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Phenomenology, methods and experimental program for fluoride-salt-cooled, high-temperature reactors (FHRs)

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ABSTRACT

Due to their combination of high-temperature coated-particle fuel, molten salt coolant and related materials requirements, fluoride-salt-cooled, high-temperature reactors (FHRs) exhibit different thermal hydraulic, neutronic and structural mechanics phenomena compared to conventional and more extensively studied other advanced nuclear reactor concepts. This paper highlights key phenomena unique to FHRs, and reviews general issues for developing, verifying, and validating evaluation models for FHR technology that may apply to other advanced reactors. System response codes that are appropriate to predict the behavior of FHRs under steady-state operation and licensing basis events are identified, along with experimental data needs to validate these codes. FHR materials requirements are highlighted, and the missions and licensing program for an FHR test reactor, providing ultimate validation data and proof of concept before a commercial prototype is built, are presented. This review draws upon information compiled in a series of four white papers based on FHR experts workshops held in 2012 in the U.S.

1. Introduction

In 2012, the University of California, Berkeley (UCB), Massachusetts Institute of Technology, and University of Wisconsin, Madison hosted a series of four expert workshops to develop an improved technical basis to design, license, and deploy fluoride-salt-cooled, high-temperature reactors (FHRs) (Cisneros et al., 2013a; Cisneros et al., 2013b; Cao et al., 2013; Carpenter et al., 2013). This review article describes resulting recommendations for FHR methods and experiments, while a companion article reviews design and licensing strategies for FHR technology (Scarlat et al., 2014).

FHR technology uses a novel combination of high-temperature coated-particle fuel, fluoride-salt coolant, and a low-pressure primary system to deliver heat in the temperature range from 600 °C to 700 °C or higher (Forsberg et al., 2013). FHRs exhibit different thermal hydraulic, neutronic and structural mechanics phenomena compared to other more extensively studied advanced nuclear reactor concepts (Cisneros et al., 2013b). While low pressure, liquid coolant and large fuel thermal margins are significant advantages of FHR technology, the higher neutron flux the FHR graphite, ceramic and metallic structural materials are exposed to — compared to high temperature, gas-cooled reactors (HTGRs) — introduces an additional challenge in the design and licensing strategies for this class of reactors (Cao et al., 2013).

The novel combination of fuel, coolant, and structural materials requires the development of FHR evaluation models (EMs) capable of handling key phenomena unique to FHRs, in order to correctly predict their response characteristics to a variety of licensing basis events (LBEs). Experts at the FHR workshops strongly recommended that methods used in FHR analysis rely heavily on existing general-purpose thermal hydraulic, neutronic and structural mechanics codes with a significant, existing verification and validation (V&V) basis for design and licensing by the U.S. Nuclear Regulatory

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Commission (NRC). However, these codes must also have a sufficient V&V basis for specific application to FHR technology. Because no FHRs have been built to-date, this V&V effort involves identification of an existing experimental basis relevant to key FHR phenomena, the development of an FHR-specific experimental program where validation data is missing, and the definition of key confirmatory experiments to be performed during startup testing of test and demonstration FHRs. Eventually, selected codes must have the capability to calculate a requisite set of figures of merit (FOMs) and accurately model FHR key phenomena in order to ensure that the system remains within safety boundaries during steady-state operation and for a set of postulated transients.

Similarly, it must be proven that a set of selected materials can perform well in an FHR environment. The high neutron flux that graphite components are exposed to, the high temperatures in the system, and the control of corrosion of structural materials are key challenges that must be faced during the design phase of FHRs. Wherever needed – for example, in the key FHR area of redox control for corrosion, for a corrosion control protocol – American Society for Testing and Materials standard test procedures must be established to qualify materials for nuclear reactor applications. Where information on the compatibility of materials in fluoride salts is limited, corrosion data to validate lifetime predictions of these materials in FHRs, including irradiation experiments, protocols to monitor and verify adequate material performance during operation, and approaches to repair or replace components that experience degradation, will be needed.

Significant efforts are being pursued, particularly in the U.S. and China, at universities and national laboratories, to identify code capabilities that could be used in the design and licensing phases of FHRs, as well as limitations to these capabilities for FHR key phenomena and FOMs, existing V&V basis, and future experimental needs to fill gaps in the validation basis in the areas of thermal hydraulics, neutronics and structural mechanics (Cisneros et al., 2013b). In parallel, evaluation of the performance of a selected set of materials in FHR environment is underway, with the goal of qualifying these materials for use in an FHR commercial prototype (Cao et al., 2013).

