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Summary of Bounding Conditions for Development of the NGNP Project

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Next Generation Nuclear Plant Project
Idaho Falls, Idaho 83415

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Next Generation Nuclear Plant Project

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ABSTRACT

This report documents bounding operating, configuration and programmatic conditions 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 bounding conditions derive from the conceptual design work completed for NGNP during FY08 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 functional and operational requirements for NGNP developed by the three contractor teams in the FY07 NGNP Pre-conceptual design work. 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, 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.

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ACRONYMS

AVR	Arbeitsgemeinschaft Versuchsreaktor
CFR	Code of Federal Regulations
COL	construction and operating license
COLA	construction and operating license application
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
SSC	systems, subsystems, and components
THTR	Thorium Hochtemperatur Reaktor
W/PBMR	Westinghouse/Pebble Bed Modular Reactor, LLC

Summary of Bounding Conditions for Development of the NGNP Project

1. PURPOSE

This report documents bounding operating, configuration and programmatic conditions 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 bounding conditions derive from the conceptual design work completed for NGNP during FY08 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 functional and operational requirements (F&ORs) for NGNP developed by the three contractor teams in the FY07 NGNP Pre-conceptual design work. 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 FY07, the three contractor 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. Although some of the requirements specified by each contractor team were specific to the plant design recommended for NGNP, in general the F&ORs provided by each team were similar. The areas specific to the design recommended by each team are easily separated from the larger population of those generically applicable. These are considered to be general enough to continue to be applicable throughout the NGNP Project. Accordingly, a reconciliation of the F&ORs supplied by the three contractor teams in FY07 and judged to be generally applicable to the NGNP Project is provided in Appendix A (NOTE: this Appendix will be provided later). Once the Public-Private Partnership is constituted and the specific requirements for NGNP are developed, these F&ORs will be revised and augmented.

2.2 FY08 Conceptual Design Trade Studies

Several conceptual design trade studies were completed early in FY08 to address critical issues identified in the FY07 pre-conceptual design work. These studies addressed:

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

- 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]
- 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, 24]
- Project risk management [Ref. 20]
- Concepts and preliminary F&ORs for the Component Test Facility [Ref. 21, 22].

These studies were focused on these generic issues since the nuclear system design(s), plant operating conditions, and configuration have not been selected for NGNP. 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 affect the determination of the operating conditions and configuration of the selected design(s) for NGNP is the responses to the DOE RFI/EOI for the 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 conditions cited herein are intended to provide information necessary to support this process.

3. BOUNDING CONDITION CONSIDERATIONS

This report defines bounding conditions within which the operating parameters, specific configuration, and certain “programmatic” approaches for the selected NGNP design(s) are to be developed. These are presented as Bounding Conditions in the several areas addressed in the FY08 conceptual design trade studies. This report also provides the bases for these conditions. The following subsections discuss the specific objectives and approaches 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 FY08 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 in FY08 addressed other issues affecting the design selections and programs for NGNP. These included licensing risk reduction, specific prismatic fuel design and setting requirements and developing concepts for a Component Test Facility. The reports for these studies are, also listed in Section 6.

