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Thermal Hydraulics Phenomena Identification and Ranking Table (PIRT) for Advanced High Temperature Reactor (AHTR)

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Executive Summary

A team of researchers, led by the Georgia Institute of Technology (GT) and including major collaborators from The Ohio State University (OSU), Texas A&M University College Station (TAMU), Texas A&M University Kingsville (TAMU-K), Oak Ridge National Laboratory (ORNL), and AREVA, as well as international partners at University of Zagreb, Politecnico di Milano, and Shanghai Institute of Applied Physics (SINAP) contribute to investigation of technology gaps and licensing challenges of Fluoride salt-cooled High-temperature Reactor (FHR) under the current integrated research project (IRP). The most recent version of the Advanced High Temperature Reactor (AHTR), an FHR pre-conceptual design by ORNL, is selected as a candidate design for analysis and technology development.

An FHR thermal hydraulics Phenomena Identification and Ranking Table (PIRT) panel was assembled and met at OSU on May 24-26, 2016, which was organized by OSU and ORNL. The primary objective of the thermal hydraulics PIRT exercise is to identify key phenomena that require further detailed study and impose challenges on thermal hydraulics codes/methodologies to support AHTR licensing. The thermal hydraulics PIRT exercise provides guidance and insights in designing separate-effect and integral-effect tests for validation of thermal hydraulics codes. The thermal hydraulics PIRT panel consisted of fifteen experts specialized in salt reactor technologies, reactor thermal hydraulics, and code and methods development. Eleven out of the fifteen panelists were voting members while all the panelists actively participated during this PIRT panel meeting. Some student observers from GT, University of California-Berkeley, and OSU also attended this thermal hydraulics PIRT exercise.

This report discussed steps of developing a PIRT, FOM (Figures of Merit) and phenomena identification in Chapter 2. Chapter 3 reviewed AHTR thermal hydraulics design since the PIRTs were categorized based on regions of the reactor, including reactor core, vessel, cavity, primary loops, intermediate loops, and Direct Reactor Auxiliary Cooling System (DRACS). Two scenarios, i.e., station blackout and simultaneous withdrawal of all control rods, were discussed in detail during the workshop. The PIRT results and modeling path forward of these two events were reported in Chapters 4 and 5. For the two identified scenarios, the PIRTs consisted of phenomena, FOM of each phenomenon, importance level, knowledge level, and comments from the panelists. Chapter 6 summarized the phenomena which need further work and research for FHR analysis to support of reactor licensing and the verification and validation (V&V) of thermal hydraulics system-level analysis codes and computational fluid dynamics (CFD) simulation tools for FHRs.

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List of Abbreviations

AHTR	Advanced High Temperature Reactor
C-C	Carbon-Carbon
CFD	Computational Fluid Dynamics
CHM	Carbon to Heavy Metal
DHX	DRACS Heat Exchanger
DOE	U.S. Department of Energy
DRACS	Direct Reactor Auxiliary Cooling System
FHR	Fluoride High-Temperature Reactor
FOM	Figure of Merit
IRP	Integrated Research Project
I-PHX	Intermediate to Power Loop Heat Exchanger
LOCA	Loss of Coolant Accident
MSRE	Molten Salt Reactor Experiment
NDHX	Natural Draft Heat Exchanger
ORNL	Oak Ridge National Laboratory
OSU	The Ohio State University
P-IHX	Primary to Intermediate Heat Exchanger
PIRT	Phenomena Identification and Ranking Table
TMSR	Thorium Molten Salt Reactor Energy System
TRISO	Tristructural-Isotropic
V&V	Verification and Validation

1. Introduction

1.1. Overview

Fluoride-salt-cooled High-temperature Reactor (FHR) is one of the advanced reactor designs that combines improved technologies including low-pressure fluoride salt coolant, coated particle fuel (TRISO particles), Brayton power cycles, and passive safety systems. FHRs obtain several advantages including increased efficiency, low operation pressure, high core power density and high safety feature (Forsberg, 2005; Bardet et al., 2008). The Advanced High-Temperature Reactor (AHTR) is a FHR design concept proposed by Oak Ridge National Laboratory (ORNL). This report documents a thermal hydraulics Phenomena Identification and Ranking Table (PIRT) exercise for AHTR. The thermal hydraulics PIRT exercise was organized by The Ohio State University (OSU) and ORNL.

The primary objective of the thermal hydraulics PIRT exercise panel was to identify key phenomena requiring further detailed study and requirements on thermal hydraulics codes/methodologies to support AHTR licensing. The PIRT process identifies and ranks safety relevant phenomena that impact the fidelity of thermal hydraulics analysis for AHTR, and determines needed new databases, modeling, and detailed analysis to validate simulation tools and methods. In addition, PIRT provides guidance and insights in designing separate-effect and integral-effect experimental programs for validation of thermal hydraulics codes. A two and a half day thermal hydraulics PIRT panel workshop was held at the OSU from May 24 to 26, 2016. The thermal hydraulics PIRT panel consisted of fifteen experts specialized in salt reactor technologies, reactor thermal hydraulics, code and method development. Some student observers from GT, University of California-Berkeley, and OSU also attended this thermal hydraulics PIRT exercise.

Table 1 shows a subset of the initial proposed scenarios and the figures of merit (FOM) to be discussed during the workshop. However, due to time constraint, only the first two scenarios, including station blackout and simultaneous withdrawal of all control rods were discussed and evaluated in detail.

Table 1. A list of initially proposed scenarios and FOM for discussion

Scenario	FOM
Station blackout	Peak vessel temperature Average temperature increase of carbonaceous materials in the core Peak temperature of the DHX Coolant temperature of the NDHX
Simultaneous withdrawal of all control rods	Hot leg temperature Maximum kernel temperature
Flow blockage	Peak fuel temperature Percentage of flow decrease
Loss of coolant accident (LOCA)	Concrete temperature Stainless steel temperature

1.2. Report Organization

A detailed discussion of the thermal hydraulics PIRT exercise process, including thermal hydraulics PIRT panelists, scenario description, etc., is given in Chapter 2. The thermal hydraulics PIRT during the meeting were categorized based on region of the reactor, including reactor core, vessel, cavity, primary loops, intermediate loops and Direct Reactor Auxiliary Cooling System (DRACS). Therefore, the AHTR thermal hydraulics design is reviewed in Chapter 3. Chapters 4 and 5 provide the information, such as phenomena identification and ranking, knowledge level ranking, the path forward, etc., for the events of station blackout and simultaneous withdrawal of all control rods, respectively. Chapter 6 summarizes the phenomena which need further work and research for FHR analysis to support of reactor licensing and the verification and validation (V&V) of thermal hydraulics system-level analysis codes and computational fluid dynamics (CFD) simulation tools for FHRs.

2. Overview of the PIRT Process

2.1. Background

The thermal hydraulics PIRT exercise is an expert elicitation process with the phenomena ranking tables as the final output. The PIRT approach has been utilized in the nuclear industry for new reactor designs. The U.S. NRC developed the PIRT process for the next generation nuclear plant (Ball et al., 2008), which is beneficial for developing the AHTR thermal hydraulics PIRT.

2.2. Thermal Hydraulics PIRT Panelist

The thermal hydraulics PIRT panel consisted of fifteen experts specialized in salt reactor technologies, reactor thermal hydraulics, code developers and method developers. The panel members are listed in Table 2 and only the first twelve experts are voting members. In addition to panelists listed in Table 2, there were eleven observers, including Pietro Avigni from Georgia Institute of Technology, Nicholas Brown from Oak Ridge National Laboratory, James Kendrick and Xin Wang from University of California Berkeley, Chong Zhou from Shanghai Institute of Applied Physics, and Hsun-Chia Lin, Shanbin Shi, Xiao Wu, Junlian Yin, Sheng Zhang and Xiaoqin Zhang from The Ohio State University. David Diamond led the thermal hydraulics PIRT panel discussions and acted as the facilitator for the process.

Table 2. Thermal hydraulics PIRT exercise panelists and organization

Name	Organization
David Diamond (Facilitator)	Brookhaven National Laboratory
Syd Ball	Oak Ridge National Laboratory
Stephen Bajorek	U.S. Nuclear Regulatory Commission
Kun Chen	Shanghai Institute of Applied Physics
Richard Christensen	The Ohio State University
Richard Denning	The Ohio State University
Yujun Guo	Canada Nuclear Safety Commission
Prashant Jain	Oak Ridge National Laboratory
Brian Mays	AREVA
W. David Pointer	Oak Ridge National Laboratory
Kevin Robb	Oak Ridge National Laboratory
Carl Stoots	Idaho Ridge National Laboratory
David Holcomb*	Oak Ridge National Laboratory
Xiaodong Sun*	The Ohio State University
Grady Yoder*	Oak Ridge National Laboratory

*: Non-voting members

2.3. Thermal Hydraulics PIRT Exercise Process

The panelists were first provided with the following three introductory presentations:

- “The PIRT Process-Application to FHR Thermal Hydraulics” by David Diamond;
- “Review of Advanced High-Temperature Reactor (AHTR) Thermal Hydraulic Design” by Hsun-Chia Lin;
- “Summary of the White Paper prepared for FHR Thermal Hydraulics PIRT Panel” by Xiaodong Sun.

Following the introduction, the panelists discussed AHTR design issues and finalized scenarios of interest in AHTR to be discussed by the panel. The panelists then identified and ranked phenomena in each scenario. PIRT panelists finally reviewed and commented on the established phenomena ranking tables.

A detailed PIRT consists of the following nine steps (Ball et al., 2008):

Step 1: Define the issue that is driving the need for a PIRT;
Step 2: Define the specific objectives for the PIRT;
Step 3: Define the hardware and the scenario for the PIRT;
Step 4: Define the evaluation criterion;

Step 5: Identify, compile, and review the current knowledge base;
Step 6: Identify plausible phenomena, that is, PIRT elements;
Step 7: Develop importance ranking for phenomena;
Step 8: Assess knowledge level for phenomena; and
Step 9: Document PIRT results.

2.3.1. Step 1: Define the Issue

The objective of this step is to define the issue for AHTR future licensing applications. Issues related to AHTR safety should be identified. The definition may start with safety goals and descend to a consideration of important physical processes.

2.3.2. Step 2: Define the Specific Objectives

The objective of the thermal hydraulics PIRT exercise panel was to determine the important phenomena that impact the fidelity of thermal hydraulics analysis for the AHTR and determine where new databases, modeling, and detailed analysis need to be performed to validate computer codes and methods. In addition, it also provides guidance in establishing the requirements for separate-effects and integral-effects experimental programs in support of the AHTR licensing.

2.3.3. Step 3: Define the Hardware and Scenario

The AHTR design is the subject of this PIRT exercise. Four scenarios of the AHTR, including station blackout, simultaneous withdrawal of all control rods, reactor core flow blockage, and loss of coolant accident (LOCA) were proposed by the panelist. However, due to the limited time available (two and a half days), two scenarios, station blackout and simultaneous withdrawal of all control rods were selected for detailed discussion.

2.3.4. Step 4: Define the Evaluation Criterion

FOM defines the evaluation criterion. Since FOM depend on the scenario, each scenario has different FOM.

