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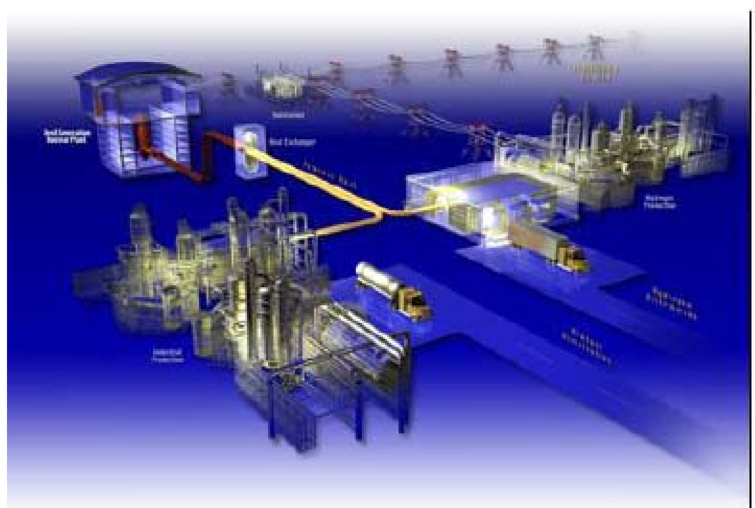
Next Generation Nuclear Plant Project Technology Development Roadmaps: The Technical Path Forward

John W. Collins

January 2009



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Next Generation Nuclear Plant Project

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Approved by:

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EXECUTIVE SUMMARY

Industry experience repeatedly demonstrates the consequences of proceeding with projects using technologies that are not sufficiently mature. The U.S. General Accounting Office noted that these consequences manifest themselves as cost overruns and schedule delays late in the project life cycle [GAO 2007]. To avoid these undesirable consequences, the Next Generation Nuclear Plant (NGNP) project initiated efforts to assess technology readiness of critical plant, areas, systems, subsystems, and components (PASSC) and identify the steps required to ensure sufficient maturity prior to inclusion into the NGNP design.

This document presents the NGNP critical PASSCs, establishes a baseline for the current technology readiness status, and provides a path forward to achieve increasing levels of technical maturity and reduce risk. In May 2008, the suppliers were provided a scope of work in which they were asked to conduct a Technology Readiness Assessment and identify critical PASSCs. Technology Readiness Levels (TRL) were assessed and Technology Development Roadmaps (TDRM) were generated for each critical PASSC based on a set of requirements, including high level operating conditions. These requirements and operating conditions are consistent with those found in the *NGNP System Requirements Manual* (SRM) [INL 2008a] and *Summary of Bounding Requirements for the NGNP Demonstration Plant F&ORs* [INL 2008b]. The salient features of these pre-conceptual design requirements are as follows:

- Reactor outlet temperature of 900–950°C
- Pressure of 5–9 MPa
- Indirect Cycle (i.e., steam generator in the secondary loop)
- Hydrogen Production in the secondary or tertiary loop
- GenIV fuel type.

This document describes the technology readiness assessment and roadmapping process and features the resulting TRLs and TDRMs. As such, this document includes:

- Identification of NGNP's Critical PASSCs
- Design Description of Critical PASSCs
- TRLs assessed against critical PASSCs
- TDRMs depicting the path forward for each critical PASSC
- Impact analysis of reducing the reactor outlet temperature from 950°C to 750–800°C (see Appendix A)
- Supplier submitted TDRMs and TRLs (see Appendix B)
- Supplier submitted Test Plans to document tests required to increase Technical Maturity (see Appendix B).

Technology Readiness of Critical NGNP PASSCs

Of over 400 identified PASSCs, 18 were determined to be critical from a technology perspective. Critical PASSCs are defined as those components that are not commercially available or do not have proven industry experience. Three supplier teams (i.e., AREVA, General Atomics, and Westinghouse) were tasked to evaluate and identify the critical PASSCs of their proposed design configurations. The suppliers each identified 14–16 PASSCs. Additionally, the Idaho National Laboratory (INL) is currently conducting research on prismatic fuel elements and Hydrogen Production System (HPS) options. These PASSCs were consolidated into the 18 NGNP critical PASSCs.

Table ES-1 provides a mapping between the NGNP consolidated critical PASSCs and supplier-identified critical PASSCs. The table consists of five primary columns, representing the consolidated NGNP critical PASSCs, the AREVA critical PASSCs, the General Atomics critical PASSCs, the Westinghouse Electric Company critical PASSCs, and the INL Fuel Element and HPS PASSCs. The sub-columns to the left of the PASSC names identify the section number of the supplier report wherein the technology readiness assessment details are provided. In the case of NGNP consolidated PASSCs, the number represents the section in this document. Blank cells in the table represent an absence of supplier-identified PASSCs corresponding to the NGNP consolidated PASSCs. PASSCs are organized according to the five NGNP areas: Nuclear Heat Supply System (NHS), Heat Transport System (HTS), HPS, Power Conversion System (PCS), and Balance of Plant (BOP). One addition to the table not used in the rest of the document is Other Development Issues. This is presented to provide a place holder for additional PASSCs that suppliers deemed important, but not critical, in the TDRM work and activities associated with the scope of work tasked to them. As the design matures and requirements change, additional PASSCs may be added to those already identified in this report.

Table ES-1. NGNP Critical PASSCs

NGNP Consolidated		AREVA		General Atomics		Westinghouse Electric Company		Idaho National Laboratory	
Section	TDRM	Sectio	TDRM	Sectio	TDRM	Sectio	TDRM	Sectio	TDRM
Nuclear Heat Supply									
2.1	Reactor Pressure Vessel	6.1.1	Vessel System	SSC5	Reactor Pressure Vessel				
2.2	Reactor Vessel Internals	6.1.2	Reactor Vessel Internals						
2.3	Reactor Core & Core Structure	6.1.3	Reactor Core Design Features	SSC4a	Reactor Core	012	Core Structure Graphite & Ceramics		
				SSC4b	Reactor Graphite				
2.4	Fuel Elements					011	Fuel Element – Pebble-bed		Fuel Element – Prismatic
2.5	Reserve Shutdown System					013	Reserve Shutdown System		
2.6	Reactivity Control System	6.1.4	Neutron Control System	SSC1	Reactor Control Equipment	014	Reactivity Control System		
				SSC2	Control Rods				
2.7	Core Conditioning System			SSC8	Shutdown Cooling Heat Exchanger	015	Core Conditioning System		
2.8	Reactor Cavity Cooling System	6.1.6	Reactor Cavity Cooling System	SSC9	Reactor Cavity Cooling System	016	Reactor Cavity Cooling System		
Heat Transfer System									
3.1	Intermediate Heat Exchangers	6.2.3	Helical Tube IHX	SSC7	Intermediate Heat Exchanger	004	IHX A		
		6.2.7	Compact IHX			005	IHX B		
3.2	Circulators	6.2.1	Primary Gas Circulator	SSC6	Helium Circulators	003	Primary Circulator		
		6.2.5	Secondary Gas Circulator						
3.3	Cross Vessel Piping	6.2.4	Primary Hot Gas Duct	SSC3	Hot Duct	006	Piping		
3.4	High Temperature Valves	6.2.2	High Temperature Flapper Valve	SSC12	High Temperature Valves				
		6.2.6	High Temperature Isolation Valve						
3.5	Mixing Chamber					007	Flow Mixing Chamber		
Hydrogen Production System									
4.1	Hydrogen Production System			SSC13	Sulfur-Iodine HPS	008	Hybrid Sulfur HPS		High Temp. Electrolysis HPS
Power Conversion System									
5.1	Steam Generator	6.3.1	Steam Generator	SSC10	Steam Generator	009	Steam Generator		
5.2	PCS Equipment for Direct Combined Cycle *			SSC11	PCS Turbomachinery				
Balance of Plant									
6.1	Fuel Handling System	6.4.2	Fuel Handling System	SSC14	Fuel Handling and Storage System				
6.2	Instrumentation and Control	6.4.1	Primary Loop Instrumentation	SSC15	Primary Circuit and BOP Instrumentation				
				SSC16	Reactor Protection, Investment Protection, Plant Control, Data and Instrumentation				
Other Development Issues (Not a Critical PASSC)									
N/A						010	Software Codes V&V		

* This alternate configuration is for a power conversion option that places the steam generator in the primary loop. It is included here because of the attractiveness of this combined-cycle option for an electricity producing plant.

Each critical PASSC was evaluated through a Technology Readiness Assessment and assigned a TRL based on the technical maturity of the PASSC. TRLs are an input to inform NGNP project management of the readiness of a particular PASSC. The TRL provides one measure of the level of risk encountered by the project. For TRLs 1-5, assessment typically occurs on an individual technology or component with a calculated roll up TRL for the associated subsystems, systems, and areas. As the technology or component progress to further maturity, integrated testing occurs, allowing TRL assessments directly against subsystems and systems. The integrated testing or modeling occurs at increasingly larger scales and in increasingly relevant environments, thus achieving higher TRL ratings. Abbreviated TRL definitions are shown in Figure ES-1.

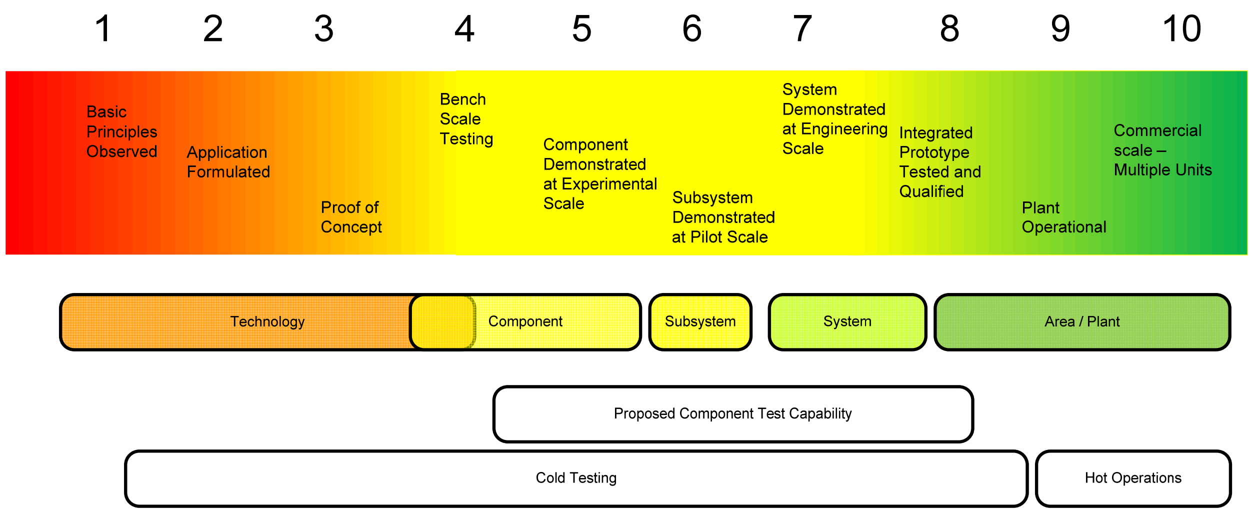

Figure ES-1. Technology Readiness Levels

Understanding the TRL of the NGNP's critical PASSCs creates a starting point for developing the steps needed to further mature the technologies and demonstrate reliable performance of components or systems. These steps are consolidated into TDRMs, which provide the framework to systematically perform decision analysis, reduce risk, and mature technologies early in the project, and thus avoid cost overruns and schedule delays late in the project.

Technology Development Roadmaps

With the baseline PASSCs and their associated TRLs defined, a TDRM is developed to guide the needed maturation, as shown in Figure ES-2. As the technology matures, an early step is to select between competing technologies. In technology down selection, decision discriminators are developed as the important parameters that a successful technology would have to satisfy to assist NGNP in meeting its mission. This list of parameters is then consolidated into key selection discriminators that focus the data collection on the parameters important to the NGNP, namely those that distinguish the benefits of one technology from another. Typically, technologies or components must be matured to a TRL of 5 to proceed with down selection when the technologies are sufficiently understood and the risks of making the wrong choices are minimized. The tasks required for technology down selection include studies, tests, evaluations, modeling, simulations, qualitative analyses, and quantitative analyses.

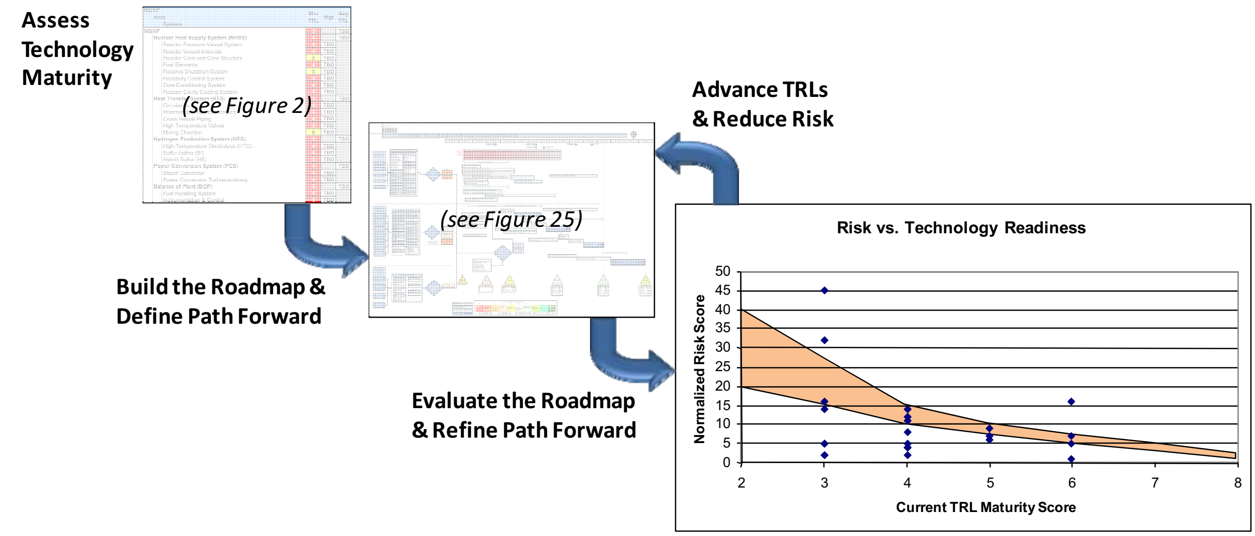

Figure ES-2. Following a TDRM increases Readiness while Reducing Risk.

The TDRM process focuses the research and development (R&D) efforts and engineering studies on the known risks to advancing the selected technology and satisfying the increasingly demanding and scaled up tests. In the NGNP application, TDRMs provide the required structure and are the primary means to systematically perform risk-informed decision making, risk reduction, technology down selection, and technology qualification and maturation in a cost effective and timely manner. Additionally, TDRMs serve to coordinate engineering, R&D, and licensing efforts. The steps in the process include Structure Identification, Technology Readiness Assessment, Technology Selection, Technology Maturation, and Test Plan Development. Technology roadmaps for critical NGNP PASSCs were developed to:

- Set the vision for maturing technologies to the required TRL
- Identify the key selection discriminators and drive the needed actions to down select technologies and designs
- Ensure technology readiness is demonstrated through testing, modeling, simulations, piloting, and prototyping
- Provide early identification and resolution of technical risks
- Avoid late project technical challenges, which manifest themselves as cost overruns and schedule delays
- Develop the test plans to provide demonstrable evidence of the technology maturation required for codification and qualification.

Test Plans are established for the critical PASSCs, including high-temperature heat applications. These test plans are specific to the supplier identified critical PASSC and proposed research; modeling; and laboratory, bench-scale, environmental, pilot-scale, integrated, and engineering-scale testing required to advance the technology from its current readiness level through the next and subsequent levels to a TRL level of 8. Included in the test plans are the test objective, the duration of the test, the scale of the test, and the proposed location. Additionally, the items to be tested, the features to be tested, the test approach, the pass/fail criteria, safety considerations, and test deliverables are included, where possible, in the test plans found in Appendix B.

It is anticipated that the operating parameters and requirements will be modified to meet the end user needs and the market driven needs for the NGNP. Specifically, as Senior Advisory Group meetings have been held and agreements reached, a new reference design may include:

- Reactor outlet temperature of 750–800°C
- Pressure of 5–9 MPa
- Indirect cycle
- Steam Generator in the Primary Loop (for the Prismatic Reactor).

As requirements change, the critical PASSCs and TRLs will need to be evaluated against the new requirements.

Although the TRL ratings and associated TDRMs are against the pre-conceptual design requirements, Appendix A identifies potential impacts to the technology readiness as requirements are changed to a reactor outlet temperature of 750–800°C. This impact analysis goes beyond that required for this deliverable and foreshadows the potential impact of a change in requirements. Furthermore, PCS Equipment for Direct Combined Cycle is included as a critical PASSC that is required for the General Atomics' design with the Steam Generator in the primary loop. General Atomics developed this PCS option because of the attractiveness of a combined-cycle for producing electricity.

Summary Roadmaps for NGNP Areas

The near-term tasks required to mature a technology from its current readiness level to the next level are captured by area in the summary roadmaps for each of the consolidated critical PASSCs (see Figures ES-3 through ES-7). For some critical PASSCs (e.g., the HPS), the advancement to the next TRL will allow for down selection between competing technologies. For other PASSCs, this TRL advancement is designed to occur in a timely fashion to support conceptual, preliminary, and final design; Combined License Application submittals, and safety basis development.

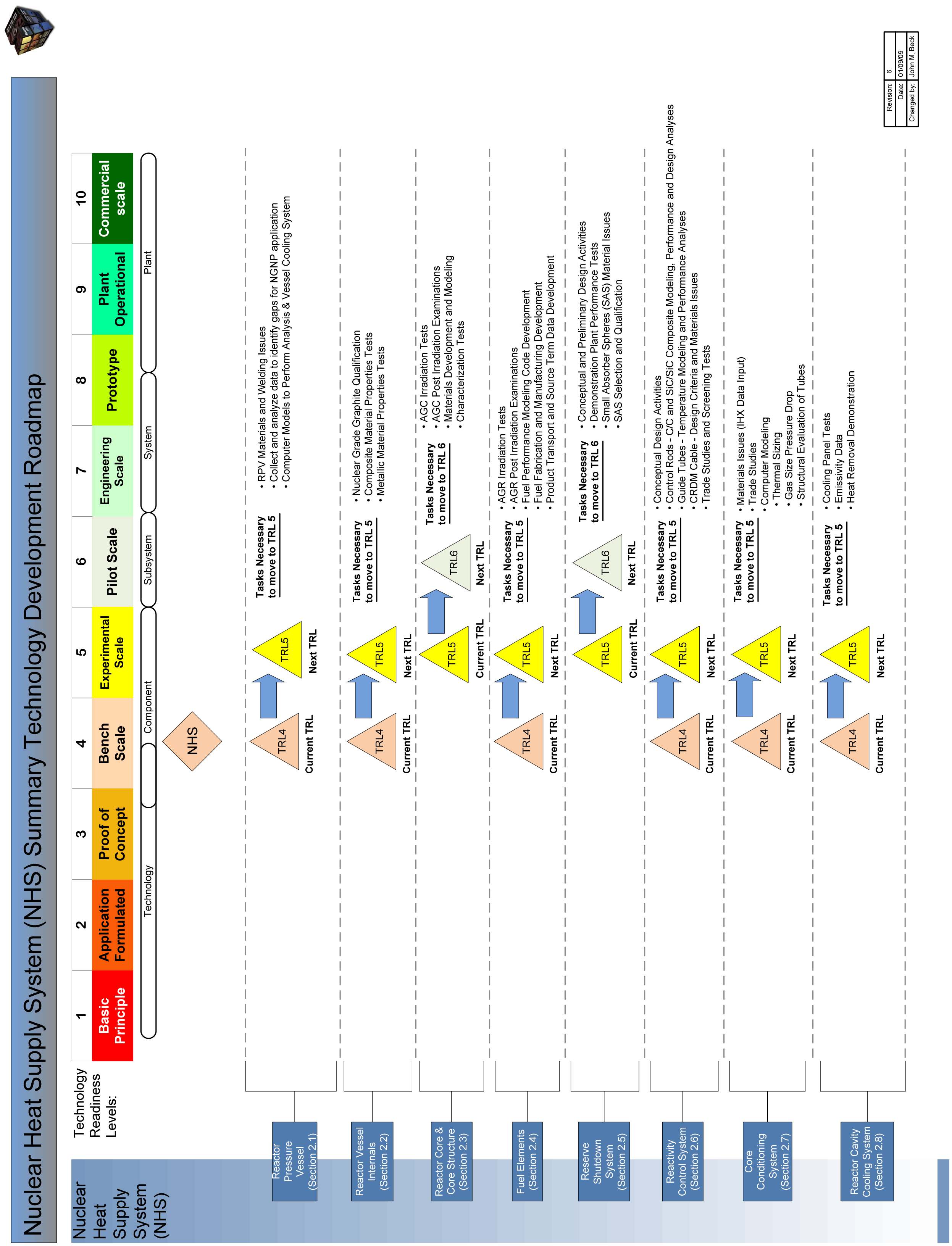

Figure ES-3. Nuclear Heat Supply System Summary Roadmap

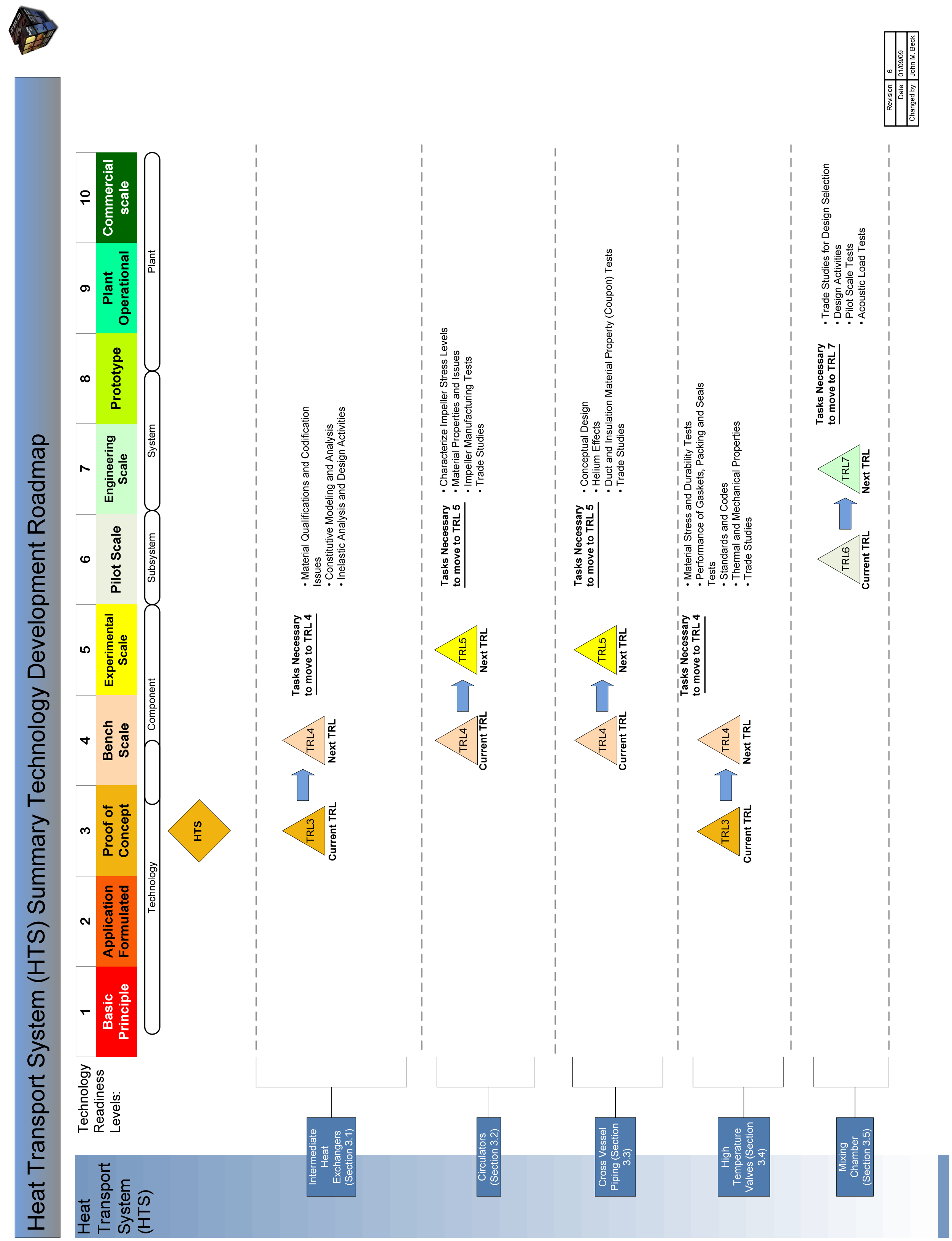

Figure ES-4. Heat Transport System Summary Roadmap

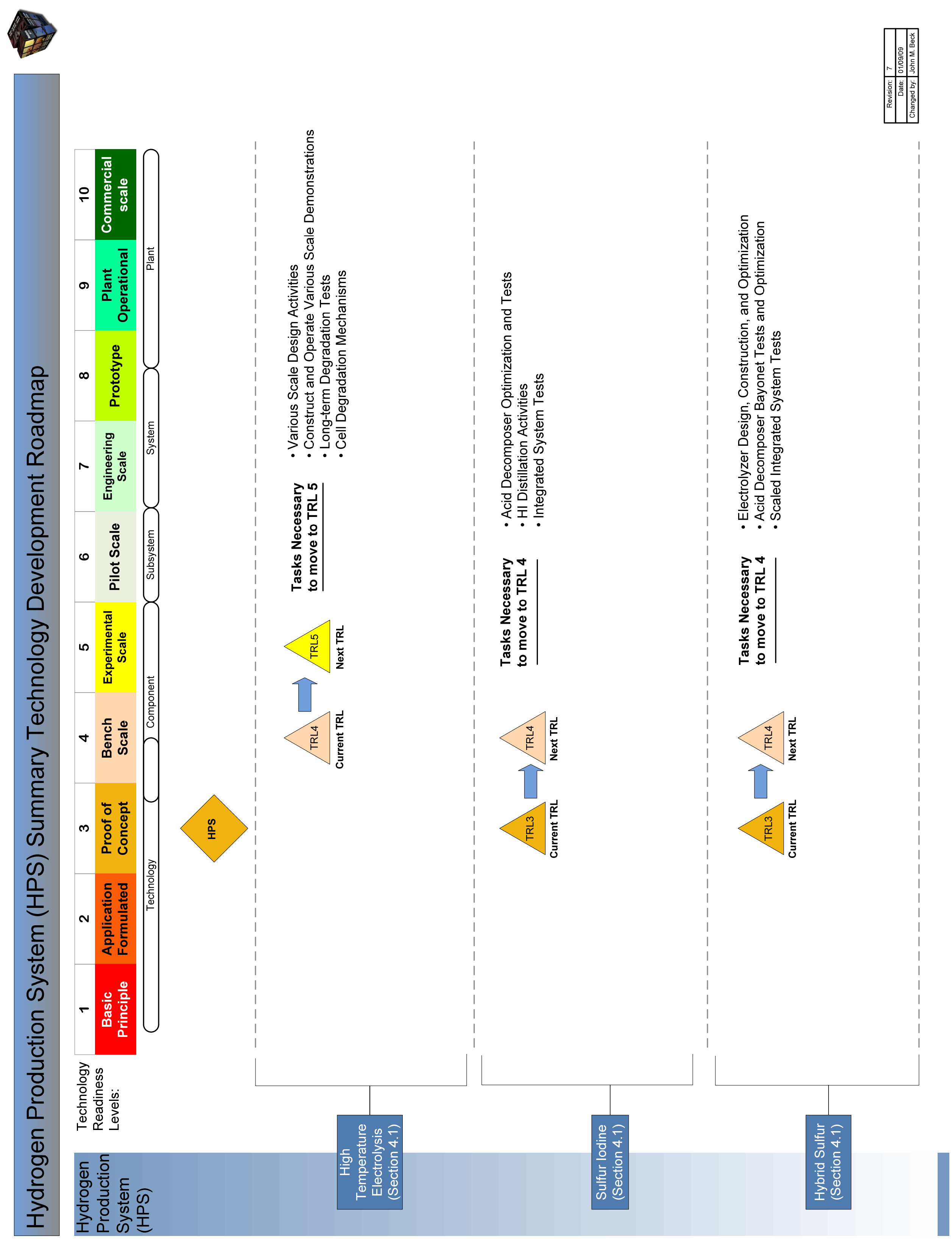

Figure ES-5. Hydrogen Production System Summary Roadmap

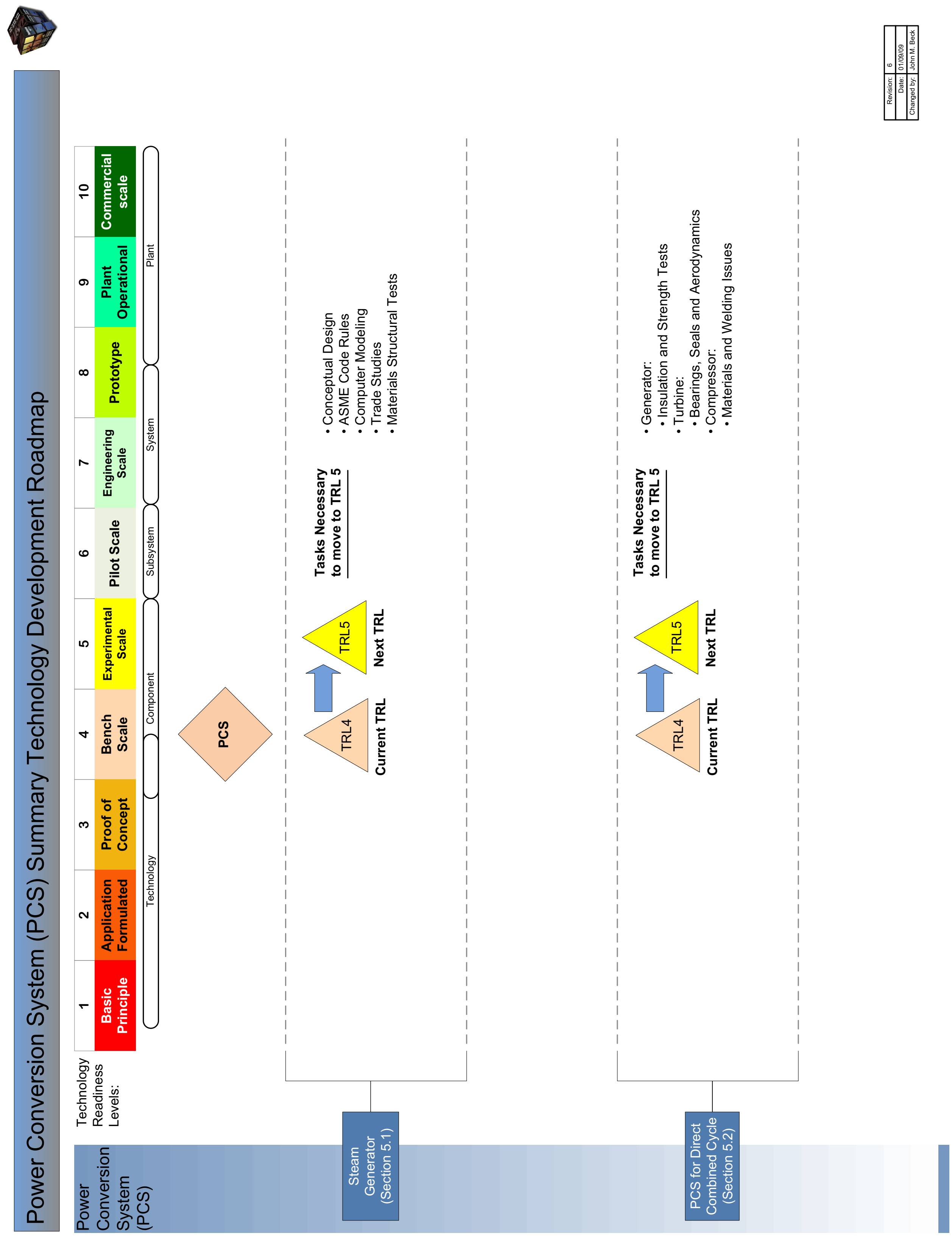

Figure ES-6. Power Conversion System Summary Roadmap

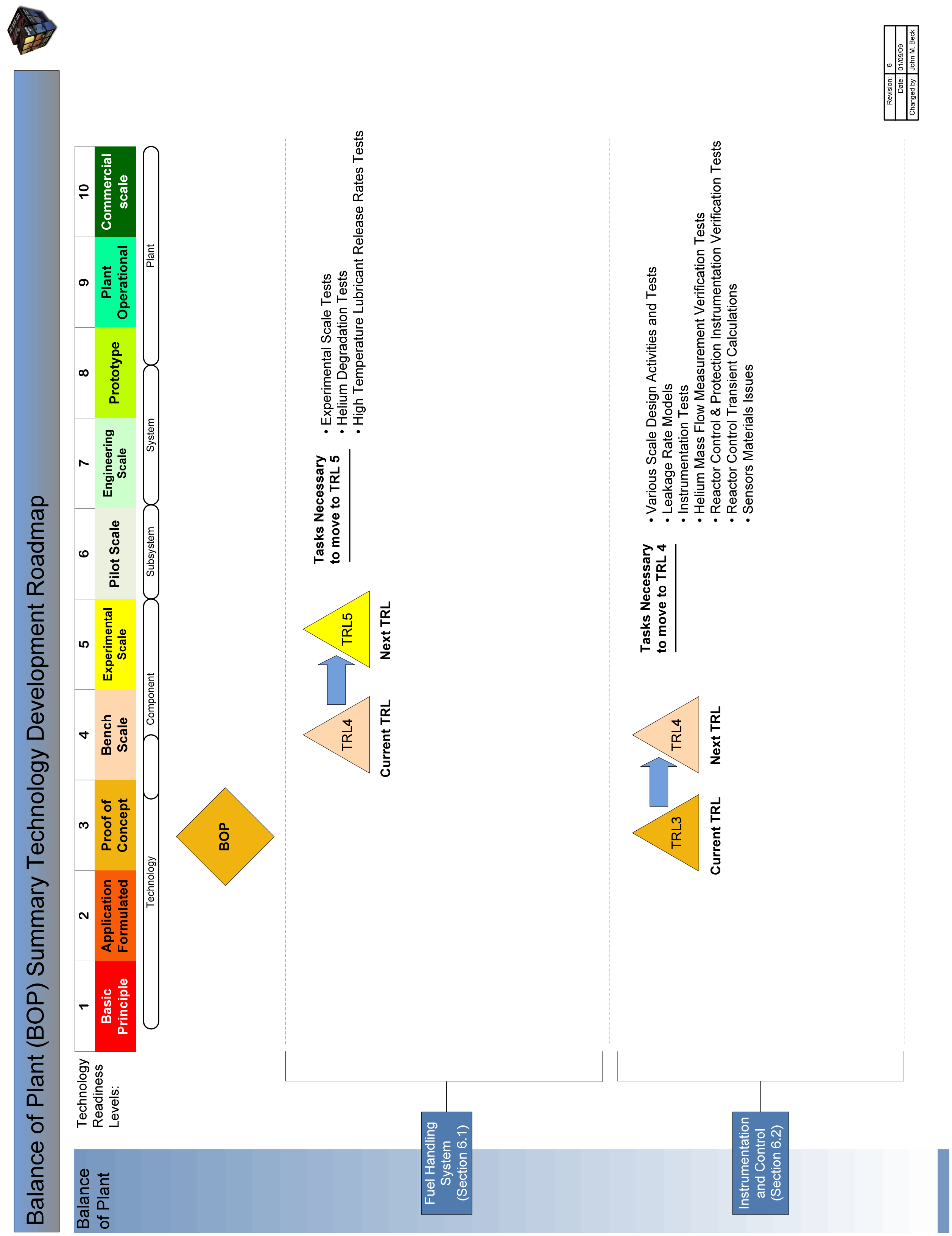

Figure ES-7. BOP Summary Roadmap

Conclusions

Conclusions and needed actions discovered during the Technology Readiness Assessment and the creation of TDRMs are as follows:

1. **Conclusion: NGNP Critical PASSCs are currently at a low level of technical maturity**. The minimum PASSC TRL is a 3. This lack of maturity is primarily due to the fact that materials issues are outstanding for a reactor outlet temperature of up to 950°C.

