INEEL/EXT-03-01163

Next Generation Nuclear Plant High-Level Functions and Requirements

September 2003

Idaho National Engineering and Environmental Laboratory
Bechtel BWXT Idaho, LLC

INEEL/EXT-03-01163

Next Generation Nuclear Plant – High-Level Functions and Requirements

John M. Ryskamp

Contributors

Edwin A. Harvego
Edward J. Gorski

Soli T. Khericha

George A. Beitel

September 2003

Idaho National Engineering and Environmental Laboratory
Idaho Falls, Idaho 83415

ACKNOWLEDGEMENTS

We are very thankful for help generating this document from the following consultants. Hans Wolfgang Chi provided consulting and review services on reactor safety and operations, specific to gas-cooled reactors. Sten A. Caspersson and Richard S. Turk provided guidance to the INEEL in the areas of reactor safety and Nuclear Regulatory Commission licensing.

We thank the following Department of Energy individuals for their help in providing constructive review and comment on the document: Trevor L. Cook, Clifford P. Fineman, John W. Herczeg, A. David Henderson, R. Shane Johnson, S. Jason Remer, Amy C. Taylor, and Robert M. Versluis.

In addition, we acknowledge the support of the INEEL staff that made this report possible: Richard G. Ambrosek, Lori A. Braase, Ronald R. Barden, Paul D. Bayless, Brett W. Carlsen, Gray S. Chang, Darlene R. Desomer, Dennis J. Harrell, Mark R. Holbrook, Philip E. MacDonald, Ronald E. Mizia, Charles V. Park, David A. Petti, Kim O. Stein, Finis H. Southworth, William K. Terry, Gregg W. Wachs, and Christine E. White.

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy, Science and Technology
Under DOE Idaho Operations Office
Contract DE-AC07-99ID13727

Next Generation Nuclear Plant – High-Level Functions and Requirements

Prepared by: John M Ryskamp 9/24/03

John M. Ryskamp

Reviewed by: Dennis Harrell 9/24/03

Dennis J. Harrell

Approved by: Finis H. Southworth 9/25/03

Finis H. Southworth

SUMMARY

This functions and requirements (F&R) document was prepared for the Next Generation Nuclear Plant (NGNP) Project. The highest-level functions and requirements for the NGNP preconceptual design are identified in this document, which establishes performance definitions for what the NGNP will achieve. NGNP designs will be developed based on these requirements by commercial vendor(s).

The Generation IV International Forum (GIF), along with the U.S. Department of Energy's (DOE) Nuclear Energy Research Advisory Committee (NERAC), has published "A Technological Roadmap for Generation IV Nuclear Energy Systems", which defines eight goals in the four broad areas of sustainability, economics, safety and reliability, and proliferation resistance and physical protection. The requirements for the NGNP that are identified in the F&R document are based on Generation IV goals.

Of the six most promising Generation IV nuclear energy systems selected by the GIF for further development, the Very High Temperature Reactor (VHTR) is the nearest-term reactor concept that also has the capability to efficiently produce hydrogen. Therefore, DOE has selected the VHTR as the concept to demonstrate the use of nuclear power for electricity and hydrogen production without greenhouse gas emissions.

The VHTR concept is an innovative, super-safe advanced nuclear power system that addresses many of the issues confronting today's nuclear industry. Although today's plants have achieved an outstanding safety record, regulatory and cost issues jeopardize the nuclear industry. The VHTR offers a diverse means of addressing these concerns. Its passive safety features and inherent characteristics simplify reactor safety, which should simplify compliance with regulatory requirements and greatly reduce the commercial risks associated with nuclear power plant ownership. With successful development and demonstration by means of the NGNP, the VHTR will suit a broad range of prospective owner/operators seeking a competitive, low-risk nuclear option.

DOE envisions that a deliberate and focused research and development (R&D) program supporting a disciplined design and construction project will make an early demonstration of the VHTR with a hydrogen production system operational by the middle of the next decade, as shown in the following desired schedule:

- Preconceptual design completed during Fiscal Year 2004 (FY-04)
- Final design completed in FY-09
- Construction starts in FY-11
- A commercial-scale demonstration reactor, capable of producing hydrogen and generating electricity, will begin operation by the middle of the next decade.

The NGNP Project design incorporates the following high-level functions, as shown in Figure 1:

- Develop and demonstrate a commercial-scale prototype VHTR
- Develop and demonstrate high-efficiency power conversion
- Obtain licenses and permits to construct/operate the NGNP
- Develop and demonstrate hydrogen production
- Include provisions for future testing
- Enable demonstration of energy products and processes.

The operational objectives of the NGNP are to demonstrate the superior capabilities of the VHTR for high-temperature, high-efficiency energy conversion to electricity, and to demonstrate hydrogen production using VHTR produced process heat and electricity in a cogeneration mode. In addition, the NGNP will include provisions for future testing. These objectives imply three basic modes of operation for the NGNP (i.e., electric power production mode, cogeneration mode, and testing mode). Therefore, sufficient flexibility must be provided in the design of the plant for operation in each of these modes. The licensing of the NGNP by the Nuclear Regulatory Commission (NRC) will demonstrate that many of the current issues associated with NRC licensing of non-Light Water Reactors and the use of nuclear power for hydrogen production will be resolved.

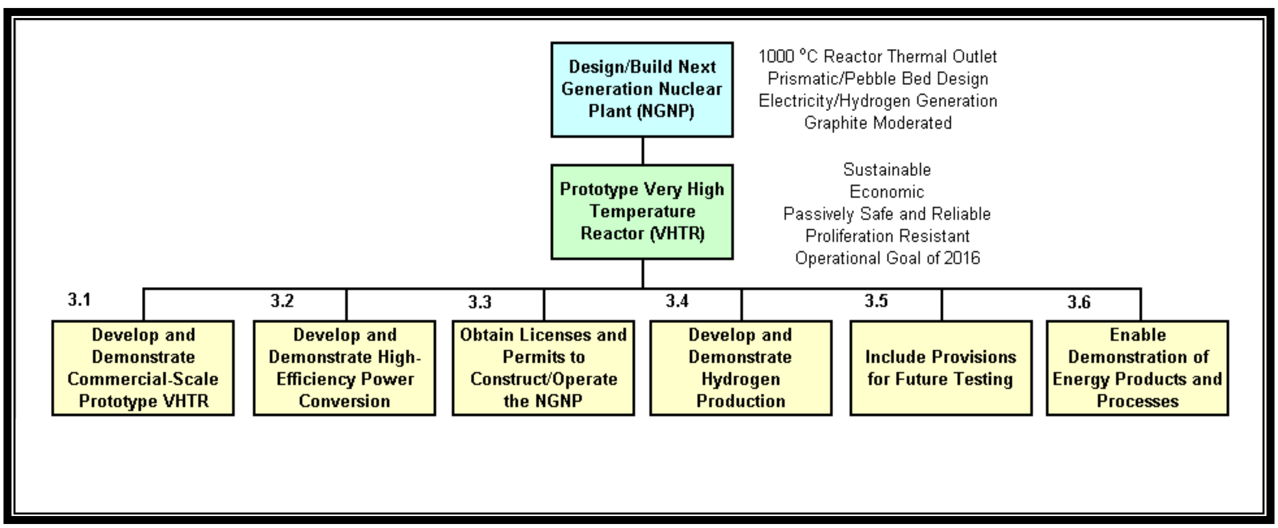

Figure 1. High-level functions for the Next Generation Nuclear Plant.

Table of Contents

Figures

ABBREVIATIONS AND ACRONYMS

ASME	American Society of Mechanical Engineers
CD	critical decision
CFR	Code of Federal Regulations
DOE	Department of Energy
EIS/ROD	Environmental Impact Statement/Record of Decision
EPA	Environmental Protection Agency
F&R	functions & requirements
FY	fiscal year
GIF	Generation IV International Forum
HTR-10	High Temperature Reactor 10 (China)
HTTR	High Temperature Engineering Test Reactor (Japan)
IAEA	International Atomic Energy Agency
INEEL	Idaho National Engineering and Environmental Laboratory
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
LLC	Limited Liability Corporation
LWR	light water reactor
MWe	megawatts-electrical
MWt	megawatts-thermal
NE-ID	Department of Energy – Idaho Field Office
NGNP	Next Generation Nuclear Plant
NRC	Nuclear Regulatory Commission
PRA	probabilistic risk assessment
QA	quality assurance
QAP	quality assurance plan

PNNL	Pacific Northwest National Laboratory
R&D	research and development
RAMI	reliability, availability, maintainability, inspectability
SiC	silicon carbide
S-I	sulfur-iodine
SEMP	Systems Engineering Management Plan
SRM	Staff Requirements Memorandum (Nuclear Regulatory Commission)
UCO	uranium oxycarbide
USC	United States Code
VHTR	very high temperature reactor

1. INTRODUCTION

This functions and requirements (F&R) document was prepared for the Next Generation Nuclear Plant (NGNP) Project to establish the highest-level functions and requirements for input to a future preconceptual design effort. The U.S. Department of Energy (DOE) has selected the Very High Temperature Reactor (VHTR) for the NGNP Project to demonstrate the use of nuclear power for electricity and hydrogen production without greenhouse gas emissions by the middle of the next decade. The Idaho National Engineering and Environmental Laboratory (INEEL), as the lead nuclear reactor technology laboratory within the DOE complex, will update the requirements for the NGNP Project, as needed. One or more commercial vendors will develop NGNP designs based on these requirements.

The NGNP system will be designed to provide a reactor core outlet temperature of 1000 ^{o}C, use an innovative and highly-efficient power conversion cycle, provide process heat for hydrogen production, demonstrate passive safety innovations, incorporate proliferation resistance, and establish a Nuclear Regulatory Commission (NRC) licensing basis for future commercialization of the VHTR.

1.1 NGNP Project

1.1.1 Purpose of the Functions and Requirements Document

This F&R document was prepared for the NGNP Project to establish the highest-level functions and requirements for the preconceptual design of the NGNP as required by DOE Order 413.3. These requirements also establish performance definitions for what the NGNP will achieve.

The F&R document is organized according to the NGNP Project functions defined in Section 2, NGNP Project Overview. Section 3, Functions, Requirements, and Bases, identifies the highest-level NGNP functions and technical requirements and their bases. Section 4, Project Engineering Requirements, identifies those requirements generic to a nuclear and/or chemical process facility. Section 5, Project Management Requirements, identifies generic requirements for managing the NGNP project. Section 6, References, identifies the specific references used in the document.

1.1.2 Program Background and Strategy

To meet future world energy needs, ten countries – Argentina, Brazil, Canada, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom, and the United States – have agreed on a framework for international cooperation in research for an advanced generation of nuclear energy systems known as Generation IV. These ten countries have joined together to form the Generation IV International Forum (GIF) to develop future-generation nuclear energy systems that can be licensed, constructed, and operated in a manner that will provide competitively priced and reliable energy products while satisfactorily addressing nuclear safety, waste, proliferation, and public perception concerns. The objective of Generation IV is to provide nuclear energy systems for international deployment before the year

2030, when many of the world's currently operating nuclear plants will be at or near the end of their operating licenses.

In 2001, the GIF agreed to proceed with development of a technology roadmap for Generation IV nuclear energy systems (see Ref. 1). The purpose of the Generation IV roadmap is to identify the most promising nuclear energy systems (consisting of both a reactor and a fuel cycle) for meeting the challenges of sustainability, safety and reliability, economics, and proliferation resistance and physical protection.

The GIF used more than 100 experts from their ten countries to evaluate more than 100 Generation IV nuclear energy system concepts proposed by the worldwide research and development (R&D) community. The Generation IV roadmap process culminated in the selection of six of the most promising Generation IV systems for further development. The motivation for the selection of six systems was to:

- Identify systems that make significant advances toward the technology goals
- Ensure that the important missions of electricity generation, hydrogen and process heat production, and actinide management are adequately addressed by Generation IV
- Provide some overlapping coverage of capabilities, because not all of the systems may ultimately be viable or attain their performance objectives and attract commercial deployment
- Accommodate the range of national priorities and interests of the GIF countries.

1.1.3 Goals for Generation IV

To guide the Generation IV review and selection process, the GIF established a set of goals for the new reactor systems. These goals have three purposes. First, they served as the basis for developing criteria to assess and compare the systems in the technology roadmap. Second, they are challenging and stimulate the search for innovative nuclear energy systems—both fuel cycles and reactor technologies. Third, they serve to motivate and guide the R&D on Generation IV systems.

The GIF defined eight goals in the four broad areas of sustainability, economics, safety and reliability, and proliferation resistance and physical protection (noted here):

- ***Sustainability–1.*** *Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.*
- ***Sustainability–2.*** *Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden in the future, thereby improving protection for the public health and the environment.*
- ***Economics–1.*** *Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.*

- ***Economics–2.*** *Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.*

- ***Safety and Reliability –1.*** *Generation IV nuclear energy systems operations will excel in safety and reliability.*

- ***Safety and Reliability–2.*** *Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.*

- ***Safety and Reliability–3.*** *Generation IV nuclear energy systems will eliminate the need for offsite emergency response.*

- ***Proliferation Resistance and Physical Protection-1.*** *Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.*

The requirements for the NGNP that are identified in this document are based on the Generation IV goals. Figure 2 is a matrix showing that the Generation IV goals stated above are met by the NGNP high-level requirements defined in Section 3 of this report.

The Generation IV roadmap and its related documents also define a number of criteria for system performance relative to the above goals. The use of a common evaluation methodology is a central feature of the Generation IV roadmap providing a consistent basis for evaluating the potential of many concepts to meet the Generation IV goals. The basic approach was to formulate a number of factors that indicate performance relative to goals, called criteria, and then evaluate concept performance against these criteria using specific measures, called metrics. Figure 3 presents the four goal areas, with the eight goals arranged under them, and the 15 criteria and their 24 metrics assigned to the various goals. The criteria and metrics are grouped to indicate which goals they were assigned to. Therefore, system concept performance can be evaluated against those criteria using the specific measures or metrics defined below.

The Generation IV roadmap recommends viability and performance evaluation methodology and the R&D needed to develop this methodology.

In addition, other information is also available to guide NGNP designers in the development of the NGNP preconceptual designs. The International Atomic Energy Agency (IAEA) led an International Project on Innovative Nuclear Reactors and Fuel Cycles, referred to as INPRO (see Ref. 2). The 15 nations involved in INPRO defined a set of Basic Principles, User Requirements, and Criteria, which are similar to the Generation IV goals developed by the GIF. The INPRO principles, requirements, and criteria are not requirements for the NGNP, but NGNP designers should be aware of and consider them in their preconceptual design activities.

