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Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs)

Volume 4: High-Temperature Materials PIRTs

OAK RIDGE NATIONAL LABORATORY

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ABSTRACT

The Phenomena Identification and Ranking Table (PIRT) technique was used to identify safety-relevant/safety-significant phenomena and assess the importance and related knowledge base of high-temperature structural materials issues for the Next Generation Nuclear Plant (NGNP), a very high temperature gas-cooled reactor (VHTR). The major aspects of materials degradation phenomena that may give rise to regulatory safety concern for the NGNP were evaluated for major structural components and the materials comprising them, including metallic and nonmetallic materials for control rods, other reactor internals, and primary circuit components; metallic alloys for very high-temperature service for heat exchangers and turbomachinery, metallic alloys for high-temperature service for the reactor pressure vessel (RPV), other pressure vessels and components in the primary and secondary circuits; and metallic alloys for secondary heat transfer circuits and the balance of plant. These materials phenomena were primarily evaluated with regard to their potential for contributing to fission product release at the site boundary under a variety of event scenarios covering normal operation, anticipated transients, and accidents. Of all the high-temperature metallic components, the one most likely to be heavily challenged in the NGNP will be the intermediate heat exchanger (IHX). Its thin, internal sections must be able to withstand the stresses associated with thermal loading and pressure drops between the primary and secondary loops under the environments and temperatures of interest. Several important materials-related phenomena related to the IHX were identified, including crack initiation and propagation; the lack of experience of primary boundary design methodology limitations for new IHX structures; and manufacturing phenomena for new designs. Specific issues were also identified for RPVs that will likely be too large for shop fabrication and transportation. Validated procedures for on-site welding, postweld heat treatment (PWHT), and inspections will be required for the materials of construction. High-importance phenomena related to the RPV include crack initiation and subcritical crack growth; field fabrication process control; property control in heavy sections; and the maintenance of high emissivity of the RPV materials over their service lifetime to enable passive heat rejection from the reactor core. All identified phenomena related to the materials of construction for the IHX, RPV, and other components were evaluated and ranked for their potential impact on reactor safety.

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FOREWORD

The Energy Policy Act of 2005 (EPAct), Public Law 109-58, mandates the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) to develop jointly a licensing strategy for the Next Generation Nuclear plant (NGNP), a very high temperature gas-cooled reactor (VHTR) for generating electricity and co-generating hydrogen using the process heat from the reactor. The elements of the NGNP licensing strategy include a description of analytical tools that the NRC will need to develop to verify the NGNP design and its safety performance and a description of other research and development (R&D) activities that the NRC will need to conduct to review an NGNP license application.

To address the analytical tools and data that will be needed, NRC conducted a Phenomena Identification and Ranking Table (PIRT) exercise in major topical areas of NGNP. The topical areas are: (1) accident analysis and thermal-fluids including neutronics, (2) fission product transport, (3) high temperature materials, (4) graphite, and (5) process heat and hydrogen production. Five panels of national and international experts were convened, one in each of the five areas, to identify and rank safety-relevant phenomena and assess the current knowledge base. The products of the panel deliberations are Phenomena Identification and Ranking Tables (PIRTs) in each of the five areas and the associated documentation (Volumes 2 through 6 of NUREG/CR-6944). The main report (Volume 1 of NUREG/CR-6944) summarizes the important findings in each of the five areas. Previously, a separate PIRT was conducted on TRISO-coated particle fuel for VHTR and high temperature gas-cooled reactor (HTGR) technology and documented in a NUREG report (NUREG/CR-6844, Vols. 1 to 3).

The most significant phenomena (those assigned an importance rank of “high” with the corresponding knowledge level of “low” or “medium”) in the thermal-fluids area include primary system heat transport phenomena which impact fuel and component temperatures, reactor physics phenomena which impact peak fuel temperatures in many events, and postulated air ingress accidents that, however unlikely, could lead to major core and core support damage.

The most significant phenomena in the fission products transport area include source term during normal operation which provides initial and boundary conditions for accident source term calculations, transport phenomena during an unmitigated air or water ingress accident, and transport of fission products into the confinement building and the environment.

The most significant phenomena in the graphite area include irradiation effect on material properties, consistency of graphite quality and performance over the service life, and the graphite dust issue which has an impact on the source term.

The most significant phenomena in the high temperature materials area include those relating to high-temperature stability and a component’s ability to withstand service conditions, long-term thermal aging and environmental degradation, and issues associated with fabrication and heavy-section properties of the reactor pressure vessel.

The most significant phenomenon in the process heat area was identified as the external threat to the nuclear plant due to a release of ground-hugging gases from the hydrogen plant. Additional phenomena of significance are accidental hydrogen releases and impact on the primary system from a blowdown caused by heat exchanger failure.

The PIRT process for the NGNP completes a major step toward assessing NRC's research and development needs necessary to support its licensing activities, and the reports satisfy a major EPAct milestone. The results will be used by the agency to: (1) prioritize NRC's confirmatory research activities to address the safety-significant NGNP issues, (2) inform decisions regarding the development of independent and confirmatory analytical tools for safety analysis, (3) assist in defining test data needs for the validation and verification of analytical tools and codes, and (4) provide insights for the review of vendors' safety analysis and supporting data bases.

Farouk Eltawila, Director
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ACRONYMS

ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
ASME B&PV	ASME Boiler and Pressure Vessel (Code)
BOP	balance of plant
C–C	carbon–carbon
CHX	compact heat exchanger
DOE	Department of Energy
FOM	figure of merit
HCF	high-cycle fatigue
HTGR	high-temperature gas-cooled reactor
HX	heat exchanger
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
KM	Knowledge Management
LOFC	loss-of-forced circulation
LWR	light-water reactor
MHTGR	modular high-temperature gas-cooled reactor
MIT	Massachusetts Institute of Technology
NDE	nondestructive evaluation
NGNP	next generation nuclear plant
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
PCV	power conversion vessel
PIRT	phenomena identification and ranking table
PWHT	postweld-heat treatment
RCCS	reactor cavity cooling system
RPV	reactor pressure vessels
SOK	state of knowledge
T-H	thermal-hydraulic
VHTR	very high-temperature gas-cooled reactor

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1. PIRT OBJECTIVES

The Phenomena Identification and Ranking Table (PIRT) technique is a structured process to identify safety-relevant/safety-significant phenomena and assess the importance and knowledge base by ranking the phenomena. The Next Generation Nuclear Plant (NGNP) is anticipated to be a very high temperature gas-cooled reactor (VHTR). The NGNP high-temperature-materials PIRT identifies those phenomena important for normal operations, anticipated transients, and postulated accidents (design basis and beyond). All structural materials other than the graphite to be used in the core and core support structures were addressed in this PIRT exercise (Note: NGNP graphite issues were explicitly examined in another PIRT exercise). The results of this PIRT exercise are documented in PIRT tables and will be used as a tool for identifying and prioritizing research needs. The results and the specifics of the table are detailed below.

This NGNP is similar to other high-temperature gas-cooled reactor (HTGR) designs that the Nuclear Regulatory Commission (NRC) has come across in past years, but differs in the following ways:

1. The outlet gas and many of the primary circuit components are anticipated to operate at higher temperatures than the past.
2. A steam generator connected directly to the primary circuit is no longer anticipated to be part of the design; it has been eliminated from the design entirely by either going to a direct cycle turbine or it has been replaced by an intermediate heat exchanger (IHX) for the purposes of supplying process heat for other uses (e.g., hydrogen production) and/or downstream electric power conversion systems.

