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

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Next Generation Nuclear Plant Project

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ABSTRACT

This report documents bounding functional and operating requirements (F&ORs) for the Next Generation Nuclear Plant (NGNP) Project to support selection of the nuclear system design and specification of the operating conditions and configuration of NGNP once the nuclear system design is selected. These requirements supplement the detailed F&ORs for NGNP developed in the FY07 NGNP pre-conceptual design work.

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ACRONYMS

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

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

1. PURPOSE

This report documents bounding functional and operating requirements (F&ORs) for the Next Generation Nuclear Plant (NGNP) Project to support selection of the nuclear system design and specification of the operating conditions and configuration of NGNP once the nuclear system design is selected. These requirements supplement the detailed F&ORs for NGNP developed in the FY07 NGNP pre-conceptual design work.

2. BACKGROUND

2.1 NGNP Functional & Operational Requirements

As part of the pre-conceptual design work in FY07, the three reactor vendor teams provided detailed design F&ORs for the plant designs proposed for NGNP [Ref. 2, 3, 4, 5]. These are comprehensive, generically addressing general requirements for the NGNP Project and the demonstration plant, and for each of the plant facilities, consistent with the work breakdown structure provided by the Project [Ref. 6]. The plant facilities include the nuclear system, heat transport and transfer system, power conversion system (PCS), hydrogen plant, balance of plant, and the overall site and infrastructure supporting NGNP. The F&ORs provided by each team were similar for all three recommended designs. The areas specific to the design recommended by each team are easily separated from the larger population of those generically applicable. These F&ORs continue to be generally applicable to the NGNP Project.

Also, as part of the pre-conceptual design work in FY07, the three reactor vendor teams provided detailed Systems Requirements Manuals for the plant designs proposed for NGNP [Ref. 2, 3, 4]. The Systems Requirements Manual defines the requirements hierarchy for the NGNP Plant with Hydrogen Production and Electricity Production and includes initial requirements based on the current maturity state of the NGNP project. The three vendors' System Requirements Manuals have been summarized in the *NGNP System Requirements Manual* [Ref. 26]. This manual is included as Appendix A to this document.

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:

- 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 (CTF) [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.

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

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

The responses to this RFI/EOI 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.

3. OBJECTIVE OF THIS REPORT

This report defines bounding conditions within which the F&ORs for the selected NGNP design(s) are developed. These are presented as Bounding Conditions in the several areas addressed in the FY08 conceptual design trade studies. This document also provides the bases for these conditions. The following subsections discuss the specific objectives in defining these bounding conditions.

3.1 Operating Conditions

Three principal factors were considered in selecting the bounding operating conditions for NGNP:

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 the end users and through prior reactor vendor 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 availability and performance of materials for the RPVand other primary pressure vessels, and the IHX. 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 reactor vendor 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.

In summary, 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.

3.2 Design Selections and Programmatic Issues

Additional work performed early in FY08 addressed other issues affecting the design selections and programs for NGNP. These included licensing risk reduction, specific prismatic fuel design [Ref. 25] and setting requirements and developing concepts for a CTF. The reports for these studies are, also listed in the References section.

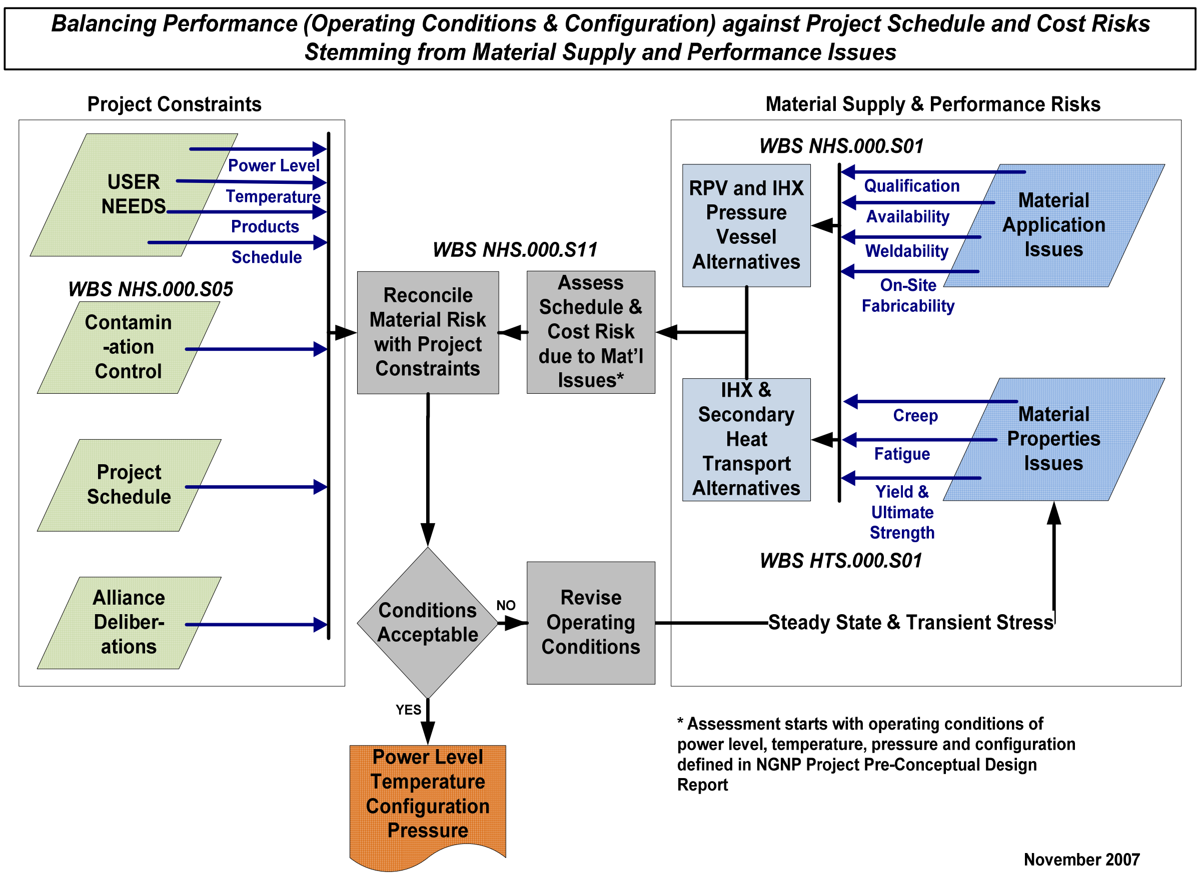

Figure 1. Conceptual Design Technical Selection Studies Integration

4. SUMMARY OF RECOMMENDATIONS AND BASES

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

4.1 Reactor Type

4.1.1 Bounding Condition – 001

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

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

Summary of Basis:

There are no discriminating technical factors among the designs that suggest one has an advantage either in the NGNP demonstration plant or in commercial applications [Ref. 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 preferred reactor design can be identified for the demonstration plant. The responses to the DOE RFI/EOI [Ref. 1] and the strategy developed by the DOE for the NGNP Project based on these responses is expected to have a significant influence on the selection of the reactor type for NGNP.

4.2 Reactor Design Power Level

4.2.1 Bounding Condition – 002

The NGNP shall be capable of operation at power levels up to 600 Mwt, depending on the core design, and core power densities that will demonstrate the technical and economic feasibility of commercial HTGRs with a passive safety basis such that maximum fuel temperatures under normal and abnormal (design basis and beyond design basis) conditions are acceptable. Specifically, the reactor shall be designed for the maximum power level achievable for the core (pebble and prismatic) that ensures the following:

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

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 reactor vendor 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 reactor 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 reactor vendors that the private sector will prefer the largest power module because of this cost factor.
- 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.

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.

4.2.2 Bounding Condition – 003

The characteristics of the nuclear system with a lower power rating (e.g., one half the maximum power design) shall be developed 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.