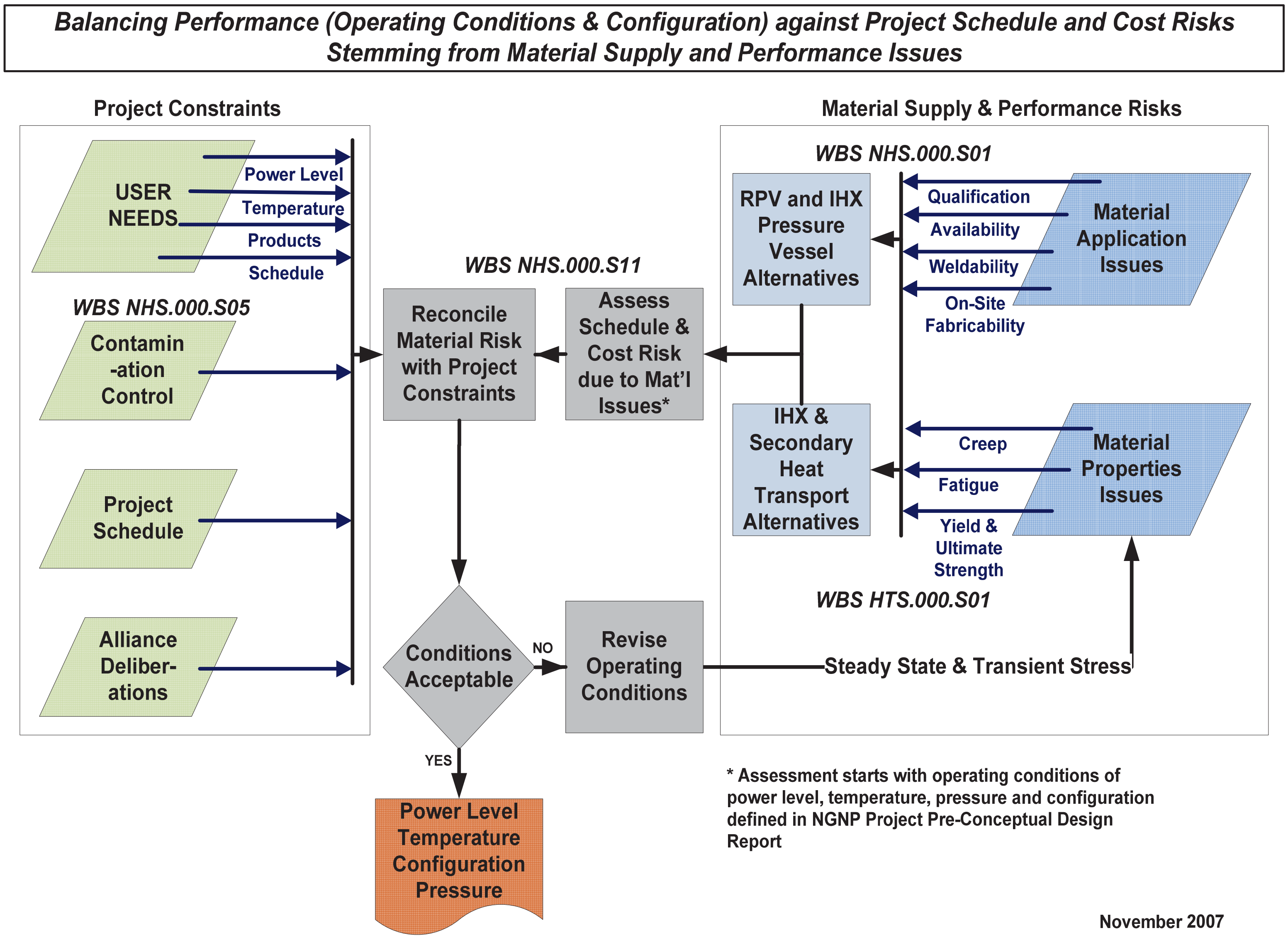

Figure 1. Conceptual Design Technical Selection Studies Integration

4. SUMMARY OF RECOMMENDATIONS AND BASES

The following section of the report summarizes the bounding conditions and their bases for the NGNP Demonstration Plant. Subsequent sections of the report provide the detailed bases for selection of the bounding conditions (NOTE: The subsequent sections will be provided later).

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:

At this time, 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. 23]. 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 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.

[b] "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.

- The peak fuel temperature does not exceed 1600°C under accident conditions.

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. 23]:

- 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 FY07 and FY08 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:

- 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)

- 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.

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. 23]. 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 FY07 pre-conceptual design work and in FY08 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 contractors in FY08, 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].

Additionally, 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, for example, 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. These processes will be demonstrated at the higher temperatures and at engineering scale in the Component Test Facility (CTF) prior to installation in NGNP. Once installed in NGNP and if the temperature restrictions are still in place, these processes can be demonstrated at lower efficiency or at the design 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 above) and material choices, particularly the RPV.

Summary of Bases:

The pre-conceptual designs provided by the reactor vendors in FY07 have inlet temperatures in the range 350°C to 500°C [Ref. 23]. 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. Note that this is based on preliminary analyses and further evaluation is required to verify this result [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. The impact of operating temperature on RPV material selection is explored in more depth below.