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2. BRIEF INTRODUCTION TO NGNP HIGH-TEMPERATURE MATERIALS ISSUES

The major aspects of the materials degradation phenomena for potential regulatory safety concerning the NGNP can be divided by major structural components and the materials comprising them, as follows:

- graphite for core structures, including replaceable and permanent components,
- nonmetallic or metallic materials for control rods,
- nonmetallic materials for other reactor internals and primary circuit components,
- metallic alloys for very high temperature service for heat exchangers,
- metallic alloys for very high temperature service for turbo machinery,
- metallic alloys for high temperature service for the reactor pressure vessel,
- metallic alloys for high temperature service for other pressure vessels and components in the primary circuit,
- metallic alloys for secondary heat transfer circuits and balance of plant (BOP), and
- materials for valves, bearings, and seals.

For each category of materials and components described above, technical data and information on material's strength and creep, fatigue, and creep-fatigue performance for the anticipated times and temperatures of service are needed to support the design, expected performance, and the adequacy of safety margins that could potentially degrade over time. Where appropriate, it will also be necessary to understand the effects that the service environments may have on the materials baseline properties, including the effects of coolants, heat transfer media, and irradiation exposure.

For metal usage within the temperature range where time-dependent behavior occurs, it will also be necessary to ensure that a validated methodology for high-temperature design and analysis is available to predict materials performance and failure.

Several major classes of materials are considered in this PIRT exercise. They are briefly described along with component applications in Table 1.

Table 1. Major classes of materials expected to be used in the NGNP

Material type	Examples of materials	Potential component application
Low-alloy steel	SA508 steel SA 533B steel 2-1/4 Cr–1 MoV steel 9 Cr–1MoV steel	Reactor pressure vessel and piping
Stainless steel	304 stainless steel 316 stainless steel 347 stainless steel	Core barrel Ducting Recuperators
High alloys	Inconel 617 Haynes 230 Incoloy 800H Hastelloy X and XR Inconel 740	Core barrel Intermediate heat exchanger Piping Bolting Control rods Turbomachinery
Nanostructured and oxide dispersion strengthened alloys	MA 956 PM 2000	

Table 1 (continued)

Material type	Examples of materials	Potential component application
Nonmetallic composites	Carbon–carbon (C–C) SiC-SiC	Control rods Core restraints Liners for hot ducts and insulation
Nonmetallic materials (ceramics)	Alumina Silica Kaowool	Insulation

Note that a companion activity will evaluate the phenomena associated with graphite, so they will not be addressed here.

2.1 Previous NRC Activities and Material

The NRC investigation of the Modular HTGR (MHTGR) in the 1980s [1] and the supporting documentation developed by the Department of Energy (DOE) [2] provide information on extensive regulatory review of a plant similar to those currently under consideration. One major difference with respect to licensing is the former's (MHTGR) use of a steam generator BOP approach, where the dominant risk was from water-ingress due to steam generator tube breaks. A second difference is the inclusion of process heat (hydrogen production) systems in NGNP designs. Pertinent references are currently being accumulated in the NRC Knowledge Management (KM) online database.

Additional studies [3, 4] identify most of the metallic materials degradation and performance issues associated with the codification of design of metallic materials for HTGRs. A review of *American Society of Mechanical Engineers (ASME) Code* issues for metals for broader high-temperature reactor usage was also performed and documented in another NRC-sponsored study [5].

2.2 Major Structural Materials Phenomena Issues

High-Temperature Metals**—**It is necessary to develop data and models needed by ASME Boiler & Pressure Vessel (B&PV) Code subcommittees to formulate time-dependent failure criteria that will assure adequate life and safety for metallic materials in the NGNP. Specifically, experimentally based constitutive models that are the foundation of the inelastic design analyses specifically required by ASME B&PV Sect. III Division I Subsect. NH must be developed for the construction materials safety assessments, dependent on time-dependent flaw growth and the resulting leak rates from postulated pressure-boundary breaks, will require a flaw assessment procedure capable of reliably predicting crack-induced failures as well as the size and growth of the resulting opening in the pressure boundary. Additionally, materials data and extrapolation procedures must be developed and guidance provided to ensure that allowable operation period and range of stress and temperature for materials of construction are extended to meet the proposed operating temperatures and lifetimes. Creep-fatigue rules are an area of particular concern for the materials and temperatures of interest and must be updated and validated.

Of all the high-temperature metallic components, the one most likely to be heavily challenged in the NGNP that includes the use of secondary loops for power generation or process heat applications will be the IHX. Its thin, internal sections must be able to withstand the stresses associated with thermal loading and pressure drops between the primary and secondary loops, which may be quite substantial. Additionally, since these sections must operate at the full exit temperature of the reactor, metallurgical stability and environmental resistance of the materials comprising them in anticipated impure helium coolant environments must be adequate for the lifetimes anticipated. Several materials-related phenomena related to the IHX were identified as having a high importance for potentially contributing to fission product release at the site boundary and a low level of knowledge with which to assess their contribution to such a release. These included crack initiation and propagation (due to creep crack growth, creep, creep-fatigue, and aging); the lack of experience of primary boundary design methodology limitations for new IHX structures; manufacturing phenomena for new designs (including joining issues); and the ability to inspect and test new IHX designs. These are called out in Table 6 as phenomena 35, 36, 37, and 38, respectively.

An alternative to a very high-temperature metallic heat exchanger being considered is one made of ceramics or ceramic composites. This would dramatically reduce concerns about high-temperature operation, because such materials have much higher temperature capabilities, but would introduce major concerns about design and fabrication methods as well as use of brittle materials in a nuclear pressure boundary.

Specific issues must be addressed for reactor pressure vessels (RPVs) that are too large for shop fabrication and transportation. Validated procedures for on-site welding, postweld heat treatment (PWHT), and inspections will be required for the materials of construction. For vessels using materials other than those typical of light-water reactor (LWR) construction to enable operation at higher temperatures, confirmation of their fabricability (especially, effects of forging size and weldability) and data on their irradiation resistance will be needed. Three materials-related phenomena related to the RPV fabrication and operation were identified as having a high importance for potentially contributing to fission product release at the site boundary and a low level of knowledge with which to assess their contribution to such a release, particularly for 9 Cr–1 MoV steels capable of higher temperature operation than LWR vessel steels. These included crack initiation and subcritical crack growth, field fabrication process control, and property control in heavy sections. These are called out in Table 6 as phenomena 5, 16, and 17, respectively.

Small amounts of impurities that will contaminate the reactor coolant can degrade the materials both by corrosion processes and by effects on mechanical properties. Carburization, decarburization, and internal oxidation are issues of particular concern in high-temperature metals. The effects of corrosion of the impure helium environment on metals and nonmetals must be evaluated. Moreover, since the actual levels of impurities within the coolant of the NGNP will be controlled largely by the presence of large quantities of hot graphite, in conjunction with all sources of contamination, the ability to accurately simulate this environment for meaningful laboratory evaluations is critical. The overall stability of the proposed helium environment that will be representative of the NGNP must be evaluated in order to ensure any testing is performed in environments that have chemical potentials consistent with that encountered in the reactor. General corrosion evaluations of the candidate materials to establish their overall compatibility with that environment must also be performed for all temperatures of interest. This will include determining the effects that the helium environment has on long-term mechanical properties, such as creep, or creep-fatigue, as well as the impact on microstructural stability of aging in the environments of interest.

Environmental effects of other heat transfer media outside the primary circuit on the corrosion behavior and the mechanical properties of the structural materials must also be evaluated. Of particular concern are gas mixtures that may be used in Brayton-cycle power conversion cycles (e.g., 80% N–20% He) and heat transfer fluids associated with process heat applications (e.g., molten salt).

