INL/RPT-23-72036
Revision 1

Review and Assessment of NGNP PIRTs for TRISO and HTGR Technologies

April 2023

Mark Holbrook
Technology Insights

Idaho National Laboratory

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http://www.art.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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INL ART Program

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INL/RPT-23-72036
Revision 1

May 2023

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ACRONYMS

ACRS	Advisory Committee on Reactor Safeguards
ACTH	Accident and Thermal Fluids
AGR	Advanced Gas Reactor
ANL	Argonne National Laboratory
ATWS	Anticipated Transient without SCRAM
BOP	balance of plant
CFP	coated fuel particles
CTE	coefficient of thermal expansion
DBA	design basis accident
D-LOFC	depressurized loss-of-forced circulation
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
FCP	factors, characteristics, and phenomena
FHR	Fluoride Salt-Cooled, High Temperature Reactor
FIMA	fissions per initial metal atom
FLiBe	$2LiF:BeF_2$ (molten fluoride salt mixture)
FP	fission products
FPT	fission product transport
HTGR	high-temperature gas reactor
HTR	igh-temperature reactors
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
IPyC	inner pyrolytic carbon
LBE	licensing basis event
LEU	low-enriched uranium
LOFC	loss-of-forced circulation
LWR	light-water reactor
MST	mechanistic source term
NGNP	Next Generation Nuclear Plant
NRC	U.S. Nuclear Regulatory Commission
NSTF	Natural Convection Shutdown Heat Removal Test Facility
OPyC	outer pyrolytic carbon
ORNL	Oak Ridge National Laboratory

PBR	Pebble-bed reactor
PDC	Principal Design Criteria
PHX	process heat exchanger
PIE	post-irradiation examination
PIRT	Phenomena Identification and Ranking Table
P-LOFC	pressurized loss-of-forced circulation
R&D	research and development
RCCS	Reactor Cavity Cooling System
RPV	reactor pressure vessel
RTDP	Regulatory Technology Development Plan
SER	Safety Evaluation Report
SiC	silicon carbide
SSC	Structures, systems, and components
TAVA	time-average volume-average
TR	topical report
TRISO	tristructural isotropic
UC_2	uranium dicarbide
UCO	uranium oxicarbide
UO_2	uranium dioxide
V&V	verification and validation
VHTR	very-high-temperature gas-cooled reactor

Review and Assessment of NGNP PIRTs for TRISO and HTGR Technologies

1. INTRODUCTION

In anticipation of future licensing applications for advanced reactor designs that utilize tristructural isotropic (TRISO)-coated particle fuel (CFP) (e.g., gas-cooled reactors, select molten-salt reactors with solid fuel, and select microreactors) the United States Nuclear Regulatory Commission (NRC) and the TRISO-design vendors need to fully understand the significant features of TRISO-coated particle fuel design, manufacture, and operation, as well as behavior during accidents.

1.1 Report Objective

The main objective of this technical report is to ensure that research and development (R&D) needs are identified to address the significant (highly ranked) technical challenges related to TRISO-coated particle fuel, high-temperature gas reactor (HTGR) technologies, and other TRISO-related advanced designs by recognizing the existing foundation of identified R&D needs and augmenting that foundation with insights drawn from current TRISO-related research results and R&D needs related to novel applications of TRISO-related technologies that extend beyond the traditional HTGR designs.

To support this objective and to establish a baseline, a review of the two foundational Phenomena Identification and Ranking Table (PIRT) reports (2004 and 2008) was conducted [1,2]. The PIRT methodology is a deterministic expert elicitation process that provides an expert assessment of safety-relevant TRISO phenomena and for assessing R&D needs that can be used to support the licensing of TRISO-based technologies. The review of these PIRTs focused on identification and summarization of those phenomena that were evaluated by the PIRT participants as having high importance to TRISO-coated particle fuel and HTGR structures, systems, and components (SSC) and where the associated currently available R&D knowledge levels were judged by expert panel members to be low or medium.

In addition to the two TRISO-related reports mentioned above, other recently available sources were evaluated and included in this report to reflect the current understanding of TRISO-related R&D needs. These additional document sources were reviewed to determine if there are new or different insights that would modify (or add to) the original TRISO-related R&D programs that grew out of the 2004 TRISO-Coated Particle Fuel PIRT and the 2008 Next Generation Nuclear Plant (NGNP) PIRT.

1.2 Scope

Areas considered outside the scope of this report include balance of plant (BOP) topics such as process heat applications and hydrogen production. In addition, due to limited resources, a detailed review of the current knowledge level status for each of the phenomena identified by the TRISO and NGNP PIRTs was not determined.

1.3 Report Organization

Section 1 includes introductory material and an overview of the report's structure. Section 2 provides a discussion of TRISO-coated particle fuel technology and a summary of the TRISO-Coated Particle Fuel PIRT Report and its conclusions. Included is a discussion of the Department of Energy's (DOE) Advanced Gas Reactor (AGR) program. Tables are included to provide access to a listing of important phenomena identified in the PIRT report. Section 3 includes an overview of HTGR technologies and the related NGNP PIRT. A discussion of similar HTGR designs is included. Like Section 2, tables are included that lists important phenomena identified in the NGNP PIRT report. [2] Section 4 provides a summary of this report's conclusions, Section 5 includes a list of references. Appendix A provides a table of all TRISO PIRT high-importance phenomena with low or medium-knowledge levels, organized by phenomenon. Appendix B provides a table of all NGNP PIRT high-importance phenomena with low or medium-knowledge levels, organized by phenomenon.

2. TRISO-COATED PARTICLE FUEL TECHNOLOGIES

2.1 TRISO-Coated Particle Fuel Experience

The research, development, and application of TRISO-coated particle fuel has a long history that is well documented. The fuel form has evolved over the last six decades to become a design that can be manufactured with very high-quality and excellent performance at extremely high temperatures. The fuel was primarily intended for use in HTGRs, which have graphite cores and are cooled by pressurized helium with coolant outlet temperatures in the range from 700 to 950°C. However, the fuel is also considered for other reactor designs, such as the fluoride salt-cooled high-temperature reactor (FHR) [3]. It should be noted that the evolution of TRISO particle fuel includes changes in particle materials and structural configuration.

2.2 Particle Fuel Designs

As documented in a recent journal article [4], coated particle fuel has a long development history that is represented by an expansive publication record in scientific literature. As the fuel form evolved and the experience base broadened, modifications to the particle design were implemented that addressed specific shortcomings and improved overall fuel performance.

Given the relative technical maturity of TRISO-coated particle fuel, several excellent reviews have been published in the new millennium, covering all areas of the technology including the evolution of the fuel form, fabrication methods and quality control, irradiation performance, high-temperature accident testing, particle failure mechanisms, and computational modeling of fuel performance (as cited in [4]).

In addition, numerous publications are available that focus on specific past fuel development efforts. These include many references summarizing the history and successes of the extensive German program in the 1980s and early 1990s to develop and test the performance of LEU UO2 TRISO fuel (as cited in [4]), which has been influential on many subsequent endeavors across the globe.

2.3 AGR Program

2.3.1 Test Program Origin

"The U.S. DOE Advanced Gas Reactor (AGR) Fuel Development and Qualification program was initiated in 2002 [4]. The objective is to generate fuel qualification data to support licensing of an HTGR through fabrication, irradiation, post-irradiation examination, and accident safety testing of high-quality, TRISO-coated fuel. While both UO_2 and UCO fuel have been fabricated and irradiated, the program has focused primarily on UCO fuel to take advantage of performance benefits at high operating temperatures and burnups as high as 20% FIMA. Four irradiation experiments have been initiated in the program. Three of these (AGR-1, AGR-2, and AGR-5/6/7) involved intact TRISO fuel particles in cylindrical fuel compacts to assess fuel performance. The fourth (AGR-3/4) was an irradiation dedicated to evaluating fission-product transport in fuel matrix and core graphite materials, involved both intact driver fuel and a 1% fraction of designed-to-fail fuel (as cited in [4]), and has been discussed recently by Collin et al. (as cited in [4])."

2.3.2 Test Program Goals

The goals for the AGR Program were identified as follows [5]:

- Provide a fuel qualification data set in support of the licensing and operation of an HTGR. HTGR fuel performance demonstration and qualification comprise the longest duration R&D tasks required for design and licensing. The fuel form is to be demonstrated and qualified for service conditions, which include normal operation and potential accident scenarios.
- Support deployment of HTGRs for hydrogen, process heat, and energy production in the U.S. by reducing market entry risks posed by technical uncertainties associated with fuel production and qualification.
- Extend the value of DOE Office of Nuclear Energy resources by using international collaboration mechanisms where practical.
- Establish a domestic TRISO particle fuel manufacturing capability for fabricating demonstration and qualification experiment fuel.
- Improve understanding of the fabrication process, its impact on as-fabricated fuel properties and attributes, and their impacts on in-reactor performance.

Additional details are available that describe the AGR Program elements and the related irradiation experiments used to evaluate TRISO-coated particle fuel performance (see [5], pages 5–4 to 5–6).

Technical direction for the AGR Program benefited from a collaboration between the U.S. NRC and the DOE that resulted in identification of TRISO-related phenomena (i.e., PIRT activities) that needed new or additional R&D focus to support future licensing activities. These PIRT activities that provided direction for the AGR Program will be discussed next by this report.

2.3.3 TRISO-Coated Particle Fuel PIRT Report

2.3.3.1 TRISO Particle Fuel PIRT Report Objectives

The TRISO-Coated Particle Fuel PIRT Report identified that the following objectives guided the execution of the TRISO PIRT activities [1].

"The objectives of the PIRT program on TRISO-coated particle fuel are to (1) identify key attributes of gas-cooled reactor fuel manufacture which may require regulatory oversight, (2) provide a valuable reference for the review of vendor gas-cooled reactor fuel qualification plans, (3) provide insights for developing plans for fuel safety margin testing, (4) assist in defining test data needs for the development of fuel performance and fission-product transport models, (5) inform decisions regarding the development of NRC's independent gas-cooled reactor fuel performance code and fission-product transport models, (6) support the development of NRC's independent models for source term calculations, and (7) provide insights for the review of vendor gas-cooled fuel safety analyses."

To support these objectives for HTGRs, the NRC commissioned a panel to identify and rank the factors, characteristics, and phenomena (FCP) associated with TRISO-coated particle fuel to obtain a better understanding of the significant features of TRISO-coated particle fuel design, manufacture, and behavior during both normal reactor operation and accidents. PIRTs were developed for (1) manufacturing, (2) operations, (3) a depressurized heat-up accident, (4) a reactivity accident, (5) a depressurization accident with water ingress, and (6) a depressurization accident with air ingress.

2.3.3.2 TRISO-Coated Particle Fuel PIRT Report Summary

As noted on Page 5-1 of the "TRISO-Coated Particle Fuel PIRT Report" [1], the PIRT analysis and summary information presented is based on the detailed inputs submitted by the TRISO-coated particle fuel PIRT panel members as found in Appendices A–F of the subject report. In addition, Section 4 of the subject report includes Tables 4-1 through 4-6 that were used to combine and summarize the panel's detailed inputs. General observations from Section 5 (pages 5-1 and 5-2) of the PIRT report and the author's evaluation of Tables 4-1 through 4-6 are included below.

It should be emphasized that all the FCP discussed in this technical report are phenomena that were judged by a majority (or in many cases, a consensus) of the panel to be of high importance. FCP with medium or low importance are not included in this analysis. Therefore, the main discriminator between the FCP are the related knowledge levels associated with the phenomena (i.e., low, medium[a] [or "mid-range"], and high). In many cases, the panel had different evaluation results related to the specific knowledge levels. For example, if a majority of the panel members assigned the knowledge level for a particular phenomenon as medium or less, it is designated in this report as "low or medium." If a majority of the panel agreed on a single knowledge level designation, then that is identified in the tables (e.g., "low" or "medium"). FCP that were evaluated as having high-knowledge levels are not included in any of the discussions or tables in this report.

For each of the seven plant conditions assessed by the TRISO PIRT, a summary table is provided that coalesces the analyses found in Sections 4 and 5 of the PIRT Report. These summary tables focus on the FCP, which were of high importance, and evaluated to have a low or medium level of research data and/or analyses (i.e., "knowledge level") available at the time of the report's publication. For an FCP to be identified in a table, a consensus or a majority (two out of three) of the PIRT panel members had to agree that (1) the FCP was of high importance, and (2) the FCP had a related low- or medium-knowledge level.

---

[a] Note that the TRISO-coated particle fuel PIRT report's use of "mid-range" has been changed to "medium" in this report to provide consistency with the terminology used by the NGNP PIRT discussed in the next section of this report.

1. Manufacturing
   - The knowledge levels related to the following FCP were judged to be low or medium:
     - Bonding strength (inner PyC [IPyC] to SiC)
   - The SiC layer and Other were evaluated as being potentially impacted by the largest number of FCP (3) (see Table 1).
   - Anisotropy (initial) was the FCP that impacted the largest number of particle fuel elements (2) (see Table 1).

Table 1. High-importance manufacturing phenomena.

Plant Condition	TRISO Particle Element	Factor, Characteristic or Phenomenon (With High Importance)	Knowledge Level
Manufacturing[b]	Inner PyC Layer	Anisotropy (initial)	Medium
		Bonding strength (inner Pyke to SiC)	Low or Medium
	SiC Layer	Fracture strength	Medium
		Stoichiometry	Medium
		Defects	Medium
	Outer PyC Layer (OPyC)	Anisotropy (initial)	Medium
	Other	Layer coating process specifications - coater size	Medium
		Layer coating process	Medium
		Process control	Medium

2. Operations
   - The knowledge levels related to the following FCP were judged to be low or medium:
     - Temperature gradient
     - Cracking
     - Anisotropy
     - Condensed-phase diffusion.
   - The inner PyC layer was evaluated as being potentially impacted by the largest number of FCP (6) (see Table 2).
   - Condensed-phase diffusion was the FCP that impacted the largest number of particle fuel elements (4) (see Table 2).

[b] Note that only two of the three panel members provided FCP importance and knowledge level ranking for the manufacturing plant condition.

Table 2. High-importance operations phenomena.