Summary of Bases:

Other results of the evaluations of potential commercial applications (e.g., additional to those cited above that indicate the maximum achievable power is preferred) 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 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.

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 reactor 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 – 004

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

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

The reactor vendors have proposed reactor gas outlet design temperatures in the range of 900°C to 950°C, depending on the reactor design [Ref. 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 reactor vendors 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].

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

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

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

4.4 Reactor Gas Inlet Temperature

4.4.1 Bounding Condition – 005

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

Summary of Bases:

The pre-conceptual designs provided by the reactor vendors in 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. [Ref. 11].
- Either modified 9Cr material or an active vessel cooling system would be required for inlet temperatures above 490°C if SA 508 material is used [Ref. 10, 11].

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

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

4.5 Contamination Control

4.5.1 Bounding Condition – 006

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

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

- The occupational dose to individual adults shall be limited on an annual basis to 10% of the 10 CFR 20 limits.
- Tritium 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 vendor teams applied similar requirements. From these, W/PBMR and GA established preliminary fuel specifications and plant shielding requirements that result in acceptable radionuclide release rates and exposure levels that meet the specified limits [Ref. 16, 17].

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

The W/PBMR and GA reports identified potential approaches for meeting the tritium concentration limits. These are summarized under Bounding Condition – 007, below. Tritium generation and transport studies were performed in 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 reactor vendor teams to support the conclusions are preliminary and in some cases (e.g., the GA calculations) were performed with codes that need to be updated and validated. Work is required to develop, verify, and validate codes covering the following:

- Generation, depletion, and release from the fuel of radionuclides, including tritium
- Transport and plate out of radionuclides
- Tritium transport, sorption in graphite, and permeation through heat exchanger tubes and plates
- Cleanup system effectiveness.

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

4.5.2 Bounding Condition – 007

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. However, they also concluded that the reductions in permeation rates that would be expected would not be sufficient to limit the concentrations to meet the activity levels specified. Each report identified several methods that need to be explored for application to NGNP to meet these limits. The principal methods included:

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

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

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

4.5.3 Bounding Condition – 008

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

Summary of Bases:

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

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

Reaktor (THTR). These systems are judged by W/PBMR to be effective in obtaining acceptable equipment performance and component lifetimes in the primary loop.

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

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

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Appendix A

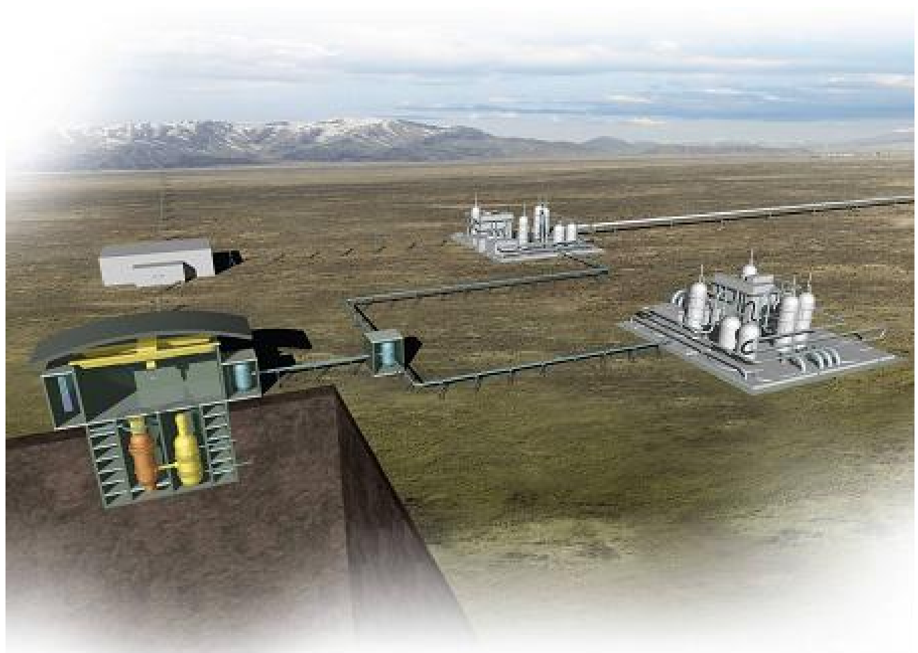
Next Generation Nuclear Plant System Requirements Manual

INL/EXT-07-12999, Rev. 1

INL/EXT-07-12999
Revision 1

Next Generation Nuclear Plant
System Requirements Manual

June 2008



Idaho National Laboratory

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Revision 1

Next Generation Nuclear Plant System Requirements Manual

June 2008

Idaho National Laboratory
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Idaho Falls, Idaho 83415

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Next Generation Nuclear Plant Project

Next Generation Nuclear Plant System Requirements Manual

INL/EXT-07-12999
Revision 1

June 2008

Approved by:

______________________________ ______________________________
Richard Garrett Date
NGNP Engineering Director

______________________________ ______________________________
Greg Gibbs Date
NGNP Project Director

CONTENTS

FIGURES

ACRONYMS

ALARA	as low as reasonably achievable
AOO	Anticipated Operation Occurances
ASME	American Society of Mechanical Engineers
B&PV	boiler and pressure vessel
BOP	Balance of Plant
CFR	Code of Federal Regulations
DBA	design basis accident
DC	direct current
DOE	U.S. Department of Energy
DPP	Demonstration Pilot Plant
EPA	Environmental Protection Agency
EPAct	Energy Policy Act
F&OR	Functional and Operational Requirements
FERC	Federal Energy Regulatory Commission
FHS	Fuel Handling System
FIMA	fissions per initial metal ion
GT-MHR	Gas Turbine-Modular Helium Reactor
HDA	Hot Duct Assembly
HPB	Helium Pressure Boundary
HTGR	High Temperature Gas-cooled Reactor
HTS	Heat Transport System
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
ISI	In-Service Inspection
LEU	low enriched uranium
MHC	Main Helium Circulator
MHTGR	Modular High Temperature Gas Reactor
MPa	mega-pascals
NGNP	Next Generation Nuclear Plant
NHI	Nuclear Hydrogen Initiative
NQA	Nuclear Quality Assurance
NRC	Nuclear Regulatory Commission
PAG	protective action guide

PASSC	Plant, Area, Systems, Subsystem (or Structures), and/or Components
PBMR	Pebble Bed Modular Reactor
PCS	Power Conversion System
PGA	peak ground acceleration
PHTS	Primary Heat Transport System
R&D	research and development
RCCS	Reactor Cavity Cooling System
SCS	Shutdown Cooling System
SFSS	spent fuel storage system
SMA	seismic margin assessment
SME	seismic margin earthquake
SRM	System Requirements Manual
SSE	safe shutdown earthquake
TRISO	TRi-ISOtropic coated fuel particle design with three materials in coating system (low-density PyC, high-density PyC, and SiC)
UPS	uninterruptible power supply

Next Generation Nuclear Plant System Requirements Manual

1. INTRODUCTION AND SCOPE

1.1 Introduction

The Energy Policy Act of 2005 (H.R. 6; EPAct), which was signed into law by President George W. Bush in August 2005, required the Secretary of the U.S. Department of Energy (DOE) to establish a project to be known as the Next Generation Nuclear Plant (NGNP) Project. According to the EPAct, the NGNP Project shall consist of the research, development, design, construction, and operation of a prototype plant (to be referred to herein as the NGNP) that (1) includes a nuclear reactor based on the research and development (R&D) activities supported by the Generation IV Nuclear Energy Systems initiative, and (2) shall be used to generate electricity, to produce hydrogen, or to both generate electricity and produce hydrogen. The NGNP Project supports both the national need to develop safe, clean, economical nuclear energy and the Nuclear Hydrogen Initiative (NHI), which has the goal of establishing greenhouse-gas-free technologies for the production of hydrogen. The DOE has selected the helium-cooled High Temperature Gas-Cooled Reactor (HTGR) as the reactor concept to be used for the NGNP because it is the only near-term Generation IV concept that has the capability to provide process heat at high-enough temperatures for highly efficient production of hydrogen. The EPAct also names the Idaho National Laboratory (INL), the DOE's lead national laboratory for nuclear energy research, as the site for the prototype NGNP.