NGNP High-Level Functions and Requirements	Generation IV Goals	Sustainability-1	Sustainability-2	Economics-1	Economics-2	Safety and Reliability-1	Safety and Reliability-2	Safety and Reliability-3	Proliferation/ Protection
3.1 - Develop and Demonstrate Commercial-Scale Prototype VHTR									
Commercial-Scale Prototype	3.1.1			X	X				
Passive Safety Design	3.1.2					X	X	X	
Reactor Type - Prismatic or Pebble Bed	3.1.3			X	X	X	X	X	
Average Core Outlet Temperature	3.1.4	X		X					
Moderator	3.1.5					X	X	X	
Fuel Cycle	3.1.6								X
TRISO-Coated Fuel	3.1.7					X	X	X	X
Enrichment	3.1.8	X		X					X
Fuel Burnup	3.1.9		X	X					X
Fuel Qualification	3.1.10					X		X	
Design Life	3.1.11	X			X				
Defense-in-Depth Philosophy	3.1.12				X	X	X	X	
Fuel Performance	3.1.13					X	X	X	
Reactor System Interactions	3.1.14					X			
3.2 - Develop and Demonstrate High-Efficiency Power Conversion									
Brayton Power Conversion Cycle	3.2.1		X	X					
High Efficiency Electric Power Conversion	3.2.2		X	X					
Electric Power Production at Commercial Scale	3.2.3			X					
3.3 - Obtain Licenses and Permits to Construct/Operate the NGNP									
License NGNP Reactor Using 10 CFR 50 or 10 CFR 52 Rules	3.3.1					X	X	X	
Risk-Informed, Performance-Based Approach	3.3.2					X	X	X	
Probabilistic Risk Assessment	3.3.3					X	X	X	
3.4 - Develop and Demonstrate Hydrogen Production									
Hydrogen Production in Cogeneration Mode	3.4.1	X		X					
Thermochemical Process and High-Temperature Electrolysis	3.4.2	X	X	X					
Interface Performance	3.4.3					X	X	X	
Hydrogen Production System Interactions	3.4.4					X	X	X	
Tritium Migration	3.4.5					X	X	X	
Hydrogen Radioactivity Level	3.4.6		X			X			
Hydrogen Purity Level	3.4.7			X					
3.5 - Include Provisions for Future Testing									
Safety and Operational Performance Testing	3.5.1					X	X	X	
Evaluation of Investment Protection Features	3.5.2				X	X			
Human-Machine Interface	3.5.3			X		X	X	X	
Need for Operator Actions	3.5.4			X		X	X	X	
Integrated Control Room Design	3.5.5			X		X	X	X	
Staffing for Operation and Maintenance of Integrated Facility	3.5.6			X					
3.6 - Enable Demonstration of Energy Products and Processes									
Hydrogen Applications	3.6.1	X		X					
Hydrogen Storage and Distribution	3.6.2	X		X					
Indirect Power Conversion System	3.6.3			X					

Figure 2. Generation IV goals and NGNP requirements matrix.

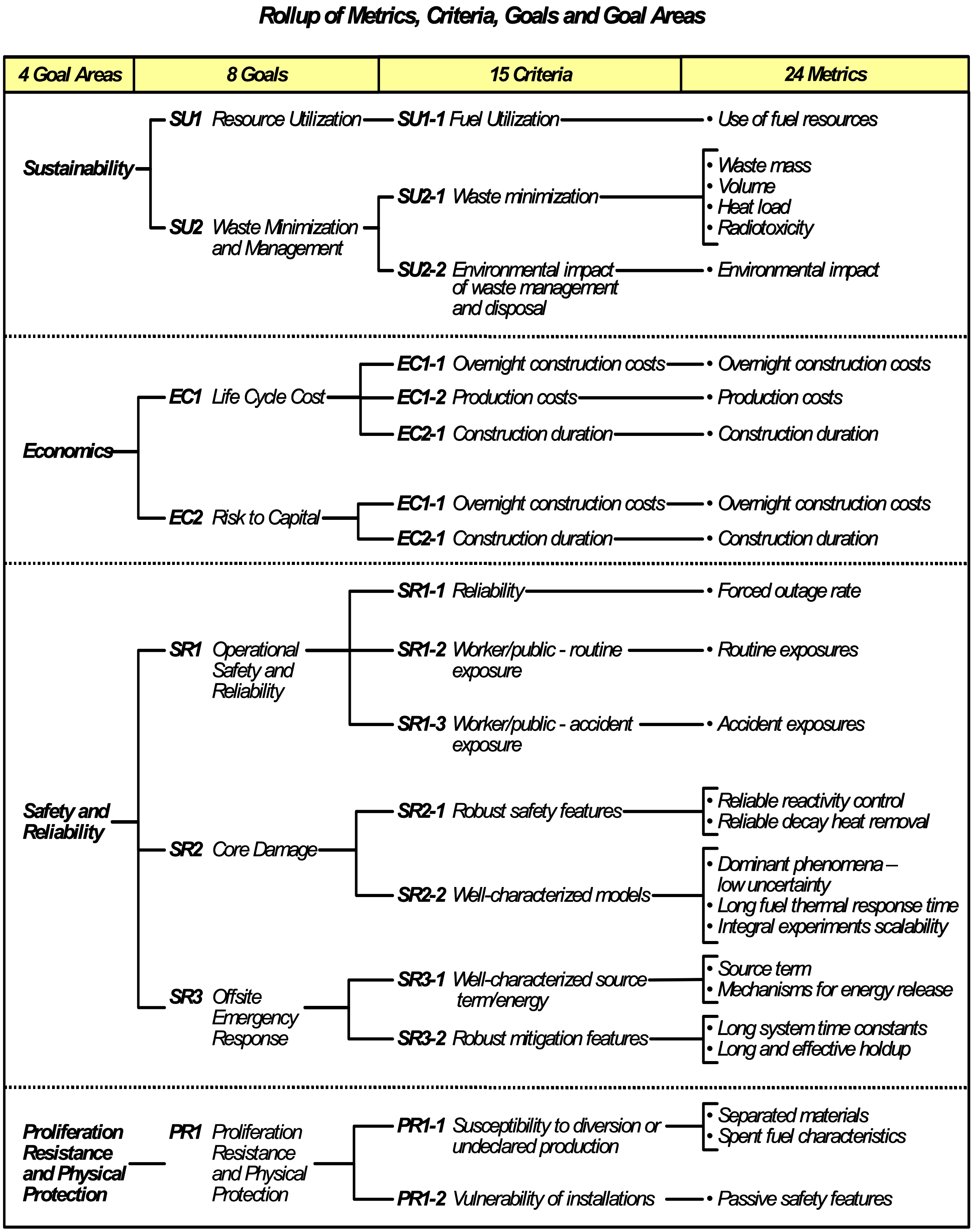

Figure 3. Roll-up of metrics, criteria, goals and goal areas.

1.1.4 Selection of the VHTR: An Innovative Concept for Electricity and Hydrogen Production

A major driving force for the Generation IV roadmap (see Ref. 1) was the recognition that in the coming decades, energy demand in the United States, other industrialized countries, and the entire world will escalate considerably beyond current supply capabilities. This increased energy demand will require the development of new energy sources and the upgrading of the world's energy infrastructure. Meeting future energy requirements by simply expanding today's mix of production options will not address concerns about potential adverse environmental impacts or the need for cost-effective, reliable, and sustainable energy sources. While nuclear power can play an important role in filling future energy needs, the GIF recognized that new and innovative reactor designs would be required to realize the full benefits of nuclear power as a source for production of both electrical power and hydrogen (for transportation and industrial uses).

An early step in the Generation IV roadmap was to identify and evaluate innovative reactor concepts for meeting the challenges of safety, economics, waste, and proliferation resistance. The identification of reactor concepts was accomplished with a wide solicitation for advanced innovative reactor designs that produced over 100 concepts from around the world. These concepts ranged from the more traditional light water reactor designs to non-traditional designs like the plasma-gas core reactor. These concepts were extensively evaluated by focused groups of experts from ten different countries to identify the most promising innovative concepts for continued development. From this evaluation, six concepts were selected for possible further development by the participating countries. The rigor in the approach used to identify and evaluate the different concepts provides a high degree of confidence that the most significant and important innovations had been considered in selecting the six concepts for further development. To ensure that the results of this process were not lost, and to avoid the potential for specific concept proponents "revisiting" old issues, the process methodologies and results were well documented in the Generation IV roadmap report and supporting documentation. This initial phase of the process is now complete, and the next phase, developing and demonstrating the viability of one or more of the selected innovative concepts, has begun.

For the United States, the next phase in the Generation IV nuclear energy system development process is to proceed with preconceptual designs for the NGNP to be built at the INEEL or another DOE site. Innovation continues to be a major focus of this phase of the program, but with the constraint that the technologies employed are consistent with completion of the NGNP reactor licensing and construction process by 2016. Of the six most promising Generation IV nuclear energy systems identified in the Generation IV roadmap, the helium-cooled VHTR was identified as the nearest-term concept (capable of meeting the 2016 target date) that also has the capability to efficiently produce hydrogen.

Based on the results of the Generation IV technology roadmap, the current state of technology, and the potential for successful development of near-term and future advanced technologies, the VHTR was selected as the concept to be used for the NGNP. The technology characteristics for the VHTR that led to its selection are depicted in Figure 4.

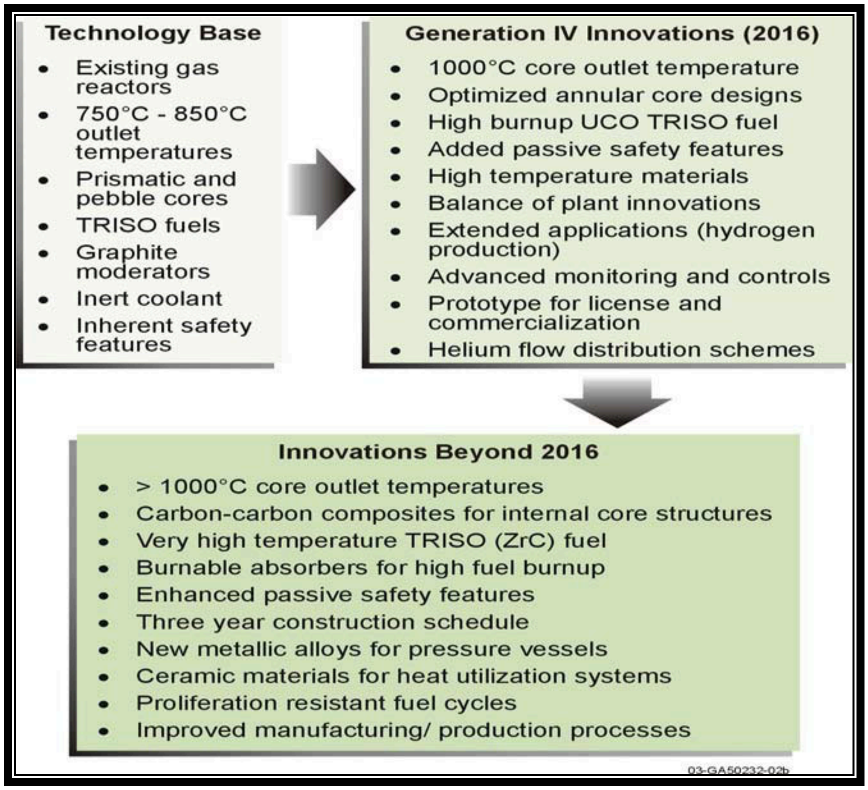

Figure 4. Technology characteristics of the VHTR.

Figure 5 depicts a VHTR with an indirect cycle and a hydrogen plant. Figure 6 depicts a VHTR with a direct helium Brayton cycle for electricity production. The current technology base supporting the development of the VHTR is identified in the upper box of the figure. This technology base has primarily evolved from commercial gas-cooled reactors built and operated in Western Europe and the United States prior to 1990, and two research reactors (HTTR and HTR-10) currently operating in Japan and China. Key elements in this technology base are the proven performance of the helium-cooled, graphite-moderated prismatic and pebble bed core designs, the inherent safety features of the high thermal heat capacity core (with a strong negative temperature coefficient), and the single-phase inert gas coolant.

Despite the existing VHTR technology base, the safety and performance goals established for the VHTR significantly exceed the capabilities of the current technology. Therefore, significant innovations and advancements in technology will be required to achieve the established goals in the 2016 timeframe. For example, a vendor could propose an innovative molten-salt-cooled VHTR with an indirect air (nitrogen) Brayton cycle to produce electricity. The projected technology development areas required to meet the established goals for the VHTR are identified in the "Generation IV Innovations" box in Figure 4. These innovations will occur in the areas of core optimization; fuel design, production, and qualification; approaches to passive safety features and defense-in-depth; materials research; energy conversion innovations (i.e., heat exchanger designs, advanced gas turbines, and advanced cooling and insulating techniques); instrumentation and control; and construction and licensing processes.

Preliminary preconceptual designs for two potential versions of the NGNP, one for a prismatic fuel-type helium-cooled reactor and one for a pebble bed fuel-type helium-cooled reactor, are presented in Reference 3. This reference provides more details on innovative features of the VHTR reactor.

Finally, the VHTR offers significant potential for enhanced performance beyond 2016. The required technology developments, however, will be substantially more challenging, and will extend the development timeframe to 2030 and beyond. The anticipated areas of technology development are identified in the "Innovations Beyond 2016" box in Figure 4. These technology development areas will focus less on reactor design issues and more on general fuels and materials issues, and process improvements. Areas of technology development and innovation include advanced fuel designs; high-temperature materials for core internal structures and pressure vessels; ceramic materials for interfacing heat utilization systems (pipes, heat exchangers, etc.); proliferation resistant fuel cycles; and improved manufacturing and production processes to reduce capital costs.

In summary, the focus on innovation and technology development needs that led to the selection of the six most promising Generation IV reactor concepts identified by the GIF for future development will be carried forward into the development and construction of the NGNP. The anticipated innovations and technology development needs depicted in Figure 4 should also be expected to evolve with time, since new innovations will come only with the experience gained by moving forward with development of the selected VHTR design concept.

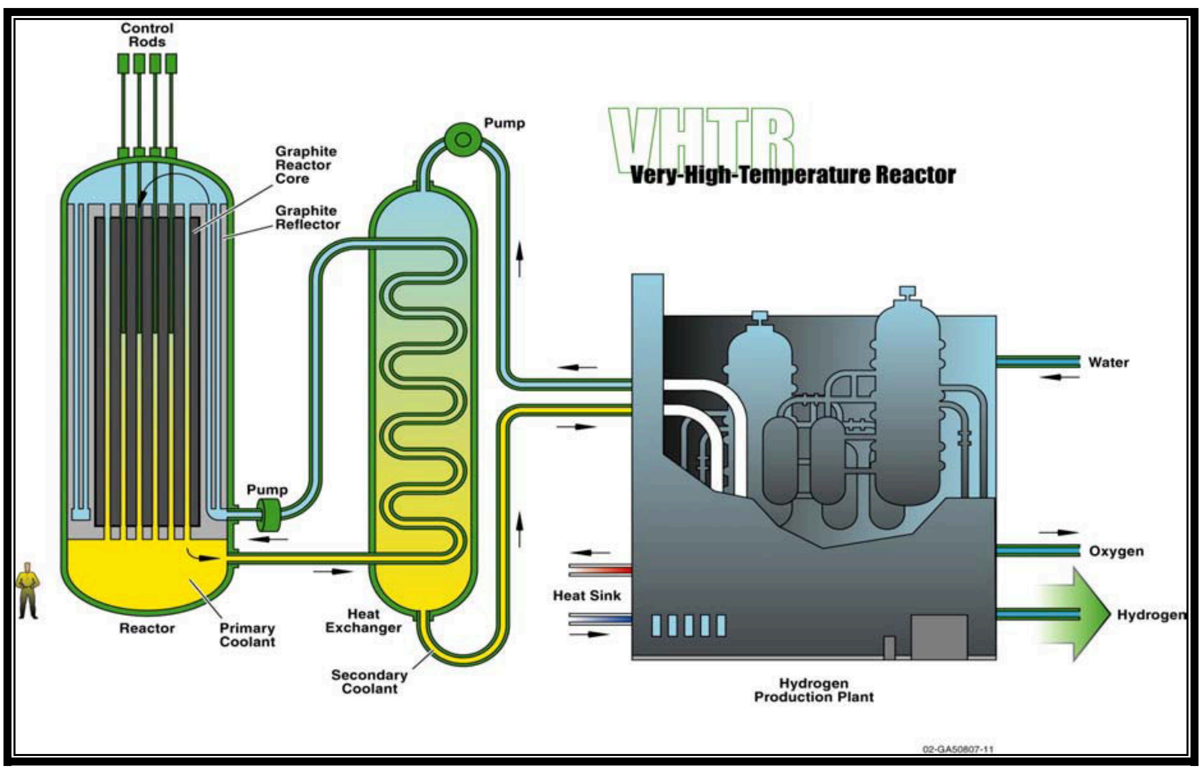

Figure 5. A VHTR with an indirect cycle to produce hydrogen.