Because the ability to passively reject heat adequately during certain transients in the NGNP is dependent upon transmitting decay heat from the core and radiating it from the exterior of the RPV, it is critical that emissivity of the various potential candidate materials for the RPV and core barrel remains sufficiently high over their lifetimes. Depending on the emissivity of the selected materials, it may be necessary to qualify and incorporate high-emissivity, durable coatings on the surfaces of these components. Two materials-related phenomena related to the RPV and core barrel emissivity were identified as having a high importance for potentially contributing to fission product release at the site boundary and a low level of knowledge with which to assess their contribution to such a release. This is the potential loss of passive heat rejection ability due to compromise of emissivity caused by loss of desired surface layer properties (phenomena 11and 46 in Table 6).

High-level issues for high-temperature metallic components that will require evaluation include the following:

- inelastic materials behavior for materials, times, and temperatures for very high temperature structures (e.g., creep, fatigue, creep-fatigue, etc.);
- adequacy and applicability of current ASME Code allowables with respect to service times and temperatures for operational stresses;
- adequacy and applicability of current state of high-temperature design methodology (e.g., constitutive models, complex loading, failure criteria, flaw assessment methods, etc.);
- effects of product form and section thickness;
- joining methods including welding, diffusion bonding, and issues associated with dissimilar materials in structural components;
- effects of irradiation on materials strength, ductility, and toughness;
- degradation mechanisms and inspectibility;
- oxidation, carburization, decarburization, and nitriding of metallic components in impure helium and helium-nitrogen;
- microstructural stability during long-term aging in helium environment;
- effects of short- and long-term exposure on mechanical properties (e.g., tensile, fatigue, creep, creep-fatigue, ductility, toughness, etc.);
- high-velocity erosion/corrosion;
- rapid oxidation of graphite and C–C composites during air-ingress accidents;
- compatibility with heat-transfer media and reactants for hydrogen generation; and
- development and stability of surface layers on RPV and core barrel affecting emmissivity.

Control Rods—Considering that the control rods (and possibly some other internals) in the NGNP may see temperatures in excess of those that can be safely handled by commercial high-temperature alloys, it may be necessary to use structural composites such as carbon–carbon or SiC–SiC. If these materials are used, it will be essential that their design and fabrication methods be evaluated to ensure their structural integrity. Additionally, testing methods must be developed (and standardized, if possible) to reliably characterize their mechanical properties in the nonirradiated and irradiated conditions

If metallic materials are used for control rods, their satisfactory performance under all anticipated temperatures and irradiation doses must be demonstrated.

High-level issues that will need to be evaluated related to the use of structural composites as described above include the following:

- effects of composite component selection and infiltration method;
- effects of architecture and weave;
- material properties up to and including very high temperatures (e.g., strength, fracture, creep, corrosion, thermal shock resistance, etc.);
- effects of and relationship between specimen and component geometries;
- effects of irradiation on materials strength and dimensional stability;
- fabrication scaling processes;
- adequacy and validation of design methods; and
- degradation mechanisms and inspectibility.

3. PIRT DESCRIPTION

There are nine steps in conducting the PIRT exercise. Each step is enumerated and described here:

3.1 Step 1—Issue

The issues driving this PIRT exercise may be summarized as follows:

1. NGNP is a major design change from the current LWR design. Materials, coolant, moderators, and potential applications are different.
2. Both the industry and NRC experience base is very limited with respect to the NGNP. While a few HTGRs have been constructed, the operational history has been mixed, and the current plans are a radical extrapolation of the past technology. In particular, with regard to past HTGRs we are interested in the higher temperature effects of the NGNP on materials of construction. Additionally, the adequacy of design methodology for use of materials in the high-temperature regime, where time-dependent behavior must be considered, is also of significant concern.
3. The database for these new designs is not nearly as well developed as the LWR database, or for that matter, other past or existing HTGRs. The materials database to support the NGNP is incomplete, and the current high-temperature design methodology is inadequate.

3.2 Step 2—PIRT Objectives

The major objectives of the NGNP high-temperature materials PIRT exercise are to (1) identify and rank potential degradation mechanisms for structural materials under normal operating, transient, and accident conditions, (2) identify important parameters and dependencies that affect the degradation processes, (3) assess material performance requirements to assure safety, including needs for additional codes and standards, and (4) assess material properties data bases and identify new data needs, where appropriate. Because the NGNP exists as only a rough concept, it was not possible to perform this exercise for a specific plant design; however, it was surmised that the NGNP would share much in common with past HTGR designs. Moreover, several new preconceptual designs are being actively developed. These were cumulatively used as a reference. Phenomena and knowledge base were evaluated with respect to normal operations, anticipated transients, and postulated accidents (design basis and beyond).

3.3 Step 3—Hardware and Scenarios

NGNP systems and/or components (e.g., reactor vessel, core, internals, IHX, etc.) were identified with regard different scenarios that could challenge them. This was done with the current, but incomplete, knowledge of component hierarchy and their safety significance, consistent with the overall PIRT exercise scope and objectives.

Possible accidents were presented at the February 2007 PIRT meeting, which outlined the expected behavior of the NGNP. The three areas discussed by the panel follow.

Normal operation, which for the purposes of the high temperature materials PIRT provided the long-term, baseline loading conditions for the components and materials of construction.

Anticipated transients that can cause changes in temperature, pressure, flow, and mechanical vibrations or shocks and can increase the potential for developing failures, leaks, or ruptures in components that would provide a pathway for the release of fission products.

Postulated accidents drew the majority of the panel's time because they had the greatest likelihood for producing challenges to materials that increase the potential for developing failures, leaks, or ruptures in components that would provide a pathway for the release of fission products.

The NGNP event scenarios, contained below in Table 2, identify the conditions to which plant and components are exposed and provide a key to the situations for which the phenomena in Table 6 were evaluated.

Table 2. HTGR event scenarios for materials PIRT exercise

Normal operations
1. Startup
2. Shutdown
3. Steady state
4. Helium inventory control
Transients
5. Anticipated transient without scram (ATWS)
6. Turbine trip
7. Loss of load
Postulated accidents
8. Pressurized loss of forced circulation
9. Depressurized loss of forced circulation
10. Rupture with air ingress
11. Rupture with water ingress
12. Reactivity events

3.4 Step 4—Evaluation Criteria

Step 4 of the process involved the selection of a figure of merit (FOM) related to each system or component. These were the criteria against which importance of phenomena is judged. While these are often derived from regulations (e.g., dose limit, siting criteria) at top levels and related to the issue being addressed, and scenario and component selected at subsidiary levels, in all cases the FOMs provided guidance with regard to the likelihood of radiation release at the site boundary.

The process by which the panel developed the FOMs is described, because it is important to understand the relationship between the reactor system or component being considered, the FOM itself, and the potential development of a pathway for the release of fission products at the site boundary. The first step that the panel took was to identify the major reactor system or structural components that were felt to have the potential to contribute to fission product release, such as the RPV, the piping, etc. Criteria were then established by which the significance of individual phenomena could be evaluated with regard to their contribution to release at the site boundary, for example, maintaining the integrity of the pressure boundary in the RPV or piping, limiting the peak temperature of the fuel, maintaining the geometry of core support structures and their related nuclear characteristics, etc. These criteria were the FOMs. The component-specific phenomena were then evaluated against each FOM for their contribution to fission product release via a specific pathway, for example, breach of piping or pressure vessels, excessive deformation of core supports, and coolant flow blockage from debris or component passage collapse.

Hence, it is important to understand that each phenomenon identified is ranked for its importance and knowledge base with respect to a particular component, FOM, and pathway to release. Table 3 contains the FOMs and pathways to release used to rank the phenomena identified for each component.