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. 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 FY07 and FY08 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. FY08 studies by the W/PBMR and GA contractor 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 as long as normal and off-normal fuel temperatures remain within acceptable levels. 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 – 006, below. Tritium generation and transport studies were performed in FY07 in a joint effort between the Idaho National Laboratory (INL) and the Japan Atomic Energy Agency [Ref. 24]. 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 contractor 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. Additional work is also required with the potential end users to develop tritium activity limits for products that will be using the HTGR technology.

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, 24] 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. The use of ceramic materials for the heat exchange surfaces would also provide an effective barrier. This is highly developmental at this time and is not judged to be feasible for the initial applications of the HTGR technology.

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 exposure of the workers and 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 contractor 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.

4.6 Primary System Pressure Vessels

4.6.1 Bounding Condition – 008

The nuclear heat supply system, which includes the heat transfer/transport system, shall be designed to minimize schedule risk for the primary pressure vessels at full design power level and inlet and outlet temperatures. In this regard, the design of the primary pressure vessels, including the RPV, shall incorporate standard LWR RPV material (e.g., SA 508/533). If required, use of active cooling or other measures shall be identified and the design developed as necessary to meet this requirement.

A parallel effort shall be continued by the NGNP Project in collaboration with the appropriate reactor vendors to develop the modified 9Cr (Grade 91) material as a viable alternative to the SA 508/533 material. This issue applies to the AREVA and GA prismatic designs, which are currently configured with higher reactor inlet temperatures than the W/PBMR design, and Grade 91 as the originally recommended material for the primary system pressure vessels.

Summary of Bases:

AREVA and GA performed assessments of the risks to schedule and costs attendant to the use of modified Grade 91 material for the primary pressure vessels [Ref. 8, 9]. The conclusions from these assessments were that the risk to schedule was high because of the lack of availability and codification of the Grade 91 material for this application.

Alternative operating condition changes and design modifications were identified by GA and AREVA that would permit use of the common LWR RPV material – SA 508 in lieu of the Grade 91 material. These included reducing reactor inlet temperature (which would also require reducing outlet temperature for the same power level), re-directing the inlet flow through channels that provide an insulating barrier to the pressure vessel from the coolant, and adding an active vessel cooling system [Ref. 8, 9, 10, 11].

The SA 508/533 material is widely used in LWRs, and the risks associated with its use for the RPV are judged to be less than for the Grade 91 material. However, it has an upper bound on its permissible long-term operating temperature that is lower than it would be exposed to in other than the W/PBMR design. Accordingly, either active cooling systems or other means (e.g., insulation or thermal barriers) will have to be included in the prismatic designs to permit its use at the higher inlet temperature. This is judged, however, to be a less risky path than relying on a single path based on the availability of Grade 91 material. Additional work is required to verify the feasibility and reliability of the configurations and systems proposed by GA and AREVA for this purpose [Ref. 10, 11].

Because the Grade 91 material has a much higher permissible sustained operating temperature than SA 508/533, the parallel approach to continue development and codification of this material is recommended. The higher permissible operating temperature provides more margin and flexibility in setting the core inlet temperatures and would eliminate the need for developing and implementing a means to limit the RPV temperature for higher inlet temperatures if SA508/533 material is used. It is intended that parallel design efforts be maintained so that if sufficient confidence in the availability of Grade 91 material is developed before the fabrication of the RPV that the Grade 91 design could be applied.

4.7 Intermediate Heat Exchanger Design

4.7.1 General

The IHX designs and operating conditions shall be the result of analyses that balance the style of the heat exchangers (e.g., shell & tube, compact), number of heat exchangers, complexity of the primary and secondary loops, size, and overall cost with the functional requirements of heat transfer, overall heat transfer and transport efficiency, and the availability of components (e.g., heat exchanger, circulators, valves, if required) in a time frame to support the NGNP deployment schedule. The heat exchange system may include multiple heat exchanger designs to satisfy different functional requirements (e.g., supplying the hydrogen plant, supplying the PCS). Testing in the CTF will be a key factor in the development of the heat transfer/transport system.