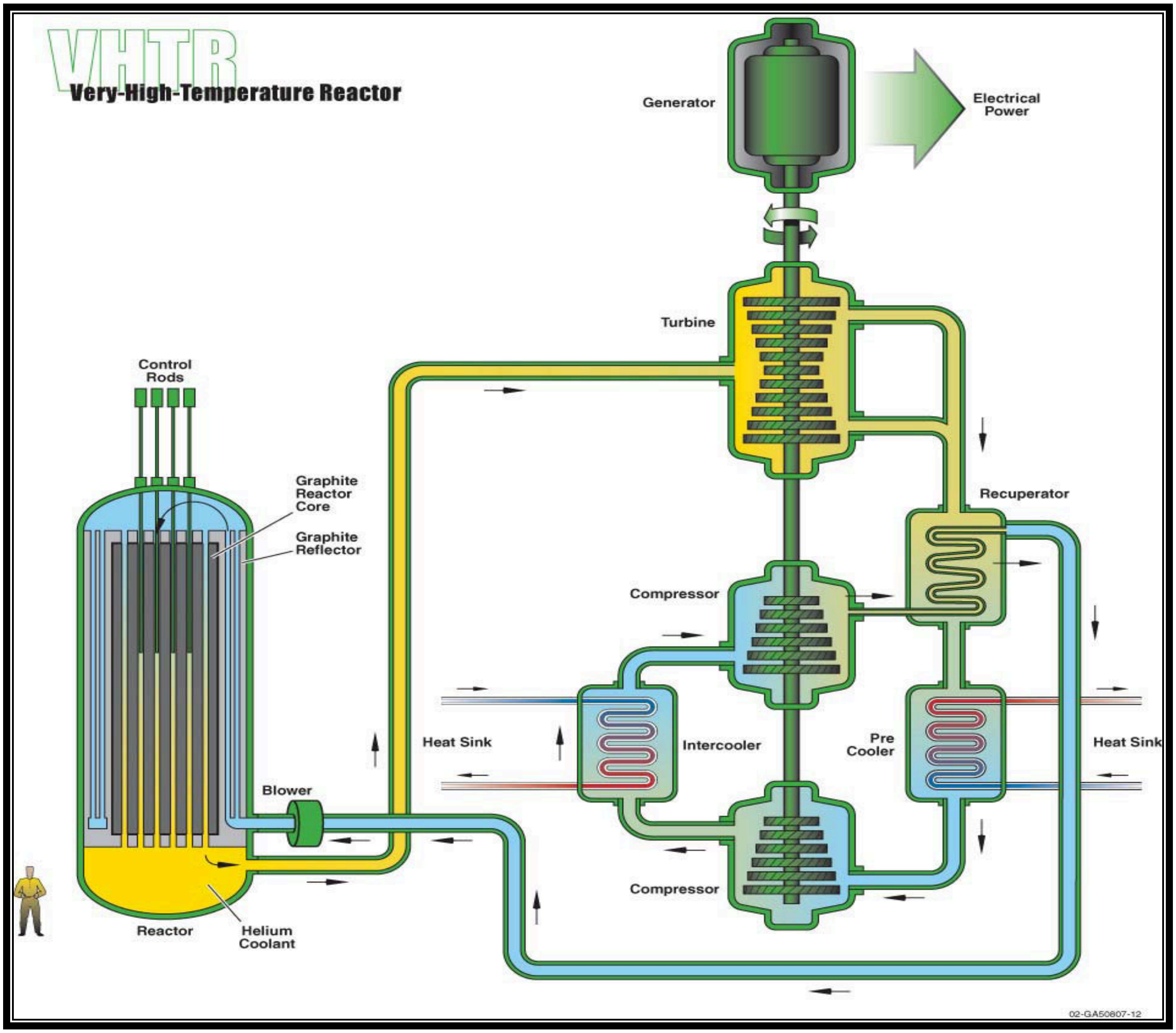

Figure 6. A VHTR with a direct helium Brayton cycle to produce electricity.

1.1.5 Location of NGNP

For the purpose of defining the functions and requirements for the NGNP, the INEEL site was used as the basis for some requirements. A previous Environmental Impact Statement/Record of Decision (EIS/ROD) for a new reactor site located northeast of the Idaho Nuclear Technology Engineering Center (INTEC – see Figure 7) was used to support requirements. Extensive characterization of this site has previously been completed and studies have found it suitable for a new reactor. In addition, Secretary of Energy Spencer Abraham has identified the INEEL as the lead laboratory for nuclear reactor technology. The INEEL has developed, designed, and built over 50 reactors at the INEEL over the last 50+ years. EBR-I was the first reactor to produce electric power in 1951 and stands today as a National Historic Landmark.

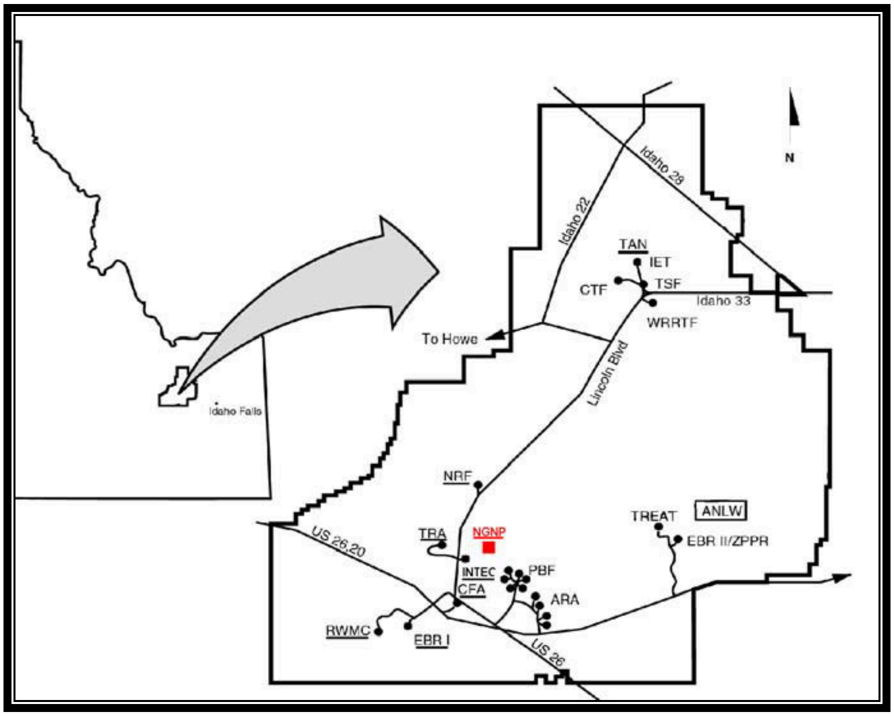

Figure 7. Basis site for NGNP.

1.2 Limitations of the F&R Document

The requirements in this F&R document are applicable solely to the NGNP design. Although the intent is to demonstrate the safety and licensing of commercial-scale VHTRs, this Project will not produce nor will it be responsible for the production of a commercial VHTR design. This document specifies requirements for the reactor fuel, but the NGNP does not include the fuel fabrication facilities, which will be designed and built separately. It is anticipated that the hydrogen generation plants included within the NGNP (and specified in this document) and other applications of process heat will require the construction and testing of bench scale and intermediate sized pilot plants. However, these test facilities are not within the scope of this document.

1.2.1 Open Issues

The following is a description of unresolved issues that influence the design of the project. Some of these concerns are currently being resolved while others may not be resolved within the time frame of the conceptual design.

1.2.1.1 NRC License

The NGNP Project will obtain a Nuclear Regulatory Commission license in accordance with the requirements of 10 CFR 50 or 10 CFR 52. As a first-of-a-kind non-light-water reactor (LWR) licensed as a demonstration plant for both electric power and hydrogen production at a

DOE site, the NGNP presents several licensing issues that will need to be addressed. These issues are (1) generic licensing issues, (2) issues relating to NRC licensing of non-LWRs, (3) issues relating to the licensing of an integrated nuclear power plant and hydrogen production facility, and (4) issues relating to demonstration testing at a DOE site. Each of these general issues is briefly described below.

1.2.1.1.1 Licensing Issues

There are several licensing issues that concern the licensing of a prototype demonstration plant. These issues will require early resolution, possibly during licensing preapplication reviews, to ensure smooth progression into the licensing process. Three of the principal issues to resolve are:

Issue 1: *Will the NRC agree to commence a combined license review prior to completion of the NGNP design?*

Issue 2: *Who will be the holder of the NRC operating license (DOE or site contractor)?*

Issue 3: *How will contradicting/overlapping DOE and NRC requirements be resolved?*

1.2.1.1.2 Licensing of a Non-LWR

Issues relating to the NRC licensing of non-LWRs have been a continuing topic of discussion between the NRC and industry for several years. Since the NGNP is a demonstration plant for first-of-a-kind reactor concept(s), the conceptual design and ultimate NRC licensing of the NGNP will need to address these issues. These issues, summarized by the NRC staff in SECY-02-0139 (see Ref. 4), with follow-up recommendations in SECY-03-0047 (see Ref. 5), were partially addressed by the subsequent Commission Voting Records/Staff Requirements Memorandum (see “Combined Index of Related Commission Documents for 2003” for SECY-03-0047). These issues and the status of their resolution are listed below for consideration of their potential impact on the NGNP project:

Issue 1: *How should the Commission's expectations for enhanced safety be implemented for future non-LWRs*?

Staff recommendation accepted on Issue 1 with: “ the exception of accounting for the integrated risk posed by multiple reactors. The staff should provide further details on the options for, and associated impacts of, requiring that modular reactor designs account for the integrated risk posed by multiple reactors. Historically, the NRC has issued operating licenses to sites with as many as three units, granted Construction Permits for four at one site (Shearon Harris), and docketed another application for five at one site (Palo Verde). The staff should review those dockets for relevant historical regulatory positions on these issues, including potential precedents. The staff will need to establish a usable definition of core damage and will need to determine if the concept of large early release frequency is meaningful or if a level 3 risk assessment would be needed.”

Issue 2: *Should specific defense-in-depth attributes be defined for non-LWRs?*

Staff recommendation approved by the Commissioners: Commission to develop a policy statement on defense-in-depth that is technology neutral and risk-informed.

Issue 3: *How should NRC requirements for future non-LWR plants relate to international codes and standards?*

Commissioners rejected Staff recommendation to engage in international Codes and Standards at this time.

Issue 4: *To what extent should a probabilistic approach be used to establish the plant-licensing basis?*

Staff recommendation approved by the Commissioners: greater use of probabilistic approach to event identification, safety classification of equipment, and replacement of single failure with a reliability criterion.

Issue 5: *Under what conditions, if any, should scenario-specific accident source terms be used for licensing decisions regarding containment and site suitability?*

Staff recommendation approved by the Commissioners**:** retain previous guidance for use of scenario specific source term provided there is sufficient understanding of fuel and fission product behavior.

Issue 6: *Under what conditions, if any, can a plant be licensed without a pressure-retaining containment building?*

Staff recommendation was disapproved by the Commissioners with the following comment: At this time there is insufficient information for the Commission to prejudge the best option and staff should work with industry to evaluate options taking into account design features.

Issue 7: *Under what conditions, if any, can emergency planning zones be reduced, including a reduction to the site exclusion area boundary?*

Staff recommended and Commissioners approved: no change from guidance issued July 30, 1993 and provisions in 10 CFR 50.47.

1.2.1.1.3 Licensing of an Integrated Nuclear Power/Hydrogen Plant

Issues relating to the licensing of an integrated nuclear power plant and hydrogen production facility are basically concerned with the safety implications of the combined operations. Some of these issues include:

Issue 1: *How will licensing safety analyses address integrated safety issues?*

Issue 2: *What will be the role of Probabilistic Risk Assessment (PRA) in addressing integrated safety issues?*

Issue 3: *How will separation/isolation of the nuclear power source from the hydrogen production facility be addressed for licensing purposes?*

Issue 4: *Are there jurisdictional issues associated with licensing the integrated nuclear and hydrogen production facilities?*

1.2.1.1.4 Licensing of a Demonstration Facility

Since the NGNP will be used to demonstrate the exceptional safety characteristics of advanced high-temperature reactors, licensing of the NGNP will have to consider operation of the plant in testing modes that go beyond simply generating electric power and producing hydrogen. In particular, if the NGNP is to be used for prototype testing in support of design certification under 10 CFR 52.47, additional NRC requirements will likely be imposed. The NGNP may receive a license in 2016 to operate in the electricity production mode and hydrogen cogeneration production modes, and then receive license modifications at later dates to perform specific safety tests. Potential licensing issues for demonstration testing may include:

Issue 1: *What will be the range of normal operating conditions, transient conditions, and specified accident sequences to support testing under 10 CFR 52.47?*

Issue 2: *Will beyond-design-basis events be considered?*

Issue 3: *Will testing of normal, transient, and accident sequences involve both the reactor and the hydrogen production facility?*

Issue 4: *Will any additional safety features and provisions be required for the NGNP as a result of planned demonstration testing?*

1.2.1.2 High-Temperature Materials

The thermal, environmental, and service life conditions of the NGNP will make material selection and qualification a significant challenge. New approaches and new materials may be required. The materials will be exposed to temperatures beyond what is now allowed in Section III of the ASME Code. Some important issues that must be addressed are:

- High-temperature mechanical properties (tensile, creep, creep fatigue, stress-rupture, low and high cycle fatigue, fracture toughness) in air and impure He environments
- Environmental degradation processes (metal reactions) due to impure coolant
- Long-term irradiation effects on the materials (tensile, creep, creep fatigue, stress-rupture, low and high cycle fatigue, fracture toughness) and alloying element activation
- High-temperature metallurgical stability (thermal aging effects).