   Action: Revise the program requirements, including the reactor outlet temperature of 950°C. Note that the Senior Advisory Group has recommended a reactor outlet temperature of 750–800°C. As this requirement change is adopted, the TDRMs and technical readiness levels will be evaluated for modification, as identified in Appendix A. The tasks called out on the TDRMs and detailed in the Test Plans will be incorporated into the integrated project schedule for use in such decision making activities as annual funding reviews.

2. **Conclusion: Differences exist between the PASSCs determined to be critical by each supplier**. Some of the designs proposed by the suppliers are at differing levels of technical maturity. Hence, one supplier might consider a system to be more mature and not satisfy the definition for a critical system. For example, the Core Conditioning System is not considered critical by all suppliers.

   Action: Use the technical maturity of the proposed designs as one criterion in evaluating and down selecting the design used in the NGNP, such as in the due diligence reviews.

3. **Conclusion: Differences exist between the NGNP Project and the suppliers on the current TRL of each critical PASSC and on the steps needed for technology maturation**. For example, when materials issues are yet to be resolved, NGNP has not granted a TRL higher than 4.

   Action: Resolve the differences in TRL assessment by convening an independent TRL validation board and generate a set of validated NGNP TRLs. This validation board will also review the results of the TRL modifications associated with the requirements changes agreed to at the Senior Advisory Group meetings held in September and October of 2008. The tests and test schedules required to advance the various technologies will be integrated into the project schedule, as noted in Action 1.

4. **Conclusion: Major decisions must be made at key points in the project life cycle to select technologies and design strategies that reduce risk and enhance the opportunity for project success**. The major decision options and technology hurdles will be addressed throughout the TDRM process as a basis for conceptual, preliminary, and final design, and for updating the integrated project schedule.

   Action: Work the TDRM process, including the down selection of technologies based on identified decision discriminators, to provide the technology readiness input needed to make design decisions.

5. **Conclusion: A component test capability is required to reduce the risk and fully mature critical PASSCs prior to insertion in the NGNP**. Based on reviews of the available international test capabilities/facilities, the reactor suppliers have identified 90 tests to be performed in a component test capability to adequately mature the technologies and components prior to insertion in the NGNP.

   Action: Develop a component test capability needed to conduct supplier-identified tests.

CONTENTS

FIGURES

TABLES

ACRONYMS

AGC	Advanced Graphite Capsule
AGR	Advanced Gas Reactor
AOO	Anticipated Operational Occurance
ASME	American Society of Mechanical Engineers
AVR	Arbeitsgemeinschaft Versuchsreaktor (Germany)
BOP	Balance of Plant
C/C	Carbon/Carbon (composite)
CCS	Core Conditioning System
CRDM	Control Rod Drive Mechanism
CTC	Component Test Capability
CVP	Cross Vessel Piping
DBA	Design Basis Accident
DOD	U.S. Department of Defense
DPP	Demonstration Pilot Plant
FHM	Fuel Handling Machine
FHS	Fuel Handling System
FIMA	fissions per initial metal atom
GWd/MTHM	Gigawatt days/Metric Tons Heavy Metal
GT-MHR	Gas Turbine-Modular Helium Reactor
HPS	Hydrogen Production System
HyS	Hybrid Sulfur
HTE	High Temperature Electrolysis
HTGR	High Temperature Gas-Cooled Reactor
HTS	Heat Transport System
HTTR	High Temperature Test Reactor (Japan)
I&C	Instrumentation and Controls
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
LWR	Light Water Reactor
MHTGR	Modular High-Temperature Gas-cooled Reactor
MWd/tU	Megawatt days/Thermal Unit
NASA	National Aeronautic and Space Administration
NGNP	Next Generation Nuclear Plant

NHS	Nuclear Heat Supply System
NPR	New Production Reactor
PASSC	Plant, Areas, Systems, Subsystems, and Components
PBMR	Pebble-Bed Modular Reactor
PCS	Power Conversion System
PHTS	Primary Heat Transport System
PIE	Post-Irradiation Examination
R&D	Research and Development
RAMI	Reliability, Availability, Maintainability, and Inspectabilty
RAPHAEL	ReActor for Process heat, Hydrogen, And ELectricity Generation
RCCS	Reactor Cavity Cooling System
RCS	Reactivity Control System
RPV	Reactor Pressure Vessel
RSA	Republic of South Africa
RSS	Reserve Shutdown System
RVI	Reactor Vessel Internals
SAR	Safety Analysis Report
SCHE	Shutdown Cooling Heat Exchanger
SHTS	Secondary Heat Transport System
SI	Sulfur-Iodine
SiC/SiC	Silicon-Carbide/Silicon-Carbide (composite)
SRM	System Requirements Manual
TBD	To Be Determined
TDRM	Technology Development Roadmap
THTR	Thorium Hocktemperatur Reaktor (Germany)
TRISO	tri-isotropic (particles)
TRL	Technology Readiness Level
VCS	Vessel Cooling System
VHTR	Very High Temperature Reactor

Next Generation Nuclear Plant Project Technology Development Roadmaps: The Technical Path Forward

1. INTRODUCTION

Industry experience repeatedly demonstrates the consequences of proceeding with projects using technologies that are not sufficiently mature. The U.S. General Accounting Office noted that these consequences manifest themselves as cost overruns and schedule delays late in the project life cycle [GAO 2007]. To avoid these undesirable consequences, the Next Generation Nuclear Plant (NGNP) project initiated effort to assess technology readiness of critical Plant, Areas, Systems, Subsystems, and Components (PASSCs) and identify the steps required to ensure sufficient maturity prior to inclusion into the NGNP design.

This document presents the NGNP Critical PASSCs and defines their technical maturation path through Technology Development Roadmaps (TDRMs) and their associated Technology Readiness Levels (TRLs). As the critical PASSCs advance through increasing levels of technical maturity, project risk is reduced and the likelihood of within-budget and on-schedule completion is enhanced. The current supplier-generated TRLs, TDRMs, and Test Plans specific to each supplier are collected in Appendix B.

1.1 Background

1.1.1 Technology Readiness Levels for Critical Structures, Systems, and Components

The Technology Readiness Assessment process originates with NASA and the U.S. Department of Defense (DOD) and evaluates the deployment readiness of a technology and its readiness to function in an integrated environment. The NGNP uses TRLs with a tailored scale of 1 to 10, compared to the standard 1 to 9 scale used by NASA and DOD. The additional rating allows the NGNP to assess readiness for full commercialization following the construction and successful operation of the NGNP.

Technology Readiness Levels are an input to inform NGNP project management of the readiness of a particular technology, component, or system. For TRLs 1-5, assessment typically occurs on an individual technology or component with a calculated roll up TRL for the associated area, systems, and subsystems. As the technology or component progress to further levels of maturity, integrated testing occurs and allows TRL assessments directly against subsystems and systems. The integrated testing or modeling occurs at increasingly larger scales and in increasingly relevant environments, thus achieving higher TRL ratings. Abbreviated TRL definitions are shown in Figure 1.

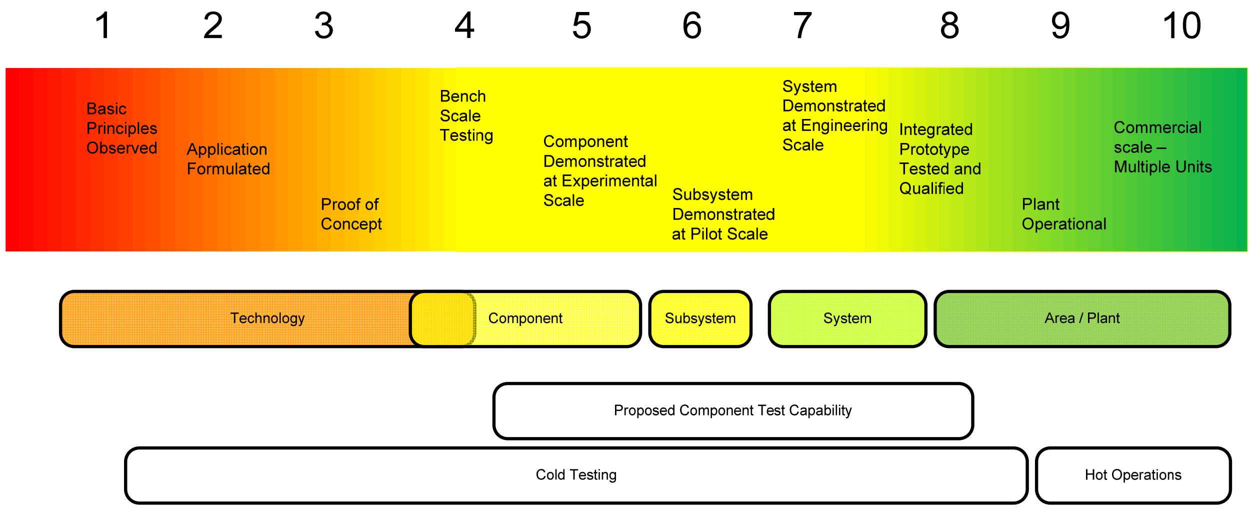

Figure 1. Technology Readiness Levels

Full definitions of the TRLs are provided in Table 1.

Table 1. TRL Definitions

Rating Level	Technology Readiness Level Definition	TRL Abbreviated Definition
1	**Basic principles observed** and reported in white papers, industry literature, lab reports, etc. Scientific research without well defined application.	Basic principles observed
2	**Technology concept and application formulated**. Issues related to performance identified. Issues related to technology concept have been identified. Paper studies indicate potentially viable system operation.	Application formulated
3	**Proof-of concept**: Analytical and experimental critical function and/or characteristic proven in laboratory. Technology or component tested at laboratory-scale to identify/screen potential viability in anticipated service.	Proof of Concept
4	**Technology or Component is tested at bench-scale** to demonstrate technical feasibility and functionality. For analytical modeling, use generally recognized benchmarked computational methods and traceable material properties.	Bench-scale testing
5	**Component demonstrated at experimental scale in relevant environment**. Components have been defined, acceptable technologies identified and technology issues quantified for the relevant environment. Demonstration methods include analyses, verification, tests, and inspection.	Component Verified at Experimental Scale
6	**Components have been integrated into a subsystem** and demonstrated at a pilot-scale in a relevant environment.	Subsystem Verified at Pilot-scale
7	**Subsystem integrated into a system** for integrated engineering-scale demonstration in a relevant environment.	System demonstration at Engineering-scale
8	**Integrated prototype of the system is demonstrated** in its operational environment with the appropriate number and duration of tests and at the required levels of test rigor and quality assurance. Analyses, if used support extension of demonstration to all design conditions. Analysis methods verified. Technology issues resolved pending qualification (for nuclear application, if required). Demonstrated readiness for hot startup	Integrated Prototype Tested and Qualified
9	**The project is in final configuration** tested and demonstrated in operational environment.	Plant Operational.
10	**Commercial-scale demonstration** is achieved. Technological risks minimized by multiple units built and running through several years of service cycles.	Commercial Scale – Multiple Units

In May 2008, three supplier teams (i.e., AREVA, General Atomics, and Westinghouse) were tasked to (1) determine the critical PASSCs of their respective designs, (2) perform a Technology Readiness Assessment of the critical PASSCs, and (3) develop TDRMs to mature the technology sufficiently for insertion into the NGNP. Additionally, these tasks were to be performed based on a set of pre-conceptual design requirements and high level operating conditions consistent with those found in the *NGNP System Requirements Manual* (SRM; INL, 2008a) and the *Summary of Bounding Requirements for the NGNP Demonstration Plant F&ORs* (INL, 2008b). The salient features of these pre-conceptual design requirements are as follows:

- Reactor outlet temperature of 900–950°C
- Pressure of 5–9 MPa
- Indirect Cycle (i.e., steam generator in the secondary loop)
- Hydrogen Production in the secondary of tertiary loop
- GenIV fuel type.

Each supplier performed this task and presented evidence to justify their proposed TRL rating (see Appendix B). While many of the selected critical PASSCs differed by supplier, several PASSCs were common to all suppliers. The common critical PASSCs were rated with different TRLs by each supplier based on differing supplier designs, different supplier supported demonstrations of those designs, and different interpretations of the TRL definitions. The Idaho National Laboratory (INL) reviewed these justifications and associated paths forward and developed NGNP consolidated TRL ratings and consolidated NGNP TDRMs. These consolidated TRL ratings:

- Establish the current state of proposed technologies that are used as the starting point for TRLs
- Provide a consistent measure of readiness levels and confidence in the levels as inputs to quantifying performance, cost, and schedule risks.

NGNP / Area / System	Min TRL	Wgt	Avg TRL
NGNP	3		TBD
Nuclear Heat Supply System (NHSS)	4		TBD
Reactor Pressure Vessel System	4	TBD	
Reactor Vessel Internals	4	TBD	
Reactor Core and Core Structure	5	TBD	
Fuel Elements	4	TBD	
Reserve Shutdown System	5	TBD	
Reactivity Control System	4	TBD	
Core Conditioning System	4	TBD	
Reactor Cavity Cooling System	4	TBD	
Heat Transfer System (HTS)	3		TBD
Circulators	4	TBD	
Intermediate Heat Exchangers	3	TBD	
Cross Vessel Piping	4	TBD	
High Temperature Valves	3	TBD	
Mixing Chamber	6	TBD	
Hydrogen Production System (HPS)	3		TBD
High-Temperature Electrolysis (HTE)	4	TBD	
Sulfur-Iodine (SI)	4	TBD	
Hybrid Sulfur (HS)	3	TBD	
Power Conversion System (PCS)	4		TBD
Steam Generator	4	TBD	
Power Conversion Turbomachinery	4	TBD	
Balance of Plant (BOP)	3		TBD
Fuel Handling System	4	TBD	
Instrumentation & Control	3	TBD	

Figure 2. NGNP TRL Consolidation of Critical PASSCs

Figure 2 depicts the consolidated TRLs of the critical PASSCs. The method depicted here will be used to evaluate the technical readiness of each area and the NGNP as a whole. Once the TRLs are validated by an independent review board, the relative contribution to the weighted average will be factored into the rollup, currently depicted as TBDs. At that time, this tool will be used to evaluate (1) one proposed NGNP design against another, (2) one design associated with certain requirements versus another design associated with another set of requirements, and (3) progress over time.

1.1.2 Critical PASSC Selection

The NGNP can be divided into five areas: Nuclear Heat Supply System (NHS), Heat Transport System (HTS), Hydrogen Production System (HPS), Power Conversion System (PCS), and Balance of

Plant (BOP). Each area is further broken down into systems, which are comprised of subsystems, which are further comprised of components. The current status of the TRLs, TDRMs, and Test Plans for the critical PASSCs forming these five areas is the focus of this document.

Critical PASSCs are defined as those components that are not commercially available or have not been proven in relevant industry environments, at appropriate scale, or fully integrated with other components. Given the five areas for the NGNP, each supplier recommended 14–16 critical PASSCs required to perform the desired functions and meet the requirements specified by the project. The contractor-recommended PASSCs and Idaho National Laboratory (INL) prismatic fuel elements and Hydrogen Production System (HPS) options were consolidated into the 18 NGNP critical PASSCs. Each of the supplier selected designs is summarized below:

AREVA

The AREVA design uses a High Temperature Gas-Cooled Reactor (HTGR) as the NGNP that is envisioned as providing a reactor outlet temperature of 900ºC on an indirect steam cycle and being operational by 2021. Since a final selection of the NGNP configuration and operating conditions has not been made, the TDRM task focused on those PASSCs that comprise the baseline reference configuration used by AREVA for the initial *Conceptual Design Studies* performed in early FY-2008 (see Figure 3).

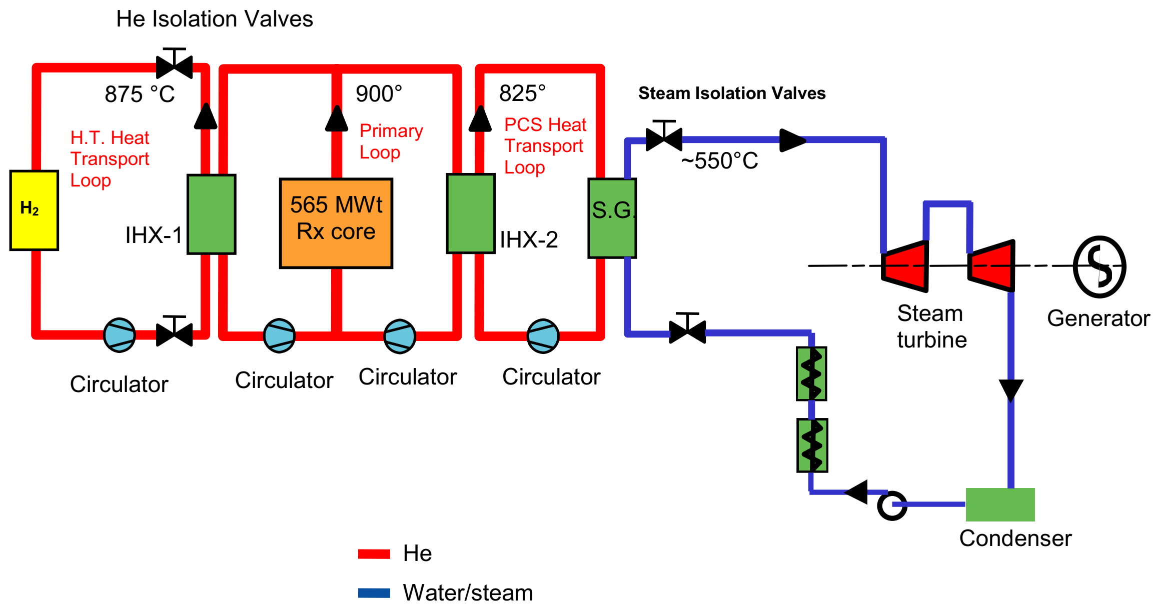

Figure 3. Schematic of AREVA Reference Plant Design for TDRM Process (prior to Senior Advisory Group Reviews)

General Atomics

General Atomics based their TDRM effort on the NGNP configuration shown in Figure 4, which General Atomics selected as its preferred configuration for the NGNP during the initial *Conceptual Design Studies* in early 2008. This plant configuration is consistent with the high-level requirements for the NGNP that existed at that time, and was selected at the onset of the NGNP TDRM task as the basis for the TDRM effort.

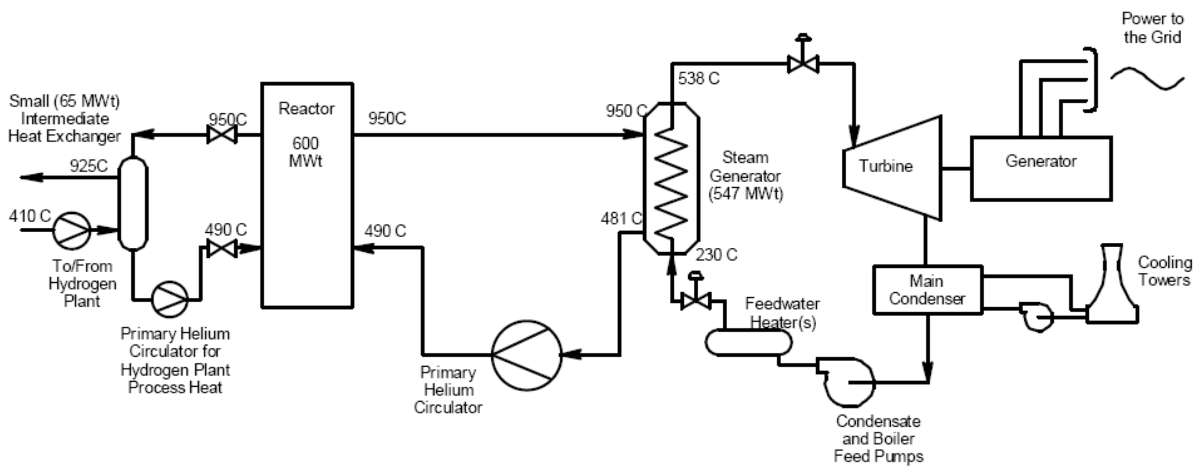

Figure 4. General Atomics NGNP Configuration for Technology Development Roadmapping (prior to Senior Advisory Group Reviews)

In the absence of a conceptual design, the following assumptions were made with respect to the NGNP design to provide a basis for this TDRM effort. These assumptions are based on the various NGNP conceptual design studies that have been performed to date by the General Atomics team.

- The plant will have two primary power conversion loops (i.e., two steam generators and two primary helium circulators) that provide steam to one turbine-generator facility. This limits the maximum size of the steam generator to ≤ 300 MWt and the maximum size of the helium circulator to ≤ 6 MW.
- The working fluid for both the primary and secondary loops will be helium.
- All vessels will be made out of light water reactor (LWR) steel (i.e., SA-508/533). A vessel cooling system (VCS) will be used to keep reactor pressure vessel (RPV) maximum temperatures below ASME code limits for SA-508/533.
- The 65 MWt Intermediate Heat Exchanger (IHX) will be a printed-circuit-type compact heat exchanger; however, a helically-coiled tube-and-shell heat exchanger of similar design to the IHX used in the High Temperature Test Reactor (HTTR) in Japan will be developed in parallel as a backup to the compact IHX.

Westinghouse

Westinghouse proposed a 500 MWt pebble-bed reactor with primary and secondary helium loops coupled to a 50 MWt process coupling heat exchanger with a 950°C reactor outlet temperature for the demonstration of hydrogen production, and a 470 MWt steam generator for a Rankine cycle power generation plant. The process flow diagram of the NGNP Demonstration Plant for Hydrogen Production is shown in Figure 5.

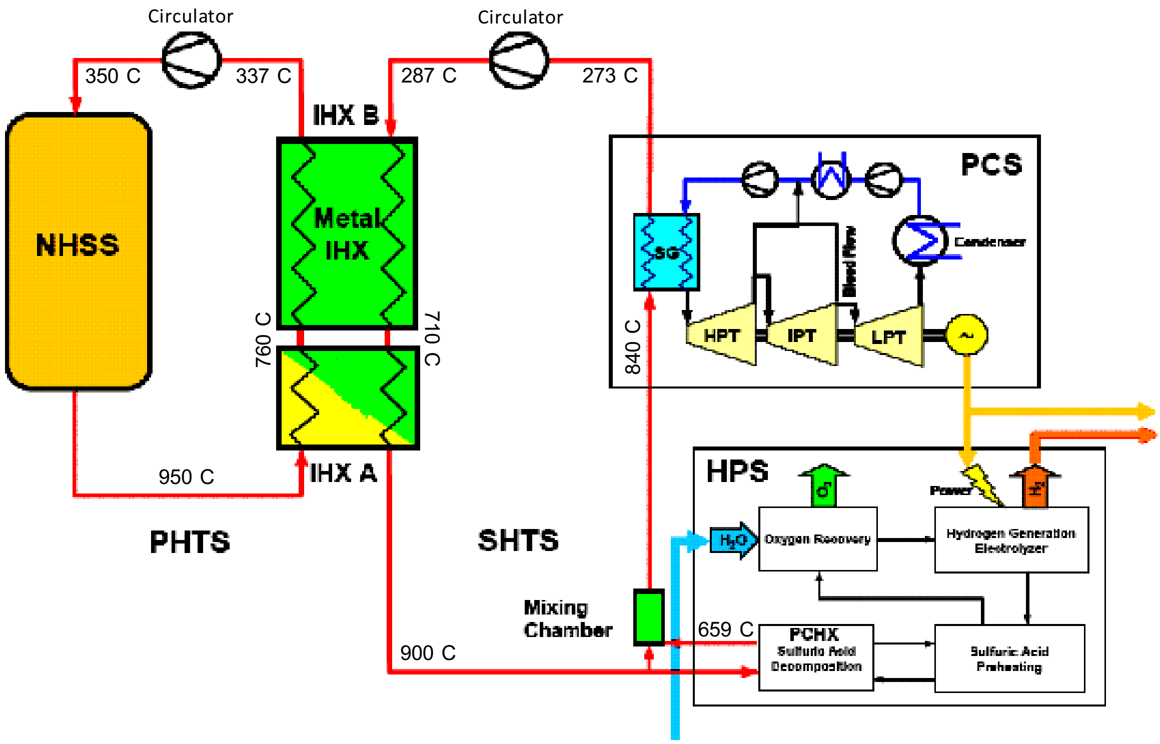

Figure 5. PBMR NGNP Demonstration Plant Process Flow Diagram – H_2 Production (950°C) (prior to Senior Advisory Group Reviews)

Table 2 provides a mapping between the NGNP consolidated critical PASSCs and supplier-identified critical PASSCs. The table consists of five primary columns, representing the consolidated NGNP critical PASSCs, the AREVA critical PASSCs, the General Atomics critical PASSCs, the Westinghouse Electric Company critical PASSCs, and the INL Fuel Element and HPS PASSCs. The sub-columns to the left of the PASSC names identify the section number of the supplier report wherein the technology readiness assessment details are provided. In the case of NGNP consolidated PASSCs, the number represents the section in this document. Blank cells in the table represent an absence of supplier-identified PASSCs corresponding to the NGNP consolidated PASSCs. PASSCs are organized according to the five NGNP areas: Nuclear Heat Supply System (NHS), Heat Transport System (HTS), HPS, Power Conversion System (PCS), and Balance of Plant (BOP). One addition to the table not used in the rest of the document is Other Development Issues. This is presented to provide a place holder for additional PASSCs that suppliers deemed important, but not critical, in the TDRM work and activities associated with the scope of work tasked to them. As the design matures and requirements change, additional PASSCs may be added to those already identified in this report.

Table 2. Supplier-Identified Critical PASSCs as of September 2008.

NGNP Consolidated		AREVA		General Atomics		Westinghouse Electric Company		Idaho National Laboratory	
Section	TDRM	Sectio	TDRM	Sectio	TDRM	Sectio	TDRM	Sectio	TDRM
Nuclear Heat Supply									
2.1	Reactor Pressure Vessel	6.1.1	Vessel System	SSC5	Reactor Pressure Vessel				
2.2	Reactor Vessel Internals	6.1.2	Reactor Vessel Internals						
2.3	Reactor Core & Core Structure	6.1.3	Reactor Core Design Features	SSC4a	Reactor Core	012	Core Structure Graphite & Ceramics		
				SSC4b	Reactor Graphite				
2.4	Fuel Elements					011	Fuel Element – Pebble-bed		Fuel Element – Prismatic
2.5	Reserve Shutdown System					013	Reserve Shutdown System		
2.6	Reactivity Control System	6.1.4	Neutron Control System	SSC1	Reactor Control Equipment	014	Reactivity Control System		
				SSC2	Control Rods				
2.7	Core Conditioning System			SSC8	Shutdown Cooling Heat Exchanger	015	Core Conditioning System		
2.8	Reactor Cavity Cooling System	6.1.6	Reactor Cavity Cooling System	SSC9	Reactor Cavity Cooling System	016	Reactor Cavity Cooling System		
Heat Transfer System									
3.1	Intermediate Heat Exchangers	6.2.3	Helical Tube IHX	SSC7	Intermediate Heat Exchanger	004	IHX A		
		6.2.7	Compact IHX			005	IHX B		
3.2	Circulators	6.2.1	Primary Gas Circulator	SSC6	Helium Circulators	003	Primary Circulator		
		6.2.5	Secondary Gas Circulator						
3.3	Cross Vessel Piping	6.2.4	Primary Hot Gas Duct	SSC3	Hot Duct	006	Piping		
3.4	High Temperature Valves	6.2.2	High Temperature Flapper Valve	SSC12	High Temperature Valves				
		6.2.6	High Temperature Isolation Valve						
3.5	Mixing Chamber					007	Flow Mixing Chamber		
Hydrogen Production System									
4.1	Hydrogen Production System			SSC13	Sulfur-Iodine HPS	008	Hybrid Sulfur HPS		High Temp. Electrolysis HPS
Power Conversion System									
5.1	Steam Generator	6.3.1	Steam Generator	SSC10	Steam Generator	009	Steam Generator		
5.2	PCS Equipment for Direct Combined Cycle *			SSC11	PCS Turbomachinery				
Balance of Plant									
6.1	Fuel Handling System	6.4.2	Fuel Handling System	SSC14	Fuel Handling and Storage System				
6.2	Instrumentation and Control	6.4.1	Primary Loop Instrumentation	SSC15	Primary Circuit and BOP Instrumentation				
				SSC16	Reactor Protection, Investment Protection, Plant Control, Data and Instrumentation				
Other Development Issues (Not a Critical PASSC)									
N/A						010	Software Codes V&V		

* This alternate configuration is for a power conversion option that places the steam generator in the primary loop. It is included here because of the attractiveness of this combined-cycle option for an electricity producing plant.

1.1.3 Technology Development Roadmaps for Critical Structures, Systems, and Components

In the NGNP application, TDRMs provide the framework and structure required to systematically perform decision analysis, reduce risk, and mature technologies in a cost effective and timely manner. The process includes Structure Identification, Technology Readiness Assessment, Technology Selection, and Technology Maturation.

A TDRM documents the tasks needed to obtain information in key discriminating criteria to support technology down selection, and the tasks and tests required to sufficiently mature the technology and enhance project performance. The set of TDRMs along with their associated documentation will represent the path forward for the NGNP project to complete its mission to develop and demonstrate design, performance, operational, licensing, and economic viability of HTGR and leading process heat technologies. Performance criteria are shown on the TDRM as a basis for TRL advancement. Where specific values are not known, TBDs are used. This document contains the TDRMs necessary to facilitate risk-informed decision making, technology down selection, management of technical uncertainty, and technology qualification and maturation for critical PASSCs, while also serving to coordinate engineering, research and development (R&D), and licensing efforts and mitigate risks early in the NGNP project.

This process provides the following benefits to the NGNP project:

- Identifies precise project objectives and helps focus resources on critical technologies that are needed to meet those objectives
- Creates a consensus vision of NGNP project needs based on capabilities needed now and in the future
- Provides early identification of high-risk items and allows early focused attention to enhance project cost and schedule success
- Supports engineering, R&D, and management priorities, which inform schedule development and resource allocation
- Sets the vision for and drives the needed actions to down select technologies and designs
- Ensures technology readiness is demonstrated through testing, modeling, piloting, and prototyping
- Develops the test plans required to provide demonstrable evidence of the technology maturation required for codification and qualification.

1.1.4 Risk Reduction

The major technical risks identified for each critical PASSC represent the overall uncertainties that must be addressed and reduced to enhance the probability of a successful NGNP. These risks are generally reduced as technology is developed per the TDRMs. A risk that is not shown but is consistent for each of the PASSCs is one of system interconnectivity. Interconnectivity is proven and further reduced as one tests integrated and large-scale systems rather than mere components. This risk is not reduced entirely until the NGNP is system operability tested and successfully receives a TRL of 8. Figure 6 shows the risk reduction that occurs as the TDRM plan is executed and as technologies are matured through the advancing readiness levels.

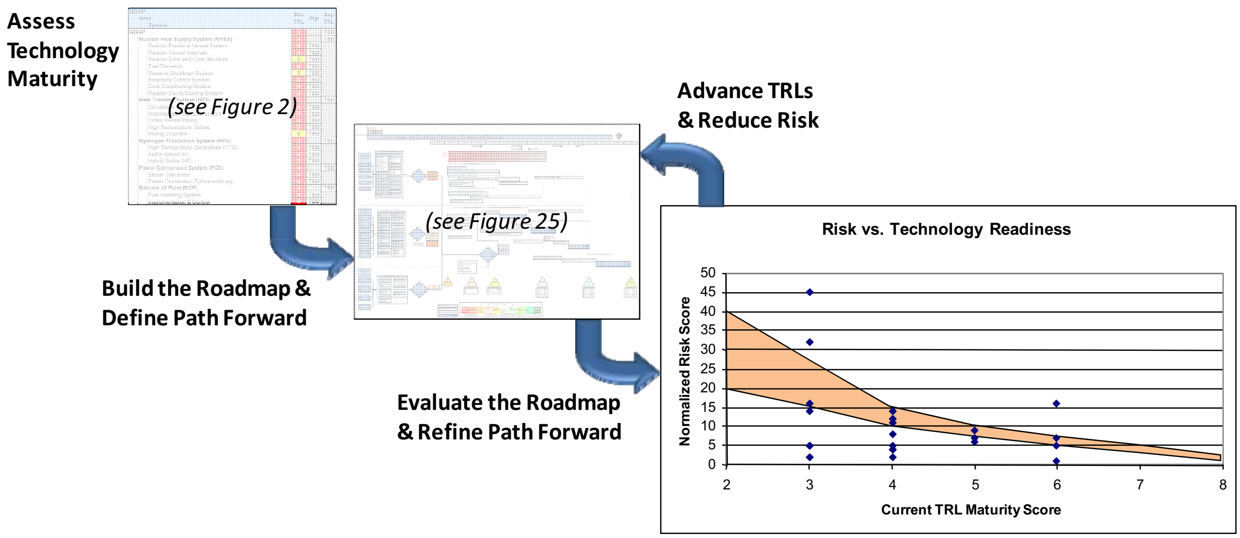

Figure 6. Following a TDRM increases Readiness while Reducing Risk.

1.2 Document Structure and General Comments

Sections 2 through 6 contain specific information regarding the five main NGNP areas, as follows:

- Section 2 – Nuclear Heat Supply System
- Section 3 – Heat Transfer System
- Section 4 – Hydrogen Production System
- Section 5 – Power Conversion System
- Section 6 – Balance of Plant.

The subsections therein address specific PASSCs (typically at the system level) within those areas and provide the following general information:

Consolidated INL Technology Development Roadmaps

A consolidated TDRM, produced from pertinent supplier-provided data combined with NGNP R&D data, is provided for each critical PASSC. These TDRMs consist of 11×17 fold-out diagrams that visually depict the current TRL of critical PASSC; the steps required to advance the system to the desired end state; the schedule associated with TRL advancement activities; related design decisions, alternatives, and discriminators; and a summary of the major risks. E-sized, print-ready versions of the TDRMs are provided in Appendix B.

Design Description

Functional design descriptions are provided for each of the supplier-identified critical PASSCs. Each description discusses the functions performed; potential design options, if any; and discriminators to aid selection between alternative designs. Identified discriminators have not yet been weighted to reflect their relative impact on design decisions, nor have performance measures and other metrics been assigned. These parameters and additional discriminators, if needed, will be identified through on-going design efforts. Details on supplier-proposed design solutions can be found in Appendix B.

Technology Readiness Level Status

Technology Readiness Level ratings, as provided by each supplier, are presented in tabular format alongside an NGNP assessment of the associated PASSC. Occasionally, a particular supplier's TRL assessment is shown as "Not Provided" to indicate that either the supplier did not provide a design alternative for the PASSC or that they consider an existing design alternative as already having a TRL rating of 6 or greater. Consolidated NGNP TRLs are based on currently available information and will be updated pending validation by an independent review board. At that time, TRLs will be weighted according to the relative importance of the PASSC to determine an overall TRL rating for the NGNP.

Maturation Path Forward

The maturation path forward describes key tasks and tests required to advance only the 18 critical NGNP PASSCs to their desired end states.