Plant Condition	TRISO Particle Element	Factor, Characteristic or Phenomenon (With High Importance)	Knowledge Level
Operations	Kernel	Fission-product chemical form	Medium
		Temperature gradient	Low or Medium
	Buffer Layer	Pressure	Medium
		Temperature gradient	Low or Medium
		Cracking	Low or Medium
	Inner PyC Layer	Anisotropy	Low or Medium
		Dimensional change	Medium
		Fast fluence	Medium
		Radiation-induced creep	Medium
		Condensed-phase diffusion	Low or Medium
		Cracking	Low or Medium
	SiC Layer	Fission-product corrosion	Medium
		Condensed-phase diffusion	Low or Medium
		Cracking	Low or Medium
	Outer PyC Layer	Condensed-phase diffusion	Low or Medium
	Fuel Element	Condensed-phase diffusion	Medium

3. Depressurized Heat-up Accident (fuel temp. $\leq$1600°C)
   - The knowledge levels related to the following FCP were judged to be low or medium:
     - Condensed-phase diffusion
     - Buffer carbon-kernel interaction
     - Gas-phase diffusion
     - Layer oxidation
     - Cracking
     - Fission-product release through undetected defects
     - Fission-product release through failures (e.g., cracking)
     - Transport of metallic fission products through fuel element—chemical form
     - Irradiation history.
   - The fuel kernel was evaluated as being potentially impacted by the largest number of FCP (4) (see Table 3).
   - Gas-phase diffusion was the FCP that impacted the largest number of particle fuel elements (3) (see Table 3).

Table 3. High-importance depressurized heat-up accident (fuel temp. ≤1600°C) phenomena.

Plant Condition	TRISO Particle Element	Factor, Characteristic or Phenomenon (With High Importance)	Knowledge Level
Depressurized Heat-up Accident Fuel Temp. ≤1600°C	Kernel	Condensed-phase diffusion	Low or Medium
		Buffer carbon-kernel interaction	Low or Medium
		Thermodynamic state of fission products	Medium
		Gas-phase diffusion	Low or Medium
	Buffer Layer	Layer Oxidation	Low or Medium
	Inner PyC Layer	Cracking	Low or Medium
		Gas-phase diffusion	Medium
	SiC Layer	Fission-product release through undetected defects	Low or Medium
		Fission-product release through failures e.g., cracking	Low or Medium
	Outer PyC Layer	Cracking	Low or Medium
	Fuel Element	Transport of metallic FPs through fuel element – Chemical form	Low or Medium
		Irradiation history	Low or Medium
		Gas-phase diffusion	Medium

4. Depressurized Heat-up Accident (fuel temp. >1600°C)
   - The knowledge levels related to the following FCP were judged to be low or medium:
     - Condensed-phase diffusion
     - Buffer carbon-kernel interaction
     - Gas-phase diffusion
     - Layer oxidation
     - Cracking
     - Fission-product corrosion
     - Fission-product release through undetected defects
     - Thermal deterioration/decomposition
     - Fission-product release through failures (e.g., cracking)
     - Transport of metallic fission products through fuel element—chemical form
     - Irradiation history.
   - The SiC layer was evaluated as being potentially impacted by the largest number of FCP (6) (see Table 4).
   - Gas-phase diffusion was the FCP that impacted the largest number of particle fuel elements (3) (see Table 4).

Table 4. High-importance depressurized heat-up accident (fuel temp. >1600°C) phenomena.

Plant Condition	TRISO Particle Element	Factor, Characteristic or Phenomenon (With High Importance)	Knowledge Level
Depressurized Heat-up Accident Fuel Temp. > 1600°C	Kernel	Condensed-phase diffusion	Low or Medium
		Buffer carbon-kernel interaction	Low or Medium
		Thermodynamic state of fission products	Medium
		Gas-phase diffusion	Low or Medium
	Buffer Layer	Layer Oxidation	Low or Medium
	Inner PyC Layer	Cracking	Low or Medium
		Gas-phase diffusion	Medium
	SiC Layer	Fission-product corrosion	Low or Medium
		Condensed-phase diffusion	Low or Medium
		Fission-product release through undetected defects	Low or Medium
		Thermal deterioration/decomposition	Low or Medium
		Thermodynamics of the SiC-fission-product system	Medium
		Fission-product release through failures e.g., cracking	Low or Medium
	Outer PyC Layer	Cracking	Low or Medium
	Fuel Element	Transport of metallic FPs through fuel element – Chemical form	Low or Medium
		Irradiation history	Low or Medium
		Gas-phase diffusion	Medium

5. Reactivity Accident
   - The knowledge levels related to the following FCP were judged to be low or medium:
     - Maximum fuel gaseous fission-product uptake
     - Response to kernel swelling
     - Gas-phase diffusion
     - Pressure loading (carbon monoxide)
     - Fission-product release through failures (e.g., cracking)
     - Condensed-phase diffusion.
   - The kernel, buffer layer, and inner PyC layer were evaluated as being potentially impacted by the largest number of FCP (3) (see Table 5).
   - Gas-phase diffusion was the FCP that impacted the largest number of particle fuel elements (4) (see Table 5).

Table 5. High-importance reactivity accident phenomena.

Plant Condition	TRISO Particle Element	Factor, Characteristic or Phenomenon (With High Importance)	Knowledge Level
Reactivity Accident	Kernel	Condensed-phase diffusion	Medium
		Gas-phase diffusion	Medium
		Energy transport: conduction within the kernel	Medium
	Buffer Layer	Gas-phase diffusion	Medium
		Maximum fuel gaseous fission-product uptake	Low or Medium
		Response to kernel swelling	Low or Medium
	Inner PyC Layer	Gas-phase diffusion	Low or Medium
		Pressure loading (Fission products)	Medium
		Pressure loading (Carbon monoxide)	Low or Medium
	SiC Layer	Fission-product release through failures e.g., cracking	Low or Medium
	Fuel Element	Condensed-phase diffusion	Low or Medium
		Gas-phase diffusion	Low or Medium

6. Depressurization Accident with Water Ingress
   - The knowledge levels related to the following FCP were judged to be low or medium:
     - Buffer carbon-kernel interaction
     - Layer oxidation
     - Chemical attack by water – changes in chemical form of fission products
     - Cracking
     - Gas-phase diffusion
     - Chemical attack by water – kinetics
     - Chemical attack by water – temperature distributions
     - Condensed-phase diffusion
     - Chemical attack by water – changes in graphite properties.
   - The inner PyC layer, SiC layer, and fuel element were evaluated as being potentially impacted by the largest number of FCP (6) (see Table 6).
   - Chemical attack by water – changes in chemical form of fission products, chemical attack by water – kinetics, and chemical attack by water – temperature distributions were the FCP that impacted the largest number of particle fuel elements (5) (see Table 6).

Table 6. High-importance depressurization accident with water ingress phenomena.

Plant Condition	TRISO Particle Element	Factor, Characteristic or Phenomenon (With High Importance)	Knowledge Level
Depressurization Accident with Water Ingress	Kernel	Buffer carbon-kernel interaction	Low or Medium
		Thermodynamic state of fission products	Medium
	Buffer	Layer oxidation	Low or Medium
		Chemical attack by water – Changes in chemical form of fission products	Low or Medium
	Inner PyC Layer	Layer oxidation	Low
		Cracking	Low or Medium
		Gas-phase diffusion	Low or Medium
		Chemical attack by water – Kinetics	Low or Medium
		Chemical attack by water – Changes in chemical form of fission products	Medium
		Chemical attack by water – Temperature distributions	Low or Medium
	SiC Layer	Condensed-phase diffusion	Low or Medium
		Fission-product release through failures e.g., cracking	Medium
		Gas-phase diffusion	Medium
		Chemical attack by water – Kinetics	Low or Medium
		Chemical attack by water – Changes in chemical form of fission products	Medium
		Chemical attack by water – Temperature distributions	Medium
	Outer PyC Layer	Layer oxidation	Low or Medium
		Cracking	Low or Medium
		Chemical attack by water – Kinetics	Low or Medium
		Chemical attack by water – Changes in chemical form of fission products	Medium
		Chemical attack by water – Temperature distributions	Low or Medium
	Fuel Element	Condensed-phase diffusion	Low or Medium
		Transport of metallic FPs through fuel element – Chemical form	Medium
		Chemical attack by water – Kinetics	Medium
		Chemical attack by water – Changes in chemical form of fission products	Medium
		Chemical attack by water – Changes in graphite properties	Low or Medium
		Chemical attack by water – Temperature distributions	Medium

7. Depressurization Accident with Air Ingress

- The knowledge levels related to the following FCP were judged to be low or medium:
  - Buffer carbon-kernel interaction
  - Chemical attack by air – kinetics
  - Layer oxidation
  - Cracking
  - Chemical attack by air – temperature distributions
  - Condensed-phase diffusion
  - Chemical attack by air – graphite properties.
- The fuel element was evaluated as being potentially impacted by the largest number of FCP (8) (see Table 7).
- Chemical attack by air—changes in chemical form of fission products was the FCP that impacted the largest number of particle fuel elements (6) (see Table 7).

Table 7. High-importance depressurization accident with air ingress phenomena.

Plant Condition	TRISO Particle Element	Factor, Characteristic or Phenomenon (With High Importance)	Knowledge Level
Depressurization Accident with Air Ingress	Kernel	Buffer carbon-kernel interaction	Low or Medium
		Thermodynamic state of fission products	Medium
		Chemical attack by air – Kinetics	Low or Medium
		Chemical attack by air – Changes in chemical form of fission products	Medium
	Buffer Layer	Layer oxidation	Low or Medium
		Chemical attack by air – Changes in chemical form of fission products	Medium
		Chemical attack by air – Temperature distributions	Medium
	Inner PyC Layer	Layer oxidation	Low
		Cracking	Low or Medium
		Gas-phase diffusion	Medium
		Chemical attack by air – Kinetics	Medium
		Chemical attack by air – Changes in chemical form of fission products	Medium
		Chemical attack by air – Temperature distributions	Low or Medium
	SiC Layer	Condensed-phase diffusion	Low or Medium
		Layer oxidation	Medium
		Fission-product release through failures (e.g., cracking)	Medium
		Gas-phase diffusion	Medium
		Chemical attack by air—Kinetics	Medium
		Chemical attack by air—Changes in chemical form of fission products	Medium
		Chemical attack by air—Temperature distributions	Medium

Plant Condition	TRISO Particle Element	Factor, Characteristic or Phenomenon (With High Importance)	Knowledge Level
	Outer PyC Layer	Condensed-phase diffusion	Low or Medium
		Layer oxidation	Low or Medium
		Cracking	Low or Medium
		Gas-phase diffusion	Medium
		Chemical attack by air—Kinetics	Low or Medium
		Chemical attack by air—Changes in chemical form of fission products	Medium
		Chemical attack by air—Temperature distributions	Low or Medium
	Fuel Element	Condensed-phase diffusion	Low or Medium
		Transport of metallic FPs through fuel element – Chemical form	Medium
		Gas-phase diffusion	Medium
		Chemical attack by air—Kinetics	Medium
		Chemical attack by air—Catalysis	Medium
		Chemical attack by air—Changes in chemical form of fission products	Medium
		Chemical attack by air—Changes in graphite properties	Low or Medium
		Chemical attack by air—Temperature distributions	Medium

2.3.4 AGR Research Program

2.3.4.1 Program Description

Through several decades of development, testing, and improvements, fuel particle coatings have matured into what is in practice an international consensus design, with two types of kernels (UO_2, UCO) pursued in current development programs. Fabrication and quality control methods have been demonstrated that are capable of producing fuel with low manufactured defect fractions and low-residual contamination [4].

The AGR Program to date has focused on manufacturing and testing the fuel design for HTR concepts using the most recent gas turbine modular helium reactor fuel product specification as a starting point. Irradiation, safety testing, and post-irradiation examination (PIE) plans support fuel development and qualification in an integrated manner (see [5], page 1-1].

High-quality fuel exhibits very low particle failure rates during irradiation, with failure fractions approximately 10-5 (upper bound at 95% confidence) demonstrated for UO_2 fuel up to ~11% FIMA and UCO fuel up to ~20% FIMA. This performance translates into low fission-product release from the fuel under normal conditions and is a major factor controlling the radiological source term released from the reactor.

See Section 4.1 of the Electric Power Research Institute (EPRI) UCO TRISO Topical Report (TR) [5] for additional information regarding the five major program elements and Section 4.2 for details regarding the AGR Program Irradiations.

2.3.4.2 EPRI TRISO Topical Report Conclusions with NRC Evaluations

The following conclusions are indicative of the outcomes that have been produced by the AGR Program to date (see [5], pages 8-1 to 8-2). Feedback from the NRC staff regarding these conclusions [6] has also been included along with conditions and limitations that would apply to application of the data in future advanced reactor license applications.

Conclusion 1. Testing of UCO TRISO-coated fuel particles in AGR-1 and AGR-2 constitutes a performance demonstration of these particle designs over a range of normal operating and off-normal accident conditions. Therefore, the testing provides a foundational basis for use of these particle designs in the fuel elements of TRISO-fueled HTR designs (that is, designs with pebble or prismatic fuel and helium or salt coolant).

NRC Evaluation. "The associated discussion…provides the performance ranges of the subject particles in terms of burnup, time-averaged temperatures, fast neutron fluence, and power density. Coupled with the time-averaged particle power – important because it accounts for differences in compacts and thus focuses on the particles themselves – discussed in Section 6 of the TR, staff agrees this set of performance parameters adequately captures the envelope of the AGR-1 and AGR-2 test conditions… Subject to the conditions laid out in the limitations and conditions discussed in this evaluation, staff finds Conclusion 1 to be applicable and acceptable."

Conclusion 2: The kernels and coatings of the UCO TRISO-coated fuel particles tested in AGR-1 and AGR-2 exhibited property variations and were fabricated under different conditions and at different scales, with remarkably similar excellent irradiation and accident safety performance results. The ranges of those variations in key characteristics of the kernels and coatings are reflected in measured particle layer properties provided in Table 5-5 from AGR-1 and AGR-2. UCO TRISO-coated fuel particles that satisfy the parameter envelope defined by these measured particle layer properties in Table 5-5 can be relied on to provide satisfactory performance.