Materials not used previously in the nuclear industry such as carbon-carbon composites and ceramics may be required in components where accident conditions could expose the materials to temperatures approaching 1250 ^{o}C. A program must be instituted to assure compliance with the ASME Boiler and Pressure Vessel Code. The materials issues are significant and will require a well-designed R&D program to resolve.

1.2.1.3 Fuel Design, Fabrication, Testing, and Qualification

Although the general fuel type has been selected (TRISO-coated particles - see Figure 8 below), the final fuel that will be demonstrated has not yet been designed, fabricated, tested, or qualified. A fuel development and qualification program is underway to fabricate, irradiate, and perform post-irradiation simulated accident condition testing. The test fuels will be used to verify that TRISO-coated fuel manufactured under reference process conditions performs satisfactorily under the full range of VHTR normal operating and accident conditions. This work will require significant resources over an extended period with a goal to qualify and fabricate the first NGNP fuel by 2011.

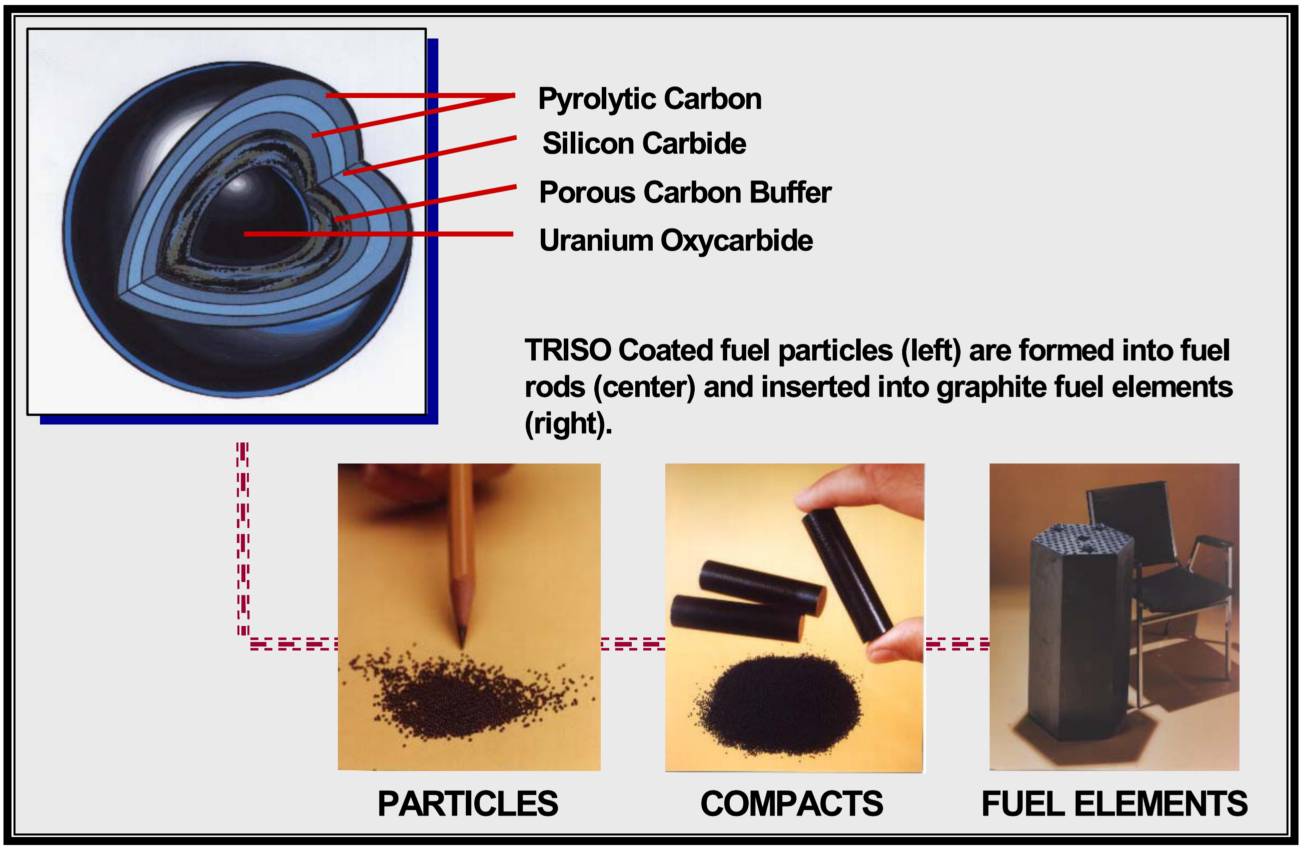

Figure 8. TRISO-coated fuel particles, compacts and fuel elements.

1.2.1.4 Other Open Issues

The existing fuel performance and fission product transport database must be expanded to support the licensing of the VHTR.

Air and water ingress during an accident is a potential problem that needs better definition in terms of understanding the fundamental phenomenon and actual in-reactor performance, without making overly simplified and conservative assumptions that result in requirements that negate some of the natural safety advantages of the technology. Once better understood, air and water ingress mitigation strategies need to be developed.

The graphite components of the reactor are the permanent side reflector, the core blocks, and the core supports. Previous in-core graphite usage in the United States was limited to H-327/H-451, a product that is no longer available. A number of replacements for H-327/H-451 may be available, but irradiation and properties test data are needed to qualify the new materials.

The sulfur-iodine (S-I) and other thermochemical processes for splitting water to generate hydrogen have never been demonstrated beyond laboratory scale. The process may offer advantages in efficiency and environmental friendliness over the presently used electrolysis and steam reforming processes. However, there may be issues associated with demonstrating commercial-scale processes at tens of megawatts thermal power.

A significant materials effort will be required for the reactor pressure vessel, which may have a nominal operating temperature of up to 650 °C with potentially higher off-normal conditions for 10s of hours. The operating and off-normal temperatures and component size will stretch the limits of available ASME approved materials and manufacturing capability.

1.2.2 Constraints

The following are project constraints that will influence the ultimate successful outcome of this project:

1.2.2.1 Schedule

The critical path items that drive the final reactor licensing process are fuel qualification; qualification of high-temperature materials; qualification of graphite; procurement and fabrication of long lead items, such as the pressure vessel; and adaptation of current industry codes and standards to the VHTR. Developing/changing ASME, Institute of Electrical and Electronics Engineers, or other standards and codes may be critical path items that could alter the NGNP schedule.

The current desired schedule for the NGNP is as follows:

- Preconceptual design will be completed during FY-04
- Conceptual design will be completed in FY-05
- Preliminary design will start in FY-06 and be completed in FY-07
- Final design will start in FY-07 and end in FY-09
- Construction will start in FY-11
- A commercial-scale demonstration reactor, capable of producing hydrogen and generating electricity, will begin operation in 2016.

1.2.2.2 Funding

For NGNP operation to begin by 2016, full project funding must be received as projected on a schedule consistent with the NGNP Project schedule for completion of major milestones.

1.2.2.3 Fuel Qualification

All of the initial core load fuel design, fabrication, and qualification must be accomplished successfully by 2011.

1.2.3 Assumptions

The following is a list of project assumptions that form the initial concepts and guidelines for the project. These assumptions shall be updated and/or removed as the project matures and more information becomes available.

- The NRC will have the needed resources available to support the NGNP licensing process in a timely manner
- Hydrogen production will be scalable with pilot and bench scale demonstrations
- Oxygen generated by the hydrogen plant will be bottled or diluted as an off-gas
- Electrical output will be supplied to an interface point with an interconnect to the grid
- All significant technical issues will be resolved in a timely manner to meet the 2016 schedule.

1.3 Ownership of the Functions and Requirements Document

This F&R document is the product of the combined activities of the NGNP Project team. The NGNP Federal Program Director (Jason Remer) or his designee has the responsibility for the content and approval of this document. Requests for changes to this document shall be directed to him. This document is under configuration control and all changes will be approved using formal change control documentation, review, and approval.

2. NGNP PROJECT OVERVIEW

This section provides a descriptive view of the NGNP project as perceived prior to preconceptual studies or conceptual design. It focuses on the functions of the system. There are no requirements in this section. Requirements associated with each of the functions identified in this section are identified in Section 3 of this F&R document. Project engineering requirements are identified in Section 4. Project management requirements are identified in Section 5.

2.1 NGNP Project Functions

The NGNP Project design is to be undertaken to satisfy the following high-level NGNP functions (see Figure 9 below):

- Develop and demonstrate a commercial-scale prototype VHTR
- Develop and demonstrate high efficiency power conversion
- Obtain licenses and permits to construct/operate the NGNP
- Develop and demonstrate hydrogen production
- Include provisions for future testing
- Enable demonstration of energy products and processes.

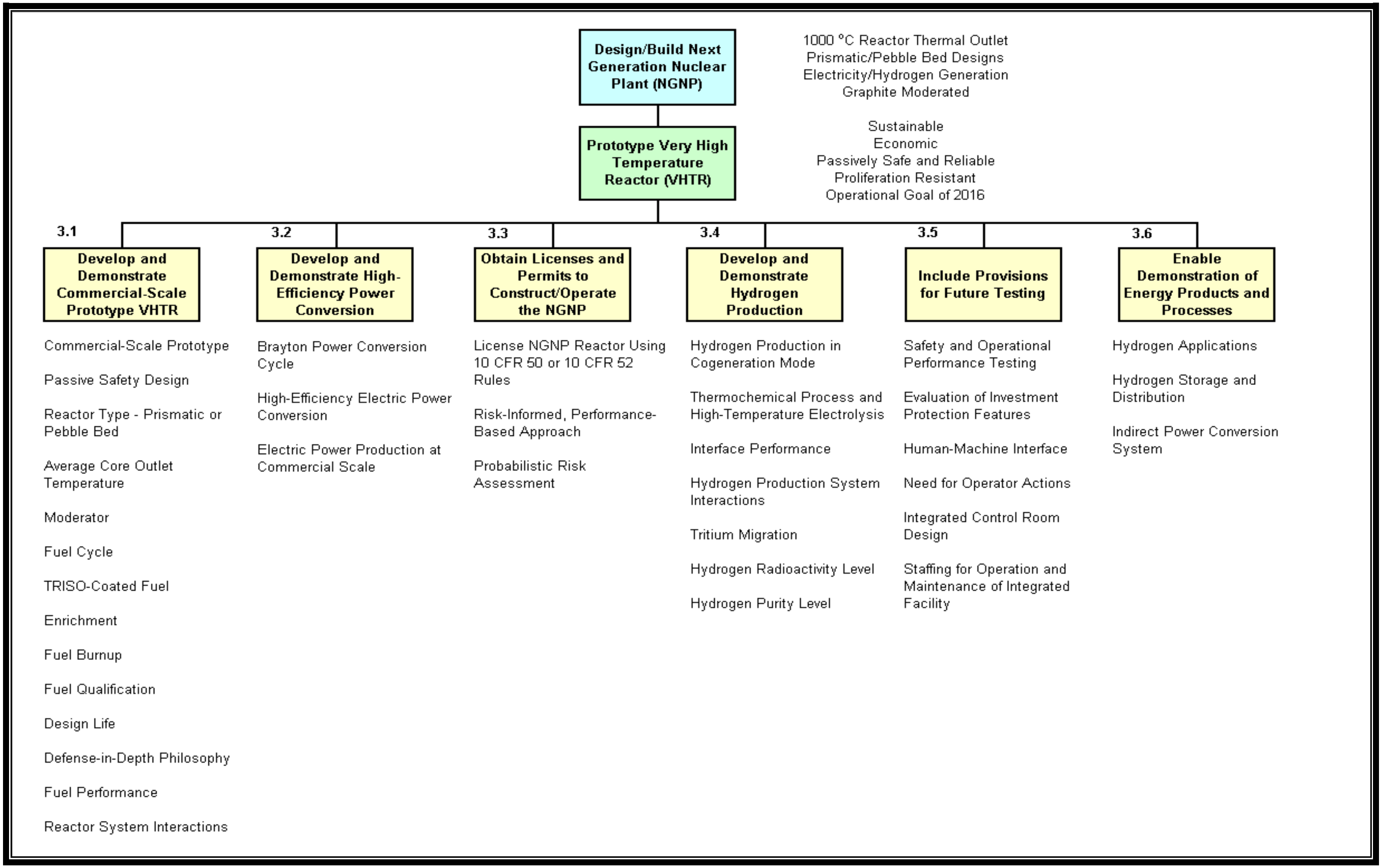

Figure 9. Functions and requirements chart.

2.1.1 Develop and Demonstrate a Commercial-Scale Prototype VHTR

A commercial-scale prototype of a VHTR with a pebble-bed or prismatic core design will be built, tested, and operated to demonstrate the performance characteristics of future advanced high-temperature reactors. The prototype VHTR is called the NGNP. The primary function of this prototype plant will be to verify both operational and safety performance of high-temperature reactors over a range of normal and transient conditions. This demonstration phase will include an extended startup test program to confirm various aspects of the licensing bases for this first-of-a-kind reactor concept. Specific objectives of this phase will include plant operation and control during startup and shutdown, and under full- and part-load conditions. Fuel, coolant, and safety system performance will also be evaluated to address proposed inspections, tests, analyses, and acceptance criteria that would apply to the licensing of future high-temperature nuclear power plants under 10 CFR 52. Because of the nature of an extended testing program, the NGNP will likely include instrumentation and other design features that would not necessarily be included in follow-on commercial nuclear plants. The NGNP will demonstrate the ability to generate process heat in an efficient and reliable manner.

2.1.2 Develop and Demonstrate High-Efficiency Power Conversion

The NGNP will be equipped with a high-temperature a Brayton cycle power conversion system to deliver electric power to the electric grid. The primary function of this power conversion system is to demonstrate the ability of a VHTR to produce low-cost electricity, using high-temperature gas-turbine technology in an efficient and reliable manner.

2.1.3 Obtain Licenses and Permits to Construct/Operate the NGNP

In accordance with the Energy Reorganization Act of 1974, the NGNP will be licensed by NRC under 10 CFR 50 or 10 CFR 52, for the purpose of demonstrating the suitability of a VHTR for commercial electric power and hydrogen production applications. The licensing of the NGNP by NRC will also demonstrate the effectiveness of licensing future advanced high-temperature reactor concepts for commercial applications. In particular, it is anticipated that many of the current issues associated with NRC licensing of a non-LWR and the use of nuclear power for hydrogen production will be resolved during the licensing of the NGNP. The licensing of the NGNP by NRC should also contribute to the stabilization of future non-LWR licensing activities by identifying weaknesses or gaps in the licensing data needs and eliminating uncertainties in the cost and schedule associated with obtaining construction and operating licenses for future nuclear power plants.

2.1.4 Develop and Demonstrate Hydrogen Production

Hydrogen production plant(s) will be included as part of the NGNP facility to demonstrate the capability of high-temperature reactors to produce hydrogen in a cogeneration mode and demonstrate hydrogen production. Hydrogen production will be demonstrated using high-temperature water electrolysis and a thermochemical process (see Figures 10 and 11 in Section 3).

