Vessel Alternatives [WBS NHS.000.S01]

This study will evaluate options for the Reactor Pressure Vessel (RPV) and IHX pressure vessel materials considering required and achievable metallurgical and physical properties, acquisition, fabricability, and reliability. This study will also identify and evaluate the advantages of options to provide cooling or other design features to use less developmental materials for these components that reduce cost and schedule risk to the NGNP Project. This study will be completed by selected members of the contractor teams and subject matter experts.

This study should include the following:

- Defining the required material properties for the operation of these pressure boundary components

- Identifying candidate materials for each component and determining the expected properties of each candidate material in the dimensions and conditions of each application

- Determining whether the candidate material is capable of achieving the required material properties for each application. For example, this study should consider required thickness, operating temperature window, welding and post-weld heat treatment requirements, availability with the required metallurgical and physical properties, size, manufacturability, fabricability, etc.

- Evaluating the maximum power level and temperatures that can be achieved using SA508/533 material for the RPV

- Evaluating the alternatives for cooling or other design features for the RPV as an option to revising power level and temperature to permit use of SA508/533 material for the RPV.

4. Reactor Containment and Building Functions[WBS NHS.000.S02]

   This study will define initial operating strategies to preclude the need for containment, recognizing the state of qualification of NGNP at the time of initial operation, and will review certain requirements for the reactor building. This will include:

   - Review of the NRC regulations regarding design basis threats and hazards
   - Evaluation of the need for a vented/filtered confinement and, if needed, definition of its requirements
   - Consideration of the effects of air ingress on calculated dose rates (i.e., under postulated air ingress events) and the potential application of an inert atmosphere to reduce the effects.

5. Contamination Control [WBS NHS.000.S05]

   This study will determine expected generation and transport rates and allowable limits on expected contamination of the gas and other heat transport loops during operation (e.g., contamination with tritium, cesium, silver, and dust), the required limits on the concentrations in the HTS and the product streams (e.g., steam, hydrogen, and oxygen), the requirements for cleanup, and the impact of the contaminants on primary and other HTS components operation and reliability. This study will evaluate, for example:

   - The potential of contamination of the product streams with tritium and the limits on concentrations of tritium in the product streams depending on the application (e.g., hydrogen use in refining applications vs. transportation)
   - The potential for dust erosion of primary system components (e.g., pipes, valves, and circulators), contamination of the electromagnetic bearings in the circulators, and plugging in the IHX
   - The impact of silver plate out and cesium contamination on the ability to maintain primary coolant components
   - The equipment required for cleanup of the contaminants and/or the need for multiple stages of heat transport to limit transfer to the product streams.

6. Helium Circulator Limitations and Design Issues [WBS HTS.000.S02]

   This study will evaluate the current state-of-the-art for circulator design (e.g., maximum capacity) relative to the flow and developed head requirements of the potential primary and secondary loop configurations proposed for the NGNP. It will also identify any constraints on the individual loop flow rates and pressure drops due to expected limitations in the capacities of the circulators available for NGNP construction. This study will also include:

   - A review of the reactor vendor requirements
   - A review of the circulator supplier experience and capabilities, particularly with respect to application of magnetic bearings and the maximum size used to date and practically achievable.

7. White Paper on Pebble Bed Core Analysis Methods [WBS NHS.000.S08]

   This study will identify the methods that will be used to analyze the nuclear, thermal, and hydraulic characteristics of the mobile pebble-bed core and how these will be verified and validated to develop sufficient confidence on the operational and safety performance of the plant to meet private sector expectations and NRC licensing requirements.

Design Development Studies

Sixteen areas were also identified for consideration during the initial phase of conceptual design that are important to the progression of the NGNP design. Five of these are considered to have the highest priority. They include the following:

1. Plant Design Requirements to Support Initial Operations [WBS BOP.000.S04]

   This study will establish specific design features of the plant that will be required to support the proof-of-principle initial operating period of the NGNP (e.g., instrumentation, in-service inspection (ISI), critical component replacement, and post-irradiation examination [PIE]). The study will identify the critical plant operating parameters to be measured to support design verification and the instrumentation required for this purpose, including development of instrumentation that will be required to satisfy these needs.

2. Design Code of Record [WBS BOP.000.S05]

   This study will identify the industry consensus mechanical, electrical, civil, and structural codes and any DOE, INL, and NRC standards that will apply specifically to the NGNP.

3. Reactor Building Embedment Depth [WBS NHS.000.S09]

   This study will develop the requirements and criteria for embedment of the reactor building. This study will include embedment studies for the HTGR reactor building concepts, considering the interaction among factors that influence the depth of the embedment. These factors include cost, design basis threats, seismic effects, hazards resistance, etc. The results of this study will be used to characterize the interactions of these factors on embedment depths for commercial application of this technology. The recommendations from relevant sections of the Electric Power Research Institute (EPRI)'s *Advanced Light Water Reactor Utility Requirements Document* will be evaluated for applicability in this study.

4. INL Site Selection [WBS BOP.000.S02]

   This study will finalize the site selection within the INL for the NGNP. This study will be performed by a contractor with expertise and relevant experience in the power plant site selection process. The recommendations from relevant sections of the EPRI *Advanced Light Water Reactor Utility Requirements Document* will be evaluated for applicability in this study.

5. High Temperature Gas Reactor Component Test Facility F&OR and Pre-Conceptual Design Requirements [WBS HTS.000.S05]

   A test facility (referred to as the High Temperature Gas Reactor – Component Test Facility [CTF]) is planned to support development of high-temperature gas thermal-hydraulic technologies (e.g., helium, helium-nitrogen, CO_2) as applied in heat transport and heat transfer applications in HTGRs. The initial use of this facility will be in support of the completion of the NGNP.