NRC Evaluation: "…the applicant provided a clear basis for use of the values in Table 5-5, and the values in Table 5-5 are not representative of an exclusive set of parameters for acceptable TRISO performance. However, the values in Table 5-5 serve to tie the empirical data discussed in this TR to the tested AGR-1 and AGR-2 particles, and so the staff finds the scope of Conclusion 2 acceptable. Subject to the limitations and conditions discussed in this evaluation, staff finds Conclusion 2 to be applicable and acceptable."

Conclusion 3. Aggregate AGR-1 and AGR-2 fission-product release data and fuel failure fractions… can be used for licensing of reactors, employing UCO TRISO-coated fuel particles that satisfy the parameter envelope defined by measured particle layer properties in Table 5-5 from AGR-1 and AGR-2.

NRC Evaluation. The supporting discussion notes this conclusion is limited to the isotopes discussed in Section 6.7, 6.8, 7.1 and 7.3 of the TR—that is, short-lived fission gases and longer-lived isotopes (Cs, Eu, Sr, Ag, Kr) discussed in greater detail in Section 7 of the TR. Based on the provided data, 95% confidence interval failure fractions for the irradiation testing are provided, and staff finds these values can be used by applicants referencing this TR. Relative values for radionuclide releases are confined to intact particles, and demonstration of any retention within the fuel form outside the particle is the responsibility of the applicant or licensee referencing this TR, as stated in Limitation 1 of this evaluation.

As discussed in the above evaluation, safety testing data post-irradiation should only be used considering the context of the specific design and the applicability of the data to the expected fuel conditions. The data itself is valid, but transient and accident conditions may or may not match the conditions experienced by the tested AGR particles. Thus, justifying the applicability of the safety testing data is an exercise left to an applicant or licensee referencing this TR.

2.3.4.3 NRC Limitations and Conditions for Use of EPRI TRISO TR Conclusions

Limitation 1. The scope of this TR applies only to the UCO TRISO particles themselves. How the final fuel form is qualified and any impacts of the fuel form or other influences of the specific reactor design beyond the fuel form on the holistic fuel performance (for instance, any uranium contamination in the compact material) is the responsibility of the vendor or designer referencing this TR.

Limitation 2. This TR applies only to UCO TRISO particles that fall within the ranges discussed in Section 5.3 of the TR. If an applicant chooses to use UO_2/UC_2 ratios or burnup values that differ meaningfully from those used in the AGR Program, the applicant must provide a justification for how the burnup and carbon content ratios conform to the performance ranges discussed in Section 5.3 of the TR.

Condition 1. An applicant or licensee referencing this TR must evaluate any discrepancies between their fuel particles and the TRISO particles used in the AGR Program—specifically, reviewing the ranges specified in Table 5-6 for stress values to capture any effects from different kernel sizes to ensure the data in the TR remain applicable.

Condition 2. The performance limits in Table 6-6 and Figure 6-30 of the TR are the result of different tests with distinct samples, not all of which had the maximum bounds occur during the same test. The test results include considerations for uncertainty discussed in Sections 6.4 and 6.5 of the TR. Further, when failures may occur, the data supporting the TR provides empirical evidence of failure based on aggregate test conditions rather than evidence of individual particle failure. Applicants referencing this TR must ensure they either remain within the tested bounds or justify how their proposed operating conditions remain applicable, considering uncertainty in both the AGR test results as described in the TR and any analytical uncertainty resulting from the proposed analytical method.

Condition 3. Data discussed in this TR does not consider the impacts of short-lived fission products beyond those captured in the gas-phase during experiments. Any applicant or licensee referencing this TR must disposition the impacts, if any, of short-lived fission products on the safety analyses and operational dose considerations, or any other regulatory considerations resulting from short-lived fission products, in addition to the data discussed in the TR.

2.3.4.4 ACRS Feedback on the NRC Staff's SER on EPRI's TRISO Topical Report

In July 2020 timeframe, the Advisory Committee on Reactor Safeguards (ACRS) conducted a review of the NRC staff's Safety Evaluation Report (SER), Revision 2, EPRI topical report "Uranium Oxycarbide (UCO) TRISO-Coated Particle Fuel Performance." [6] This review included discussions with the NRC staff, EPRI, and with national laboratory personnel. The conclusions and recommendations from the review were provided to the NRC's Executive Director for Operations by letter on August 4, 2020 [7]. The summary from this letter includes the following:

- The EPRI topical report [5] provides a valuable starting point and database for future coated particle fuel designs. However, incorporating coated particles that meet the specifications in the topical report into an overall fuel design should be done with caution to avoid introducing degradation phenomena not accounted for in the irradiation program.
- The transition from coated particle to overall fuel system will likely require additional coated particle and fuel system irradiation programs to validate the overall design.

The key take-away from the ACRS's summary is that additional irradiation testing (beyond the AGR Program test results) may be needed to validate the fission-product release performance of the integrated TRISO-coated particle fuel, especially if some element of the fuel design deviates in a significant way from that tested by the AGR Program.

2.3.4.5 AGR Program Insights and Future Activities

The data from the AGR-1 and AGR-2 experiments demonstrate some broad trends in fission-product release behavior of this fuel form. The particles retain fission gas exceptionally well when any of the dense coating layers remain intact and retain cesium nearly completely when the SiC layer remains intact. Hence, the release of these fission products is dependent primarily on coating failure rates, which are very low. Europium and strontium are released in modest amounts from intact TRISO particles; the total release fraction from fuel compacts under normal HTGR operating temperatures is less than ~5 × 10-4. As observed over decades of TRISO fuel irradiation experience, silver transports readily out of intact TRISO particles at temperatures above 1,000–1,100°C. Silver behavior in individual coated particles in these two radiation experiments depended primarily on fuel temperature and ranged from nearly complete retention to nearly complete release [8].

A few other examples of new phenomena or phenomena that have been observed in greater detail than before would be:

SiC Failures. The 2004 TRISO-coated particle fuel PIRT identified several phenomena that could lead to failure of the SiC layer. As noted in Section 7 of the TR, "SiC failure is defined as loss of integrity of the SiC layer with at least one pyrocarbon layer remaining intact, such that fission gases will be retained but fission products such as cesium may be released in significant quantities. TRISO failure is defined as loss of integrity of all three dense coating layers, such that fission gases will be released from the particle. This is also often referred to as an exposed kernel." (see [5], page 7-1)

X-ray imaging of particles suspected to have SiC failures led to identification of the mechanism that was evident in each case: buffer shrinkage contributed to IPyC fracture due to incomplete debonding at the buffer-IPyC interface. The IPyC fracture then exposed the SiC layer to concentrated chemical attack of fission products (notably Pd), which caused degradation through the entire layer. It is noteworthy that significant attack of the SiC layer was never observed in particles without this sort of IPyC fracture, nor in these three particles in areas away from the IPyC fracture. While these failures were ultimately caused by Pd attack on SiC, prior fracture of the IPyC layer appears to be a prerequisite for the attack to occur (see [5], page 7-20).

The TRISO PIRT included buffer shrinkage as a phenomenon to evaluate, but it was determined to be of low or medium importance with medium to high levels of related knowledge. One panelist noted that (for normal operations) "no serious problems surround the buffer layer" (see [1], page B-70). The possibility of incomplete debonding at the buffer-IPyC interface and its potential effect on the IPyC and SiC layers was not discussed. Identifying SiC failure is one of the AGR Program's focus areas, but the AGR Program's sophisticated PIE techniques now allow for the quantification of SiC failures separate from TRISO failures. This has led to the development of particle fuel failure data that was not considered by the 2004 TRISO PIRT.

Buffer Failures: While all the coating layers appeared intact for most particles in the plane examined, fracture of the buffer layer was not uncommon in the AGR-1 and AGR-2 particles. The percentage of particles with observable buffer fracture was relatively consistent among six AGR- 1 compacts examined in cross section, varying 13–35% with an average of 23% [5]. The extent of buffer fracture exhibited much greater variation in AGR-2 UCO compacts (compact-average values from 0 to 86% based on examination of particles from seven UCO compacts), and this appeared to be influenced to some degree by irradiation temperature. Comparing compacts irradiated to a calculated fast fluence of 3×10^{25} n/m^2 $\pm$ 0.12×10^{25}, those irradiated at time-average volume-average (TAVA) temperatures of approximately 1100°C exhibited an observed buffer failure fraction of 86%, while those irradiated at TAVA temperatures >1200°C exhibited buffer failure fractions of 1–2%. This is believed to be due to greater magnitude of thermal creep occurring at the higher temperatures, which relaxes stresses developed due to buffer densification and shrinkage. Given the relatively high rates of buffer fracture observed in many of the UCO compacts along with the very low SiC and TRISO-coating failure fractions, it is clear that buffer fracture does not represent a significant threat to particle integrity (see [5], pages 7-7 and 7-8].

Eu and Sr Releases. Eu and Sr exhibited modest release through intact coatings, although significant retention was observed in the fuel matrix. Inventory in the compact matrix could be as high as ~10^{-2} (^{154}Eu) and 3×10^{-3} (^{90}Sr) for fuel irradiated at normal operating temperatures, but fractional release from fuel compacts was $\leq 4.6 \times 10^{-4}$ (^{154}Eu) and $\leq 8.2 \times 10^{-5}$ (^{90}Sr). At higher irradiation temperatures (up to a time-average maximum of 1360°C), Eu and Sr release from compacts is notably higher (approximately 4×10^{-3} for ^{154}Eu and 10^{-3} for ^{90}Sr). Releases of Ag, Sr, and Eu at 1600 and 1700°C are attributed to diffusion of these fission products into the fuel matrix during irradiation and subsequent release from the matrix upon high-temperature heating (see [5], Page 8-3).

Data on fission-product migration during the irradiation [of AGR-3/4] will allow researchers to refine the fundamental parameters (including diffusivities) that govern the transport of these elements through the graphitic matrix and reactor core materials. This vital data will support development of fission-product transport models used to predict the radiological source terms during reactor operation and accidents [8]. Currently, PIE of AGR-3/4 is nearing completion and results are expected to be available by the end of 2023. In addition, irradiation of AGR-5/6/7 is currently in progress, which will be followed by PIE and safety testing.

A critical part of the work—and a component of the fuel qualification program that has not been addressed in previous experiment campaigns—is the evaluation of fuel performance at high temperatures in oxidizing environments. Work is currently underway to develop a capability for heating irradiated fuel specimens in the presence of various concentrations of oxygen or moisture while measuring the release of gaseous and condensable fission products [12]. These tests are crucially important for assessing the behavior of the fuel in conditions that could exist in a high-temperature reactor during inadvertent ingress of oxidants (steam or air) into the core [8]. Moisture-ingress testing is anticipated to commence in the 2024 timeframe.

3. NEXT GENERATION NUCLEAR PLANT (NGNP)

The NGNP reactor design features are based on the modular HTGR concept for Generation IV reactors. The modular HTGR is designed to meet fundamental safety objectives and requirements, as well as design requirements. The typical HTGR design features include the following [2]:

- High-performance coated fuel particles with the capability of containing radioactive fission products for the full range of operating and postulated accident conditions, with a very low fuel failure fraction and subsequent release of fission products. The coated fuel particles are embedded in either a rod compact inserted into a stacked prismatic block or a spherical compact that constitutes a pebble.
- An inert single-phase high-pressure coolant (helium).

- A graphite-moderated core with the characteristics of low-power density, large heat capacity, high effective core thermal conductivity, and large thermal margins to fuel failure.
- Negative fuel and moderator temperature coefficients of reactivity sufficient to shut down, in conjunction with the negative reactivity feedback of the fission-product xenon-135, the reactor in loss-of-forced circulation (LOFC) events. This aspect provides for stabilizing power-control feedback, for most reactivity insertion events (for both start-up and power operation) for the entire fuel life cycle and for all applicable temperature ranges.
- A design basis accident decay heat removal system, typically a passive system utilizing natural convection-driven processes (the Reactor Cavity Cooling System [RCCS]).
- A confinement-style reactor building structure (accommodates depressurizations dynamically and may be used instead of a leak tight sealed containment). The NGNP core design will be either prismatic or pebble-bed. The BOP will consist of an electrical power generation unit (most likely a gas turbine) and a high-temperature process heat component for production of hydrogen. The design power level will be between 400 and 600 MW(t), with approximately 10% of the total thermal power production applied to the hydrogen plant. Coupling of the reactor to the hydrogen plant will be via an intermediate heat exchanger (IHX) and a long-heat transport loop, with various options for the transport fluid currently under consideration. Figure 1 shows a sketch of the NGNP concept highlighting the reactor, power conversion, and the hydrogen production units. Figure 2 and Figure 3 show examples of the two types of NGNP reactor cores, prismatic, and pebble-bed, respectively."

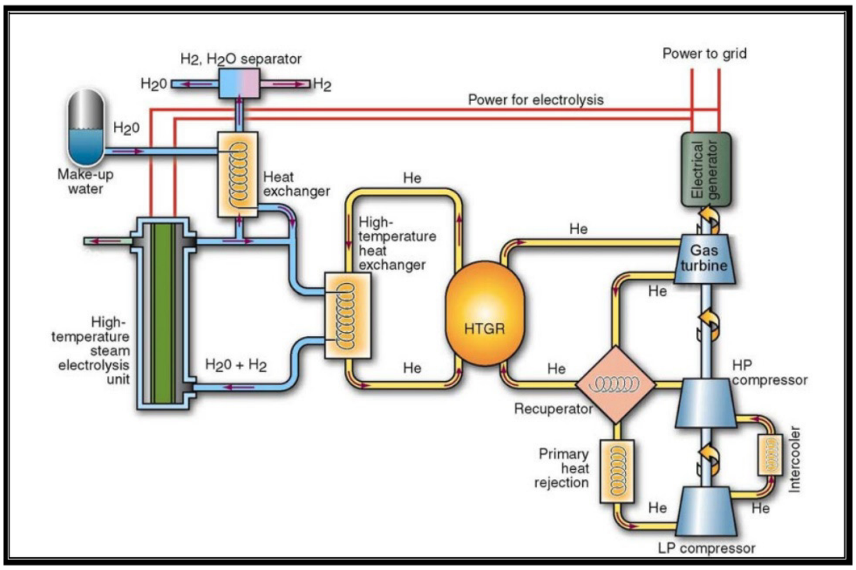

Figure 1. Representative schematic of the NGNP.