Fifty MWt of the plant energy will be available for producing hydrogen in a cogeneration mode. The intent of this demonstration phase is to verify hydrogen production efficiencies and evaluate hydrogen system operation and control. Interface issues, including system interactions, instrumentation and control, and safety features (barriers and isolation features), will also be evaluated.

2.1.5 Include Provisions for Future Testing

The NGNP will include provisions for conducting future test programs after the initial licensing and demonstration test program is complete. The intent of these provisions is to provide sufficient design flexibility to ensure that future research and development missions are not precluded by unnecessary system design constraints. Examples of future testing programs that should be considered in developing the preconceptual designs for the NGNP include: testing programs to evaluate plant safety and performance margins, assessment of proposed investment protection concepts, training programs, evaluation of advanced control room designs, and development and testing of advanced instrumentation and control systems. The tests could also cover a range of normal operating conditions, transient conditions, and specified accident conditions, that would provide data needed for high-temperature reactors (with similar safety features) to meet the NRC design certification requirements of 10 CFR 52.47.

2.1.6 Enable Demonstration of Energy Products and Processes

Americans import over 50 percent of their oil and are expected to import nearly 70 percent by 2025. If the nation is to liberate itself from dependence on imported oil, it must achieve scientific breakthroughs on alternative fuels and technologies. The most promising long-term revolution in energy use is the expansion of hydrogen energy. Transportation accounts for 70 percent of total U.S. oil consumption. Widespread use of hydrogen fuel cell vehicles would reduce United States oil imports and increase energy independence. United States fuel cell leadership in transportation also could reap enormous economic benefits, as the U.S. auto industry alone accounts for five percent of the U.S. gross domestic product and supports 6.6 million jobs. Also, hydrogen fuel cells, which produce only water as a by-product rather than the pollutants in gasoline vehicle emissions, can help clean the air we breathe.

Hydrogen-powered fuel-cell vehicles have the potential to provide energy diversity, fuel economy, and environmental benefits. Since hydrogen can be manufactured from water using nuclear energy as well as other renewable resources, it offers the potential for eventual “freedom” from the nation’s near-exclusive reliance on petroleum for transportation.

The President’s budget includes a major new partnership between the federal government and energy companies to help accelerate widespread use of fuel-cell vehicles by focusing on hydrogen fuel production, storage, and infrastructure. The NGNP project implements the basic infrastructure necessary to meet the President’s goals. The NGNP reactor is a long-range, high-payoff research and development effort that could dramatically improve the performance and cost effectiveness of hydrogen production without displacing private investments.

In addition, the NGNP will be designed to allow testing other applications requiring process heat. Up to 50 MWt of the plant power will be available for evaluating the performance characteristics of the process heat applications (e.g., the electric-power production efficiencies of a supercritical-CO_2 Brayton cycle). It is envisioned that the process heat applications will utilize either a tertiary loop with heat provided by the same intermediate loop that provides heat to the hydrogen production plant(s), or may possibly utilize waste heat provided by primary system precooler(s) and/or intercooler(s) in a bottoming cycle configuration. This will allow the NGNP to be operated in the 100% a Brayton cycle power production mode, or at somewhat less electricity production with 50 MWt power used for hydrogen production or other process heat applications (a total of 50 MWt will be available for hydrogen and process heat applications). The intent of this demonstration phase is to evaluate the performance characteristics of other process heat applications, such as the potentially higher efficiencies achievable with a Brayton cycle that uses supercritical CO_2 compared with other Brayton-cycle working fluids (i.e., helium) at equivalent temperatures.

2.2 NGNP Operational Overview

For the purposes of this document, it is assumed that the management and operating contractor (Bechtel BWXT Idaho, LLC or its successor) at the U.S. Department of Energy's Idaho National Engineering and Environmental Laboratory will have overall operational responsibility for the NGNP demonstration plant. Operations of the NGNP plant will be in compliance with all applicable NRC, DOE, state, and local regulations and requirements.

The operational objectives of the NGNP are to demonstrate the superior capabilities of a VHTR for high-temperature, high-efficiency energy conversion to electricity and to demonstrate hydrogen production (and other process heat applications) in a cogeneration mode. In addition, the NGNP will include provisions for future testing. These objectives imply three basic modes of operation for the NGNP (i.e., electric power production mode, cogeneration mode, and testing mode). Therefore, sufficient flexibility must be provided in the design of the plant for operation in each of these modes. Additional instrumentation and safety features will be required to ensure safe operation of the NGNP and the collection of adequate data for validating system performance over a range of conditions.

The following sections briefly discuss each of these modes of operation and the plant features to accommodate these modes of operation.

2.2.1 Electric Power Production

Electric power production will be accomplished using a high-temperature a Brayton cycle. The principal objective of NGNP during this mode of operation is to assess overall plant performance characteristics for the production of electricity. These performance characteristics include plant operation and control under full and partial load conditions and during various operational transients, including startup and shutdown. NGNP characteristics to be evaluated include reactor systems and plant performance, plant control system capabilities, plant economics, and overall plant efficiencies. In addition, evaluation of investment protection features, safety margins, and operational procedures may be included in this mode of operation.

For this mode of operation, the electrical power conversion system will be designed and rated for operation up to 100% rated reactor power and with a net electrical output efficiency of at least 45%.

2.2.2 Cogeneration

The principal objective of this mode of operation is the evaluation of hydrogen production in a cogeneration power plant configuration. To accomplish this objective, the plant will be designed to utilize 50 MWt of the plant's thermal power for the production of hydrogen. A thermochemical process and/or the thermally assisted electrolysis of water will be used to produce hydrogen. Operation in the cogeneration mode will allow evaluation of the overall performance of the integrated NGNP and hydrogen production plant(s). Specific areas of interest would be the performance characteristics of the intermediate heat exchanger and potential interactions between the nuclear and hydrogen production plants. Overall plant operation and control features will be assessed and hydrogen production efficiencies will be evaluated.

A key feature in the design of the plant for operation in this mode will be the integration of the hydrogen production plant and nuclear power source to maximize overall plant production efficiency. This could involve utilization of waste heat from intercoolers/precoolers to assist in the hydrogen production process. Desired temperatures for some of the thermochemical processes (i.e., the sulfuric acid decomposition phase of the S-I process) are in the range of 850 ^{o}C to 1000 ^{o}C and between 750 ^{o}C and 900 ^{o}C for high-temperature steam electrolysis. Therefore, options for utilization of these low-grade waste heat sources may be limited.

2.2.3 Safety and Performance Demonstration Testing

A high-level objective of the NGNP is to demonstrate by test the exceptional safety and performance capabilities of VHTRs. To achieve this objective, the NGNP, as a first-of-a-kind prototype of a VHTR, will be subjected to extended testing to assess not only normal operational performance, but also various upset conditions, including anticipated operating occurrences, design basis events, and potentially beyond design basis events. These tests will demonstrate the robustness of the NGNP reactor design and provide valuable data for verification and validation of analysis tools to be used in the design and analysis of future commercial gas-reactor concepts. Sufficient instrumentation must therefore be provided to ensure the collection of adequate data for validating system performance over a range of normal and accident conditions. The instrumentation provided would also provide needed capabilities to support future NGNP research and development missions such as those identified in Section 2.1.5.

It is also anticipated that these testing programs will provide the basis for future commercial VHTR design certifications under 10 CFR 52. Specifically, the design certification requirements of 10 CFR 52.47, for reactor designs that differ significantly from current light water reactors, include requirements for "…testing of an appropriately sited, full-size, prototype of the design over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions." To accomplish this, the NGNP will include designed provisions to evaluate individual plant safety functions/systems, integrated plant safety systems, and the safety related characteristics of the coupled VHTR and hydrogen production plant.

3. FUNCTIONS, REQUIREMENTS, AND BASES

Statements in Sections 1 and 2 are descriptive, are for information only, and are not requirements. Not all statements in Section 3 are requirements. Requirements are specifically identified by the inclusion of one and only one of the terms “shall”, “shall where practical”, or “may”. These terms have very specific and legal definitions. The use of the term “shall” indicates a mandatory provision for which the contractor (or designer) is liable under contract (or work package). The use of the term “shall where practical” likewise indicates such a mandatory provision, any deviation from which shall be justified by a trade study. The use of the term “may” indicates an option or alternative that is allowed, but not necessarily required. Descriptive and non-binding statements specifically do not include a “shall,” “shall where practical,” or “may”.

The Generation IV goals listed in Section 1.1.3 are mapped to the requirements of Section 3 in Figure 2. In addition, the “Basis” statement for each requirement below identifies the Generation IV goal or goals from which the requirement is derived. The Generation IV roadmap is Reference 1.

3.1 Develop and Demonstrate a Commercial-Scale Prototype VHTR

The requirements in this section support the development and demonstration of a commercial-scale prototype VHTR. The NGNP will demonstrate both operational and safety performance of the NGNP over a range of normal and transient conditions and demonstrate superior economics for the nth-of-a-kind reactors compared to alternate energy sources. The NGNP will demonstrate the ability to generate process heat in an efficient and reliable manner.

3.1.1 Commercial-Scale Prototype

The reactor shall be built to commercial scale with a power level consistent with passive safety features.

Basis: This requirement supports Generation IV Economics-1 and -2 goals. The requirement supports the viability of licensing and commercialization of future plants without having to demonstrate scalability. This will help to ensure acceptance in the private sector and reduce costs to license follow-on facilities. The NGNP power level should be as high as possible consistent with the use of passive safety features and accounting for design uncertainties. For example, for a single prismatic or pebble bed reactor module, a power level greater than 500 MWt or even 700 MWt may be achievable. The intent is to maximize the power for a single reactor module to achieve a lower cost per unit power. The NGNP will consist of only one reactor module.

3.1.2 Passive Safety Design

The NGNP shall have adequate passive safety systems to cool the core down from full power to safe shutdown mode and limit the fuel temperatures under accident conditions to levels consistent with the fuel performance requirements defined in 3.1.13.

Basis**:** This requirement supports the Generation IV Safety and Reliability-1, -2 and -3 goals. The intent of this requirement is to incorporate passive safety features that do not depend on active engineered safety features or human actions to protect the worker, public, and environment.

3.1.3 Reactor Type – Prismatic or Pebble Bed

The reactor shall be either prismatic or pebble bed.

Basis: This requirement supports the Generation IV Economics-1, -2, and Safety and Reliability-1, -2, and -3 goals. The Generation IV technology roadmap identifies both the prismatic and pebble bed reactor concepts as potential VHTR systems with high scores in economics because of their high efficiency. High scores were received in safety and reliability due to the inherent safety features of the fuel and reactor. The VHTR is a high-efficiency system that can produce electricity or supply process heat to a broad spectrum of high-temperature and energy-intensive, non-electric processes.

3.1.4 Average Core Outlet Temperature

The primary system coolant shall provide for an average reactor vessel outlet temperature of at least 1000 °C.

Basis: This requirement supports the Generation IV Sustainability-1 and Economics-1 goals. In addition, the requirement is defined in the Generation IV roadmap (p.16, p.48).

3.1.5 Moderator

The reactor shall be graphite moderated.

Basis: This requirement supports the Generation IV Safety and Reliability-1, -2, and -3 goals. It is also defined in the Generation IV roadmap (p.48). Graphite moderated reactors are proven and have been licensed in the United States.

3.1.6 Fuel Cycle

The NGNP shall use a once-through uranium fuel cycle.

Basis: This requirement supports the Generation IV Proliferation Resistance and Physical Protection-1 goal. The Generation IV roadmap assumes (p.51) a once-through (open) fuel cycle for the VHTR. Like LWR spent fuel, VHTR spent fuel could be disposed of in a geologic repository or conditioned for optimum waste disposal. The NGNP system may have the flexibility to adapt to other fuel cycles in the future that offer enhanced waste minimization (Roadmap p.13).

3.1.7 TRISO-Coated Fuel

The fuel to be demonstrated for the VHTR shall be made from TRISO-coated particles, each containing a kernel of uranium oxycarbide (UCO) or uranium dioxide enclosed in coating *shells. The fuel particles may be agglomerated into cylindrical compacts or into spherical pebbles. For initial fuel loadings, qualified uranium dioxide fuel may be acceptable, to be replaced by UCO, when it is qualified.*

Basis: This requirement supports the Generation IV Safety and Reliability-1, -2, -3 and Proliferation Resistance and Physical Protection-1 goals. The fuel for the NGNP builds upon the successful demonstration of TRISO-coated particle fuel in Germany. The initial fuel loading(s) may utilize uranium dioxide to be replaced by uranium oxycarbide when it is qualified. This phasing of fuel types will add assurance to meeting the NGNP schedule for full demonstration and operation by 2016. The TRISO-coated particle is a spherical layered composite about 1 mm in diameter. Each micro-sphere acts as a miniature pressure vessel, a feature that is intended to impart robustness to the reactor fuel system.

The desired fuel kernel for VHTR demonstration in the NGNP is a low-enriched mixture of UO_2 and UC_2 (referred to as UCO) surrounded by a porous graphite buffer layer. UCO was selected because the mixture of carbide and oxide components results in very little free oxygen being released due to fission. As a result, very little carbon monoxide is generated during irradiation, and little kernel migration (i.e., amoeba effect) is expected. The oxycarbide fuel also ties up the rare earth (lanthanide) fission products as immobile oxides in the kernel, which gives the fuel added resiliency under accident conditions.

3.1.8 Enrichment

The fuel shall contain uranium with an enrichment of less than 20% U-235.

Basis: This requirement supports the Generation IV Sustainability-1, Economics-1, and Proliferation Resistance and Physical Protection-1 goals. The Generation IV Roadmap assumes (p.51) use of low-enriched uranium for the VHTR to minimize proliferation concerns.

3.1.9 Fuel Burnup

The fuel burnup shall be such that maximum fuel utilization is achieved while minimizing waste streams for the open fuel cycle, optimizing fuel economics, and ensuring reduced proliferation risks.

Basis: This requirement supports the Generation IV Sustainability-2, Economics-1, and Proliferation Resistance and Physical Protection-1 goals. The *Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program*, p. F-1 (see Ref. 6) plans to demonstrate that a fuel burnup of at least 16% can be achieved. Higher burnup will increase the fuel utilization factor and reduce the need for storage per MWe power produced. In addition, the ratio of Pu-240 to total Pu in the fuel increases with burnup, which reduces proliferation risks.

3.1.10 Fuel Qualification

Fuel performance shall be qualified and shall include a fuel design specification, fuel fabrication specification, quality assurance plan and program, irradiation testing and identification of failure probabilities as a function of operating condition.

Basis: This requirement supports the Generation IV Safety and Reliability-1 and -3 goals. The *Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program*, p.xi and F-1 (see Ref. 6), and Generation IV roadmap, p. 49, provide additional bases for this requirement. This requirement is also based on a desire to meet an Environmental Protection Agency (EPA) Protective Action Guideline on the elimination of all consequences of radiotoxicity outside the site area boundary.

3.1.11 Design Life

The NGNP shall be designed for a 60-year life. For components that cannot be designed for 60-year operation, provisions shall be made in the design for economic replacement of the part or component.

Basis: This requirement supports the Generation IV Sustainability-1 and Economics-2 goals. The commercialization of the design concept (NGNP) assumes an economical solution and rate-of-return commensurate with other investment opportunities that will encourage private industry investment.