The three contractor teams have proposed different design concepts and configurations for NGNP [Ref. 9, 10, 11, 12, 13]. They have also prepared assessments of the risks to Project cost and schedule depending on the operating conditions selected for NGNP and the configuration of the heat transfer/transport system [Ref. 7, 8, 9]. Each of the recommended systems has advantages and varying risks. Once the selection is made on the nuclear system, operating conditions, and configuration of NGNP, the heat transfer/transport system configuration can be finalized. Until that selection is made, design work shall be continued to address the high-risk areas for this system. The following provide bounding conditions within which this work shall be conducted.

4.7.2 Bounding Condition – 009

Multiple heat exchanger designs shall continue to be pursued, including one and two stage shell and tube, printed circuit, plate fin and welded plate designs in varying combinations.

Summary of Bases:

Pursuing several heat exchanger designs that could be used for NGNP mitigates the risk associated with availability of the more developmental designs for installation on the objective schedule for initial operation of the plant. Different design may be better suited depending on the functional requirement of the heat transfer system (e.g., supplying the hydrogen plant, supplying the PCS). These designs will be pursued with the vendors and through continued support of the heat exchanger development activity of the Nuclear Hydrogen Initiative.

4.7.3 Bounding Condition – 010

Materials being evaluated for the NGNP heat transfer/transport system shall be capable of sustained operation (i.e., 10 effective full-power years of operation or longer) at the upper bounds of the reactor gas outlet and inlet temperatures. R&D shall be conducted to support development and codification of these materials for use in NGNP and future HTGR commercial applications.

Summary of Bases:

The NGNP is to be designed to not preclude operating at the upper design temperatures of the nuclear system (e.g., 900°C to 950°C). There are currently no ASME Section III materials qualified for sustained operation at these temperatures. The three contractor teams have focused on IN-617 for the high-temperature regions and 800H for the lower-temperature regions. The NGNP R&D program is also characterizing the high-temperatures properties of Haynes 230.

Based on information to date, these appear to have the best potential for availability for application in the high-temperature and low-temperature regions within the objective schedule. Work has been and is continuing to be performed to characterize the properties (e.g., creep and creep fatigue) of these materials as well as others in the high-temperature regions. Methods are also being developed for use of these materials in fabricating shell and tube, printed circuit board, and plate-fin and welded plate heat exchanger designs (e.g., within the NGNG Project R&D High Temperature Materials program and in ASME Standards Technology, LLC tasks) [Ref. 10, 11, 12, 25, 26]. These programs shall be continued. Once the selection of the nuclear system and operating conditions is made for NGNP, the required material properties will be established and appropriate materials applied.

Additional work is required to characterize the permeability of these materials (particularly IN-617) to tritium over the expected operating temperature range and to develop coatings for these materials that will reduce its permeability. Additional work is also required to develop ceramic materials for the high-temperature regions of the heat exchange equipment.

4.7.4 Bounding Condition – 011

At least two primary loops shall be provided: a full power loop(s) for the PCS and a smaller loop (e.g., up to 60 Mwt) for the hydrogen plant.

Summary of Bases:

A secondary primary loop supplying the hydrogen process provides required flexibility in operations and in accommodating the variations in schedule and configuration anticipated for supplying the several candidate hydrogen processes that may be demonstrated in NGNP (e.g., HTE, sulfur-iodine and hybrid sulfur processes). These processes will not be operated all of the time and will be installed sequentially as their technical and design readiness has progressed sufficiently (e.g., after engineering-scale testing in the CTF). A parallel arrangement for supplying the hydrogen process independent of the PCS will simplify the design and operation of both of these processes. Although this arrangement adds complexity to the primary system design and operation, it provides flexibility in adapting to different heat exchanger designs, alternative secondary fluids (e.g., CO_2 ,molten salts), and different processes over the longer-term operation of the plant (e.g., direct Brayton and CO_2 turbines, heat transport equipment).

4.8 Helium Circulators

4.8.1 Bounding Condition – 012

The ability to operate multiple circulators in parallel shall be evaluated and tested as an alternative to installation of a single high-power design that requires significant development. Development of high-power designs that are required for application in the secondary loop shall be continued.