This study will prepare the F&ORs for the CTF and PCD requirements. This will include site plan, floor plans, elevations with typical sections, piping and instrumentation drawings, block flow drawings, electrical one-line drawings, a System Engineering Management Plan (SEMP), and a Facility Design Description (FDD) all at a PCD level. A contractor to perform this work will be identified and the work will be initiated in early FY-08. A white paper on the justification and specification for the CTF is included as Appendix H.

Key Development Risks

The results of the pre-conceptual phase of the design work form the foundation from which the design of the NGNP will evolve through a process of progressive selection of design conditions and features. To make these decisions, the NGNP Project needs to develop a better understanding of the development risks and the factors affecting their resolution to be effective in selecting operating conditions and configurations that balance the timing and risk to development of a condition or feature (e.g., reactor gas outlet temperature, heat exchanger design) against the schedule for deployment. The Project must also understand the needs and expectations of the private sector in use of the technology (e.g., applications, required schedule for availability, operating conditions, and reliability). The former factors will be addressed through completion of additional studies in the early phase of conceptual design in FY-08, as summarized above. The latter factors are being explored through Alliance efforts that will support development of the NGNP, and through meetings and discussions with potential end users (e.g., petro-chemical companies, petroleum companies, and hydrogen producers).

Completion of the PCD work in FY-07 represented the beginning of the design development process for the NGNP. Prior to this work, high-level technical requirements had been established for the project [ref. *Next Generation Nuclear Plant High Level Functions and Requirements*, INEEL/EXT-03-01163] and an independent technical review group (ITRG) had assessed the risks associated with development and demonstration of the technology [ref. *Design Features and Technology Uncertainties for the Next Generation Nuclear Plant*, INL/EXT-04-01816]. This latter assessment recommended reducing the aggressive proposed extension of the technology in the *High Level Functions and Requirements* document, principally recommending a reduction in objective reactor gas outlet temperature from 1000°C to no more than 900 to 950°C. *Design Features and Technology Uncertainties for the Next Generation Nuclear Plant* provides a comprehensive summary of technical issues that the review group considered must be resolved for successful implementation of the HTGR technology by the NGNP. The PCD work has confirmed, in general, the conclusions on the technical risks in that report and identified activities that will be necessary to resolve them.

The principal technical risks include:

- Qualification and acquisition of reactor fuel (e.g., qualification of fuel production facilities); reactor core ceramics, including graphite and graphite production facilities; and metals in the high-temperature regions of the plant (e.g., in the reactor and HTS)
- Verification and validation of analysis methods required to support design development; American Society of Mechanical Engineers (ASME) code acceptance; American Society for Testing and Materials (ASTM) standards acceptance; and NRC licensing
- Availability of materials with acceptable metallurgical and physical properties in the required sizes and thicknesses and the ability to fabricate large vessels on-site using these materials

- Availability and development of instrumentation (e.g., to monitor the fluence, high temperatures, and gas flow rates in the plant)
- Development of the hydrogen production processes and components
- Potential contamination of the product streams and meeting acceptable limits of contamination.

It is also noted that there are other project risks of equal or greater significance (e.g., obtaining sufficient funding to complete the NGNP Project). These are being addressed by the NGNP Project but are not addressed herein. This report addresses only the design, licensing, and commercialization risks from a technical perspective.

The NGNP operating conditions that have the most impact on the significance of these risks include the NGNP reactor power level, the reactor core gas inlet and outlet temperatures, and primary system pressure. These affect the required capabilities of materials in the nuclear heat supply system (NHSS). They also have impact on the demonstration of commercialization (i.e., ensuring that these are in ranges that are consistent with a wide range of private sector applications).

Material Risks

The metallic material risks are considered among the more significant from a development perspective. The NGNP R&D High-Temperature Material Development program will address these risks; the program plan will be completed in the spring of 2008. Equal concerns also exist regarding development, qualification, and acquisition of the reactor fuel and core ceramics. These are being addressed in well-defined R&D programs as discussed below.

The material risks stem from uncertainties in the availability, and ability to fabricate, some major components using materials that have the properties to operate reliably at the highest recommended gas temperatures by 2018. The principal concerns pertain to the large vessels and heat exchange components, in particular, the RPV, the IHX pressure vessel, and components of the IHX and secondary HTS.

The AREVA and General Atomics' designs have reactor inlet gas temperatures in the range of 500°C. The current designs for these plants expose the RPV and IHX pressure vessel to this temperature during normal operating conditions. The RPV is also exposed to higher temperatures for some period of time during the postulated depressurized / pressurized conduction cool down design basis events. This extended high-temperature exposure requires use of material with an acceptable strength and creep resistance at these temperatures. AREVA is recommending the use of 9Cr-1Mo (P91) for these vessels. General Atomics is considering P91 and 2-1/4Cr-1Mo material. There are several areas of concern with the use of the P91 material that need to be resolved (Note that 2-1/4Cr-1Mo does not appear to be acceptable for either application), namely:

- Japan Steel Works (JSW) has very limited experience with forging P91 in the sizes required for a full-scale NGNP. JSW is the only foundry in the world that can handle the ingots that will be required to forge the flanges of the RPV in a full size reactor.
- There is no commercial nuclear experience with application and welding of P91 for the large sections required in these vessels. These vessels are too large to be shipped assembled by land. Accordingly, they will have to be site fabricated for at least the NGNP; requiring on-site welding, post-weld heat treatment, and inspection.
- New code cases will be required to apply P91 at these temperatures.