3.1.12 Defense-in-Depth Philosophy

The NGNP shall be designed in accordance with defense-in-depth philosophy and the intent to eliminate the need for off-site evacuation and sheltering.

Basis: This requirement supports the Generation IV Economics-2, and Safety and Reliability-1, -2, and -3 goals. The NGNP design should be guided by PRA results that include a broad spectrum of challenges initiated by either internal or external events and the consequences of the hydrogen production plant nearby. It is expected that the NGNP will demonstrate exceptional safety capabilities. The anticipated operating occurrences and design basis events will be confirmed during licensing. Beyond design basis events, identified by the PRA analysis, will be investigated while maintaining fuel integrity. This testing will confirm one of the several layers of the defense-in-depth strategy to reduce the consequences of postulated severe accidents and protect the NGNP against internal and external events.

3.1.13 Fuel Performance

The NGNP fuel shall perform to a level such that the following top-level requirements are satisfied:

- *During normal operations, offsite radiation doses to the public shall be less than the limits specified in Appendix I of 10 CFR 50 and 40 CFR 190.*
- *Occupational radiation exposures shall be no greater than 10% of the limits specified in 10 CFR 20.*
- *During design-basis accidents, offsite doses at the site Exclusion Area Boundary (EAB) shall be less than those specified in the Manual of Protective Action Guides and Protective Actions for Nuclear Incidents (EPA-520/1-75-001) for sheltering and evacuation.*

Basis: This requirement supports the Generation IV Safety and Reliability-1, -2, and -3 goals. The *Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program*, p. xi and F-1 and Generation IV roadmap p. 49 also identifies this requirement. This requirement is based on a desire to meet an Environmental Protection Agency (EPA) Protective Action Guideline on the elimination of all consequences of radiotoxicity outside the site area boundary, as referenced above.

3.1.14 Reactor System Interactions

The interfaces between the NGNP reactor and the hydrogen production plants or other process heat systems shall be designed to ensure that failures or upset conditions in the reactor primary system do not result in failures or adverse impacts to the other interfacing systems.

Basis: This requirement supports the Generation IV Safety and Reliability-1 goals. The intent of this requirement is to ensure that failures in the reactor primary system do not propagate into failures in other interfacing systems. For example, a break in the intermediate heat exchanger at the primary system interface should not cause overpressurization of components in the hydrogen production system(s).

3.2 Develop and Demonstrate High-Efficiency Power Conversion

The requirements in this section support the development and demonstration of a high-temperature, high-efficiency power conversion system to produce low-cost electricity, using high-temperature gas-turbine technology, in an efficient and reliable manner.

3.2.1 Brayton Cycle Power Conversion

The NGNP shall generate electric power using a Brayton cycle power conversion system.

Basis: This requirement supports the Generation IV Sustainability-2 and Economics-1 goals. The NGNP Project wishes to demonstrate commercial-scale production of electric power using a Brayton cycle power conversion system. The electric power conversion system efficiency increases with reactor coolant outlet temperature. The reactor coolant outlet temperature is expected to be at least 1000 ^{o}C. Increased efficiency will reduce the waste mass, volume, and radiotoxicity per MWe power produced. The power conversion system will include the gas turbine, electrical generator, and other ancillary equipment as necessary. Most of the power conversion system components may use current industry state-of-the-art technology.

3.2.2 High-Efficiency Electric Power Conversion

The electric power conversion system, in the all-electric mode, shall have an overall efficiency (defined as net electrical output divided by net thermal output at the reactor outlet) of at least 45% to convert reactor thermal power to electrical. Overall efficiency shall be as high as possible, and consistent with other key commercial parameters, to optimize economics.

Basis: This requirement supports the Generation IV Sustainability-2 and Economics-1 goals. If many of these plants are to be built in the future, the overall cost for the nth-of-a-kind NGNP plant on a $/MWe basis has to be competitive with other modes of electric power generation. The high-temperature Brayton cycle has the potential to achieve overall power conversion efficiency in the range of 45% to 50% while retaining other desirable commercial characteristics, such as capacity factor and ease of maintenance. Increased efficiency will reduce the waste mass, volume, and radiotoxicity per MWe power produced.

3.2.3 Electric Power Production at Commercial Scale

The electric power production system shall be designed and sized to produce electricity at commercial scale using 100% of the NGNP thermal energy from the reactor.

Basis: This requirement supports the Generation IV Economics-1 goal. This is a management decision to demonstrate the viability of commercialization of future plants without having to demonstrate scalability. Electricity will be sold to the commercial grid to help offset NGNP construction and operation expenses.

3.3 Obtain Licenses and Permits to Construct/Operate the NGNP

The requirements in this section support the licensing and permitting of the NGNP, in accordance with the Energy Reorganization Act of 1974, by NRC under 10 CFR 50 or 10 CFR 52, for the purpose of demonstrating the suitability of the VHTR for commercial electric power and hydrogen production applications. In particular, it is anticipated that many of the current issues associated with NRC licensing of a non-LWR and the use of nuclear power for hydrogen production will be resolved during the licensing of the NGNP and, therefore, set the stage for commercial plant licensability.

3.3.1 License NGNP Reactor Using 10 CFR 50 or 10 CFR 52 Rules

The NGNP reactor shall obtain an NRC license via 10 CFR 50 or 10 CFR 52 rules for operation by the middle of the next decade.

Basis: This requirement supports the Generation IV Safety and Reliability-1, -2, and -3, goals. In addition, the NRC Regulation NUREG-0980, June 2002, incorporates the following Legislation that requires licensing of a demonstration reactor used as part of the power generation system:

> *Energy Reorganization Act of 1974, Title II – Nuclear Regulatory Commission, Sec. 202, which states in part:*
>
> "Notwithstanding the exclusions provided for in section 110a, or any other provisions of the Atomic Energy Act of 1954, as amended (42 USC 2140(a)), the Nuclear Regulatory Commission, except as otherwise specifically provided by section 110 b. of the Atomic Energy Act of 1954, as amended (42 USC 2140(b)), or other law, has licensing and related regulatory authority pursuant to chapters 6, 7, 8, and 10 of the Atomic Energy Act of 1954, as amended, as to the following facilities of DOE:
>
> Other demonstration nuclear reactors when operated as part of the power generation facilities of an electric utility system, or when operated in any other manner for the purpose of demonstrating the suitability for commercial application of such a reactor."

3.3.2 Risk-Informed, Performance-Based Approach

The NGNP project shall use a risk-informed, performance-based approach to regulatory decision-making.

Basis: This requirement supports the Generation IV Safety and Reliability-1, -2, and -3 goals. Licensing of a nuclear plant currently requires an extensive Probabilistic Risk Assessment to supplement deterministic requirements. Since many of these deterministic requirements do not apply to advanced reactors, the NRC has also indicated its intent to work with industry to:

> "…develop an approach (and ultimately a framework) that would be applicable to all of the advanced reactor designs currently under consideration. This approach, referred to as "technology-neutral", would take advantage of lessons learned from prior regulatory experience and assure an effective use of both deterministic and probabilistic methods in licensing and regulating advanced reactors." (see Ref. 7).

A risk-informed, performance-based approach to regulatory decision-making combines the "risk-informed" and "performance-based" elements and applies these concepts to NRC rulemaking, licensing, inspection, assessment, enforcement, and other decision-making. Stated succinctly, a risk-informed, performance-based regulation is an approach in which risk insights, engineering analysis and judgment including the principle of defense-in-depth and the incorporation of safety margins, and performance history are used, to (1) focus attention on the most important activities, (2) establish objective criteria for evaluating performance, (3) develop measurable or calculable parameters for monitoring system and licensee performance, (4) provide flexibility to determine how to meet the established performance criteria in a way that will encourage and reward improved outcomes, and (5) focus on the results as the primary basis for regulatory decision-making.

3.3.3 Probabilistic Risk Assessment

The NGNP project shall perform a full-scope probabilistic risk assessment analysis for internal and external events. The analysis shall be conducted under either 10 CFR 50 or 10 CFR 52.

Basis: This requirement supports the Generation IV Safety and Reliability-1, -2, and -3 goals. The PRA analysis will help in meeting the following goals:

- Identification of development needs for analysis of off-normal conditions such as transients, design basis events, and severe accidents
- Development and/or modification of analytical methods and computer codes, their validation, and application
- Development and/or assessment of experimental information required for validation of safety characteristics and methods
- Identification of the impact and necessary mitigating features associated with a coupled Hydrogen Generation Plant.

The NRC PRA policy statements are (60FR42622, August 16, 1995):

- The use of PRA technology should be increased in all regulatory matters to the extent supported by the state of the art in PRA methods and data and in a manner that complements the NRC's deterministic approach and supports the NRC's traditional defense-in-depth philosophy.

- PRA and associated analyses should be used in regulatory matters, where practical within the bounds of the state of the art, to reduce unnecessary conservatism associated with current regulatory requirements, regulatory guides, license commitments, and staff practices. Where appropriate, PRA should be used to support the proposal for additional regulatory requirements in accordance with 10 CFR 50.109 (Backfit Rule). The existing rules and regulations shall be complied with unless these rules and regulations are revised.

- PRA evaluations in support of regulatory decisions should be as realistic as practicable and appropriate supporting data should be publicly available for review.

- The Commission's safety goals for nuclear power plants and subsidiary numerical objectives are to be used with appropriate consideration of uncertainties in making regulatory judgments on the need for proposing and backfitting new generic requirements on nuclear power plant licenses.

3.4 Develop and Demonstrate Hydrogen Production

The requirements in this section support the capability of high-temperature reactors to produce hydrogen in a cogeneration mode. Hydrogen production will be demonstrated using high-temperature water electrolysis and thermochemical processes. Fifty MWt of the plant thermal energy will be available for producing hydrogen in a cogeneration mode. Interface issues, including system interactions, instrumentation and control, and safety features (barriers and isolation features) will also be evaluated.

3.4.1 Hydrogen Production in Cogeneration Mode

The NGNP shall be designed for continuous operation in either the 100% electric power production mode or in the cogeneration mode with the equivalent of up to 50 MWt of the reactor's thermal energy used for hydrogen production.

Basis: This requirement supports the Generation IV Sustainability-1 and Economics-1 goals. The hydrogen production plant should be designed to produce hydrogen as efficiently and economically as possible. For the thermochemical process, the entire 50 MWt can be utilized as heat for the reaction processes. For the high-temperature steam electrolysis process, the energy content of the 50 MWt can be partitioned such that a portion of the electricity generated from the main turbine is used for steam electrolysis with the remaining portion of the 50 MWt used to heat the water feeding the process. For either process, assuming a 40% efficient hydrogen production process and 50 MWt of thermal power, about 0.17 kg/s of hydrogen should be produced on a continuous basis. This level of hydrogen generation is enough to demonstrate commercial processes.

3.4.2 Thermochemical Process and High-Temperature Electrolysis

Hydrogen production shall be demonstrated using a thermochemical process and a high-temperature steam electrolysis process.

Basis: This requirement supports the Generation IV Sustainability-1 and -2, and Economics-1 goals. The splitting of water has the potential to produce hydrogen economically and safely without releasing any greenhouse gases, while conserving other natural resources such as methane.

Sample thermochemical and electrolysis processes are depicted in Figures 10 and 11 below:

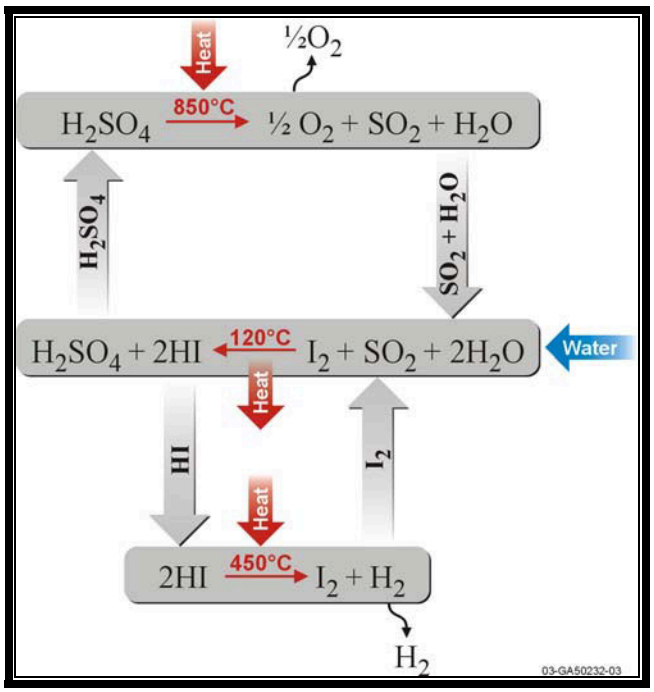

Figure 10. Sulfur-iodine thermochemical process.

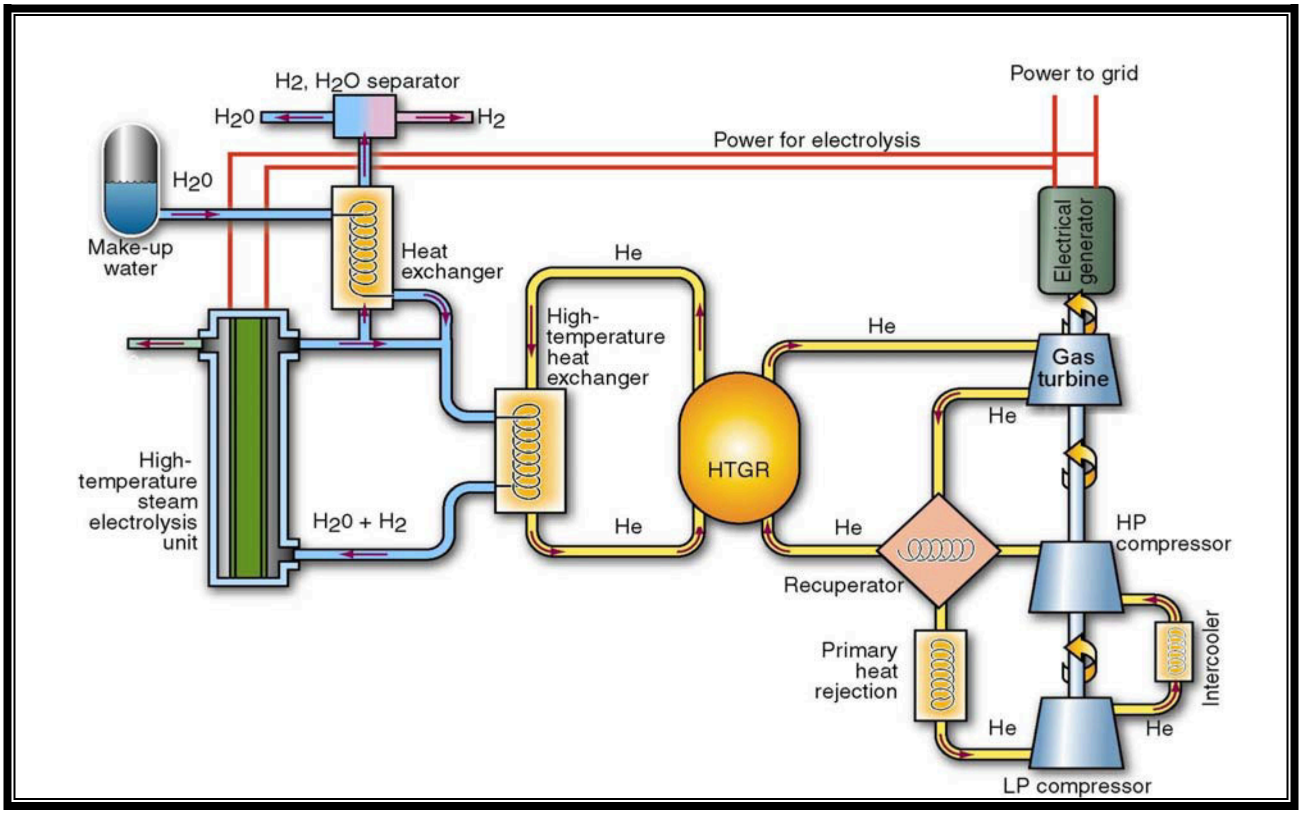

Figure 11. High-temperature electrolysis.