Summary of Bases:

The largest helium circulators currently in use in the gas reactor industry are in the 5 MWe to 6 MWe range. This is in the range of circulator power required for the primary loop. The circulator in the power conversion secondary loop will be significantly larger than in the primary loop because the pressure differential across the secondary side of the IHX is higher than across the core. It is estimated that the power requirement for a single circulator in the secondary loop would be in the range of ~16 MWe [Ref. 12]. Development of this size circulator for use in the initial operation of NGNP is expected to be a high-risk element of the Project. Accordingly, the alternative of using two standard size circulators in parallel is to be pursued along with development of the larger circulator design.

Another alternative would be to use multiple loops to supply the PCS and restrict the size of each loop to be consistent with the standard size circulator. This does not provide sufficient flexibility in the design and configuration of the secondary loop and could add to the complexity and cost of the heat transfer/transport system. It is preferable to install multiple circulators in parallel, at least at initial plant operation, if a single circulator of required size is not available. The ability to successfully operate and control the circulators in parallel will be demonstrated in the CTF prior to installation in NGNP.

4.9 Power Conversion System

4.9.1 Bounding Condition – 013

The NGNP PCS shall be an indirect sub-critical Rankine cycle (i.e., the steam generator shall be installed in the secondary loop supplying a standard steam turbine generator) with a rating equivalent to the nuclear system power rating. The steam conditions and configuration of the cycle shall be selected to result in a net generation efficiency of at least 42%; balancing cost with efficiency and reliability.

Summary of Bases:

The AREVA and W/PBMR recommended plant configurations use an indirect sub-critical Rankine cycle PCS [Ref. 2, 3]. GA originally proposed a direct Brayton cycle, but has provided evaluations of the Rankine cycle configuration for NGNP [Ref. 4]. All three designs take advantage of highly developed steam turbine generator designs in power utility services and steam generator designs with low developmental risk.

The initial PCS should be non-developmental to facilitate completion of the NGNP within the objective schedule and to promote industry standard reliability for electric power production. It is anticipated that electric power will be the first demonstration of the NGNP for sale to a power utility company. It is also one of the components of co-generation plants, which are judged to be among the first applications of the HTGR technology in commercial applications [Ref. 15].

An objective of longer-term operation of the plant should be to support demonstration of more developmental cycles (e.g., supercritical steam and CO_2) that have the potential for significantly higher overall plant efficiency.

4.10 Hydrogen Plant

4.10.1 Bounding Condition – 014

The interface for the hydrogen plant shall be via a separate parallel primary loop with an IHX designed to accommodate the process with the highest production module energy requirement (expected to be in the 60 Mwt range). This loop shall be designed to operate at temperatures up to 950°C at power levels from 5 Mwt to 60 MWt.

Summary of Bases:

The thermal energy requirements of the three candidate hydrogen production processes cover a wide range [Ref. 2, 3, 4]:

- HTE – 5 Mwt
- Hybrid Sulfur – 50 Mwt
- Sulfur – Iodine – 60 Mwt.

The heat transfer/ transport system supplying these processes must be capable of a turndown ratio of 10:1 to accommodate these variations.

The HTE process is judged by the NGNP Project as the most likely to be available for installation in a production scale at the initial operating date of NGNP [Ref. 23]. This will follow testing at the engineering-scale in the CTF to provide confidence of successful performance in NGNP. As noted, a production module for the HTE process will require a modest heat load and electricity provided by the PCS.

The interface between NGNP and the hydrogen process must be designed to accommodate the thermo-chemical processes as they become available for demonstration at the production module level.

These processes require significantly more thermal energy than HTE and electricity from the PCS. These will also have been tested at the engineering-scale in the CTF.

As noted above, additional work is required to establish tritium activity limits in the hydrogen and to develop methods to control tritium transfer from the primary loop to the hydrogen production process. The material and potential material coatings will be explored to limit the permeability of the tritium through the heat exchanger.