For the event of station blackout, the four FOM identified were:

- FOM_1: Peak vessel temperature
- FOM_2: Coolant temperature of the natural draft heat exchanger (NDHX)
- FOM_3: Peak temperature of the DRACS heat exchanger (DHX)
- FOM_4: Average temperature increase of carbonaceous materials in the core

For the event of station blackout, active cooling systems, such as the power conversion cycle loops, the maintenance cooling system, are out of commission. Although the DRACS are under operation, the three DRACS release only 0.75% of nominal thermal power. Therefore, vessel temperature may increase dramatically and affect its integrity. Thus, the peak vessel temperature was selected as a FOM for the event of station blackout. The coolant in the NDHX may freeze due to overcooling by the air and thus reduces DRACS cooling performance. Thus, the coolant temperature of the NDHX was selected as another FOM for the event of station blackout. Peak temperature of the

DHX is selected as a FOM for the event of station blackout because it affects DRACS cooling performance by influencing the integrity of the DHX. Average temperature increase of carbonaceous materials in the core is selected as a FOM for the event of station blackout because it characterizes stored energy in carbonaceous materials which may delay and reduce vessel temperature increase. Temperature increase in the carbonaceous materials will also lead to potential tritium release. Furthermore, the amount of tritium released also depends on the original amount of tritium retained in carbonaceous materials.

For the event of simultaneous withdrawal of all control rods, the two FOM identified were:

- FOM_1: Hot leg temperature
- FOM_2: Maximum kernel temperature

When all control rods are withdrawn at one time, a positive reactivity is introduced making the reactor supercritical. Although the primary pumps are operating, the coolant temperature may still increase significantly. The hot leg temperature is the maximum temperature of the entire primary loop; it may exceed the structural material melting temperature and thus affects primary loop integrity. As for maximum kernel temperature, it was selected because of its significant influence on kernel integrity.

For reactor core flow blockage, two FOM identified were:

- FOM_1: Percentage of flow decrease
- FOM_2: Peak fuel temperature

Under reactor core flow blockage condition, temperature increase of blocked assemblies depends on the percentage of flow decrease. Therefore, the percentage of flow decrease was selected as a FOM for reactor core flow blockage. For the second FOM, the peak fuel temperature has a large effect on fuel integrity.

For LOCA, two FOM identified were:

- FOM_1: Concrete temperature
- FOM_2: Stainless steel temperature

Concrete temperature was selected as a FOM for LOCA because it affects concrete integrity. Stainless steel temperature was selected as a FOM because that its temperature affects integrity of structure material such as guard vessel.

2.3.5. Step 5: Identify, Compile, and Review the Current Knowledge Base

PIRT Panel members reviewed the thermal hydraulics whitepaper and relevant references. In addition, presentations at the meeting were beneficial for panelists to develop an understanding of current knowledge base related with AHTR technologies.

2.3.6. Step 6: Identify Plausible Phenomena

Systems and components in AHTR were defined and classified by panelists as follows,

- Core: fuel, primary coolant
- Vessel/internals/cavity: upper plenum, lower plenum, fluidic diode, reactor vessel, cavity
- Primary loop: pump, piping, primary to intermediate heat exchanger (P-IHX)
- Intermediate loop: pump, piping, P-IHX, intermediate to power loop heat exchanger (I-PHX)
- Power conversion loop: I-PHX
- DRACS: piping, DHX, NDHX, DRACS salt, chimney

Phenomena for each scenario was identified, defined, and documented in Chapter 4 and 5.

2.3.7. Step 7: Develop Importance Ranking

After the phenomena had been identified, phenomena importance ranking level was decided by panelists based on its effects on the FOMs. Table 3 shows the phenomena importance ranking and rationale. Under consideration of its importance to each FOM in a specific scenario, panelists then voted for each phenomenon, and phenomena importance ranking is then solidified by averaging the votes.

Voting members classified each phenomenon as having a large effect (High), moderate effect (Medium), or small effect (Low) on one FOM in a specific scenario. Votes for High (H), Medium (M), and Low (L) importance were assigned numerical scores of 8, 5, and 2, respectively. If the average was larger than 6.5, the importance was assigned as High. If the average was between 3.5 and 6.5, the importance was assigned as Medium. If the average was below 3.5, the importance was set to Low.

Table 3. Phenomena importance ranking and rationale (Ball et al., 2008)

Ranking	Description
High (H)	Significant or dominant influence on FOM
Medium (M)	Moderate influence on FOM
Low (L)	Small influence on FOM (including the possibility that the phenomena is not present or possible)

2.3.8. Step 8: Assess Knowledge Level

Similar to Step 7, panelists voted for the knowledge level of each phenomenon. In this step, knowledge level was classified as known (K), partially known (P), and unknown (U). Table 4 shows knowledge level ranking and rationale. If more than 75% of voting members ranked one phenomenon as known, it was set to known. If less than 25% of voting members ranked one phenomenon as unknown, it was set to unknown. Otherwise, it was set to partially known.

Table 4. Knowledge level ranking and rationale (Ball et al., 2008)

Ranking	Description
Known (K)	Phenomenon is well understood and can be accurately modeled
Partially Known (P)	Phenomenon is understood, however, can only be modeled with moderate uncertainty
Unknown (U)	Phenomenon is not well understood. Modeling is current either not possible or is possible only with large uncertainty

After phenomena importance ranking and knowledge level ranking, we then moved to determine the phenomena that need further consideration. Table 5 shows the phenomena determination rules for further consideration. As can be seen from the table, phenomena under three combinations of importance ranking and knowledge level require further consideration: 1) the importance ranking is high (H) and knowledge level is partially known (P), 2) the importance ranking is high (H) and knowledge level is unknown (U), and 3) the importance ranking is medium (M) and knowledge level is unknown (U).

Table 5. Determination of phenomena for further consideration

		Importance Ranking (IR)		
		H	**M**	**L**
	K			
	P	YES		
	U	YES	YES	

2.3.9. Step 9: Document PIRT Results

PIRT results, including phenomena definition, importance ranking, knowledge level ranking, rationale for all rankings, next steps for phenomena that need further consideration and prioritization of next steps should be documented in this step.

3. Introduction of AHTR

In parallel to the effort have organized by Georgia Tech in developing a neutronics PIRT, researchers at OSU and ORNL are organizing a thermal hydraulics PIRT exercises for the AHTR. To be consistent, the AHTR conceptual design developed by ORNL was selected as the reference design for the present thermal hydraulics PIRT study. In the subsequent sections, a general overview of the ORNL AHTR conceptual design will be presented, focusing on the thermal hydraulics related design including core, reactor vessel, reactor coolant systems and reactor safety system in the AHTR. The information presented hereafter is mainly based on the partially optimized AHTR design report by Varma et al. (2012), supplemented by an earlier AHTR design report by Holcomb et al. (2011).

3.1. General Overview of the AHTR Plant Design

The AHTR is an FHR design concept with a thermal power output of 3400 MW. The AHTR consists of three primary loops and three intermediate loops that are coupled to a supercritical water power cycle. The molten salt FLiBe (2LiF-BeF_2), which was extensively investigated in the Molten Salt Reactor Experiment (MSRE) project, is adopted as the AHTR primary coolant, while a mixture of KF and ZrF_4 featuring a low melting point is used as the intermediate coolant. The AHTR relies on three DRACS loops for passive decay heat removal. The DRACS also employs KF-ZrF_4 as the coolant in the DRACS secondary circuit that is coupled to the ultimate heat sink, the ambient air.

The main heat transfer paths for the AHTR are illustrated in Figure 1. The reactor core is divided into the central core region and the outer annular downcomer region through the barrel structure. During the normal operation, the forced flow provided by the pump first enters the reactor vessel, flowing downward in the downcomer, turning around at the lower plenum, flowing upward and being heated up in the core region, and then flowing toward the P-IHX. The primary coolant exchanges heat with the intermediate coolant in the P-IHX, while the latter eventually transfers heat to the supercritical water power cycle. In parallel to the main forced flow through the core during normal operation, there is also a small forced flow passing the DHX, transferring heat to the DRACS coolant and maintaining it in the liquid state. A fluidic diode is employed to limit this parasitic secondary flow (in the reverse flow direction of the fluid diode) and, accordingly, the parasitic heat loss into the DRACS during reactor normal operation. Upon the loss of the forced flow and reactor shutdown, a natural circulation flow will develop in the forward flow direction of the fluidic diode featuring low flow resistance in the primary salt pool. This will transfer heat to the DRACS loop and, ultimately, to the air through natural circulation/convection.

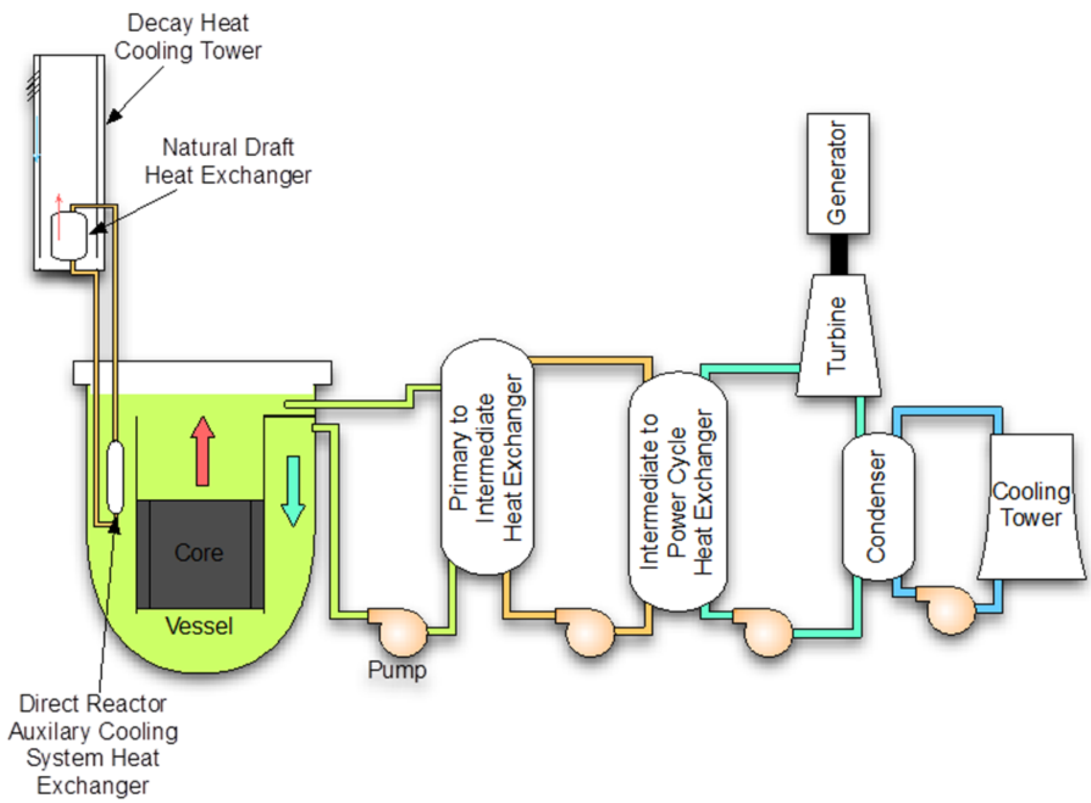

Figure 1. AHTR heat transfer paths (Varma et al., 2012)

The general AHTR plant design parameters are summarized in Table 6. The average core outlet temperature is limited to 700 ºC, mainly due to the limits imposed by the ASME code for the structural materials. Due to the high melting point and low vapor pressure of the adopted fluoride salt coolants, the entire AHTR except the power cycle is operated at the atmospheric pressure. The AHTR utilizes the TRISO particle embedded in graphite plates with a fuel enrichment of 9.00 wt% (vs 19.75 wt% in the first report by Holcomb et al., (2011)). Details on the core and heat transfer loop designs will be provided in the following sections. They can also be found in the two reference reports (Holcomb et al., 2011; Varma et al., 2012).