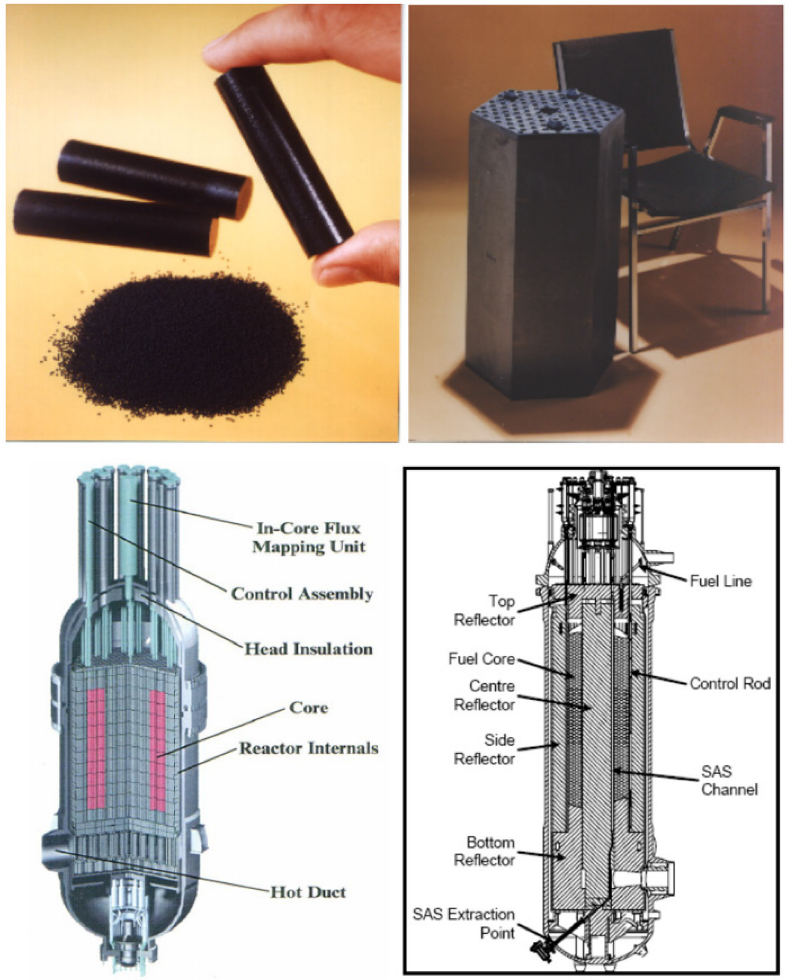

Figure 2. NGNP prismatic core option.

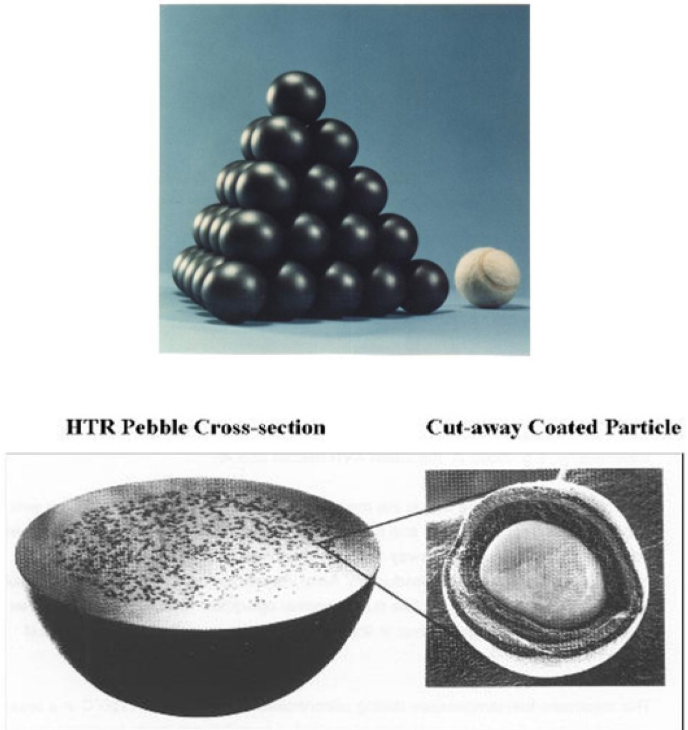

Figure 3. NGNP pebble-bed core option.

3.1 NGNP PIRT Report

3.1.1 NGNP PIRT Objectives

The NGNP was a design concept that was intended to be a very high-temperature gas-cooled reactor (VHTR) for generating electricity and co-generating hydrogen using the process heat from the reactor. Candidates for the conceptual design development included a modular reactor using a direct-cycle gas turbine with a prismatic block helium-cooled core. The candidates also included an indirect-cycle prismatic core design and a pebble-bed reactor (PBR) version. The candidate designs all relied heavily on taking credit for passive phenomena in the safety aspects of the design. The NGNP's primary product was to be electricity but also included a process heat loop (utilizing an intermediate heat exchanger) coupled to the reactor to produce hydrogen.

The NRC needed to develop analytical tools to verify the NGNP design and its safety performance, and a description of other R&D activities to conduct a review of an NGNP license application. To address the analytical tools and data needs, the NRC conducted a PIRT exercise focused on major topical areas of the NGNP design. A nine-step PIRT process was conducted by five panels of experts for the NGNP in the following topical areas:

- Accident and thermal fluids
- Fission product transport and dose
- High-temperature materials
- Graphite
- Process heat and hydrogen co-generation production.

“The scope of the Accident and Thermal Fluids [ACTH] PIRT addressed the need to identify phenomena associated with design and technology development areas that either influence safety or otherwise have relevance to regulatory requirements. The scope included both normal operations and a spectrum of accidents covering various cool-down events, reactivity events, and other scenarios related to aspects of a process heat loop...” (see [2], Section 3.4.2, page 15)

“Postulated accident scenario and phenomena considerations were based in part on the ACTH panel’s previous experience with HTGR plant operation and accident analysis. Prior studies and interactions with members from different PIRT panels helped to guide the ACTH panel’s evaluations.” (see [2], Section 3.4.2, page 15)

The scenarios considered by the PIRT panels included (1) the pressurized loss-of-forced circulation (P-LOFC) accident, (2) the depressurized loss-of-forced circulation (D-LOFC) accident, (3) the D-LOFC followed by air ingress, (4) reactivity-induced transients, (5) steam-water ingress events, and (6) events related to coupling the reactor to the process heat plant (including external events/chemical releases coming from the process heat plant).

Phenomena important to safety systems and components were identified and figures of merit were established. The panels rated (as high, medium, or low) the importance and the associated knowledge level of the phenomena. Panel deliberations and rationale for the ratings were documented.

3.1.2 Accident and Thermal Fluids Panel Knowledge Gap Summary

3.1.2.1 Normal Operation

The following is a summary of the panel’s conclusions concerning normal NGNP plant operations:

- A large uncertainty in the core coolant bypass flow was identified; this phenomenon is very difficult or impossible to measure in HTGRs. Core coolant bypass flow was ranked as high importance with the knowledge level low, indicating that the panel suggested further study of this phenomenon.
- The panel ranked the reactivity-temperature feedback coefficients as high-importance/low-knowledge level due to the lack of experimental data for this specific core configuration and the eventual large plutonium content, which increases with burnup due to the use of low-enriched uranium (LEU).
- A form of bypass flow in pebble-bed reactors is the flow at the pebble-wall interfaces. In annular core designs, this applies both to the side and central reflector interfaces. This was also ranked (high-importance, low-knowledge level) by the panel, although several studies have been able to successfully characterize the effective gap (flow area) as a function of distance from the wall.
- Fuel performance modeling was also ranked as high-importance/low-knowledge level by the panel since such performance is a crucial factor in determining the source terms.
- Power/flux profiles in pebble-bed reactors were of concern to the panel due to the history of problems with prediction of pebble operating temperature, and due to the lack of operating experience with tall annular cores. Uncertainties are worsened by the flux’s tendency to peak sharply at pebble-reflector wall interfaces.
- Other phenomena characterized as high-importance/low-knowledge level by the panel included the outlet plenum flow distribution (see Table 8). This phenomenon raises concerns about the effects of possible hot steaks in the helium on stresses in the plenum and outlet duct (and the downstream gas turbine, where applicable).

- Another high-importance/low-knowledge level-ranked phenomenon relates to fission-product release and transport of silver (Ag-110m), where, for example, the potential for deposition on turbine blades for direct-cycle gas turbine is a maintenance or worker dose concern. Silver is released from intact SiC coating layers on TRISO particles by a yet-to-be-understood mechanism, primarily at very high operating temperatures and high burnups.

Table 8. High-importance normal operations phenomena for accident and thermal fluids.

NGNP PIRT - Accident and Thermal Fluids			
Plant Condition	System or Component	Factor, Characteristic or Phenomenon (with High Importance)	Knowledge Level
Normal Operation	Core	Core coolant bypass flow	Low
		Core flow distribution, flow in active core	Medium
	Fuel	Pebble-bed core wall interface effects on bypass flow	Low
		Reactivity-temperature feedback coefficients	Low
		Coolant heat transfer correlations (pebble-bed reactor)	Medium
		Pebble flow	Medium
		Effective fuel-element thermal conductivity	Medium
		Fuel performance modeling	Low
		Power and flux profiles (initial conditions for accidents)	Medium
	Core Support Structures	Outlet plenum flow distribution	Low
	Vessel	Reactor vessel cavity air circulation and heat transfer	Low
	RCCS	RCCS heat removal	Medium
	Shutdown Cooling	Shutdown cooling system start-up transients during core heat-up	Medium
	Primary and Secondary System Hardware	Ag-110m release and plate-out	Low

3.1.2.2 General Loss-of-Forced Cooling (LOFC) Accident Scenarios

- One phenomenon ranked as high importance with low-knowledge level was the emissivity estimate for the reactor pressure vessel (RPV) surface and RCCS panel, particularly due to uncertainties from aging effects.
- Another phenomenon given high importance with low-knowledge level ratings was the RPV cavity air circulation and heat transfer. While this typically provides a small fraction of the total heat removal in LOFCs, it is crucial to temperature distributions within the RPV cavity.
- Conductivities and other heat transfer mechanisms in the side reflector and core barrel areas were also of concern to the panel, some receiving (high-importance, medium-knowledge level) and (medium importance, low-knowledge level) rankings, indicating the advisability for some further study (see Table 9).

Table 9. High-importance general loss-of-forced cooling accident phenomena.

NGNP PIRT - Accident and Thermal Fluids			
Plant Condition	System or Component	Factor, Characteristic or Phenomenon (with High Importance)	Knowledge Level
General Loss-of-Forced Cooling Accident	Core	Core thermal conductivity	Medium
	Fuel	Decay heat (temporal and spatial)	Medium
	Vessel	Emissivity	Low
		Vessel to RCCS effective view factors	Medium
		Reactor vessel cavity air circulation and heat transfer	Low
	Reflectors	Reflectors: conductivity and annealing	Medium
	Core Barrel	Core barrel emissivity	Medium
	RCCS	RCCS panel emissivity	Low
		RCCS fouling on coolant side	Medium
		RCCS spatial heat loadings	Medium
		RCCS performance including failure of 1 of 2 channels	Medium
		RCCS failure of both channels; heat transfer from RCCS to concrete cavity wall	Medium
		RCCS forced-to-natural circulation transitions	Medium
		RCCS single-phase boiling transitions	Medium
		RCCS parallel channel interactions	Medium
		RCCS natural circulation in horizontal panel(s)	Medium

3.1.2.3 RCCS - Passive Heat Removal Test Program

Many advanced reactor designs (including HTGRs) presume a safety-related passive heat removal system will be employed to ensure core heat is removed during off-normal events. This system is called the RCCS.

Preliminary RCCS designs using air and water as the cooling medium have been developed. However, capabilities to prototypically test such systems have been limited. Test data is necessary to firmly establish RCCS passive capabilities and provide data for analytic code V&V. While some safety core cooling system information is available (e.g., Fort St Vrain), design advancements revealed a need for further experimental analysis.

After the publication of the NGNP PIRT, Argonne National Laboratory (ANL) conducted a series of experiments to test, evaluate, and validate important design parameters and performance capabilities of the modular HTGR core safety heat removal system at its Natural Convection Shutdown Heat Removal Test Facility (NSTF). The purpose of this testing was to demonstrate that excess heat can be transferred to the ultimate heat sink (using air or water as the primary heat transfer medium) at rates adequate to maintain safety. Assessment of system capabilities considered atmospheric effects, system degradation factors, and system failure potential while in a passive heat removal mode (see [9], Page 48).

NSTF's air cooling configuration tests were completed in the 2016 timeframe. The test facility was observed to be most stable when operating at high powers in a single chimney configuration. During early start-up periods with multiple chimney exhausts, the natural convection phenomena was unable to maintain symmetric flow out of the chimneys, which was observed to lead to degraded heat removal performance. Perturbations at the outlet boundaries (e.g., wind fluctuations) caused instabilities to form, leading to reverse flow situations where cool air was drawn down one chimney while hot air was exhausted out of the other (see [10], Page 245).

Finally, under conditions of a heavy (non-air) gas ingress, the facility exhibited complete stagnation of system flow and subsequent failure of heat removal function. Based on the observations from the overall testing program, several unresolved issues remain. The coupling of low flow velocities, small differences in density when using air as the working fluid, and multiple parallel paths create a system that is vulnerable to instabilities with even minor flow disruptions (see [10], Page 246).

NSTF's water cooling tests started in the 2018 timeframe and are still in progress as of the completion of this report. The testing plan moving forward will focus on a continuation of accident scenario test cases, including both design basis and off-normal conditions, such as partially blocked piping along both inlet and outlet of the adiabatic chimney region, and fully blocked piping within the heated test section. In addition, a focus will be placed on exploring different methods for introducing a cold refill following depletion with the aim to identify best practices to minimize or prevent violent flow excursions and geysering behavior (see [11], Page 138).

3.1.2.4 Pressurized Loss-of-Forced Cooling (P-LOFC) Accident Scenario

- In the P-LOFC case, the main concern shifts to the tops of the core and vessel, which become the hottest, rather than the coolest areas. While no phenomena were given high importance with low-knowledge level rankings, several concerns were rated high importance with medium-knowledge levels related to the convection and radiation heating of the upper vessel area and the design of the special insulation inside the top head (see Table 10).