1.2 Scope of the SRM

This System Requirements Manual (SRM) defines the requirements hierarchy for the NGNP Plant with Hydrogen Production and Electricity Production and includes initial requirements based on the current maturity state of the NGNP Project.

This document was prepared at the early stages of conceptual design and is to be used as a means to identify and document top-level requirements that apply to various aspects of the NGNP. The requirements hierarchy is structured in a way that allows for further enhancement and the derivation of additional requirements without changing the original structure as the project is further defined. The management of these and future requirements throughout the project lifecycle will be the subject of a separate document, "The *NGNP Requirements Management Plan*," scheduled for completion during FY 2009. It is intended that this SRM will lead to the development of documents that make up the *NGNP Requirements Management Plan*.

The requirements in this SRM are intended to be a starting point for the NGNP Project and represent only those requirements initially identified in the NGNP Pre-Conceptual Design Report. With that in mind, it should noted that these requirements are not complete and account for only those requirements collected and assessed thus far.[a] As the conceptual design phase of this project progresses, a structured and rigorous approach to systems engineering will be applied as part of the NGNP Requirements Management program. NGNP requirements will be managed in a relational database.

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[a] Items appearing in brackets ([ ]) represent approximations and/or undefined values.

2. REQUIREMENTS HIERARCHY

2.1 Overall Requirements Hierarchy

As noted, the *NGNP Requirements Management Plan* is in development and scheduled for issue in FY 2009. Figure 1 illustrates the hierarchy of current requirements documents that comprise the *NGNP Requirements Management Plan* for the NGNP Project.

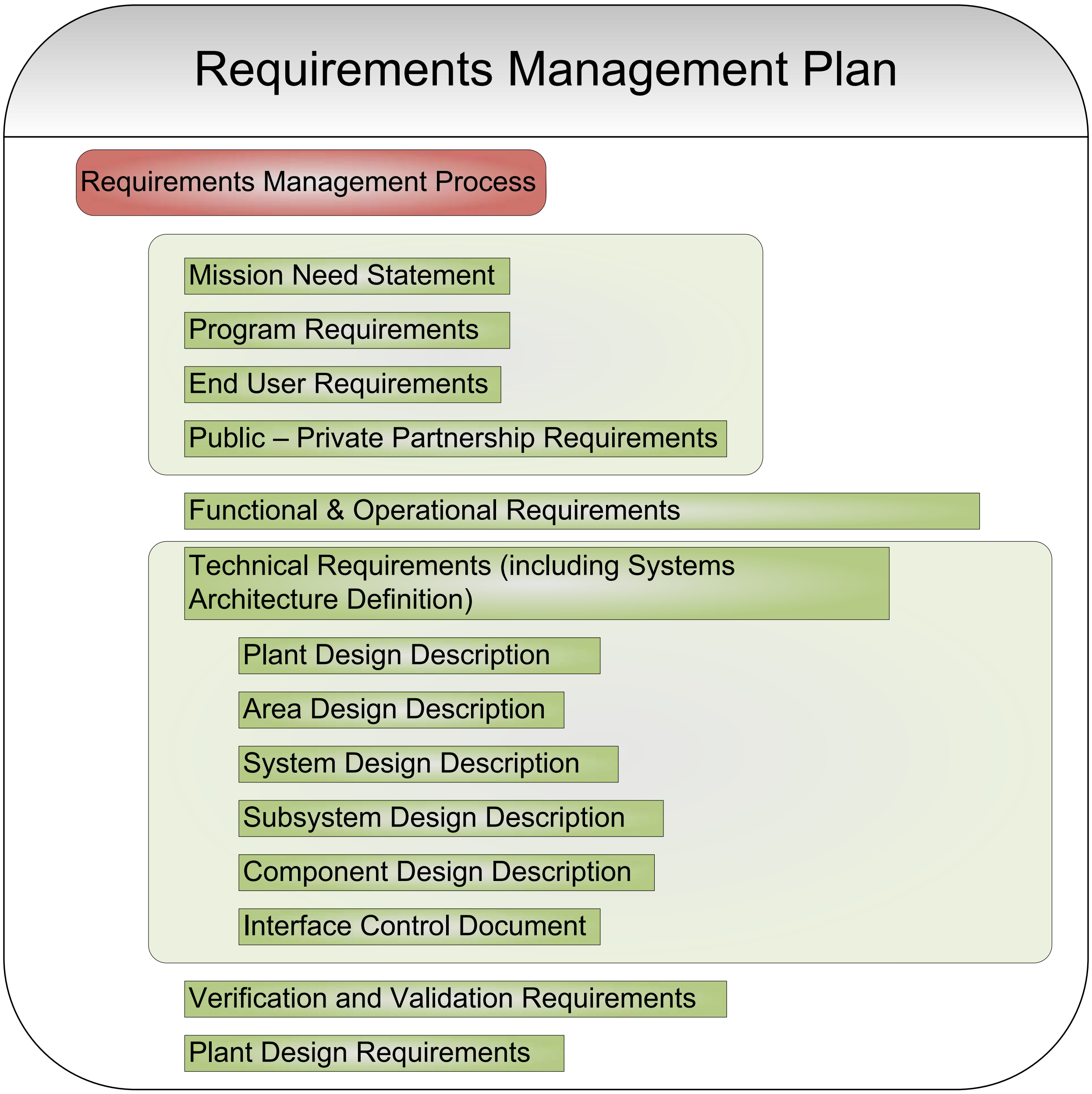

Figure 1. Requirements Management Plan Document Hierarchy

At the top level, requirements are derived from the Public/Private Partnership, Program Requirements (e.g., 2005 EPAct, DOE Request for Information/Expression of Interest), and End-User Requirements. From these top-level requirements, functions are analyzed and Functional and Operational Requirements

(F&OR) are developed to cover, for example, availability, reliability, maintainability, transportability, manufacturability, and operability. Ultimately, technical requirements, including design requirements and design criteria, are developed for all plant areas, systems, subsystems (or structures), and/or components (PASSC). These requirements then form the bases for developing specifications, drawings, system descriptions, etc. required for the final design, construction, testing, and commissioning of the plant.

A traditional Verification and Validation process will be applied. Verification confirms that the PASSC has been constructed (implemented) and performs as required to meet its intended form, fit, and function (e.g., through successful completion of inspections, tests, evaluations, etc.), and that necessary and sufficient operational, maintenance, and surveillance (or in-service) test and inspection processes are in place to ensure continued reliable performance of the PASSC throughout plant life. Validation confirms that the PASSC design basis documentation and analyses (e.g., calculation inputs, assumptions and design criteria, specifications, drawings) are consistent with the technical, functional, and operational requirements of the PASSC.

Within this hierarchy, the requirements are based on the physical structure of the plant where the plant is divided into NGNP PASSCs. The lowest levels of requirements are at the plant design level. Detailed requirements are documented in the *Plant Design Requirements* for all PASSCs within the five areas of NGNP

- Nuclear Heat Supply System
- Heat Transport System (HTS)
- Power Conversion System (PCS)
- Hydrogen Production System
- Balance of Plant (BOP).

2.2 Conceptual Design Requirements Process

The requirements summarized in this revision of the Systems Requirement Manual were originally developed by the reactor vendors during the pre-conceptual design phase of the NGNP Project. The top level requirements were derived from NGNP project goals and objectives as well as applicable regulatory requirements. At the system and sub-system level, some of the requirements were developed by the reactor vendors from prior gas reactor designs, such as the AREVA ANTARES design, the General Atomics Gas Turbine-Modular Helium Reactor (GT-MHR) and Modular High Temperature Gas Reactor (MHTGR) designs, and the Pebble Bed Modular Reactor (PBMR) Demonstration Pilot Plant (DPP) design. The set of requirements summarized herein are judged sufficient for the early NGNP conceptual design work and set the starting point for the subsequent stages of design.