Table 3. Figures of Merit and pathways to release for different reactor systems or components

FOM (evaluation criteria)	Pathways to release
Reactor pressure vessel (RPV)	
RPV integrity	Breach, excess deformation
FOM1: RPV integrity; FOM2: peak fuel temperature	Inadequate heat transfer
Power conversion vessels (PCVs) and turbomachinery	
FOM1: primary system pressure boundary integrity, FOM2: integrity of rotating equipment	Breach of vessel, turbine failure
Circulators	
FOM1: primary system pressure boundary integrity, FOM2: integrity of rotating equipment	Oil bearing failure, impeller failure
Piping	
Primary system pressure boundary integrity	Breach, failure to insulate
Peak fuel temperature	Insulation debris generation
Intermediate heat exchanger (IHX) vessel	
FOM1: integrity of IHX; FOM2: integrity of vessel	Breach to ambient
Intermediate heat exchanger (IHX)	
FOM1: integrity of IHX; FOM2: secondary loop failure/breach	Breach to secondary system
FOM1: integrity of IHX; FOM2: integrity of hot duct (and other systems)	Breach from secondary to primary
Integrity of IHX	Catastrophic loss of function
Control rods (nonmetallic)	
Maintain insertion ability	Failure to insert
Control rods (metallic)	
Maintain insertion ability	Failure to insert
RPV internals (metallic)	
Maintain heat transfer capability	Inadequate heat transfer
Maintain structure geometry;	Excess deformation and fracture/failure
FOM1: core barrel integrity; FOM2: RPV integrity	Failure

Table 3 (continued)

FOM (evaluation criteria)	Pathways to release
RPV internals (nonmetallic)	
FOM1: maintain structure geometry; FOM2: maintain insulation capability	Core restraint and support failure
Maintain structure geometry	Core restraint failure
Maintain insulation capability	Fibrous insulation degradation
Reactor cavity cooling system (RCCS)	
Emergency heat removal capability	Inadequate heat removal
Auxiliary shutdown system	
Primary system pressure boundary integrity	Water contamination of primary coolant
Valves	
Primary system pressure boundary integrity	Malfunction, failure to operate and breach

3.5 Step 5—Knowledge Base

To establish the state of the knowledge base, it is necessary to compile and review background information that captures relevant knowledge for the materials of interest for the conditions they are expected to experience during operating, upset, and accident conditions. Because the NGNP does not have a firm design at this time, it was necessary to envelop the range of materials and their operating conditions currently under discussion for the various systems and components. A comparison of this envelop of candidate materials and their operating conditions with the overall knowledge base for such materials was used to rank the specific knowledge base available to assess the phenomena identified.

3.6 Step 6—Identify Phenomena

All plausible materials-related phenomena that could contribute to the overall concern of radiation release at the site boundary were identified by system or component. In this case, the term "phenomenon" is broadly defined to include not only "physical phenomenon" but also a process or a property.

3.7 Step 7—Importance Ranking

In this step, the panel developed importance ranking and rationale for the phenomena identified in Step 6. The phenomenological hierarchy starts at the system level and proceeds through component and subcomponent level. Also, the lowest level of hierarchical decomposition should be consistent with the data and modeling needs from a regulatory perspective.

The importance rankings process consisted of the generation of individual and independent ranking by panel members, discussion and documentation of the rationale for such rankings (including references to published information on the subject), and finally the development of a collective panel ranking based on the discussion. Note that the collective ranking assigned by the panel was not an average ranking but rather was reached as a consensus among the panel members following individual rankings and discussion of the phenomenon. Importance was ranked relative to the evaluation criteria adopted in Step 4. A qualitative ranking, that is, High (H), Medium (M), Low (L), and Unknown (UNK) was adopted.

Table 4 defines the scale used to provide guidance in ranking the importance of the individual phenomena.

Table 4. Phenomena importance ranking scale

Rank	Definition	Application outcomes
High (H)	Phenomenon has a controlling impact on the FOM	Experimental simulation and analytical modeling with a high degree of accuracy is critical
Medium (M)	Phenomenon has a moderate impact on the FOM	Experimental simulation and/or analytical modeling with a moderate degree of accuracy
Low (L)	Phenomenon has a minimal impact on the FOM	Modeling must be present to preserve functional dependencies

3.8 Step 8—Knowledge Level

In this step, the panel assessed the level of knowledge regarding each phenomenon identified in Step 6, and for which an importance ranking is assigned in Step 7. The process consisted of the generation of individual and independent ranking by panel members, discussion and documentation of the rationale for such rankings (including references to published information on the subject, for example, experimental data base, analytical tools, etc.), and finally the development of a collective panel ranking based on the discussion. Note that the collective ranking assigned by the panel was not an average ranking but rather was reached as a consensus among the panel members following individual rankings and discussion of the knowledge level. A qualitative ranking, that is, High (H), Medium (M), Low (L), and Unknown (UNK) was used. Table 5 defines the scale used to provide guidance in ranking the knowledge base of the individual phenomena.

Table 5. State of knowledge (SOK) ranking scale

Rank	Definition
High (H)	Experimental simulation and analytical modeling with a high degree of accuracy is currently possible
Medium (M)	Experimental simulation and/or analytical modeling with a moderate degree of accuracy is currently possible
Low (L)	Experimental simulation and/or analytical modeling is currently marginal or not available

3.9 Step 9—Document PIRT

The objective of this step was to provide sufficient coverage and depth in the documentation so that a knowledgeable reader could understand what was done to develop and substantiate the outcome of the NGNP high-temperature materials PIRT exercise. This includes a listing of background materials, PIRT objectives, tables of identified phenomena, their importance and knowledge level ranking, and associated text describing the process of phenomena identification and rationale of the ranking process. This document fulfills this step.

The overall summary containing the phenomena identified, their rankings of importance and knowledge base, and related rationale for all systems and their respective FOMs is provided in Table 6. Note that the collective rankings assigned by the panel for both importance and knowledge level were developed as a panel consensus, though individual rankings were retained and reported to show where an individual panel member ranked an item with respect to the panel consensus.

Table 7 contains the group of selected phenomena that the panel considered to be of particular significance due to their combination of a high ranking of importance and a low or moderate ranking of low knowledge. The reader should be cautioned that merely selecting phenomena based on high importance and low knowledge may not capture the true uncertainty of the situation.

Table 6. PIRT table for high-temperature materials

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
			Reactor pressure vessel				
1	RPV integrity	Breach/1–4	Thermal aging (long term)	H	Uncertainty in properties of 9 Cr–1 Mo steel (grade 91), especially degradation and aging of base metals and welds for a critical component like the RPV, must be addressed for 60-year lifetimes. Although it was not discussed in our meeting, Type IV cracking has been observed in operating fossil plants at 545°C after 20,000 h. Although unlikely, is Type IV cracking at NGNP operating temperatures possible for very long time (60 years) exposure?	M	It is assumed that Grade 91 is the prime candidate for NGNP, and no back up material is considered in this report for designs without active cooling. This is beyond experience base for conditions of interest, extensive fossil energy experience and code usage, though significant aging data exist at high temperatures (>500°C). Need is for long-term aging data at NGNP relevant temperatures. [10, 15–17]
2	RPV integrity	Breach/1–4	Thermal aging (long term)	L	LWR steels within existing experience.	H	Extensive database for LWR applications
3	RPV integrity	Breach/8,9	Thermal aging (short term, high temperature)	M	Grade 91 aging during high-temperature, short-term excursions of ~100 h, economic impact on continued plant operation, potential for microstructural changes and impact on properties.	M	Grade 91, extensive database for fossil energy applications. Some data exist for P91 at NGNP-relevant temperatures. [10, 15–17]
4	RPV integrity	Breach/8,9	Thermal aging (short-term, high temperature)	L	LWR steels within existing experience.	H	More known on 508, (more information needed on extended times, temperatures for Code Case 499)