Table 10. High-importance pressurized loss-of-forced cooling accident phenomena.

NGNP PIRT - Accident and Thermal Fluids			
Plant Condition	System or Component	Factor, Characteristic or Phenomenon (with High Importance)	Knowledge Level
Pressurized Loss-of-Forced Cooling Accident	Core	Inlet plenum stratification and plumes	Medium
		Radiant heat transfer from top of core to upper vessel head	Medium
		Core coolant flow distribution	Medium
		Core coolant (channel) bypass flow	Medium
		Coolant flow friction/viscosity effects	Medium
	RCCS	RCCS spatial heat loading	Medium

3.1.2.5 Depressurized Loss-of-Forced Cooling (D-LOFC) Accident

- No phenomena received (high-importance, low-knowledge level) rankings by the panel, although there was considerable attention given to the major factors affecting peak fuel and vessel temperatures. The consensus (with high-importance, medium-knowledge level rankings) was that although there are uncertainties in these factors (core effective conductivity and afterheat for fuel temperature, plus RCCS performance for vessel temperature), the importance factors were mitigated somewhat considering the large safety margins typically included in the designs (see Table 11).
- Fuel performance modeling, as it applies to heat-up accidents, was ranked as having high importance with medium-knowledge level, noting its importance and the need to adapt it to each fuel design.
- Dust suspension in the RPV cavity (caused by depressurization) could impede the radiant heat transfer from the vessel to the RCCS. The radioactive dust in the primary circulating gas released to the confinement, along with other dust that becomes loose, is typically considered to be a major source term factor for PBRs (see evaluation by the FPT PIRT).

Table 11. High-importance depressurized loss-of-forced cooling accident phenomena.

NGNP PIRT - Accident and Thermal Fluids			
Plant Condition	System or Component	Factor, Characteristic or Phenomenon (with High Importance)	Knowledge Level
Depressurized Loss-of-Forced Cooling Accident	Fuel	Core effective thermal conductivity	Medium
		Decay heat and distribution versus time	Medium
		Heat-up accident fuel performance modeling	Medium
	Reactor Pressure Vessel Cavity	Hydrodynamic conditions for dust suspension (fluid structure interactions)	Medium
		Pressure pulse in confinement	Medium

3.1.2.6 Air Ingress Following Depressurization

- The integrity of the graphite core support system depends on design details as well as the conditions for oxidation, where oxidation at lower temperatures tends to result in more structural damage. This phenomenon was ranked as high importance with medium-knowledge level by the panel.
- Potential damage to the fuel from oxidation, ranked as high importance with medium-knowledge level, was a concern; however, it was noted, based on experimental data, that the SiC coating layer in TRISO fuel retains fission products well when exposed to air in the temperature ranges expected in the ingress scenarios (see Table 12).

Table 12. High-importance loss-of-forced cooling accident with air ingress phenomena.

NGNP PIRT - Accident and Thermal Fluids			
Plant Condition	System or Component	Factor, Characteristic or Phenomenon (with High Importance)	Knowledge Level
Loss-of-Forced Cooling Accident with Air Ingress	Fuel	Fuel performance with oxygen attack	Medium
		Phenomena (various accident conditions) that affect cavity gas composition and temperature with inflow	Medium
	Fuel and Core	Core oxidation	Medium
	Core Support and Fuel	Molecular diffusion	Medium
		Core support structure oxidation	Medium
	Reactor Cavity	Cavity filtering performance	Medium
		Reactor cavity-to-reactor vessel air ingress	Medium
		Confinement-to-reactor cavity air ingress	Medium
	Primary System	Duct exchange flow	Medium

3.1.2.7 Reactivity (Including ATWS) Events

- The reactivity-temperature feedback coefficients for the fuel, moderator, and reflectors were ranked as high importance with medium-knowledge level since negative feedback is essential to the inherent defense against reactivity insertions (see Table 13).

Table 13. High-importance reactivity accident phenomena.

NGNP PIRT - Accident and Thermal Fluids			
Plant Condition	System or Component	Factor, Characteristic or Phenomenon (with High Importance)	Knowledge Level
Reactivity Accident	Fuel	Reactivity-temperature feedback coefficients (fuel, moderator, and reflectors)	Medium
		Reactivity insertion due to steam-water ingress accidents	Medium
	Core	Control and scram rods, and reserve shutdown worths	Medium

3.1.3 Fission-Product Transport and Dose Panel Knowledge Gap Summary

- Because of the small allowable releases during a depressurization from this reactor type (into a vented confinement), dust and aerosol issues are important to quantify even though the amounts of fission products involved may be modest (compared to potential aerosol generation in a severe light-water reactor [LWR] accident). The initial fission-product contamination of the reactor circuit is of great importance because the most powerful driving term, helium pressure, will most likely act during the earliest stages of the accident. If an air ingress accident occurs with an unimpeded flow path, larger fission-product releases can occur later in the accident.
- One phenomenon that was rated as important and may not have been explored in the past was the effect of mechanical shock and vibration in a D-LOFC on the transport and re-entrainment of dust and spalled-off oxide flakes. A failure of a large pipe would generate large mechanical forces (vibration, shocks, and pipe whip), and the resulting flow can generate a large amount of acoustic energy, both of which can launch dust and small particles into the existing gas flow, as well as cause additional failures (see Table 14).

Table 14. High-importance fission-product transport and dose phenomena.

NGNP PIRT - Fission-Product Transport and Dose			
Plant Condition	System or Component	Factor, Characteristic or Phenomenon (with High Importance)	Knowledge Level
All Conditions	Core	Re-criticality (slow)	Medium
	Fuel and Primary Coolant System	Dust generation	Medium
	Graphite and Fuel	Fission-product speciation in carbonaceous material	Low
	Graphite and Core Materials	Matrix permeability, tortuosity	Low
		Fission-product transport through matrix	Low
		Fuel block permeability, tortuosity	Medium
		Fission-product transport through fuel block	Medium
		Sorptivity of graphite	Medium
		Fluence effects on transport in graphite	Medium
	Graphite in Primary System	(De)Adsorption on dust	Medium
	Primary Coolant System	Material/structure properties (critical initial and/or boundary condition)	Medium (graphite)
		Thermal-fluid properties	Medium
		Gas Composition	Medium
		Fission-product speciation during mass transfer	Medium
	Confinement	Radiolysis effects in confinement	Medium
		Combustion of dust in confinement	Medium
		Confinement leakage path, release rate through penetrations	Medium
		Confinement aerosol physics	Medium
		Cable pyrolysis, fire	Medium
	Primary Coolant System, Cavity, Confinement	Ag-110m generation and transport	Low
		Aerosol growth	Low
		Resuspension	Low
		Aerosol/dust deposition	Medium
	Primary Coolant System and Confinement	Fission-product diffusivity, sorptivity in nongraphite surfaces	Low
		Coolant chemical interaction with surfaces	Medium
Normal Operations	Fuel and Primary Coolant System	Fission-product plate-out and dust distribution under normal operation	Medium
Loss-of-Forced Cooling Accident with Air Ingress	Graphite and Core Materials	Air attack on graphite	Medium
		Steam attack on graphite	Medium
		Wash-off	Medium
Reactivity Accident	Fuel	Fuel-damaging reactivity-initiated accident (RIA)	Medium

3.1.4 High-Temperature Materials Panel Knowledge Gap Summary

- Several Intermediate Heat Exchanger (IHX) materials-related phenomena were rated as 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 with primary boundary design methodology for new IHX structures; manufacturing phenomena for new designs (including joining issues); and the ability to inspect and test new IHX designs.
- Three materials-related phenomena related to the RPV fabrication and operation were rated as 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 nine Cr-MoV steels capable of higher temperature operation than light-water reactor vessel steels. These included crack initiation and subcritical crack growth, field fabrication process control, and property control in heavy sections.
- Two materials-related phenomena for the RPV and core barrel emissivity were rated as 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 (see Table 15). These phenomena (emissivity degradations caused by loss of desired surface layer properties) were rated as high importance because of their potential impact on passive heat rejection ability.

Table 15. High-importance high-temperature materials phenomena.

NGNP PIRT - High-Temperature Materials			
Plant Condition	System or Component	Factor, Characteristic or Phenomenon (With High Importance)	Knowledge Level
All Conditions	Control Rods (nonmetallic)	Composites structural design methodology limitations for new structures (lack of experience)	Low
	Intermediate Heat Exchanger (IHX)	Crack initiation and propagation (due to creep crack growth, creep, creep-fatigue, aging [with or without load], subcritical crack growth)	Low
		Primary boundary design methodology limitations for new structures (lack of experience)	Low
		Manufacturing phenomena (such as joining)	Low
		Inspection/testing phenomena	Low
	Piping	Aging fatigue, environmental degradation of insulation	Low
	Rector Pressure Vessel (RPV) Internals (metallic)	Change in emissivity	Low
		Radiation-creep	Low
	Rector Pressure Vessel (RPV) Internals (nonmetallic)	Composites structural design and fabrication methodology limitations for new structures (lack of experience)	Low
		Environmental and radiation degradation and thermal stability at temperature	Low
	Reactor Pressure Vessel (RPV)	Crack initiation and subcritical crack growth	Low
		Compromise of emissivity due to loss of desired surface layer properties	Low
		Field fabrication process control	Low

NGNP PIRT - High-Temperature Materials			
Plant Condition	System or Component	Factor, Characteristic or Phenomenon (With High Importance)	Knowledge Level
		Property control in heavy sections	Low
		Thermal aging (long-term)	Medium
	Valves	Isolation valve failure	Low
		Valve failure (general)	Low

3.1.5 Graphite Panel Knowledge Gap Summary

The panel noted several significant phenomena (stress, creep, and coefficient of thermal expansion) related to graphite properties and material characterization of these properties as functions of temperatures and neutron irradiation. Stress that is due to differential thermal strain and differential neutron irradiation-induced dimensional changes would very quickly cause fracture in the graphite components if it were not for the relief of stress due to neutron-irradiation-induced creep. Currently, no creep data are available for the graphite grades being considered for use in the NGNP. A new model for creep is needed which can account for the observed deviations from linearity of the creep strain rate with neutron dose. Differential thermal strains occur in graphite components due to temperature gradients and local variation in the coefficient of thermal expansion (CTE). The variations in the CTE are dependent upon the irradiation conditions (temperature and neutron dose) and the irradiation-induced creep. Irradiation-induced changes in CTE are understood to be related to changes in the oriented porosity in the graphite structure. There are insufficient data available for the effect of creep strain on CTE in graphite. Moreover, none of the available data are for the grades being considered for the NGNP. For these three phenomena, a high importance and low-knowledge level assignment was made.

Mechanical properties such as strength, toughness, and the effect of creep strain were also identified by the panel. The properties of the graphite are known to change with neutron irradiation, the extent of which is a function of the neutron dose, irradiation temperature, and irradiation-induced creep strain. Local differences in moduli, strength, and toughness due to neutron fluence and temperature gradients must be accounted for in the design. The importance of this phenomenon is thus ranked high. Although data exist for the effect of neutron dose and temperature on the mechanical properties of graphite, there are insufficient data on the effects of creep strain on the mechanical properties. Moreover, none of the available data are for the grades currently being considered for the NGNP (thus knowledge level is low).

Several graphite phenomena leading to a blocked fuel-element coolant channel (or in a blockage to reactivity control element insertion) were identified by the panel. Significant uncertainty exists as to the stress state of any graphite component in the core. Moreover, the strength of the components changes with neutron dose, temperature, and creep strain. The combination of these factors makes the probability of local failure, graphite spalling, and possible blockage of a fuel-element coolant channel difficult to determine. Consequently, the panel rated this phenomenon's importance as high. Although the changes in properties of graphite have been studied for many years, there are still data gaps that make whole core modeling very difficult (e.g., effect of creep strain on properties). Moreover, data on the grades being considered for NGNP are not available. Therefore, the panel rated the knowledge level for this phenomenon as low (see Table 16).

Table 16. High-importance graphite phenomena.

NGNP PIRT - Graphite			
Plant Condition	System or Component	Factor, Characteristic or Phenomenon (with High Importance)	Knowledge Level
All Conditions	Graphite	Irradiation-induced creep (irradiation-induced dimensional change under stress)	Low
		Irradiation-induced change in CTE, including the effects of creep strain	Low
		Irradiation-induced changes mechanical properties (strength, toughness), including the effect of creep strain (stress)	Low
		Statistical variation of non-irradiated properties	Medium
		Consistency in graphite quality over the lifetime of the reactor fleet (for replacement, for example)	Medium
		Graphite contains inherent flaws	Medium
		Irradiation-induced dimensional change	Medium
		Irradiation-induced changes in elastic constants, including the effects of creep strain	Medium
		Tribology of graphite in (impure) helium environment	Medium
	Graphite Component	Blockage of fuel-element coolant channel – due to graphite failure, spalling	Low
		Blockage of coolant channel in reactivity control block due to graphite failure, spalling	Low
		Blockage of reactivity control channel – due to graphite failure, spalling	Low
		Graphite temperatures	Medium
		Tribology of graphite in (impure) helium environment	Medium
Accident Conditions	Graphite	Irradiation-induced thermal conductivity change	Medium
Loss-of-Forced Cooling Accident	Graphite Component	Degradation of thermal conductivity	Medium

4. CONCLUSIONS

4.1 TRISO PIRT Summary

The objectives of the 2004 TRISO-Coated Particle Fuel PIRT effort included the identification of key attributes of TRISO-coated particle fuel manufacture, to provide insights for developing plans for fuel safety margin testing, and to assist in defining test data needs for the development of fuel performance and fission-product transport models. The expert panel considered seven plant conditions (associated with HTGR designs) when identifying the FCP of most concern where low levels of knowledge existed. It should be noted that the results from this expert panel evaluation were instrumental in guiding the direction and development of the subsequent AGR Program.

Anisotropy, cracking of the various layers (and associated fission-product releases), condensed-phase and gas-phase diffusion, and the chemical attacks that occur from air and water ingress were FCP that were evaluated as having a potentially large effect on particle fuel performance. The impacts from these phenomena have been addressed by the AGR Program, or will be addressed in the future (i.e., air and moisture-ingress testing).