3.4.3 Interface Performance

The interface between the NGNP reactor and the hydrogen production plants shall be designed to allow for safe transitions between all-electric power production at levels up to 100%, to the production of hydrogen and electric power in the cogeneration mode (where the hydrogen production consumes up to 50 MWt) without reactor shutdown.

Basis: This requirement supports the Generation IV Safety and Reliability-1, -2, and -3 goals. The intent of this requirement is to provide plant design capabilities to accommodate thermal transients (cycles) and to operate efficiently and safely in the following steady state or continuous operating modes:

- 100% electric power operation
- 50 MWt used to generate hydrogen with the remainder used to produce electricity.

3.4.4 Hydrogen Production System Interactions

The interfaces between the hydrogen production plant(s) and the NGNP reactor 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 NGNP reactor.

Basis: This requirement supports the Generation IV Safety and Reliability-1, -2, and -3 goals. The intent of this requirement is to ensure that failures in the hydrogen production systems do not propagate to failures in the reactor primary system or to conditions in the reactor primary system that could result in plant component damage and/or technical specification limits being exceeded.

3.4.5 Tritium Migration

The interface system between the NGNP and the hydrogen production plant(s) shall be designed to ensure that tritium migration into the hydrogen production system(s) will be limited, such that the maximum amount of tritium released from the integrated NGNP facilities or found in drinking water does not exceed EPA standards.

Basis: This requirement supports the Generation IV Safety and Reliability-1, -2, and -3 goals. Applicable requirements include the Clean Water Act/Water Programs and 40 CFR 100-149 as well as the applicable requirements of 40 CFR 190.

3.4.6 Hydrogen Radioactivity Level

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 for the integrated NGNP and hydrogen production facilities do not exceed NRC regulatory limits.

Basis: This requirement supports the Generation IV Sustainability-2 and Safety and Reliability-1 goals. The requirement is intended to ensure occupational dose limits defined in 10 CFR 20, Subpart C, and dose limits to the public specified in 10 CFR 20, Subpart D are not exceeded.

3.4.7 Hydrogen Purity Level

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

Basis: This requirement supports the Generation IV Economics-1 goal. Required industry hydrogen purity levels vary depending on the particular application. For example, proton exchange membrane fuel cells may tolerate relatively high levels of some impurities, but cannot tolerate sulfur and carbon monoxide (CO) impurities. For many fuel cell applications, purity levels up to 99.999% are desirable (see Ref. 8). This purity level is also consistent with current industry purification capabilities using Pressure Swing Adsorption processes.

3.5 Include Provisions for Future Testing

The requirements in this section are written in anticipation of potential future needs or missions for the NGNP reactor after the initial licensing and demonstration-testing program is completed. The intent of this section is to ensure that sufficient flexibility is provided in the design to allow future research and development testing programs to be conducted. As a prototype of potential future commercial nuclear power plants, the NGNP will represent a national asset whose value should not be compromised by near-term design decisions that do not include consideration of future uses for the facility after its initial mission is completed. Examples of future testing programs include: testing programs to evaluate plant safety and operational performance margins, assessment of proposed investment protection concepts, training programs, evaluation of advanced control room designs, and development and testing of advanced instrumentation and control systems.

3.5.1 Safety and Operational Performance Testing

The NGNP reactor design shall include sufficient flexibility to allow for the future investigation of safety and operational performance margins in the plant responses to anticipated operating occurrences and risk-important events, as advancements and modifications for future designs are considered.

Basis: This requirement supports Generation IV Safety and Reliability-1, -2, and -3 goals. As commercial plant designs evolve from the prototype NGNP design, design enhancements to improve long-term availability of systems, effective fuel utilization, and plant safety and reliability will undoubtedly be developed. The NGNP reactor can serve as a test bed for evaluating these design enhancements. In addition, with appropriate instrumentation, the NGNP can provide data needed for verification and validation of codes used for licensing and design certification of future evolutionary VHTR plants.

3.5.2 Evaluation of Investment Protection Features

The NGNP shall include provisions for incorporating and evaluating investment protection systems that are separate and independent of plant safety and control systems.

Basis: This requirement supports the Generation IV Economics-2 and Safety and Reliability-1 goals. Future VHTR designs can be expected to include investment protection systems that monitor and maintain plant parameters within acceptable limits to ensure plant component and technical specification limits are not exceeded. Since these systems are primarily intended to protect the initial plant investment and ensure continued power production capability, the testing of these systems would be separate from normal safety and licensing test requirements. Therefore, the ability to develop and test different investment protection systems should be considered as a future NGNP mission.

3.5.3 Human-Machine Interface

The NGNP design shall optimize the human-machine interface based on human factors engineering principles and operating experience to the extent possible for a single integrated reactor and hydrogen plant without compromising plant safety.

Basis: This requirement supports Generation IV Economics-1 and Safety and Reliability-1, -2, and -3 goals. Improved ergonomics (e.g., control room layout), state-of-the-art plant diagnostic and prognostic systems and training will enhance proper operator response to normal and off-normal integrated plant conditions. Although the NGNP will have only one module, future commercial plants may be multi-module designs.

3.5.4 Need for Operator Actions

The NGNP integrated facility shall be designed to minimize the need and maximize the time available for operator actions in response to plant transients, and other routine/non-routine activities during normal operations, startup, shutdown, and surveillance/testing.

Basis: This requirement supports the Generation IV Economics-1 and Safety and Reliability-1, -2, and -3 goals. Such a design will reduce operator stresses and burden in the early phases of transients by maximizing the length of time available following the initiation of an event for proper plant diagnostics and prognostics. During this time, operators can confirm the event, and take control of the plant or can "stand back" from the control panels while the sequence proceeds with or without automatic control (active and passive modes respectively).

3.5.5 Integrated Control Room Design

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

Basis: This requirement supports the Generation IV Economics-1 and Safety and Reliability-1, -2, and -3 goals. This will promote high operational reliability of the man-machine interface for operation and control of the complete plant.

3.5.6 Staffing for Operation and Maintenance of Integrated Facility

The NGNP facility shall be designed to optimize the staffing needed for integrated operation and maintenance activities to the extent possible without compromising plant safety.

Basis: This requirement supports the Generation IV Economics-1 goal. The reduced requirements of reactor and hydrogen process operators for surveillance/testing and the routine/non-routine activities will minimize the operation and maintenance costs, making plant economics more attractive.

3.6 Enable Demonstration of Energy Products and Processes

The requirements in this section support a future potential testing mission for the NGNP that would utilize the process heat and hydrogen production capabilities of the NGNP to support future energy infrastructure R&D needs. The intent of this section is to ensure that sufficient flexibility is provided in the design to allow future research and development testing programs to utilize the unique capabilities of the NGNP facilities. Examples of these capabilities include the production of hydrogen to support future hydrogen infrastructure research and development programs and the use of process heat from the NGNP reactor for evaluating alternative electric energy conversion systems and process heat applications. It is not anticipated that the NGNP project would fund these projects. Rather, the facilities would be made available to other government and industry programs that would pay for the use of the facilities and they would conduct their own research programs, subject to the constraints and requirements of the NGNP Project Office.

3.6.1 Hydrogen Applications

The NGNP Project shall establish a test bed for evaluating various uses of hydrogen produced by the NGNP hydrogen production plant(s).

Basis: This requirement supports the Generation IV Sustainability-1 and Economics-1 goals. There are many DOE and industry initiatives or programs that would benefit from a hydrogen infrastructure test bed for demonstration and evaluation of alternative uses or applications of the hydrogen generated by the NGNP. These initiatives or programs include DOE's Freedom Car Initiative, fuel cell programs being conducted by both DOE and industry, other transportation related hydrogen applications, and various petrochemical programs that utilize hydrogen. The hydrogen infrastructure test bed would also effectively utilize the hydrogen produced by the NGNP that might otherwise be wasted if an effective use were not identified.

3.6.2 Hydrogen Storage and Distribution

The NGNP Project shall establish hydrogen storage and distribution systems adequate to support the needs of the hydrogen infrastructure test bed, and designed to demonstrate the safety and economics of the different hydrogen storage and distribution technologies.

Basis: This requirement supports the Generation IV Sustainability-1 and Economics-1 goals. As an energy carrier, hydrogen poses some unique technical challenges that need to be evaluated. Hydrogen storage as a liquid or compressed gas requires energy-intensive processes. Similarly, hydrogen distribution by pipelines or transport involves tradeoffs between the energy required to deliver the hydrogen and the distribution requirements of the system (i.e., pumping or transport distances involved). These considerations will influence the overall economics and viability of a future hydrogen economy. In addition, many of the issues associated with building a hydrogen infrastructure in the United States (materials issues, pipeline and transport safety requirements, refueling station standards, etc.) can all be addressed as part of the development of the hydrogen infrastructure test bed.

3.6.3 Indirect Power Conversion System

The NGNP shall include provisions for the later addition of an indirect supercritical-CO_2 Brayton cycle power conversion system that uses up to 50 MWt from the NGNP reactor to produce electricity at a target overall power conversion efficiency of 45%.

Basis: This requirement supports the Generation IV Economics-1 goal. The NGNP Project wishes to include the option for demonstrating/testing of an indirect supercritical-CO_2 Brayton cycle power conversion system utilizing a portion of the thermal power provided by the NGNP reactor. This will demonstrate the potentially higher overall cycle efficiencies at lower turbine inlet temperatures for supercritical CO_2, compared to other Brayton cycle working fluids. While this option would not be part of the initial preconceptual design, the implications of the addition of this system 2–3 years after initial plant startup should be addressed along with the identification of any special provisions to be included in the preconceptual design to minimize future cost and schedule impacts.

4. PROJECT ENGINEERING REQUIREMENTS

The requirements listed in this section are intended to be a minimum list to be used as a starting point for preconceptual design. The need for additional specific requirements will flow from the preconceptual design.

4.1 Generic Requirements

The regulatory and contractual requirements, and standards, contained in this Section shall be followed as applicable.

4.1.1 DOE Orders

This project shall comply with appropriate DOE Orders identified in the Bechtel BWXT, LLC, M&O Contract with NE-ID, DE-AC07-99ID13727, List B.

The following Orders, Policies, and Manuals have specific applicability to this project. The applicable Orders, Policies, and Manuals include, but are not limited to, the following list:

- DOE O 413.3, Program and Project Management for the Acquisition of Capital Assets
- DOE O 420.1A, Facility Safety
- DOE O 435.1, Radioactive Waste Management
- DOE Policy 450.4, Safety Management System Policy.

Note: Codes and standards applicable to the design and construction of the reactor, power conversion unit, and the hydrogen generation plant shall where practicable be commercial codes and standards. However, to the extent that the NGNP will be built within a Department of Energy facility, and will interface with other existing facilities, the project must evaluate DOE Orders to ensure that the NGNP can interface with the DOE Site and be acceptable to the DOE.

4.1.2 Regulations

The following regulations are of specific applicability to the NGNP:

- 10 CFR 20, Standards for Protection Against Radiation
- 10 CFR 50, Domestic Licensing of Production and Utilization Facilities
- 10 CFR 51, Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions
- 10 CFR 52, Early Site Permits; Standard Design Certifications; and Combined Licenses for Nuclear Power Plants
- 10 CFR 73 Physical Protection of Plants and Materials

- 10 CFR 74 Material Control and Accounting of Special Nuclear Material
- 10 CFR 75 Safeguards on Nuclear Material -- Implementation of US/IAEA Agreement
- 10 CFR 95 Security Facility Approval and Safeguarding of National Security Information and Restricted Data
- 10 CFR 100, Reactor Site Criteria
- 29 CFR 1910, Occupational Safety and Health Standards, Subpart H - Hazardous Materials
- 40 CFR 50 - 99, Clean Air Act
- 40 CFR 100 - 149, Clean Water Act
- 10 CFR 835, Occupational Radiation Protection
- 40 CFR 190, Environmental Radiation Protection Standards for Nuclear Power Operations
- 40 CFR 1502, Environmental Impact Statement.

4.2 Design Requirements

4.2.1 Architectural Engineering Standards

The buildings and structural design for non-nuclear facilities associated with the high-temperature reactor shall comply with the applicable DOE, Federal, state, and local codes, as appropriate.

4.2.2 Industry Codes and Standards

Industry codes and standards shall be selected and followed for all structures and systems as appropriate.

Since an objective of this project is to demonstrate a VHTR whose design can support the design and construction of commercial plants of similar design, commercial codes and standards applicable to the design and construction of the reactor, power conversion unit, and the hydrogen generation plant shall, where appropriate, be commercial codes and standards.

In July 1996 Pacific Northwest National Laboratory (PNNL) prepared and published "Codes and Standards and Other Guidance Cited in Regulatory Documents", Rev. 3, NUREG/CR-5973. PNNL performed an exhaustive search of NRC regulatory documents and compiled a list of about 4,500 codes, standards, and guidance documents applicable to the design of a nuclear power plant. It indicates the source (traced to a regulatory document) of each such citation, and whether it is acceptable, partially acceptable, or unacceptable to the NRC, or whether it is simply background information.

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

4.2.3 Reliability, Availability, Maintainability and Inspectability

The NGNP shall be designed for high reliability, availability, maintainability, and inspectability (RAMI). Innovative designs to maximize RAMI for the NGNP shall be considered where cost effective and feasible. Design goals shall be established to minimize human error. Consideration for maximum use of innovative techniques that allow for remote maintenance and easy replacement or repair of components shall be provided.

4.2.4 Safeguards

The NGNP will be fueled with enriched uranium. Therefore, the NGNP shall incorporate measures necessary to prevent unauthorized access to nuclear material items, theft, diversion, hoaxes, and other malevolent acts, including sabotage intended to release radioactivity or disrupt operations as stated in 10 CFR 74, *Material Control and Accounting of Special Nuclear Material*, and 10 CFR 75, *Safeguards on Nuclear Material – Implementation of US/IAEA Agreement.* In conjunction with 10 CFR 95, *Security Facility Approval and Safeguarding of National Security Information and Restricted Data*, the licensee shall include all controls as defined in the regulation necessary to protect the subject information.