4.11 Containment

4.11.1 Bounding Condition – 015

NGNP shall include reactor and reactor building containment features that, in combination with the other mechanisms for radionuclide containment (e.g., fission product retention capabilities of the fuel) and transport, (e.g., entrainment, plateout), result in calculated dose rates at the EAB that meet the criteria established above (see Public and Worker Exposure Limits) for normal operation, abnormal conditions, and accident conditions.

Summary of Bases:

Vented low-pressure filtered containment designs were proposed in the pre-conceptual design work in FY07 [Ref. 2, 3, 4]. The structural and functional characteristics of these designs are considerably different from those of the containments of LWRs because of several factors:

- There is little energy stored in the helium coolant because of its low heat capacity when compared with that of water (e.g., there is no significant steam release in an HTGR LOCA).
- The vent (pressure relief) systems will activate only on very rapid de-pressurization of the primary coolant system (e.g., very large LOCA).
- On large and low leakage events, the natural removal mechanisms, including radioactive decay, condensation, fallout, and plateout, reduce the concentration of radionuclides released in the early part of the transient, thus reducing the offsite releases.
- The time periods for reaching peak temperature conditions in the core during loss of flow or coolant accidents are in hours and days rather than seconds.
- Venting of the pressure early in the transient reduces the driving force for subsequent release of radionuclides later in the transient as the fuel temperatures are raised to peak values.
- The vents are closed after the pressure is reduced to contain radionuclides that may diffuse out of the fuel during the time at high-temperature conditions.
- There are no combustible gases in the HTGR LOCA so gas deflagration is not a concern. Oxidation of dust has been raised in Phenomena/Process Identification and Ranking Table reviews as a potential concern. This is currently being evaluated.
- The quantity of radionuclides postulated to be released in an HTGR LOCA is significantly lower than for an LWR because the core fuel and graphite are the primary and effective barriers to release in the HTGR design as long as the fuel temperatures remain within limits.

Accordingly, the pressures reached in HTGR LOCAs are low (a few psi after venting) compared with LWRs (60 psi), so the containment structure does not have to be as massive. Additionally, the containment does not have to be as leak tight because the inventory of radionuclides following the depressurized loss of flow accident is small. Further analyses are required to determine if filtration on the vent system will be needed to meet the objective exposure limits at the EAB for these postulated accident conditions.

Tasks will be completed in the latter part of FY08 by the reactor vendors to establish the F&ORs and configurations for the NGNP containment. These tasks will consider all potential accident conditions in which the containment and vent, and possibly filter, systems will be required. These tasks will also include similar evaluations of the reactor building requirements as they pertain to design basis threats, external events, and environmental factors. These need to be considered when establishing the containment requirements to ensure the containment and reactor building functions are integrated.

The pre-conceptual design work identified a potential risk that the NRC may require a LWR containment design for NGNP in the licensing process [Ref. 2, 18]. It should be an objective in the development of the containment requirements for NGNP that sufficient bases are developed to address this issue during licensing.

4.12 Licensing

4.12.1 Bounding Condition – 016

The NGNP licensing strategy shall be developed and implemented based on the one-step licensing process of 10 CFR 52. A combined construction and operating license (COL) shall be obtained for NGNP, and a subsequent certification of the nuclear heat supply system design shall be obtained to support subsequent construction and operating license applications (COLAs) using this design in commercial applications.

Summary of Bases:

The conclusion of the FY07 pre-conceptual design work was that a 10 CFR 50 process in which separate COLs were obtained should be pursued for NGNP [Ref. 23]. This conclusion was based on analysis conclusions that this approach minimized the schedule risk to the project. In FY08, additional work was performed by the W/PBMR team on licensing risk that showed use of the 10 CFR 52 could be applied without undue schedule risk. A joint meeting of the vendors, potential owner/operators, DOE, and INL Project personnel reached a consensus that the 10 CFR 52 one-step licensing approach should be applied for NGNP [Ref. 18]. Subsequently, tasks will be performed in the latter part of FY08 to develop a licensing specification for NGNP. This specification will include:

- A detailed strategy for completing this process, including initiating early pre-application discussions with the NRC
- Identification and characterization of the documents and analyses (e.g., topical reports, safety analyses, Environmental Report, Probabilistic Risk Analysis) that will need to be developed to support the pre-application reviews and the applications for the COL and design certification
- A schedule for document development, submittal of applications, support of the NRC reviews through issue of the COL, and resolution of open items during construction, startup testing, and plant operation

- An update of the cost estimate for the process
- Early Site Permit and Limited Work Authorization.