Section 4 of the 2004 TRISO-Coated Particle Fuel PIRT report provided a series of tables (one for each of the seven plant conditions) that summarized the findings from each panel member, and Section 5 of the report provided analysis and a summary of the findings. The tables included in this report have been developed to look at the expert panel data (found in Section 4 of the source report) in a different manner to add consistency and clarity to the findings and the resulting conclusions.

4.2 AGR Program Summary

The origins of the AGR program are found in the early development stages of DOE's NGNP project. While this project did not fully materialize, DOE has continued to support the AGR program execution due to the TRISO-coated particle fuel's positive fuel performance potential and the strong interest expressed by the advanced reactor community to utilize the passive safety advantages of this fuel form as part of their designs.

The AGR program's early results originate from the AGR-1 and AGR-2 fuel irradiation tests that included post-irradiation accident safety testing. These results are documented in the TRISO topical report that was published by EPRI and has been reviewed by the NRC (as discussed in Sections 2.3.4.2 and 2.3.4.3 of this report).

The overall success (to date) of the AGR program comes from irradiation testing designed to observe many of the FCP discussed in the TRISO PIRT. Therefore, the AGR program results are augmenting the various knowledge levels of related FCP that were previously identified by the TRISO PIRT. It should be noted that the AGR program has ongoing experiments, such as AGR-3/4 PIE and AGR-5/6/7 irradiation, and future air and moisture-ingress testing to complete. Any of these program elements have the potential to identify new FCP that could be significant in nature. In addition, improved PIE technologies have provided valuable insights into the interactions that can occur with the progression of interrelated phenomena. The ability to identify SiC failures (separate from a failure of the integrated TRISO particle) is an outgrowth of the application of these advanced technologies. New insights into how buffer shrinkage combined with incomplete debonding at the buffer-IPyC interface can cause IPyC fractures, which in turn can lead to SiC failures, is an example of a phenomena interrelationship that was not identified by the TRISO PIRT.

The part of the AGR program intended to evaluate TRISO fuel performance at high temperatures in oxidizing environments has yet to be completed. These tests are needed to assess the behavior of the fuel in conditions that could exist in an HTR during inadvertent ingress of air or moisture into the core. The 2004 TRISO PIRT identified several related high-importance FCP (e.g., layer oxidation and various chemical attack phenomena related to depressurization accidents with water or air ingress) that the panel judged to have low or medium levels of knowledge. The AGR program's air and moisture-ingress testing should address these FCP and is anticipated to commence in the 2024 timeframe.

4.3 NGNP PIRT Summary

The Energy Policy Act of 2005 (EPAct), required the NRC and DOE to develop a licensing strategy for the NGNP, which was envisioned to be VHTR for generating electricity and co-generating hydrogen using the process heat from the reactor. To address the analytical tools and data that would be needed, the NRC initiated the NGNP PIRT exercise to address major topical areas of interest (see Section 3 for a discussion of these topical areas and the related high-importance phenomena identified by the PIRT panels).

Accident and Thermal Fluids. The Accident and Thermal Fluids panel identified several phenomena with high-importance and low-knowledge levels related to normal and accident conditions. For general LOFC accidents, emissivity of the RPV surface and the overall performance of the various RCCS components were identified as of high importance with low-knowledge levels. It is vitally important that the RCCS can passively remove reactor decay heat under all plant conditions in reliable manner. Recent air-cooled RCCS test experiments (conducted by ANL) have identified that the coupling of low flow velocities, small differences in density when using air as the working fluid, and multiple parallel paths create a system that is vulnerable to instabilities with even minor flow disruptions. This recent experiment data identifies concerns for designs that include the use a passive air-cooled RCCS.

Fission-Product Transport and Dose. Because of the small allowable releases during a depressurization from an HTGR into a vented reactor building, dust and aerosol issues are important to quantify. One phenomenon that was rated as important (and may not have been explored in the past) was the effect of mechanical shock and vibration during a D-LOFC on the transport and re-entrainment of dust and spalled-off oxide flakes.

High-Temperature Materials. IHX high-importance materials-related phenomena included crack initiation and propagation due to creep crack growth, creep, creep-fatigue, and aging; the lack of experience with primary boundary design methodology for new IHX structures; manufacturing phenomena for new designs (including joining issues); and the ability to inspect and test new IHX designs. Materials phenomena related to RPV fabrication and operation that were rated as high importance included crack initiation and subcritical crack growth, field fabrication process control, and property control in heavy sections. Emissivity degradations of the RPV and core barrel (caused by loss of desired surface layer properties) were rated as high importance because of their potential impact on passive heat rejection ability.

Graphite Components. The NGNP panel noted several significant phenomena (stress, creep, and CTE) related to graphite properties and material characterization of these properties as functions of temperatures and neutron irradiation. The panel noted that there is no creep data for the graphite grades being considered at that time for use in the NGNP. The panel also noted that graphite mechanical properties, such as strength, toughness, and the effect of creep strain, are known to change with neutron irradiation, the extent of which is a function of the neutron dose, irradiation temperature, and irradiation-induced creep strain. It was noted that insufficient data on the effects of creep strain on the mechanical properties exist. Moreover, none of the available data was for the grades being considered for the NGNP. These are areas of concern (along with the other graphite phenomena ranked as having high importance) for advanced reactor designs that may use unique variations of graphite from new sources.

4.4 Conclusions

The TRISO-coated particle fuel form has significant positive safety characteristics that support high-temperature advanced reactor designs that rely on passive safety measures to ensure adequate safety for the public and the environment. These safety characteristics (e.g., SiC layer fission product retention and resistance to high temperatures) are demonstrated by past international test programs, the R&D insights gained from the TRISO and NGNP PIRTs, and the results from the ongoing AGR R&D program.

This report assesses the TRISO-coated particle fuel and NGNP design high-importance phenomena that were originally evaluated (by a group of international experts) to have associated low- or medium-knowledge levels and provides a series of tables designed to allow efficient access to the existing foundation of PIRT-identified phenomena that may be of interest to the reader.

In addition, this report identified phenomena-sequence insights and environmental phenomena that had not been considered by the subject PIRT reports. They include the following.

- SiC failures (separate from a failure of the integrated TRISO particle) can occur when buffer shrinkage pulls away from the IPyC layer causing IPyC fractures. These IPyC fractures, in turn, allow fission products to attack the SiC layer and can lead to a SiC failure.
- Experiments have identified that RCCS that use passive air cooling in their designs can be vulnerable to instabilities with even minor flow disruptions.

4.5 Future Activities/Next Steps

Section 4 of this report notes several knowledge gaps that were identified in the original PIRTs and where additional R&D may be needed to develop data needed to support future development and licensing of TRISO-based technologies. These R&D areas include

- Evaluation of TRISO-coated particle fuel performance at high temperatures in oxidizing environments.
- Air and moisture-ingress testing is needed and is anticipated to commence in the 2024 timeframe.
- Detailed analysis of the data obtained from future AGR program activities and other test data against the phenomena identified in the 2004 TRISO-coated particle fuel PIRT.
- The 2004 TRISO PIRT and the NGNP PIRT efforts were focused on high temperature gas-cooled reactor concepts. It is recognized that future TRISO-based design variants will need to assess the potential for additional high-importance phenomena that must be addressed.
- Expand the analysis to examine TRISO-based microreactors as they develop design maturity.
- Continue/Expand testing of the air-cooled RCCS test experiments that identified vulnerabilities of TRISO fuel to instabilities with flow disruptions.
- Continue to utilize improved PIE technologies to provide new insights into the interactions that can occur with the progression of interrelated phenomena such as SiC failures, buffer shrinkage, etc.

5. REFERENCES

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Appendix A

TRISO PIRT – High Importance Phenomena

An independent (row by row) review of the TRISO-coated particle fuel tables found in Section 4 of the TRISO PIRT report [1] was conducted. All phenomena (FCP) that were evaluated as high importance by a majority (2 out of 3) of the panel and where the knowledge level was judged to be either low or medium by any two members of the panel are included in Table A 1.

One of the panel members did not provide separate knowledge level numbers for the two accident conditions (Depressurized Heat-up Accident for ≤1600°C and >1600°C). In these cases, the stated values for knowledge level were assumed to apply to both accident categories.

Table A 1. High-importance TRISO and NGNP PIRT phenomena.

ID	Source	High Importance Factor, Characteristic, or Phenomenon	Plant Condition	Component	Knowledge Level (KL)
1.1	Table 4-2 TRISO PIRT (Page 4-8)	**Anisotropy** (Operation-induced [thermal + radiation] change in grain orientation along principal directions as measured by the BAF)	Normal Operations	Inner PyC Layer	Low or Medium
1.2	Table 4-2 TRISO PIRT (Page 4-8)	**Dimensional change (Unrestrained radial and tangential changes with fast fluence)**	Normal Operations	Inner PyC Layer	Medium
1.3	Table 4-2 TRISO PIRT (Page 4-8)	**Fast fluence** (Accumulated fast neutron fluence greater than 0.18 MeV)	Normal Operations	Inner PyC Layer	Medium
1.4	Table 4-2 TRISO PIRT (Page 4-7)	**Fission product chemical form** (Chemical speciation of fission products as a function of burnup and temperature)	Normal Operations	Kernel	Medium
1.5	Table 4-2 TRISO PIRT (Page 4-7)	**Pressure** (Gas pressure generated in the void volume associated with the buffer layer)	Normal Operations	Buffer Layer	Medium
1.6	Table 4-2 TRISO PIRT (Page 4-7)	**Temperature gradient** (Temperature gradient across the kernel or buffer layer)	Normal Operations	Kernel	Low or Medium
				Buffer Layer	Low or Medium
1.7	Table 4-2 TRISO PIRT (Page 4-8)	**Radiation-induced creep** (Strain release because of radiation-induced dimensional change)	Normal Operations	Inner PyC Layer	Medium
1.8	Table 4-2 TRISO PIRT (Page 4-9)	**Fission product corrosion** (Attack of layer by fission products, e.g., Palladium)	Normal Operations	SiC Layer	Medium
	Table 4-3 TRISO PIRT (Page 4-12)		Depressurized Heat-up Accident Fuel Temp. >1600C		Low or Medium

ID	Source	High Importance Factor, Characteristic, or Phenomenon	Plant Condition	Component	Knowledge Level (KL)
1.9	Table 4-2 TRISO PIRT (Pages 4-6 4-8, and 4-9)	**Condensed-phase diffusion** (Inter-granular diffusion and/or intra-granular solid-state diffusion)	Normal Operations	Inner PyC Layer	Low or Medium
				SiC Layer	Low or Medium
				Outer PyC Layer	Low or Medium
				Fuel Element	Medium
	Table 4-3 TRISO PIRT (Pages 4-12 and 4-15)		Depressurized Heat-up Accident Fuel Temp. ≤1600C	Kernel	Low or Medium
			Depressurized Heat-up Accident Fuel Temp. >1600C	Kernel	Low or Medium
				SiC Layer	Low or Medium
	Table 4-4 TRISO PIRT (Pages 4-16 and 4-20)		Reactivity Accident	Kernel	Medium
				Fuel Element	Low or Medium
	Table 4-5 TRISO PIRT (Pages 4-21 and 4-23)		Depressurization Accident with Water Ingress	SiC Layer	Low or Medium
				Fuel Element	Low or Medium
	Table 4-6 TRISO PIRT (Pages 4-29 4-30, and 4-31)		Depressurization Accident with Air Ingress	SiC Layer	Low or Medium
				Outer PyC Layer	Low or Medium
				Fuel Element	Low or Medium
1.10	Table 4-3 TRISO PIRT (Page 4-15)	**Buffer carbon-kernel interaction** (Chemical reaction between carbon and the fuel (UO2) to form UC2 and CO [gas])	Depressurized Heat-up Accident Fuel Temp. ≤1600C	Kernel	Low or Medium
			Depressurized Heat-up Accident Fuel Temp. >1600C		
	Table 4-5 TRISO PIRT (Page 4-27)		Depressurization Accident with Water Ingress		
	Table 4-6 TRISO PIRT (Page 4-35)		Depressurization Accident with Air Ingress		
1.11	Table 4-3 TRISO PIRT (Page 4-14)	**Layer Oxidation** (Buffer Layer: Reaction of buffer layer with oxide materials in the fuel kernel) (Inner PyC: Reaction of pyrolytic graphite with oxygen released from the kernel) (SiC Layer: Uptake of oxygen by the layer through a chemical reaction)	Depressurized Heat-up Accident Fuel Temp. ≤1600C	Buffer Layer	Low or Medium
			Depressurized Heat-up Accident Fuel Temp. >1600C		Low or Medium
	Table 4-5 TRISO PIRT (Pages 4-22 4-25, and 4-26)		Depressurization Accident with Water Ingress	Buffer Layer	Low or Medium
				Inner PyC Layer	Low
				Outer PyC Layer	Low or Medium

ID	Source	High Importance Factor, Characteristic, or Phenomenon	Plant Condition	Component	Knowledge Level (KL)
	Table 4-6 TRISO PIRT (Pages 4-30 4-31, 4-33, and 4-34)		Depressurization Accident with Air Ingress	Buffer Layer	Low or Medium
				Inner PyC Layer	Low
				SiC Layer	Medium
				Outer PyC Layer	Low or Medium
1.12	Table 4-2 TRISO PIRT (Pages 4-7 4-8, and 4-9)	**Cracking** (Buffer Layer: Shrinkage cracks produced in layer during operation. Other Layers: Lengths, widths, and numbers of cracks produced in layer during operation or accident)	Normal Operations	Buffer Layer	Low or Medium
				Inner PyC Layer	
				SiC Layer	
	Table 4-3 TRISO PIRT (Pages 4-12 and 4-13)		Depressurized Heat-up Accident Fuel Temp. $\leq$1600C	Inner PyC Layer	
				Outer PyC Layer	
			Depressurized Heat-up Accident Fuel Temp. >1600C	Inner PyC Layer	
				Outer PyC Layer	
	Table 4-5 TRISO PIRT (Pages 4-22 and 4-25)		Depressurization Accident with Water Ingress	Inner PyC Layer	
				Outer PyC Layer	
	Table 4-6 TRISO PIRT (Pages 4-30 and 4-33)		Depressurization Accident with Air Ingress	Inner PyC Layer	
				Outer PyC Layer	
1.13	Table 4-3 TRISO PIRT (Page 4-12)	**Fission product release through undetected defects** (Passage of fission products from the buffer region through defects in the SiC layer)	Depressurized Heat-up Accident Fuel Temp. $\leq$1600C	SiC Layer	Low or Medium
			Depressurized Heat-up Accident Fuel Temp. >1600C		
1.14	Table 4-3 TRISO PIRT (Page 4-11)	**Transport of metallic FPs through fuel element – Chemical form** (Chemical stoichiometry of the chemical species that includes the radioisotope of interest)	Depressurized Heat-up Accident Fuel Temp. $\leq$1600C	Fuel Element	Low or Medium
			Depressurized Heat-up Accident Fuel Temp. >1600C		
	Table 4-5 TRISO PIRT (Page 4-21)		Depressurization Accident with Water Ingress		Medium
	Table 4-6 TRISO PIRT (Page 4-29)		Depressurization Accident with Air Ingress		