The Westinghouse Pebble Bed Modular Reactor (PBMR) design uses a lower inlet temperature that does not require the use of higher alloy material; a more commonly used SA-508/533 steel is proposed for these vessels. The code case for this material will have to be extended to these operating temperatures, and the vessels will also need to be fabricated on-site. These are judged by the reactor vendors and subject matters experts consulted by the NGNP Project to require less developmental efforts than will be required for P91.

There are similar concerns with the heat exchanger materials, which could be exposed to the maximum gas outlet temperatures of 950°C (e.g., in the IHX and secondary HTS). Inconel 617 and Haynes 230 are being considered for these applications. Additional creep and creep-fatigue testing and associated code cases are required to apply these materials at the NGNP conditions. The reactor vendors do not believe Hastelloy XR will be required and are not currently considering it for these applications. This material can be considered if necessary in the future.

These material risks add uncertainty to the successful completion of the NGNP on time. Accordingly, the NGNP Project is considering a phased approach to achieving the objective design operating conditions. In this approach, the plant would be operated at a lower than design temperature in early operation of the plant to provide more design margin for the available materials of construction. For example, the creep rupture life of Inconel 617 increases by two orders of magnitude for an operating temperature of 815°C when compared to an operating temperature of 925°C at the same stress level. This approach would also provide more time for expanding high-temperature material databases and for finding suitable higher-temperature replacement materials (e.g., oxide dispersion-strengthened alloys, ceramics, etc.). This approach is discussed further below.

The NGNP R&D program includes testing of the high chromium materials as well as Inconel 617 and Haynes 230, materials that will be used in the heat exchangers and potentially hot ducts and piping, to support extending code cases for these materials into the NGNP temperature ranges. The principal concern at temperatures above 800°C is establishing where the onset of significant material creep and creep-fatigue occurs. R&D testing has already been initiated for some of these materials to obtain creep data at high temperature and long periods.

The other significant technical risks are being addressed principally in the NGNP Project R&D programs in Fuel Development and Acquisition, Graphite Development and Acquisition, High Temperature Materials, and Methods Development.

Resolution of Principal Technical Risks

Tables ES-2 and ES-3 summarize the continuing evaluations that will be completed in the early phase of conceptual design to resolve the technical issues. These evaluations will reconcile:

- The recommendations on operating conditions and plant configuration and the bases for these recommendations by the contractor teams
- On-going or planned work within the NGNP Project R&D programs
- Prior work performed by others
- Consultation with subject matter experts, as required.

The objectives of these evaluations are to develop recommendations that will be used as part of the bases for establishing NGNP operating conditions and configuration. This decision making process will also include input from the private sector as discussed below.

Table ES-2. Nuclear heat supply operating configuration and design

Issue	Contractor Recommendations				Plan for Resolution
	Westinghouse		AREVA & General Atomics		
	Value	Basis	Value	Basis	
Operating Conditions, including Power Level, Gas Temperatures, and Gas Pressure	500 MWt 950°C Out 350°C In 9 MPa	Reactor Power is the maximum achievable to retain passive safety basis Satisfies customer needs Demonstrates availability of material and fabricability of the large vessels at these operating conditions Translates licensing, cost, operation, and reliability experience to the private sector at the maximum achievable power level and temperature Temperatures are consistent with high-level requirements as modified by the ITRG report These conditions are considered to be achievable but require significant development	550 – 600 MWt 900 – 950°C Out 490 – 500°C In 7 – 9 MPa	Same bases as identified for pebble-bed	An assessment of the appropriate design operating conditions [WBS NHS.000.S11] will be initiated in FY- 08 to review the recommendations of the contractor teams and to recommend the specific operating conditions for NGNP based on assessment and trade-off of the following (Note this assessment will be performed by nuclear plant owner/operators, potential end users (e.g., petro-chemical and petroleum companies), and subject matter experts): – Technical Risk affected by the selection of power level (e.g., size and material of vessels, fuel and core ceramic performance, maturity of design, primary loop configuration, design and material of IHX) – Cost vs. size – Schedule – Translation of the NGNP licensing experience to support certification of the design for application by the private sector – Private sector confidence that the demonstration is fully adequate to translate the experience for commercial applications and has been effective in resolving all technical, licensing, and development risks (e.g., availability of materials, fabricability of the large vessels, cost of construction and testing, O&M costs) This study will be coordinated with the following two studies in this table, which address the effect of high reactor operating temperatures on the technical risks in design and materials for the reactor and IHX pressure vessels and the IHX.

Issue	Contractor Recommendations				Plan for Resolution
	Westinghouse		AREVA & General Atomics		
	Value	Basis	Value	Basis	
Reactor Pressure Vessel and IHX Pressure Vessel	SA508 Material	The reactor pressure vessel is exposed to the inlet gas and the reactor cavity cooling system (RCCS). The IHX pressure vessel is exposed to the inlet gas temperature. The 350°C inlet temperature and calculation of the duration of the maximum temperature reached in the depressurized / pressurized conduction cooldown design basis events permits the use of SA 508 material.	9Cr-1Mo 2-1/4 Cr – 1Mo	With the current design, the RPV is required to accommodate the 500 °C gas inlet temperature and the temperatures reached in the depressurized / pressurized conduction cooldown design basis event. A high alloy material (e.g., P91) is required to satisfy these conditions. Design changes can be pursued that would permit using the more traditional SA508 material. These would include reduced operating gas temperatures, insulating the vessel and/or adding a vessel cooling system.	A study will be performed early in FY-08 [WBS.NHS.000.S01] including input from selected members of the contractor teams and subject matter experts to develop recommendations for the reactor and IHX pressure vessel designs and materials, considering the following factors (Note: these evaluations will cover the full range of operating conditions recommended by the reactor vendors [i.e., power level, gas temperatures and gas pressures]): – Review of the recommendations of the reactor vendor Pre-conceptual Design Reports (PCDRs) – Review of relevant prior studies (e.g., Argonne National Laboratory (ANL) evaluations of materials for RPV and IHX pressure vessel) – Material requirements (e.g., primary and stress levels, average temperatures under normal operating and accident conditions) – Extension of ASME code case requirements and feasibility – The structural capacity of the material vs. temperature under operating and accident conditions. The principal concern is with establishing the onset of significant creep and creep-fatigue. This will include work and results of the R&D High Temperature Material Development Program. – The availability and metallurgical properties of the material in the sizes and thicknesses required for the application – The fabricability and welding capabilities using this material for on-site fabrication – Operating and/or design changes required to utilize SA508 as the material – ISI requirements and practicality in achieving these requirements.