2. NUCLEAR HEAT SUPPLY SYSTEM

2.1 Reactor Pressure Vessel

The Reactor Pressure Vessel (RPV) houses the reactor, the reactor internals, and the reactor support structure. The primary development issues with the RPV are the choice of material and the inclusion of a VCS.

2.1.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from pertinent supplier RPV TDRM data combined with NGNP R&D data, is shown in Figure 7.

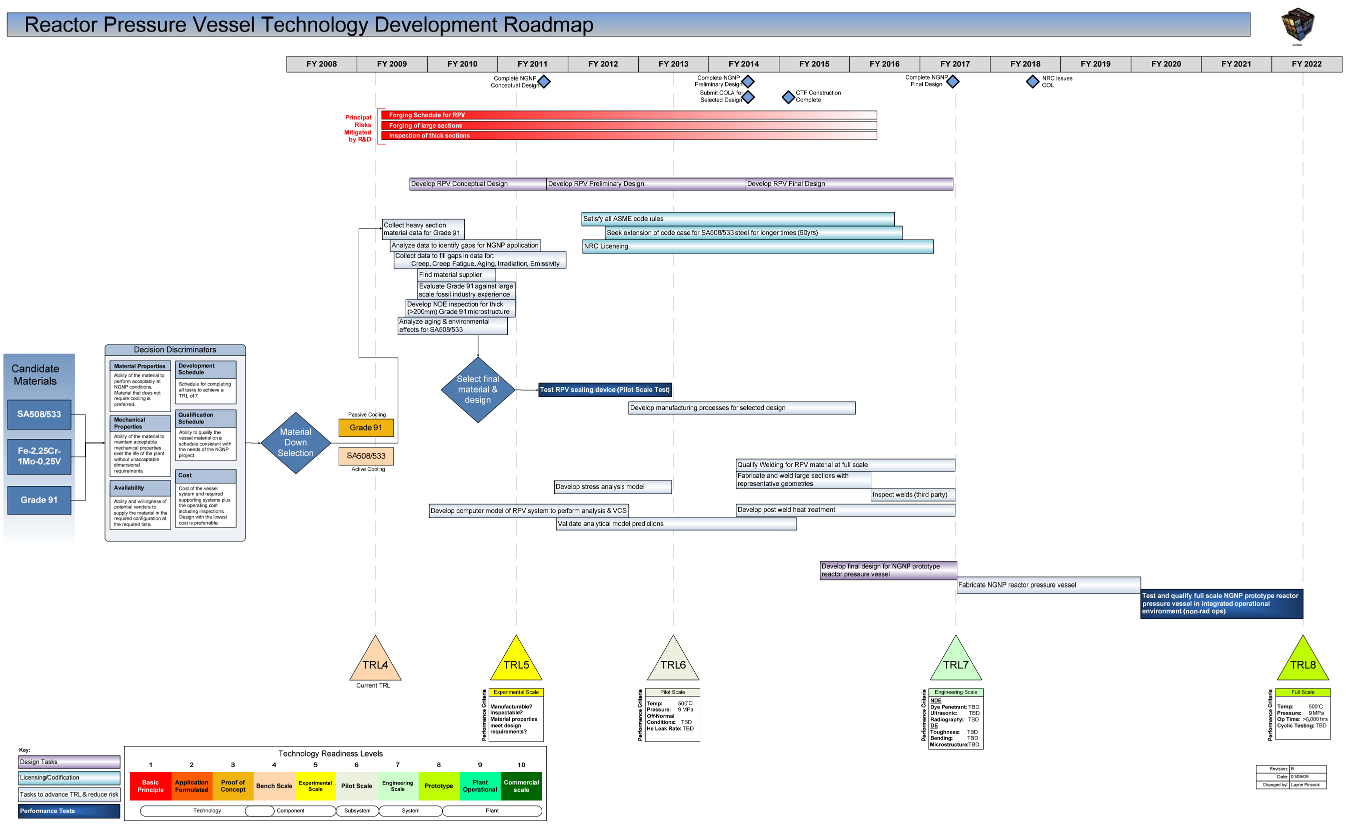

Figure 7. Reactor Pressure Vessel Roadmap

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2.1.2 Reactor Pressure Vessel Design Description

The RPV provides containment and structure for the reactor components, including the Reactor Core and the control rods, capable of withstanding the pressure that is generated by the reaction heat. Figure 8 represents a typical reactor vessel and support system.

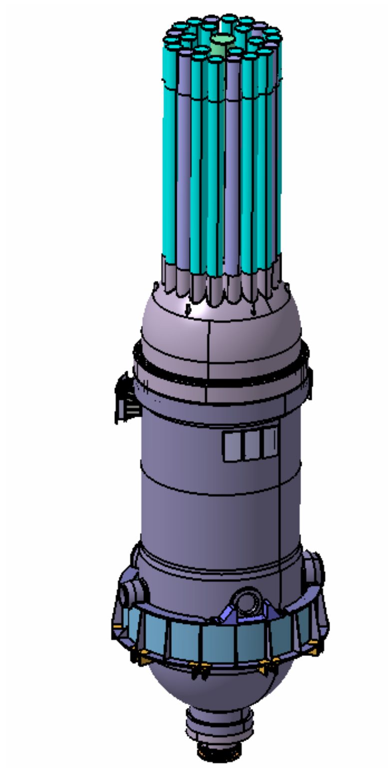

Figure 8. Typical Reactor Vessel & Support System

2.1.2.1 Functions Performed

The functions performed by the RPV System are:

- House and support the components of the Reactor Core, Reactor Internals, and Reactor Support Structure
- Maintain positioning relative to the control rods
- Contain the primary coolant inventory within a leak-tight pressure boundary
- Maintain the integrity of the coolant pressure boundary.

2.1.2.2 Design Options

The RPV represents fairly mature technology. The design of the RPV will be impacted somewhat by the design of the reactor core (e.g., pebble-bed or prismatic), but the primary development issues are the choice of material and the inclusion of a VCS.

AREVA recommends using either a modified Grade 91 steel or SA-508 Grade 3 steel, with Grade 91 steel being the preferred material. However, the effectiveness of the seal between the upper closure head and the main RPV still needs to be confirmed, the welding process needs to be qualified, and the Grade 91 needs to be codified through ASME.

General Atomics recommends using SA-508/533. However, limited data are available on the long-term thermal and environmental aging effects in an impure helium environment. In particular, creep deformation has been identified as a potential concern over a 60-year design life of normal operations at 350°C. General Atomics contends that the risk can be reduced or avoided through inclusion of a VCS, which could be designed to keep RPV temperatures well below 350°C during normal reactor operations. In fact, General Atomics has concluded that core outlet and inlet helium temperatures of 950°C and 490°C, respectively, will definitely require a direct VCS to keep maximum vessel temperatures within ASME code limits for SA-508/533 steel with high confidence. The VCS is not envisioned to be particularly complex or to require development of new technology.

Westinghouse does not consider the RPV to be a critical system, with regard to NGNP, based on an assumption that testing planned for a similar vessel associated with the Pebble-Bed Modular Reactor (PBMR) Demonstration Pilot Plant will sufficiently advance the technology to an acceptable readiness level.

2.1.2.3 Design Discriminators

The design discriminators for the RPV include:

- Material properties – The ability of the material to perform acceptably at NGNP conditions. Material that does not require cooling is preferred.
- Mechanical properties – The ability of the material to maintain acceptable mechanical properties over the life of the plant without unacceptable dimensional requirements.
- Availability – The ability and willingness of potential suppliers to supply the material in the required configuration at the required time.
- Development Schedule – The amount of time required to complete all tasks to achieve a TRL of 7.
- Qualification Schedule – The ability to qualify the vessel material on a schedule consistent with the needs of the NGNP project.
- Cost – The cost of the vessel system and required supporting systems plus the operating cost, including inspections.

2.1.3 Reactor Pressure Vessel TRL Status

Since the RPV design concept has been formulated, experimental proof-of-concept demonstrated, and the component demonstrated in a typical, relevant environment, the RPV currently has a TRL rating of 4. This rating is based on the absence of crucial data on materials, which need to be collected and analyzed before a TRL of 5 can be granted (see Table 3).

Table 3. Reactor Pressure Vessel Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
TRL	5	5	Not provided	4

The primary technology development issue with the RPV is the choice of material. Much of the work leading to Grade 91 steel has already been completed under the ReActor for Process heat, Hydrogen, and ELectricity generation (RAPHAEL) program in Europe, but questions remain regarding material availability from suppliers and the possibility of fabricating the vessel system from plates rather than circular forgings. TRL assessment of SA-508/533 material is based on the experience of using it in current generation LWR RPVs and codification of this material in Section III of the ASME code.

2.1.4 Reactor Pressure Vessel Maturation Path Forward

To mature the RPV design to a TRL of 5, material issues must be resolved for each of the designs. Specifically, Grade 91 material data need to be analyzed to identify gaps for the NGNP application, detailed requirements need to be established for material performance, code case for Grade 91 steel needs to be extended above 371°C, and the RPV sealing device needs to be validated. Additionally, Grade 91 steel welding procedures for fabricating large sections in representative geometries, performing welds, and enforcing third party weld inspection are necessary. For an RPV with SA-508/533 material, a TRL of 5 will be achieved as material issues of aging and environmental effects are addressed.

To mature the RPV design from a TRL of 5 to a TRL of 6, the following tasks are necessary: develop the RPV conceptual design of the VCS, perform analyses to determine the expected operating temperatures for the RPV during normal operation and during conduction cool down events, define the required materials testing program for SA-508/533, and conduct the required materials testing program.

To mature the RPV design from a TRL of 6 to a TRL of 7, the following tasks are necessary: prepare procurement specifications, develop the detailed design of the RPV system, refine the RPV computer model, perform analyses to verify that maximum vessel temperatures will be within ASME code limits with adequate margin, and conduct design verification testing of an engineering-scale model of the vessel and the VCS, if part of the selected design.

To achieve a TRL of 8, an integrated system containing the RPV will need to be demonstrated in an operational environment. Testing in the final NGNP configuration including normal and abnormal operating conditions will need to be completed, and this component will need to be proven through multiple cycles of hot operations.

2.2 Reactor Vessel Internals

The Reactor Vessel Internals (RVI) provide the mechanical, thermal, and radiological interfaces between the Reactor Core and the RPV.

2.2.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from pertinent supplier Reactor Vessel TDRM data combined with NGNP R&D data, is shown in Figure 9.

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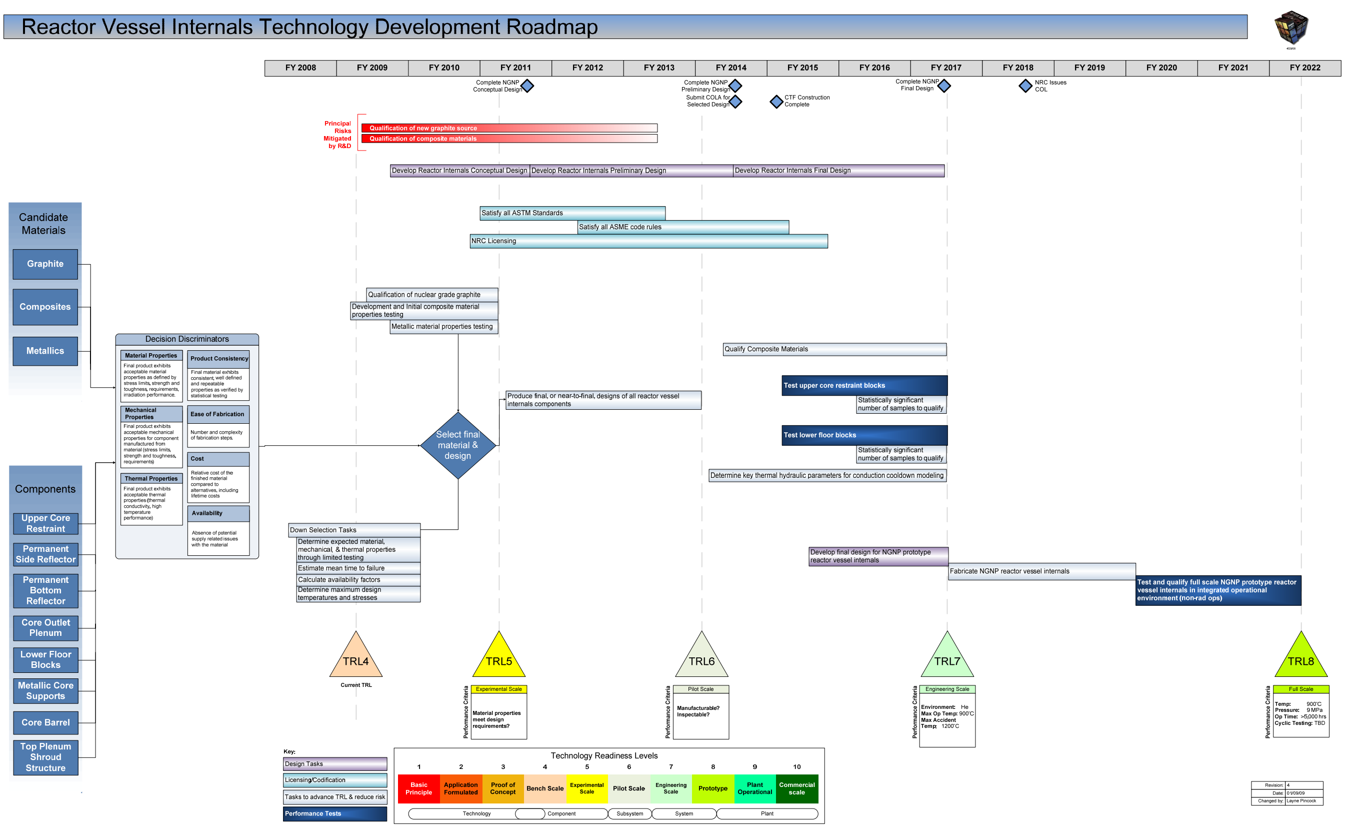

Figure 9. Reactor Vessel Internals Roadmap

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2.2.2 Reactor Vessel Internals Design Description

The RVI consists of a combination of floorings, plenums, reflectors, shrouds, restraints, and supports that maintain the reactor core geometry within the RPV, provide thermal and radiological shielding, and transport heat. Figure 10 depicts a typical RVI.

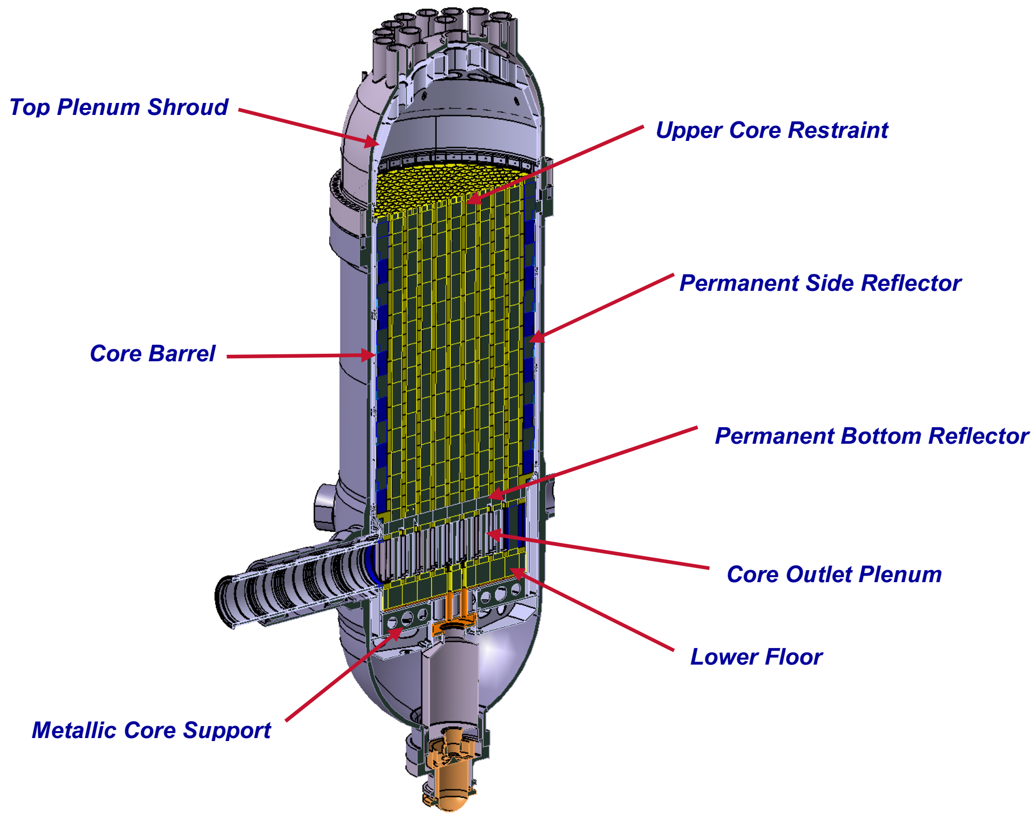

Figure 10. Typical Reactor Vessel Internals

2.2.2.1 Functions Performed

The functions performed by the RVI are as follows:

- Provide the mechanical or structural interface between the Reactor Core and the RPV to maintain reactor core geometry
- Provide heat transfer, during conduction cool down, by routing helium between the Reactor Core and the Primary Heat Transport and Shutdown Cooling Systems
- Provide thermal and radiological shielding of the reactor vessel
- Conserve neutrons during power production.

2.2.2.2 Design Options

The RVI components can be divided into three groups: metallic components, graphite components, and composite components. The metallic components are a mature technology, requiring little or no technology development prior to use. The graphite components require qualification of a new graphite source to replace the H451 graphite used in older reactors. The composite components will require significant development prior to use.

2.2.2.3 Design Discriminators

The design discriminators for the RVI include:

- Thermal aging
- Environment – corrosion
- Neutron Irradiation Embrittlement
- Codification of material.

2.2.3 Reactor Vessel Internals TRL Status

Since the analytical and experimental proof-of-concept exists and the technology has been demonstrated in a bench-scale environment, the status of the current technology for the RVI is a TRL of 4.

Table 4. Reactor Vessel Internals Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
TRL	4	Not provided	Not provided	4

The RVI technology development includes the selection of a material design for the Lower Floor Blocks, qualification of a new graphite supply to replace the historical H451 graphite grade, and selection and qualification of a composite design for those components that require such material (see Table 5). Data and analyses are needed in the areas of corrosion of carbon/carbon (C/C) composites in an impure helium environment. Corrosion data to validate the life of C/C composite materials in the NGNP reactor environment is also necessary for maturation.

Table 5. Reactor Vessel Internals Maturity Assessment

Component	Materials	Maturity Assessment
Top Plenum Shroud	Metallic/Ceramic	Mature technology – no development required
Upper Core Restraint	Composite or Metallic	Mature if metallic – Alloy 800H Significant development required for composite
Permanent Side Reflector	Graphite	Mature Technology – requires new graphite qualification
Permanent Bottom Reflector	Graphite	Mature Technology – requires new graphite qualification
Core Outlet Plenum	Graphite	Mature Technology – requires new graphite qualification
Lower Floor	Composite or Graphite	Significant Development required for composite material Graphite qualification required for graphite material

Component	Materials	Maturity Assessment
Metallic Core Support	Metallic	Mature technology – no development required
Core Barrel	Metallic	Mature technology – no development required

The material properties values for the selected graphites and composite materials will be required to qualify for use in the NGNP. Physical, thermal, and mechanical properties will need to be determined as a function of temperature and neutron fluence over the ranges expected in the NGNP plant. The composite material will also need to be codified prior to use. Details of the tests required to obtain this data and the actions necessary for codification are provided in Appendix B.

2.2.4 Reactor Vessel Internals Maturation Path Forward

To mature the RVI design to a TRL of 5, the qualification of nuclear grade graphite will need to be complete and the development and initial material properties testing of composite materials will need to be finalized.

To mature the RVI design from a TRL of 5 to a TRL of 6, the final or near-to-final designs of all RVI components that are to be composed of composite or ceramic materials should be produced. ASTM standards should be completed by issuance of TRL 6, and some of the ASME codes should be approved.

To mature the RVI design from a TRL of 6 to a TRL of 7, the upper core restraint blocks and lower floor blocks should be tested and the key thermal hydraulic parameters for conduction cool down modeling should be determined. These tests are at pilot-scale, with preparations being formulated for engineering-scale tests.

To achieve a TRL of 8, an integrated system containing the RVI will need to be demonstrated in an operational environment. Testing in the final NGNP configuration, including normal and abnormal operating conditions, will need to be completed, and this component will need to be proven through multiple cycles of hot operations.

2.3 Reactor Core and Core Structure

The Reactor Core and Core Structures are the heart of the reactor. Within it, the thermonuclear reaction (e.g., generation of heat through nuclear fission) occurs and is contained and controlled.

2.3.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from pertinent supplier Reactor Core and Core Structure TDRM data combined with NGNP R&D data, is shown in Figure 11.

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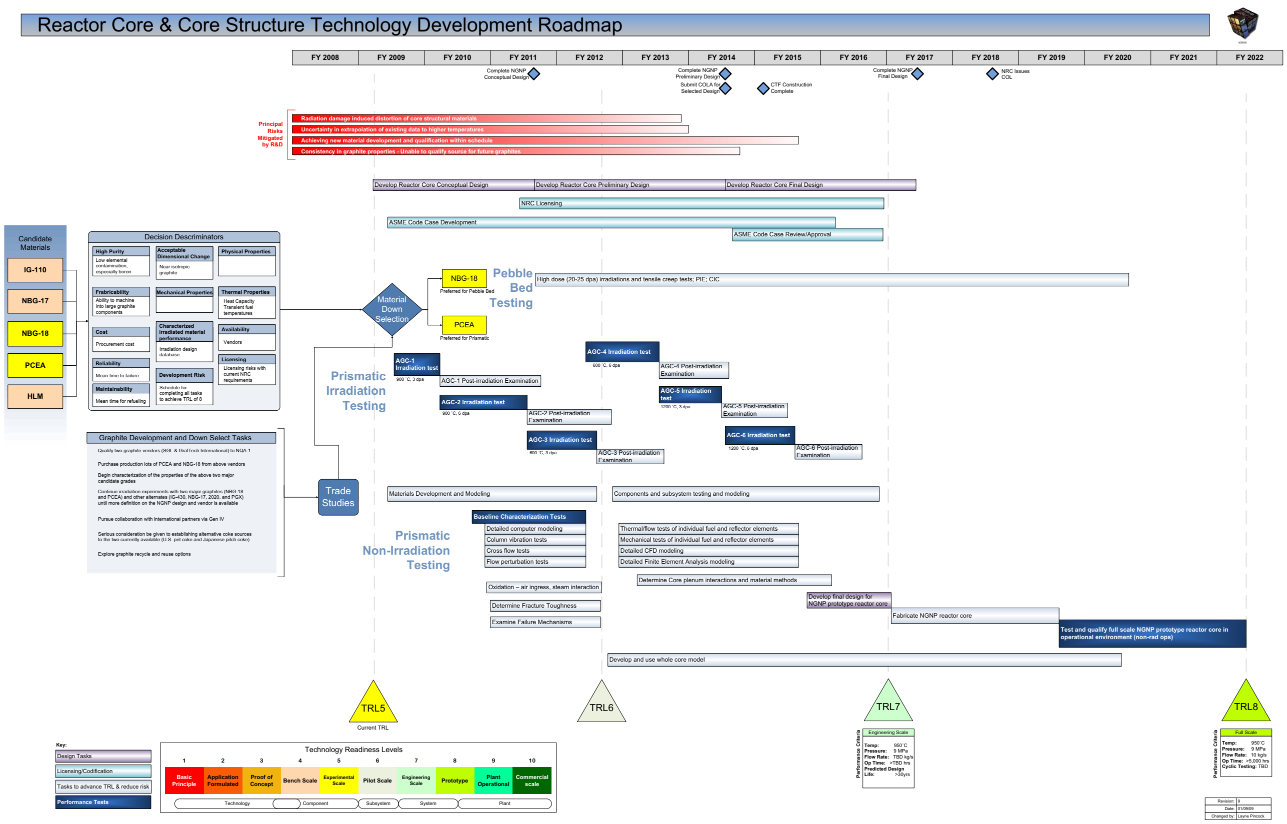

Figure 11. Reactor Core and Core Structure Roadmap

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2.3.2 Reactor Core and Core Structure Design Description

The Reactor Core and Core Structure refer to the reactor core and its support structure. The reactor core provides the housing for the fissile fuel material, moderator material, control rods, and reflectors. The fuel material is the source of heat while undergoing the fission reaction. The moderator material may be fixed in place or placed in the moveable control rods, and moderates or controls the sustained fission reaction. The reflectors provide containment and assist in sustaining the reaction. Figure 12 depicts a representative annular prismatic reactor core design showing these components. The core structure also provides channels for the flow of helium coolant for heat exchange.

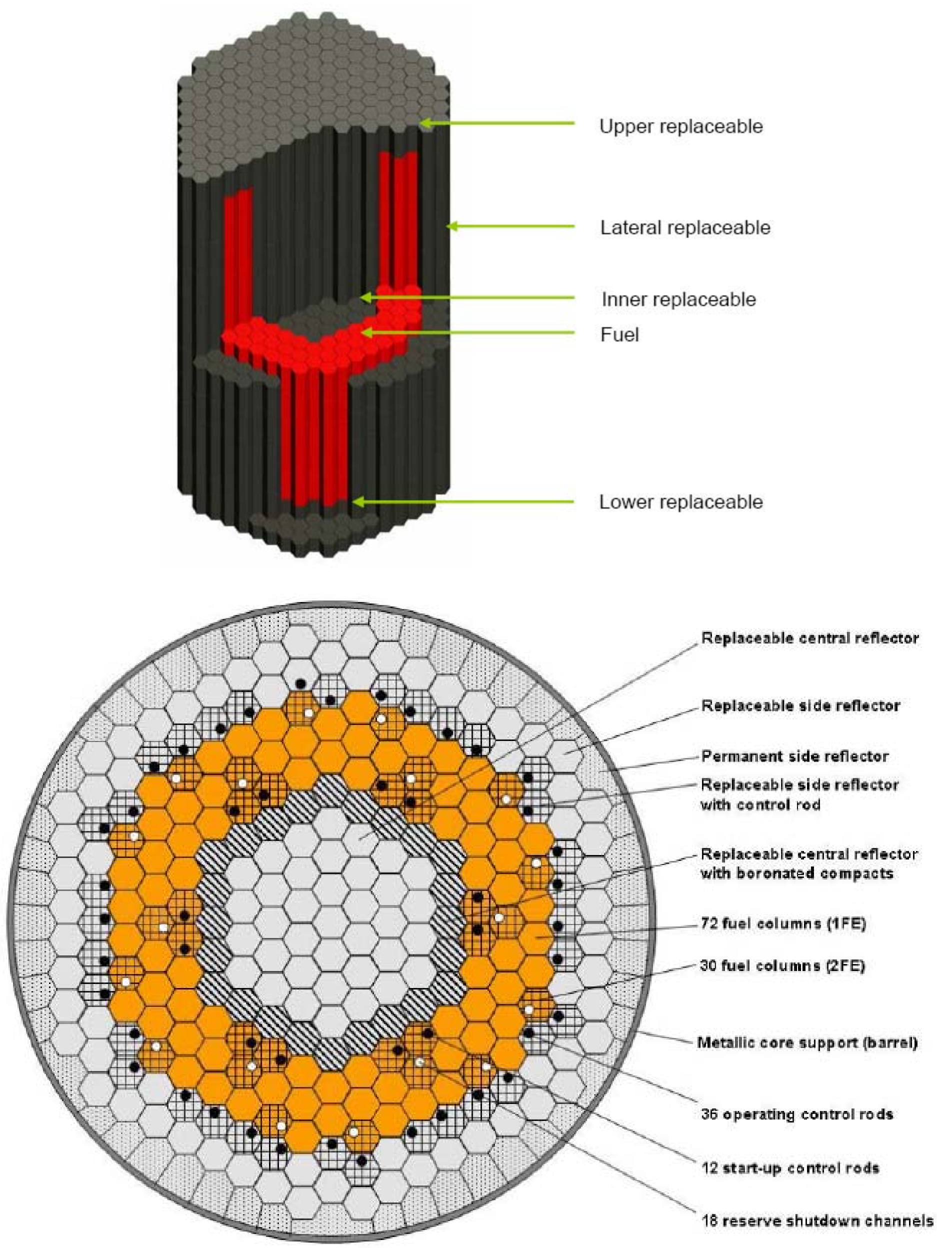

Figure 12. Representative Annular Prismatic Core Design

2.3.2.1 Functions Performed

The functions performed by the Reactor Core are as follows:

- Start the reaction
- Generate high-temperature heat using nuclear fission
- Transfer the heat to the helium coolant
- Control radiation from the core
- Sustain the fission reaction through neutron reflection in the core
- Maintain flow passage configuration
- Limit the temperatures and the fast neutron fluence.

Many additional lower level functions can be found in Appendix B.

2.3.2.2 Design Options

Two general reactor core designs have been suggested. AREVA and General Atomics both propose a prismatic design, while Westinghouse proposes a pebble-bed design. The prismatic design employs prismatic or hexagonal columnar blocks of either fuel, moderator, or reflector material placed in a columnar array. Control rods, containing additional moderator material, are inserted into tubes within the columnar blocks to control the reaction in the fuel. In the pebble-bed design, the fuel elements are spheres rather than prismatic columnar blocks.

One potential challenge with the prismatic design is machining the fuel, coolant, and neutron absorber holes with acceptable tolerances at a reasonable throughput rate. Also, an annular prismatic core has never been operationally demonstrated.

For both designs, commercial availability of acceptable grades of graphite is an issue since some previously used and proven materials are no longer commercially available. New nuclear-grade graphites are being developed and qualified, including PCEA, NBG-17, and NBG-18. Development of the fuel and fuel compacts is also currently being addressed.

2.3.2.3 Design Discriminators

The major design discriminators for the Reactor Core include: cost; schedule, for both development and material qualification; and material performance in the thermal and radiation environment, including heat capacity and dimensional changes. Additional design discriminators might include: material purity, fabricability, development risk, licensing, reliability, maintainability, and availability.

2.3.3 Reactor Core and Core Structure TRL Status

There is high confidence that the annular core with prismatic blocks design will meet all requirements for safety, licensing, and operation at NGNP operating parameters. Some existing data needs to be collected to aid the design of the NGNP. If such data is unavailable to the reactor core designer during the design phase, then additional test work may be identified to fill data gaps. A rating of TRL 5 is given to the Reactor Core and Core Structure based on the current state of technology development (see Table 6).

Table 6. Reactor Core and Core Structure Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
TRL	6	4	4	5

2.3.4 Reactor Core and Core Structure Maturation Path Forward

At this stage, the following development needs are considered to be necessary.

- **Structural performance of core blocks** – Demonstrate that the blocks will not be damaged during loading and unloading maneuvers and that the alignment pins will survive stressed induced from seismic loads.
- **Bypass flow** – The bypass flow is a key parameter and is a complex value to determine. Bypass through the gaps between block columns and in the horizontal gap between the blocks within a column must be characterized. This must be done at cold and hot conditions with blocks that simulate both unirradiated and irradiated conditions.
- **Thermo-mechanical performance** – The stresses that the blocks will experience due to thermo-mechanical stresses may be close to the structural limits of the graphite material. Testing is needed to quantify the stresses that will be generated in the block during operation.

To mature to a TRL of 5, two graphite suppliers need to be qualified, product lots from the suppliers purchased, the irradiation experiments with two major graphites and other alternatives continued, and graphite recycle and reuse options explored.

To mature the RPV design from a TRL of a 5 to a TRL of a 6, the high dose irradiations and tensile creep tests will be underway, and the Advanced Graphite Capsule (AGC)-3 irradiation test and baseline characterization tests will be complete.

To mature the RPV design from a TRL of a 6 to a TRL of a 7, bypass flow testing, thermo-mechanical testing, and structural integrity testing must be complete. In addition, the ASME code case review and approval will be complete and the Reactor Core final design will be well underway with the components and subsystem testing and modeling complete. After the requisite design data have been obtained for mock-up testing involving multiple graphite components and requisite design data have been obtained for the new graphite, other data will be acquired to advance to TRL 7.

To achieve a TRL of 8, an integrated system containing the Reactor Core and Core Structures will need to be demonstrated in an operational environment; testing in the final NGNP configuration, including normal and abnormal operating conditions, will need to be completed; and the component will need to be proven through multiple cycles of hot operations. Since no new technology development is required for the Reactor Core and Core Structures, this critical system will advance to a TRL of 8 during commissioning in the NGNP.

2.4 Fuel Elements

The Fuel Elements consist of a fissile material kernel coated with various layers of refractory materials. The design offers high flexibility in terms of geometric parameters, arrangement of layers, and choice of materials.

2.4.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from pertinent supplier Fuel Elements TDRM data combined with significant NGNP R&D data, is shown in Figure 13.

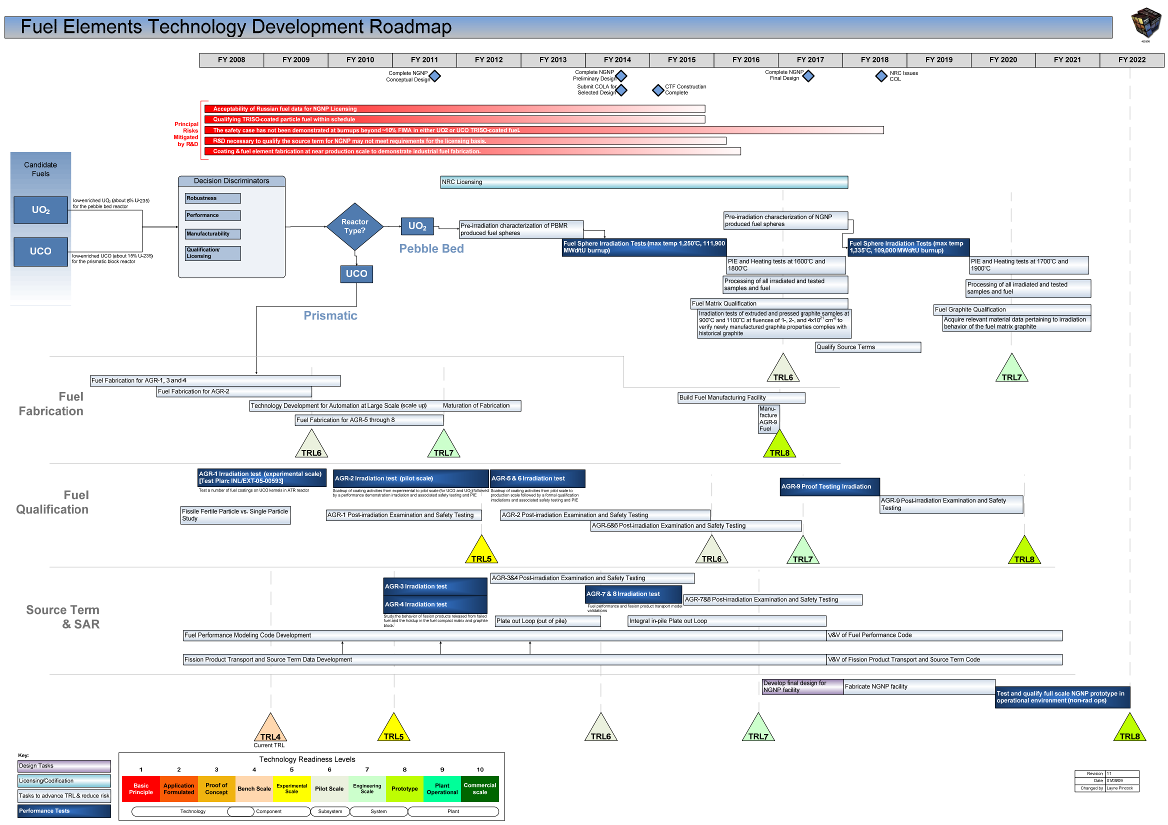

Figure 13. Fuel Elements Roadmap

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2.4.2 Fuel Elements Design Description

The fuel elements are comprised of tri-isotropic (TRISO) particles containing low enriched uranium kernels embedded in a pressed graphite matrix, as shown in Figure 14. This fuel has shown very low particle failure when restrictive parameters are imposed consistent with fuel irradiation and heatup testing (e.g., burnups, fluences, and maximum temperatures). The outstanding high-temperature performance has been established by years of irradiation and testing experience where a very small fraction of particle failure and/or fission product release occurred under simulated accident conditions.