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
5	RPV integrity	Breach/1–7	Crack initiation and subcritical crack growth	H	9 Cr–1 Mo steel (grade 91) must be assessed for phenomena due to transients and operationally induced—thermal loading, pressure loading, residual stress, existing flaws (degradation of welds, cyclic loading, low cycle fatigue).	L	There is a limited database from fossil energy applications at these temperatures. Low cycle fatigue data in air, vacuum and sodium (ANL unpublished data) at >482°C show life is longest in sodium, followed by vacuum and air. Aging in helium (depending on impurities) will most likely be greater than in air. Aging in impure helium may perhaps depend on impurity type and content [10, 15–17]
6	RPV integrity	Breach/1–7	Crack initiation and subcritical crack growth	H	LWR steels within existing experience. Differing opinions; question raised about whether important for HTGR application. Thermal gradients not expected to be as severe as for LWRs.	H	Extensive database for LWR applications
7	RPV integrity	Breach/1–7	High cycle fatigue (HCF)	L	Grade 91 HCF loading expected to be minimal in vessel.	M	Extensive database for fossil energy applications. HCF life being spent mostly on initiation, is likely to be a function of the environment [10, 15–17]

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
8	RPV integrity	Breach/1–7	High cycle fatigue	L	LWR steels HCF loading expected to be minimal in vessel.	H	Extensive database for LWR applications. Design curve in ASME code (NH) for 1000°F [15–17]
9	RPV integrity	Breach/3	Radiation degradation	M	Grade 91 for fluences, temperatures, and fluxes of interest—need to demonstrate lack of radiation degradation over 60 year.	L	Moderate data base at high flux available from fusion power program resources [10, 15–17]
10	RPV integrity	Breach/3	Radiation degradation	L	LWR steels—some question about softer spectrum effects, but not expected to control material response.	H	Extensive database from LWR applications [10, 15–17]
11	FOM1: RPV integrity; FOM2: peak fuel temperature	Inadequate heat transfer/1–3	Compromise of emissivity due to loss of desired surface layer properties	H	To ensure passive safety, high emissivity of the RPV is required to limit core temperatures—must maintain high emissivities on both inside and outside surfaces. Formation and control of surface layers must be considered under both helium and air environments.	L	There are limited studies on SS and on 508 that show potential for maintaining high emissivity. (4/16/07 note following meeting with T/F PIRT panel, there are some studies currently being conducted by UIUC, U. Mich. on emissivity but NOT on materials of concern).

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
12	RPV integrity	Excess deformation/8,9	Creep (transient)	M	Grade 91, creep during high-temperature, short-term excursions of ~100 h, economic impact on continued plant operation, potential for excessive vessel deformation could potentially affect core geometry.	M	Moderately extensive fossil energy database. Most of the laboratory creep data are at >550°C. Lower temperature data are needed, specially for thick section specimens [10, 15–17]
13	RPV integrity	Excess deformation/ 8,9	Creep (transient)	M	LWR materials, creep during high-temperature, short-term excursions of ~100 h each, economic impact on continued plant operation, potential for excessive vessel deformation could potentially affect core geometry.	M	Existing code coverage, but necessary to assess time and temperature [15–17]
14	RPV integrity	Excess deformation/ 1–7	Creep (normal operations)	M	Grade 91, differing definitions of what is defined as negligible creep under different codes,* ensure negligible creep during normal operations.	L	Inadequate data at time and temperatures of interest [10, 15–17]
15	RPV integrity	Excess deformation/ 1–7	Creep (normal operations)	L	LWR materials—ensure negligible creep during normal operations. Problem not anticipated for LWR materials; design will limit temperatures of operation to regimes where this is not an issue.	M	Temperature of use for LWR material is below defined insignificant creep range, ASME code coverage [10, 15–17]

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
16	RPV integrity	Breach, excess deformation/ 1–9	Field fabrication process control	H	Because of vessel size, must address field fabrication [including welding, postweld heat treatment, section thickness (especially with 9 Cr–1 Mo steel)] and preservice inspection.	L	Fossil energy experience indicates that caution needs to be taken. On-site nuclear vessel fabrication is unprecedented. [10, 15–17]
17	RPV integrity	Breach, excess deformation/ 1–9	Property control in heavy sections	H	Heavy-section properties are difficult to obtain because of hardenability issues. Adequate large ingot metallurgy technology does not exist for 9 Cr–1 Mo steel. Maintaining fracture toughness, microstructural control, and mechanical properties in through-thickness of heavy sections, 9 Cr materials must be maintained. (Utilities consider heat treatment of P_{91}, > 3-in. diameter piping challenge).	L	Very limited data, not much over 3 to 4 in. thickness. Few data available for specimens from 300-mm-thick forgings show thick section properties lower than thin section. [10, 15–17]
Power conversion vessels (PCVs) and turbomachinery							
18	FOM1: primary system pressure boundary integrity, FOM2: integrity of rotating equipment	Breach of vessel/1–7	Thermal aging	L	Operation expected within existing LWR experience database range.	H	Extensive LWR database [15–17]

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
19	FOM1: primary system pressure boundary integrity, FOM2: integrity of rotating equipment	Breach of vessel/1–7	Crack initiation and subcritical crack growth in power conversion vessel (PCV).	L	Operation expected within existing LWR experience database range.	H	Extensive LWR database [15–17]
20	FOM1: primary system pressure boundary integrity, FOM2: integrity of rotating equipment	Breach of vessel/3,4	High cycle fatigue in PCV	M	Loading deriving from rotational and thermal-hydraulic (T-H) feedback. Severity must be assessed.	H	Extensive LWR database [15–17]
21	FOM1: primary system pressure boundary integrity, FOM2: integrity of rotating equipment	Breach of vessel/1–7	Missile (disc failure)	M	Turbomachinery failure could be caused during normal operations—analog with jet engines (creep, creep crack growth, thermal loading, rotational stresses, fatigue, creep-fatigue of turbine disk).	M	Jet engine and gas turbine experience [15–17]
22	FOM1: primary system pressure boundary integrity, FOM2: integrity of rotating equipment	Turbine failure/1–7	Creep, creep crack growth, thermal loading, rotational stress, fatigue, creep fatigue	M	Concern about debris plugging core cooling channels, causing damage.	M	Jet engine and gas turbine experience [5, 16–24]

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
23	FOM1: primary system pressure boundary integrity, FOM2: integrity of rotating equipment	Oil bearing failure/1–7	Primary coolant contamination (carburization?)	M	Coolant chemistry can be affected by oil contamination and exacerbates issues with heat exchanger.	M	Experience with coolant chemistry control in earlier HTGR systems.
				Circulators			
24	FOM1: primary system pressure boundary integrity, FOM2: integrity of rotating equipment	Oil bearing failure/1–7	Primary coolant contamination (carburization?)	M	Coolant chemistry can be affected by oil contamination and exacerbates issues with heat exchanger.	M	Experience with coolant chemistry control in earlier HTGR systems.
25	FOM1: primary system pressure boundary integrity, FOM2: integrity of rotating equipment	Impeller failure/ 1–7	Creep, creep crack growth, thermal loading, rotational stress, fatigue, creep fatigue	M	Concern about debris plugging core cooling channels, causing damage.	M	Jet engine and gas turbine experience.
				Piping			
26	Primary system pressure boundary integrity	Breach/1–7, 9	Thermal aging	L	Thermal aging due to long-term conditions and short-term high temperature; assuming all ferritic piping operated below the creep range.	M	Extensive industrial use.
27	Primary system pressure boundary integrity	Breach	Crack initiation and subcritical crack growth	M	Operation expected within existing LWR experience database range.	M	Extensive LWR database.