ID	Source	High Importance Factor, Characteristic, or Phenomenon	Plant Condition	Component	Knowledge Level (KL)
1.15	Table 4-3 TRISO PIRT (Page 4-12)	**Thermal deterioration or decomposition** (Decline in the quality of the layer due to thermal loading)	Depressurized Heat-up Accident Fuel Temp. >1600C	SiC Layer	Low or Medium
1.16	Table 4-3 TRISO PIRT (Page 4-12)	**Thermodynamics of the SiC-fission product system** (Chemical form of fission products including the effects of solubility, intermetallics, and chemical activity)	Depressurized Heat-up Accident Fuel Temp. >1600C	SiC Layer	Medium
1.17	Table 4-3 TRISO PIRT (Page 4-15)	**Thermodynamic state of fission products** (Chemical and physical state of fission products)	Depressurized Heat-up Accident Fuel Temp. ≤1600C	Kernel	Medium
			Depressurized Heat-up Accident Fuel Temp. >1600C		
	Table 4-5 TRISO PIRT (Page 4-27)		Depressurization Accident with Water Ingress		
	Table 4-6 TRISO PIRT (Page 4-35)		Depressurization Accident with Air Ingress		
1.18	Table 4-3 TRISO PIRT (Page 4-12)	**Fission product release through failures e.g., cracking** (Passage of fission products from the buffer region through regions in the SiC layer that fail during operation or an accident)	Depressurized Heat-up Accident Fuel Temp. ≤1600C	SiC Layer	Low or Medium
			Depressurized Heat-up Accident Fuel Temp. >1600C		
	Table 4-4 TRISO PIRT (Page 4-17)		Reactivity Accident		Medium
	Table 4-5 TRISO PIRT (Page 4-23)		Depressurization Accident with Water Ingress		
	Table 4-6 TRISO PIRT (Page 4-31)		Depressurization Accident with Air Ingress		
1.19	Table 4-3 TRISO PIRT (Page 4-11)	**Irradiation history** (The temperature, burnup and fast fluence history of the layer)	Depressurized Heat-up Accident Fuel Temp. ≤1600C	Fuel Element	Low or Medium
			Depressurized Heat-up Accident Fuel Temp. >1600C		

ID	Source	High Importance Factor, Characteristic, or Phenomenon	Plant Condition	Component	Knowledge Level (KL)
1.20	Table 4-3 TRISO PIRT (Pages 4-11 4-12, 4-13, and 4-15)	**Gas-phase diffusion** (Diffusion of gaseous fission products through layer [Knudsen and bulk diffusion through pore structure, and pressure driven permeation through structure]). Other factors include holdup, cracking, adsorption, site poisoning, permeability, sintering, and annealing. [**Check this against the appendices**]	Depressurized Heat-up Accident Fuel Temp. $\leq$1600C	Kernel	Low or Medium
				Fuel Element	Medium
			Depressurized Heat-up Accident Fuel Temp. >1600C	Kernel	Low or Medium
				Inner PyC Layer	Medium
				SiC Layer	
				Fuel Element	
	Table 4-4 TRISO PIRT (Pages 4-16 4-18, and 4-20)		Reactivity Accident	Kernel	
				Buffer	
				Inner PyC Layer	Low or Medium
				Fuel Element	
	Table 4-5 TRISO PIRT (Pages 4-23 and 4-24)		Depressurization Accident with Water Ingress	Inner PyC Layer	Medium
				SiC Layer	
	Table 4-6 TRISO PIRT (Pages 4-29 4-30, 4-31, and 4-32)		Depressurization Accident with Air Ingress	Inner PyC Layer	
				SiC Layer	
				Outer PyC Layer	
				Fuel Element	
1.21	Table 4-4 TRISO PIRT (Page 4-19)	**Energy transport: conduction within the kernel** (Flow of heat within a medium from a region of high temperature to a region of low temperature)	Reactivity Accident	Kernel	Medium
1.22	Table 4-4 TRISO PIRT (Page 4-19)	**Maximum fuel gaseous fission product uptake** (Maximum loading of fission products that can deposit from the gas-phase onto surfaces of materials surrounding the fuel kernel)	Reactivity Accident	Buffer Layer	Low or Medium
1.23	Table 4-4 TRISO PIRT (Page 4-18)	**Pressure loading (Fission products)** (Stress loading of the layer by increased pressure from fission products)	Reactivity Accident	Inner PyC Layer	Medium
1.24	Table 4-4 TRISO PIRT (Page 4-18)	**Pressure loading (Carbon monoxide)** (Stress loading of the layer by carbon monoxide by increased pressure)	Reactivity Accident	Inner PyC Layer	Low or Medium
1.25	Table 4-4 TRISO PIRT (Page 4-18)	**Response to kernel swelling** (Mechanical reaction of the layer to the growth of the kernel via swelling)	Reactivity Accident	Buffer Layer	Low or Medium
1.26	Table 4-5 TRISO PIRT (Pages 4-21 4-22, 4-24, and 4-25)	**Chemical attack by water – Kinetics** (Rate of reaction per unit surface area as a function of temperature and partial pressure of steam)	Depressurization Accident with Water Ingress	Inner PyC Layer	Low or Medium
				SiC Layer	
				Outer PyC Layer	
				Fuel Element	Medium

ID	Source	High Importance Factor, Characteristic, or Phenomenon	Plant Condition	Component	Knowledge Level (KL)
1.27	Table 4-5 TRISO PIRT (Pages 4-21 4-22, 4-24, 4-25, and 4-26)	**Chemical attack by water – Changes in chemical form of fission products** (Changes in chemical form resulting from oxidizing or reducing fission products)	Depressurization Accident with Water Ingress	Buffer Layer	Low or Medium
				Inner PyC Layer	Medium
				SiC Layer	
				Outer PyC Layer	
				Fuel Element	
1.28	Table 4-5 TRISO PIRT (Page 4-21)	**Chemical attack by water – Changes in graphite properties** (Changes in diffusivity, porosity, absorptivity, etc.)	Depressurization Accident with Water Ingress	Fuel Element	Low or Medium
1.29	Table 4-5 TRISO PIRT (Pages 4-22 4-23, 4-23, and 4-25)	**Chemical attack by water – Temperature distributions** (Impact of graphite oxidation on temperature distribution through material)	Depressurization Accident with Water Ingress	Inner PyC Layer	Low or Medium
				SiC Layer	Medium
				Outer PyC Layer	Low or Medium
				Fuel Element	Medium
1.30	Table 4-6 TRISO PIRT (Pages 4-29 4-30, 4-32, 4-33, and 4-35)	**Chemical attack by air – Kinetics** (Rate of reaction per unit surface area as a function of temperature and partial pressure of air)	Depressurization Accident with Air Ingress	Kernel (UCO)	Low or Medium
				Inner PyC Layer	Medium
				SiC Layer	
				Outer PyC Layer	Low or Medium
				Fuel Element	Medium
1.31	Table 4-6 TRISO PIRT (Page 4-29)	**Chemical attack by air – Catalysis** (Modification of the reaction rate by fission products or impurities)	Depressurization Accident with Air Ingress	Fuel Element	~~Low or~~ Medium
1.32	Table 4-6 TRISO PIRT (Pages 4-29 4-30, 4-32, 4-33, 4-34, and 4-35)	**Chemical attack by air – Changes in chemical form of fission products** (Changes in chemical form resulting from oxidizing or reducing fission products)	Depressurization Accident with Air Ingress	Kernel	Medium
				Buffer Layer	
				Inner PyC Layer	
				SiC Layer	
				Outer PyC Layer	
				Fuel Element	
1.33	Table 4-6 TRISO PIRT (Page 4-29)	**Chemical attack by air – Changes in graphite properties** (Changes in diffusivity, porosity, absorptivity, etc.)	Depressurization Accident with Air Ingress	Fuel Element	Low or Medium
1.34	Table 4-6 TRISO PIRT (Pages 4-30 4-31, 4-32, 4-33, and 4-34)	**Chemical attack by air – Temperature distributions** (Impact of graphite oxidation on temperature distribution through material)	Depressurization Accident with Air Ingress	Buffer Layer	Medium
				Inner PyC Layer	Low or Medium
				SiC Layer	Medium
				Outer PyC Layer	Low or Medium
				Fuel Element	Medium

Appendix B

NGNP PIRT – High-Importance Phenomena

An independent (row by row) review of NGNP PIRT Table 7 through Table 11 found in Section 4 of the NGNP PIRT report was conducted. All FCP that were evaluated as high importance by a majority (2 out of 3) of the panel and where the knowledge level was judged to be either low or medium by any two members of the panel are included in Table B 1 below.

Table B 1. High importance NGNP phenomena.

ID	Source	High Importance Factor, Characteristic, or Phenomenon	Plant Condition	Component	Knowledge Level (KL)
1.	NGNP - Accident and Thermal Fluids (ACTH) PIRT Panel Results				
1.1	Table 7 NGNP PIRT	**Core bypass flow** (Determines active core cooling; affects maximum fuel temperature)	Normal Operations and Accidents	Fuel	Low
1.2	Table 7 NGNP PIRT	**Pebble-bed core wall interface effects on bypass flow** (Diversion of some core cooling flow. Number of pebbles across impacts interface effects)	Normal Operations	Fuel	Low
1.3	Table 7 NGNP PIRT	**Reactivity-temperature feedback coefficients** (Affects core transient behavior)	Normal Operations	Fuel	Low
1.4	Table 7 NGNP PIRT	**Fuel performance modeling** (Fuel type dependent. Crucial to design and siting; depends on performance envelope, quality assurance, quality control, etc.)	Normal Operations and Accidents	Fuel	Low
1.5	Table 7 NGNP PIRT	**Core effective thermal conductivity** (Affects maximum fuel temperature for Depressurized Loss-of-Forced Cooling accident	Depressurized Loss-of-Forced Cooling accident	Fuel	Medium
1.6	Table 7 NGNP PIRT	**Power and flux profiles (initial conditions for accidents)** (Affects fuel potential for failures in accident conditions due to long-term exposures)	Normal Operations	Fuel	Medium
1.7	Table 7 NGNP PIRT	**Decay Heat (temporal and spatial)** (Time dependence and spatial distribution major factors in estimated maximum fuel temperature)	General: Loss-of-Forced Cooling Accidents	Fuel	Medium
1.8	Table 7 NGNP PIRT	**Fuel performance with oxygen attack** (Consideration for long-term air ingress involving core [fueled area], oxidation; fission product releases observed for high-temperature exposures)	Loss-of-Forced Cooling with Air Ingress	Fuel	Medium
1.9	Table 7 NGNP PIRT	**Phenomena (various accident conditions) that affect cavity gas composition and temperature with inflow** (Provides gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties. Possible entrainment through relief valve, etc.)	Loss-of-Forced Cooling Accident with Air Ingress	Fuel	Medium

ID	Source	High Importance Factor, Characteristic, or Phenomenon	Plant Condition	Component	Knowledge Level (KL)
1.10	Table 7 NGNP PIRT	**Confinement-to-reactor cavity air ingress** (Determines long-term oxidation rate if accident is unchecked)	Loss-of-Forced Cooling Accident with Air Ingress	Fuel	Medium
1.11	Table 7 NGNP PIRT	**Reactivity-temperature feedback coefficients (fuel, moderator, and reflectors)** (Affects passive safety shutdown characteristics)	Reactivity Accident	Fuel	Medium
1.12	Table 7 NGNP PIRT	**Core oxidation** (Determination of "where" in core the oxidation would take place, graphite oxidation kinetics affected by temperature, oxygen content of air, and irradiation of graphite)	Loss-of-Forced Cooling Accident with Air Ingress	Fuel and Core	Medium
1.13	Table 7 NGNP PIRT	**Molecular diffusion** (Air remaining in the reactor cavity enters into reactor vessel by molecular diffusion, prior to onset of natural circulation)	Loss-of-Forced Cooling Accident with Air Ingress	Core Support and Fuel	Medium
1.14	Table 7 NGNP PIRT	**Core support structure oxidation** (Low-temperature oxidation potentially damaging to structural strength)	Loss-of-Forced Cooling Accident with Air Ingress	Core Support and Fuel	Medium
1.15	Table 7 NGNP PIRT	**Outlet plenum flow distribution** (Affects mixing thermal stresses in plenum and downstream, outlet pressure distribution)	Normal Operations	Core Support Structures	Low
1.16	Table 7 NGNP PIRT	**Vessel and RCCS Panel emissivity** (Radiant heat transfer from vessel to RCCS affects heat transfer process at accident temperatures)	General: Loss-of-Forced Cooling Accidents	Vessel	Medium
1.17	Table 7 NGNP PIRT	**Reactor vessel cavity air circulation and heat transfer** (Affects upper cavity heating)	All Conditions	Vessel	Low
1.18	Table 7 NGNP PIRT	**Cavity filtering performance** (Affects radioactive dust releases; dust can contribute to the source term for PBR)	Loss-of-Forced Cooling Accident with Air Ingress	Reactor Cavity	Medium
1.19	Table 7 NGNP PIRT	**Fission product transport through intermediate heat exchanger loop (part of confinement bypass)** (Deposit/removal of fission products, dust, scrubbing of molten salt, adsorption, plate-out)	Intermediate Heat Exchanger Failure (Molten Salt)	Primary System; Secondary Side	Medium
1.20	Table 7 NGNP PIRT	**Ag-110m release and plate-out** (A function of fuel type, burnup, and temperature; could be a maintenance [dose] problem for gas turbine maintenance [if direct-cycle])	All Conditions	Primary and Secondary System Hardware	Low