A major goal of the Advanced Gas Reactor (AGR) Fuel Development and Qualification Program is to establish coated particle fuel fabrication technology in the United States for the Very High Temperature Reactor (VHTR) that is capable of producing fuel at a quality level at least as good as produced by German fuel technology. The AGR is used as a basis for the TRLs for the NGNP Fuel Elements.

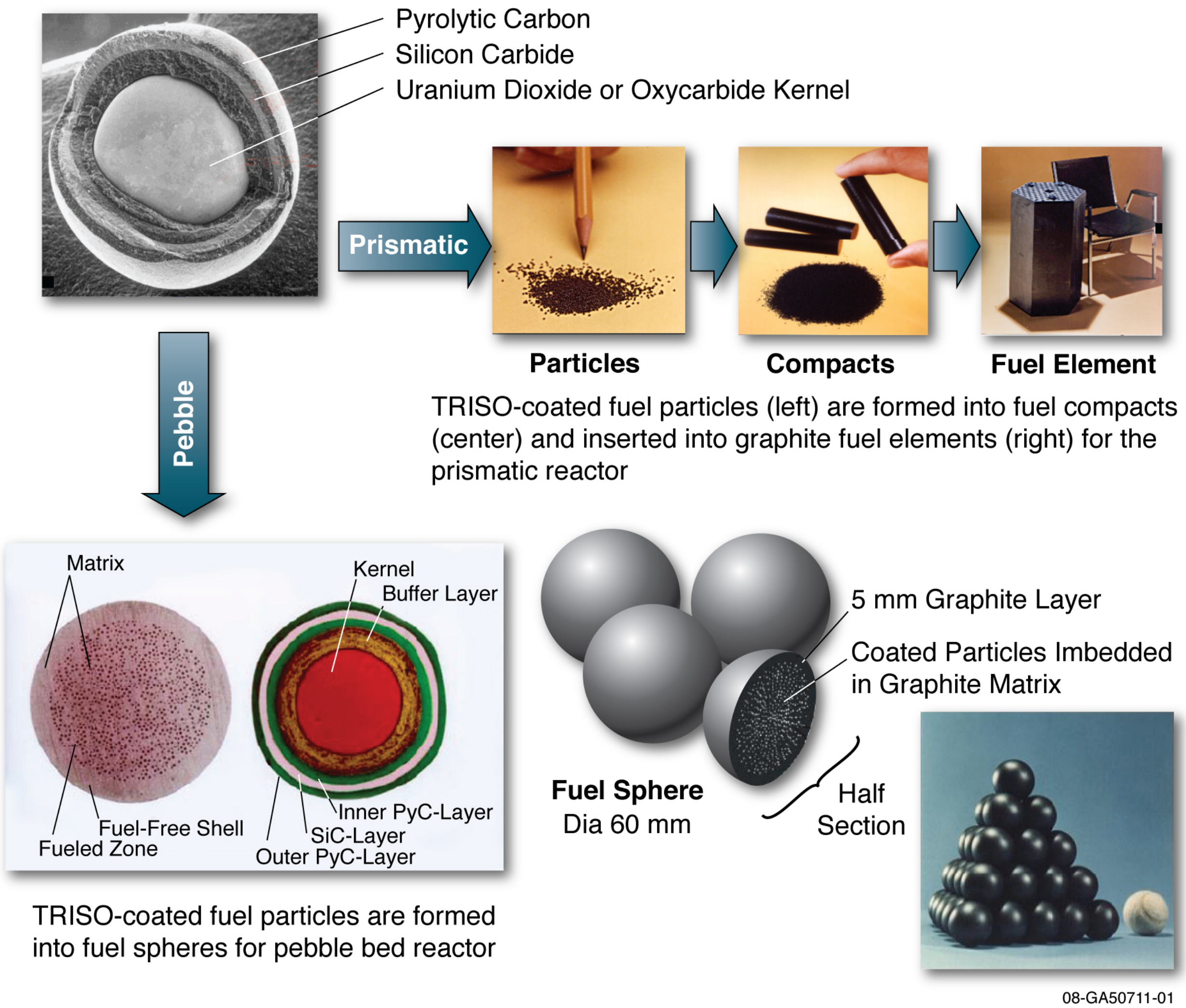

Figure 14. TRISO Particle Fuel Element

2.4.2.1 Functions Performed

The function performed by the Fuel Elements is to provide fissile fuel material for the fission reaction.

2.4.2.2 Design Options

The design specifications for the NGNP are not yet well-defined, but the maximum burnup envisioned in a VHTR is in the range 150–200 GWd/MTHM, or 16.4–21.8% fissions per initial metal atom (FIMA). The composition of the fuel kernel and the fuel element geometry are open items. Although the Germans have demonstrated excellent performance of SiC TRISO-coated UO_2 particle fuel up to about 10% FIMA and 1150ºC, UO_2 fuel is known to have limitations because of CO formation and kernel migration at the high burnups, power densities, temperatures, and temperature gradients that may be needed in the NGNP design. With UCO fuel, the kernel composition is engineered to prevent CO formation and kernel migration, which are key threats to fuel integrity at higher burnups, temperatures, and temperature gradients. Furthermore, the excellent performance of German SiC TRISO-coated UCO fuel up to 22% FIMA (as measured by the in-pile gas release in irradiation test FRJ-P24) gives added confidence that high-quality SiC TRISO-coated UCO fuel can be made and its performance statistically demonstrated. Thus, SiC TRISO-coated UCO has been chosen as the baseline fuel to be fabricated and tested in this program. A prismatic fuel element design has been chosen to be consistent with past fuel fabrication experience in the United States and to be complementary to the ongoing pebble-bed R&D elsewhere in the world. If a pebble-bed design should be developed for the NGNP, the UCO fuel could be compacted into spherical elements to fit this design. Similarly, if ongoing R&D in China, Europe, Japan, or South Africa should indicate that UO_2 fuel could operate successfully at sufficiently extended burnups, the program could be modified to test this fuel to NGNP conditions.

2.4.2.3 Design Discriminators

The design discriminators for the Fuel Elements include:

- Robustness
- Performance
- Manufacturability
- Qualification and Licensing.

2.4.3 Fuel Elements TRL Status

Both prismatic and pebble-bed fuel elements are currently rated as TRL 4 (see Table 7). Advancements of fuel elements readiness level depend greatly upon the AGR tests being performed, or planned to be performed, at the INL. Both AREVA and General Atomics are relying on the development of prismatic fuel elements at the INL as part of their design; hence, no TRL rating is provided by those suppliers. Based on review of the Westinghouse *NGNP Technology Development Road Mapping Report* (see Appendix B), the NGNP grants a TRL of 4 for Fuel Elements.

While the past fuel maturity of pebble-bed fuel elements through historic high-temperature reactors is recognized, there are too many uncertain and un-tested parameters with the current generation of fuel to grant the supplier suggested rating of TRL 6. The NGNP feels there is inadequate demonstration with the current generation of fuel and that demonstration via fabrication quality control, fuel irradiation, post-irradiation examination (PIE), and safety testing be completed before advancement to the next TRL can be granted.

Table 7. Fuel Element Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
TRL	Not provided	Not provided	6	4

2.4.4 Fuel Elements Maturation Path Forward

The Fuel Elements TDRM illustrates the two paths necessary to advance fuel technology development. Because of the unique fuel characteristics of both reactor cores types, prismatic and pebble-bed, path forwards are on different maturation paths regarding timing and unique fuel characteristics. Fuel fabrication for each of the AGR experiments varies, depending on the timing of the experiment and the input previous AGR experiments provide as feedback for enhancing fuel fabrication.

2.4.4.1 Prismatic Fuel Elements Maturation Path Forward

The path forward for the prismatic fuel maturation is described in the Table 8. Each of the AGR experiments includes a series of progressive activities necessary to fabricate and qualify fuels and to provide data for source term and safety analysis activities.

Table 8. Fuel Element Summary TRL Table

	TRL 4 to 5 (Laboratory-scale)	TRL 5 to 6 (Pilot-scale)	TRL 6 to 7 (Engineering-scale)	TRL 7 to 8 (Plant/Prototype-scale)
Fabrication	AGR-1 fuel fabrication	AGR-2 fuel fabrication	AGR-5/6 fuel fabrication	AGR 9 fuel fabrication
Fuel Qualification	AGR-1 irradiation, PIE, and safety testing	AGR-2 irradiation, PIE, and safety testing	AGR-5/6 irradiation, PIE, and safety testing	AGR-9 irradiation, PIE, and safety testing
Source Term & SAR	(historical database)	AGR-3/4 out-of-pile loop	AGR-7/8 integrated in-pile loop	

Overarching activities include fuel performance modeling code development and fission product transport and source term data development. Final TRL advancement will require final NGNP design, fabrication of the NGNP, and non-radiological operational tests and qualification.

2.4.4.2 Pebble-bed Fuel Elements Maturation Path Forward

Pebble-bed fuel elements require a series of tasks and tests to advance them to a TRL of 6. These include irradiation experiments, necessary fuel qualification, PIEs, and safety analyses.

Source term qualification and irradiation experiments continue for a TRL of 7 to be granted. The most pertinent task is the beginning of fuel sphere irradiation tests with parameters at 1355°C at a burnup of 109,000 MWd/tU, along with a series of PIE and irradiation processing. Fuel graphite qualification must also begin for TRL 7 issuance.

Completion of all of the final PIE, irradiation processes, and final fuel graphite qualification tests is necessary for the pebble-bed fuel to achieve a TRL of 8 and be considered ready for insertion into the NGNP.

2.5 Reserve Shutdown System

The Reserve Shutdown System (RSS) is used to regulate the reactor, maintaining it subcritical below an average core temperature of at least 100°C during shutdown. Because a drastic and sharp change in temperature in the reactor may cause critical stress related problems, the RSS moderates the temperature change during shutdown.

2.5.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from RSS TDRM data from the suppliers combined with NGNP R&D data, is shown in Figure 15.

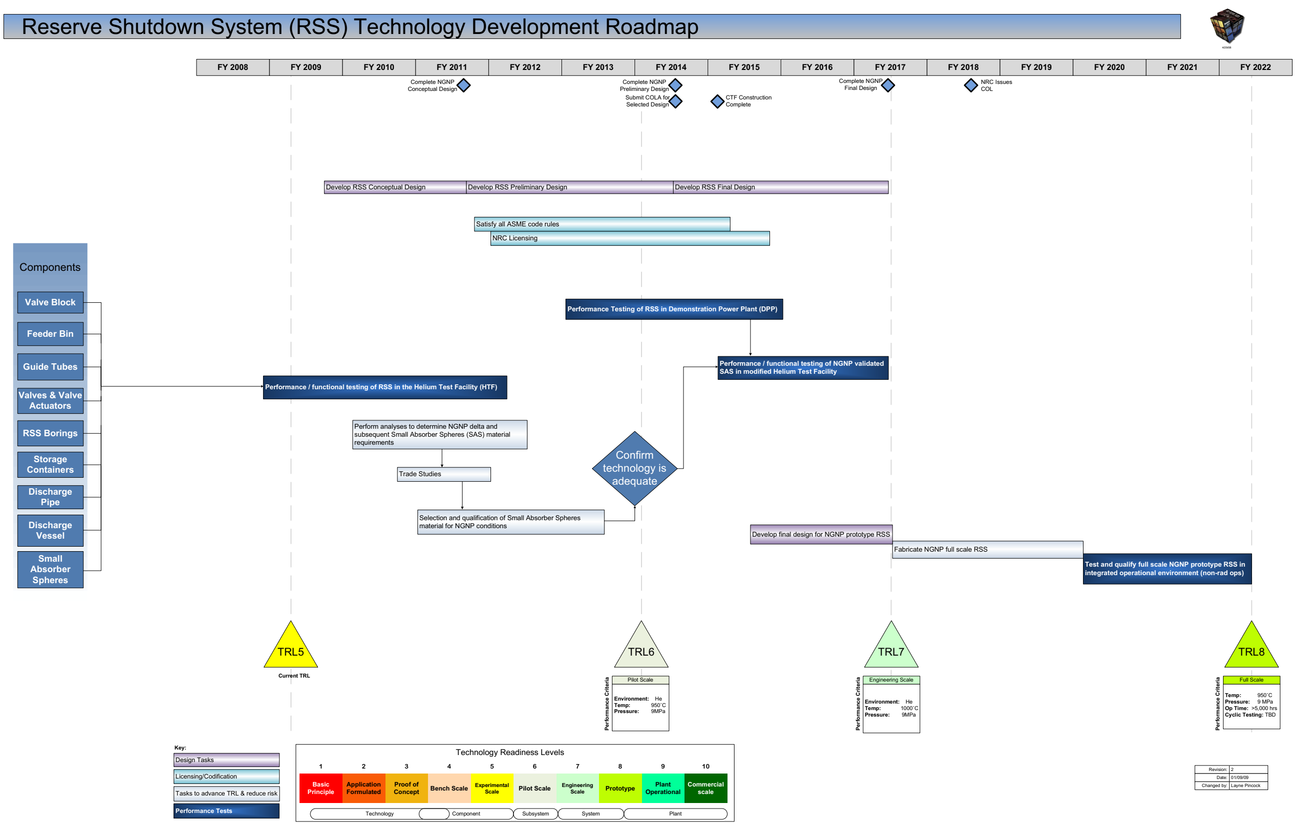

Figure 15. Reserve Shutdown System Roadmap

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2.5.2 Reserve Shutdown System Design Description

The RSS interfaces with the RPV and Reactor Core and operates at the same temperature and pressure as the reactor. The RSS typically consists of additional or reserved control rods, containing moderator or neutron absorption material, that are inserted into the core to slow down the thermonuclear reaction and bring the reactor to 'cold' conditions for maintenance operations. When engaged, the RSS maintains the reaction at a subcritical level while permitting the continued flow of helium to keep the average core temperature at 100°C or less. Figure 16 depicts a representative RSS.

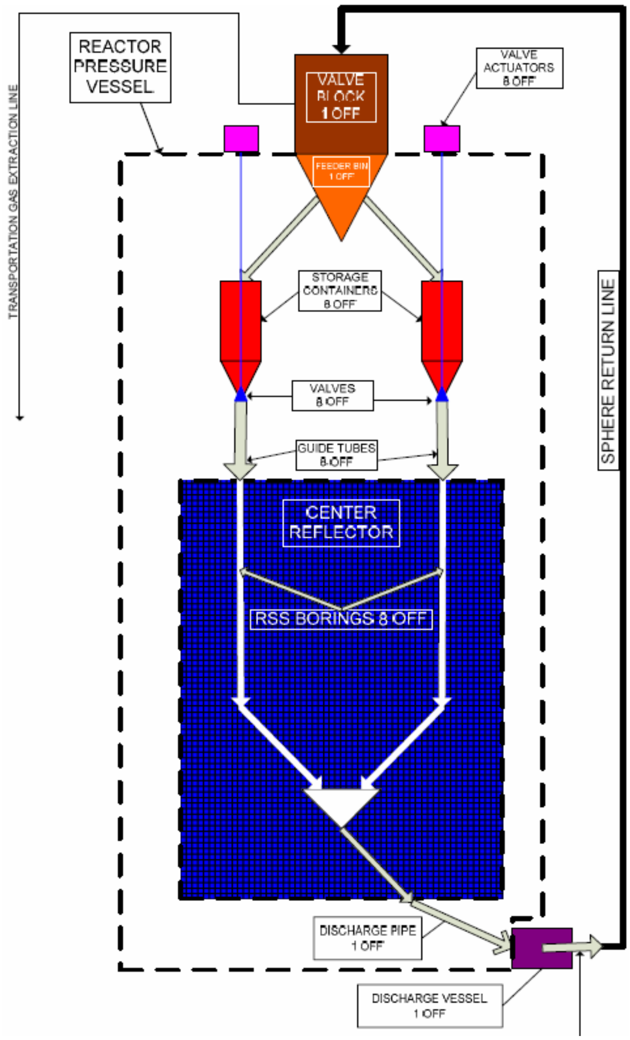

Figure 16. Representative Reserve Shutdown System Schematic Layout

2.5.2.1 Functions Performed

At a high level, the RSS keeps the reactor subcritical and operating below an average core temperature of 100°C during shutdown. The RSS shuts down the reactor by neutron absorption. The RSS also maintains the RPV Pressure Boundary, where some RSS components penetrate the RPV, thus becoming part of the boundary.

2.5.2.2 Design Options

Only Westinghouse identified the RSS as a critical system. There are no alternative designs for the RSS.

2.5.2.3 Design Discriminators

Since there are no alternative designs, there are no design discriminators.

2.5.3 Reserve Shutdown System TRL Status

The RSS for the NGNP is currently rated at a TRL of 5 (see Table 9). This TRL rating is based on the justification that operating experience already exists for similar shutdown systems in other gas-cooled graphite moderated reactor applications, particularly in Fort St. Vrain, the Japanese HTTR, and the German Thorium Hocktemperatur Reaktor (THTR).

Table 9. Reserve Shutdown System Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
TRL	Not Provided	Not Provided	6	5

2.5.4 Reserve Shutdown System Maturation Path Forward

Advancement from TRL 5 to TRL 6 will require performance at a pilot-scale, with performance criteria being in a helium environment at an operating temperature of 950°C and a pressure of 9MPa. Performance and functional tests need to be performed at a facility that can test the RSS at necessary performance criteria. Additionally, trade studies and Small Absorber Spheres performance activities need to be conducted prior to declaring technology viability.

Performance and functional test of the RSS need to be conducted to achieve a TRL of 7. Performance of tests will be conducted at the engineering-sale within a helium environment at a temperature of 1000°C and pressure of 9MPa.

TRL 8 is achieved upon full-scale testing of the RSS in the NGNP, within a non-radiological environment at a temperature of 950°C and a pressure of 9 MPa, and for a time intervals of >5,000 hours. This entails integrated operations for the tests.

2.6 Reactivity Control System

The Reactivity Control System (RCS), also known as the neutron control system, is part of the Reactivity Control and Shutdown System. It controls the reactivity in the core and provides for quick shutdown, if needed.

2.6.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from supplier RCS TDRM data combined with NGNP R&D data, is shown in Figure 17.

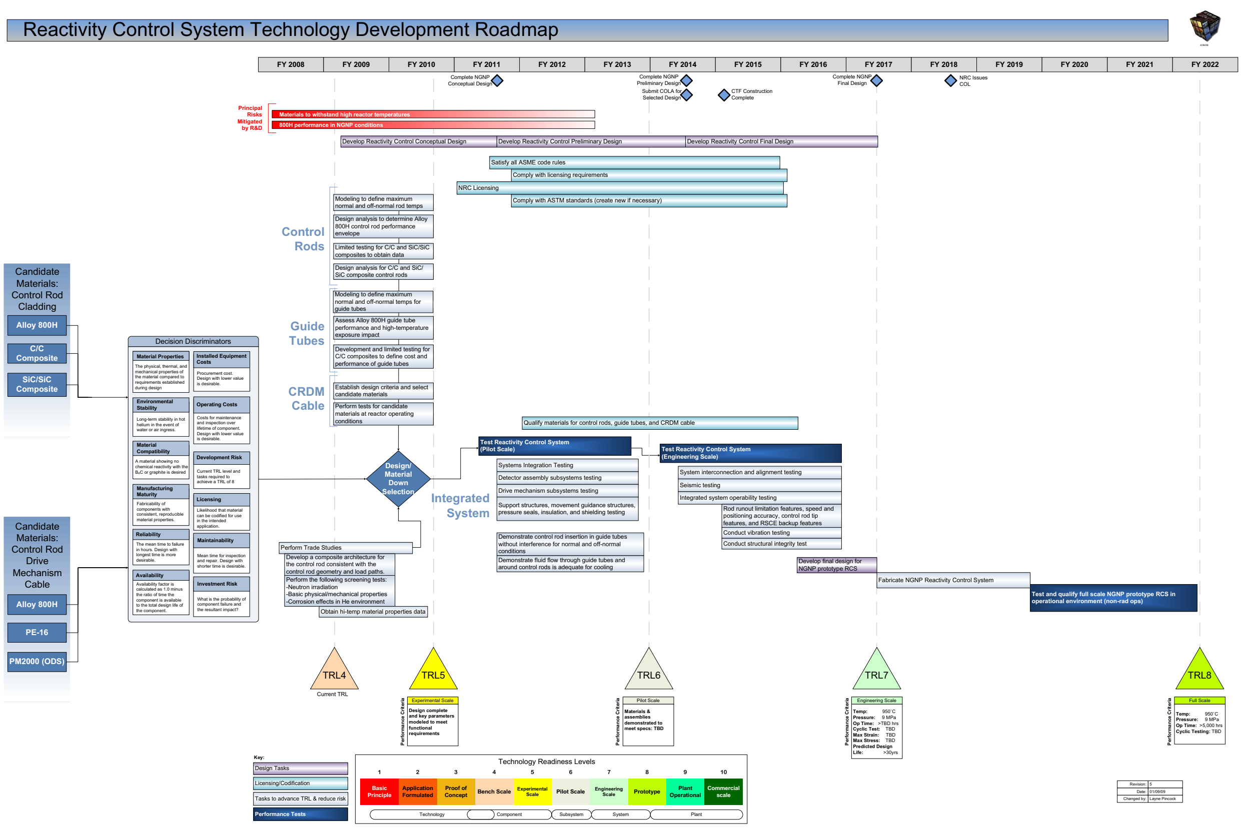

Figure 17. Reactivity Control System Roadmap

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2.6.2 Reactivity Control System Design Description

The RCS is used to control reactivity in the core and to quickly shutdown the reactor and keep it in a shutdown state, if necessary. This is accomplished by inserting a neutron-absorbing material into the reactor core to moderate the reaction.

The neutron-absorbing moderator, in the form of rings or annular cylinders, is encased in a sleeve or tube, and the combined sleeve and moderator comprise a control rod. The control rods are inserted into the core, and the amount of absorption is determined by the depth to which the rods are inserted. Primary components will include control rods (sleeves and moderator), guide tubes, and a drive mechanism (including cables).

2.6.2.1 Functions Performed

The RCS controls the nuclear chain reaction in the reactor core by absorbing neutrons in any operational mode.

2.6.2.2 Design Options

Design options differ in the number of startup, operating, and/or shutdown control rods, and in the materials used. All of the proposed designs are based on using boronated graphite, or boron-carbide (B_4C), as the moderator, but materials for other components, such as sleeves and cables, have not yet been specified.

Due to the extremely high temperatures in the reactor core, thermal gradients across the rods may cause thermal bending. Therefore, material selection for some components will be based on thermal performance in the high-temperature environment. Candidate materials for the control rod sleeves include: Alloy 800H, C/C composites, and silicon carbide/silicon carbide (SiC/SiC) composites. Candidate materials for drive mechanism cables include: Alloy 800H, PE-16, and PM2000 (ODS).

2.6.2.3 Design Discriminators

Primary design discriminators include operating cost and material properties, as they impact the mechanical and thermal performance in the high-temperature environment. Additional discriminators, carrying less weight, include: material compatibility, environmental stability, installed equipment costs, development risk, investment risk, manufacturing maturity, licensing, reliability, maintainability, and availability.

2.6.3 Reactivity Control System TRL Status

Table 10 summarizes the current TRL assessments for the RCS. General Atomics assigned a TRL of 2, AREVA assigned a TRL of 4, and Westinghouse assigned a TRL of 6. NGNP has evaluated the overall readiness of the RCS technology and assigned a TRL of 4. This TRL rating is an average of the three suppliers, and the level of technology maturity for each of RCS components (i.e., Control Rods, Guide Tubes, and Control Rod Drive Mechanism [CRDM] Cable) is within the TRL 4 range.

Table 10. Reactivity Control System Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
TRL	4	2	6	4

2.6.4 Reactivity Control System Maturation Path Forward

Reactivity Control System technology will achieve a TRL of 5 after materials have been selected and experimental-scale tests have been conducted. These material tests effect all three RCS components, which need to overcome material issues and design issues before advancement to the next TRL is granted.

A TRL of 6 will be achieved once materials and assemblies have been demonstrated in pilot-scale tests. This includes systems integration, subsystems assembly, and other mechanical/design tests.

TRL 7 is achieved once interconnection and alignment tests are completed in engineering-scale. Performance criteria for engineering-scale includes a testing temperature of 950°C, pressure at 9 MPa, and a predicted design life of >30 years.

Full-scale tests are required to advanced RCS technology to a TRL of 8, which includes final testing and qualifications of the RSS in a non-radiation operational environment.

2.7 Core Conditioning System (Shutdown Cooling)

The Core Conditioning System (CCS) removes decay heat from the reactor when the heat exchanger is not operational. The CCS is imperative to have when maintenance and other operational situations mandate the NHS to be isolated from other NGNP areas.

2.7.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from supplier CCS (Shutdown Cooling) TDRM data combined with NGNP R&D data, is shown in Figure 18.

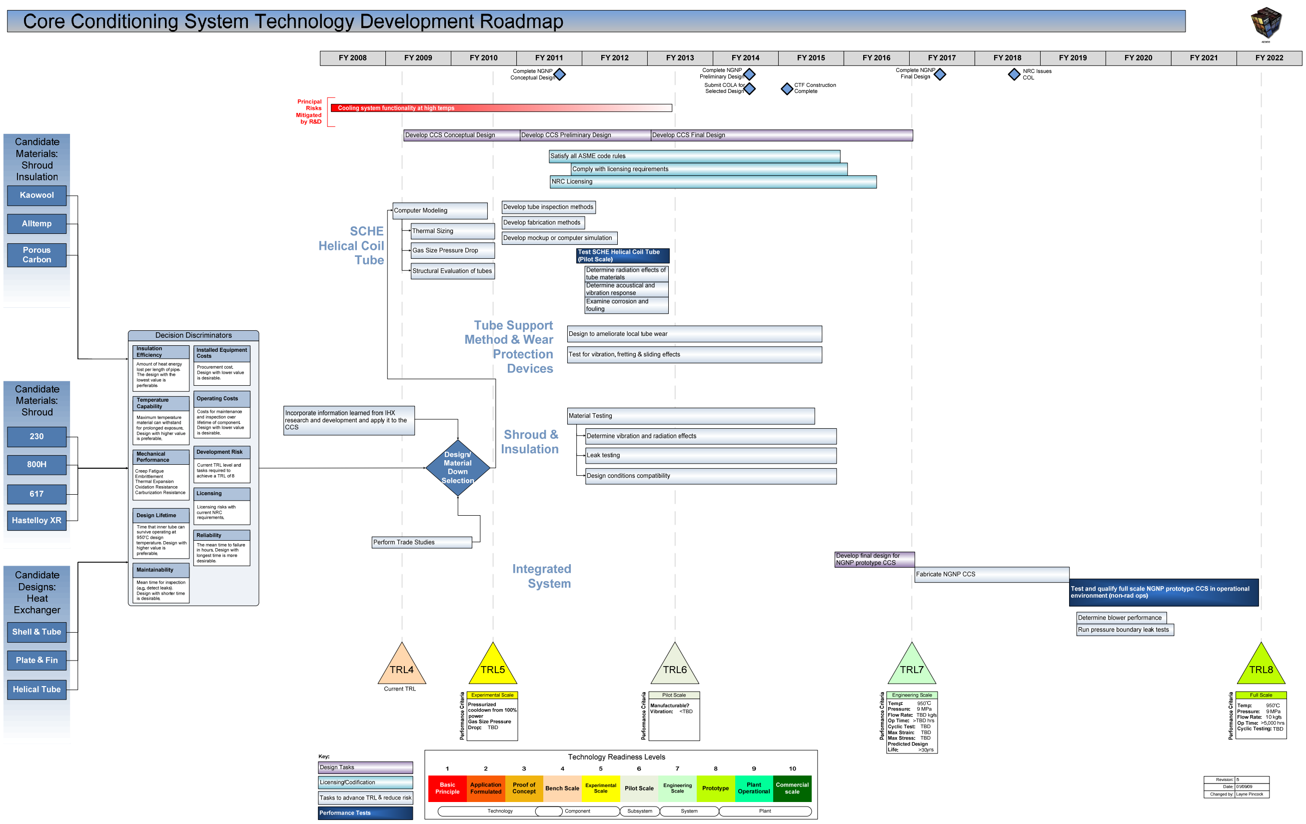

Figure 18. Core Conditioning System Roadmap

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2.7.2 CCS (Shutdown Cooling) Design Description

When the CCS is operating, hot gas is extracted from the core outlet pipe and passed through a water-cooled heat exchanger, the CCS blower, and then back into the annular cooling cavity of the hot gas ducts and the core inlet pipe. A CCS by-pass control valve regulates the amount of gas directed back to the core. This way the core temperature may be controlled. The CCS consists of two identical loops, which are housed and operated separately for redundancy. A process flow diagram for a typical CCS concept is shown in Figure 19.

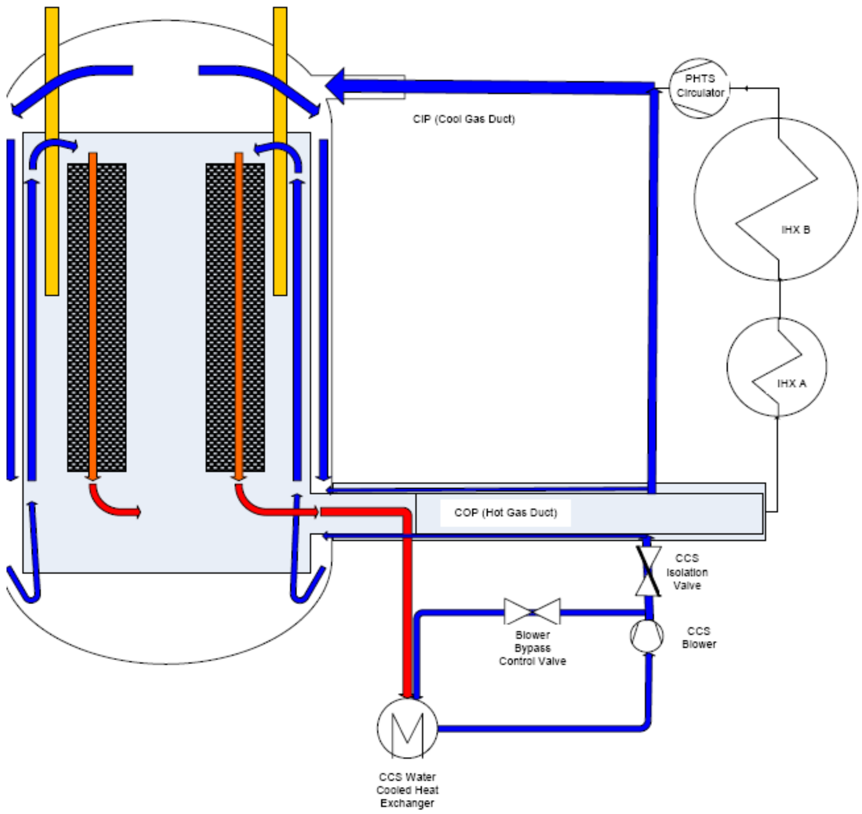

Figure 19. Typical Process Flow Diagram of CCS

2.7.2.1 Functions Performed

Some of the operational functions of the CCS include:

- Normal maintenance operations to keep the core temperature within set limits
- Cool down the core to maintenance conditions or keep it at operating conditions should there be small leaks in the Helium Pressure Boundary
- Provide cooling flow to the reactor during maintenance.

2.7.2.2 Design Options

Design options include using a Shutdown Cooling Heat Exchanger (SCHE; General Atomics design) or a generalized CCS (Westinghouse design) in a helical tube configuration. Two areas still require down selection prior to completion of conceptual design. These are (1) selection of the shroud material from either Haynes 230, Alloy 800H, Inconel 617, or Hastelloy XR, contingent on input from the IHX R&D effort; and (2) selection of the shroud insulation material from either Kaowool, Alltemp, or Porous Carbon.

2.7.2.3 Design Discriminators

Major design discriminators for the CCS include: insulation efficiency, installed equipment costs, temperature capability, operating costs, mechanical performance, development risk, licensing, design lifetime, maintainability, and reliability.

2.7.3 CCS (Shutdown Cooling) TRL Status

The current TRL ratings of the General Atomics and Westinghouse CCSs are 5 and 6, respectively, as shown in Table 11. After evaluating the suppliers' TRL ratings and incorporating R&D input, the NGNP assigns the CCS a TRL of 4. This critical PASSC requires tests and tasks at the late bench-scale leading to experimental-scale to demonstrate technical feasibility and functionality.

Table 11. CCS Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
TRL	Not provided	5	6	4

2.7.4 CCS (Shutdown Cooling) Maturation Path Forward

Maturation tests and tasks for the CCS can be categorized into four areas: SCHE Helical Coil Tube; Tube Support Method and Wear Protection Devices; Shroud and Insulation; and Integrated System.

To advance to a TRL of 5, several key activities must be completed, including: trade studies, incorporating IHX input into CCS technology development, and computer modeling of specific criteria for the SCHE Helical Coil Tube. One performance criteria to obtain TRL 5 is the pressurized cool down from 100% power.

To advance the CCS from TRL 5 to TRL 6, material issues need to be resolved and the components of the CCS tested, as shown on the CCS TDRM. Other tasks and tests include more detailed analysis on each of the CCS areas; important to this is the method development to be performed. Additionally, pilot-scale testing begins on the SCHE, along with other tasks being performed for the Tube Support, and Shroud and Insulation development. Significant materials testing for Shroud and Insulation begins and continues through TRL 6.

To mature the CCS from TRL 6 to TRL 7, the CCS will be tested in a relevant environment, as shown on the TDRM. Engineering-scale testing is required, with identified performance criteria being at 950°C and a pressure of 9 MPa. Completion of Tube Support and Shroud and Insulation tasks grants the CCS a TRL of 7, with Final Design of the NGNP CCS being started and completed.

To mature from a TRL 7 to TRL 8, the CCS will be inserted into the NGNP for full-system operability testing. Testing and qualification of the full-scale NGNP CCS in a non-radiation operating environment grants a TRL of 8.

2.8 Reactor Cavity Cooling System

The Reactor Cavity Cooling System (RCCS) removes waste heat from the Reactor Cavity, through common heat exchange techniques, to cool the Reactor Cavity and maintain its temperature within safe operating limits.

2.8.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from supplier RCCS TDRM data combined with NGNP R&D data, is shown in Figure 20.