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
28	Primary system pressure boundary integrity	Breach/1–7	High cycle fatigue	M	HCF from T-H loading; from resonance—design still not well enough known to dismiss HCF; however, operation expected within existing LWR experience database range.	M	Extensive LWR database.
29	Primary system pressure boundary integrity	Breach/1–7	Erosion	M	The potential exists for particle erosion in the piping system, particularly at elbows, due to entrainment of graphite dust in high-velocity helium.	M	There is a relatively extensive operating history of helium-cooled graphite-moderated reactors that can be evaluated to provide system experience with respect to this phenomenon
30	Peak fuel temperature	Insulation debris generation/1–7	Aging fatigue, environmental degradation of insulation	H	Concern is about insulation debris plugging core cooling channels, causing damage due to chunks of internal insulation falling off (ceramic sleeves or carbon–carbon composites would be most likely source of problems).	L	Little system-relevant information about insulation failure mechanism is available.
31	Primary system pressure boundary integrity	Failure to insulate/1–7	Aging fatigue, environmental degradation of insulation	M	Failed insulation leads to hot spots or cooling system leak (in PBMR)—focus is on failure to insulate and effect on piping due to transients operationally induced—thermal loading, pressure loading, residual stress, existing flaws.	L	Little system-relevant information about insulation failure mechanism is available.

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
			Intermediate heat exchanger (IHX) vessel				
32	FOM1: integrity of IHX; FOM2: integrity of vessel	Breach to ambient/1–9	Thermal aging	L	Operation expected within existing LWR experience database range but shorter service life due to replacement.	H	Extensive LWR database.
33	FOM1: integrity of IHX; FOM2: integrity of vessel	Breach to ambient/1–9	Crack initiation and subcritical crack growth	M	Operation expected within existing LWR experience database range but shorter service life due to replacement.	H	Extensive LWR database.
34	FOM1: integrity of IHX; FOM2: integrity of vessel	Breach to ambient/1–9	High cycle fatigue	L	HCF from T-H loading; from resonance—design still not well enough known to dismiss HCF; however, operation expected within existing LWR experience database range but shorter service life due to replacement.	H	Extensive LWR database.
			Intermediate heat exchanger (IHX)				
35	FOM1: integrity of IHX; FOM2: secondary loop failure/breach	Breach to secondary system/1–9	Crack initiation and propagation (due to creep crack growth, creep, creep-fatigue, aging (with or without load), subcritical crack growth)	H	Environmental effects on subcritical crack growth—subject to impacts of design issues, particularly for thin-section must be addressed. Stresses on IHX (both thin and thick sections) can lead to these failure phenomena; thermal transients can cause toughness concerns and carbide redistribution as a function of thermal stress can change through-thickness properties.	L	More is known about 617 from HTGR and industry usage than for 230. Both environment and creep play significant roles in initiation and cyclic crack growth rate of 617 and 230. Mechanistic models for predicting damage development and failure criteria for time-dependent phenomena have to be developed to enable

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
							conservative extrapolation from short term laboratory test data to long term design life.
36	FOM1: integrity of IHX; FOM2: secondary loop failure/breach	Breach to secondary system/1–9	Primary boundary design methodology limitations for new structures (lack of experience)	H	Time-dependent design criteria for complex structures need to be developed and verified by structural testing. ASME Code approved simplified methods have not been proven and are not permitted for compact IHX components.	L	No experience for the complex shape IHX. No experience for designing and operating high temperature components in the class 1 environment. Difficulties of design and analyses of compact IHX are discussed in the references.
37	FOM1: integrity of IHX; FOM2: secondary loop failure/breach	Breach to secondary system/1–9	Manufacturing phenomena (such as joining)	H	Compact heat exchanger (CHX) cores (if used) will require advanced machining, forming, and joining (e.g., diffusion bonding, brazing, etc.) methods that may impact component integrity. Must assess CHX vs traditional tube and shell concepts. However, these phenomena are generic and extend beyond the CHXs to all the very high-temperature heat exchangers (HXs).	L	HXs have not been used in nuclear applications; the candidate alloys and their joining processes not adequately established in nonnuclear applications.
38	FOM1: integrity of IHX; FOM2: secondary loop failure/breach	Breach to secondary system/1–9	Inspection/testing phenomena	H	Traditional nondestructive evaluation (NDE) methods will not work for CHXs because of geometrical constraints. Proof-testing of some kind will be required (maybe leak testing with tracer). Preservice testing	L	Preoperational testing, preservice inspection, fitness for service, issue with leak tests, have very little knowledge here. What is the margin?

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
					will be difficult, and in-service testing will be even harder. Condition monitoring may be useful.		
39	FOM1: integrity of IHX; FOM2: integrity of hot duct (and other systems)	Breach to secondary system/1–9	Water or chemical ingress/attack	M	Considering that all current proposed systems for the NGNP will utilize helium or helium nitrogen on the secondary side of the IHX, the normal operating environment will be moderately benign. The potential exists for contamination of the secondary circuit with water or process chemicals from the hydrogen production plant. In the short term, even for significant intrusion, such contamination is not expected to challenge the IHX. Long-term mild contamination is a greater concern, but should be able to be avoided by process control.	M	There is a fairly extensive body of data regarding the effect that water or likely process chemicals could have on the IHX membrane materials, but little operating or system experience to shed light on the probability of such an occurrence
40	Integrity of IHX	Catastrophic loss of function/9	Plastic instability	M	Degradation due to brazing, diffusion-bonding, next generation joining techniques can result in structural instability and plastic collapse (buckling problem). May be ultimately safety issue because of core overheating, analogous in some respects to tube plugging and leakage above threshold. Exacerbated by extreme high service	L	Expert opinion [12–17]

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
					temperatures with regard to available material capabilities (e.g., low margin).		
Control rods (nonmetallic)							
41	Maintain insertion ability	Failure to insert/ 1–12	Radiation-induced degradation	M	Limits on strength and dimensional stability during irradiation; assumption that dimensional stability also includes anisotropy.	L	Limited data from fusion power program, but applicability needs to be assessed.
42	Maintain insertion ability	Failure to insert/ 1–12	Oxidation	M	Long-term exposure to low partial pressure of oxygen and more rapid oxidation during air ingress.	M	Limited data from fusion power program, but applicability needs to be assessed.
43	Maintain insertion ability	Failure to insert/ 1–12	Composites structural design methodology limitations for new structures (lack of experience)	H	Carbon–carbon composites are prime candidates, but need approved method of designing, proof testing, model testing, testing standards, and validation tests.	L	Some code work is being developed by ASME, ASTM, and international partners. Extensive aerospace industry design and usage can be assessed for applicability.
Control rods (metallic)							
44	Maintain insertion ability	Failure to insert/ 1–12	Radiation degradation (embrittlement/ swelling/ radiation creep)	M	Insertion issue particularly for alloy 800H re low-dose ductility reduction, and dimensional changes associated with Ni-alloy based swelling and radiation-induced creep at moderately low doses.	M	Limited information available on swelling and ductility reduction at moderate doses, no information on irradiation creep [12–17]