Issue	Contractor Recommendations				Plan for Resolution
	Westinghouse		AREVA & General Atomics		
	Value	Basis	Value	Basis	
IHX Design and Materials	2-stage PCHE Inconel 617 or Haynes 230	A two-stage printed circuit heat exchanger (PCHE) is recommended. The smaller first stage will be exposed to the highest temperatures (710 – 900°C) and can be replaced as frequently as needed. The second stage will operate at lower temperatures (325 – 710°C) and will not need frequent change out.	Shell & Tube and PCHE Inconel 617 or Haynes 230	AREVA recommends use of multiple helical tube and shell heat exchangers to supply full load to the PCS, and a smaller PCHE to supply the hydrogen production facility. General Atomics recommends the use of a single full-power compact heat exchanger (either PCHE or plate-fin design) to supply the PCS and hydrogen facility.	An assessment [WBS.HTS.000.S01] will be initiated in early FY-08 to evaluate and recommend the design and materials for the IHX. This study will be performed by selected members of the contractor teams and subject matter experts and will include the following (Note: these evaluations will cover the full range of operating conditions recommended by the reactor vendors (i.e., power level, gas temperatures and gas pressures): – Review of the recommendations of the reactor vendor PCDRs – Review of relevant prior studies (e.g., ANL evaluations of materials for RPV and IHX) – Status of and planning for the demonstration of candidate material properties in thick and thin sections. This review will include the NHI programs focused on heat exchanger design development and the R&D High Temperature Material Program[2] – Status and planning for design, lab-scale, pilot-scale, and engineering-scale testing of the candidate designs – Fabricability and welding of the material and design configurations – ISI requirements and abilities (e.g., there is currently no acceptable way to inspect plate-and-fin or printed circuit style heat exchangers. These will need to be developed to satisfy Code and other requirements.). This study will also identify a course of action required for longer-term material development to support the use of NGNP as a test facility for demonstration of evolving and emerging technologies.

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[2] The **High Temperature Materials Program** will establish the relevant thermomechanical performance data to support the development of IHX and other high-temperature components for an outlet temperature up to 950°C. Creep, creep-fatigue, aging, and environmental degradation testing is planned using the candidate high-temperature material selected for NGNP. Thick and thin sections of base material, weldments, and other joints (e.g., diffusion bonding) will be evaluated given the different design options under consideration for the IHX (Current candidates are Inconel 617 and Haynes 230). Depending on the outlet temperature selected by the NGNP project, additional high-

Table ES-3. Generic technical development

Issue	Pebble-Bed Reactor (Westinghouse)	Prismatic Reactor (AREVA & General Atomics)	Plan for Resolution
Verification and validation of neutronic and thermal hydraulic codes	Verification and validation of nuclear and thermal hydraulic analyses for the mobile pebble-bed core.	The static nature of the prismatic core does not require special considerations. The validation of codes will be addressed as part of the design and licensing process supported by the R&D Methods Development and Verification and Validation (V&V) Program.	A white paper is to be commissioned in early FY- 08 from PBMR Ltd (Republic of South Africa [RSA]) describing the methods used for analysis of the mobile pebble-bed core and the approach that will be used to V&V these methods. [WBS NHS.000.S08] See discussion of R&D Methods Development and V&V program, below.
Dust formation, cleanup, impact on component reliability, and fission product release	Assessment of dust formation due to the movement of the pebbles through the core on primary component reliability and performance, primary system helium cleanup system duty, and quantification of fission product source terms to support release rate calculations under postulated loss-of-coolant design basis events	Assessment of dust formation due to the relative movement of the fuel and reflector blocks in the core on primary component reliability and performance, primary system helium cleanup system duty, and quantification of fission product source terms to support release rate calculations under postulated loss-of-coolant design basis events	A study will be performed to address control of contamination in the heat transfer loops and product streams in general. This study will include an evaluation of the effects of dust for each reactor type early in FY-08 [WBS NHS.000.S04]: For the pebble-bed reactor, input from PBMR Pty (RSA), and data from AVR operation and industry subject matter experts will be used to characterize the impact of this issue on the use of the PBMR design for the NGNP. For the prismatic reactor, input from AREVA and General Atomics, and data from HTTR, Fort St. Vrain, and Peach Bottom operation and industry subject matter experts will be used to characterize the impact of this issue on the use of the prismatic design for NGNP.

temperature data may be needed to support relevant ASME code cases for the material. R&D to establish requisite ISI techniques will be developed as key components are being designed. Prototype testing of key components is envisioned in a high-temperature flow loop to characterize overall behavior under prototypic flowing HTGR conditions and validate ISI techniques.