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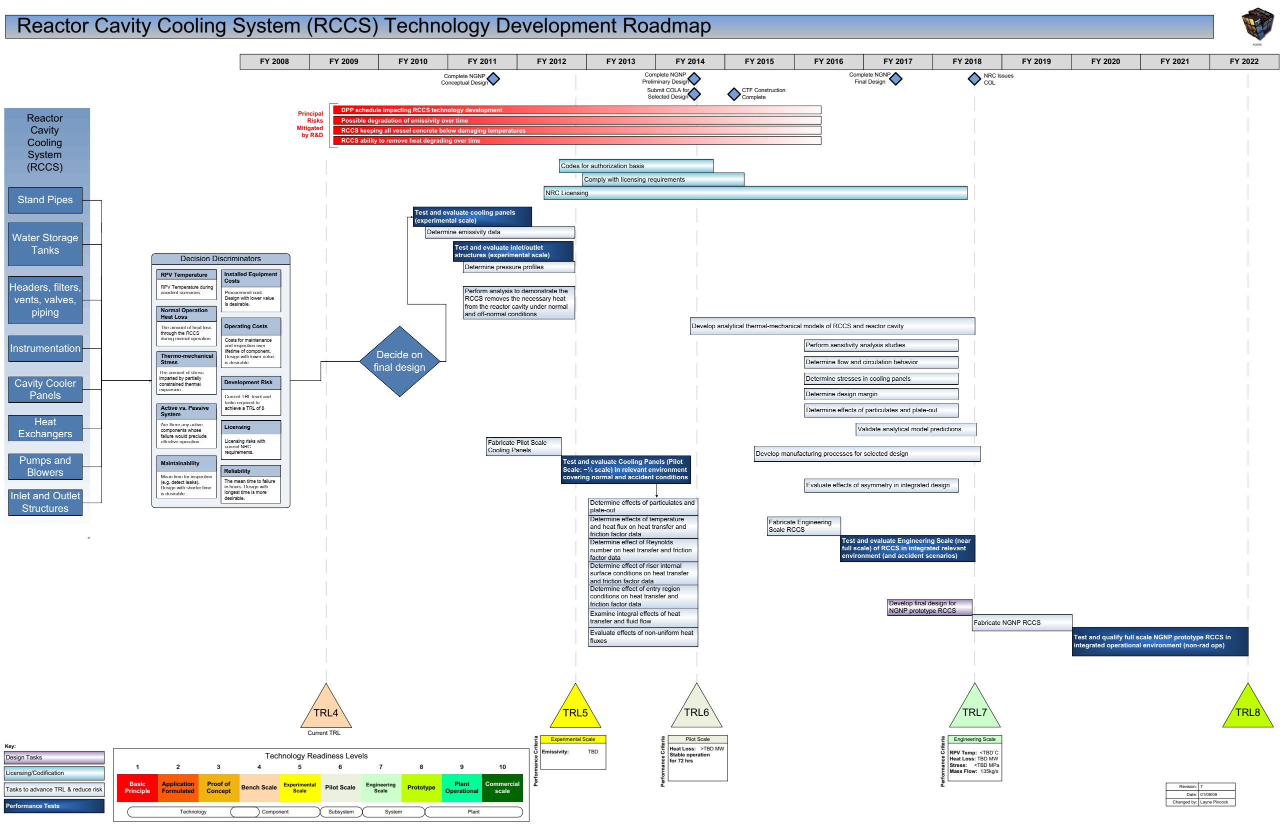

Figure 20. Reactor Cavity Cooling System Roadmap

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2.8.2 Reactor Cavity Cooling System Design Description

The RCCS is a simple system that relies on radiative, conductive, and convective heat transport mechanisms to transfer heat away from the Reactor Cavity in the RPV. During normal operations, the RCCS pumps and circulates water or air past the RPV. Heat is transferred to the water or air and dissipated through a heat sink or heat exchanger. The RCCS also protects the reactor cavity concrete, including RPV supports, from overheating during normal operation. Common components may include water storage, heat exchangers, pipes, and cooling panels. A representative RCCS layout is shown in Figure 21.

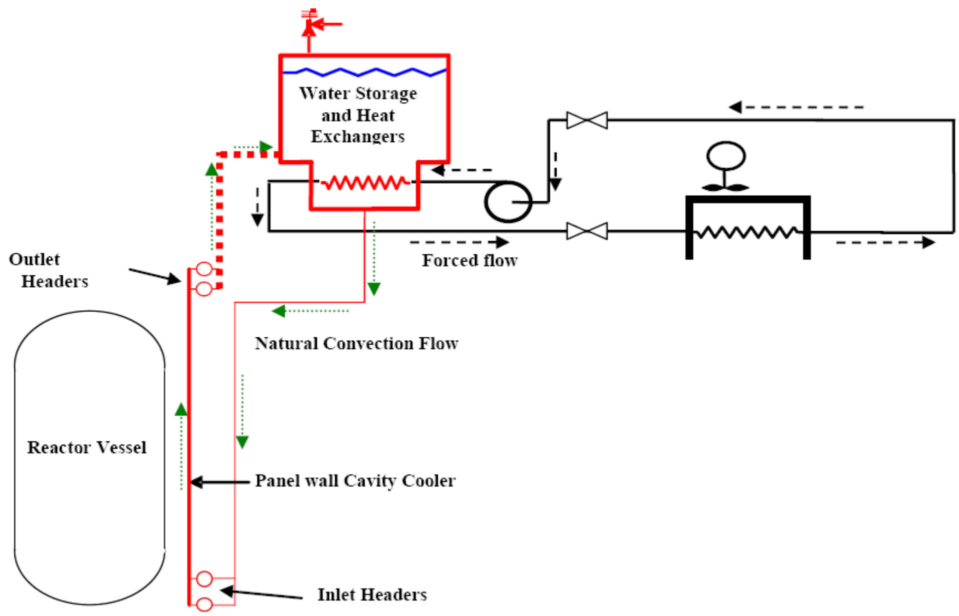

Figure 21. Representative RCCS Layout

2.8.2.1 Functions Performed

The primary functions of the RCCS are:

- Remove normal operating waste heat from the Reactor Cavity
- Maintain Reactor Cavity concrete surface temperature below code limits
- Protect the RPV from overheating during normal operation
- Provide alternative means of heat removal when the Primary Heat Transport System (PHTS) and the Shutdown Cooling System are not operating.

2.8.2.2 Design Options

Current RCCS design configurations show that AREVA and Westinghouse favor a water-cooled RCCS design over an air-cooled design. General Atomics, on the other hand, considers the possibility of using air or water as the coolant fluid.

In the Westinghouse design, redundancy is provided by feeding 72 standpipes from 18 independent tanks, as shown in Figure 22. The standpipes from the same tank are segregated to limit concentration of hot areas should one system fail. An alternative design being considered by Westinghouse, which utilizes heat pipes, is being evaluated for future plants.

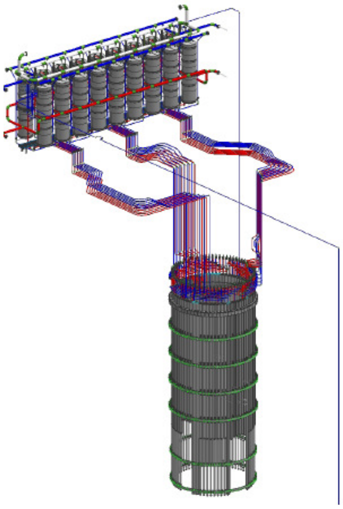

Figure 22. General arrangement of RCCS components

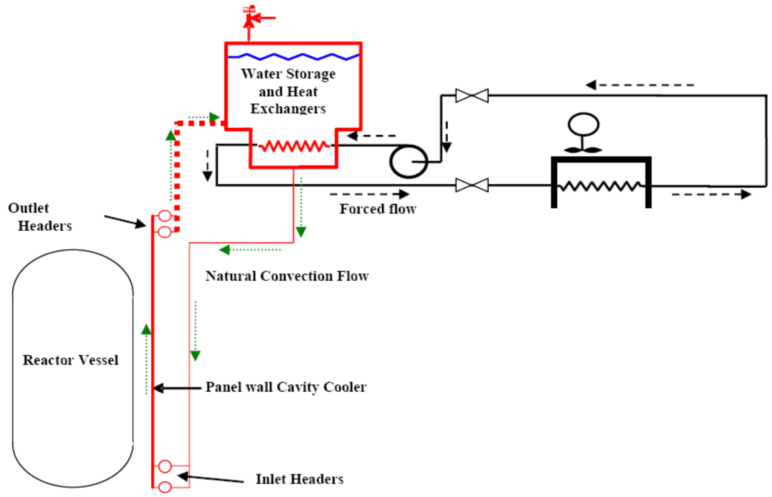

Figure 23. AREVA RCCS Layout

Like Westinghouse, AREVA's design, shown in the Figure 23, includes a water storage tank above the RPV. During normal shutdown, decay heat is removed through the PHTS or through the CCS. However, in the event that these paths are unavailable, decay heat is transferred by passive means from the RPV to RCCS panels.

General Atomics' configuration is a concentric cylindrical stack design with an elevated intake and exhaust. The configuration minimizes the effect of wind speeds and directions by elevating the stack intake and exhausts above the point where the local site structures have a significant effect on the wind flow boundary layer.

2.8.2.3 Design Discriminators

Major design discriminators for the RCCS include: schedule; thermal performance, particularly the ability to keep maintain RPV concrete temperature below damaging-inducing levels (RPV temperature and thermo-mechanical stress); and material performance, in terms of susceptibility to degradation in heat removal capability and in emissivity. Additional discriminators may include: cost, development risk, licensing, reliability, maintainability, and availability.

2.8.3 Reactor Cavity Cooling System TRL Status

A TRL of 4 is issued by the NGNP for the RCCS (see Table 12). There are significant tests and tasks to overcome before advancing to the next TRL. Generally speaking, these tasks orient around cooling panels and inlet/outlet structures work to be performed. At a TRL 4, the components of the RCCS must be tested at a bench-scale to demonstrate technical feasibility and functionality. When these material issues are overcome and information has been provided to prove feasibility of the components at a bench-scale, the RCCS will advance to TRL 5.

Table 12. Reactor Cavity Cooling System Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
TRL	6	4	6	4

2.8.4 Reactor Cavity Cooling System Maturation Path Forward

To mature the RCCS from TRL 4 to TRL 5, the components of the RCCS will be demonstrated at experimental-scale in a relevant environment. This includes the testing and evaluation of cooling panels (at pilot-scale) and the testing and evaluation of inlet/outlet structures. Emissivity and pressure are some of the parameters being examined. A heat removal analysis of the RCCS is also conducted for normal and off-normal conditions.

To advance the RCCS from TRL 5 to TRL 6, the components will be integrated into a subsystem and demonstrated at a pilot-scale in a relevant environment. Completion of pilot-scale testing of cooling panels examines some specific parameters defined in the TDRM.

To mature the RCCS from TRL 6 to TRL 7, the RCCS subsystems will be integrated into an engineering-scale system and demonstrated in a relevant environment. A demonstration at this stage shows fabricability, flow and circulation behavior, and stress in the cooling panels. Tasks to be performed at this stage are shown on the TDRM.

To mature from a TRL 7 to TRL 8, the RCCS will be inserted into the NGNP for full-system operability testing. Fabrication of the NGNP RCCS must begin and be completed before the full-scale RCCS is ready for integrated operational (non-radiation ops) testing.

3. HEAT TRANSPORT SYSTEM

Section 3 provides a detailed description of the functions performed in the Heat Transport System (HTS). The key systems within the HTS are the primary loop, the secondary loop, IHX Vessel, the primary and secondary gas circulators, the heat exchanger, the primary Hot Gas Duct, and the High-temperature Valves.

3.1 Circulators

The Circulators force primary helium through the reactor core and cooling loops at high temperatures to cool the system.

3.1.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from the supplier Circulators TDRM data combined with NGNP R&D data, is shown in Figure 24.

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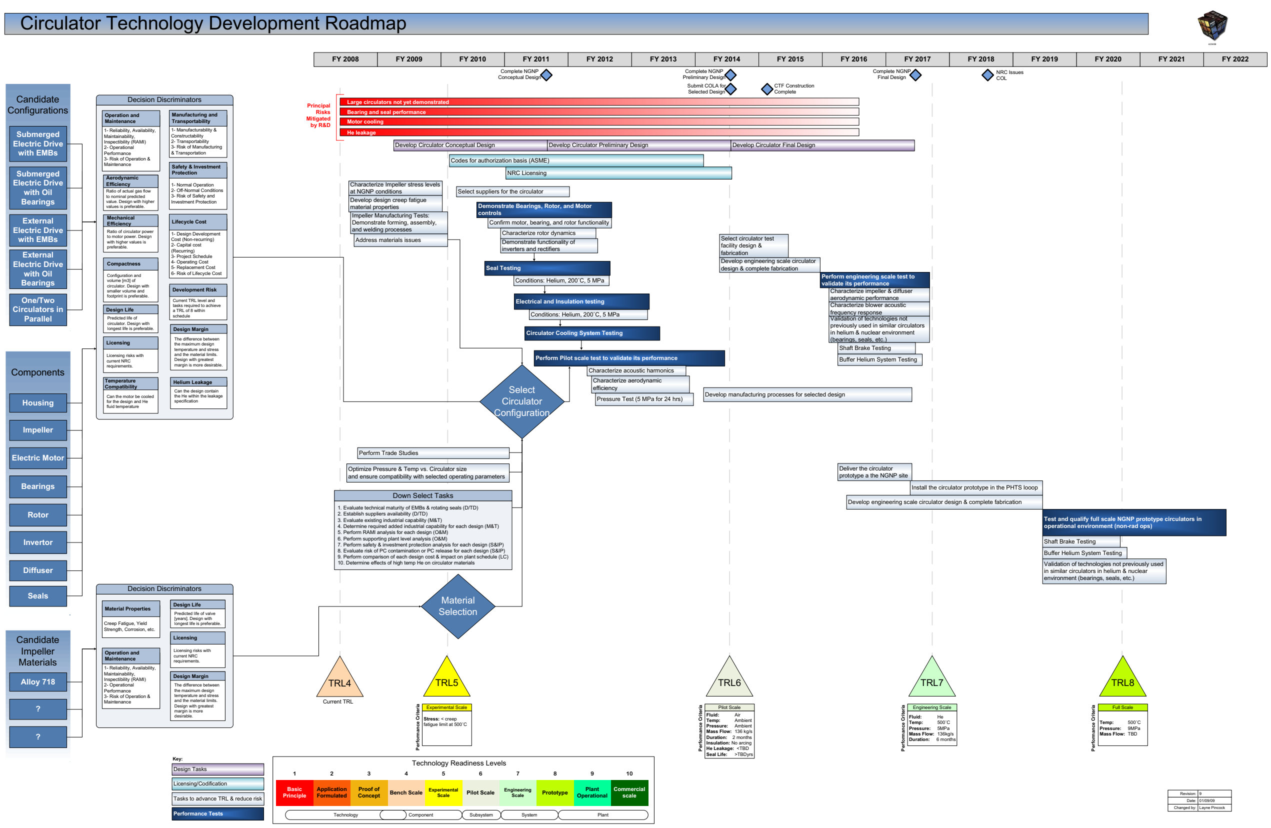

Figure 24. Circulators Roadmap

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3.1.2 Circulators Design Description

The circulators are sized based on the coolant pressure drop through the reactor cooling system when the reactor is at 100% power (anticipated helium flow rate is 136 kg/s). The circulators include the following components:

- Housing
- Impeller
- Diffuser electric motor
- Bearings (electro-magnetic and mechanical catcher)
- Rotor
- Inverter
- Seals.

3.1.2.1 Functions Performed

The high-level function performed by the circulators is to circulate helium through the primary and secondary loops. Lower-level functions include:

- Turn the rotor
- Supply power
- Convert power
- Control flow rate.

Depending on whether the design includes a submerged or external electric drive, the circulators may also be required to control leakage.

3.1.2.2 Design Options

Two possible sizing options exist for the circulator: a single large circulator (8 MWe) for the primary loop, and a 16 MWe for the secondary loop (AREVA). Circulators greater than 6 MWe have not been used in the Nuclear Industry. Therefore, technology development is required to ensure readiness for insertion of an 8 to 16 MWe circulator in the NGNP. In the event that technology challenges of 8 to 16 MWe are insurmountable, smaller 5 to 6 MWe circulators will be used in parallel to achieve the power needed for the mass flow rate needed in the loop. It may also be that circulators in parallel add redundancy and ability to perform maintenance with a reactor outage. Additional studies are needed to make this design decision.

There are four possible design options for the 8 MWe circulator: a submerged electric drive with either electromagnetic (EM) bearings or oil bearings, or an external electric drive with either EM bearings or oil bearings. A submerged electric drive with EM bearings is the preferred option to avoid helium leakage through the seals and oil leakage into the primary loop. However, in the event that the technical challenges associated with this option are insurmountable, an external electric drive with EM bearings or oil bearings will be considered.

There are several different technology options: the impeller type, motor type, and the motor cavity seal type within the previously mentioned design options.

3.1.2.3 Design Discriminators

The major design discriminators for the circulators include: thermal performance (i.e., can the motor be adequately cooled for the design and helium temperature), helium leakage, and bearing and seal performance. Additional design discriminators may include: manufacturability and transportability, aerodynamic efficiency, mechanical efficiency, life-cycle cost, development risk, design margin, licensing, compactness, reliability, maintainability, availability, and operations and maintenance risk. Additional information on each discriminator can be found in the TDRM (see Figure 24).

3.1.3 Circulators TRL Status

The current TRL rating for each supplier is shown in Table 13. For gas circulators greater than 6 MWe, NGNP has issued a TRL of 4. This is due to the lack of demonstration of this size of circulator. A gas circulator less than 6 MWe has been tested in the past and is at a TRL of 6. Several lesser power level gas circulators connected in parallel is a backup option should the higher power level circulators prove problematic.

Table 13. Circulators Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
> 6 MWe	4	5	6	4
< 6 MWe	Not provided	6	Not provided	6

3.1.4 Circulators Maturation Path Forward

To advance from a TRL of 4 to TRL of 5, the key tasks needing to be performed are testing of the manufacturability of the impeller, determining the impeller type and material, and the down selecting the circulator configuration.

To progress to a TRL of 6, selection of the circulator supplier will occur to build a pilot-scale circulator to demonstrate the bearings, rotor, and motor controls; test the possibility of arching in a helium environment; test the gas circulator cooling system; test seals for leakage (both oil and helium), and p validate the circulator’s performance. Key tests will also be performed to determine which sized circulator will be used. These include bearing, rotor, motor controls, seals, electrical, insulation, and cooling tests. Final integration of these tests will be performed at pilot-scale in ambient air performance parameters.

Testing of an engineering-scale circulator is required to progress to a TRL of 7. The types of tests are like those of the pilot-scale, but in a high-temperature helium environment. Shaft brake testing will begin at this scale, as will preparatory work for design and fabrication of the prototype.

To achieve a TRL of 8, a full-scale NGNP circulator will be tested in a component test capability or the NGNP. Full-scale testing and qualifying of the circulators are performed within a non-radiological environment.

3.2 Intermediate Heat Exchangers

The Intermediate Heat Exchangers (IHX) accept heat from the primary loop and transfer it to the secondary loop.

3.2.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from the supplier IHX TDRM data combined with NGNP R&D data, is shown in Figure 25.

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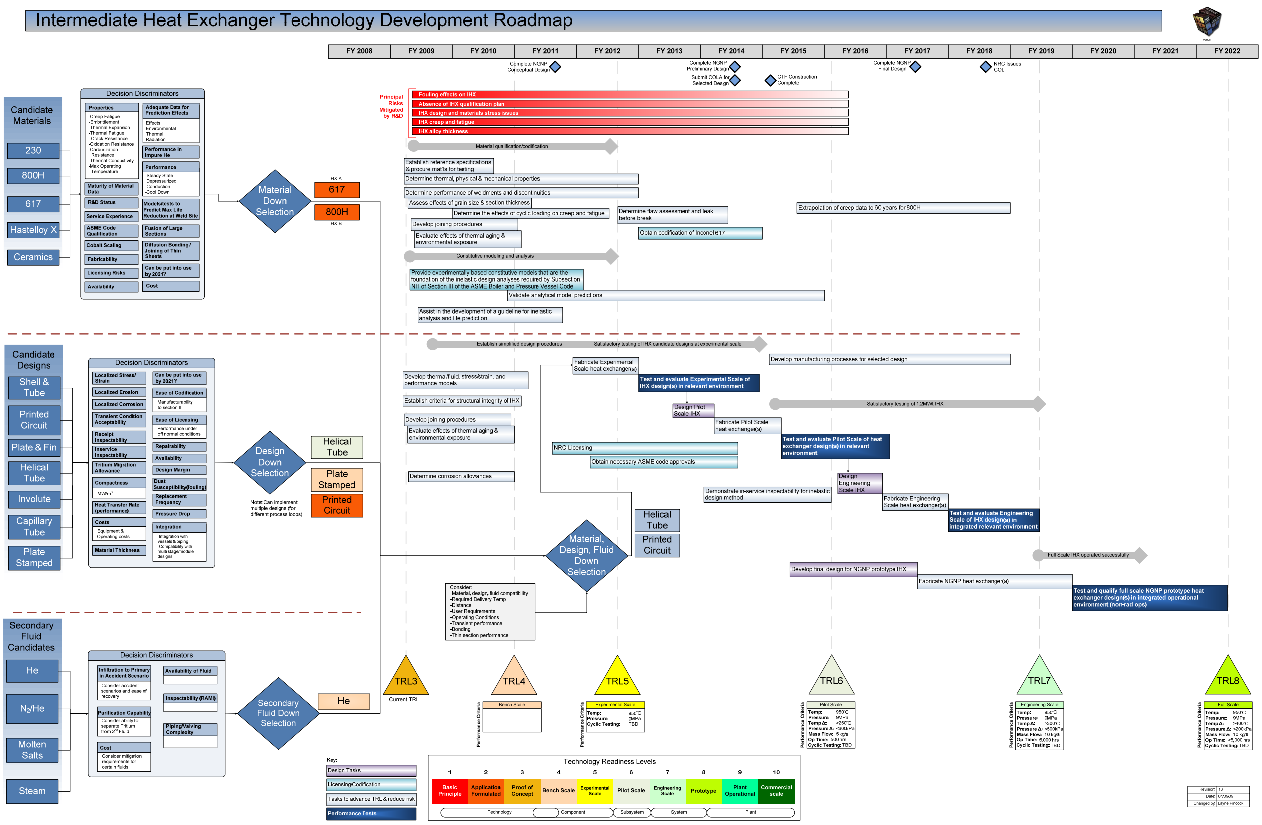

Figure 25. Intermediate Heat Exchangers Roadmap

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3.2.2 Intermediate Heat Exchangers Design Description

The IHX transfers heat between the PHTS and the Secondary Heat Transport System (SHTS). The PHTS is comprised of the primary piping, primary circulator, and primary helium working fluid. The SHTS is comprised of the secondary piping, secondary circulator, and secondary helium working fluid. Heat is also transferred by the IHX to downstream applications, including hydrogen production, power production (steam generation), and process heat.

The IHX is comprised of the following components:

- Heat exchanger cores and/or modules containing the heat transfer surface
- The IHX vessel
- Headers and/or piping that provide a transition between the heat exchanger cores and/or modules and the PHTS and SHTS piping
- Internal structures that provide for support (steady state, transients, and seismic loading) of the IHX and related internal components within the IHX vessel
- Thermal baffles and insulation.

3.2.2.1 Functions Performed

The primary functions of the IHX are to contain the primary and secondary helium coolants and to transport thermal energy, in the form of heat, from the reactor's PHTS to the SHTS working fluid. Secondary functions include: providing a pressure boundary, insulating the vessel, and preventing cross contamination (secondary to primary or vice versa).

3.2.2.2 Design Options

There are multiple options for the IHX vessel and the IHX internals. Options involve materials, fluids, structure types, and number of heat exchanges.

Five candidate materials are being considered for the pressure vessel:

- Haynes 230
- Alloy 800H
- Inconel 617
- Hastelloy X
- Ceramics.

Seven candidate configurations exist for the heat exchanger:

- Shell and Tube
- Involute
- Capillary Tube
- Helical Tube
- Plate and Fin

- Plate Stamped
- Printed Circuit.

Four candidates are being considered for the secondary coolant fluid:

- Helium
- Nitrogen/Helium
- Molten Salts
- Steam (H_2O).

One supplier has suggested steam (H_2O) instead of helium on the secondary side, but currently the preferred option is helium in both the primary and secondary heat transport loops.

The two primary IHX configurations differ in the number of heat exchangers. One configuration calls for a single heat exchanger, and another configuration calls for two heat exchangers in series.

3.2.2.3 Design Discriminators

The key material decision discriminators for the vessel include: material properties (creep fatigue, embrittlement, thermal expansion, thermal fatigue, crack resistance, oxidation resistance, carburization, resistance, thermal conductivity, max operating, and temperature); availability of adequate evaluation data; and performance (steady state, depressurized, conduction, and cool down). Additional discriminators may include: maturity of material data, R&D status, services experience, ASME code qualification, cobalt scaling, fabricability, licensing, availability, performance in an impure helium environment, and cost.

The key structural design decision discriminators for the type of heat exchanger include: localized stress/strain, erosion, and corrosion; dust susceptibility; material thickness; qualification/codification; and both equipment and operating costs. Additional discriminators may include: transient condition acceptability, receipt inspectability, tritium migration allowance, compactness, heat transfer rate (performance), repairability, and availability.

The key fluid decision discriminators include: infiltration to the primary loop in an accident scenario and ease of recovery; availability of the fluid; purification capability (i.e., removal of tritium); and cost. Additional discriminators may include inspectability and piping/valving complexity (see the TDRM in Figure 25).

3.2.3 Intermediate Heat Exchangers TRL Status

The current TRL status provided by the suppliers is shown in Table 14. The rollup of the TRLs from the suppliers allows for a comparison of the various reference designs; the complete supplier TRLs are contained in Appendix B. NGNP has issued a TRL of 3 to all components associated with IHX.

Table 14. Intermediate Heat Exchangers Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
IHX vessel	5	2	Not provided	3
Helical tube	6	2	Not provided	3
Compact Heat Exchanger	4	2	2(A) 3(B)	3
Tube and Shell	Not provided	2	Not provided	3

3.2.4 Intermediate Heat Exchangers Maturation Path Forward

Three IHX technology development areas are illustrated in the TDRM: materials, design, and secondary fluids. Each area has a series of tasks and tests to complete to advance from one TRL to the next.

3.2.4.1 IHX Materials

A TRL of 4 is granted once material qualification/codification and constitutive modeling and analysis tasks begin.

To achieve a TRL of 5, significant IHX materials properties need to be matured and associated tasks must be completed. Overall, these maturations orient around material qualification/codification and constitutive modeling and analyses.

TRL 6 is granted once material qualification/codification tasks are complete. Additionally, flaw assessments and lead-before-break tasks must be performed. Key material achievement for TRL 6 is obtained upon codification of Inconel 617.

Extrapolation of Alloy 800H creep data for a 60 year life cycle must be completed to achieve a TRL of 7.

3.2.4.2 IHX Designs

Intermediate Heat Exchanger designs tasks to advance to TRL 4 include simplified design procedures, focusing various models, testing criteria, joining procedures, and corrosion allowance.

For a TRL of 5, experimental-scale testing, fabrication of the IHXs at experimental-scale, and start of NRC licensing and ASME codification approvals must begin.

TRL 6 issuance requires testing and evaluation of IHXs at experimental-scale. Design and fabrication of pilot heat exchangers and various in-service inspectability tasks also need to be performed so that full testing of pilot-scale heat exchangers and the final design for NGNP prototype can begin.

Technology development tasks for TRL 7 requires completion of pilot-scale IHXs; design, fabrication, and testing of engineering-scale IHXs. At this stage, fabrication of NGNP heat exchangers also begins.

3.2.4.3 Secondary Fluids

Down selection of secondary fluids was already identified is an input into down select decisions performed during TRL 4 to TRL 5.

3.3 Cross Vessel Piping

The Cross Vessel Piping (CVP) is a piping arrangement that connects the RPV and the IHX to carry coolant fluid for heat transport.

3.3.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from supplier CVP TDRM data combined with NGNP R&D data, is shown in Figure 26.

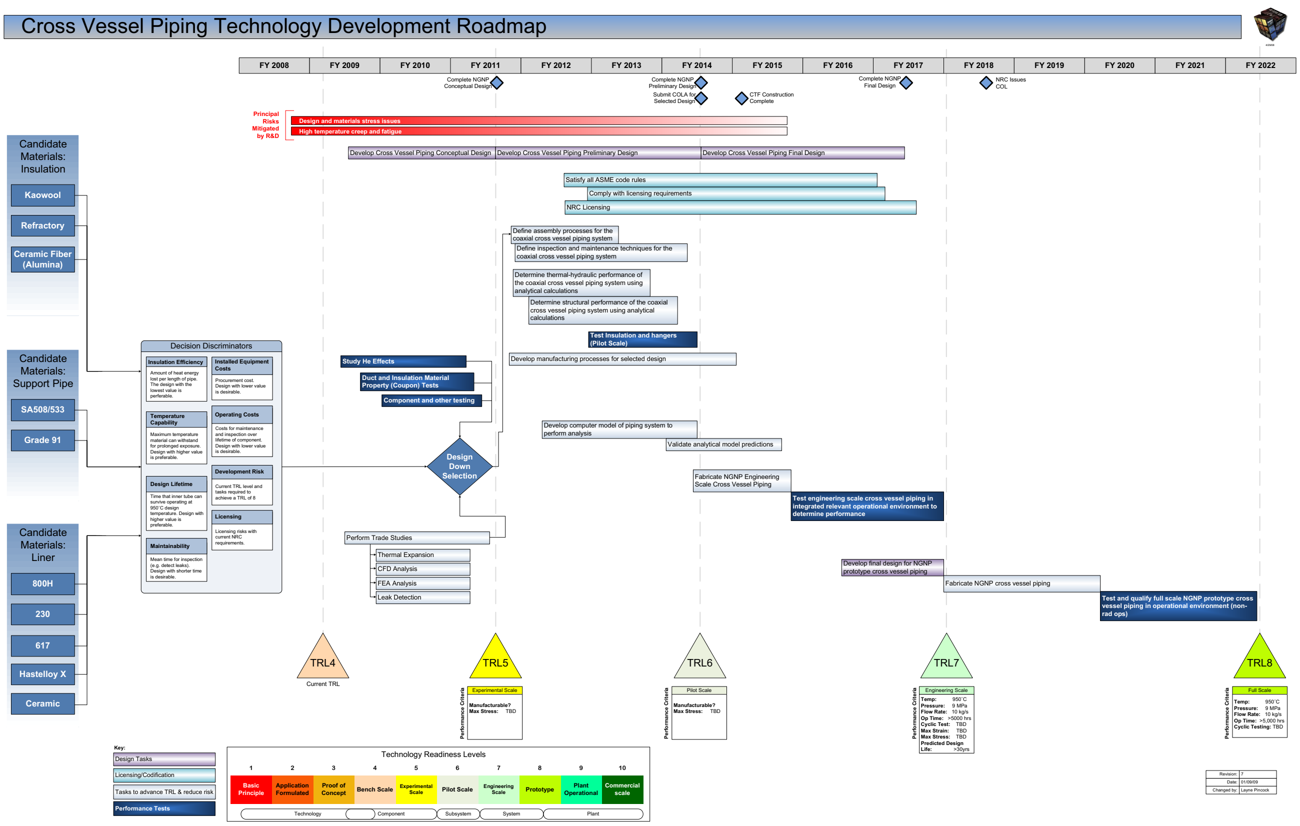

Figure 26. Cross Vessel Piping Roadmap

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3.3.2 Cross Vessel Piping Design Description

The CVP consists of four main components: the support structure, hot and cold ducts, the insulating materials, and the insulation liner. The CVP is located between the RPV and the IHX. Hot helium coolant (900°C) is transferred via the hot duct from the core, while cold helium coolant (500°C) is returned via the cold duct to the core.

3.3.2.1 Functions Performed

The function of the hot and cold ducts is to carry the coolant fluid between the RPV and the IHX. The function of the insulation is to reduce fluid thermal losses between the RPV and the IHX vessel. The function of the liners is to separate the cold duct from the hot duct, if they are collocated.

3.3.2.2 Design Options

The support structure material options are SA-508/533 and Grade 91 steels. The insulation material options are Kaowool, refractory, and ceramic fiber (alumina). The liner material options are Alloy 800H, Haynes 230, Inconel 617, Hastelloy X, and ceramic. Two designs have been suggested. In one, the hot and cold ducts are spatially separated, following two different paths, and an insulation liner is not required. In the other, the hot and cold ducts are collocated and separated by an insulation liner. This design may enhance heat transfer and serve as a preheater to the fluid entering the reactor.

3.3.2.3 Design Discriminators

The design discriminators are insulation efficiency, temperature capability, design lifetime, maintainability, operating costs, development risks, licensing, and replaceability.

3.3.3 Cross Vessel Piping TRL Status

NGNP determined that the CVP is at a TRL 4 (see Table 15). The rollup of the TRLs from the suppliers allows for a comparison of the various reference designs. The complete supplier TRL rating sheets are contained in Appendix B.

Table 15. Cross Vessel Piping Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
TRL	5	2	Not provided	4

3.3.4 Cross Vessel Piping Maturation Path Forward

To mature the CVP from TRL 4 to TRL 5, a design down select must occur, and the study of the helium effects, development of a duct and insulation materials properties database, and component testing must take place.

To progress to TRL 6, ASME code approvals and licensing must be addressed, and the testing of hangers and insulation at pilot-scale needs to be performed. Other physical and design characteristics and computer model tasks are performed during advancement to TRL 6.

To achieve a TRL of 7, an engineering-scale hot-duct and cross-vessel test needs to determine overall CVP performance. This involves integration testing of various components in relevant operational environments. Final design of the NGNP prototype is completed before the final issuance of TRL 7.

To reach a TRL of 8, full-scale testing and qualification of the NGNP in an operational, non-radiation environment must be completed.

3.4 High Temperature Valves (Isolation, Flapper, and Relief)

The High Temperature Valves are in the secondary heat transport loop, at the inlet with the main circulator, and on the inlet to the secondary shutdown circulator piping to provide isolation and pressure relief.

3.4.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from supplier High Temperature Valves TDRM data combined with NGNP R&D data, is shown in Figure 27.

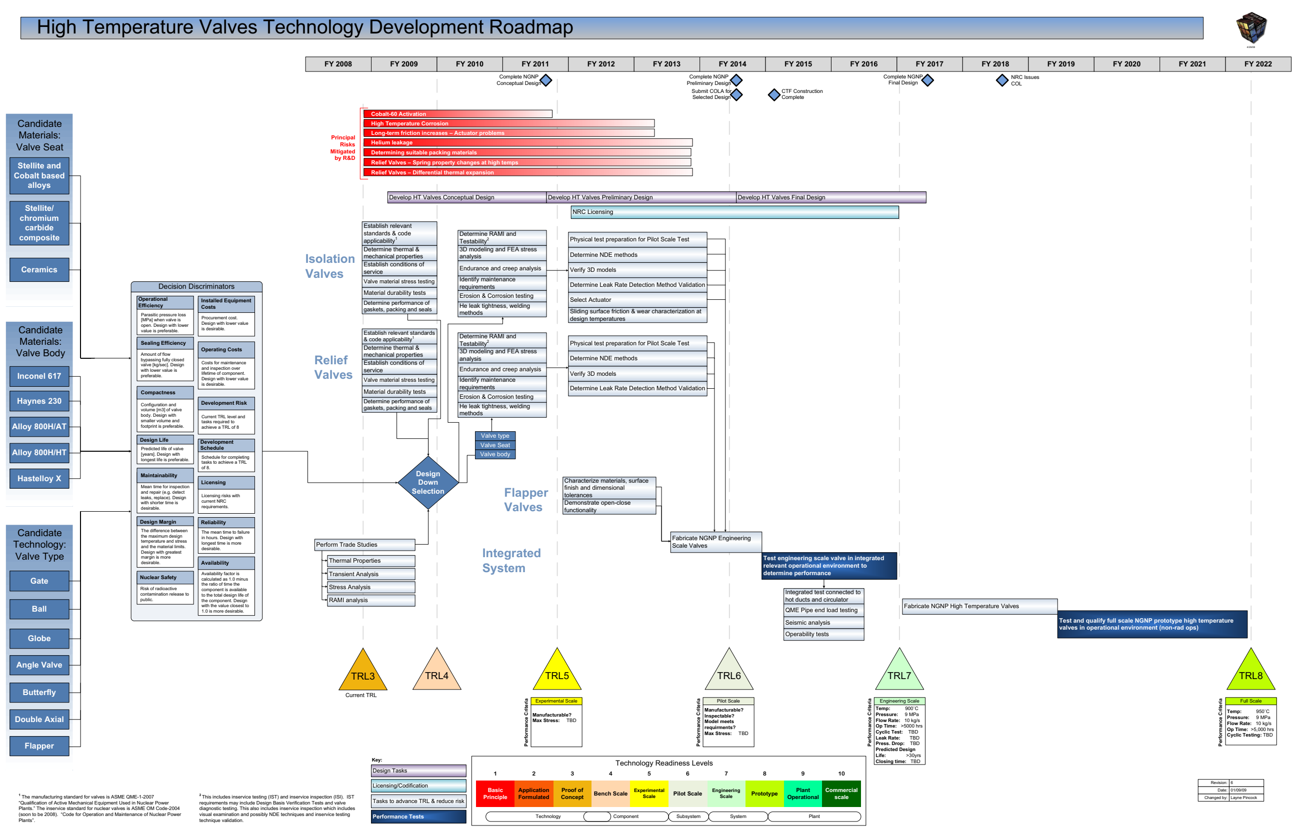

Figure 27. High Temperature Valves Roadmap

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3.4.2 High Temperature Valves Design Description

Each gas circulator is equipped with a self-actuating valve set at the impeller inlet. This valve closes in the event of a malfunction or failure of the circulator or during a maintenance operation of the HTS or PCS. The primary gas circulator flapper valve prevents possible reverse flow from the reactor and core by-pass from the shutdown cooling system or the other primary cooling loop. The valve is opened by aerodynamic flow of gas over the flapper valve into the circulator inlet.

