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Phenomena identification and ranking table study for thermal hydraulics for Advanced High Temperature Reactor

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ABSTRACT

The Advanced High Temperature Reactor (AHTR) is a conceptual design of a Fluoride salt-cooled High-temperature Reactor (FHR) utilizing $^7LiF\text{-}BeF_2$ (66–34 mol%) as its primary coolant. To identify key phenomena that impose potential challenges on thermal hydraulics modeling and simulation of such a reactor system, a thermal hydraulics phenomena identification and ranking table (TH-PIRT) study was performed for the AHTR in a Department of Energy Nuclear Energy University Program (NEUP) integrated research project led by Georgia Institute of Technology. A panel of experts from regulators, industries, national laboratories, and academia was assembled for the study. In this paper, the TH-PIRTs identified by the panel for two events, namely, station blackout and simultaneous withdrawal of all control rods, are summarized and discussed in detail. In addition, the key phenomena that warrant further study and research for AHTR analysis are identified to support the validation of thermal hydraulics system-level analysis codes and computational fluid dynamics simulation tools, as well as future FHR reactor licensing.

1. Introduction

The Fluoride salt-cooled High-temperature Reactor (FHR) is a next-generation nuclear reactor concept that combines improved technologies, including coated particle fuel (TRISO particles), low-pressure fluoride salt coolants and passive safety systems. Compared to the current Light Water Reactors (LWRs), FHRs possess several advantages, such as increased power conversion efficiency, low primary and intermediate loop operation pressures, high core power density, and enhanced safety features (Forsberg, 2005; Ingsersoll et al., 2007; Holcomb et al., 2009). The Advanced High Temperature Reactor (AHTR) is a pre-conceptual FHR design using $^7LiF\text{-}BeF_2$ (66–34 mol%, FLiBe) as its primary coolant, proposed by Oak Ridge National Laboratory (ORNL) (Holcomb et al., 2011; Varma et al., 2012; Yoder et al., 2014) and was selected as a reference design for analysis in the current study. The AHTR preliminary design was proposed in 2012 (Varma et al., 2012; Flanagan et al., 2012) with subsequent further development.

Due to FHR's significant departure from the LWR technologies, such as the use of low-pressure, high-temperature molten salt primary coolant, the applicability of existing analysis tools to FHR modeling, simulation, and safety analysis need to be carefully evaluated with appropriate experimental data. Characterization of the challenges of model and code verification and validation (V&V) is vital to enhance our understanding of the reactor response under different transients and accident scenarios, and to further improve the reactor design. A Nuclear Energy University Program (NEUP) integrated research project led by Georgia Institute of Technology was initiated in 2015 under the support of the Department of Energy with the project goal to address key technology gaps associated with FHRs and thereby reduce technological uncertainties for FHR development and future deployment. One of the tasks of this project is to perform V&V of thermal hydraulics modeling and simulation tools in support of FHR licensing. This study therefore aims at supporting the AHTR modeling, safety analysis, and

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Table 1
TH-PIRT study panelists.

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 National Laboratory
David Holcomb*	Oak Ridge National Laboratory
Xiaodong Sun*	The Ohio State University
Graydon Yoder*	Oak Ridge National Laboratory

* Non-voting members.

ultimately licensing by identifying key phenomena that impose significant challenges on thermal hydraulic modeling and simulation of the AHTR. A thermal hydraulics phenomena identification and ranking table (TH-PIRT) study was performed in parallel with a neutronics PIRT study (Rahnema et al., 2016; Rahnema et al., 2019) and a structural material PIRT study (Singh et al., 2017; Singh et al., 2018) for the AHTR.