Issue	Pebble-Bed Reactor (Westinghouse)	Prismatic Reactor (AREVA & General Atomics)	Plan for Resolution
Product stream contamination with tritium and the acceptable levels in the streams depending on the intended use and/or market for the product	Identified as a potential contaminant in the primary system.	Identified as a potential contaminant in the primary system.	The prior referenced study on contamination control [WBS NHS.000.S04] will also address the effects of tritium generation, transfer, and control. This study will determine the expected generation rates of tritium in the primary system, the expected transport into and through the heat transfer loops to the product stream (e.g., steam, hydrogen, oxygen), and the required limits on concentrations of tritium in the product streams depending on the application (e.g., hydrogen use in refining applications vs. transportation). This study will develop recommendations on cleanup system requirements and establish if multiple heat transfer loops will be required to isolate the product streams from the tritium source as a practical approach to meet concentration limits.
Reactor fuel	Qualification of the fuel and fuel fabrication facilities: UO_2 – first core UO_2 – 2nd and subsequent cores	Qualification of the fuel and fuel fabrication facilities: UO_2 – first core UCO – 2nd and subsequent cores	The Fuel Development and Qualification Program will qualify TRISO-coated particle fuel for use in the NGNP. TRISO-coated particles will be fabricated at pilot scale for use in the formal qualification testing. The testing program consists of irradiations, safety testing, and PIEs that will characterize the behavior of TRISO-coated fuel under both normal and off-normal conditions. The program also contains out-of-pile experiments, special irradiations, and safety testing to characterize the release and transport of fission products from the kernel through the coatings, the fuel matrix, the graphite, and the primary system (i.e., source term). Formal validation testing is also planned to validate fuel performance and fission product models, required for core performance assessments and safety analysis. The program is currently considering both UCO and UO_2. Once a design decision is reached by the project, the program will focus on either UCO or UO_2. Feasible acquisition strategies for both design concepts, which include qualification of the production facility, have been established and will be executed once the reactor design decision is made.

Issue	Pebble-Bed Reactor (Westinghouse)	Prismatic Reactor (AREVA & General Atomics)	Plan for Resolution
Graphite	Qualification of graphite used in the reflectors and support structures: PCEA – replaceable reflectors NBG-18 – all other	Qualification of graphite used in the reflectors and support structures: The General Atomics PCDR is non-specific on the selection of graphite at this time. The statement is made that the selected graphite will have properties equivalent to or better than H-451, the graphite used in Ft. St. Vrain. In prior discussions, General Atomics cited potential use of IG-110, NBG-17 and NBG-18. AREVA cites the use of NBG-17 and NBG-18.	The NGNP Graphite Program will develop the qualification dataset of thermomechanical and thermophysical properties for unirradiated and irradiated candidate grades of graphite for NGNP. Where practical, other grades of graphite may be tested/characterized to provide a baseline for comparison or to help understand material property changes for the NGNP graphite grades. The program consists of statistical characterization of unirradiated graphite material properties to establish the lot-to-lot, billet-to-billet, and within billet variability of the material. Irradiations are planned at specified temperatures and doses within the design service condition envelope anticipated for NGNP. Extensive PIEs are planned to establish the change in relevant material dimensions and properties as a function of temperature and neutron dose. Of particular interest is the irradiation induced creep of graphite, which is critical to determining the lifetime of the graphite under irradiation. From these datasets, constitutive relations will be established for use in a detailed predictive thermo-mechanical finite element model. These data will also support development of relevant ASTM standards and ASME design rules. In the longer term, the program plans to evaluate processing route and raw material constituent influences on graphite behavior so that additional large qualification irradiation programs are not needed when new coke sources are used to make graphite for HTGRs.
High-temperature materials for core internals and ducting, including core ceramics other than graphite	800H – core barrel & inner ducts C/C and SiC – control rod sleeves C/C reflector restraint straps & insulation hangers	800 H – core barrel & inner ducts 316H – core barrel C/C and SiC – control rod sleeves	The Incoloy 800H nickel alloy and the high carbon 316H stainless steel alloy are commercially available materials used in high-temperature applications. It is judged by the contractor teams and the NGNP Project that these materials are well characterized and significant development work is not required for their use in the core barrel and ducting applications. These materials may also be used in control rod applications. The carbon-carbon (C/C) and silicon carbide (SiC) are highly developmental materials. There is no current work or planned work within the INL R&D program for testing and development of these materials. Work on these materials by the reactor vendors has not been characterized by the Project. It is judged that Incoloy 800H will initially be used for the control rod sleeves in NGNP. The SiC material is judged by the Project to be the most likely suitable for use in the longer term but will require development.

Issue	Pebble-Bed Reactor (Westinghouse)	Prismatic Reactor (AREVA & General Atomics)	Plan for Resolution
Methods development and V&V	Part of design development and licensing	Part of design development and licensing	The Design and Safety Methods Validation Program will develop validation experiments and data to validate models and analytical tools for the NGNP to resolve key safety, performance, and technical issues through confirmatory modeling and/or tool development when existing models and/or tools are judged to be inconclusive or inadequate, and to modify, upgrade, and/or develop new analytical tools for future use that will reduce uncertainties and improve the capability of understanding the behavior and operating margins of the plant. Current areas of focus include developing improved differential cross-sections for Pu isotopes to reduce uncertainties in the reactivity performance of high burnup low enriched uranium (LEU) HTGR cores, assessing and improving reactor physics and kinetic methods for prismatic and pebble-bed HTGRs, performing physics benchmark studies on past relevant experiments, evaluating important phenomena that influence thermal-fluid behavior in HTGRs and establishing relevant experiments for V&V, evaluating of air-ingress phenomena in HTGRs and participating in relevant validation experiments, developing experiments to validate reactor cavity cooling system behavior, and evaluating and establishing system level codes appropriate for HTGR safety analysis.