ID	Source	High Importance Factor, Characteristic, or Phenomenon	Plant Condition	Component	Knowledge Level (KL)
2.	NGNP - Fission Product Transport PIRT Panel Results				
2.1	Table 8 NGNP PIRT	**Fuel-damaging reactivity-initiated accident (RIA)** (An intense pulse could damage fuel. Increases source by expected to affect transport path)	Reactivity Accident	Fuel	Medium
2.2	Table 8 NGNP PIRT	**Re-criticality (slow)** (Effect on fission products not completely known)	All Conditions	Core	Medium
2.3	Table 8 NGNP PIRT	**Dust generation**	All Conditions	Fuel and Primary Coolant System	Medium
2.4	Table 8 NGNP PIRT	**Fission product plate-out and dust distribution under normal operation**	Normal Operations	Fuel and Primary Coolant System	Medium
2.4	Table 8 NGNP PIRT	**Fission product speciation in carbonaceous material**	All Conditions	Graphite and Fuel	Low
2.5	Table 8 NGNP PIRT	**Steam attack on graphite**	All Conditions	Graphite and Fuel	Medium
2.6	Table 8 NGNP PIRT	**Matrix permeability, tortuosity**	All Conditions	Graphite and Core Materials	Low
2.7	Table 8 NGNP PIRT	**Fission product transport through matrix**	All Conditions	Graphite and Core Materials	Low
2.8	Table 8 NGNP PIRT	**Fuel block permeability, tortuosity**	All Conditions	Graphite and Core Materials	Medium
2.9	Table 8 NGNP PIRT	**Sorptivity of graphite**	All Conditions	Graphite and Core Materials	Medium
2.10	Table 8 NGNP PIRT	**Fluence effects on transport in graphite**	All Conditions	Graphite and Core Materials	Medium
2.11	Table 8 NGNP PIRT	**Air attack on graphite**	Loss-of-Forced Cooling Accident with Air Ingress	Graphite and Core Materials	Medium
2.12	Table 8 NGNP PIRT	**(De)Adsorption on dust**	All Conditions	Graphite in Primary System	Medium
2.13	Table 8 NGNP PIRT	**Material/structure properties (critical initial and/or boundary condition)**	All Conditions	Primary Coolant System	Medium (graphite)
2.14	Table 8 NGNP PIRT	**Thermal-fluid properties**	All Conditions	Primary Coolant System	Medium
2.15	Table 8 NGNP PIRT	**Gas Composition**	All Conditions	Primary Coolant System	Medium
2.16	Table 8 NGNP PIRT	**Fission product speciation during mass transfer**	All Conditions	Primary Coolant System	Medium

ID	Source	High Importance Factor, Characteristic, or Phenomenon	Plant Condition	Component	Knowledge Level (KL)
2.17	Table 8 NGNP PIRT	**Radiolysis effects in confinement**	All Conditions	Confinement	Medium
2.18	Table 8 NGNP PIRT	**Combustion of dust in confinement**	All Conditions	Confinement	Medium
2.19	Table 8 NGNP PIRT	**Confinement leakage path, release rate through penetrations**	All Conditions	Confinement	Medium
2.20	Table 8 NGNP PIRT	**Cable pyrolysis, fire**	All Conditions	Confinement	Medium
2.21	Table 8 NGNP PIRT	**Ag-110m generation and transport**	All Conditions	Primary Coolant System, Cavity, Confinement	Low
2.22	Table 8 NGNP PIRT	**Aerosol growth**	All Conditions	Primary Coolant System, Cavity, Confinement	Low
2.23	Table 8 NGNP PIRT	**Resuspension**	All Conditions	Primary Coolant System, Cavity, Confinement	Low
2.24	Table 8 NGNP PIRT	**Aerosol/dust deposition**	All Conditions	Primary Coolant System, Cavity, Confinement	Medium
2.25	Table 8 NGNP PIRT	**Fission product diffusivity, sorptivity in nongraphite surfaces**	All Conditions	Primary Coolant System and Confinement	Low
2.26	Table 8 NGNP PIRT	**Coolant chemical interaction with surfaces**	All Conditions	Primary Coolant System and Confinement	Medium
3.	NGNP - High Temperature Materials PIRT Panel Results				
3.1	Table 9 NGNP PIRT	**Composites structural design methodology limitations for new structures (lack of experience)** (Maintain insertion ability)	All Conditions	Control Rods (nonmetallic)	Low
3.2	Table 9 NGNP PIRT	**Crack initiation and propagation (due to creep crack growth, creep, creep-fatigue, aging [with or without load], subcritical crack growth)** (Integrity of the intermediate heat exchanger; secondary loop failure/breach; develop mechanistic models for materials)	All Conditions	Intermediate Heat Exchanger (IHX)	Low
3.3	Table 9 NGNP PIRT	**Primary boundary design methodology limitations for new structures (lack of experience)** (No experience for complex IHX shape or for designing and operating high-temp. components in safety class environment)	All Conditions	Intermediate Heat Exchanger (IHX)	Low
3.4	Table 9 NGNP PIRT	**Manufacturing phenomena (such as joining)** (Will require advanced machining, forming, and joining methods that may impact component integrity)	All Conditions	Intermediate Heat Exchanger (IHX)	Low

ID	Source	High Importance Factor, Characteristic, or Phenomenon	Plant Condition	Component	Knowledge Level (KL)
3.5	Table 9 NGNP PIRT	**Inspection/testing phenomena** (Preoperational testing, preservice inspection, etc.)	All Conditions	Intermediate Heat Exchanger (IHX)	Low
3.6	Table 9 NGNP PIRT	**Aging fatigue, environmental degradation of insulation** (Insulation debris plugging core cooling channels)	All Conditions	Piping	Low
3.7	Table 9 NGNP PIRT	**Change in emissivity** (High emissivity must be maintained to limit core temperatures)	All Conditions	Reactor Pressure Vessel (RPV) Internals (metallic)	Low
3.8	Table 9 NGNP PIRT	**Radiation-creep** (Maintain structure geometry; little information for alloy 800H)	All Conditions	Reactor Pressure Vessel (RPV) Internals (metallic)	Low
3.9	Table 9 NGNP PIRT	**Composites structural design and fabrication methodology limitations for new structures (lack of experience)** (Use of composite materials in core design must be determined)	All Conditions	Reactor Pressure Vessel (RPV) Internals (nonmetallic)	Low
3.10	Table 9 NGNP PIRT	**Environmental and radiation degradation and thermal stability at temperature** (Determine stability of fibrous insulation)	All Conditions	Reactor Pressure Vessel (RPV) Internals (nonmetallic)	Low
3.11	Table 9 NGNP PIRT	**Crack initiation and subcritical crack growth** (New materials must be assessed for applicable phenomena under environmental conditions)	All Conditions	Reactor Pressure Vessel (RPV)	Low
3.12	Table 9 NGNP PIRT	**Compromise of emissivity due to loss of desired surface layer properties** (New materials must maintain high emissivity to limit core temperatures)	All Conditions	Reactor Pressure Vessel (RPV)	Low
3.13	Table 9 NGNP PIRT	**Field fabrication process control** (Lack of experience in on-site nuclear vessel fabrication)	All Conditions	Reactor Pressure Vessel (RPV)	Low
3.14	Table 9 NGNP PIRT	**Property control in heavy sections** (Determine heavy-section properties for expected new vessel materials)	All Conditions	Reactor Pressure Vessel (RPV)	Low
3.15	Table 9 NGNP PIRT	**Thermal aging (long-term)** (Gather long-term data related to aging of base metals and welds for expected vessel materials)	All Conditions	Reactor Pressure Vessel (RPV)	Medium
3.16	Table 9 NGNP PIRT	**Isolation valve failure** (Primary system pressure boundary integrity for helium leak-tightness)	All Conditions	Valves	Low
3.17	Table 9 NGNP PIRT	**Valve failure (general)** (Address a variety of potential valve failure mechanisms that may be design-dependent)	All Conditions	Valves	Low

ID	Source	High Importance Factor, Characteristic, or Phenomenon	Plant Condition	Component	Knowledge Level (KL)
4.	NGNP - Graphite PIRT Panel Results				
4.1	Table 10 NGNP PIRT	**Irradiation-induced creep (irradiation-induced dimensional change under stress)** (Could potentially reduce significantly internal stress)	All Conditions	Graphite	Low
4.2	Table 10 NGNP PIRT	**Irradiation-induced change in coefficient of thermal expansion (CTE), including the effects of creep strain** (Prevent excessive mechanical loading)	All Conditions	Graphite	Low
4.3	Table 10 NGNP PIRT	**Irradiation-induced changes mechanical properties (strength, toughness), including the effect of creep strain (stress)** (Tensile, bend, compression, shear [multiaxial], stress-strain relationship, fracture, and fatigue strength)	All Conditions	Graphite	Low
4.4	Table 10 NGNP PIRT	**Statistical variation of non-irradiated properties** (Variability in properties (textural and statistical); isotropic. Probabilistic approach use is prudent. Purity level; implications for chemical attack, degradation, decommissioning)	All Conditions	Graphite	Medium
4.5	Table 10 NGNP PIRT	**Consistency in graphite quality over the lifetime of the reactor fleet (for replacement, for example)** (Need to predict irradiated graphite behavior)	All Conditions	Graphite	Medium
4.6	Table 10 NGNP PIRT	**Graphite contains inherent flaws** (Need methods for flaw evaluation)	All Conditions	Graphite	Medium
4.7	Table 10 NGNP PIRT	**Irradiation-induced dimensional change** (Largest source of internal stress)	All Conditions	Graphite	Medium
4.8	Table 10 NGNP PIRT	**Irradiation-induced thermal conductivity change** (Thermal conductivity lower than required by design basis licensing basis event (LBE) heat removal due to (a) inadequate database to support design over component lifetime and (b) variations in characteristics of graphites from lot to lot; potential is to exceed fuel design temperatures during LBEs)	Accident Conditions	Graphite	Medium
4.9	Table 10 NGNP PIRT	**Irradiation-induced changes in elastic constants, including the effects of creep strain** (Concept of increase in modulus due to “pinning”; better mechanistic understating is desirable)	All Conditions	Graphite	Medium
4.10	Table 10 NGNP PIRT	**Tribology of graphite in (impure) helium environment**	All Conditions	Graphite	Medium
4.11	Table 10 NGNP PIRT	**Blockage of fuel-element coolant channel – due to graphite failure, spalling** (Debris generated from withing the graphite core structures)	All Conditions	Graphite Component	Low

ID	Source	High Importance Factor, Characteristic, or Phenomenon	Plant Condition	Component	Knowledge Level (KL)
4.12	Table 10 NGNP PIRT	**Blockage of coolant channel in reactivity control block due to graphite failure, spalling** (Debris generated from nongraphite components withing the reactor pressure vessel [RPV])	All Conditions	Graphite Component	Low
4.13	Table 10 NGNP PIRT	**Blockage of reactivity control channel – due to graphite failure, spalling** (Debris generated from withing the graphite core structures)	All Conditions	Graphite Component	Low
4.14	Table 10 NGNP PIRT	**Degradation of thermal conductivity** (Has an implication for fuel temperature limit for loss-of-forced cooling accident)	Loss-of-Forced Cooling Accident	Graphite Component	Medium
4.15	Table 10 NGNP PIRT	**Graphite temperatures** (All graphite component life and transient calculations [structural integrity] require time-dependent and spatial predictions of graphite temperatures. Graphite temperatures for normal operations and transients are usually supplied to graphite specialists. However, in some cases, gas temperatures and heat transfer coefficients are supplied, and the graphite specialists calculate the graphite temperatures from these)	All Conditions	Graphite Component	Medium
4.16	Table 10 NGNP PIRT	**Tribology of graphite in (impure) helium environment**	All Conditions	Graphite Component	Medium
5.	NGNP - Process Heat and Hydrogen Co-Generation Production PIRT Panel Results				
5.1	Table 11 NGNP PIRT	**Fuel and primary system corrosion** (Process heat exchanger [PHX] failure)	All Conditions	Primary System SSCs	Medium
5.2	Table 11 NGNP PIRT	**Blow-down effects, large mass transfer; pressurization of either secondary or primary side [IHX failures])** (Fluid hammer; thermal and concentration gradients can work against the differential pressure such that chemicals can diffuse toward the IHX)	Accident Conditions	Primary System SSCs	Medium
5.3	Table 11 NGNP PIRT	**Loss of main heat sink (hydrodynamic loading on IHX; cutting margins down by increasing differential pressure over IHX; decrease operating life of IHX [loss of intermediate fluids])** (Rapid pulse cooling of reactor during depressurization of intermediate loop and IHX. Very rapid event. Self-closing valves act faster than instrumentation and controlssystem)	Accident Conditions	Primary System SSCs	Medium
5.4	Table 11 NGNP PIRT	**Reactivity spike due to neutron thermalization (mass addition to reactor; hydrogenous materials)** (Power spike in fuel grains, could lead to TRISO failure with prolonged high temperature)	Accident Conditions	Primary System SSCs; TRISO Fuel Coatings	Medium

ID	Source	High Importance Factor, Characteristic, or Phenomenon	Plant Condition	Component	Knowledge Level (KL)
5.5	Table 11 NGNP PIRT	**Chemical attack of TRISO layers and graphite (mass addition to reactor; hydrogenous materials)** (Steam and graphite react; TRISO. More concerned with gases produced in core by the steam, rather than the chemical attack on fuel. Pressure relief valve would open in primary loop releasing hydrogen into confinement)	Accident Conditions	Primary System SSCs; TRISO Fuel Coatings	Medium
5.6	Table 11 NGNP PIRT	**Allowable concentrations (oxygen releases)** (What oxygen levels cause damage?)	Accident Conditions	Safety System SSCs	Medium
5.7	Table 11 NGNP PIRT	**Spontaneous combustion (oxygen releases)** (What levels cause spontaneous combustion?)	Accident Conditions	SSCs	Medium