3.4.2.1 Functions Performed

The normal function performed by the High Temperature Valves is to direct flow. The direction of flow serves different purposes depending upon design. For the High Temperature Flapper Valve, the direction of flow serves the function of allowing normal flow and stopping reverse flow in the primary loop.

The High Temperature Isolation and Relief Valves are located at three different places in secondary loop and have multiple functions. The isolation valves allow normal flow and stop reverse flow at the main circulator, allow normal flow and stop reverse flow at the inlet to the secondary shutdown circulator piping, and maintain pressure in the secondary heat transport loop.

3.4.2.2 Design Options

General Atomics assumes that all three valve types (isolation, flapper, and relief) will be in both the hot and cold legs.

AREVA's design includes the flapper valves only in the primary heat transport loop.

There are three areas for design consideration: materials used for the valve body, the valve seat, and the valve type. The candidate valve seat materials are: Stellite and cobalt-based alloys, Stellite/chromium carbide composite, and ceramics. The candidate valve body materials are Inconel 617, Haynes 230, Alloy 800H/AT, Alloy 800H/HT, and Hastelloy X. The candidate valve types are Gate, Ball, Globe, Angle Valve, Butterfly, Double axial, and Flapper.

3.4.2.3 Design Discriminators

The key design discriminators are: operational efficiency, particularly in terms of parasitic pressure loss when the valve is open (lower value is preferable); and sealing efficiency, or leakage from a fully closed valve (lower value is preferable). Additional discriminators may include: compactness, design life, design margin, nuclear safety, installed equipment costs, life-cycle costs, development risk, development schedule, licensing, reliability, maintainability, and availability.

3.4.3 High Temperature Valves TRL Status

The rollup of the TRLs from the suppliers allows for a comparison of the various reference designs (see Table 16). The complete supplier TRL Rating sheets are contained in the Appendix B.

Table 16. High Temperature Valves Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
Flapper	6	Not provided	Not provided	5
Isolation	6	3	Not provided	3
Relief	Not provided	3	Not provided	3

3.4.4 High Temperature Valves Maturation Path Forward

Each of the high temperature valves are on parallel maturation paths. Two of the three, isolation and relief valves, mirror each other in advancement from one TRL to the next. Trade studies need to be performed prior to any TRL advancement.

3.4.4.1 Isolation Valves Maturation

To obtain a TRL of 4 for isolation valves, a series of codes/standards, physical properties, and performance tasks and tests must be performed.

A TRL 5 is awarded for isolation valves once reliability, availability, maintainability, and inspectability (RAMI); modeling; analyses; and testing are performed.

Significant pilot-scale physical testing is performed for advancement to TRL 6. Models, methods, analyses, and characterization is also performed as preparation of engineering-scale valves (including start of fabrication) testing.

The completion of the integrated engineering-scale valve tests is required for TRL 7. Specific performance criteria, temperature at 900°C, pressure at 9 MPa, flow rate of 1- kg/s, and operating time of > 5,000 hours must be demonstrated before a TRL 7 is given.

The TRL of 8 is achieved once the isolation valves for the NGNP are fabricated and the necessary testing and qualification in the NGNP prototype is completed in a non-radiological environment.

3.4.4.2 Relief Valves Maturation

To obtain TRL 4 for relief valves, a series of codes/standards, physical properties, and performance tasks and tests must be performed.

Granting of TRL 5 is awarded for relief valves once RAMI, modeling, analyses, and testing are performed.

Significant pilot-scale physical testing is performed for advancement to TRL 6. Models, methods, analyses, and characterization is also performed as preparation of engineering-scale valves (including start of fabrication) testing.

The completion of the integrated engineering-scale valve tests is required for TRL 7. Specific performance criteria, temperature at 900°C, pressure at 9 MPa, flow rate of 1- kg/s, and operating time of > 5,000 hours, must be demonstrated before a TRL 7 is given.

The TRL of 8 is achieved once the relief valves for the NGNP are fabricated and the necessary testing and qualification in the NGNP prototype is completed in a non-radiological environment.

3.4.4.3 Flapper Valves Maturation

Flapper valves start at TRL 5, so the number of tasks to advance it to TRL 6 is few. These involve full characterization and demonstration of the open-close functionality. Starting the fabrication of the engineering-scale valves also leads to a TRL of 6.

To advance to TRL 7, the flapper valve must be demonstrated via the engineering-scale tests within the same relevant environment as the isolation and relief valves.

TRL 8 is issued once the flapper valve is integrated into the NGNP prototype and non-radiological integration testing is completed.

3.5 Mixing Chamber

The Mixing Chamber TDRM data from the suppliers combined with NGNP R&D data are the basis for the consolidated Mixing Chamber TDRM. The complete TDRM packages received from the suppliers are presented in Appendix B.

3.5.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from supplier Mixing Chamber TDRM data combined with NGNP R&D data, is shown in Figure 28.

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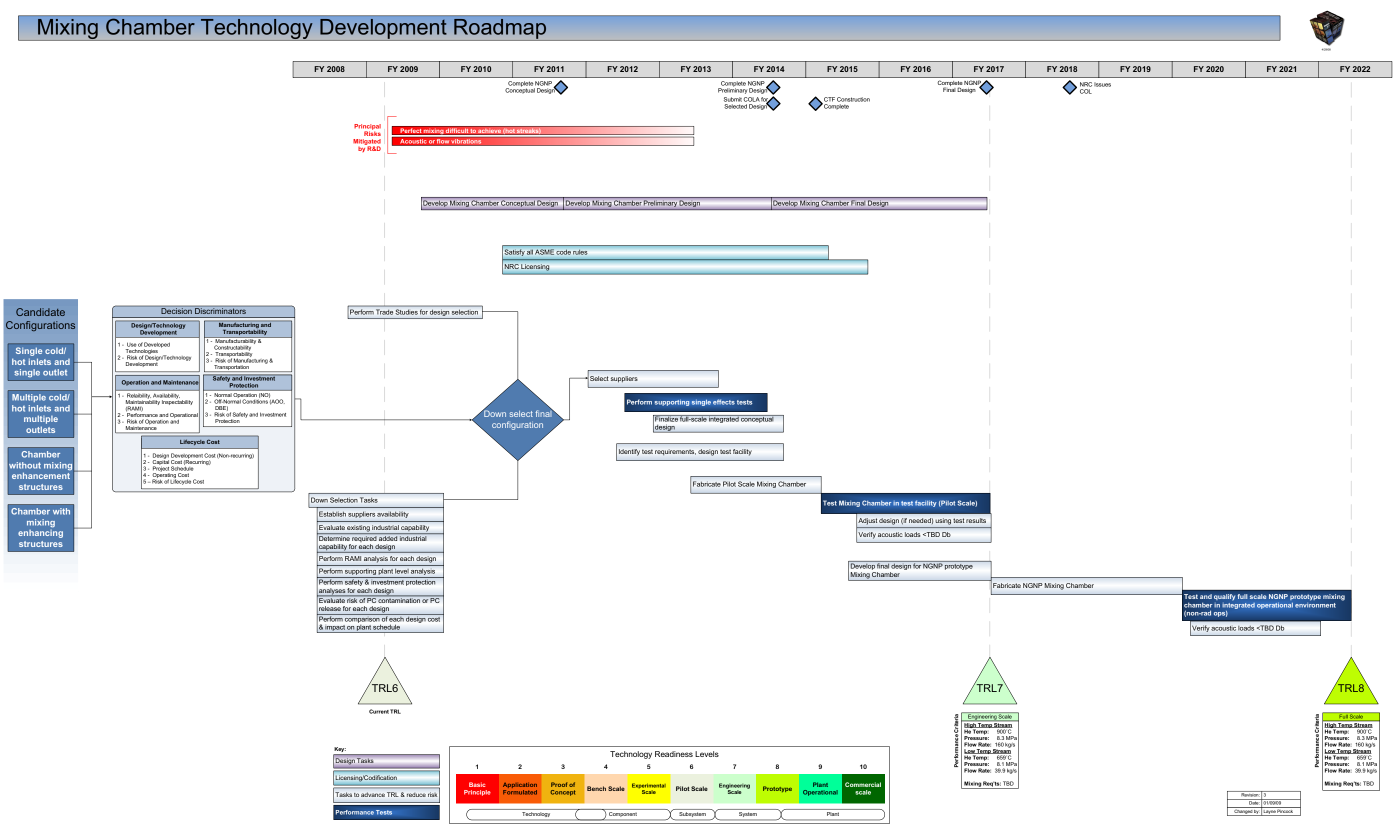

Figure 28. Mixing Chamber Roadmap

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3.5.2 Mixing Chamber Design Description

The Mixing Chamber is part of the SHTS and combines helium flows of different temperatures before they reach the Steam Generator. The Mixing Chamber subsystem is comprised of two components: the mixing plenum with enhanced mixing devices, and the devices required to control flow and acoustic induced vibrations. The SHTS Mixing Chamber design operating requirements are shown in Table 17.

Table 17. SHTS Mixing Chamber Design Operating Requirements.

Flow Conditions	SHTS Loop
High Temperature Stream at Nominal Operating Conditions	
Helium temperature, °C	900
Helium pressure, MPa	8.345
Helium flow rate, kg/s	159.6
Low Temperature Stream at Nominal Operating Conditions	
Helium temperature, °C	659
Helium pressure, MPa	8.145
Helium flow rate, kg/s	39.9
Mixing Requirements	
Maximum temperature deviation from average at Steam Generator duct inlet during steady state operations, °C	**TBD**
Maximum temperature deviation from average at Steam Generator duct inlet during key AOOs & DBAs, °C	**TBD**
Acoustic/Flow Induced Loads Requirements	
Maximum acoustic power at each mixing chamber natural frequencies during steady state operations, Db	**TBD**
Maximum acoustic power at each mixing chamber natural frequencies during key AOOs & DBAs, Db	**TBD**
Maximum flow induced load at each mixing chamber natural frequencies during steady state operations, kPa	**TBD**
Maximum flow induced load at each mixing chamber natural frequencies during key AOOs & DBAs, kPa	**TBD**

3.5.2.1 Functions Performed

The Mixing Chamber combines helium streams, mixes helium streams, controls flow, and mitigates vibrations.

3.5.2.2 Design Options

Several design options for the SHTS flow mixing chamber could satisfy the requirements identified during the pre-conceptual design of the NGNP. The simplest design option is comprised of a single plenum (flow mixing chamber) with two inlets, one for the hotter helium and one for the colder helium, and one outlet. Mixing devices can be added within the plenum to enhance the mixing process and reduce the size of the chamber. The pressure drop added by the mixing devices should not compromise the total SHTS loop pressure drop allocation. Alternative designs of the flow mixing chamber could replace single inlets with multiple inlets to reduce the pressure drop and the inlet stream velocities. These designs will be evaluated by trade studies that will use computational modeling and analysis, previous experience, similar designs, and engineering judgment to determine the advantages and disadvantages of each option. Figure 29 shows a schematic illustration of all design options.

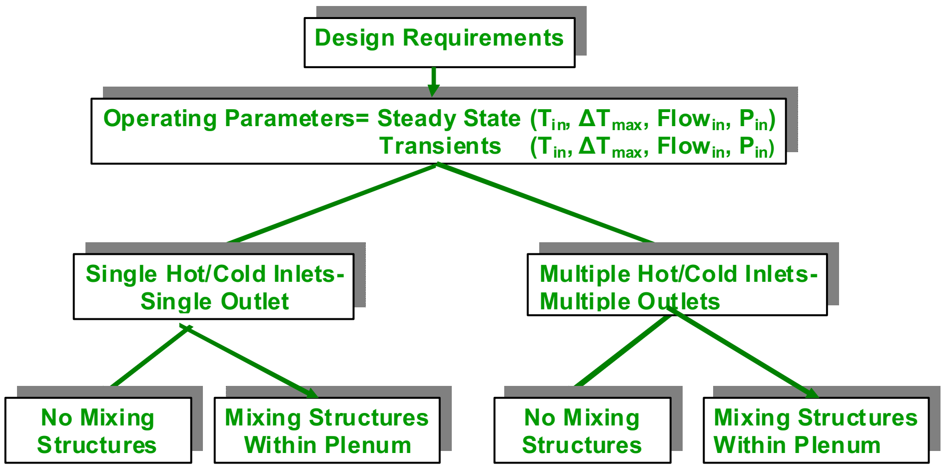

Figure 29. Schematic of all design options.

3.5.2.3 Design Discriminators

The design discriminating criteria include: design/technology development, safety and investment protection, life-cycle costs, development schedule, manufacturing and transportability, and operation and maintenance.

3.5.3 Mixing Chamber TRL Status

Only one supplier provided a roadmap for the Mixing Chamber. The NGNP agrees with this rating, due to the overall maturity of mixing chambers used by industry in similar applications (see Table 18).

Table 18. Mixing Chamber Summary TRL Table.

	AREVA	General Atomics	Westinghouse	NGNP
TRL	Not provided	Not provided	6	6

3.5.4 Mixing Chamber Maturation Path Forward

The current TRL for the Flow Mixing Chamber is a 6. To achieve a TRL of a 7, a down select for the various design options to a single mature reference design is need. Following the down select, tests are needed on components at the experimental-scale to validate the selected technologies. Finally, validation testing of the engineering-scale Flow Mixing Chamber model will be done at a component test capability or at the supplier facilities. To achieve a TRL of 8, testing and qualification of a full-scale NGNP Flow Mixing Chamber in an operational, non-radiation environment needs to be achieved to meet the needs for an NGNP.

4. HYDROGEN PRODUCTION SYSTEM

The goal of the national Nuclear Hydrogen Initiative is to demonstrate the economic, commercial-scale production of hydrogen using nuclear energy, which could lead to a large-scale, emissions-free, domestic hydrogen production capability to fuel a future hydrogen economy. The NGNP is being designed to produce both electricity and hydrogen. Hydrogen will be produced by the Hydrogen Production System (HPS) within the Hydrogen Production Area, which is basically a demonstration facility consisting of the HPS and associated buildings and structures.

4.1 Hydrogen Production System

The HPS includes the physical hardware needed to perform the hydrogen production function. Three different technologies are being developed and roadmapped until a technology down select can be performed at the appropriate time. Due to the parallel paths of the technology development, three separate roadmaps were produced to aid in illustrating the unique maturation paths.

4.1.1 Consolidated INL Technology Development Roadmap

Consolidated TDRMs, produced from supplier HPS TDRM data combined with NGNP R&D data, are shown in Figures 30 – 32.

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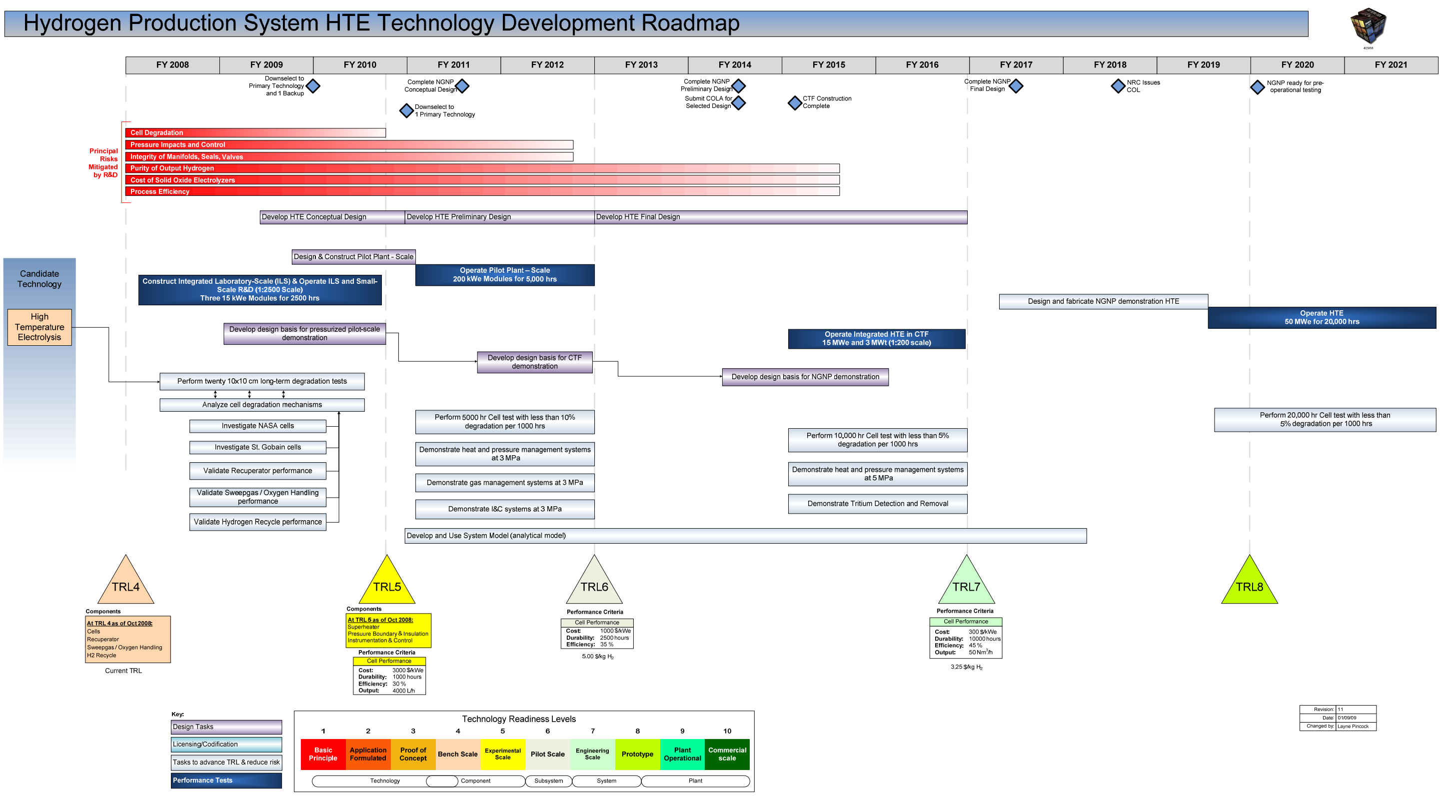

Figure 30. High Temperature Electrolysis Hydrogen Production System Roadmap

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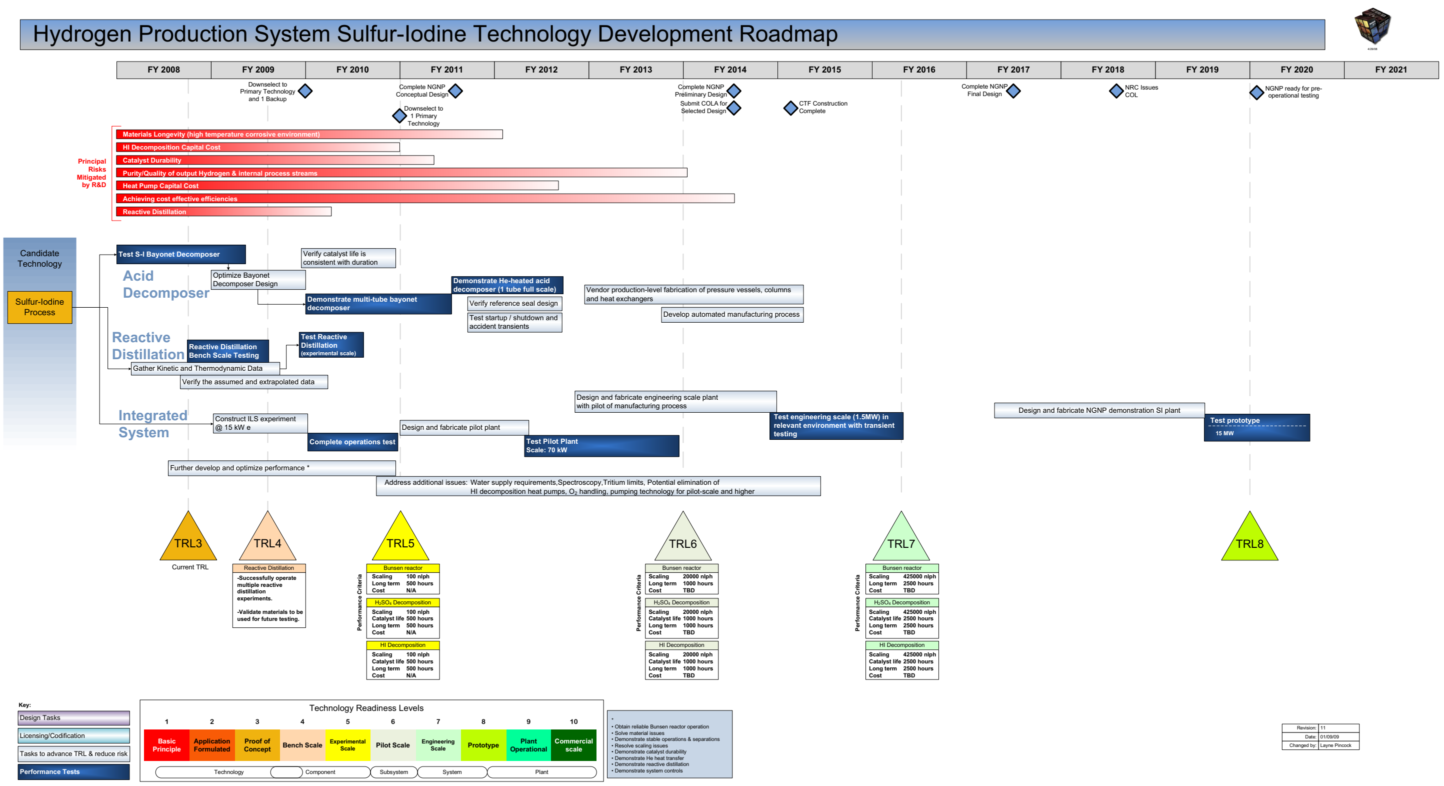

Figure 31. Sulfur-Iodine Hydrogen Production System Roadmap

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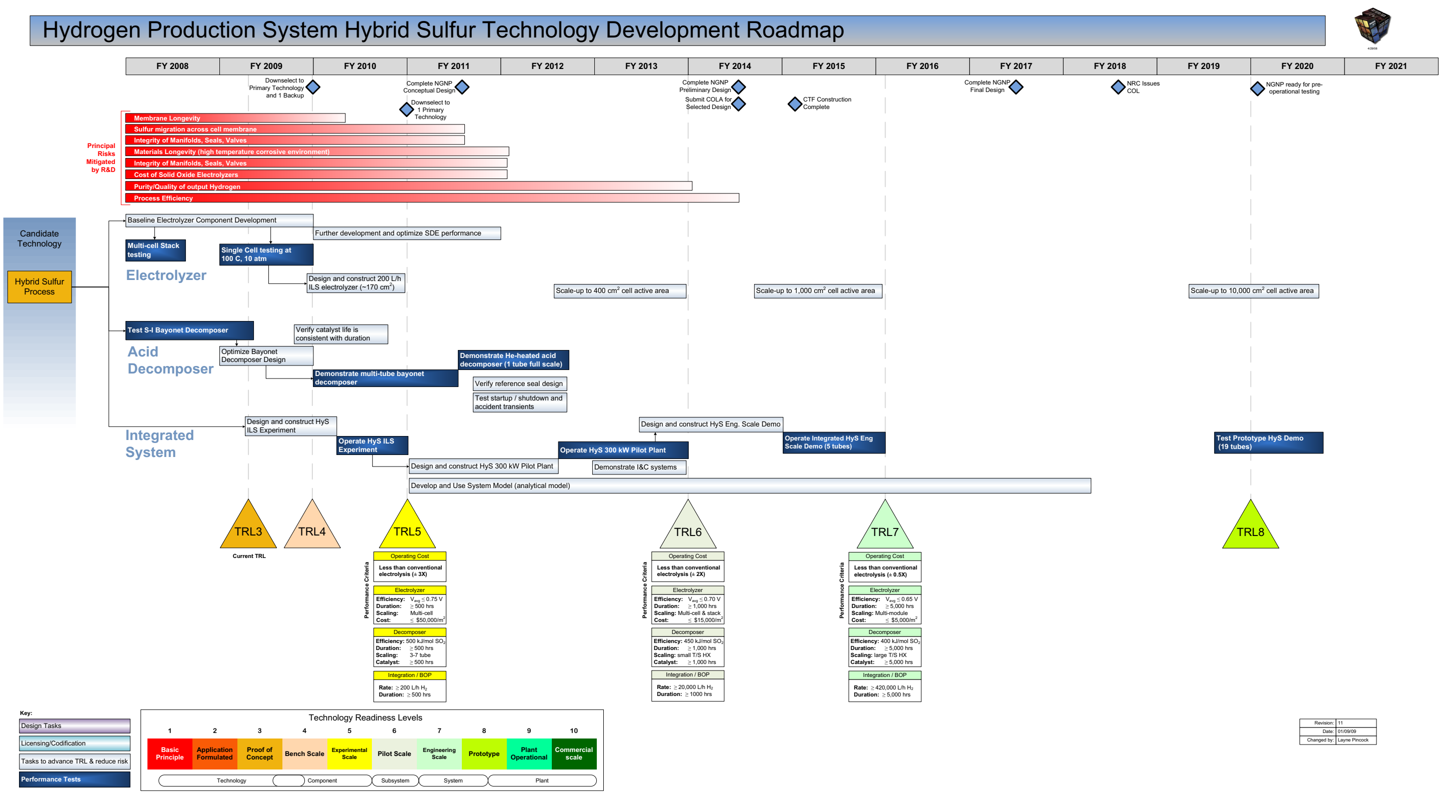

Figure 32. Hybrid-Sulfur Hydrogen Production System Roadmap

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4.1.2 Hydrogen Production System Design Description

The reference prototype concept of the NGNP includes a helium-cooled, graphite-moderated, thermal neutron spectrum reactor based on either a prismatic block or pebble-bed reactor core technology. The NGNP will use an indirect cycle with an IHX to transfer heat from the high-temperature helium reactor coolant to either a gas turbine, for generation of electricity, or a hydrogen production demonstration facility. Three candidate technologies are being considered for hydrogen production:

1. High Temperature Electrolysis (HTE) technology, which relies primarily on electrical energy and a small amount of process heat from the reactor
2. Sulfur-Iodine (SI) thermo-chemical water splitting technology, which relies primarily on process heat from the reactor
3. Hybrid Sulfur (HyS) thermo-electro-chemical technology, which is a hybrid of the HTE and SI technologies.

While the reactor technology is yet to be selected, the design basis for this evaluation includes a reactor outlet temperature of 950°C. A different reactor outlet temperature will probably have direct impact on the hydrogen production process and the HPS design. The three candidates for the HPS are still being evaluated, and the preferred technology will be selected as described on the TDRM presented in Section 4.1.1.

4.1.2.1 Functions Performed

The top-level function of the HPS is hydrogen production. However, the lower-level functions will depend on the technology ultimately selected for HPS application. Few, if any, functions are common to the HTE and SI processes; however, the HyS processes shares common functions with each of the other two processes.

- **High Temperature Electrolysis HPS** – The HTE technology accepts heat from the reactor's helium cooling system, electricity from the plant turbine and/or the offsite grid, and process feed water from the plant. The feed water is further purified, and the heat and electricity are used to convert the feed water into hydrogen and oxygen gas. After drying, the hydrogen is directly exported by pipeline, and the oxygen is vented to the atmosphere in the form of oxygen enriched air. Recovery of oxygen as a product is possible, but not a primary function.

  For the HTE technology, functions include: electrolysis, heat recovery, feed and utility, and product purification.

- **Sulfur-Iodine HPS** – The SI technology consists of three primary chemical reactions that dissociates water into hydrogen and oxygen at relatively low temperatures. The process involves decomposing sulfuric acid and hydrogen iodide, and regenerating these reagents using the Bunsen reaction. Process heat is supplied to distill (or concentrate) and decompose sulfuric acid. The exothermic Bunsen reaction releases waste heat to the environment. Process heat is used to generate hydrogen during the decomposition of hydrogen iodide.

  For the SI technology, functions include: sulfuric acid distillation and decomposition, hydrogen iodide distillation and decomposition, and the Bunsen reaction.

- **Hybrid Sulfur HPS** – The HyS technology is a hybrid of the HTE and SI technologies, and includes some subsystems and processes that are common to both. The sulfuric acid decomposer is essentially the same in the SI and HyS processes, but the sulfur dioxide is fed to electrolysis cells rather than a Bunsen reaction. The Bunsen reaction is eliminated in the HyS process, and the electrolysis cells operate at relatively low temperatures compared to the HTE process with a liquid sulfur dioxide feed instead of steam.

For the HyS technology, functions include: sulfuric acid decomposition, sulfur dioxide electrolysis, feed and utility, and product purification.

4.1.2.2 Design Options

- **High Temperature Electrolysis HPS** – For the HTE technology, the HPS would include the following subsystems: an electrolyzer, a heat recovery system, a feed and utility system, and a product purification unit.
- **Sulfur-Iodine (SI) HPS** – For the SI technology, the HPS would include the following subsystems: a Bunsen Reactor and a separator for the Bunsen Reaction, reactive stills, recuperators, and heat exchangers for distillation and decomposition of the sulfuric acid and hydrogen iodide. Process heat temperature for decomposition of sulfuric acid must be at least 750°C. The Bunsen reaction will be performed at temperatures below 120°C. The process heat temperature for decomposition of hydrogen iodide must be at least 300°C.
- **Hybrid Sulfur HPS** – For the HyS technology, the HPS would include the following subsystems: an acid decomposition system to concentrate the acid and recover and compress the SO_2, an electrolyzer, storage units, a water treatment unit, and a product purification unit.

4.1.2.3 Design Discriminators

The three candidate technologies will be evaluated and compared in terms of performance and cost. As a minimum, the successful technology will be able to demonstrate hydrogen production with greater efficiency than conventional electrolysis and will demonstrate superiority in key design discriminators, including: corrosion resistance, cost per kilogram of hydrogen produced, and operational reliability and maintainability. Also, for the HTE and HyS designs, the change in electrical energy input (to the electrolysis cells) per kilogram of hydrogen produced can be compared.

4.1.3 Hydrogen Production System TRL Status

Each HPS technology has a different TRL depending on the level of maturity. Because of the work being performed for HPS, the NGNP has not assigned a consolidated TRL. Each technology is unique in its approach to hydrogen production; therefore, not all technologies will mature at the same rate and schedule.

Table 19 presents the TRLs assigned to each candidate technology for the HPS. The basis for these TRL assignments is discussed in subsequent subsections.

Table 19. Hydrogen Production System Summary TRL Table

	HTE	**Sulfur-Iodine**	**Hybrid Sulfur**
TRL	4	3	3

4.1.3.1 High Temperature Electrolysis HPS

The NGNP is most familiar with the more common HTE technology; however, none of the suppliers involved in evaluating HPS technologies prefer it. To compare the emerging technologies being recommended, NGNP independently evaluated the HTE technology. It is more technologically ready than the two emerging technologies. The NGNP has assigned a TRL of 4 to the HTE technology.

4.1.3.2 Sulfur-Iodine HPS

NGNP assigns the SI technology an overall TRL of 3. This TRL rating is from supplier and R&D input on technology readiness.

4.1.3.3 Hybrid Sulfur HPS

NGNP assigns the HyS technology an overall TRL of 3. This TRL rating is from supplier and R&D input on technology readiness.

4.1.4 Hydrogen Production System Maturation Path Forward

The maturation paths for each of the unique HPS technologies are varied due to the complexity of each. Each of the maturation paths for each technology shown in the HPS roadmaps is discussed in greater detail below.

4.1.4.1 High Temperature Electrolysis

Advancement from TRL 4 to TRL 5 requires construction and operation of integrated laboratory-scale and small-scale HTE technologies. Additionally, design and construction of a pilot-scale HTE is started before a TRL 5 is issued. A series of cells and performance tasks must also be performed for feed into other degradation and mechanical tests.

As the HTE moves to TRL 6, the pilot plant is up and operational to meet specific performance criteria, including continuous operation of 2,500 hours. Design basis for demonstration of a component test capability is begun and completed by TRL 6. A series of performance demonstrations is also required, including development of analytical models for HTE.

TRL 7 is achieved once the HTE is integrated in a component test capability, the design basis for NGNP demonstration is developed, and demonstration tasks are completed. Analytical models continue to be developed and used to assess HTE. Some of the performance criteria include: $300/kWe, 10,000 hours of durability, 45% efficiency, and an output of 50 Nm^3/h.

Final integration of the HTE operating at 50 MWe for 20,000 hours is required for advancement to TRL 8.

4.1.4.2 Sulfur Iodine

For SI to advance to TRL 4, the initial SI bayonet decomposer tests needs to be completed, bench-scale reactive distillation testing completed, various datasets collected, and the construction of ILS experimental-scale testing at 15 kWe begun.

Three tests are required for SI to achieve a TRL of 5. They are: demonstration of multi-tube bayonet decomposer, reactive distillation, and completion integrated operations tests. Other tasks are completed to advance the SI to TRL 5, as shown in Figure 32.

A large amount of work is required for SI to advance to TRL 6, including: completion of multi-tube bayonet decomposer tests; demonstration of helium-heated acid decomposer; design, fabrication, and testing of the pilot plant; and completion of a series of TRL transitional tasks as preparation for the next readiness level.

TRL 7 is issued once the supplier level production of various SI component fabrications is completed, automated manufacturing processes developed, the engineering-scale plant designed and fabricated, and the SI tested in the engineering-scale plant within a relevant environment.

Prototype plant design, fabrication, and testing are performed to achieve a TRL of 8 SI HPS technology. This is considered an integration test with the heat source being the NGNP.

4.1.4.3 Hybrid Sulfur

Hybrid sulfur is less mature and requires tasks and tests to advance it from TRL 3 to TRL 4. This includes begin baseline electrolyzer component development, multi-cell stack testing, and SI bayonet decomposer testing into the HyS.

Furthering the HyS to TRL 5 requires that three tests and several tasks be completed before issuance. Single cell testing at scale parameters, demonstrating the multi-tube bayonet decomposer, and operating the HyS integrated laboratory-scale experiment are also performed for TRL 5.

Scaling up of the electrolyzer to a 400 cm^2 cell active area; demonstrating a full-scale single tube decomposer; and designing, constructing, and operating the HyS 300 kW pilot plant advance the technology to TRL 6. Initial develop and use of analytical models are begun, as are the development and construction of the engineering-scale HyS demonstration.