Plant Initial Operating Conditions, Longer Term Objectives, Commercialization

It is the consensus of the contractor teams and considered to be likely by the NGNP Project that, because the NGNP is a prototype plant, it will need to start initial operation at less than full design conditions with a subsequent proof-of-principle operating period of two to three years. During this operating period, extensive instrumentation of the plant, ISI, PIE of components (e.g., fuel and ceramics), and special test rigs (e.g., material test coupons) will be used to verify design assumptions as plant operating conditions are gradually moved to full design. These inspections and tests will validate operating procedures, plant steady state and transient operating characteristics, and other features of the plant, including steady state and transient interactions among the NHSS, PCS, and hydrogen production plant. This initial operating period will also demonstrate general technical performance and reliability of the primary and support structures, systems, and components (SSCs; e.g., refueling equipment). During this period, parallel efforts will also continue to extend qualification data for reactor fuel, core and internals ceramics, and high-temperature metallic materials to permit extended operation of these components.

It is possible that the plant may need to be operated for an extended period (e.g., up to ten years) at less than full objective gas outlet temperature (i.e., 950°C) because of lower temperature capabilities in the materials of the heat exchange and transport systems. If this is the case, the planning would be to continue to develop these components with full-temperature capabilities with the expectation that they could be in service no later than ten years after initial operation. To understand the impact of this possibility on the commercialization potential of the technology, brief reviews of the conditions required to support commercial applications were performed. These reviews showed that a majority of the commercial applications could be served with gas outlet temperatures lower than recommended by the contractor teams (e.g., steam production for oil sands recovery or co-generation requires less than 800°C, see Figure ES-2). The impact on the plant performance would be slightly lower efficiency in power production (if a Brayton cycle or combined-cycle PCS were used) and in the hydrogen production process. The latter could still be demonstrated at near full efficiency with the use of supplementary electric heating.

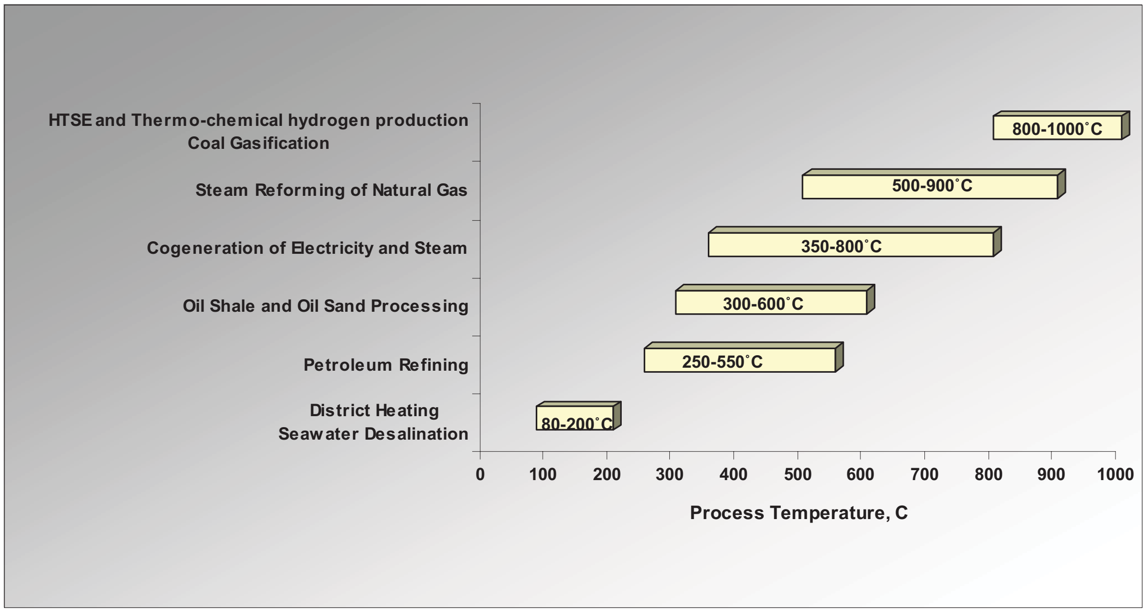

Figure ES-2. Range of temperatures required for HTGR process heat applications

In summary, a "ramp-up" in the operating conditions of the NGNP prototype will likely be necessary and desirable to prove its principles of operation and, even if material limitations require an extended period until full temperature can be realized, this does not appear to compromise the commercialization objective of the prototype.

High Temperature Gas Reactor - Component Test Facility (CTF)

A key short-term NGNP initiative is to design, construct, and startup a test facility (referred to as the CTF) to support development of high-temperature gas thermal-hydraulic technologies (e.g., helium, helium-nitrogen, CO_2) as applied in heat transport and heat transfer applications in HTGRs. Such applications include but are not limited to primary coolant; secondary coolant; direct-cycle power conversion; intermediate, secondary and tertiary heat transfer; and demonstration of processes requiring high temperatures (e.g., hydrogen production). The initial use of this facility will be in support of the completion of the NGNP. However, this test facility will be open for use by the full range of suppliers, end-users, facilitators, government laboratories, and others in the domestic and international community supporting the development and application of HTGR technology.