3. NGNP TOP-LEVEL REQUIREMENTS

3.1 Prototype NGNP Mission Need

The NGNP project mission is the development of a prototype design for a full-scale commercial plant demonstration that provides (a) high-efficiency electricity generation and (b) CO_2-free hydrogen production based on high-temperature, modular gas-cooled reactor technology as the heat source.

3.2 NGNP Program Requirements

3.2.1 Overall Objectives

The NGNP project has the following objectives, taken from Reference 1:

1. Complete demonstration of the technical, licensing, and commercial viability of the HTGR technology in a time frame that meets industry expectations and is no longer than required by the 2005 EPAct (i.e., demonstration by 2021)

2. Provide flexibility in the design to facilitate changes in the plant configuration and operating conditions to demonstrate the viability of evolving and emerging technologies over the long-term operation of the plant (e.g., higher gas temperatures, advanced materials and component designs, advanced power conversion and hydrogen processes, advanced heat transport fluids, future applications of high-temperature heat, etc.).

3.2.2 NGNP Project Requirements

The following requirements are adapted from Reference 2 as modified by the Independent Technology Review Group recommendations and documented in Reference 3.

1. NGNP shall be designed, constructed, licensed, and operating by 2021.

2. NGNP design configuration shall consider cost and risk profiles to ensure that NGNP establishes a sound foundation for future commercial deployment.

3. NGNP nuclear heat source shall be based on the MHTGR concept and utilize passive safety features to cool the core from full power to safe shutdown conditions.

4. NGNP shall produce high-efficiency electricity and generate hydrogen on a scale that sets a foundation for future commercial deployment.

5. NGNP shall be licensed by the Nuclear Regulatory Commission (NRC) as a commercial cogeneration facility producing electricity and hydrogen.

6. NGNP shall include provisions for future testing.

7. NGNP shall enable demonstration of energy products and processes utilizing its nuclear heat source.

8. The project shall include identification of necessary and sufficient R&D technical scope and priorities.

9. NGNP plant licensing shall support potential future NRC technology neutral rule-making activities (i.e., Risk-Informed, Performance-Based Alternative to 10CFR Part 50).

3.3 Regulatory Documents

The following regulatory documents from various regulatory bodies are applicable to the NGNP.

3.3.1 NRC/EPA Regulatory Documents

Federal regulatory requirements are defined by the Code of Federal Regulations (CFR), which is controlled by several regulatory bodies, such as the NRC and the Environmental Protection Agency (EPA). Specific documents include, as a minimum:

1. 51 CFR 28044 – Policy Statement on Safety Goals for the Operation of Nuclear Power Plants

2. 10 CFR 20 – Standards for protection against radiation - Permissible dose levels and activity concentrations in restricted and unrestricted areas.

3. 10 CFR 50 – Domestic Licensing of Production and Utilization Facilities (applicable portions as needed)

4. 10 CFR 51 – Environmental protection regulation for domestic licensing and related regulatory functions

5. 10 CFR 52 – Early site permit, standard design certification, and combined license for nuclear power plants

6. 10 CFR 50, Appendix I – Numerical dose guidelines for meeting ALARA criterion for power reactor effluents

7. 10 CFR 73 – Physical Protection of Plants and Materials

8. 10 CFR 74 – Material Control and Accounting of Special Nuclear Material

9. 10 CFR 75 – Safeguards on Nuclear Material – Implementation of US/IAEA Agreement

10. 10 CFR 95 – Security Facility Approval and Safeguarding of National Security Information and Restricted Data

11. 10 CFR 100 – Reactor site criteria - Numerical dose guidelines for determining the exclusion area boundary, low population zone, and population center distances

12. 10 CFR 835 – Occupational Radiation Protection

13. 29 CFR 1910 – Occupational Safety and Health Standards, Subpart H – Hazardous Materials

14. 40 CFR 50-99 – Clean Air Act

15. 40 CFR 100-149 – Clean Water Act

16. 40 CFR 190 – Environmental Radiation Protection Standards for Nuclear Power Operations

17. 40 CFR 1502 – Environmental Impact Statement

18. EPA – 520/1-75-001 – Protective Action Guide Doses for Protective Actions for Nuclear Incidents

19. 47 CFR 47073 – Accident Radioactive Contamination of Human Food and Animal Feed; Recommendations for State and Local Agencies

20. NGNP plant licensing shall comply with the NRC new technology neutral regulatory framework as described in NUREG 1860, July 2006.

3.3.2 DOE Documents

The acquisition strategy for the NGNP project may include a combination of requirements from both the federal and commercial sectors. Until a better definition of the commercial participant(s) is obtained, the DOE Acquisition Management system will be used, including the documents listed below (see Reference 1).

1. DOE O 413.3A – Program and Project Management for the Acquisition of Capital Assets

2. DOE O 420.1B – Facility Safety

3. DOE O 435.1 – Radioactive Waste Management

4. DOE Policy 450.4 – Safety Management System Policy

5. DOE O 450.1A – Environmental Protection Program

6. 10 CFR 851 – Worker Safety and Health Program.

3.3.3 FERC Regulations

The Federal Energy Regulatory Commission (FERC) sets requirements for all electricity being fed into the national power grid. Since the NGNP is expected to produce electricity for commercial use, it must follow applicable FERC requirements.

3.3.4 State of Idaho Regulations

Based on the 2005 EPAct, the NGNP will be located at INL in the State of Idaho and, therefore, must meet applicable state requirements.

3.3.5 Indian Reservation Rights

The Shoshone-Bannock Tribes are the region's primary Native American residents. Because they believe the land is sacred, the entire INL reserve is potentially culturally important to them. Cultural resources to the Shoshone-Bannock peoples include all forms of traditional life ways and usage of all natural resources. This includes not only prehistoric archaeological sites, which are important in religious or cultural heritage context, but also features of the natural landscape, air, plant, water, or animal resources that might have special significance. DOE has committed to additional interaction and exchange of information with the Shoshone-Bannock Tribes at the Fort Hall Reservation.

4. FUNCTIONAL, OPERATIONAL, AND TECHNICAL REQUIREMENTS

The subsections below summarize the pre-conceptual definitions of the NGNP F&ORs and Technical Requirements, as well as Plant Design Requirements. As noted, these are based on the FY 2007 Pre-Conceptual Design work for NGNP. These requirements will be updated as the project matures, particularly after the nuclear system design, plant operating conditions, and plant configuration are finalized. At that time, a formal numbering system will be instituted that will be consistent with the final configuration of the plant.

4.1 Requirements Applicable to Multiple Systems, Buildings and Structures

4.1.1 System Configuration and Essential Features Requirements

System configuration and essential features requirements are as follows:

1. The NGNP nuclear heat source shall use the MHTGR concept.
2. The NGNP nuclear heat source shall demonstrate commercial viability of the MHTGR.
3. The NGNP nuclear heat source shall be connected to a PCS for demonstration of high efficiency [>44%] commercial-scale electricity generation.
4. The NGNP nuclear heat source shall be connected to a hydrogen production demonstration plant through an intermediate loop and intermediate heat exchanger (IHX) and deliver up to [60 MWth] of process heat.

4.1.2 Operational Requirements

Operational requirements are as follows:

1. The NGNP nuclear heat source shall have an operational lifetime of 60 years.
2. The NGNP required operational lifetime shall be met by using components designed for a 60 year lifetime or by using components that are replaceable.
3. The NGNP nuclear heat source and the PCS shall be designed and licensed as a commercial nuclear facility for generation of electricity and process heat.
4. The NGNP nuclear heat source shall be designed for load following of the electricity generation plant.
5. The NGNP nuclear heat source shall be designed for load following in the hydrogen production plant.
6. The NGNP shall be designed to use low enriched uranium (LEU) TRISO-coated particle fuel.
7. The NGNP shall demonstrate a minimum 18-month refueling interval capability (if applicable).