Table 6. AHTR general design parameters (Varma et al., 2012)

Parameter	**Value**	**Unit**
Core Thermal Power	3,400	MW
Net Electrical Power	1,530	MW
Fuel Type	TRISO	-
Fuel Enrichment	9.00	wt%
Primary Coolant Salt	$2LiF\text{-}BeF_2$	-
Core Outlet Temperature	700	^oC
Core Inlet Temperature	650	^oC
Primary Coolant Flow Rate	28,500	kg/s
Primary Coolant Pressure	Atmospheric	-
Number of Primary Loops	3	-
Intermediate Coolant Salt	$53\%KF\text{-}47\%ZrF_4$	-
Intermediate Loop Hot Leg Temperature	675	^oC
Intermediate Loop Cold Leg Temperature	600	^oC
Intermediate Coolant Flow Rate	43,200	kg/s
Intermediate Coolant Pressure	Atmospheric	-
Number of Intermediate Loops	3	-
Fluid to High Pressure Turbine	Supercritical Steam	-
Turbine Supply Temperature	650	^oC
Turbine Supply Pressure	24	MPa
DRACS Loop Coolant	$53\%KF\text{-}47\%ZrF_4$	-
DRACS Loop Pressure	Atmospheric	-
DRACS Heat Sink	Air	-
Number of DRACS Loops	3	-
Single DRACS Loop Maximum Power	8.75	MW

3.2. AHTR Neutronics Design

The AHTR neutronics preconceptual design was first developed by Holcomb et al. (2011), and subsequently refined by Varma et al. (2012). In the new design, the AHTR fuel enrichment has been lowered to 9.00 wt% from the old design value of 19.75 wt% and the carbon-to-heavy metal (CHM) atomic ratio has been raised from 200 to 400 to minimize the fuel cost, as well as the enrichment cost. In addition, a higher density carbonaceous matrix material (1.75 kg/m^3) has been employed in the new design to achieve higher discharge burnup. The main neutronics design characteristics of the refined AHTR baseline model are summarized in Table 7. Further details of the neutronics design of the referenced AHTR, including the core power distribution, burnable poison, etc., can be found in the two ORNL reports (Holcomb et al., 2011; Varma et al., 2012).

Table 7. Main refined AHTR neutronics design characteristics (Varma et al., 2012)

Parameter	Value	Unit
Core Thermal Power	3,400	MW
Assembly Lattice Type	Hexagonal	-
Fuel Type	TRISO	-
Moderator	Graphite	-
Reflector	Graphite	-
Core Height (including axial reflector)	6.0	m
Core Diameter (including radial reflector)	9.56	m
Average Power per Grain	77	MW/particle
Average Power Density in Fueled Region	97	W/cm^3
Volumetric Core Power Density	12.9	MW/m^3
Mass of Heavy Metal (fresh core)	17.48	MT
Fuel Enrichment	9.00	wt%
Mass of Fissile	1.6	MT
Fuel Cycle Length (once-through, no BP)	0.80	years
Fuel Cycle Length (once-through, with BP)	0.72	years
Fuel Residence Time in Core (two batch)	1.0	years
Average Fuel Discharge Burnup	71	GWd/MT-heavy metal
Maximum Fuel Temperature (average assembly)	837	^oC

3.3. AHTR Thermal Hydraulics Design

In this section, the design specifications and parameters of the AHTR components that are related to the thermal hydraulics PIRT exercises are reviewed.

3.3.1. Reactor Vessel

The AHTR reactor vessel design parameters are listed in Table 8. The reactor vessel is approximately in a cylindrical shape and hung from its upper flange to minimize the vessel stresses due to thermal expansion during heat-up, as shown in Figure 2.

Table 8. AHTR reactor vessel design parameters (Varma et al., 2012)

Parameter	Value	Unit
Exterior Vessel Diameter	10.5	m
Vessel Height	19.1	m
Primary Salt Depth Above Upper Support Plate	7.15	m
Primary Piping Interior Diameter	1.24	m
Primary Salt Mass	3,076	MT
Number of DRACS Loops	3	-
Core Barrel Material	C-C Composite	-
Vessel and Primary Piping Material	Incoloy 800H w/Hastelloy N Lining	-
Number of Fuel Assemblies	252	-
Upper and Lower Core Support Plates	SiC-SiC Composite	-

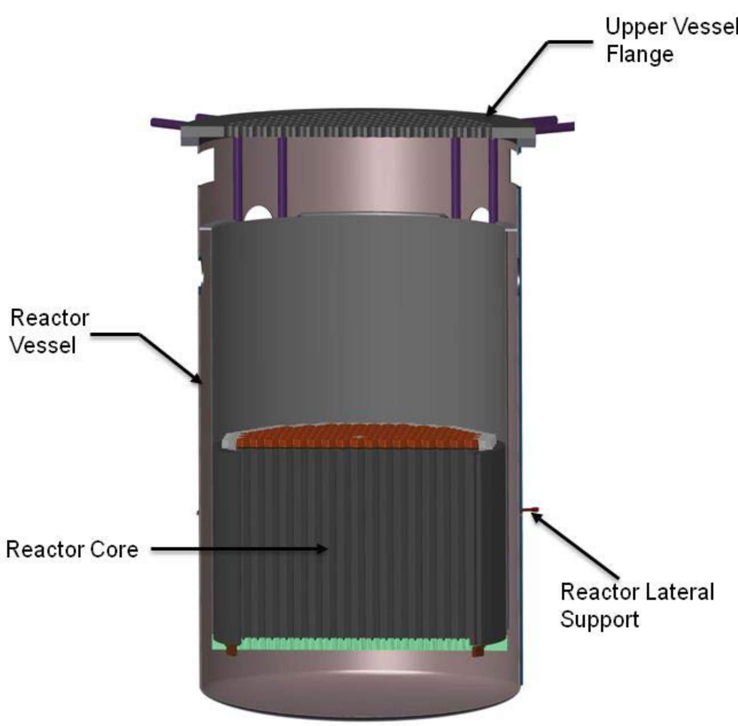

Figure 2. Sectional view of the AHTR reactor vessel (Varma et al., 2012)

The reactor vessel is made from Incoloy 800H, which features a high allowable yield strength of 20 MPa at 700ºC. Due to the potential corrosion attack by the FLiBe coolant, a thin liner (1 cm thick) of Hastelloy N is applied to the interior of the Incoloy 800H vessel. The vessel thickness is not provided in the ORNL reports; however, it should not be difficult to make an estimate based on the ASME code requirements. The top flange, as shown in Figure 3, is in a disk shape with a diameter of 11.6 m and a thickness of 35 cm. The flange consists of a truss structure fabricated by two 1.5-cm thick stainless-steel top and bottom plates to reduce weight.

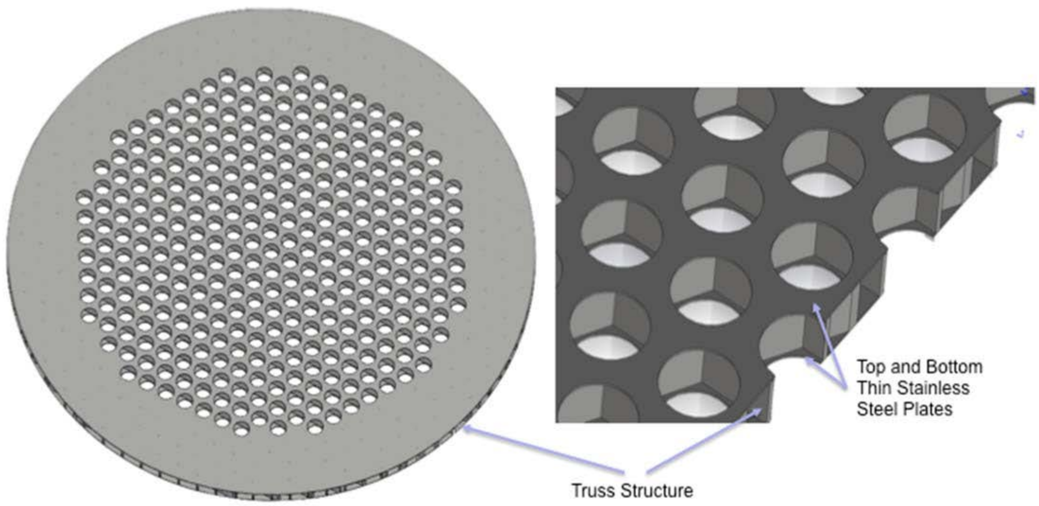

Figure 3. Top flange of the AHTR reactor vessel (Varma et al., 2012)

3.3.2. Reactor Core

The reactor core consists of 252 fuel assemblies supported by the upper and lower support plates, as shown in Figure 4. The core design features a moderator block in the center and a row of hexagonal replaceable reflector assemblies surrounding the fuel assemblies. The central moderator block and the replaceable reflector assemblies are made of graphite and have the same size and shape as the fuel assemblies. Outside of the reflector assemblies are a permanent graphite reflector and a 2-cm thick carbon-carbon (C-C) composite core barrel. The interior surface of the barrel facing the core has a 1-cm thick boron carbide plating to reduce the neutron radiation to the reactor vessel. The annulus formed between the barrel and reactor vessel is vertically divided into eight compartments, including three downcomer regions, three DRACS heat exchanger regions, one maintenance cooling system, and one refueling lobe, as shown in Figure 5.