The TH-PIRT study 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 design and analysis of new reactors. The U.S. Nuclear Regulatory Commission (NRC) developed the PIRT processes for both LWRs and the next generation nuclear plant (NGNP) (Wilson and Boyack, 1998; Fletcher et al., 2006; Ball et al., 2008), which were partially adopted in this study for developing TH-PIRT for the AHTR. An FHR TH-PIRT panel was assembled with experts from regulators, industries, national laboratories, and academia. A workshop organized by The Ohio State University (OSU) and ORNL was held at OSU on May 24–26, 2016, for the panelists to develop the TH-PIRT for the AHTR. A white paper was prepared and distributed to the panelists prior to the workshop with the purpose of providing a reference for the panel and initiating the discussion of the TH-PIRT study.

The PIRT process identified and ranked safety relevant phenomena that impact the fidelity and accuracy of thermal hydraulics analysis for the AHTR, and determined gaps in experimental databases, modeling, and analysis to validate simulation tools and methods. The TH-PIRT study offers guidance and insights in designing future separate-effect and integral-effect tests for validation of thermal hydraulics codes. The TH-PIRT panel consisted of fifteen experts specialized in salt reactor technologies, reactor thermal hydraulics, and code and methods development, as shown in Table 1, with Dr. David Diamond as the facilitator. Out of the 15 panelists, 11 were voting members. In addition to the panelists, over 10 participants from industries, national laboratories, and academia attended this PIRT workshop as observers. This paper presents a summary of the TH-PIRT study process, scenario description, phenomena identification and ranking, knowledge level ranking, and suggested path forward for two major events, namely station blackout (SBO) and simultaneous withdrawal of all control rods, which were considered by the panel as the two of the most important scenarios for reactor safety evaluation of the AHTR.

2. PIRT methodology

A detailed PIRT process consists of nine steps (Ball et al., 2008). They are described for the current TH-PIRT process in the following:

2.1. Step 1: Define the issue

The objective of this step is to define the potential issue for the AHTR future licensing applications. The issue is identified to be a lack of adequate thermal hydraulic modeling methodologies, tools, and codes that can be validated to support research and development, and eventual licensing for the FHRs with sufficient accuracy.

2.2. Step 2: Define the specific objectives

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

2.3. Step 3: Define the hardware and scenario

The AHTR design is the subject of this PIRT study. Four scenarios, including SBO, simultaneous withdrawal of all control rods, reactor core partial flow blockage, and loss of coolant accidents (LOCAs), were initially proposed together with a number of other events. Due to time constraint of the PIRT workshop and based on potential severity of the accidents, two of the identified scenarios, namely, the SBO and simultaneous withdrawal of all control rods, were selected for detailed discussion.

2.4. Step 4: Define the evaluation criterion

Figures of Merit (FOMs) are used to define the evaluation criteria for different scenarios. For the event of SBO, four FOMs were identified by the panel: (a) peak vessel temperature; (b) Direct Reactor Auxiliary Cooling System (DRACS) coolant (salt) temperature in the natural draft DRACS heat exchangers (NDHXs); (c) peak temperature of the DRACS heat exchangers (DHXs); and (d) average temperature increase of carbonaceous materials in the reactor core. For the event of simultaneous withdrawal of all control rods, two FOMs were identified: (a) hot-leg salt temperature and (b) maximum fuel kernel temperature.

2.5. Step 5: Identify, compile, and review the current knowledge base

The PIRT panel members reviewed the prepared whitepaper and relevant references prior to the TH-PIRT workshop. In addition, three presentations were given at the beginning of the meeting to summarize the AHTR design, discuss the whitepaper, and introduce the PIRT process, which helped the panelists develop a good understanding of current knowledge base related to the AHTR technologies and the PIRT process.

2.6. Step 6: Identify plausible phenomena

Phenomena are identified by the panelists based on the systems and components in the AHTR, which were defined and classified as follows:

- Core: fuel and primary coolant
  - o Heat capacity of the carbonaceous materials
  - o Thermal conductivity of the carbonaceous materials
  - o Heat capacity of the fuel stripe
  - o Thermal conductivity of the fuel stripe
  - o Heat capacity of the fuel kernel
  - o Thermal conductivity of the fuel kernel
  - o Geometry of the fuel plate