TRL 7 is issued once the electrolyzer is scaled up to a 1000 cm^2 cell active area and final construction and operation of an engineering-scale HyS demonstration is complete. Continued development and use of the analytical models is also conducted.

TRL 8 for HyS includes final scale up of the electrolyzer to a 10,000 cm^2 cell active area and testing of the prototype HyS demonstration with 19 tubes.

5. POWER CONVERSION SYSTEM

5.1 Steam Generator

The Steam Generator converts water into steam from a heat source, in this case heat produced in a nuclear reactor core, which drives turbines to generate electricity. Pressurized water is channeled through alloy tubes, which heats up non-radioactive water around the tube to form the steam.

5.1.1 Consolidated INL Technology Development Roadmaps

A consolidated TDRM, produced from Steam Generator TDRM data from the suppliers combined with NGNP R&D data, is shown in Figure 33.

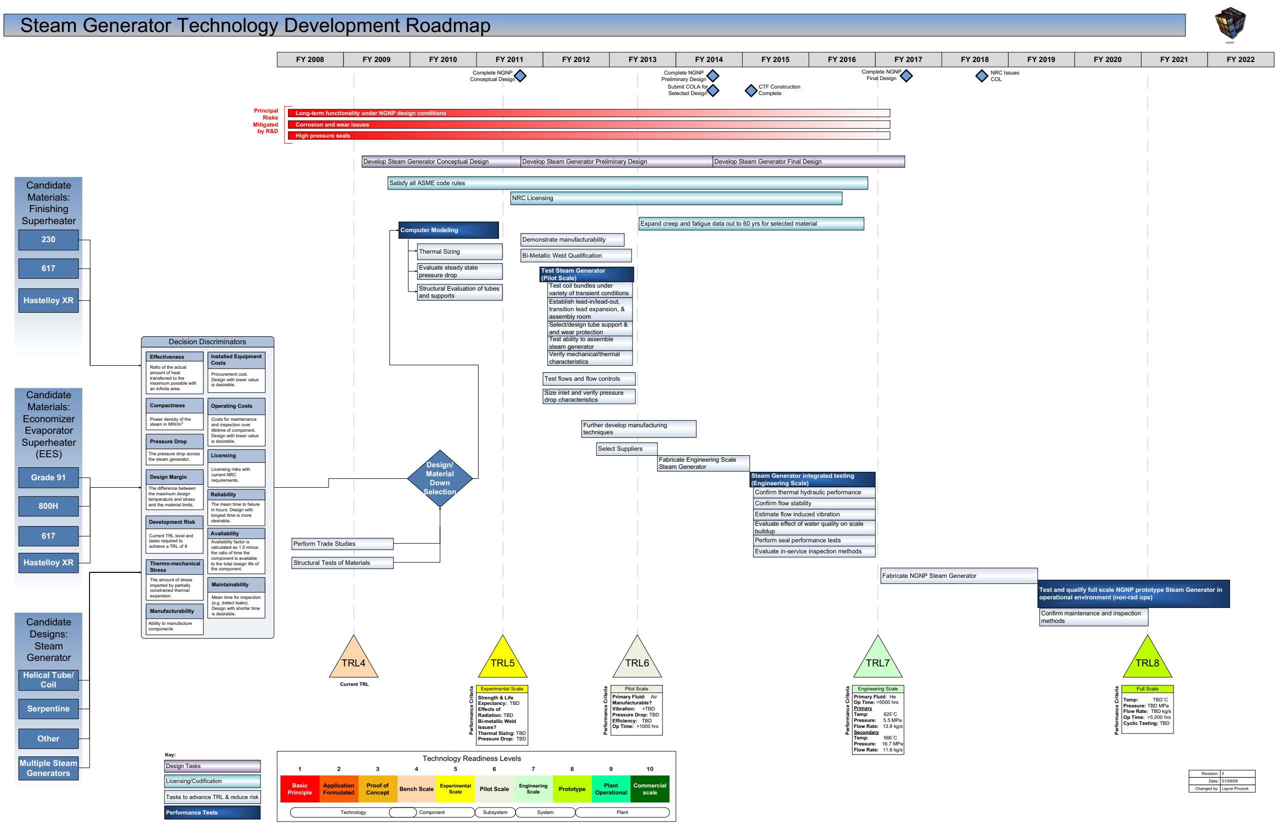

Figure 33. Steam Generator Roadmap

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5.1.2 Steam Generator Design Description

In the Steam Generator, sub-cooled feed water acquires heat from the higher temperature helium circulating in the SHTS and the water vaporizes, becoming superheated steam. Piping transports the steam to the turbine inlet to drive the turbine rotation. The Steam Generator design concept is a direct-cycle helical tube steam generator. It is a vertically oriented, counter-flow, shell-and-tube, once-through, non-reheat tubular heat exchanger with helium on the shell side and water/steam in the tubes. The Steam Generator will interface with the secondary heat exchanger and PCS, which is a significant departure from prior HTGR applications in which the Steam Generator was located in the PHTS. Internal structure materials (e.g., tube supports, tube surfaces, shrouds) are selected consistent with their respective operating temperatures. The Steam Generator incorporates an economizer, an evaporator, and first-stage superheater in one helical tube bundle, followed by a finishing superheater in a second helical tube bundle.

5.1.2.1 Functions Performed

The function of the Steam Generator is to produce superheated, high-pressure steam for conversion into mechanical work to turn a turbine that will generate electricity.

5.1.2.2 Design Options

A serpentine design has been suggested as one alternative to the helical tube design. It has also been suggested that using multiple steam generators may have advantages. Other design decisions involve the selection of materials. Candidate materials for the economizer, evaporator, and superheater include: Grade 91, Alloy 800H, Inconel 617, and Hastelloy XR. Candidate materials for the finishing superheater include: Haynes 230, Inconel 617, and Hastelloy XR.

5.1.2.3 Design Discriminators

Key design discriminators include: thermal performance (heat transfer efficiency), mechanical performance (thermo-mechanical stresses, corrosion, and wear), and equipment and operating cost. Additional discriminators may include: compactness (power density of the steam), pressure drop, design margin, development risk, manufacturability, licensing, reliability, maintainability, and availability.

5.1.3 Steam Generator TRL Status

The NGNP rates the Steam Generator at a TRL of 4 (see Table 20). The suppliers rate the Steam Generator as further advanced, but with consideration for the R&D needed to further mature the materials needed, a TRL of 4 is warranted.

Table 20. Steam Generator Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
TRL	5	5	6	4

5.1.4 Steam Generator Maturation Path Forward

Some computer modeling needs to be developed and operated before at TRL 5 can be issued. Other items that must occur to justify a TRL of 5 include trade studies and structural testing of the materials.

Pilot-scale testing of the Steam Generator is necessary for a TRL of 6, including, manufacturability demonstrations, weld qualifications, and characterizations. The selection process of suppliers begins at TRL 6.

Fabrication and integrated testing of the Steam Generator, at an engineering-scale, needs to be completed for TRL 7. Integrated Steam Generator tests include a series of performance tasks associated with specific Steam Generator areas.

TRL 8 is granted once the NGNP Steam Generator is fabricated and installed, and non-radiological testing in the NGNP begins.

5.2 PCS Equipment for Direct Combined Cycle

PCS Equipment for Direct Combined Cycle is included as a critical PASSC because it is required for a new reference design with the Steam Generator in the primary loop. One supplier (General Atomics) developed this PCS option because of the attractiveness of a combined-cycle for producing electricity. PCS Equipment for Direct Combined Cycle includes three components: a generator, a turbine, and a compressor. This particular PASSC is unique in that it is outside the requirements defined in the scope of work. The direct-cycle option is an alternative provided by only one supplier and is included to provide completeness of the critical PASSCs provided by the suppliers.

5.2.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from PCS Equipment for Direct Combined Cycle TDRM data from the suppliers combined with NGNP R&D data, is shown in Figure 34.

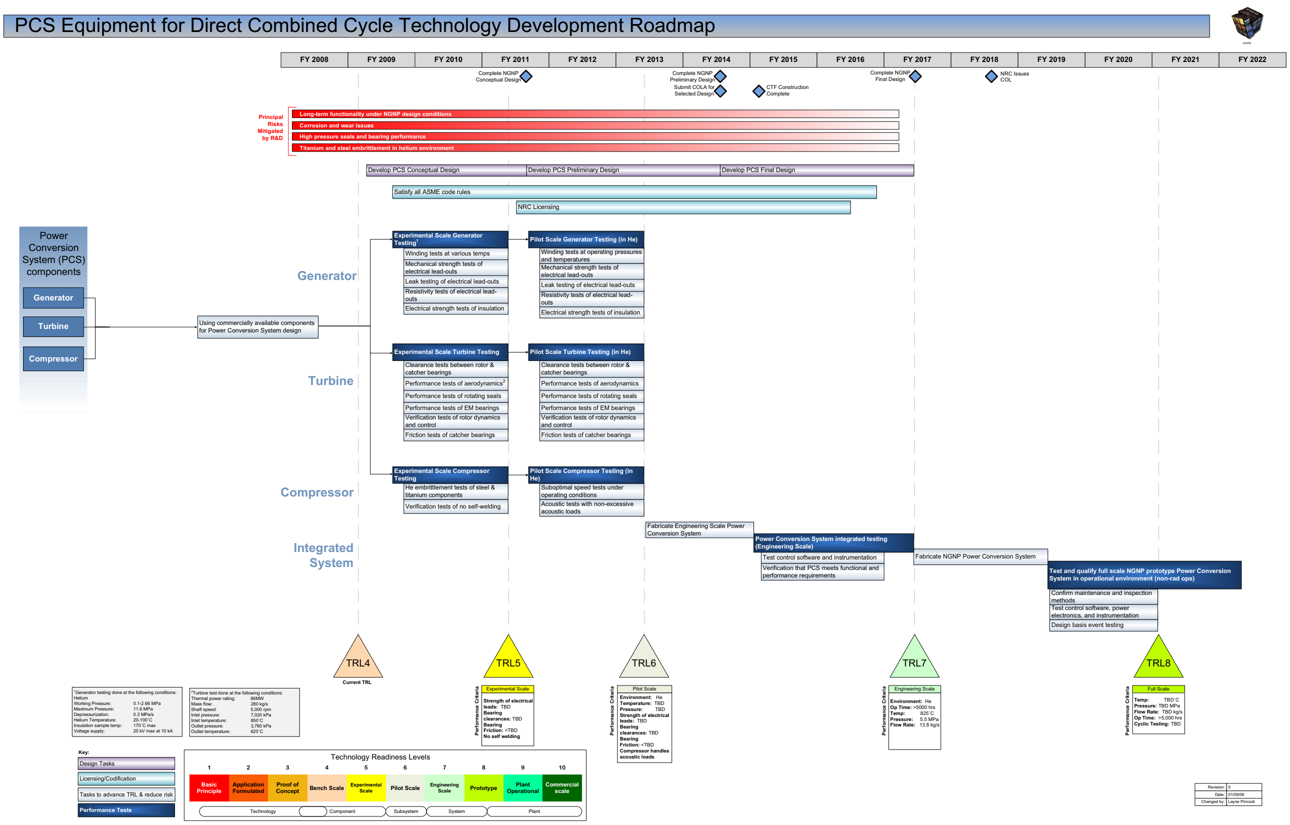

Figure 34. PCS Equipment for Direct Combined Cycle Roadmap

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5.2.2 PCS Equipment for Direct Combined Cycle Design Description

PCS Equipment for Direct Combined Cycle is included as a critical PASSC that is required for the General Atomics' design with the Steam Generator in the primary loop. General Atomics developed this PCS option because of the attractiveness of a combined-cycle for producing electricity. The function and design of the PCS Equipment for Direct Combined Cycle is described in the following subsections.

5.2.2.1 Functions Performed

The purpose of the PCS Equipment for Direct Combined Cycle is to convert heat from the nuclear reaction into electricity. This is accomplished by generating steam and using it to turn a turbine.

5.2.2.2 Design Options

Major components of the PCS Equipment for Direct Combined Cycle include a turbine, a compressor and a generator. The turbine and compressor may be replaced by an integrated turbocompressor. Subcomponents include EM bearings, turbine blades, generator insulation, and seals.

5.2.2.3 Design Discriminators

The suppliers and NGNP identified no design discriminators due to the maturity of the components in PCS Equipment for Direct Combined Cycle.

5.2.3 PCS Equipment for Direct Combined Cycle TRL Status

The PCS Equipment for Direct Combined Cycle is rated at a TRL of 4 (see Table 21). Readiness of all three components is the same.

Table 21. PCS Equipment for Direct Combined Cycle Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
TRL	Not Provided	4	Not Provided	4

5.2.4 PCS Equipment for Direct Combined Cycle Maturation Path Forward

5.2.4.1 Generator

For advancement of the generator to TRL 5, specific generator tests must be performed, including, winding insulation samples and electrical lead-out strength tests.

A TRL 6 is achieved through insulation dielectric at operating conditions testing, as well as lead-outs performance testing at operating conditions.

Full-scale model testing within ambient air conditions is necessary for TRL 7.

TRL 8 is achieved via integrated full-scale turbine, compressor, and generator testing. Operations will commence at production temperatures and pressurized helium environment. This is often referred as turbomachinery testing.

5.2.4.2 Turbine

A TRL of 5 is achieved for the turbine through experimental-scale testing, including, aerodynamics, rotating seals, EM bearings, and catcher bearing tests. All are performed in an ambient air environment.

Pilot-scale turbine testing in a helium environment is necessary for TRL 6. The tasks include aerodynamics, rotating seals, EM bearing, and catcher bearing tests within operating temperatures.

Advancement from TRL 6 to TRL 7 involves integrated turbine and compressor testing. This includes full-scale model testing at ambient temperature and pressure (air) conditions.

Final advancement of the turbine to TRL 8 required full-scale, integrated testing of the generator, turbine, and compressor at operations temperatures and helium pressure conditions.

5.2.4.3 Compressor

Experimental-scale compressor testing is necessary for a TRL of 5. Tasks associated with this TRL advancement include verifying material embrittlement issues within helium, absence of self-welding of materials issues, and stage performance testing.

A TRL of 6 is granted by pilot-scale testing of the compressor in a helium environment. This includes acoustic load testing and stage performance at less than optimal speeds at operational conditions.

Full-scale model testing of the compressor with the turbine is required for TRL 7. This testing is conducted within ambient temperatures and pressure (air) conditions.

Final advancement to TRL 8 is achieved by conducting full-scale, integrated testing of the turbine, compressor, and generator at operations temperatures and helium pressure conditions, incumbent on the NGNP.

6. BALANCE OF PLANT (BOP)

6.1 Fuel Handling System

The Fuel Handling System (FHS) is used to refuel the reactor. The FHS consists of a series of machines and devices that transfer fuel and reflector blocks between the Reactor Core and the Near Reactor Spent Fuel Storage location.

6.1.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from Fuel Handling System TDRM data from the suppliers combined with NGNP R&D data, is shown in Figure 35.

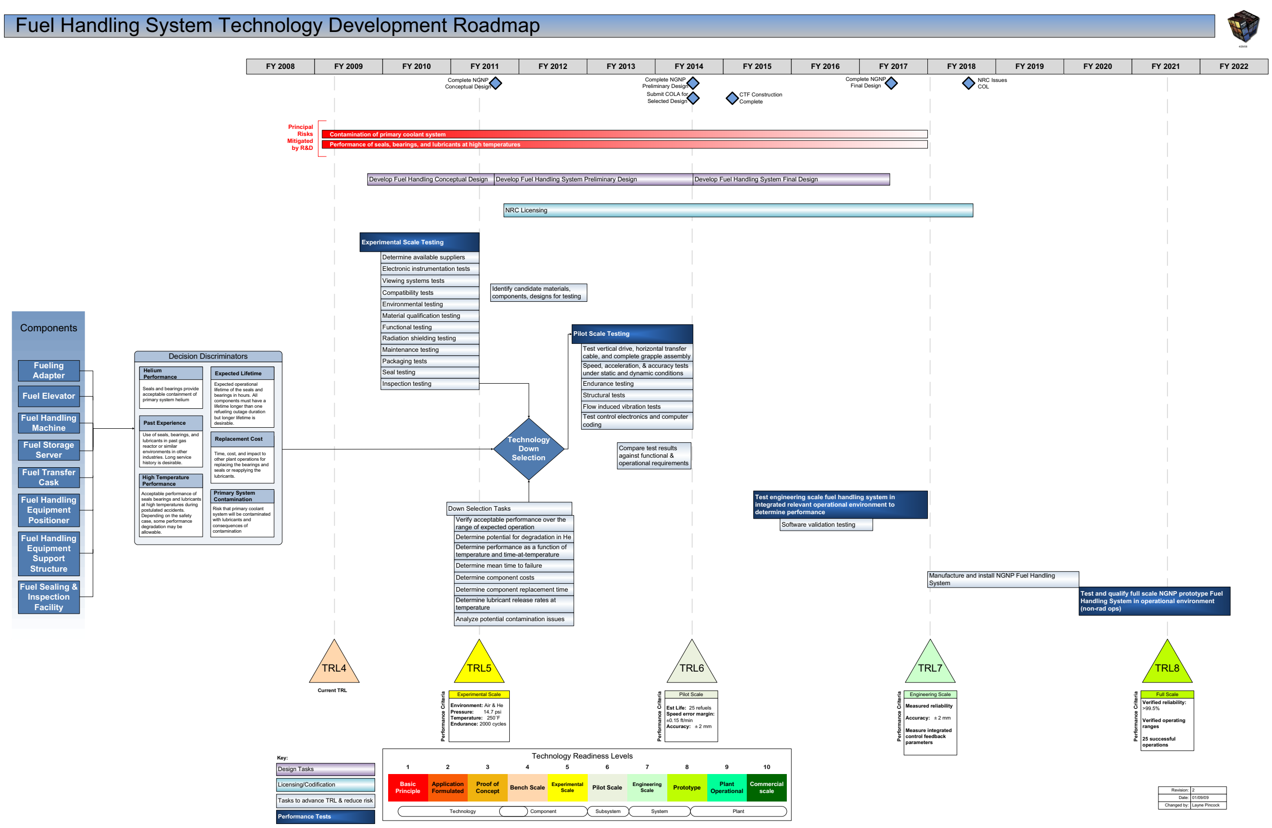

Figure 35. Fuel Handling System Roadmap

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6.1.2 Fuel Handling System Design Description

The FHS is a robotic manipulator that can be inserted into an inner control rod drive penetration and is equipped with a grapple probe that can be inserted into the handling hole in the top of any hexagonal block. The probe can be expanded to engage the block so the machine can lift it. Blocks are grappled and raised one at a time. The FHS is equipped with a pantograph-like mechanism giving it the capability to extend the grapple out to a radius sufficient to reach all the blocks within a sector, including all hexagonal reflector blocks.

The FHS can rotate, extend, and raise/lower, so that it can access all the hexagonal blocks in a sector from an inner Control Rod Drive Mechanism (CRDM) nozzle. The FHS reduces the estimated refueling time using robotic machines that remove core blocks and transfer them to the adjacent Local Spent Fuel Storage cell, which is part of the Spent Fuel Storage System. Subsequently, new and irradiated fuel blocks are delivered to the FHS, which then places them into the reactor vessel. Access to the core region is provided by a fuel elevator, which is mounted at the central position. All fuel elements and reflector blocks go through this central position.

The components of the FHS are mobile and may be shared among all reactor modules in multi-module plants. The FHS also interacts closely with the control rod removal cask. The cask, which is part of the Reactor Service System, interfaces with the Fueling Adaptor and is used to remove and reinstall central column instrumentation and both inner and outer control rod and reserve shutdown assemblies. The Spent Fuel Storage System also interfaces closely with facilities for storage of graphite elements and waste treatment systems. Figures 36 and 37 illustrate the general design concept and the interaction of some of these components.

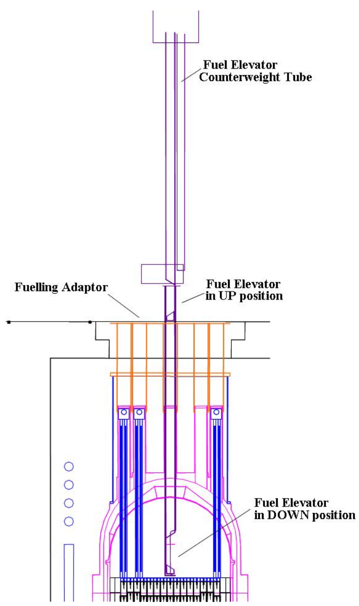

Figure 36. Fueling Adaptor and Fuel Elevator

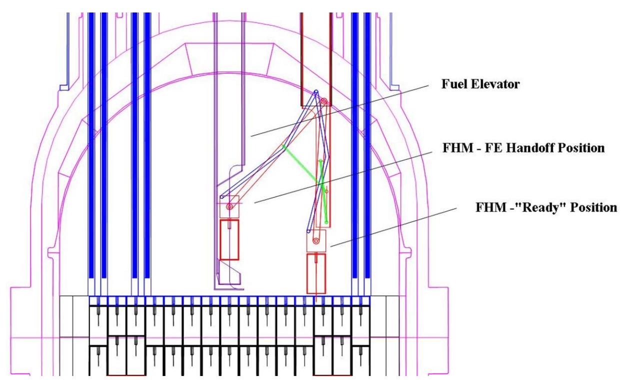

Figure 37. Fuel Handling Machine

6.1.2.1 *Functions Performed*

At a high level, the FHS is used to transfer fuel and reflector elements between the reactor and local storage facilities and between the local storage facilities and the packaging and shipping facility. The system is also used to manipulate special tools for in-service inspection of reactor components.

6.1.2.2 Design Options

No functionally alternative design concepts are presented; however, the specific designs proposed by any supplier will differ in the details.

6.1.2.3 Design Discriminators

Since there are no alternative designs, there are no design discriminators for comparing design concepts. When evaluating one specific design implementation against another, decision discriminators might include: helium sealing performance, high temperature performance, expected lifetime, replacement cost, primary system contamination, and past experience.

6.1.3 Fuel Handling System TRL Status

The NGNP issues the FHS a TRL of 4 (see Table 22). Specific R&D experimental scale tests and tasks need to be completed before advancement to the next level of maturity.

Table 22. Fuel Handling System Summary TRL Table

	AREVA	General Atomics	Westinghouse	NGNP
TRL	6	6	Not provided	4

6.1.4 Fuel Handling System Maturation Path Forward

Experimental-scale testing is necessary to advance the FHS from TRL 4 to TRL 5. This includes tasks like assessing the availability of suppliers, material qualification testing, packaging testing, and inspection testing. All of the down selection tasks must be started before a TRL 5 can be granted.

To mature the FHS from TRL 5 to TRL 6, the FHS will be demonstrated in a pilot-scale with a speed error margin of ±0.15 ft/min and an accuracy of ±2 mm. The pilot-scale testing includes such tasks as structural tests; flow induced vibration tests; and speed, acceleration, and accuracy testing.

To mature the technology from TRL 6 to TRL 7, the FHS must undergo full engineering-scale testing of the integrated system within a relevant environment. Software validation testing in also required.

Advancement from TRL 7 to TRL 8 requires manufacture, installation, testing, and qualification of a full-scale NGNP Fuel Handling System within a non-radiological operating environment. Verified reliability must be performed at a rate >99.5% with 25 successful operations.

6.2 Instrumentation and Control

The NGNP Instrumentation and Control (I&C) provides the sensors and I&C systems needed to remotely operate the NHS and other critical systems of the NGNP. The I&C provides an interface for operators to monitor the operating parameters of critical NGNP systems. Information retrieved from I&C systems will include: temperature, flow rates, pressure, radiation leakage, and other system malfunctions. Information provided to operators from I&C systems will enable them to take necessary action.

6.2.1 Consolidated INL Technology Development Roadmap

A consolidated TDRM, produced from I&C TDRM data from the suppliers combined with NGNP R&D data, is shown in Figure 38.

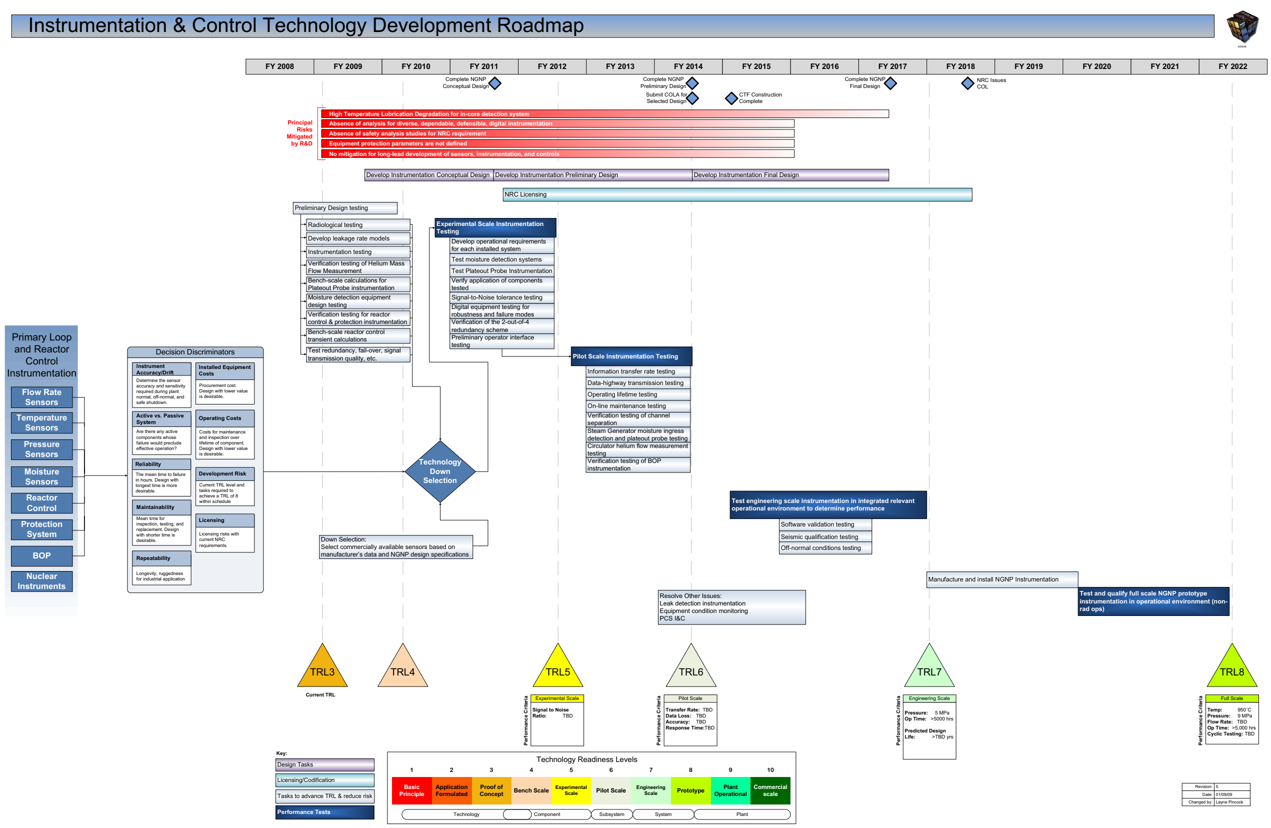

Figure 38. Instrumentation and Control Roadmap

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6.2.2 Instrumentation and Control Design Description

Instrumentation is a critical part of the Reactor Protection System and Investment Protection System. The I&C interfaces with the NHS, HPS, HTS, and PCS and includes the following subsystems:

- Plate out Instrumentation
- Helium flow-rate Instrumentation
- Pressure Instrumentation
- Moisture Monitoring Instrumentation
- Helium Leakage Instrumentation.

6.2.2.1 Functions Performed

At a high level, the I&C provides an interface for the operators to monitor the operations of critical NGNP systems. Some functions of the I&C include:

- Detect primary coolant leakage through measurement of pressure, temperature, or radiation levels within the Reactor Building or in helium-to-helium heat exchanger piping
- Detect steam leakage via moisture monitoring, which provides safety-related input to the reactor trip system and provides information to alert operators at operating consoles
- Measure the helium flow in each of the helium flow circulators using helium flow-rate Instrumentation.

Measurements from the I&C include steam or feed water flow rate, temperature, and pressure.

6.2.2.2 Design Options

Previous designs of the BOP I&C systems have been proven in existing reactor systems; however, advances in digital instrumentation have occurred and will be exploited for application in the NGNP.

6.2.2.3 Design Discriminators

Issues that may help the selection of appropriate sensors, instruments, and control schemes include: detector accuracy and drift, preference towards passive systems, reliability, maintainability, repeatability, and precision.

6.2.3 Instrumentation and Control TRL Status

U.S. gas-reactor operating experience is outdated and a new database must be developed to ensure the application of I&C in the NGNP. As such, the TRL rating for the BOP I&C is 3 (see Table 23).

Table 23. Instrumentation and Control Summary TRL Table

	AREVA	**General Atomics**	**Westinghouse**	**NGNP**
TRL	Not provided	3	Not provided	3

6.2.4 Instrumentation and Control Maturation Path Forward

To mature I&C technology from TRL 3 to TRL 4, material issues must be resolved to prove viability. When a proof-of-concept has been achieved, the BOP I&C will be advanced to TRL 4. Preliminary design testing and associated tasks are necessary to advanced to TRL 4. The down selection process begins at this stage as well.

Final technology down selection is completed during TRL 5. Experimental-scale testing and associated tasks, as shown in the TDRM, are necessary for TRL 5 issuance.

To advance the I&C from TRL 5 to TRL 6, the sensors and I&C system must undergo pilot-scale testing in a relevant environment. At least eight tasks are needed at the pilot-scale to grant the I&C a TRL of 6. Key concern needing resolution during and after TRL 6 are leak detection instrumentation, equipment condition monitoring, and PCS I&C.

To mature the BOP I&C from TRL 6 to TRL 7, the BOP I&C subsystems will be integrated as an engineering-scale test to determine integration performance. Such a test will most likely be performed at a component test capability.

To mature from TRL 7 to TRL 8, the I&C will be integrated into the NGNP for full-scale system operability testing. Manufacture and installation of the NGNP I&C, along with testing and qualification in a non-radiological operating environment, must be complete before the final issuance of TRL 8.

7. IMPACT OF CHANGING REQUIREMENTS

As each PASSC is assessed and TRLs established for each PASSC, an overall NGNP consolidated TRL (depicted in Figure 39) is established for the suppliers' proposed designs associated with a given set of operating parameters.

These designs become baseline scenarios for satisfying the NGNP functional requirements. Alternative designs can then be assessed and the relative technology readiness of each compared. The technology assessments performed and documented herein are based on operating parameters and pre-conceptual design requirements consistent with *System Requirements Manual* (SRM; June 2008) and *Summary of Bounding Requirements for the NGNP Demonstration Plant F&ORs* (June 2008). The salient features are:

- Reactor outlet temperature of 900–950°C
- Pressure of 5–9 MPa
- Indirect Cycle (i.e., steam generator in the secondary loop)
- Hydrogen Production in the secondary or tertiary loop
- GenIV fuel type.

NGNP / Area / System	Min TRL	Wgt	Avg TRL
NGNP	3		TBD
Nuclear Heat Supply System (NHSS)	4		TBD
Reactor Pressure Vessel System	4	TBD	
Reactor Vessel Internals	4	TBD	
Reactor Core and Core Structure	5	TBD	
Fuel Elements	4	TBD	
Reserve Shutdown System	5	TBD	
Reactivity Control System	4	TBD	
Core Conditioning System	4	TBD	
Reactor Cavity Cooling System	4	TBD	
Heat Transfer System (HTS)	3		TBD
Circulators	4	TBD	
Intermediate Heat Exchangers	3	TBD	
Cross Vessel Piping	4	TBD	
High Temperature Valves	3	TBD	
Mixing Chamber	6	TBD	
Hydrogen Production System (HPS)	3		TBD
High-Temperature Electrolysis (HTE)	4	TBD	
Sulfur-Iodine (SI)	4	TBD	
Hybrid Sulfur (HS)	3	TBD	
Power Conversion System (PCS)	4		TBD
Steam Generator	4	TBD	
Power Conversion Turbomachinery	4	TBD	
Balance of Plant (BOP)	3		TBD
Fuel Handling System	4	TBD	
Instrumentation & Control	3	TBD	

Figure 39. NGNP TRL Consolidation of Critical PASSCs

It is anticipated that the operating parameters and requirements will be modified to meet the end user needs and the market driven needs for the NGNP. Specifically, as Senior Advisory Group[a] meetings have been held and agreements reached, a new reference design may include:

- Reactor outlet temperature of 750–800°C
- Pressure of 5–7 MPa
- Indirect cycle (for the Pebble-bed Reactor)
- Steam Generator in the Primary Loop (for the Prismatic Reactor)

As requirements change, the critical PASSCs and TRLs will need to be evaluated against the new requirements.

Although the TRL ratings and associated TDRMs are against the pre-conceptual design requirements, Appendix A identifies potential impacts to the technology readiness as requirements are changed to a reactor outlet temperature of 750–800°C. This impact analysis goes beyond that required for this deliverable and foreshadows the potential impact of a change in requirements. Furthermore, the PCS Equipment for Direct Combined Cycle is included as a critical PASSC, which is required for a new reference design with the Steam Generator in the primary loop. One supplier (General Atomics) developed this PCS Option because of the attractiveness of a combined-cycle for an electricity producing option.

8. CONCLUSIONS

Conclusions and needed actions discovered during the Technology Readiness Assessment and the creation of TDRMs are as follows:

1. **Conclusion: NGNP Critical PASSCs are currently at a low level of technical maturity**. The minimum PASSC TRL is a 3. This lack of maturity is primarily due to the fact that materials issues are outstanding for a reactor outlet temperature of 950°C.

   Action: Revise the program requirements, including the reactor outlet temperature of 950°C. Note that the Senior Advisory Group has recommended a reactor outlet temperature of 750–800°C. As this requirement change is adopted, the TDRMs and technical readiness levels will be evaluated for modification, as identified in Appendix A. The tasks called out on the TDRMs and detailed in the Test Plans will be incorporated into the integrated project schedule for use in such decision making activities as annual funding reviews.

2. **Conclusion: Differences exist between the PASSCs determined to be critical by each supplier**. Some of the designs proposed by the suppliers are at differing levels of technical maturity. Hence, one supplier might consider a system to be more mature and not satisfy the definition for a critical system. For example, the CCS is not considered critical by all suppliers.

a A group of senior personnel representing the interests of owner/operators and suppliers. The objective is to establish and agree on the NGNP project work scope that represents the best utilization of funds for the government funded portion of the NGNP project between now and establishment of the DOE/Private Partnership(s),.

Action: Use the technical maturity of the proposed designs as one criterion in evaluating and down selecting the design used in the NGNP, such as in the due diligence reviews.

3. **Conclusion: Differences exist between the NGNP Project and the suppliers on the current TRL of each critical PASSC and on the steps needed for technology maturation**. For example, when materials issues are yet to be resolved, NGNP has not granted a TRL higher than 4.

   Action: Resolve the differences in TRL assessment by convening an independent TRL validation board and generate a set of validated NGNP TRLs. This validation board will also review the results of the TRL modifications associated with the requirements changes agreed to at the Senior Advisory Group meetings held in September and October of 2008. The tests and test schedules required to advance the various technologies will be integrated into the project schedule, as noted in Action 1.

4. **Conclusion: Major decisions must be made at key points in the project life cycle to select technologies and design strategies that reduce risk and enhance the opportunity for project success**. The major decision options and technology hurdles will be addressed through the TDRM process as a basis for conceptual, preliminary, and final design, and for updating the integrated project schedule. These decisions are summarized in Table 24 and will be made as the TDRM process is followed.

   Action: Work the TDRM process, including the down selection of technologies based on identified decision discriminators, to provide the technology readiness input needed to make design decisions.