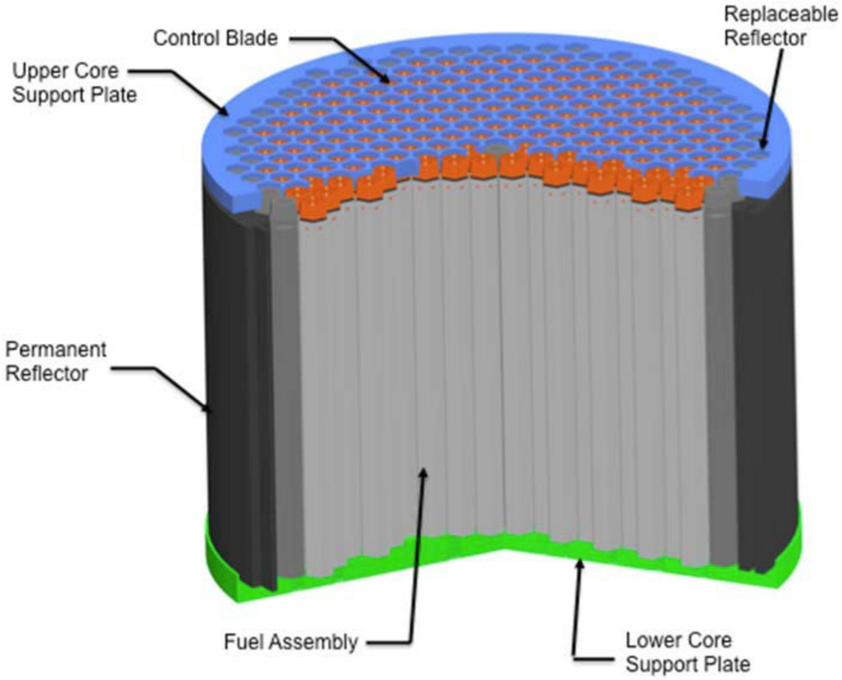

Figure 4. Cross-sectional view of the reactor core (Varma et al., 2012)

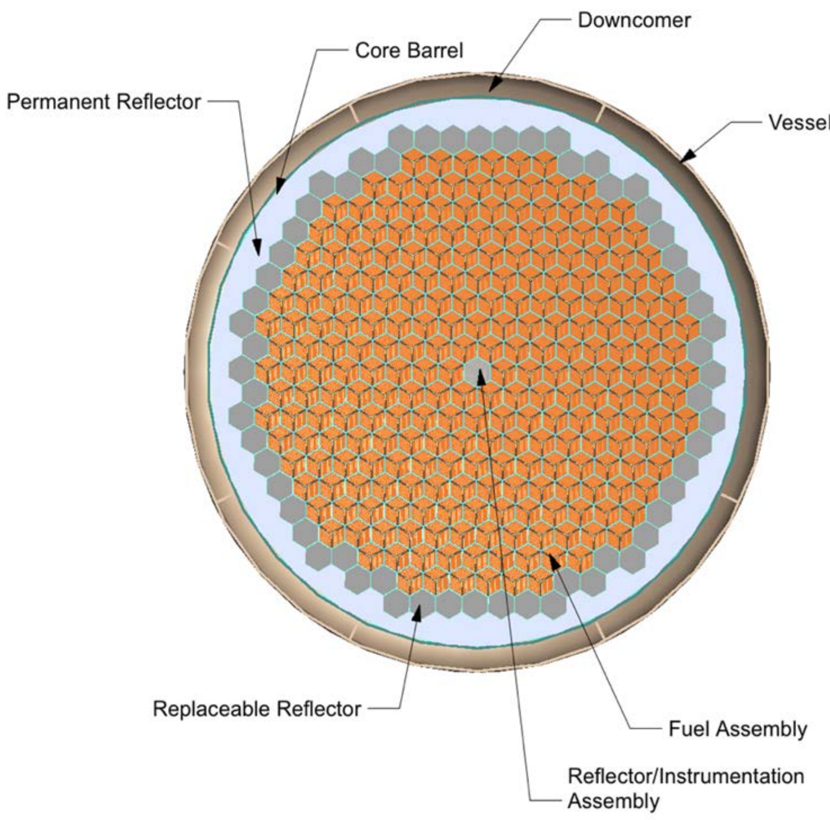

Figure 5. Cross-sectional view of the reactor vessel (Varma et al., 2012)

The lower core support plate provides support to the reactor core. This plate has a honeycomb structure made from 35-cm thick SiC-SiC composite pieces. Channels are fabricated in the lower support plate to direct the flow into the fuel assemblies, as shown in Figure 6. In addition, indexing holes and guides are fabricated to assist with the alignment of the fuel assemblies, which have a gap distance of 1.75 cm with the neighboring fuel assemblies. The main function of the upper core support plate is to align and hold the fuel assemblies in place against the upward flowing salt during reactor operation. The upper support plate is made from the same material and has the same thickness as the lower support plate. The geometric parameters of the AHTR reactor core are summarized in Table 9.

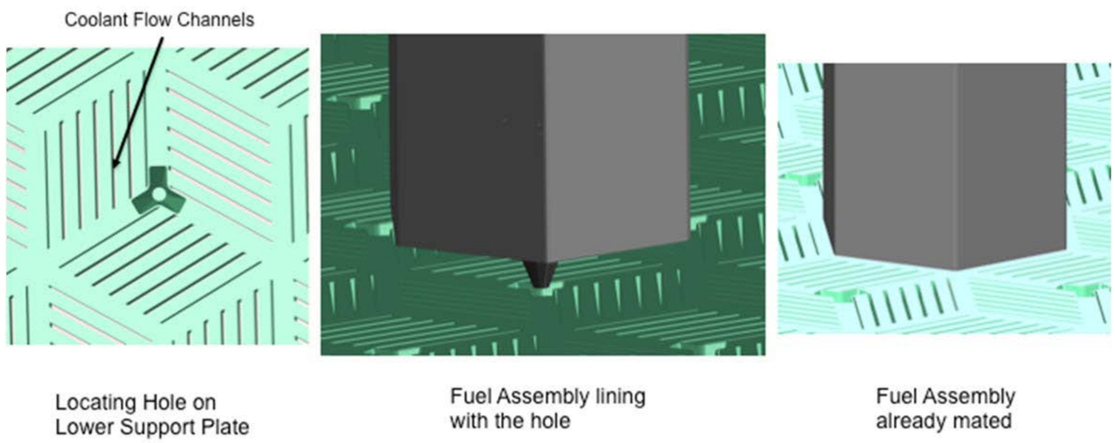

Figure 6. AHTR lower support plate (Varma et al., 2012)

Table 9. Geometric parameters of the AHTR reactor core (Varma et al., 2012)

Parameter	Value	Unit
Equivalent Core OD (fueled region)	7.81	m
Equivalent Replaceable Reflector OD	8.69	m
Equivalent Permanent Reflector OD	9.56	m
Boron Carbide Layer OD	9.58	m
Barrel OD	9.62	m
Core Height (fueled region)	5.5	m
Core Height (including axial reflector)	6.0	m
Vessel OD	10.50	m

3.3.3. Fuel Assembly

The fuel assembly consists of eighteen fuel plates enclosed in a 6-m long hexagonal prismatic box with 1-cm thick C-C composite walls. The fuel plates, with a thickness of 2.55 cm, are divided into three groups that are separated by a 4-cm thick Y-shaped C-C composite structure, as shown in Figure 7. The 0.7-cm thick gap between two interior fuel plates allows the primary salt flow. For the two fuel plates adjacent to the channel box wall and Y-structure wall, the flow channel is 0.35 cm thick. The gap between two neighboring fuel assemblies is 1.75 cm thick, resulting in a fuel assembly pitch of 46.75 cm. The geometric parameters of the fuel assembly can be found in Table 10.

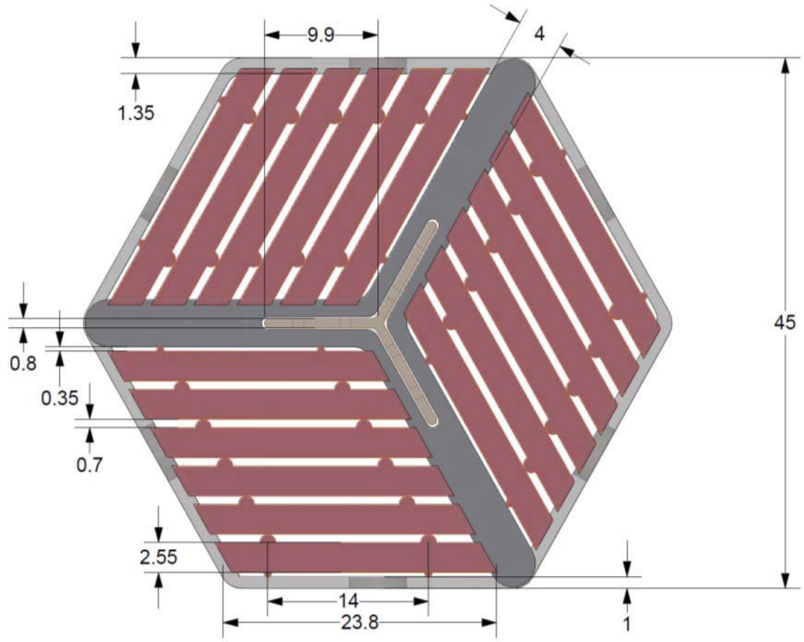

Figure 7. Cross section of the fuel assembly, Unit: cm (Varma et al., 2012)

Table 10. Geometric parameters of the AHTR fuel assembly (Varma et al., 2012)

Parameter	Value	Unit
Total Height	6.0	m
Fueled Region Height	5.5	m
Fuel Assembly Pitch	46.75	cm
Outer Apothem	22.5	cm
Channel Box Wall Thickness	1	cm
Y-structure Thickness	4	cm
Coolant Thickness between Plates	0.7	cm
Coolant Thickness between Plate and Wall	0.35	cm
Fuel Plate Thickness	2.55	cm
Number of Fuel Plates	18	-

3.4. Reactor Coolant Systems

The AHTR reactor cooling is achieved through the three primary loops (that are coupled with the three intermediate loops) during reactor normal operation, while the three DRACS loops are responsible for the decay heat removal during accidents. In the two

ORNL reference reports, detailed designs of the cooling systems are not provided. In the study of thermal hydraulics analysis of the AHTR by Wang et al., (2015), some preliminary design parameters of the AHTR cooling systems are available and thus adopted in this white paper as a reference.

3.4.1 Primary Loop and Intermediate Loop

During reactor normal operation, primary heat removal is achieved through three primary coolant loops, consisting of the primary piping, the P-IHX, and the primary salt pump. The three primary loops are coupled with three intermediate loops through the P-IHX's, as shown in Figure 8. The piping in both loops has an inner diameter of 1.24 m and are made from Hastelloy N (Varma et al., 2012). The hot leg length and cold leg length are assumed to be 15.75 and 9.37 m, respectively (Wang et al., 2015).

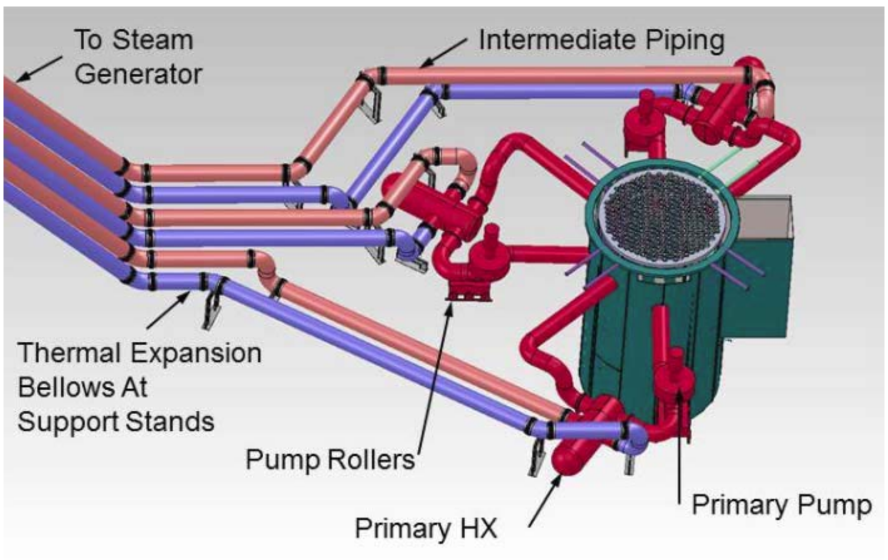

Figure 8. AHTR primary and intermediate cooling loops (Varma et al., 2012)

A shell-and-tube type heat exchanger is adopted for the P-IHX. Wang et al. (2015) assumed a simple design with one pass for both the shell and tube sides. The design parameters and coolant thermal properties assumed by Wang et al. are summarized in Table 11. A few P-IHX designs with different fluid allocation on the shell and tube sides were developed by Wang et al. and the final design adopted is summarized in Table 12.