8. The NGNP shall be designed to operate during loss of hydrogen production and stabilize in the electricity generation phase.

4.1.3 Structural Requirements

Structural requirements are as follows:

1. NGNP PASSCs shall be designed and constructed using and demonstrating modular plant construction.

2. NGNP plant external structures, important to nuclear safety, shall be designed and constructed to withstand the impact of a single large commercial airliner without exceeding the 1.0 rem Protective Action Guide (PAG) radioactive exposure limit at the site boundary.

3. The NGNP shall be designed for a reference safe shutdown earthquake (SSE) horizontal peak ground acceleration (PGA) of [0.3g].

4. The NGNP shall be designed such that the minimum level at which a shutdown is required to evaluate the condition of the plant following an earthquake shall be [0.1g] PGA.

5. A seismic margin assessment (SMA) shall be performed to demonstrate that there is seismic margin in the NGNP beyond the design level SSE. The seismic margin earthquake (SME) used in the SMA process shall be the NUREG/CR-0098 median shape curve anchored to a [0.5g] PGA.

4.1.4 Environmental Requirements

Environmental requirements are as follows:

1. The NGNP and hydrogen production facilities shall comply with applicable requirements of the Clean Air Act/Air Programs.

2. The NGNP project shall minimize the generation of all wastes, including radioactive, non-radioactive, and mixed wastes, and it shall comply with applicable DOE Orders, NRC Regulations, and EPA Regulation in the treatment of these wastes.

4.1.5 Instrumentation and Control Requirements

Instrumentation and control (I&C) requirements are as follows:

1. The NGNP plant shall be controlled from a single control room.

2. The main control room shall include controls for the PCS and high-temperature heat transport loop.

3. The NGNP design shall optimize the human-machine interface based on human factors engineering principles and operating experience to the extent possible without compromising plant safety.

4.1.6 Surveillance and In-Service Inspection requirements

Surveillance and In-Service Inspection (ISI) requirements are as follows:

1. The NGNP design shall provide access to the primary and secondary loop pressure boundary to permit ISI as required by appropriate sections of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code.

4.1.7 Availability Requirements

Availability requirements are as follows:

1. Excluding NGNP mission-specific outages for inspection and testing, the NGNP design capacity factor for supplying process heat over the plant lifetime shall be at least [TBD %] when modeled with equipment mean time to failure and mean time to repair data for the same or similar systems and/or components.

2. Excluding NGNP mission-specific outages for inspection and testing, the capacity factor loss due to NGNP planned outages averaged over the lifetime of the plant shall not exceed [TBD %], including all planned inspection and maintenance activities that must be accomplished with the reactor shut down.

3. Excluding NGNP mission-specific outages for inspection and testing, the calculated capacity factor loss due to unplanned outages averaged over the lifetime of the plant shall not exceed [TBD %].

4.1.8 Maintenance Requirements

Maintenance requirements are as follows:

1. The NGNP design shall include provisions for monitoring equipment status, configuration, and performance and for detecting and diagnosing malfunctions as a basis for predictive maintenance plans and decision making.

4.1.9 Safety Requirements

Safety requirements are as follows:

1. The nuclear system shall not depend on active cooling systems during design basis accident (DBA) conditions.

4.1.10 Codes and Standards Requirements

Codes and standards requirements are as follows:

1. The design of the NGNP shall comply with all applicable federal, state, and local codes and standards. Codes and standards pertinent to the nuclear industry shall only be utilized in the design, fabrication, and installation of the structures, systems, and equipment where such codes and standards are applicable. The plant designer shall list all applicable codes and standards, and the applicable revision of each document.

2. NUREG/CR-5973 should be used as a starting point for the identification of codes and standards to be followed during conceptual design.

3. Since the NGNP will be built within a DOE facility and will interface with other existing facilities, the plant designer must evaluate DOE orders to ensure that the NGNP can interface with the DOE site and be acceptable to DOE.

4.1.11 Quality Assurance Requirements

Quality assurance requirements are as follows:

1. The NGNP project shall use the U.S. national consensus standard ASME Nuclear Quality Assurance (NQA)-1-2000, "Quality Assurance Program Requirements for Nuclear Facilities Applications."

4.1.12 Construction Requirements

Construction requirements are as follows:

1. Advanced techniques, such as the use of factory or field-fabricated and assembled modules containing portions of systems and/or structures, shall be utilized (as appropriate) to reduce erection costs and schedule risks and to enhance quality control.

2. The design of buildings and equipment shall facilitate plant construction and the installation, repair, and replacement of equipment.

4.1.13 Decommissioning Requirements

Decommissioning requirements are as follows:

1. Upon completion of its useful life, the NGNP nuclear heat source shall be put into a condition of safe storage for 10 years and then decommissioned and dismantled to allow continued use of the land as a power plant or industrial site.

4.2 Requirements Applicable to Fuel

The fuel shall be designed with the following requirements:

<u>As-manufactured Quality Requirements:</u>

1. The allowable fraction of failed fuel particle coatings at the time of manufacture shall be [TBD].

2. The free uranium outside the particle coating in fabricated fuel shall be [TBD].

<u>In-service Fuel Performances Requirements:</u>

3. Fuel performance retention capabilities during normal operation (accounting for the failure of fuel particle coatings and, if significant, for the radiocontaminants diffusion in the fuel particles) shall be [TBD].

4. Fuel performances retention capabilities during off-normal events (accounting for any incremental failure of fuel particle coatings and, for any increased diffusion of radiocontaminants in the fuel particles) shall be [TBD].

4.3 Requirements Applicable to Nuclear Heat Source

4.3.1 Reactor System

The following are the required functions of the reactor system:

1. Generate heat and transfer it to the primary coolant
2. Maintain reactor shutdown.

The reactor system shall be designed with the following requirements:

3. The reactor system shall be designed to provide passive residual heat removal.
4. The reactor system shall be designed for an operational lifetime of 60 years.
5. The reactor system shall be designed to provide dual hydrogen and electricity generation.
6. The core shall use forced circulation helium as the heat transport fluid.
7. Non-replaceable structural materials in contact with helium shall resist corrosion and erosion during plant cycle life.

4.3.1.1 Reactor Core

The following are the required functions of the reactor core:

1. Generate heat
2. Transfer heat to coolant and/or reactor internals.

The following requirements shall be placed on the reactor core:

3. The decay heat removal shall be possible by passive heat transfer means (conduction and radiation) from the fuel to the reactor internals without reaching unacceptable fuel temperatures during all DBA conditions.
4. The core shall utilize thermal spectrum neutrons for fission reaction.
5. The core shall be moderated with graphite.
6. The active core height shall ensure the axial stability of the neutron flux and preclude the risk of xenon oscillations.
7. Reference fuel shall LEU-based (UCO or UO_2) with an enrichment limited to <20.0% (in mass) and with a peak burn-up limited to 20% fissions per initial metal ion (FIMA).

8. The core bypass flow shall be maintained within an acceptable range [TBD], which ensures a good compromise for the fuel temperature in normal and accidental conditions (existence of a minimum amount of bypass in lateral reflector).

9. The reactivity temperature coefficient shall be sufficiently negative to shutdown the nuclear chain reaction before an unacceptable fuel temperature is reached, and maintain the core in a safe state for a time offering the certainty to reliably introduce absorber elements.