The facility shall provide for full scale:

- Testing and qualification of high temperature fluid flow systems, components, and equipment (e.g., circulators, intermediate and tertiary heat exchangers, piping, and isolation valves)
- Instrumentation and control development and qualification (e.g., reliability, calibration, response, stability, and transient response)
- V&V of methods/codes to support licensing and future commercial applications (e.g., thermal, hydraulic, transients, etc.)
- Heat transfer component development and fluid testing (e.g., shell & tube and compact heat exchangers, sulfuric acid decomposers)
- Materials performance (e.g., metallics and ceramics)
- Mock-up for high-temperature heat applications testing and research (e.g., prior to installation into the NGNP)
- Testing of fluid inventory and quality control systems
- Development and qualification of control room human factors
- Operations procedure development and qualification training (e.g., for NGNP and for future commercial plants)
- Operational problem/trouble shooting (e.g. for the NGNP prior to hot system repair/modifications and to support future commercial applications)
- High-temperature applications mockup engineering-scale testing and qualifications (e.g., hydrogen production, coal to liquids, steam generators for Alberta Oil Sands application, etc.)
- Maintenance and repair program and process development
- Component replacement program and process development.

As noted above, a study will be initiated in early FY-08 to develop the specific design requirements and operating conditions for the facility. A white paper on the facility is provided in Appendix H.

NGNP Design Requirements

The PCD work has bounded the ranges of operating parameters that are believed to be achievable for the NGNP and initiated the characterization of the technical risks at the extremes of these ranges. This work forms the bases for going forward in the early phase of conceptual design to expand the understanding of the risks and the alternatives to mitigate these risks in the time period left to initiate NGNP operation in 2018. The outcome of the early phase of conceptual design work will establish the F&ORs and fundamental configuration of the NGNP. NGNP Project Engineering evaluations and reconciliations of the PCD work have resulted in selecting a narrow and high-level set of design requirements that will be applied to the design progression in addition to the high-level requirements defined in the EPAct, ITRG study, and other evaluations (see Section 5, Systems Requirements Manual). These requirements are summarized as follows:

1. <u>Nuclear Island</u>

   - Both pebble-bed and prismatic reactor designs should be considered.

     Further work is required to support making the final decision on the reactor design. The PCD work did not identify any discriminating factors that would provide a significant technical advantage of either design.

   - The nuclear island design should not preclude achieving a gas outlet temperature of 950°C.

     This temperature goal affects the design of major components within the reactor that cannot be realistically replaced over the lifetime of the plant (e.g., RPV). This goal would support achieving the ultimate objective of a 950°C gas outlet temperature over the long-term operation of the plant, but allow for a lower temperature configuration for initial operation, recognizing the potential technology limitations associated with the heat exchanger.

   - The NGNP nuclear island will not include a direct-cycle PCS.

     Precluding the use of a direct-cycle PCS provides more flexibility in the operating conditions and configuration of the NGNP and emphasizes the application of the technology as a process heat provider.

2. <u>Intermediate HTS</u>

   The system to transfer heat from the primary (helium gas) side to the secondary side of the plant should incorporate multiple primary and secondary heat transport loops. The system should be configured to facilitate change out of heat exchange, circulating, and valve components. The secondary side of the plant will supply heat to the power conversion and hydrogen production system and other applications as they are identified over the life of the plant.

   This arrangement supports the demonstration of the HTGR as principally a process heat supply. It also provides the greatest degree of flexibility for demonstrating new technologies and components over the life of the plant. For example:

- Plate-fin and printed circuit style compact heat exchangers have potential size, weight, and efficiency advantages over more traditional shell & tube style heat exchangers for application as the IHX for HTGR. The current designs of these compact heat exchangers may not be capable of operating at the full operating temperature and pressure of NGNP, and the development of these designs at the required operating temperatures may not progress sufficiently to support NGNP operation by 2018. As the designs of these heat exchanger styles evolve, they can be demonstrated on a prototype engineering scale in one or more loops of NGNP.

- Steam generation technologies offering improved efficiencies (e.g., through innovative tube arrangements) can be demonstrated as they evolve.

- Alternative secondary heat transport materials (e.g., molten salts, liquid metals) can be tested.

- A Brayton-cycle turbine in either a vertical or horizontal orientation could be adapted to run in a secondary loop.

3. Nuclear Heat Supply System (NHSS)

   The NHSS should be defined to include:

   - The nuclear island and all of its support, control, monitoring, maintenance, refueling, spent fuel storage, etc. SSCs

   - The Intermediate HTS(s) including, at the least, the IHXs, primary circulation systems and the support, control, monitoring, maintenance, etc. SSCs. Depending on the design, it may also include the secondary circulation system up to and including isolation valves.

     This supports the licensing objective (stated below) of ultimately supporting NRC certification of the HTGR NHSS design independent of the application. This will require developing a set of steady state, normal transient, abnormal transient, and accident conditions that bound the potential applications to support safety analyses.

4. Power Conversion System (PCS)

   The PCS should incorporate steam generation. The configuration should not preclude, however, use of Brayton-cycle gas turbine PCSs in a combined-cycle configuration.

   - Steam is an effective medium for heat transfer and is widely applied in the private sector. This requirement facilitates demonstration of the broad applicability of the technology.