Table 11. P-IHX design parameters and coolant thermal properties (Wang et al., 2015)

Parameter	**Primary Loop**	**Intermediate Loop**
Coolant Salt	$2LiF\text{-}BeF_2$	$53\%KF\text{-}47\%ZrF_4$
HX Inlet Temperature (K)	973	873
HX Outlet Temperature (K)	923	948
Coolant Flow Rate (kg/s)	9,500	14,400
Coolant Density (kg/m^3)	1,950	2,850
Coolant Viscosity (kg/m-s)	0.00609	0.00522
Coolant Conductivity (W/m-K)	1.1	0.42
Coolant Specific Heat Capacity (J/kg-K)	2,416	1,051
Coolant Prandtl Number	13.32	12.95

Table 12. P-IHX design (Wang et al., 2015)

Parameter	**Shell Side**	**Tube Side**
Loop Allocation	Primary	Intermediate
Coolant Salt	$2LiF\text{-}BeF_2$	$53\%KF\text{-}47\%ZrF_4$
Tube Length (m)	-	20.0
Tube ID (cm)	-	1.9735
Tube Wall Thickness (cm)	-	0.1245
Number of Tubes	-	18,000
Tube Pitch (cm)	-	1.5 OD
Tube Arrangement	-	Square array
Shell Inside Diameter (m)	5.18	-
Baffle Spacing (m)	2.0	-
Baffle Cut	25%	-

3.5. Reactor Safety Systems

3.5.1. DRACS Cooling System

Decay heat removal in the AHTR is provided by three DRACS loops, each capable of removing 0.25% of the nominal core power, i.e., 8.5 MWth. A schematic of the DRACS system is shown in Figure 9.

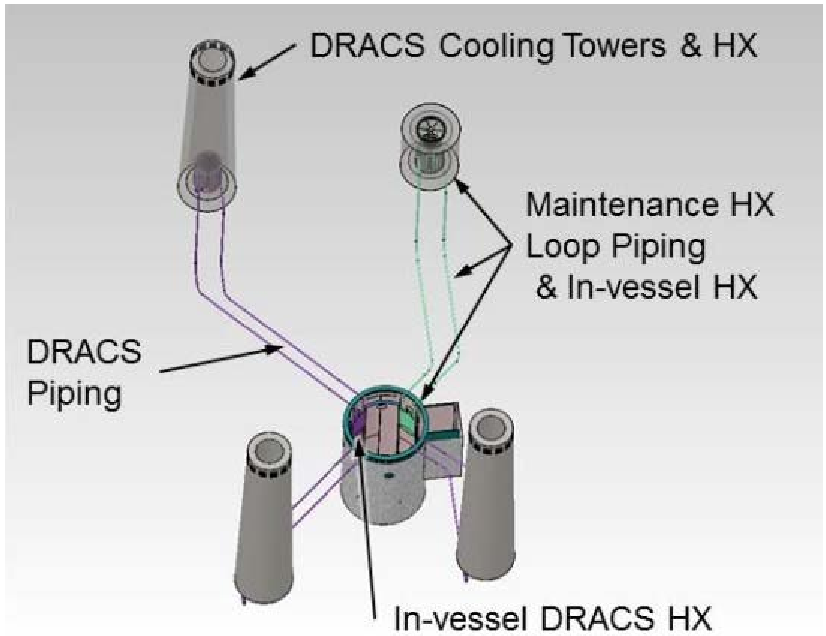

Figure 9. Schematic of the DRACS (Varma et al., 2012)

The DRACS loops are coupled with the AHTR primary salt system through the DHX's that are submerged in the reactor pool. The preliminary design parameters of the DHX by Wang et al., (2015) are summarized in Table 13. The DHX is connected to the NDHX through piping with an inner diameter of 0.4 m (Wang et al., 2015). The NDHX is at a higher elevation than the DHX by a minimum of 16 m (Varma et al., 2012). The lengths of the cold leg and hot leg of the DRACS loop are both 35 m. The DRACS cooling tower of an annular design houses the NDHX and has a height of 12.92 m, inner radius of 2.5 m and outer radius of 3 m (Wang et al., 2015). The preliminary design parameters of the NDHX are summarized in Table 14.

Table 13. Preliminary design parameters of DHX (Wang et al., 2015)

DHX Design	**Shell and Tube**
Tube Arrangement	Staggered
Primary Side	Shell
DRACS Side	Tube
Number of Tubes	1,078
Number of Tube Rows	98
Number of Tube Passes	3
Tube Length (m)	3.6
Tube OD (cm)	2.54
Tube Wall Thickness (cm)	0.1651
Tube Material	Hastelloy N

Table 14. Preliminary design parameters of NDHX (Wang et al., 2015)

NDHX Design	**Horizontal Fined Tubes**
Tube Arrangement	Inline
DRACS Loop Side	Tube
Number of Tubes	200
Number of Tube Rows	4
Number of Tube Passes	1
Tube Length (m)	4.0
Tube OD (cm)	2.54
Tube Wall Thickness (cm)	0.1651
Fin Height (cm)	2.54
Fin Spacing (cm)	1.5

3.5.2. Maintenance Cooling System

In addition to the DRACS cooling system, the maintenance cooling system also participates in heat removal from the reactor when the reactor and the primary cooling system are shut down for planned maintenance, as shown in Figure 9. The maintenance heat exchanger that is submerged in the reactor pool is the same as the DHX, but the salt flow through the maintenance heat exchanger is circulated by a pump. Also, in the salt-to-air heat exchanger, forced air circulation flow instead of natural convection flow is provided from a fan. Due to these differences, the heat removal capability of the maintenance cooling system is significantly larger than that of the DRACS system, namely, 5% of the nominal core power or 170 MWth.

3.5.3. Reactor Cavity Cooling System

The reactor guard vessel is surrounded by a concrete silo that fits closely around the reactor vessel so that, even if there was a failure in the reactor vessel, the salt level would still cover the core. Long-term passive safety calls for cooling of the reactor silo structure, limiting the temperature of the containment concrete. In normal operation, reflective insulation and a partially evacuated, argon-filled barrier are maintained between the reactor vessel and the concrete silo walls. Cold argon, supplied from the liquid argon evaporator system, will be used to help keep the silo concrete temperature down. A Stirling engine coupled to a blower will be used to assist with the flow. The required capability of the reactor cavity cooling system is affected by the design of the DRACS and the reflective insulation. The reflective insulation could reduce the heat loss from the silo to below 5 MWth (vs. 15 MWth without the insulation) during reactor normal operation. However, the use of the reflective insulation will also limit the heat removal during accident scenarios, thus resulting in higher temperature excursions with identical reactor and DRACS systems.

4. PIRT for the Event of Station Blackout

This section introduces the event of station blackout, including the event definition, the proposed FOM and reasons for selecting these FOM, and the current status of modeling of the event. Based on the significance of the identified phenomena and current research and knowledge status, path forward to better model the event is proposed. The final PIRT results for this event are listed in Section 4.4.

4.1. Definition of the Event

A station blackout event is the total loss of all offsite and onsite alternating current (AC) power. Per design, when the external AC electrical power is lost, onsite emergency diesel generators will start working to provide AC electrical power for safe operations and accident recovery. However, when the diesel generators also fail, the nuclear power plant is then left in the station blackout event.

In the event of station blackout, the pumps will trip and coast down due to no electric power supply. Therefore, forced coolant circulations is gradually lost. As an emergence response, the reactor will scram. One major concern in such situations is the generation and removal of decay heat. Safety analysis shows that station blackout is a significant contributor to overall plant risk. For the AHTR design, the fuel and coolants have large thermal margins in normal operations before failure. However, even with the superior inherent safety features, station blackout is still an event worthwhile investigating into for the AHTR design.

4.2. Proposed FOM of the Event

The PIRT panel identified and ranked phenomena based on the following FOM:

1. Peak vessel temperature:
   Under a station blackout, active cooling systems of the AHTR, such as the power conversion cycle loops and maintenance cooling system, are not available for heat removal from the reactor. After a reactor trip, DRACS cooling system can be launched and three DRACS loops takes out about 0.75% of nominal thermal power based on the AHTR design. Therefore, vessel temperature may increase dramatically and exceed its damage point if the heat removal rate keeps being less than the heat generation rate. That is the reason why peak vessel temperature is selected as an FOM for the event of station blackout.

2. Average temperature increase of carbonaceous materials in the core:
   This FOM is selected because it characterizes the stored energy in carbonaceous materials, which may significantly delay and reduce the increase of vessel temperature. Temperature increase in carbonaceous materials will also lead to potential tritium release. However, the amount of tritium released also depends on the original amount of tritium retained in these carbonaceous materials.

3. DRACS salt temperature of the NDHX:

Coolant in the NDHX may freeze due to the overcooling by the air in the natural draft chimney and thus reduces DRACS cooling performance. Therefore, this FOM is selected.

4. Peak temperature of the DHX:
   Peak temperature of the DHX is selected as an FOM for the event of station blackout because it affects DRACS cooling performance due to the potential damage to the integrity of the DHX.

4.3. Modeling the Event and Path Forward

To better understand the phenomena in the station blackout event, analysis using system-level codes and CFD codes are necessary, more studies and research are still needed for reactor safety analysis. Large-scale CFD models of the reactor core with downcomer will help the understanding of the core flow asymmetry phenomenon. CFD analysis is better positioned to investigate structure material swelling and distortion effects on the flow channels in the reactor core. For the reactor vessel, upper plenum mixing is to be modeled using CFD. In both the primary loop and the intermediate loop, although some simplified models have already been studied for pump performance, further investigation on the design and testing of pumps for salt applications should be carried out. It is the same situation with the P-IHX and I-PHX. The system-level analysis of this event should also be performed to investigate decay heat removal capability, peak temperature in structure and coolant salt, natural circulation performance, etc. based the reactor design.