4.2.5 Security

Per 10 CFR 73, *Physical Protection of Plants and Materials*, provisions for site security, including, barriers, access controls, intrusion detection systems, site security forces, central alarm facilities, backup power for security functions, protection during storage and handling, and protection during radiological, fire, or other emergencies shall be included to provide for the protection of the reactor, reactor fuel, spent fuel, electrical power, and hydrogen, all of which are anticipated to be present at high-hazard levels.

Protection methods used against the possibility of violent external assault, attack by stealth or deception, and sabotage, including the potential participation of one or more employees shall be included.

4.2.6 Hydrogen Safety Design

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. In the event that the hydrogen production facility also produces and stores significant quantities of oxygen, the requirements of 29 CFR 1910.104, Oxygen, shall also be applicable. During Preconceptual Design, 29 CFR 1910 shall be reviewed for additional applicable sections depending on the specific chemical processes to be used in the hydrogen production process. In addition, although hydrogen is not listed in Appendix A of 29 CFR 1910.119 as a highly hazardous chemical, any process that involves a flammable gas on site in one location, in quantities greater than 10,000 pounds (4,535 kg) is required to develop a process safety management program under 29 CFR 1910.119.

4.3 Quality and Configuration Management Requirements

4.3.1 Quality Assurance

The NGNP project shall use the U.S. national consensus standard ASME NQA-1-1997 "Quality Assurance Program Requirements for Nuclear Facilities Applications" (see Ref. 9) and Subpart 4.2 of ASME NQA-1-2000 “Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development” for project specific development R&D activities.

The Quality Assurance requirements for specific-project activities will be specified in project-specific Quality Assurance Plans (QAPs). The project-specific QAPs will include the management controls commensurate with the project work scope and importance to the Generation IV Program goals and objectives.

4.3.2 Configuration Management

A formal configuration management process shall be established and used throughout the NGNP life cycle to control the activities and interfaces among design, construction, and information management activities to ensure that the configuration of the facility is established, approved, and maintained. Configuration management practices shall apply to all contractors and subcontractors as identified by the Systems Engineering Management Plan (SEMP). The requirements for configuration management are found in the U.S. national consensus standard NQA-1-1997.

4.4 Environmental Requirements

The NGNP project shall minimize the use of natural resources consistent with efficient and cost effective facility and process designs.

4.4.1 Environmental Impact Statement

An Environmental Impact Statement shall be prepared for the NGNP. NRC regulations implementing the National Environmental Policy Act are contained in 10 CFR 51, *Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions*, with 10 CFR 51.45, *Environmental Report*, providing general requirements for the contents of the environmental reports, including consideration of alternatives to proposed actions.

4.4.2 Air

Emissions from the NGNP and hydrogen production facilities shall comply with all the applicable requirements of the Clean Air Act/Air Programs. Applicable Federal regulations include 40 CFR 50 - 99, *Clean Air Act*.

4.4.3 Water

For the use and release of water, the NGNP and hydrogen production facilities shall comply with all applicable requirements of the Clean Water Act/Water Programs. Applicable Federal regulations include 40 CFR 100–149, *Clean Water Act*.

4.4.4 Radioactive Releases

Offsite radioactive releases from the NGNP shall comply with all NRC, EPA and associated DOE requirements including dose limits specified in 10 CFR 20, 10 CFR 50 Appendix I, and 40 CFR 190 for normal operation and 10 CFR 100 for design basis accidents.

4.4.5 Waste

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

4.4.6 Spent Nuclear Fuel

Provision for temporary storage of discharged spent fuel shall be provided in the design of the NGNP facility. Spent nuclear fuel generated by the NGNP reactor will be packaged and shipped to a Federal Repository for burial according to the applicable regulations in effect at the time of reactor discharge.

5. PROJECT MANAGEMENT REQUIREMENTS

The NGNP Project shall be managed as a Major System (MS) Project as defined by DOE O 413.3 and in accordance with the requirements of DOE O 413.3. The NGNP Project is organized as shown below in Figure 12.

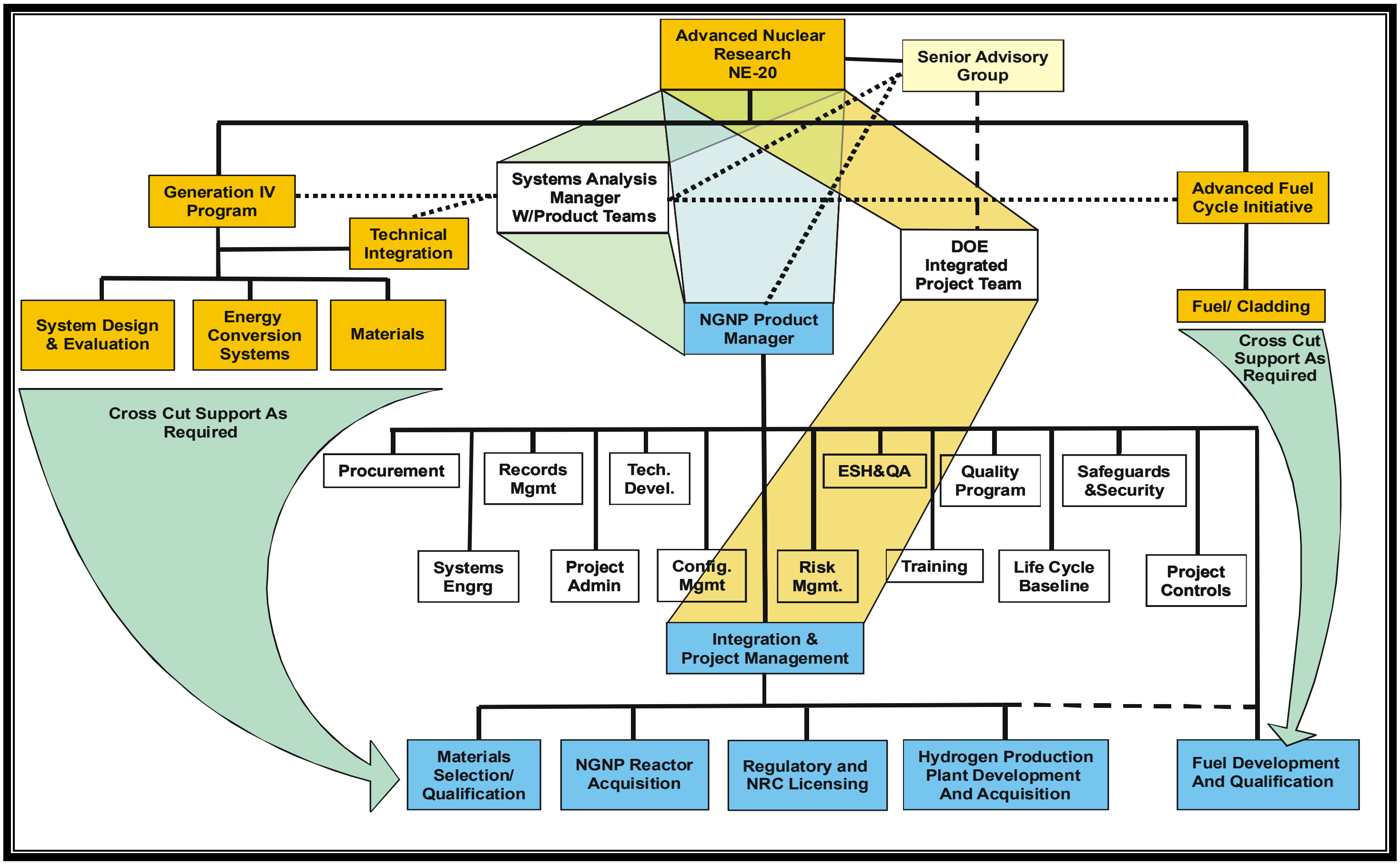

Figure 12. NGNP project organization.

5.1 Systems Engineering Management Plan

The NGNP project shall develop a SEMP that integrates all technical activities into cohesive and cost-effective processes with a goal of reducing costs and increasing the probability of project success through the implementation of practices and procedures geared towards each phase of the project. The plan shall be prepared in detail appropriate to the current phase of the project and shall be maintained for the life of the project. The format and guidance of the current version of the *Systems Engineering Handbook,* available from www.incose.org is recommended.

5.2 Project Logic and Critical Decisions

The NGNP shall be managed in project phases. A Critical Decision (CD) shall formalize the beginning of each project phase. A CD is a formal determination or decision by the

Department of Energy to proceed to the next phase and commit resources (see Figure 13). The five traditional construction project CDs shall be followed:

- CD-0, Approve Mission Need
- CD-1, Approve Preliminary Baseline Range
- CD-2, Approve Performance Baseline
- CD-3, Approve Start of Construction; and
- CD-4, Approve Start of Operations or Project Closeout.

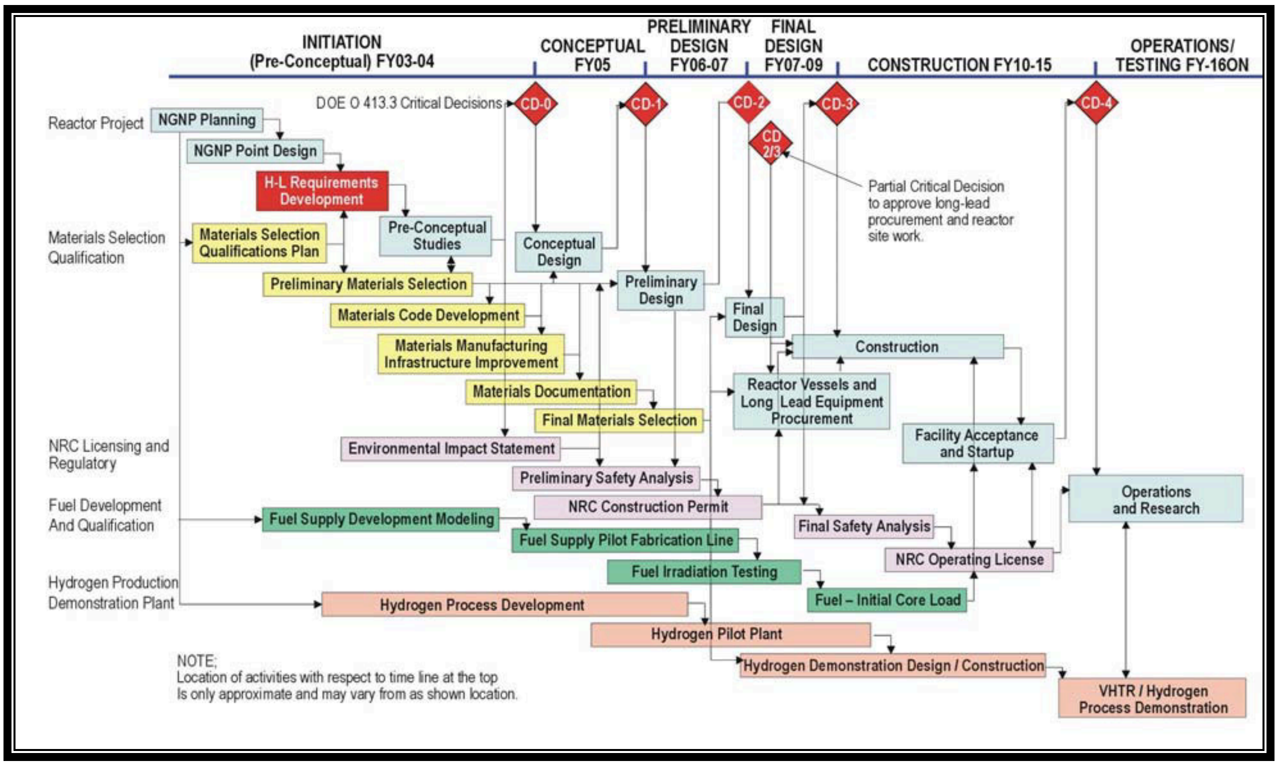

Figure 13. NGNP high-level project logic.

5.3 Management Procedures

The NGNP project shall prepare and maintain a set of managerial directives and procedures defining Contractor and sub-contractor functions, responsibilities, interfaces, and interactions.

5.4 Safety

The NGNP project shall implement an Integrated Safety Management System in accordance with DOE Policy 450.4, Safety Management System Policy and related guidance.

5.5 Quality Assurance

The NGNP project shall prepare and maintain a Quality Assurance Program Plan and provide competent and independent quality assurance oversight of project activities.

5.6 Project Risk Management

The NGNP project shall maintain a formal risk management program.

5.7 Environmental Issues

The NGNP project shall develop and maintain plans, schedules, cost estimates, special reports, and reviews covering environmental issues associated with characterization, monitoring, decontamination, and decommissioning.

5.8 Plans and Reports

The NGNP project shall maintain schedule, cost, and technical baselines and a performance reporting system in accordance with applicable DOE guidance. Cost and Schedule Control Systems shall include but not be limited to management to established baselines, variance analysis, and change control.

5.9 Funds Control System

The NGNP project shall implement and use a funds control system that satisfies the budget preparation and execution requirement of the DOE and which is reconcilable to the Contractor's cost management system.

5.10 Support Facilities

The NGNP project shall identify and define the schedule interfaces with the fuel fabrication, spent fuel storage and disposal, electrical grid, and hydrogen use facilities.

5.11 Prior Reactor Lessons Learned

The NGNP project shall apply the lessons learned from the nuclear power plant commercial sector as well as DOE experimental reactor development and operation experience.

5.12 Value-Engineering Program

The NGNP project shall implement a value-engineering program.

6. REFERENCES

1. U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, A Technology Roadmap for Generation IV Nuclear Energy Systems, GIF-002-00, December 2002, http://gif.inel.gov/roadmap/.

2. INPRO, International Project on Innovative Nuclear Reactors and Fuel Cycles, IAEA General Conference 2000, "Guidance for the Evaluation of Innovative Nuclear Reactors and Fuel Cycles," IAEA-TECDOC-1362, June 2003.

3. MacDonald, P. E., et al, NGNP Point Design – Results of the Initial Neutronics and Thermal-Hydraulic Assessments During FY-03, INEEL/EXT-03-00870, Rev.1, September 2003.

4. U.S. Nuclear Regulatory Commission, SECY-02-0139, Plan for Resolving Policy Issues Related to Licensing Non-Light-Water Reactor Designs, July 22, 2002.

5. U.S. Nuclear Regulatory Commission, SECY-03-0047, Policy Issues Related to Licensing Non-Light-Water Reactor Designs, March 28, 2003.

6. Feltus, M. A., et al, Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program, Oak Ridge National Laboratory, ORNL/TM-2002/262, April 2003.

7. U.S. Nuclear Regulatory Commission, NRC'S Advanced Reactor Research Program, SECY-03-0059, Advanced Reactor Research Infrastructure Assessment, Attachment 2, Revision 3, January 2003.

8. Ogden, J. M., Review of Small Stationary Reformers for Hydrogen, IAEA/H2/TR-02/002, 2002.

9. American Society of Mechanical Engineers, Quality Assurance Requirements for Nuclear Facilities, NQA-1-1997.