     For example, the non-utility generation industry in the United States provides significant quantities of electricity and steam to a wide range of industries and applications. The HTGR power range fits well either as a single module or in multiple modules within the range of power and steam conditions required to meet the needs of these applications. NGNP will be effective in demonstrating the technical, licensability, reliability, maintainability, and economics of the HTGR in these applications

5. Licensing and Permitting

The licensing strategy should be formulated to meet the following objectives:

- The strategy should support the objective scheduled operational date (currently 2018)
- The strategy should consider that full-term qualification data may not be available to support all design assumptions included in the Safety Analysis Reports (SARs) and that additional qualification data to fully support these assumptions will be obtained during the initial two to three years of plant operation and specific inspections and tests to be conducted during this period. For example, the final fuel irradiations and PIE may not be complete by 2018. These will be completed over the 3-year initial operating period. Periodic results from this work can be used to verify assumptions in the final SAR prior to plant operation.
- The strategy should be consistent with and take into account contemporary NRC licensing positions (e.g., during licensing of LWR designs).
- The strategy should consider the potential impact of the significant number of LWRs that may be in the licensing queue on the NRC resources available to support licensing of the NGNP.
- The strategy should include alternative paths with identified criteria and schedule for establishing if and when alternative paths should be executed.
- The ultimate objective of the licensing strategy should be to support application for and receipt of a design certification for the commercial application of the HTGR technology independent of the application.

6. Design Features to Support Short-Term and Long-Term Operating Objectives

The NGNP should be designed to monitor key operating parameters in the NHSS, PCS, and hydrogen production plant required for proving the principles of the designs. The plant should also be designed to permit change out of principal components and to vary operating conditions to perform special testing to collect data/experience to support validation of design assumptions, extension of operating conditions (e.g., to higher gas temperatures), and upgrade of components (e.g., design, capacity, efficiency, maximum temperature and lifetime of the IHXs, and higher heat capacity heat transport fluids, such as liquid metals and molten salts) over the life of the plant.

This is required to support validating design assumptions during initial operation of the plant to increase operating conditions to the objective power levels and gas temperatures, and for meeting a second objective of adapting to evolving and emerging technologies.

7. Initial Operating Conditions

The initial operating conditions and configuration for the NGNP (i.e., at initial operation in 2018) will be based on these requirements and consideration of the impact of the technical development risks on the schedule for operation.

The selection of initial operating conditions and the plant configuration for the NGNP must be balanced against the schedule and cost risks associated with design, licensing, R&D, and construction. This balance must also consider the impact of technology selections on the viability of translating the NGNP experience to the private sector.

Decision Making and Risk Management Processes

The pre-conceptual design work has highlighted the several known technical risks that must be resolved to ensure successful completion of the NGNP Project. Some of the steps planned to resolve these risks have been described. These steps and other design work will require the NGNP Project to make decisions on alternatives for the NGNP (e.g., operating power level, gas temperatures, heat transport configuration, etc.). Additionally, throughout the design process other risks will be identified. To ensure that decisions are made and risks (both known and unknown) are addressed on a consistent and objective basis, formal decision-making and risk management concepts have been developed for the NGNP Project. These are based on systems engineering principles that have been developed and applied for similar purposes in aerospace and other technical design development projects (e.g., the Global Nuclear Energy Partnership initiative).

The initial activities in developing this process were to define criteria and then apply those criteria to establish the current Technology Readiness Levels (TRL) and Design Readiness Levels (DRL) for critical SSCs. This effort was initially completed by the AREVA and Westinghouse teams, and was then refined in a subsequent task by the Westinghouse team in late FY-07. In this latter activity, preliminary roadmaps were developed to define the steps necessary to advance the TRLs and DRLs in selected areas (e.g., reactor fuel and production facility qualification).

The process for using TRLs and DRLs to support the decision-making process and for long-term risk management has been developed conceptually. Work on completing its development and beginning implementation will be initiated in early FY-08. This process will be used to ensure that TRLs and DRLs are achieved for the critical plant SSCs that provide appropriate confidence levels in the success of the project (i.e., meeting cost and schedule objectives) at the completion of each phase of design development.

Conclusion

The preceding has summarized the recommendations of the contractor teams that completed the NGNP PCD work, and has highlighted the principal technical risks to the NGNP Project and planned actions to resolve those risks. Resolution of many of the risks will lead to making final decisions on the operating conditions and configuration of the NGNP. As noted, those decisions will be heavily influenced by the needs and expectations of the private sector, specifically potential end users and owner/operators of commercial plants that will apply the HTGR technology. The needs and expectations will be communicated by close coordination between the NGNP Project and the private sector Alliance.

The pre-conceptual work by the contractor teams and the NGNP Project has identified specific needs for data and development work necessary to advance the design, summarized the work that will be performed to address known technical risks, identified potential preliminary strategies for licensing the plant, estimated costs for completing the project, and performed very preliminary economic assessments for a NOAK plant in a commercial application producing hydrogen and electricity. Each of these areas is discussed in more detail in the main body of this report.

The results of this effort indicate that application of HTGR technology in the private sector is feasible and viable from technical, licensing, cost, schedule, and economic standpoints. The pre-conceptual work has developed an adequate foundation upon which design development work can proceed. This work will proceed with initiation of the conceptual design in FY-08, continuing to pursue the objective of an operational NGNP in 2018, assuming that the necessary support from the DOE and private sector is received to achieve this objective.

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12. APPENDICES

Background and historical information associated with this PCDR is contained in the following appendices:

- Appendix A A Brief Review of High Temperature Gas-Cooled Reactor Technology
- Appendix B EOI for Design Development Engineering Services
- Appendix C Special Studies White Papers
- Appendix D Systems Requirements Manual
- Appendix E Design Data Needs and R&D Requirements
- Appendix F NGNP Schedule
- Appendix G Project Work Breakdown Structure
- Appendix H High Temperature Gas Reactor – Component Test Facility White Paper
- Appendix I Westinghouse Executive Summary Report
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- Appendix K General Atomics Executive Summary Report
- Appendix L Technical Risk Management for the NGNP Project.