4.4. PIRT for Station Blackout

Table 15. Station blackout PIRT chart - Core/Fuel

System/ID: 1. Core (a) Fuel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Heat capacity of the carbonaceous material	Heat capacity as a function of temperature and irradiation	Peak vessel temperature: M Average temperature increase of carbonaceous materials in the core: H	K	Comments: 1. After the reactor scrams, a portion of the captured tritium in carbonaceous materials will release to the salt with temperature increase. Tritium release rate depends on: a. Initial amount of captured tritium in carbonaceous materials b. Temperature difference before and after the reactor scram 2. Tritium retention in carbonaceous materials mainly depends on the temperature: a. higher temperature results in lower tritium retention b. Since temperature of the reflector is lower than that of the fuel, more tritium might be retained in the reflector than in the fuel carbonaceous materials 3. Tritium retention capability among different types of the carbonaceous differs greatly 4. Heat capacity of the carbonaceous materials of different grades is well known Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 1. Core (a) Fuel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Thermal conductivity of the carbonaceous materials	As a function of temperature and irradiation	Peak vessel temperature: M	P	Comments: Part of the TRISO particles are made of the carbonaceous materials Path forward: Consult material scientists
Heat capacity of the fuel stripe	As a function of temperature and irradiation	Peak vessel temperature: M Average temperature increase of the carbonaceous materials in the core: H	K	Comments: The fuel stripe here is included as a part of the carbonaceous materials Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Thermal conductivity of the fuel stripe	As a function of the temperature and irradiation	Peak vessel temperature: M	P	Comments: Analysis for this phenomenon is similar to that for the thermal conductivity of the carbonaceous materials Path forward: Consult material scientists

System/ID: 1. Core (a) Fuel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Heat capacity of the fuel kernel	As a function of temperature and irradiation	Peak vessel temperature: L	-	Comments: To study its effect on the vessel temperature, the mass and heat capacity of the fuel kernel need to be considered. Therefore, overall heat capacity is defined as mc_p Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Thermal conductivity of the fuel kernel	As a function of the temperature and irradiation	Peak vessel temperature: L	-	Comments: The mass of the fuel kernel is small Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 1. Core (a) Fuel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Geometry of the fuel plate	Distortion due to irradiation	Peak vessel temperature: M	U	Comments: 1. Affects the size of the flow channels, pressure drop and heat transfer 2. Highly related to mixing of flow in the plenums and therefore flow distribution 3. Generally, graphite first swells and then shrinks under irradiation 4. Lack of knowledge. Panel not equipped to address this phenomenon Path forward: Consult material scientists. It is an issue less related to thermal hydraulics
Energy generation rate in the fuel kernel	Heat generation rate axially and transversely (radially) due to accumulation of the fission products and actinides at steady-state and decay power	Peak vessel temperature: H	K	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 1. Core (a) Fuel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Radiative heat transfer	Surface of the fuel plate	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Surface condition	Surface roughness, degradation or erosion	Peak vessel temperature: M	P	Comments: 1. Fuel kernels burn out fast. Fuel elements should be replaced before serious deformation happens 2. Carbon surface obeys Young's modulus 3. Corrosion could happen to carbon Path forward: Needs further investigation in material and fuel aspects

Table 16. Station blackout PIRT chart - Core/Primary coolant flow

System/ID: 1 Core (b) Primary Coolant Flow				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Heat capacity of FLiBe	As a function of the temperature	Peak vessel temperature: H	K	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Thermal conductivity of FLiBe	As a function of the temperature	Peak vessel temperature: H	P	Comments: Review ongoing research at various institutes Path forward: Review current uncertainties in measurements; understand sensitivities to those uncertainties
Viscosity of FLiBe	As a function of the temperature	Peak vessel temperature: H	P	Comments: Similar to the previous FLiBe thermal conductivity Path forward: Review current uncertainties in the measurements; understand sensitivities to those uncertainties

System/ID: 1 Core (b) Primary Coolant Flow				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Core heat transfer coefficient	Forced/ natural convection	Peak vessel temperature: M Average temperature increase of the carbonaceous materials in the core: M	P	Comments: None Path forward: Separate-effect tests for correlation development and validation
Optical properties	Absorption and transmission as function of the temperature and wavelength	Peak vessel temperature: L	-	Comments: 1. Radiation heat transfer is much lower than convective heat transfer 2. FLiBe is transparent Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Form loss coefficients	Entrance and exit loss coefficients as a function of the area ratio and Reynolds number	Peak vessel temperature: M	P	Comments: Small change in the design could potentially lead to large difference Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

<table>
<tr><th colspan="5">System/ID: 1 Core (b) Primary Coolant Flow</th></tr>
<tr><th>Phenomenon</th><th>Definition</th><th>Figures of Merit (FOM) and Importance Level</th><th>Knowledge Level</th><th>Comments and Path Forward</th></tr>
<tr><td>Wall friction</td><td>Taking into account spacer ridges on the fuel plates</td><td>Average temperature increase of the carbonaceous materials in the core: H</td><td>P</td><td>Comments:
1. Similar to the surface condition
2. Affects local flow condition (laminar or turbulent)

Path forward:
Needs scaled experimental data</td></tr>
<tr><td>Core flow asymmetry</td><td>Due to components in the vessel</td><td>Peak vessel temperature: M</td><td>U</td><td>Comments:
1. Typical situations of the asymmetry:
a. At least one DRACS is not working properly: either has flow through but no heat rejection, or no flow and the flow distribution in the core is changed;
b. One part of the vessel has higher temperature than the other parts. During normal operation, power generation is homogeneous
2. Needs calculation of the coolant mixing in the downcomer

Path forward:
1. Perform CFD calculations of the core, downcomer, lower plenum and upper plenum
2. Conduct scaled integral-effect tests</td></tr>
</table>

System/ID: 1 Core (b) Primary Coolant Flow				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Bypass fraction	Intra-assembly flow	Peak vessel temperature: L	-	Comments: Lower flow rate compared to that in core flow channels Path forward: 1. Design needs to be solidified 2. Perform CFD analysis to investigate the fuel plate swelling/distortion
Direct energy deposition	Direct heating of the coolant from fuel as a function of the axial and radial position in the core for steady-state and decay loads	Peak vessel temperature: L Average temperature increase of the carbonaceous materials in the core: M	P	Comments: Gamma spectrum is one of the direct energy deposition sources Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

Table 17. Station blackout PIRT chart - Vessel

System/ID: 2(a). Vessel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Upper plenum mixing	Pluming and stratification and impact on upper internal structure	Peak vessel temperature: H	U	Comments: 1. Needs modeling for: a. Mixing and cross flow in this region b. Heat transfer to upper plenum structural materials 2. Needs system analysis on thermal stratification Path forward: 1. Perform CFD calculations of the lower plenum, upper plenum and downcomer 2. Perform scaled experiments for validation

System/ID: 2(a). Vessel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Fluidic diodicity	Pressure loss as a function of flow direction and flow rate	Peak vessel temperature: H	P	Comments: 1. Affects core bypass flow, circulation mass flow rate, DRACS performance, etc. 2. No reverse flow on the coolant side of DRACS, but reverse flow could happen on the primary side 3. Simulation and experimental results obtained from Low-Temperature DRACS test Facility, LTDF provide a reference Path forward: Continue investigation and research of the fluidic diodicity
Cover gas entrainment	Due to frothing at the free surface	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 2(a). Vessel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Thermal heat capacity of the vessel	To determine heat transfer across the vessel wall	Peak vessel temperature: L	-	Comments: The thin vessel wall leads to small thermal inertia Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Thermal conductivity of the vessel	To determine heat transfer across the vessel wall	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Heat transfer to the upper plenum structures	Control rod drives etc. Guide tubes	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 2(a). Vessel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Heat transfer coefficient to the vessel wall	Natural/ Forced convection heat transfer coefficient (inside the vessel)	Peak vessel temperature: M	K	Comments: Simple geometry and well known Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Friction factor on the vessel wall in the downcomer	Downcomer pressure drop	Peak vessel temperature: M	K	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Mixing in the lower plenum	From eight downcomer segments	Peak vessel temperature: M	U	Comments: 1. Similar to the situation in the upper plenum 2. The height of the lower plenum is smaller than that of the upper plenum Path forward: Perform CFD calculations of the lower plenum and downcomer

System/ID: 2(a). Vessel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Heat transfer to the cover gas and vessel top flange	Radiative and convective heat transfer	Peak vessel temperature: M	P	Comments: 1. The top flange has a large surface area 2. Core will be submerged in the salt while the decay heat keeps the salt molten. Therefore, the temperature of the top flange will not increase greatly Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

Table 18. Station blackout PIRT chart - Cavity

System/ID: 2(b). Cavity				
Phenomenon	**Definition**	**Figure of Merits (FOMs) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Thermal properties of the insulation	Density, thermal conductivity and capacity	Peak vessel temperature: L	-	Comments: 1. Argon gap between vessel and insulation 2. Certain degree of thermal expansion of the insulation has to be taken into consideration 3. Design has to be improved for easier attachment of the insulation to the guard vessel Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Heat transfer across vessel to the gas space	Net resistance to heat transfer	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 2(b). Cavity				
Phenomenon	**Definition**	**Figure of Merits (FOMs) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Heat transfer across second gap to the concrete	Convection and radiation	Peak vessel temperature: L	-	Comments: Reasons for the existence of argon gap: a. To accommodate thermal expansion of the insulation, which is inside the guard vessel b. To allow robots with mirror to get into the gap for vessel inspection. This is also the design base for the thickness of the argon gap Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Conduction in the concrete	Wall heat transfer and conductivity	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

Table 19. Station blackout PIRT chart - Primary loop

System/ID: 3 Primary Loop				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Pump performance	Relationship between driving force and flow rate, efficiency (vendor info), including coastdown (speed vs. time)	Peak vessel temperature: L	-	Comments: Pump working condition is included in the initial conditions in modeling for all events Path forward: 1. Conduct investigation on design and testing of pumps 2. Set pump requirements and share with vendors 3. Perform analysis that informs pump design inputs/parameters 4. Simple models are currently available
Pump resistance or K factor	Pressure drop across the pump	Peak vessel temperature: L	-	Comments: The pump functions as additional flow resistance when not working Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 3 Primary Loop				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Form loss in the loop	Pressure loss due to bends, fittings, valves, etc.	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Wall friction in the loop	Function of the Reynolds number	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
P-IHX performance	Heat transfer and pressure drop on the primary side	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 3 Primary Loop				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Heat loss through and from, thermal inertia of piping	Through intact insulation	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Impact of the cover gas entrainment on pump	Due to frothing at the free surface	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

Table 20. Station blackout PIRT chart - Intermediate loop

System/ID: 4. Intermediate Loop				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Pump performance	Relationship between driving force and flow rate, efficiency (vendor info)	Peak vessel temperature: L	-	Comments: None Path forward: 1. Conduct investigation on design and testing of pumps 2. Set pump requirements and share with pump vendors 3. Perform analysis that informs pump design inputs/parameters 4. Simple models are currently available
Pump coastdown	Speed versus time	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Pump resistance or K factor	Pressure drop across the pump	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 4. Intermediate Loop				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Form loss in the loop	Pressure loss due to bends, fittings, valves, etc.	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Wall friction in the loop	Function of the Reynolds number	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
I-PHX performance	Heat transfer and pressure drop on intermediate loop	Peak vessel temperature: L	-	Comments: None Path forward: 1. Conduct investigation on design and testing of P-IHX 2. Perform analysis that informs P-IHX design inputs/parameters 3. Simple models are currently available

System/ID: 4. Intermediate Loop				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Heat loss from piping	Through intact insulation	Peak vessel temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
P-IHX performance	Heat transfer and pressure drop in the intermediate loop	Peak vessel temperature: L	-	Comments: None. Path forward: 1. Conduct investigation on the design and testing of P-IHX 2. Perform analysis that informs P-IHX design inputs/parameters 3. Simple models are currently available

Table 21. Station blackout PIRT chart - Power cycle

System/ID: 5. Power Cycle				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
I-PHX performance	Heat transfer and pressure drop on the power cycle side	Peak vessel temperature: L	-	Comments: None Path forward: 1. Perform analysis that informs I-PHX design inputs/parameters 2. Simple models are currently available