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
45	Maintain insertion ability	Failure to insert/ 8,9, 12	Loss of strength at high temperatures (transient)	M	Potential for temperature to exceed short-term strength of metallic materials. Panel states that for insertion it is an H, but for safety, an M.	M	Short-term mechanical property data are available from previous nuclear applications (see ASME database being assessed under DOE-ASME contract) [12–17]
			RPV internals (metallic)				
46	Maintain heat transfer capability	Inadequate heat transfer/8,9	Change in emissivity	H	To ensure passive safety, high emissivity is required to limit core temperatures (affect coolant pathway)—need for high emissivities on both surfaces of the core barrel, and formation and control of surface layers in helium environments).	L	Limited studies on SS and on 508 show potential for maintaining high emissivity [12–17]
47	Maintain structure geometry	Excess deformation/1–9	Radiation-creep	H	Irradiation creep and dimensional changes particularly for alloy 800H at moderately low-dose should be assessed.	L	Little information on irradiation creep is available for Alloy 800H [12–17]
48	Maintain structure geometry	Fracture/failure/ 1–9	Radiation-induced embrittlement	M	Particular issue for alloy 800H regarding moderate low-dose ductility reduction.	M	Limited information available on ductility reduction at moderate doses [12–17]
49	FOM1: core barrel integrity; FOM2: RPV integrity	Failure/1–9	Creep, creep crack growth, thermal loading	L	Cracking or failure of graphite can cause a hot plume/stream to impinge on the core barrel and cause a local hot spot, but may be difficult due to low (to zero) pressure differential and high pathway resistance. However, the consequence of this	M	There is a relatively extensive operating history of helium-cooled graphite-moderated reactors that can be evaluated to provide system experience with respect to this

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
					affecting the core geometry or providing a pathway for external leakage is highly unlikely.		phenomenon
				RPV internals (nonmetallic)			
50	FOM1: maintain structure geometry; FOM2: maintain insulation capability	Core restraint and support failure/ 1–12	Radiation-induced degradation	M	RPV internals (nonmetallic) include (1) insulation, such as under core, amorphous carbon underlaid by alumina providing compressive nonmetallic material, (2) nonmetallic structural materials (e.g., carbon–carbon composites). Need to assess effects on strength, fracture, dimensional stability, and thermophysical properties during irradiation.	L	Limited data from fusion power program, but applicability needs to be assessed.
51	FOM1: maintain structure geometry; FOM2: maintain insulation capability	Core restraint and support failure/ 1–12	Oxidation	M	RPV internals (nonmetallic) include (1) insulation, such as under core, amorphous carbon underlaid by alumina providing compressive nonmetallic material, (2) nonmetallic structural materials (e.g., carbon–carbon composites). Effects of long-term exposure to low partial pressure of oxygen and more rapid oxidation during air ingress must be assessed. Oxidation effects for irradiated composites and carbon insulation are unknown.	M	Data from fusion power program and commercial applications, but applicability needs to be assessed.

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
52	Maintain structure geometry	Core restraint failure/1–12	Composites structural design and fabrication methodology limitations for new structures (lack of experience)	H	Carbon–carbon composites are prime candidates, but need approved methods for designing, proof testing, model standard testing, validation tests, and probabilistic methods of design. Scalability and fabrication issues must be addressed. Large-scale (meters in diameter) structures as well as smaller ones must be covered.	L	Extensive experience within the aerospace industry; applicability must be assessed.
53	Maintain insulation capability	Fibrous insulation degradation/1–12	Environmental and radiation degradation and thermal stability at temperature	H	Relatively low dose and exposure is expected, but loss-of-forced circulation (LOFC) can result in temperatures high enough to challenge stability of fibrous insulation such as Kaowool. Need to assess effects on microstructural stability and thermophysical properties during irradiation and high temperature exposure in impure helium.	L	Limited commercial information available for conditions of interest.
			Reactor Cavity Cooling System (RCCS)				
54	Emergency heat removal capability	Inadequate heat removal/8,9	Aqueous corrosion and fouling	L	Potential concern of water ingress into RPV and failure of RCCS due to aqueous corrosion.	H	Extensive commercial and LWR experience in aqueous corrosion control

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
			Auxiliary shutdown system				
55	Primary system pressure boundary integrity	Water contamination of primary coolant/2	Fatigue, corrosion-fatigue, stress corrosion cracking, crack initiation and subcritical crack growth, high cycle fatigue.	L	Potential concern of water ingress into RPV and failure of RCCS due to aqueous corrosion.	H	Extensive commercial and LWR experience in aqueous corrosion control.
			Valves				
56	Primary system pressure boundary integrity	Malfunction, failure to operate and breach/1,2,5,9	Isolation valve failure	H	Isolation valve failure (includes categories such as self-welding, galling, seizing) is possible. Concerns about isolation valves are similar to 'breach to secondary' issues on IHX since they would provide barriers to secondary heat transport system.	L	Information possibly available from previously constructed HTGRs but relevance needs to be assessed. State of knowledge about helium-leak-tightness in large valves is unknown [15–17]
57	Primary system pressure boundary integrity	Failure to operate, breach/1–12	Valve failure	H	Concerns about a variety of valve failure mechanisms that will be design-dependent (includes categories such as self-welding, galling, seizing) will need to be assessed once design-specific details are available. Helium-tribology issues must be considered. Allowable identified and unidentified coolant leakage must be established.	L	Information available from previously constructed HTGRs but relevance needs to be assessed [15–17]

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
			Reactor Cavity Cooling System (RCCS)				
58	Emergency heat removal capability	Inadequate heat removal/8,9	Change in RCCS panel emissivity	M	This was the only phenomenon for which the panel was unable to reach consensus with regard to its importance. This was due to a difference of opinion as to whether or not this was a safety or an economic issue. Panel members who felt it was a safety issue ranked it high. Panel members who felt it was a simply an economic protection issue ranked it low. The ranking provided for this phenomenon only is an average, not a consensus. Panel member comments follow. Majumdar: to ensure passive safety, high emissivity is required to limit core temperatures (affect coolant pathway)—need for high emissivities on both surfaces of the core barrel, and formation and control of surface layers under helium environments. Corwin disagrees with the aforegoing rationale because the failure in the RCCS panel merely results in degradation of the concrete surrounding the RPV, not a significant reduction in heat removal from it. This is an economic issue,	H	There are a wide range of data for corrosion of steel in low temperature environments (e.g., <60°C) for long exposures, but less information on the effects this corrosion has on emissivity

Table 6 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
					not a safety one. Weaver comment: In recent conversations with the vendors, they have stated that the RCCS is considered a safety system. However, it is not clear whether the RCCS is necessary to maintain fuel temperatures below the limit during an accident.		

**Scenario number refers to Table 2.*

Table 7. Selected PIRT phenomena from Table 6 that have particular significance due to their high importance and low knowledge rankings

ID No.	FOM (evaluation criteria)	Pathways to release/ scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
			Reactor pressure vessel (RPV)				
1	RPV integrity	Breach/1–4	Thermal aging (long term)	H	Uncertainty in properties of 9 Cr–1 Mo steel (grade 91), especially degradation and aging of base metals and welds for a critical component like the RPV, must be addressed for 60-year lifetimes	M	It is assumed that Grade 91 is the prime candidate for NGNP and no back up material is considered in this report for designs without active cooling. This is beyond experience base for conditions of interest, extensive fossil energy experience and code usage; though significant aging data exist at high temperatures (>500°C). Need is for long-term aging data at NGNP-relevant temperatures [10, 15–17].
5	RPV integrity	Breach/1–7	Crack initiation and subcritical crack growth	H	9 Cr–1 Mo steel (grade 91) must be assessed for phenomena due to transients and operationally induced–thermal loading, pressure loading, residual stress, existing flaws (degradation of welds, cyclic loading, low cycle fatigue)	L	There is a limited database from fossil energy applications at these temperatures. Low cycle fatigue data in air, vacuum, and sodium (ANL unpublished data) at >482°C show life is longest in sodium, followed by vacuum and air. Aging in helium (depending on impurities) will most likely be greater than in air. Aging in impure helium may perhaps depend on impurity type and content [10, 15–17]