4.13 Risk Management

4.13.1 Bounding Condition – 017

A formal program for managing technical and programmatic risks to completing the project on schedule and within budget shall be developed and managed throughout the project.

Summary of Bases:

A risk management program is a necessary component of effective project management. The development and management of the technical risk management program was initiated in FY07 and is a continuing process that is currently being conducted by the INL Systems Engineering department under the direction of NGNP Project Engineering [Ref. 20]. This program has the following elements:

- Identifying known and evolving risk elements
- Continually assessing the technical and design readiness of systems, subsystem, and components (SSCs) or programs that address the risk elements
- Formulating technology (or programmatic) development roadmaps to advance the readiness of the SSCs or programs
- Monitoring progress in the advancement of SSC and program readiness,
- Defining a risk state for the project by consolidating the risk states of the elements contributing to risk
- Establishing an appropriate contingency factor on cost- and schedule-to-complete based on the overall project risk and state of project development.

This program will need to be continued throughout the project and, if necessary, will be transferred to the project management element of the Public-Private Partnership for NGNP when it is formed. This technical risk management program will need to be combined with other programs for managing overall Project risk, including, for example, requirements management, tracking of cost and schedule variance, using EVMS, and resource allocation.

4.14 Component Test Facility

4.14.1 Bounding Condition – 018

A CTF shall be provided as part of the infrastructure supporting HTGR technologies. The facility shall be capable of completing proof-of-performance testing of major HTGR and NGNP components at engineering or full scale.

Summary of Bases:

The CTF or equivalent has been an element of the NGNP Project since its initial inception in early 2000s. It was conceived to support confirmation of the performance of the hydrogen production system prior to installation in NGNP (e.g., "testing [will be conducted] at the engineering scale using an alternate source of high-temperature process heat before coupling the hydrogen facility to the nuclear heat source") [Ref. 27]. In FY07, *NGNP Engineering White Paper: High Temperature Gas Reactor – Component Test Facility* [Ref. 28] provided more detailed definition of the requirements and justification for the facility for use in confirming the performance of other critical components prior to installation in NGNP (e.g., heat exchangers, circulators, valves). Tasks performed in FY08 have further defined the F&ORs for the facility and provided preliminary concepts for the components and layout of the facility [Ref. 21, 22]. Cost estimates and schedules have also been prepared indicating that the facility can be ready for operation to support component testing in FY14.

The CTF is needed to address the majority of Design Data Needs for completion of the NGNP Project that were defined in the FY07 pre-conceptual design work and in the conceptual design trade studies performed in FY08. Many of these identify the highly developmental nature of critical components of NGNP [Ref. 22]. These include, for example:

- Heat exchangers, particularly the compact printed circuit, plate fin, and welded plate designs that have been proposed to reduce the plant footprint and volume and improve net efficiency.
- Large circulator designs. A single circulator for the secondary loop will be significantly larger than any circulator currently in service.
- Valves, if needed for isolation under accident conditions, will need significant development and testing.
- Instrumentation for measuring plant parameters at operating temperatures in the 900 °C to 950 °C range.
- Control of multiple circulators in parallel.

A large-scale facility is also needed to address specific design features of the plant, such as streaming effects in the outlet plenum, operation of the concentric inlet and outlet piping, and operation of the control rods in the dust environment. Evaluations of existing or planned facilities elsewhere in the world that could meet these needs concluded that no such facility existed or is planned [Ref. 21, 22, 28].

Tasks will be completed in FY08 and FY09 to develop the conceptual design for the CTF. An Engineering, Procurement, and Construction contract will be issued for preliminary design, final design, and construction. The facility is currently expected to be ready for operation in FY14. This schedule will be validated during the design process and is required to support initial operation of NGNP in 2021.

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