Table 22. Station blackout PIRT chart – DRACS

System/ID: 6. DRACS				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
DRACS piping	Friction and form losses	Peak vessel temperature: H	K	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
DHX performance	Heat transfer and pressure drop on both sides	Peak vessel temperature: H	P	Comments: Needs to pay attention to DHX peak temperature and potential damage to the heat exchanger structure Path forward: 1. Perform scaled integral-effect tests 2. Keep investigation and research on the DHX performance
NDHX performance	Heat transfer and pressure drop on both sides	Peak vessel temperature: H	P	Comments: 1. Potential tritium leakage since the cooling medium is air 2. Tritium release rate depends on: a. Initial amount of tritium trapped in the carbonaceous materials; b. Temperature difference before and after reactor scram Path forward: Perform scaled integral-effect tests

System/ID: 6. DRACS				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Piping heat loss	Entire system both inside and outside	Peak vessel temperature: H	P	Comments: 1. Piping is designed as insulated pipe and structure: a. Total heat loss is also affected by other piping systems b. Needs experimental data c. Salt has to be kept from freezing Path forward: Preform scaled integral-effect tests
Chimney natural circulation and performance	Loss coefficients under different conditions	Peak vessel temperature: H	P	Comments: 1. The design should leave sufficient margins for all conditions 2. Design needed for the louvers. The most current design includes flaps to prevent ice and snow from getting accumulation on the louvers 3. Existing designs lack literature information and are highly disputed from each other 4. It is helpful to model wind directions actually for chimney natural circulation and performance modeling 5. For the opening of the louvers, these situations should be taken into consideration: a. After the AC power is lost or

System/ID: 6. DRACS				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
				station blackout, louvers have to open to ensure DRACS work b. The opening mechanism must be passive and electricity independent c. If the louver is covered by a considerable amount of ice, the DRACS performance might be affected Path forward: 1. Perform scaled integral-effect tests 2. Keep investigation and research on chimney natural circulation and performance
$KF\text{-}ZrF_4$ thermo-physical properties	Specific heat capacity, thermal conductivity, viscosity, density	Peak vessel temperature: H	U	Comments: None Path forward: 1. Keep investigation and research on the properties of $KF\text{-}ZrF_4$ 2. Measurements are needed with uncertainties identified

System/ID: 6. DRACS				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Thermal inertia of DRACS and chimney	Heat stored in the structure, insulation and chimney	Peak vessel temperature: M DRACS salt temperature of the NDHX: M Peak temperature of DHX: M	P	Comments: The time taken to respond to transients should be taken into consideration Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

5. PIRT for the Event of Simultaneous Withdrawal of All Control Rods

This section introduces the event of simultaneous withdrawal of all control rods, including the event definition, the proposed FOM and justifications of selecting these FOM, and the current status of modeling of the event. Based on the significance of the identified phenomena and current research status and knowledge base, the path forward to better model the event is proposed. The final PIRT results for this event are listed in Section 5.4.

5.1. Definition of the Event

In AHTR, the control rods (control blades) are driven by control drives that locate above the vessel upper flange. Each control rod is independently driven and connected to a leader rod. The control drive design determines the time needed of withdrawal all control rods, which has a significant effect on the time response of power change in the core. The heat transfer from the primary loop to the power conversion cycle loop is the major heat transfer path for this scenario.

The phenomena in this event are different from those in the station blackout event. In this event, forced flow and active cooling are still available. Hence, the performance of pumps and other active cooling components is more important in this event. Since the primary loops are still operating, the cavity cooling is less important compared to the station blackout event. One important safety mechanism in the AHTR design is the fusible links on the control rods. If the fusible link temperature is too high, it will melt and the associated control rod will drop down. The fusible link is immersed in the upper plenum salt. One fusible link is connected to one control rod. It is designed to melt and release the control rod when its temperature rises above the set point. In core, there is temperature distribution in the reactor core; the fusible links will melt at different times, resulting in the control rod due to the non-uniform dropping at different times. The fusible link in the hot channel is expected to melt first.

5.2. Proposed FOM of the Event

For the event of simultaneous withdrawal of all the control rods, the PIRT panel identified and ranked phenomena based on the following FOM:

1. Hot leg temperature:
   When all the control rods are accidentally withdrew at one same time, a positive reactivity will be introduced to move the reactor to super-criticality. The reactor core power will significantly increase. Meanwhile, active cooling systems are assumed still in operation. However, primary coolant temperature may still increase considerably, leading to temperature increases of the primary loop. The hot leg has the maximum temperature in the entire primary loop. Under this event, the increase in the hot leg temperature may exceed the allowed structural material temperature and therefore negatively affect the primary loop integrity.

2. Maximum fuel kernel temperature:

This FOM is selected because of its significant effect on the kernel integrity of the TRISO fuel particles. Sudden power increases due to control rod withdrawal will result in temperature increases in the fuel kernels. Carbon in the TRISO particle captures tritium. If the fuel temperature is too high, tritium may be released into the primary coolant and even escape into the environment.

5.3. Modeling the Event and Path Forward

For developing simulation models for this event, system–level and CFD models will be needed to perform calculations of the core temperature distribution. To ensure the safety of the reactor operation, it is critical to investigate the coupling of the thermal-hydraulics and neutronic analysis to take into account important multiphysics phenomena such as the thermal feedback effects to reactor physics analysis. Coupling the thermal-hydraulics and neutronic analysis is one of the key requirements to model this scenario. CFD core models should be able to investigate the effect of flow mixing in the upper plenum. Furthermore, it is essential to simulate the hot channel and determine the peak coolant temperature since the outlet of the hot channel is potentially the location of the highest salt temperature in the core that can be treated as a reference for the safety limit. If the temperature exceeds the melting point of fusible links, the associated control rods will drop. The reactor core power profile with control rods drop in should also be included in the model for simulating this event.

For simulating the heat removal capabilities in this event, the primary coolant flow distribution in the various coolant channels is important. The primary coolant temperature change will affect the its viscosity and other thermo-physical properties, which will also affect the heat transfer in the primary coolant FLiBe. In this event, since the power conversion cycle is the ultimate heat sink, it becomes imperative to accurately model the heat transfer from the fuel to the primary salt/coolant to the intermediate loop coolant and then to the power conversion cycle working fluid. A simplified model to make the calculations more efficient should be envisioned first. For example, modeling of the power cycle loop can be simplified first, since the details of the power cycle are not necessarily essential for this event.

5.4. PIRT for Simultaneous Withdrawal of All Control Rods

Table 23. Simultaneous withdrawal of all control rods PIRT chart -Core/Fuel

System/ID: 1. Core (a) Fuel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Specific heat capacity of the carbonaceous material	As a function of the temperature and irradiation	Hot leg temperature: H	K	Comments: 1. After the reactor scrams, a portion of the captured tritium in the carbonaceous materials will release to the salt with temperature increase. Tritium release rate depends on: a. Initial amount of the captured tritium in the carbonaceous materials b. Temperature difference before and after the reactor scram 2. Tritium retention in the carbonaceous materials mainly depends on the temperature: a. Higher temperature results in lower tritium retention b. Since the temperature of the reflector is lower than that of the fuel, more tritium might be retained in the reflector instead of the fuel carbonaceous materials 3. Tritium retention capability among different types of carbonaceous

System/ID: 1. Core (a) Fuel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
				materials differs greatly 4. Specific heat capacity of carbonaceous materials of different grades is well known Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Thermal conductivity of the carbonaceous material	As a function of temperature and irradiation	Hot leg temperature: H	P	Comments: Part of the TRISO particle is made of carbonaceous materials Path forward: Consult material scientists
Specific heat capacity of the fuel stripe	As a function of temperature and irradiation	Hot leg temperature: H	K	Comments: The fuel stripe here is included as a part of carbonaceous materials Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 1. Core (a) Fuel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Thermal conductivity of the fuel stripe	As a function of the temperature and irradiation	Hot leg temperature: H	P	Comments: Analysis to this phenomenon is similar to that for the thermal conductivity of the carbonaceous materials Path forward: Consult material scientists
Specific heat capacity of the fuel kernel	As a function of the temperature and irradiation	Hot leg temperature: H	K	Comments: To study its effect on the vessel temperature, the mass and specific heat capacity of the fuel kernel need to be considered. Overall heat capacity is defined as mc_p Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Thermal conductivity of the fuel kernel	As a function of temperature and irradiation	Hot leg temperature: H	K	Comments: The mass of the fuel kernel is small Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 1. Core (a) Fuel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Energy generation rate in the fuel kernel	Heat generation rate axially and transversely (radially) due to accumulation of the fission products and actinides at steady-state and decay power	Hot leg temperature: H	K	Comments: Reactivity should be accurately predicted to obtain the power distribution in the core Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Geometry of the fuel plate (Deviation from its original geometry)	Distortion due to irradiation	Hot leg temperature: L	U	Comments: The change of the geometry will affect heat transfer of the coolant as well as the coolant flow distribution Path forward: Confer with material scientist; an issue less relative to thermal hydraulics

System/ID: 1. Core (a) Fuel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Energy generation rate outside the kernel but within fuel plate	Heat generation rate axially and transversely (radially) due to accumulation of the fission products and actinides at steady-state and decay power	Hot leg temperature: M Maximum kernel temperature: M	K	Comments: Reactivity should be accurately predicted to obtain the power distribution in the core Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Radiative heat transfer	Surface of the fuel plate	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 1. Core (a) Fuel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Surface condition	Surface roughness, degradation or erosion	Hot leg temperature: L	P	Comments: No significant effect since the primary flow is forced circulation flow in this condition Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Fuel temperature coefficient of the Reactivity	The change in reactivity per degree of the change in the temperature of the nuclear fuel	Hot leg temperature: H	K	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Assembly (graphite) coefficient	-	Hot leg temperature: M	K	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

Table 24. Simultaneous withdrawal of all control rods PIRT chart -Core/Primary coolant flow

System/ID: 1. Core (b) Primary Coolant Flow				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Specific heat capacity of FLiBe	As a function of the temperature	Hot leg temperature: H	K	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Thermal conductivity of FLiBe	As a function of the temperature	Hot leg temperature: H	P	Comments: 1. Needs further investigation 2. Review ongoing research at various institutes Path forward: Review uncertainties in measurements; understand sensitivities to those uncertainties; if unacceptable, perform additional measurements

System/ID: 1. Core (b) Primary Coolant Flow				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Viscosity of FLiBe	As a function of the temperature	Hot leg temperature: H	P	Comments: 1. Viscosity affects flow and heat transfer in the core 2. Needs further investigation 3. Review ongoing research at various institutes Path forward: Review current uncertainties in measurements; understand sensitivities to those uncertainties; if unacceptable, additional measurements should be performed
Core heat transfer coefficient	Forced/ Natural convection	Hot leg temperature: H	P	Comments: None Path forward: Separate-effect tests for correlation improvement, development and/or validation
Optical properties	Absorption and transmission as function of the temperature and wavelength	Hot leg temperature: L	-	Comments: 1. Radiative heat transfer is much lower than convective heat transfer 2. FLiBe is nearly transparent Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 1. Core (b) Primary Coolant Flow				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Wall friction	Taking into account spacer ridges on the fuel plate	Hot leg temperature: M	P	Comments: 1. Similar to the surface condition 2. Affects local flow condition (laminar or turbulent) 3. Needs experiments Path forward: Perform scaled experiments.
Form loss coefficients	Entrance and exit loss coefficients as a function of the area ratio and Reynolds number	Hot leg temperature: L Maximum kernel temperature: M	P	Comments: Small change in the design could potentially lead to large difference Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Core flow asymmetry	Due to the existence of components in the vessel	Hot leg temperature: L Maximum kernel temperature: M	U	Comments: Modeling temperature distribution can help check core flow asymmetry Path forward: Large-scale CFD model of the core with downcomer and scaled integral-effect tests