Eventually, FHR technology must be demonstrated in one or more FHR test reactors (FHTRs) before a commercial demonstration reactor can be built (Carpenter et al., 2013). Test reactors provide thermal hydraulic, neutronic, structural mechanics and corrosion data for code validation, serving as key integral test capabilities for the FHR experimental program. Test reactors also provide startup test data, operational experience with handling fluoride-salt coolants and FHR fuel, control of tritium and other activation products, and the capability to test structural materials and high-temperature instrumentation under salt coolant environment. FHTR data will support qualification of in-core materials and components at FHR irradiation conditions, and FHTR tests can include LBEs such as loss of heat sink, loss of forced circulation (LOFC), overcooling transients, and reactivity insertion transients. Thus, FHTR data is a key element to ensure the viability of the FHR concept, as well as providing important information to validate neutronic, thermal hydraulic, and structural mechanics codes through integral effects tests.

Conclusions from four FHR expert workshops are reviewed here. General requirements for modeling and experiments are introduced in Section 2, followed by key FHR phenomena, modeling needs and capabilities, and existing and required V&V basis in the areas of thermal hydraulics, neutronics and structural mechanics in Sections 3, 4 and 5 respectively, leading to an FHR experimental program. Structural materials requirements and the associated test program for FHR applications are described in Section 6. Finally, FHTR missions, strategies and technical options are listed in Section 7, as the ultimate step in the FHR experimental program leading to construction of an FHR commercial prototype.

2. Requirements for modeling and experiments

This section reviews the major requirements for models and codes used for the design and licensing of FHRs. The NRC defines an EM as the "calculational framework for evaluating the behavior of the reactor system during a postulated transient or design basis accident" (U.S. Nuclear Regulatory Commission, 2005). This section reviews the NRC's recommended approach to developing and validating EMs. A more detailed version of this discussion is presented in Chapter 2 of the FHR Methods and Experiments White Paper (Cisneros et al., 2013b).

2.1. EM development and assessment process (EMDAP)

NRC Regulatory Guide 1.203 (U.S. Nuclear Regulatory Commission, 2005) defines a systematic process for developing EMs for the analysis of transient and accident behavior of reactors, referred to as the EMDAP. The process uses the Code Scaling, Applicability, and Uncertainty methodology originally developed under NRC research to study severe accidents in light-water reactors (LWRs) (Boyack et al., 1990). The methodology outlined in Regulatory Guide 1.203 applies a systematic approach to develop models that are appropriate for a specific system and specific transient, and incorporate a sufficient knowledge base to generate confidence in the analysis. This process is composed of four major elements:

1. Establish requirements for EM capability
2. Develop an assessment base
3. Develop an EM
4. Assess EM adequacy.

This review focuses predominantly on the first three elements of the EMDAP methodology, based on the needs for FHR development during the pre-conceptual design phase. The EMDAP methodology includes the development of a technical basis for the requirements of an FHR EM (Element 1) and the methods and experimental programs that should be pursued to support those requirements (Elements 2 and 3). The assessment of EM adequacy (Element 4) cannot be discussed in detail until the EM has been completely developed and thus falls inside the scope of work to be performed during detailed design of an FHR.

2.2. Phenomena Identification and Ranking Tables (PIRTs)

One key step of the EMDAP outlined in Reg. Guide 1.203 (U.S. Nuclear Regulatory Commission, 2005) is to identify and rank phenomena and processes that influence plant behavior by developing PIRTs. The Department of Energy (DOE)'s Next Generation Nuclear Plant (NGNP) program generated several PIRTs relevant to HTGR safety and licensing.

The PIRT exercise supports the prioritization of research and development efforts by identifying and narrowing the high-ranking phenomena that must be modeled in EMs. Furthermore, this set of phenomena will set the requirements for the qualification matrix to perform V&V. Finally, the PIRT process identifies gaps in the knowledge base for FHR technology.

Sections 3, 4 and 5 of this review provide high-level, qualitative descriptions of key phenomena in FHRs. While an important goal for FHR development is to use EMs, wherever possible, that have already been developed and applied for other reactor technologies (LWRs, HTGRs, and sodium-cooled fast reactors, or SFRs), some