Table 7 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/ scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
11	FOM1: RPV integrity; FOM2: peak fuel temperature	Inadequate heat transfer/ 1–3	Compromise of emissivity due to loss of desired surface layer properties	H	To ensure passive safety, high emissivity of the RPV is required to limit core temperatures—must maintain high emissivities on both inside and outside surfaces. Formation and control of surface layers must be considered under both helium and air environments	L	There are limited studies on SS and on 508 that show potential for maintaining high emissivity
16	RPV integrity	Breach, excess deformation/ 1–9	Field fabrication process control	H	Fabrication issues must address field fabrication because of vessel size [including welding, post-weld heat treatment, section thickness (especially with 9 Cr–1 Mo steel) and preservice inspection]	L	Fossil energy experience indicates that caution needs to be taken. On-site nuclear vessel fabrication is unprecedented [10, 15–17]
17	RPV integrity	Breach, excess deformation/ 1–9	Property control in heavy sections	H	Heavy-section properties are difficult to obtain because of hardenability issues. Adequate large ingot metallurgy technology does not exist for 9 Cr–1 Mo steel. Maintaining fracture toughness, microstructural control, and mechanical properties in through-thickness of heavy sections, 9 Cr materials must be maintained	L	Very limited data, not much over 3 to 4 in. thickness. Few data available for specimens from 300-mm-thick forgings show thick section properties lower than thin section [10, 15–17]

Table 7 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/ scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
			Piping				
30	Peak fuel temperature	Insulation debris generation/ 1–7	Aging, fatigue, and environmental degradation of insulation.	H	Concern is about insulation debris plugging core cooling channels, causing damage due to chunks of internal insulation falling off (ceramic sleeves or carbon–carbon composites would be most likely source of problems)	L	Little system-relevant information about insulation failure mechanism is available [16–25]
			Intermediate heat exchanger (IHX)				
35	FOM1: integrity of IHX; FOM2: secondary loop failure/ breach	Breach to secondary system/1–9	Crack initiation and propagation (due to creep crack growth, creep, creep-fatigue, aging (with or without load), subcritical crack growth)	H	Environmental effects on subcritical crack growth—impacts of design issues, particularly for thin-section must be addressed. Stresses on IHX (both thin and thick sections) can lead to these failure phenomena; thermal transients can cause toughness concerns and carbide redistribution as a function of thermal stress can change through-thickness properties.	L	More is known about 617 from HTGR and industry usage than for 230. Both environment and creep play significant roles in initiation and cyclic crack growth rate of 617 and 230. Mechanistic models for predicting damage development and failure criteria for time-dependent phenomena have to be developed to enable conservative extrapolation from short-term laboratory test data to long-term design life [16–25]

Table 7 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/ scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
36	FOM1: integrity of IHX; FOM2: secondary loop failure/ breach	Breach to secondary system/1–9	Primary boundary design methodology limitations for new structures (lack of experience)	H	Time-dependent design criteria for complex structures need to be developed and verified by structural testing. ASME Code approved simplified methods have not been proven and are not permitted for compact IHX components	L	No experience for the complex shape IHX. No experience for designing and operating high-temperature components in the class 1 environment. Difficulties of design and analyses of compact IHX are discussed in the references [16–25].
37	FOM1: integrity of IHX; FOM2: secondary loop failure/ breach	Breach to secondary system/1–9	Manufacturing phenomena (such as joining)	H	CHX cores (if used) will require advanced machining, forming, and joining (e.g., diffusion bonding, brazing, etc.) methods that may impact component integrity. Must assess CHXs vs traditional tube and shell concepts. However, these phenomena are generic and extend beyond the CHXs to all the very high-temperature HXs.	L	CHXs have not been used in nuclear applications; the candidate alloys and their joining processes are not adequately established in nonnuclear applications [16–25]
38	FOM1: integrity of IHX; FOM2: secondary loop failure/ breach	Breach to secondary system/1–9	Inspection/testing phenomena	H	Traditional NDE methods will not work for CHXs because of geometrical constraints. Proof-testing of some kind will be required (maybe leak testing with tracer). Preservice testing will be difficult, and in-service testing will be even harder. Condition monitoring may be useful	L	Preoperational testing, preservice inspection, fitness for service, issue with leak tests, have very little knowledge here. What is the margin? [16–25]

Table 7 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/ scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
				Control rods (nonmetallic)			
43	Maintain insertion ability	Failure to insert/1–12	Composites structural design methodology limitations for new structures (lack of experience)	H	Carbon–carbon composites are prime candidates, but need approved method of designing, proof testing, model testing, testing standards, and validation tests	L	Some code work is being developed by ASME, ASTM and international partners. Extensive aerospace industry design and usage can be assessed for applicability. [19–25]
				RPV internals (metallic)			
46	Maintain heat transfer capability	Inadequate heat transfer/ 8,9	Change in emissivity	H	To ensure passive safety, high emissivity of the core barrel is required to limit core temperatures—need high emissivities on both inside and outside surfaces, and formation and control of surface layers in helium environments.	L	Limited studies on SS and on 508 show potential for maintaining high emissivity [12–17]
47	Maintain structure geometry	Excess deformation/ 1–9	Radiation-creep	H	Irradiation creep and dimensional changes particularly for alloy 800H at moderately low-dose should be assessed	L	Little information on irradiation creep is available for Alloy 800H [12–17]

Table 7 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/ scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
RPV internals (nonmetallic)							
52	Maintain structure geometry	Core restraint failure/1–12	Composites structural design and fabrication methodology limitations for new structures (lack of experience)	H	Carbon–carbon composites are prime candidates, but need approved methods of designing, proof testing, model standard testing, and validation tests. Scalability probabilistic methods of design and fabrication issues must be addressed. Large-scale (meters in diameter) structures, as well as smaller ones, must be covered.	L	Extensive experience within the aerospace industry; applicability must be assessed [19–25]
53	Maintain insulation capability	Fibrous insulation degradation/ 1–12	Environmental and radiation degradation and thermal stability at temperature	H	Relatively low dose and exposure is expected, but LOFC can result in temperatures high enough to challenge stability of fibrous insulation such as Kaowool. Need to assess effects on microstructural stability and thermophysical properties during irradiation and high temperature exposure in impure helium	L	Limited commercial information available for conditions of interest [19–25]

Table 7 (continued)

ID No.	FOM (evaluation criteria)	Pathways to release/ scenarios*	Phenomena	Phenomena importance	Rationale for rankings of phenomenon importance	Knowledge level	Rationale for rankings of knowledge
				Valves			
56	Primary system pressure boundary integrity	Malfunction, failure to operate and breach/1,2,5, 9	Isolation valve failure	H	Isolation valve failure (includes categories such as self-welding, galling, seizing) is possible. Concerns about isolation valves are similar to 'breach to secondary' issues on IHX because they would provide barriers to secondary heat transport system	L	Information possibly available from previously constructed HTGRs, but relevance needs to be assessed. State of knowledge about helium-leak-tightness in large valves is unknown [15–17]
57	Primary system pressure boundary integrity	Failure to operate, breach/1–12	Valve failure	H	Concerns about a variety of valve failure mechanisms that will be design-dependent (includes categories such as self-welding, galling, seizing) will need to be assessed once design-specific details are available. Helium-tribology issues must be considered. Allowable identified and unidentified coolant leakage must be established	L	Information available from previously constructed HTGRs but relevance needs to be assessed [15–17]

**Scenario number refers to Table 2.*

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