System/ID: 1. Core (b) Primary Coolant Flow				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Bypass fraction	Intra-assembly flow	Hot leg temperature: M Maximum kernel temperature: H	U	Comments: Lower flow rate compared to that in the core flow channels Path forward: 1. Design needs to be solidified 2. CFD to investigate swelling/distortion
Direct energy deposition	Direct heating of the coolant from fuel as a function of the axial and radial position in the core for steady-state and decay loads	Hot leg temperature: L Maximum kernel temperature: M	P	Comments: Gamma spectrum is one of the direct energy deposition sources Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

Table 25. Simultaneous withdrawal of all control rods PIRT chart - Vessel

System/ID: 2(a). Vessel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Upper plenum mixing	Pluming and stratification and impact on upper internal structure	Hot leg temperature: H	U	Comments: 1. Needs modeling for: a. Mixing and cross flow in this region; b. Heat transfer to upper plenum structural materials 2. Needs system analysis on thermal stratification Path forward: 1. Carryout CFD calculations of lower plenum, upper plenum, and downcomer 2. Perform scaled experimental data for model/code validation
Fluidic diodicity	Pressure loss as a function of the flow direction and flow rate	Hot leg temperature: M	P	Comments: Determines bypass flow rate Path forward: Continue investigation and research of the fluidic diodicity

System/ID: 2(a). Vessel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Cover gas entrainment	Due to frothing at the free surface	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Specific heat capacity of the vessel	To determine heat transfer across the vessel wall	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Thermal conductivity of the vessel	To determine heat transfer across the vessel wall	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 2(a). Vessel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Heat transfer to upper plenum structures	Control rod drives etc. Guide tubes	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Heat transfer to the fusible links	To determine when fusible links melt	Hot leg temperature: H	U	Comment: The knowledge level is unknown due to lack of design specificity Path forward: 1. Testing of the specific design; Development of models for design, such as 3D heat conduction model 2. Consider SFR design strategies and use of the Curie point design 3. Control rod reliability testing
Heat transfer coefficient to the vessel wall	Natural/ Forced convection heat transfer	Hot leg temperature: L	K	Comments: Simple geometry and well known Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 2(a). Vessel				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Friction factor on the vessel wall in the downcomer	Downcomer pressure drop	Hot leg temperature: L	K	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Mixing in the lower plenum	Incoming flow from eight downcomer segments	Hot leg temperature: L	U	Comments: Mixing in lower plenum is forced flow Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Heat transfer to the cover gas and vessel upper flange	Radiative and convection heat transfer	Hot leg temperature: L	P	Comments: The top flange has a large surface area Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

Table 26. Simultaneous withdrawal of all control rods PIRT chart - Cavity

System/ID: 2(b). Cavity				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Thermal properties of the insulation	Density, thermal conductivity, and specific heat capacity	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Heat transfer across the vessel to the gas space	Net resistance to heat transfer	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 2(b). Cavity				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Heat transfer across the second gap to the concrete	Convection and radiation	Hot leg temperature: L	-	Comments: Reasons for the existence of argon gap: a. To accommodate thermal expansion of the insulation, which is inside the guard vessel b. To allow robots with a mirror to get into the gap for vessel inspection. This is also the design base for the thickness of the argon gap Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Conduction in concrete	Wall heat transfer and conductivity	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

Table 27. Simultaneous withdrawal of all control rods PIRT chart – Primary loop

System/ID: 3. Primary Loop				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Pump performance	Relationship between driving force and flow rate, efficiency (vendor info), including coast down (speed vs. time)	Hot leg temperature: H	P	Comments: Forced flow in this event. Modeling pump is a necessity Path forward: 1. Design and testing of pump; Set pump requirements and share with pump vendors 2. Simple models are currently available
Pump resistance or K factor	Pressure drop across the pump	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 3. Primary Loop				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Form loss in the loop	Pressure loss due to bends, fittings, valves, etc.	Hot leg temperature: L	-	Comments: During transients, form loss does not change significantly as compared to reactor normal operation, but the pressure drop is important to determine the salt flow rate Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Wall friction in the loop	Function of the Reynolds number	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 3. Primary Loop				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
P-IHX performance	Heat transfer and pressure drop on the primary side	Hot leg temperature: H	U	Comment: 1. Design is not known yet 2. Tritium management is important to this problem, not only heat removal but Tritium generation rate in the entire reactor lifetime is low. For P-IHX design, very small amount of Yttrium getter is needed. If the tritium removal facility works well, single wall P-IHX can be adopted. In addition, the solubility of the tritium in the salt is low Path forward: 1. Design and testing of P-IHX; Analysis that informs P-IHX design inputs/parameters; 2. Simple models are currently available;
Heat loss through and from, thermal inertia of the piping	Entire system both inside and outside	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 3. Primary Loop				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Impact of the cover gas entrainment on pump	Heat transfer and pressure drop in the primary loop	Hot leg temperature: L	-	Comments: Importance level is low unless the salt level is below the pump Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

Table 28. Simultaneous withdrawal of all control rods PIRT chart – Intermediate loop

System/ID: 4. Intermediate Loop				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Pump performance	Relationship between driving force and flow rate, efficiency (vendor info)	Hot leg temperature: H	P	Comments: None Path forward: 1. Design and testing of the pump; Set pump requirements and share with pump vendors 2. Analysis that informs pump design inputs/parameters; Simple models are currently available
Pump resistance or K factor	Pressure drop across the pump	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Form loss in the loop	Pressure loss due bends, fittings, etc.	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 4. Intermediate Loop				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Wall friction in the loop	Function of the Reynolds number	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
I-PHX performance	Heat transfer and pressure drop on intermediate loop	Hot leg temperature: H	U	Comments: None Path forward: 1. Design and testing of I-PHX; Analysis that informs I-PHX design inputs/parameters; 2. Simple models are currently available
Heat loss from piping	Through intact insulation	Hot leg temperature: L	-	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 4. Intermediate Loop				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
P-IHX performance	Heat transfer and pressure drop in the intermediate loop	Hot leg temperature: H	U	Comments: None Path forward: 1. Design and testing of P-IHX; Analysis that informs P-IHX design inputs/parameters; 2. Simple models are currently available

Table 29. Simultaneous withdrawal of all control rods PIRT chart – Power cycle

System/ID: 5. Power Cycle				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
I-PHX performance	Heat transfer and pressure drop on the power cycle side	Hot leg temperature: H	U	Comments: 1. Major heat sink in this event 2. Simplified model of the power cycle loop simulation can be performed at first stage for event of the control rods withdrawal Path forward: 1. Design and testing of I-PHX; Analysis that informs I-PHX design inputs/parameters; 2. Simple models are currently available
Power cycle performance	-	Hot leg temperature: H	U	Comments: None Path forward: Acquire design specifics; Analyze it parametrically

Table 30. Simultaneous withdrawal of all control rods PIRT chart – DRACS

System/ID: 6. DRACS				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
DRACS piping	Friction and form loss	Hot leg temperature: L	K	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
DHX performance	Heat transfer and pressure drop on both sides	Hot leg temperature: L	P	Comments: Needs to pay attention to DHX peak temperature and damage to the heat exchanger structure Path forward: Keep investigation and research on the DHX performance
NDHX performance	Heat transfer and pressure drop on both sides	Hot leg temperature: L	P	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

System/ID: 6. DRACS				
Phenomenon	**Definition**	**Figures of Merit (FOM) and Importance Level**	**Knowledge Level**	**Comments and Path Forward**
Piping heat loss	Entire system both inside and outside	Hot leg temperature: L	P	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Chimney natural circulation and performance	Loss coefficients under different conditions	Hot leg temperature: L	P	Comments: 1. Friction and loss coefficients (e.g. louver) 2. Thermal stratification of the air Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
KF-ZrF_4 thermo-physical properties	Specific heat capacity, conductivity, viscosity, density	Hot leg temperature: L	U	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration
Thermal inertia of DRACS and chimney	Heat stored in the structure, insulation, and chimney	Hot leg temperature: L	P	Comments: None Path forward: None. Based on the combined importance and knowledge level, this phenomenon does not require further exploration

6. Summary of Thermal Hydraulics PIRT Panel

An FHR thermal hydraulics PIRT panel was assembled and met at OSU on May 24-26, 2016, which was organized by OSU and ORNL. The thermal hydraulics PIRT panel consisted of fifteen experts and some student observers; eleven out of the fifteen panelists were voting members. This report documented the thermal hydraulics PIRT exercise process, including FOM and phenomena identification, importance ranking, and knowledge level ranking. Four scenarios, including station blackout, simultaneous withdrawal of all control rods, reactor core flow blockage, and LOCAs, were initially proposed together with a number of other events. FOM were identified for each of these scenarios. Due to the time constraint and potential severity of the accidents, two identified scenarios, station blackout and simultaneous withdrawal of all control rods, were selected for detailed discussion.

Peak vessel temperature, coolant temperature of the NDHX, peak temperature of the DHX, and average temperature increase of the carbonaceous materials in the core were defined as FOM for the event of station blackout. Hot leg temperature and maximum kernel temperature were defined as FOM for the event of simultaneous withdrawal of all control rods. In the thermal hydraulics PIRT, phenomena identification, importance ranking, and knowledge level ranking were performed. Furthermore, phenomena that need further consideration and corresponding path forward for modeling AHTR recommended by the panelists are included. It is suggested that large-scale CFD simulation and system-level analyses be performed for the identified phenomena that need further research to improve the current AHTR design, provide information for undefined parameters of the AHTR, as well as increase the knowledge level of these phenomena.

For the event of station blackout, phenomena that are ranked as of high importance level and low knowledge level that need further investigation, are listed as follows:

- Geometry of the fuel plates, i.e., those deviation from their original geometry
- Thermal conductivity of FLiBe
- Viscosity of FLiBe
- Wall friction in the core
- Core flow asymmetry
- Upper plenum mixing
- Fluidic diodicity
- Lower plenum mixing
- DHX performance
- NDHX performance
- DRACS piping heat loss
- Chimney natural circulation and performance
- $KF\text{-}ZrF_4$ thermo-physical properties

For the event of simultaneous withdrawal of all control rods, phenomena that are ranked as of high importance level and low knowledge level, and therefore need further investigation are listed as follows:

- Thermal conductivity of the carbonaceous materials
- Thermal conductivity of fuel stripe
- Thermal conductivity of FLiBe
- Viscosity of FLiBe
- Core heat transfer coefficient
- Primary coolant flow bypass faction
- Upper plenum mixing
- Heat transfer to fusible links for the control rods
- Primary pump performance
- P-IHX performance
- Intermediate pump performance
- I-PHX performance
- Power cycle performance

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