4.3.1.2 Reactor Internals

The following are the required functions of the reactor internals:

1. Maintain reactor core geometry

2. Provide heat transfer during conduction cooldown

3. Conserve neutrons in the reactor core and provide shielding.

The following are requirements on the reactor internals:

4. The reactor internals shall be designed to properly control bypass flows.

5. The reactor internals shall be designed to transport residual decay heat from the reactor core to the reactor vessel.

6. The reactor internals shall be designed to channel primary coolant to and from the reactor core for transfer of heat to the Primary Heat Transport System (PHTS).

7. The reactor internals shall be designed to provide radiological shielding to limit neutron fluence to the reactor vessel.

8. The reactor internals shall be designed to limit gamma radiation exposure to the plant personnel and equipment.

9. The reactor internals shall be designed to limit damage to plant components during conduction cooldown events.

4.3.1.3 Neutron Control Elements

The following are the required functions of the neutron control elements:

1. Control the nuclear chain reaction in the reactor core by absorbing neutrons in any operational mode.

The following are requirements placed on the neutron control elements:

2. The neutron control elements shall be designed to provide sufficient negative reactivity to shutdown the reactor and maintain it in sub-critical condition for any state by compensating the worst positive reactivity insertion.

4.3.2 Vessel System

The following are the required functions of the vessel system:

1. Contain and support the components of the reactor core, reactor internal supports and structures, and the nuclear heat transport components.

The vessel system shall be designed with the following requirements:

2. The duration of maintenance, ISI, and repair/replacement operations of the vessel system shall be minimized.

3. All parts of the vessel system shall be designed for operation duration of 60 years.

4. Lifetime of isolation valves of the vessel system shall be optimized according to the investment cost and replacement duration.

5. The vessel system shall be designed for design basis duty-cycle events.

4.3.2.1 Reactor Vessel

The following are the required functions of the reactor vessel:

1. Provide core support and maintain its relative position to the control rods

2. Provide decay heat and residual heat removal by radial conduction during conduction cooldown.

The following are requirements placed on the reactor vessel:

3. During normal operation, the reactor vessel shall maintain its operating temperature through a thermal balance between the core heat flux, core inlet helium flow, and the reactor cavity cooling system.

4. The reactor vessel shall maintain the primary pressure boundary integrity.

5. The operating conditions shall be considered according to the following statements:

   a) In normal operation, the creep effects on the reactor vessel shall be avoided (negligible creep).

   b) No leakage shall result from Anticipated Operating Occurrences (AOO).

   c) For AOOs and DBAs, the reactor vessel shall not prevent restarting of the plant.

4.3.2.2 Cross Vessels (where applied)

The following are the required functions of the cross vessels:

1. Provide a primary heat transport path to/from the reactor vessel and IHX vessels.

The following are requirements placed on the cross vessels:

2. The cross vessels shall maintain the primary pressure boundary integrity.

3. The cross vessels shall provide the primary heat transport path to/from the reactor vessel and IHX vessels.

4.3.2.3 IHX Vessels

The following are the required functions of the IHX vessels:

1. Support the IHX modules.

The following are requirements of the IHX vessels:

2. The IHX vessels shall maintain the primary pressure boundary integrity.

4.3.2.4 Vessel Supports

The main requirements of the vessels supports are as follows:

1. The vessel supports shall support the vertical load.

2. The vessel supports shall include keying for lateral support.

3. The vessel supports shall accommodate thermal expansion.

4. The vessel supports shall accommodate duty-cycle events.

4.3.2.5 Pressure Relief System

The following are the required functions of the pressure relief system:

1. Provide the primary coolant loop's overpressure protection as required by ASME pressure relief code.

The following requirements are placed on the pressure relief system:

2. The pressure relief system shall be designed to depressurize the primary system in the following conditions:

    a) In case of primary overpressure, the safety valves shall open to eliminate the overpressure and reclose once the overpressure condition terminates.

    b) Redundancy of the primary pressure relief system may be required for investment protection reasons.

4.3.3 Reactor Support Systems

4.3.3.1 Shutdown Cooling System

The following are the required functions of the Shutdown Cooling System (SCS):

1. Transport core residual and decay heat from the reactor system to the environment when the reactor system is shutdown and the PHTS is not operational. The helium primary coolant may be pressurized or depressurized.

2. Transport core residual and decay heat from the reactor system to the environment when the helium primary coolant is depressurized during reactor core refueling operations

3. Transport core residual and decay heat from the reactor system to the environment when the helium primary coolant is depressurized during scheduled maintenance of core, vessel, and internal components

4. Transport core residual and decay heat from the reactor system to the environment when the helium primary coolant is depressurized during certain potential unscheduled maintenance or repair activities

5. Support cooling of the IHX, as needed, and potentially for other components when the PHTS is not operating

6. Limit core bypass flow through its components during PHTS operation

7. Retain helium and radionuclides within the parts of the SCS comprising the primary Helium Pressure Boundary (HPB)

8. Limit the ingress of potential contaminants into the primary helium circuit from components of the SCS external to the primary HPB.

The following requirements are placed on the SCS:

9. The SCS shall retain helium and radionuclides within the parts of the SCS comprising the primary HPB.

10. The SCS shall limit the ingress of potential contaminants into the primary helium circuit from components of the SCS external to the primary HPB.

4.3.3.2 Reactor Cavity Cooling System

The following are required functions of the Reactor Cavity Cooling System (RCCS):

1. Protect the reactor cavity concrete structure, including the support structures of the reactor pressure vessel, from overheating during all modes of operation

2. Provide an alternate means of reactor core heat removal from the reactor system to the environment when neither the PHTS nor the SCS is available.

The following requirements are placed on the RCCS:

3. The RCCS shall operate continuously and maintain reactor cavity concrete temperatures less than [90ºC] during normal operations and less than [150ºC] for off-normal events (short term).

4. The RCCS shall be designed to operate through the utility/user duty-cycle events for the number of cycles specified [TBD] plus those events and even combinations determined to be required by plant transient analysis.

5. Inaccessible parts of the RCCS shall be designed for an operating life of 60 years.

6. The need for access to individual components during normal plant operation and under accident conditions shall be considered in developing building and component arrangements.

7. The RCCS shall be designed to meet availability/investment protection requirements.

8. The RCCS shall be designed to accommodate continuous operation at any power level up to 100% of rated power.

9. Where cost effective, the design of the RCCS shall incorporate features required to implement on-line surveillance and performance monitoring.

10. The design of the RCCS shall incorporate those features required to accomplish ISI activities within the time and scheduling constraints imposed by the allotted design planned outage time.

11. The RCCS shall be required to operate continuously in all plant states, including shutdown following loss of forced reactor cooling by the PHTS and SCS with simultaneous loss of pumped circulation of RCCS cooling water and an SSE.

12. All components and piping of the RCCS shall be designed against seismic loads.

13. All components and piping inside the reactor building, including the connections for emergency water supply (fire brigade), shall be designed against external events (e.g., aircraft crash or pressure waves).

4.3.3.3 Fuel Handling Systems

The following are the required functions of the Fuel Handling System (FHS):

1. Remove and replace fuel from the reactor core

2. Prepare new fuel for use in the reactor core

3. Store spent fuel.

The following are the requirements placed on the FHS:

4. For the prismatic reactor design during reactor shutdown, the FHS shall receive new and irradiated fuel, reflector blocks, and other core elements from the spent fuel storage system (SFSS) and place them in the reactor vessel, physically replacing and restacking the core.

5. For the pebble bed reactor design, the FHS shall be developed such that the fuel pebbles are circulated through the core to affect on-line plant refueling.

6. The FHS shall provide shielding to protect workers from radiation during certain fuel handling operations, as applicable.

7. The FHS shall limit the ingress of potential contaminants into the primary helium circuit from components of the FHS external to the primary HPB.

8. For the prismatic reactor design, the FHS shall be designed to accomplish plant refueling within a time interval specified in planned outage allocations.

4.3.3.4 Spent Fuel Cooling System

The following is the required function of the spent fuel cooling system:

1. Actively remove decay heat from the spent fuel elements within their storage containers and transfer the heat to a secondary coolant.