5. **Conclusion: A component test capability is required to reduce the risk and fully mature critical PASSCs prior to insertion in the NGNP** (see Table 25). Based on reviews of the available international test capabilities/facilities, the reactor suppliers have identified 90 tests to be performed in a component test capability to adequately mature the technologies and components prior to insertion in the NGNP.

   Action: Develop a component test capability needed to conduct supplier-identified tests.

Table 24. Major Technical Issues and Options

PASSC	Major Technical Issues	Options
Reactor Pressure Vessel	Materials of Construction	Materials Vessel Cooling or No
Reactor Internals	Materials of Construction	
Reactor Core & Core Structure	Graphite Qualification	
Fuel Elements	Qualification	
Reserve Shut Down System (RSS)		
Reactivity Control System (RCS)	Materials of Construction	
Core Conditioning System (CCS)		
Reactor Cavity Cooling System (RCCS)		Air-cooled Water-cooled
Intermediate Heat Exchanger	Material Qualification Design Configuration Qualification	Materials – Inconel 617, Alloy 800H Design – Helical Coil, Printed Circuit
Circulators	Bearing Type, Motor Type, Impeller Type	Impeller Type – Submersible or Not, Electromagnetic Bearings, Oil Bearings
Mixer Chamber		
Cross Vessel Piping	Materials of Construction, Insulation	
High Temperature Valves	Materials, Spring, Actuator	
Hydrogen Production System	Cell or Vessel Degradation, Manufacturability	High-Temperature Electrolysis, Sulfur Iodine, Hybrid Sulfur
Steam Generator	Materials of Construction	
PCS TurboMachinery		
Fuel Handling System		
Instrumentation and Control	Sensors, Instruments, Controls	

Table 25. Tests Requiring Component Test Capability.

	AREVA						General Atomics						WEC						INL						CTC Tests Count
	TRL						TRL						TRL						TRL						
Area	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	
Nuclear Heat Supply (System, Structure/Subsystem, Component)																									
Reactor Pressure Vessel											1														**1**
Reactor Vessel Internals					1																				**1**
Reactor Core & Core Structures										4	5														**9**
Nuclear Instrumentation																									**0**
Fuel Elements																									**0**
Reserve Shutdown System																									**0**
Reactivity Control System				1	1						2														**4**
Core Conditioning System																									**0**
Reactor Cavity Cooling System												1													**1**
Heat Transfer System (System, Structure/Subsystem, Component)																									
Circulators					2						4	1					1	1							**9**
IHX				1	2						1	1				3	6								**14**
Hot Duct - Cross Vessel					1						1	1					1								**4**
Mixing Chamber																	1								**1**
High Temperature Valves					1					2	12	10													**25**
Hydrogen Production System (System, Structure/Subsystem, Component)																									
Hydrogen Production System											1					3	3					3	3		**13**
Power Conversion System (System, Structure/Subsystem, Component)																									
Steam Generator					1												1								**2**
Power Conversion Turbomachinery																									**0**
Balance of Plant (System, Structure/Subsystem, Component)																									
Fuel Handling System									1																**1**
Instrumentation and Control (RPS, et al.)					2	1				1	1														**5**
# of Individuals Tests Requiring CTC	**14**						**50**						**20**						**6**						**90**

CTC

9. REFERENCES

U.S. Government Accountability Office (2007), *Department of Energy: Major Construction Projects Need a Consistent Approach for Assessing Technology Readiness to Help Avid Cost Increases and Delays*, GAO-07-336, March 2007.

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10. APPENDICES

The set of supplier provided TRLs, TDRMs, and Test Plans along with their associated documentation is presented in the following appendices:

- Appendix A: Potential Impacts to Technology Readiness from Reducing Reactor Temperatures and Power Levels and Incorporating the Reference Configuration
- Appendix B: Supplier Reports and Consolidated Roadmaps
  - AREVA NGNP TDRM, TRLs, and Test Plans
  - General Atomics NGNP TDRM, TRLs, and Test Plans
  - Westinghouse NGNP TDRM, TRLs, and Test Plans
  - INL NGNP High Temperature Electrolysis Test Plans
  - NGNP Consolidated Roadmaps (Printable E-size Drawings).

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Appendix A

Potential Impacts to Technology Readiness from Reducing Reactor Temperatures and Power Levels and Incorporating the Reference Configuration

Appendix A
Potential Impacts to Technology Readiness from Reducing Reactor Temperatures and Power Levels and Incorporating the Reference Configuration

INTRODUCTION

The development of the TDRMs and the assessments of TRLs of critical PASSCs discussed in this report are based primarily on an NGNP design that operates with a reactor outlet temperature (ROT) of 900 – 950°C, power levels of 500 MWt to 600 MWt, and includes parallel primary helium loops supplying an electric power conversion system and a demonstration hydrogen production plant. These conditions and the production of electricity and hydrogen are consistent with the objectives cited in the Energy Policy Act of 2005, which charged DOE with initiating the NGNP Project and developing a demonstration plant by 2021. This configuration and associated operating conditions were developed during the NGNP pre-conceptual design work in FY 2007 and was the reference for the initial conceptual design work performed in FY 2008.

During the conceptual design work in FY 2008, several studies were performed to identify (1) the potential end users for the HTGR technology, (2) the specific energy requirements of these end users, and (3) the HTGR conditions to meet those requirements assuming that an NGNP plant will be on-line at the end of 2021 [MPR 2008]. These studies concluded that end-user requirements could be met with lower ROTs in the 700 – 800°C range producing steam and electricity. Specific applications included energy supplied in co-generation applications with, for example, refineries and petro-chemical plants, and steam supply for oil sands recovery. Other studies also showed that the risks to schedule and cost overruns are significantly reduced if the ROT and power level of the NGNP are reduced [AREVA 2008b; General Atomics 2008d; Westinghouse 2008a; Petti 2008].

In addition, several meeting have been held with a Senior Advisory Group comprised of the HTGR suppliers and nuclear plant owner/operators to review the high-level requirements and configurations of the proposed NGNP to satisfy potential end-user needs. These meetings have resulted in proposed ROT reduction to 750 – 800°C and recommended reference configurations of the pebble bed and prismatic reactors, HTS, and PCS.

This appendix supplements the review of the work on TDRMs and TRLs in the main body of this report by summarizing the impact of lowering reactor operating temperatures, and potentially reactor power, on the objectives and technical, cost, and schedule risks of the NGNP Project. Along with this operating temperature reduction, a generic reference configuration is proposed for NGNP that covers all potential end-user needs identified to date and the configurations recommended for NGNP by the HTGR suppliers.

In summary, the reductions in operating conditions for NGNP have significant benefits in mitigating technical, licensing, and schedule risks and potential reductions in total project costs while addressing potential end user and owner/operator expectations on energy supply capabilities and schedule for commercial application.

IMPACT ON POTENTIAL END USERS AND NGNP DESIGNS

Impact on Reactor Outlet Temperature

The studies referenced above show that the needs of industry and their interest in applying HTGR technology can be met with lower ROTs. For example, steam conditions required for efficient electricity production and to supply the majority of the process demands in a petrochemical plant are in the range of 1250 psig (8.6 MPa) to 2500 psig (17 MPa) at 1000°F (538°C). Similar or lower pressure and temperature conditions are required to supply oil sands recovery. These are the steam conditions of the Fort St. Vrain reactor, which operated at a ROT of 775°C, and the German THTR, with a ROT of 750°C. However, these designs were different from that being pursued by the NGNP Project. Work was done in the 1980s, 1990s, and early 2000s on developing HTGR designs with similar steam conditions and with improved safety margins that minimize the use of active safety related systems. The NGNP designs are based, in part, on these and other predecessor designs (e.g., MHTGR, NPR, GT-MHR, and Russian OKBM reactors) and take advantage of significant improvements in materials, reactor, and fuel development. Accordingly, a lower temperature NGNP design can take advantage of this prior work to reduce risk, provide further assurance of making the 2021 schedule, and meet the needs of the potential end users.

The lower temperature HTGR can also be used to support efficient hydrogen production. This can be done with recuperative mechanisms applied to HTE or by supplementary electric heating using the efficient plant electricity. There is little net efficiency loss associated with these mechanisms, but the reduction in risk to cost and schedule attendant to reducing the need to transport the very high temperature gas to the hydrogen process is significant.

Impact on Reference Designs

A generic reference configuration for NGNP, based on the combined recommendations of the HTGR suppliers, is shown in Figure A-5.

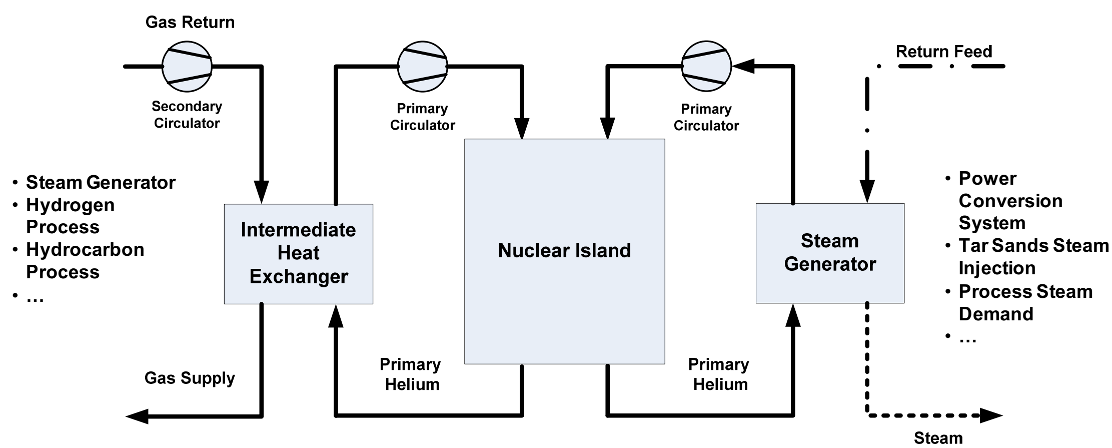

Figure A-5. Generic Reference Configuration

As the NGNP Project has progressed, different configurations with similar operating conditions have been proposed by the HTGR suppliers as having the least risk for meeting the objectives of commercializing the HTGR technology in the 2021 timeframe and meeting end-user needs. These variations on the reference configuration use helium as the primary coolant, but differ in the reactor designs and secondary coolants used to transport the energy from the reactor primary coolant system to the energy conversion system.

The pebble bed reactor design (proposed by the Westinghouse team) transfers heat from the primary loop through IHXs to secondary helium loops that supply the PCS and, if applicable, other processes (e.g., hydrogen production), as shown in Figure A-6.

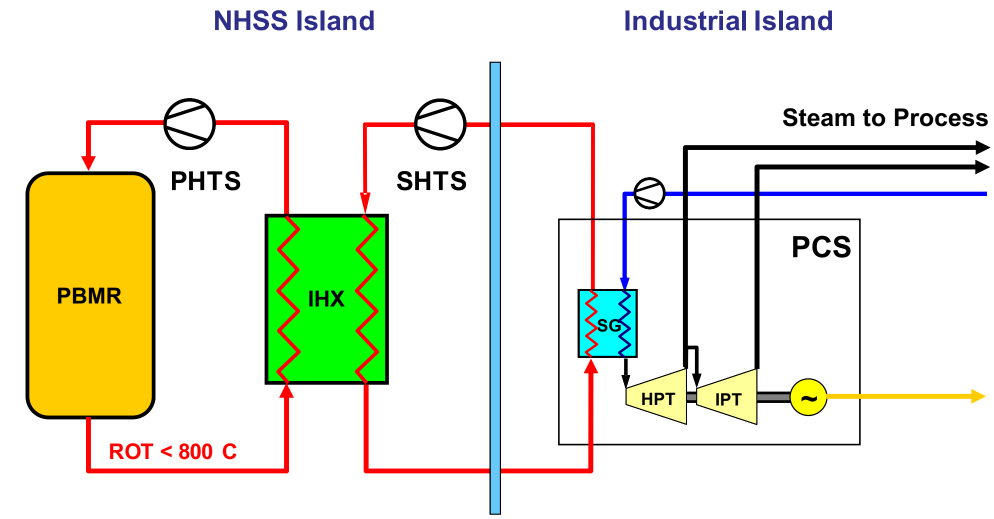

Figure A-6. Westinghouse Design

The prismatic block designs proposed by the AREVA and General Atomics teams both use steam and gas as the secondary heat transport fluid depending on the applications. If the plant were to supply high-temperature gas to a process (e.g., for hydrogen production) as well as steam and electricity, both gas and steam secondary coolant loops would be used. If, however, the plant were to produce only steam and/or electricity, the secondary gas loop would not be used, as shown in Figure A-7. In both cases, the recommended ROTs are in the range of 750 – 800°C. The power levels vary from 500 MWt for the pebble bed reactor to 600 MWt for the prismatic block reactor.

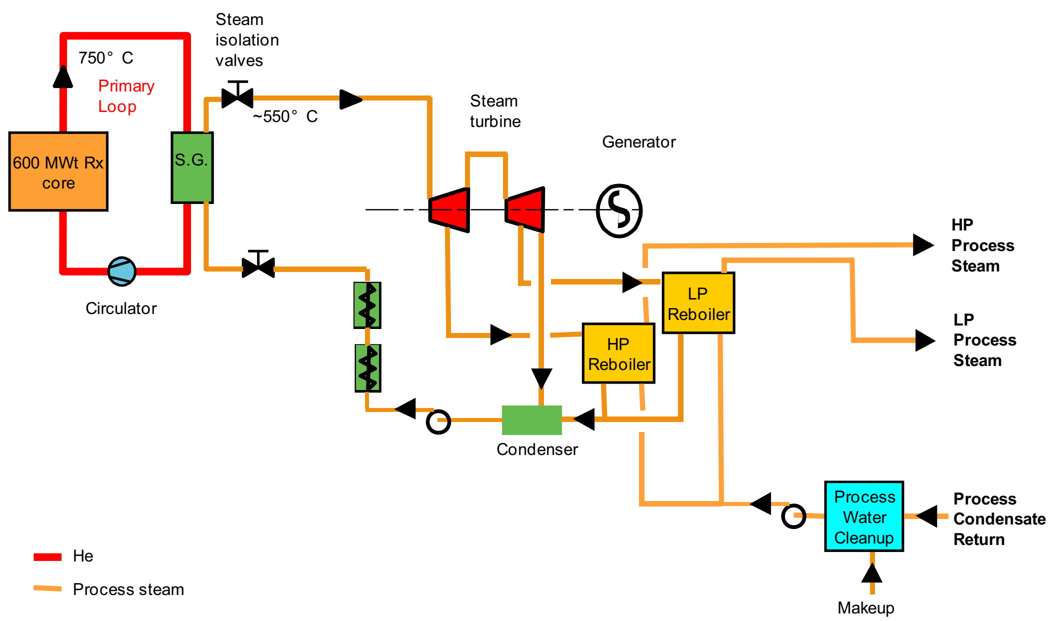

Figure A-7. Consolidated AREVA and General Atomics' Designs

Both of these proposed NGNP designs cover the full range of HTGR configurations for design certification by the NRC and facilitate subsequent use in license applications by industry. For example, there are different issues that must be resolved for using IHXs and secondary gas loops and for positioning a steam generator in the primary helium loop. The former requires potentially complex controls to limit the pressure differentials and pressure increases in the primary system in the event of a secondary circulator trip. The latter increases the potential for, and potential consequence of, a water ingress accident. In this way, the common issues as well as those unique to each configuration would be fully addressed in the design certification process.

IMPACT ON OVERALL PROJECT RISKS

Impact on HTGR Safety Basis

The fuel is the principal barrier in the HTGR design to the potential release of fission products to the environment under postulated accident conditions. The fundamental safety basis of the HTGR depends on minimal release of fission products from the fuel under all conditions. The dominant factors that affect the release of fission products from the fuel are as follows:

- Fuel production defect fraction
- Fuel initial heavy metal contamination
- Fuel burnup
- Time at peak temperatures during normal operation and under accident conditions.

The first three factors can be administratively controlled: the first two in the production process, and the third by (1) shuffling the location of fuel elements during refueling in the prismatic block reactor or through the mobility of the spheres in a pebble bed reactor and (2) by limiting the integrated exposure of individual fuel elements or spheres. Control of the fourth factor depends on the design of the reactor core and the operating conditions of the reactor. The current design objective is to design the core to limit the extent and time at which the fuel peak temperature is above 1250°C during normal operation and above 1650°C under accident conditions [Petti 2008].

It has been shown by test and operating experience that maintaining the majority of the fuel within these temperature limits results in minimal release of fission products to the primary coolant system under all conditions. The minimal release of fission products from the fuel reduces the need for substantive means (e.g., under accident conditions that could result in releases to the environment) of reducing the fission product source term during transport of the fission products from the fuel to the environment. As such, a high-pressure low-leakage containment vessel to contain fission products released from the primary coolant boundary is not required. The net result is that dose consequences at the plant boundary are calculated to be low enough to preclude the need for emergency plans that include sheltering and evacuation of the public under the most severe postulated accident conditions.

Impact on Fuel Temperature

The reactor coolant operating temperatures and reactor power level have significant effects on the fuel temperatures under normal and operating temperatures, as described in the following discussion for the pebble bed reactor [Westinghouse 2008b]:

> "Lowering of the reactor outlet temperature from 950ºC to 700ºC, reduces the maximum fuel temperature during normal operation from 1235ºC to 932ºC. … During a DLOFC [depressurized loss of forced cooling, an event that includes a breach of the primary coolant

boundary] event the maximum fuel temperature will reduce from 1703ºC to 1622ºC if the reactor outlet temperature is reduced from 950º to 700º…

"Lowering of the reactor power level from 500 MWt to 250 MWt, reduces the maximum fuel temperature during normal operation from 1235ºC to 1025ºC…. During a DLOFC event the maximum fuel temperature will reduce from 1703ºC to 1174ºC if the power is reduced from 500 MWt to 250 MWt…

"Although a DLOFC event can be initiated quickly, the reactor temperatures respond very slowly due to the immediate reactivity shut-down (negative temperature coefficient of reactivity) while the resultant temperatures are driven by decay heat generation. The maximum temperatures can be expected to be reached after hours and not within minutes (between 40-60 hours for all cases).

"In determining the expected fission product releases from the fuel, it is important to consider the actual time the fuel will be exposed to the very high temperatures (time at temperature). Only a small portion of the fuel will be exposed to these high temperatures for a relatively short period of time, which imply reduced overall releases. For a 500MWt PBMR reactor operating at 950ºC, only 5-7% of the fuel is expected to be exposed to temperatures above 1600ºC during a typical DLOFC transient."

Even though this refers to the pebble bed reactor design, similar results have been calculated for the prismatic block reactor design [AREVA 2008a; General Atomics 2008a]. Figures A-1 and A-2 depict these effects for both reactor designs.

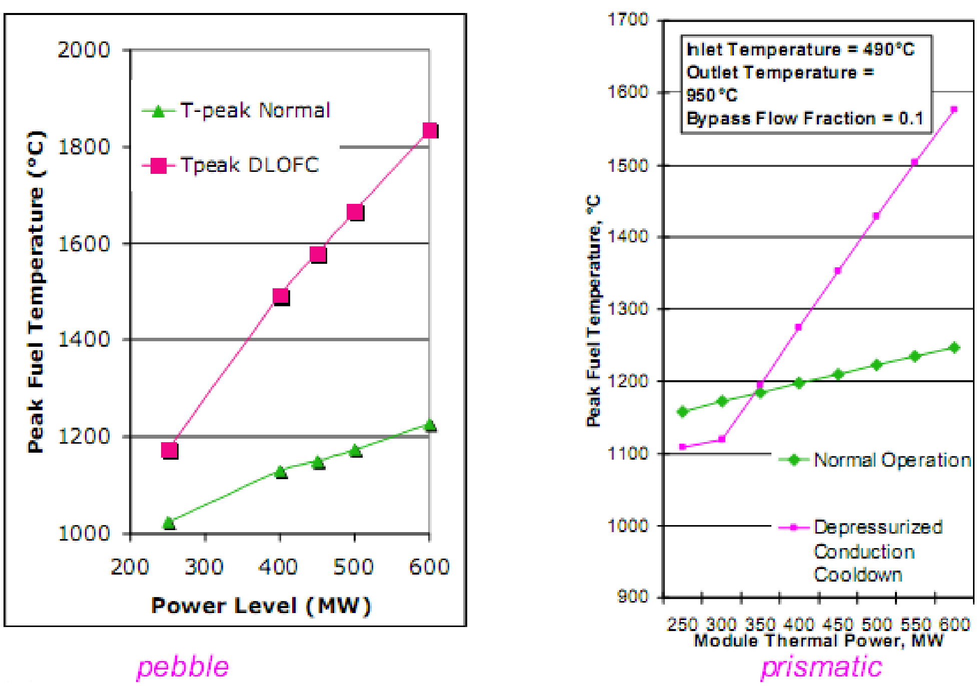

Figure A-1. Effect of Power Level on Peak Fuel Temperatures

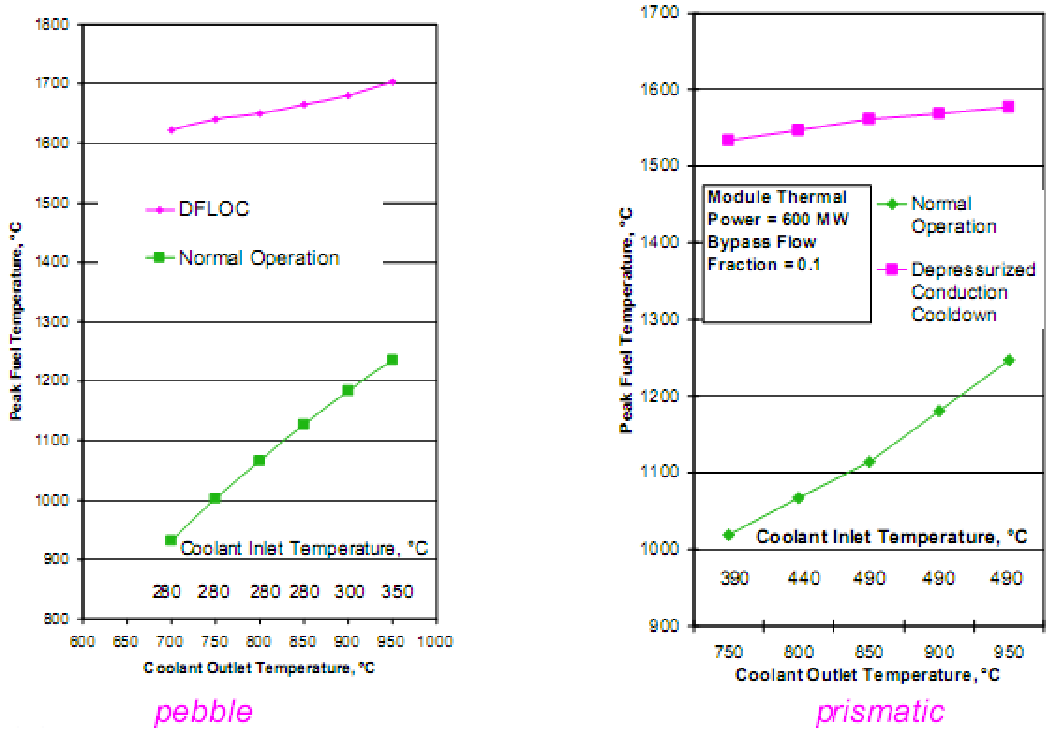

Figure A-2. Effect of Reactor Operating Temperatures on Peak Fuel Temperatures

Reductions in ROT from 900°C to 750°C are well within traditional experience and provide substantial margin to critical temperature limits. Reductions in power level and temperature also have a substantial impact on the radiological source term in that the radiological source term inventory at half power is reduced by half. The fission product release and the particle failure rates decrease exponentially with temperature. Therefore, the 150 – 200°C drop in temperature attendant to the reduction in ROT under normal operating conditions to the range 750 – 800°C should translate, based on engineering judgment, into levels of incremental particle failure and fission product release that require minimal credit for retention of fission products in the primary system and reactor building as part of source term qualification. Additional analyses will be performed to confirm this assumption and provide a robust safety basis, thereby, reducing risk of extension in the schedule for licensing.

There is, therefore, significant advantage in reducing fuel temperatures by providing margin in release of fission products from the fuel and supporting the calculation of minimal dose consequence at the site boundary under all conditions.

Impact on Other Project Risks

The reduction in reactor temperatures also has significant impact on project cost and schedule risk by reducing the technology development requirements to qualify the fuel, core graphite, and high-temperature materials for the first plant.

Fuel Qualification

The reduction in outlet temperature brings average fuel temperatures to within the historical operating envelope of these fuels and brings peak fuel temperatures to levels at which particle failure and diffusion through intact particles will be negligible. The reduction in outlet temperature brings greater surety to the program that fuel qualification will be successful and demonstrate with high confidence that the fuel meets its intended high fission product retentiveness under normal and accident conditions.

Intermediate Heat Exchanger

Reductions of the outlet temperature to the range of 750 – 800°C would permit the use of IHX and steam generator materials that are currently qualified to these temperatures with modest extension to the existing code cases. Figures A-3 and A-4 show the impact of reducing the ROT from 950°C to 750°C on the probability of completing design, qualification, fabrication, installation, and initial startup of the IHX [Westinghouse 2008a].

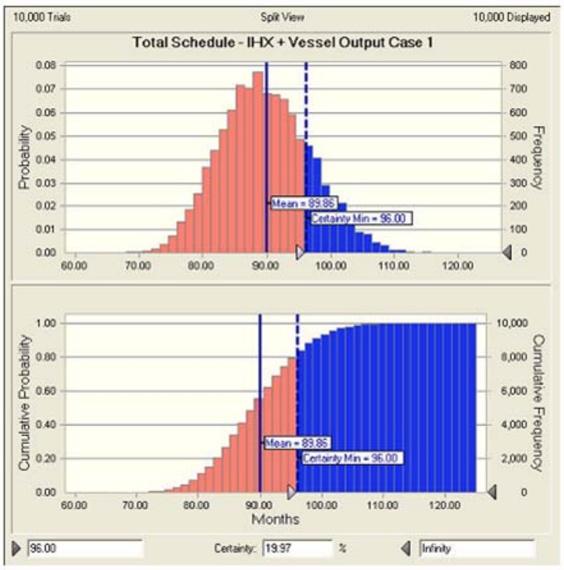

Figure A-3. 750 °C Reactor Outlet Temperature

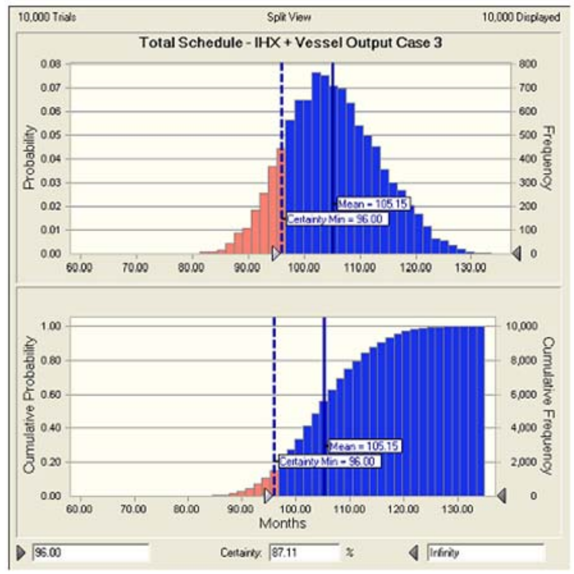

Figure A-4. 950 °C Reactor Outlet Temperature

At 950°C ROT, the mean time to complete is increased by over a year compared with the 750°C ROT. This mean time to complete for the 950°C ROT exceeds the allotted time (96 months, value in lower left box of Figures A-3 and A-4) by 9 months for the schedule assumed for this analysis. In comparison, the mean time to complete for the 750°C ROT is 6 months under the allotted time. This leads to a probability of 87% that the allotted time would be exceeded for 950°C ROT (i.e., a 13% probability of making the schedule) but a probability of only 20% (i.e., an 80% probability of making the schedule) for the 750°C ROT. These analyses were performed by the HTGR suppliers in early FY 2008 to assess the impact of the ROT on Project schedule and cost. Similar results were obtained for other major PASSCs (e.g., RPVs of modified 9Cr-1Mo and steam generators [AREVA 2008c, 2008d; General Atomics 2008b, 2008c].

Graphite

The temperature reductions should reduce the peak graphite temperatures sufficiently to reduce the performance envelope for qualification of the graphite. The lower operating temperature also reduces uncertainty in the combined effects of creep, shrinkage, and swelling of the graphite under irradiation on its thermochemical behavior. All of these factors reduce project technical risk and potential cost and schedule overruns.

Note that the higher temperature and power testing would continue in the NGNP Technology Development Office to support subsequent increases in temperature and power level, assuming funding by DOE.

Impact on TDRMs and TRLs

As shown in the main body of this report, the majority of PASSCs associated with the transport of energy from the reactor to applications have low TRLs (3 to 5) and require development and testing to achieve a TRL of 7 (i.e., that required for installation in NGNP). This reflects the high temperature operating conditions assumed for assessment of the TRLs.

During the development of the TDRMs, the suppliers provided primarily qualitative assessments of the impact of reducing ROT on the TRLs of major PASSCs and the technology development needs to qualify these PASSCs for installation in NGNP. The principal benefit of reducing operating temperatures is that standard materials could be used, thus reducing costs and schedule for qualifying advanced materials, improving availability of the materials, reducing the costs for piping and vessels, and improving fabrication schedule and certainty (e.g., use of proven rather than developmental welding and post-weld heat treatment procedures). The standard materials include SA-508/533 for pressure vessels and Alloy 800H for higher temperature piping and heat exchange components instead of more advanced and developmental materials that would be required at the higher reactor temperatures, such as modified 9Cr-1Mo, Inconel 617, and Hastelloy XR. PASSCs affected include:

- Primary System Pressure Vessels
  - This includes the RPV, IHX or steam generator pressure vessel, and cross-vessel, where used. The TRLs of these PASSCs would be expected to increase with the use of standard materials for the lower operating temperature.
- Cross-Vessel Piping and High-Temperature Valves
  - High-temperature valves have TRLs in the 3 to 5 range depending on the position in the primary and secondary loops; a TRL of 4 is assigned for cross-vessel piping due to ducts that are exposed to an ROT of 900 – 950°C. Although there are still design challenges with the high temperature piping because of a lack of prior experience with these designs, the challenges in affecting and completing a reliable design are reduced at the lower operating temperatures.
- Intermediate Heat Exchanger
  - PBMR indicates that the high-temperature IHX, which has a TRL of 2, would not be required for the lower ROT. This would eliminate three of the five testing requirements for the IHXs.
  - The suppliers note that it may be necessary to use ceramics in the high-temperature parts of the IHX if ROTs are in the 900 – 950°C range. If this is a necessary path, it is highly developmental and adds high schedule and cost risk as well as complexity to the project.
  - The lower temperature IHX has a TRL of 3 because there is no experience with the compact design, internals, and interfaces for the design proposed by PBMR. There is also little experience with the spiral tube design proposed by AREVA, and substantive design work and testing are required to advance the design to TRL 7.

PBMR, AREVA, and General Atomics state that the lower temperature conditions will reduce the challenges in the design of this heat exchanger, implying higher confidence in completing the design on budget and schedule.

- Steam Generator
  - AREVA indicates that the TRL of the steam generator would be improved from a 5 for the high temperature design to a 6. PBMR cites the steam generator at a TRL of 6 for both designs because of similarity in the design to past installations in Germany. As noted, all of the suppliers state that the material development requirements and challenges to the design would be lower at the lower operating temperature.
- Hydrogen Production System Heat Exchangers, Recuperators, and Decomposers
  - The reductions in ROT simplify the design and reduce the material requirements and cost for piping used to supply the hydrogen plant HTS. This can be a significant savings in the construction cost of plants that include hydrogen production. Development of the internals of the HPS options need to accommodate the reactor ROT but are generally independent of that temperature. Planning is to complete commercial-scale development and testing of these processes in a component test capability before coupling with the NHS.

The lower temperatures also have the following beneficial effects on the development requirements and advancement of the TRLs of critical PASSCs:

- The required effort for qualification of the materials in the NGNP R&D Program for licensing of the NGNP at the lower temperature would be significantly reduced and completed in less time than at the higher temperature.
- The lower inlet temperature that would accompany a lower ROT also reduces the development required for the circulators. Issues that need to be addressed to advance this TRL include: use of external rather than submerged motor drives, higher power levels than previously experienced, electro-magnetic versus oil bearings, advanced I&C, the outlet check valve, and integration of all PASSCs for the final operating conditions. The critical areas affected by the operating temperature include impeller material and seals. The lower operating temperature will reduce the complexities and challenges in resolving these issues.
- The technical risk of developing valve designs that can meet stroke time and leakage requirements at the plant helium operating pressures is reduced.

Accordingly, a reduction in ROT has significant benefit in improving the technical readiness of the critical PASSCs for NGNP, including the HTS components, fuel, and graphite and high-temperature materials[b], and thereby provides better assurance of achieving plant startup by the end of 2021.

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b Even if the initial NGNP Plant operates at the lower ROT, the R&D and other developmental programs would be continued, based on available funding, to achieve higher operating temperatures in future HTGR applications.

CONCLUSIONS

The considerations discussed above on the impact of the reductions in temperature and potentially power also apply to reducing licensing risk since they provide more margin in the safety basis for the plant than for the higher temperature condition. This was judged by those performing this work to be a significant factor in promoting completion of the licensing process for the NGNP first-of-a-kind plant on the desired schedule. The licensing process can be extended to the higher temperature and power conditions at a later date if the market conditions warrant it.

Applications and configurations recommended by potential end users, owner/operators, and HTGR suppliers suggest a reduction in ROT for the reference first-of-a-kind plant. An ROT reduction from a range of 900 – 950°C to a 750 – 800°C has the following results:

- Substantive reduction in Project technical cost and schedule risk
- Reduction in development requirements for advanced materials
- Potential reductions in fabrication and construction costs.

These advantages result from:

- The ability to use standard materials for major PASSCs that operate near the ROT instead of more advanced materials (e.g., Alloy 800H instead of Inconel 617, or standard LWR RPV material [SA-508/533] instead of modified 9Cr-1Mo or Inconel 617).
- The minimal extension of code cases required to apply standard materials; compared with the development of new code cases required for the more advanced materials.
- The ability to apply prior operating, testing, and design experience with gas-cooled reactors directly to the qualification and design of critical PASSCs (e.g., Fort St. Vrain, German Arbeitsgemeinschaft Versuchsreaktor [AVR] and THTR, DOE/General Atomics Modular High-Temperature Gas-cooled Reactor [MHTGR] and New Production Reactor [NPR], General Atomics Gas Turbine-Modular Helium Reactor [GT-MHR], and Republic of South Africa [RSA] Demonstration Power Plant [DPP]).
- The addition of substantial margin in the operating conditions for the fuel and graphite in comparison with the conditions (e.g., temperature, burnup, fluence) of the ongoing qualification development program for these PASSCs, which will facilitate the licensing of the first plant. NOTE: Qualification temperatures are higher than are expected for the critical conditions at the lower operating temperatures (depicted in Figures A-1 and A-2).

The reference configurations and operating conditions match potential end-users' energy needs for a wide range of applications for steam, electricity, and hot gas supply. Interactions with potential end users and nuclear plant owner/operators indicate that an accelerated schedule for commercialization of the HTGR technology at these conditions and reference configurations is preferred over a longer schedule and higher operating temperatures. These entities also strongly recommend:

- The development and licensing of more than one reactor design
- A comprehensive configuration(s) that offers choices and competition in supply of the technology and adaptability to specific process needs
- Locating the NGNP as a first-of-a-kind plant in a commercial site and application.

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