The following requirements are placed on the spent fuel cooling system:

2. The spent fuel cooling system shall be designed to continuously remove and transfer [TBD MWt] of heat absorbed by the cooling water at ambient atmospheric conditions.

3. The spent fuel cooling system shall be designed to operate continuously whenever spent fuel is located in storage.

4. Water quality requirements shall be maintained at all times.

4.3.3.5 Nuclear Island Cooling System

The following is the required function of the nuclear island cooling system:

1. Remove heat from the reactor plant components by way of a circulating coolant system and transfer heat to an ultimate heat sink.

The following requirements are placed on the Nuclear Island Cooling System:

2. The nuclear island cooling system shall serve the needs of the reactor and its associated components at all times under full-power operating conditions.

3. System makeup shall be provided from the plant Water Supply Treatment System.

4. Redundant components shall be provided for the nuclear island cooling system, as needed, to support continuous operation of the reactor and to provide for on-line maintenance of the cooling system components.

4.3.3.6 Helium Service System

The following are the required functions of the helium service system:

1. Remove chemical and particulate contaminants from the primary coolant to maintain specified values
2. Supply purified helium to systems filled with helium
3. Remove helium from the primary system and the helium-filled supporting systems and store in a gas store for purified helium
4. Accept helium from helium filled auxiliary and supporting systems during depressurization activities and, possibly, store radioactively contaminated helium
5. Evacuate primary systems and helium supporting systems.

4.3.3.7 Radioactive Waste and Decontamination System

The following are the required functions of the radioactive waste and decontamination system:

1. Provide for collecting, storing, processing, and monitoring radioactive (or potentially radioactive) liquid and gaseous wastes, including various forms of solid waste generated within the plant
2. Provide equipment and procedures to remove radioactive surface contamination from components, as necessary, to facilitate control and minimize migration of radioactive contamination and to limit personnel exposure to radionuclides.

The following requirements are placed on the radioactive waste and decontamination system:

3. The radioactive waste and decontamination system shall collect radioactive and potentially radioactive floor and equipment liquid runoff. These waste streams shall be routed to the liquid radioactive waste subsystem.
4. Provisions shall be included to reduce activity levels contained in liquid effluent.
5. Radioactive liquid waste system components shall be redundant to provide for both system reliability and on-line maintenance.
6. The gas waste portion of the radioactive waste system shall have sufficient storage capacity to allow for radioactive decay prior to release.
7. Decontamination equipment shall be skid mounted. Each decontamination skid shall provide steam, wash water (including detergent and/or additives), rinse water, drying air, and vacuuming service.
8. Decontamination system wastes shall be collected locally and routed to the appropriate radioactive waste systems.
9. All radioactive wastes generated within the facility shall be collected, monitored, treated, and processed onsite prior to shipment offsite.

4.3.3.8 Component Handling System

TBD

4.3.4 NHS Protection System

The following are the required functions of the protection system:

1. Maintain plant parameters within acceptable limits established for DBAs.

The following are requirements placed on the Protection System:

2. The protection system shall implement the relevant monitoring, analysis, and actuation functions necessary to reach the controlled state in case of abnormal events.

4.3.5 NHS Control System

TBD

4.3.6 NHS Control Room and Operator Interface System

The following is the requirement for the NHS control room and operator interface system:

1. The NGNP facility design shall permit the operators to take control of the reactor and support processes from within a single integrated control room using the manual mode at any time.

4.3.7 NHS Monitoring System

TBD

4.3.8 Startup and Decay Heat Removal System

TBD

4.3.9 Other NHS Systems

TBD

4.4 Requirements Applicable to Heat Transport System

4.4.1 Primary Heat Transport System

The following are the required functions of the PHTS:

1. Transfer heat from the reactor core to the secondary circuit.

The PHTS shall be designed with the following requirements:

2. Pure helium shall be used in the primary and secondary circuits for the H_2 plant and power conversion plant heat transfer.

3. All parts of the PHTS shall be replaceable.

4.4.1.1 Main Helium Circulator

The following are the required functions of the Main Helium Circulator (MHC):

1. Control the flow of helium to match the heat generation of the reactor core with the heat removal of the PHTS.

The MHC shall be designed with the following requirements:

2. The MHC shall be driven by electrical motors capable of rated and variable speeds.
3. Active magnetic bearings shall be used to avoid any lubricating product ingress in the primary circuit.
4. Thermal insulation shall be required to protect the internal components by reducing heat migration due to primary system temperatures.
5. The MHC shall be designed with a minimum lifetime of 10 years.
6. The MHC shall be designed with hydraulic characteristics as stable as possible over the required speed range without distinctive reversal points and without pronounced peak.
7. The MHC shall maintain primary pressure boundary integrity.

4.4.1.2 Hot Duct Assembly (where applied)

The following are the required functions of the Hot Duct Assembly (HDA):

1. Channel high-temperature helium from the reactor core outlet plenum to the IHX inlet.

The following shall be requirements placed on the HDA:

2. Radial keys shall provide a radial support during operating and seismic conditions.
3. The HDA shall provide helium leak tightness at each end (with Core support structure and IHX).

4.4.1.3 Intermediate Heat Exchanger (IHX)

The following are the required functions of the IHXs:

1. Transfer heat from the primary loop to the secondary loop during all normal conditions and between various power levels and certain accident conditions
2. Separate the primary loop from the secondary loop during all normal and abnormal conditions and during accident conditions for a specified time.

The IHX shall be designed with the following requirements (a two-stage IHX is assumed):

Type 1 IHX

3. The Type 1 IHX shall be designed for a lifetime of [5 years].

4. The Type 1 IHX shall be designed with an overall efficiency of [≥94%].

Type 2 IHX

5. The Type 2 IHXs shall be designed for a lifetime of [20 years].

6. The Type 2 IHXs shall be designed with an overall efficiency of [≥89 %].

4.4.1.4 Secondary Gas Isolation Valves

The following are the required functions of the secondary gas isolation valves:

1. Provide isolation between the primary and secondary circuits during maintenance or abnormal conditions (if required).

The following requirements are places on the secondary isolation valves:

2. The secondary gas isolation valves shall accommodate a pressure differential of [5-9 MPa].

3. The secondary gas isolation valves shall be designed to maintain primary pressure boundary integrity.

4.4.2 Secondary Heat Transport System

The following are the functions of the secondary heat transport system:

1. Provide hot helium to the hydrogen production plant and receives the circulating helium at a lower temperature from the hydrogen production plant

2. Provide hot helium to the PCS and received the circulating helium at a lower temperature from the PCS.

4.4.2.1 Secondary Helium Purification System

The following is the function of the secondary helium purification system:

1. Process a small side-stream of helium from the Secondary Heat Transport System to remove chemical and radioactive impurities

2. Provide for tritium removal as required to meet tritium transport limits to plant effluents and products.

4.5 Requirements Applicable to Power Conversion System

The following are the required functions of the PCS:

1. Convert energy from the PHTS into electricity for distribution on the commercial gird.

The following are the requirements placed on the PCS:

2. The NGNP PCS shall be connected to a local public transmission line for external distribution and sale of [250-300] MWe.

3. The NGNP PCS shall produce electricity at 60 Hz.

4. The NGNP PCS shall be designed and sized to produce electricity at commercial scale using 100% of the NGNP thermal energy from the reactor.

5. The NGNP plant electrical output shall be delivered to the operating utility at the low-voltage bushings of the main power transformer.

4.5.1 Steam Turbine and Generator

The following are the required functions of the steam turbine and generator:

1. Produce electricity using steam.

The following are the requirements placed on the steam turbine and generator:

2. The steam turbine and generator shall be designed for superheated steam at a pressure of [TBD] and temperature of [TBD] at the turbine throttle.

3. The steam turbine and generator shall be designed with a single shaft.

4. The turbine shall be designed for main steam temperature variations of up to [TBD].

5. The steam turbine generator rating shall be [TBD].

4.5.2 Generator Cooling System

TBD

4.5.3 Main Feedwater System

The following are the required functions of the main feedwater system:

1. Deliver feedwater to the steam generator at the specified temperature, pressure, flow rate, and water chemistry

2. Provide storage to accommodate process fluid surge and volume fluctuations

3. Provide isolation of the feedwater to prevent water inflow to a failed steam generator.

4.5.4 Main Steam System

The following are the required functions of the main steam system:

1. Convey steam from the steam generator outlet nozzles to the inlet nozzles of the high-pressure turbines.

4.5.5 Main Condensate System

TBD

4.5.6 PCS Control and Instrumentation System

TBD

4.6 Requirements Applicable to Hydrogen Production Plant

4.6.1 Hydrogen Production Plant Parameters and Performance

The following are the parameters and performance requirements for the hydrogen production plant:

1. The hydrogen production plant shall receive process helium at temperatures up to [900°C] and utilize heat at a rate of up to [60 MWth] in the production of hydrogen.

2. The hydrogen production plant process efficiency shall be no less than [40% higher heating value].

4.6.2 Hydrogen Production Plant Configuration

The following are the requirements for the hydrogen production plant configuration:

1. The hydrogen production plant shall be separated from the remainder of the NGNP consistent with commercial plant economic and risk tradeoffs.

2. The interfaces between the hydrogen production plant and the remainder of the NGNP shall be designed to ensure that failures or upset conditions in the hydrogen production plant do not result in failures or adverse impacts to the remainder of the NGNP facility.

3. The hydrogen production plant shall provide for storage of feedstock (e.g., water and makeup chemicals), as required.

4. The hydrogen production plant shall include all necessary pretreatment or conditioning of readily available raw materials needed for the specific hydrogen process (e.g., water treatment).

5. Hydrogen produced in the hydrogen production plant shall be made available for distribution.

6. No central storage shall be included at the hydrogen production plant other than buffer storage, as required for efficient operations.

7. The hydrogen delivery pressure shall be [TBD MPa].

8. The hydrogen product gas shall have purity levels consistent with current industry standards for bulk hydrogen applications.

9. The interface system between the hydrogen production plant and the remainder of the NGNP shall be designed to ensure that tritium migration into the hydrogen production plant will be limited, such that the maximum amount of tritium released to the hydrogen production plant does not exceed [TBD] standards.

10. The total concentration of radioactive contaminants in the hydrogen product gas and associated hydrogen production systems shall be minimized to ensure that worker and public dose limits do not exceed NRC regulatory limits for monitoring.

11. The oxygen byproduct gas shall have purity levels consistent with current industry standards for bulk oxygen applications. Provisions shall be included for the purification, cooling, and venting or shipping of the oxygen byproduct.

4.6.3 Hydrogen Production Plant Waste

The following are the requirements for the hydrogen production plant waste:

1. The hydrogen production plant design shall be such that the volume of waste shipped off-site shall be less than [TBD] annually.

2. A means of disposing (such as flaring) of out-of-specification hydrogen product during upsets or startup/shutdown shall be included.

4.6.4 Hydrogen Production Plant Safety and Licensing

The following are the requirements for the hydrogen production plant safety and licensing:

1. The hydrogen production facilities, including the conversion, storage, and distribution systems, shall comply with the requirements of 29 CFR 1910.103, Occupational Safety and Health Standards, Subpart H – Hazardous Materials, Hydrogen.

2. In the event that the hydrogen production plant also produces and stores significant quantities of oxygen, the requirements of 29 CFR 1910.104, “Oxygen,” shall also be applied.

3. The design, operation, and maintenance of the hydrogen production plant shall comply with 29 CFR 1910.119, “Process Safety Management of Highly Hazardous Chemicals.”

4.6.5 Hydrogen Production Plant Reliability and Availability

4.6.5.1 Capacity Factor

The following is the requirement for the hydrogen production plant capacity factor:

1. Excluding NGNP mission-specific outages for inspection and testing, the hydrogen production plant design capacity factor for hydrogen production averaged over the plant lifetime shall be at least [TBD %] when modeled with equipment mean time to failure and mean time to repair data for the same or similar systems and/or components.

4.6.5.2 Planned Outages

The following is the requirement for the hydrogen production plant planned outages:

1. Excluding NGNP mission-specific outages for inspection and testing, the capacity factor loss due to hydrogen production plant planned outages averaged over the plant lifetime shall be no greater than [TBD %], including all planned inspection and maintenance activities that must be accomplished with the hydrogen production plant shutdown.

4.6.5.3 Hydrogen Production Plant Investment Protection

The following is the requirement for the hydrogen production plant investment protection:

1. Excluding NGNP mission-specific outages for inspection and testing, the calculated capacity factor loss due to unplanned hydrogen production plant outages averaged over the lifetime of the plant shall not exceed [TBD. %].

4.6.6 Hydrogen Production Plant Maintenance and In-Service Inspection

4.6.6.1 Hydrogen Production Plant Maintenance Requirements

The following are the requirements for the hydrogen production plant maintenance:

1. The hydrogen production plant shall be designed to allow all components to be removed, replaced (if necessary), and reinstalled.

2. The hydrogen production plant design shall include provisions for monitoring equipment status, configuration, and performance and for detecting and diagnosing malfunctions as a basis for predictive maintenance plans and decision making.

3. The hydrogen production plant design shall provide storage facilities for an adequate amount of spare parts as determined by a preventive maintenance and facility availability plan.

4.6.6.2 Hydrogen Production Plant In-Service Inspection

The following is the requirement for hydrogen production plant ISI:

1. The hydrogen production plant design shall provide access to the pressure boundary to permit ISI as required by appropriate sections of the ASME B&PV Code.

4.7 Requirements applicable to Balance of Plant

4.7.1 Cooling Water Systems

TBD

4.7.2 Liquid and Gas Supplies

TBD

4.7.3 Piping Systems

TBD

4.7.4 Electrical Systems

The following are the required functions of the electrical systems:

1. Deliver power generated by the plant to the offsite transmission network

2. Take power from the off-site transmission network for various plant operations, including startup

3. Provide backup power to select auxiliaries when the plant power units and off-site power are not available.

4.7.4.1 High Voltage Power System

TBD

4.7.4.2 Medium Voltage Power System

TBD

4.7.4.3 Low Voltage Power System

TBD

4.7.4.4 Backup Power System

TBD

4.7.4.5 DC/UPS System

The following are the required functions of the Direct Current (DC)/Uniterruptible Power Supply (UPS) System:

1. Provide a stored energy source for the all plant DC loads.

4.7.4.6 Grounding System

The following are the required functions of the grounding system:

1. Protect personnel and equipment from system faults and lightning strikes

2. Minimize electrical noise in signal cables.

4.7.4.7 Communication and Lighting

The following are the required functions of communication and lighting:

1. Provide intra-plant communications

2. Provide internal and external lighting.

4.7.5 Plant Control Room System

The following are the required functions of the plant control room system:

1. Provide an interface between plant operators and each of the necessary systems within the plant.

4.7.6 Plant Mechanical Services System

TBD

4.7.7 Fire Detection and Suppression System

The following are the required functions of the fire detection and suppression system:

1. Rapidly detect and annunciate the presence and location of combustion by-products or the presence of fire within the plant
2. Control and extinguish fires that do occur
3. Provide protection for PASSCs such that the performance of safety functions are not prevented.

4.7.8 Communications System

The following are the required functions of the communications system:

1. Provide plant to off-site communications.

4.7.9 Safeguards and Security System

The following are the required functions of the Safeguards and Security System:

1. Provide physical protection of the plant

4.7.10 Plant I&C and Protection

TBD

4.7.11 NGNP Plant Supervisory and Control System

TBD

4.7.12 Site and Civil Works

TBD

5. REFERENCES

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