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Phenomena Identification and Ranking Table (PIRT) study for metallic structural materials for advanced High-Temperature reactor

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A B S T R A C T

The Fluoride High-Temperature Reactor (FHR) technology promises many benefits including passive safety, proliferation-resistant waste forms, and improved economics. However, selection of reliable structural materials and identification of the possible degradation mechanisms for these is important for the licensure and the safe operation of FHRs. In order to address this task, the Georgia Tech led Integrated Research Project (IRP) hosted a Phenomena Identification and Ranking Table (PIRT) panel of experts to address degradation mechanisms and other materials related issues of importance to the FHRs. Materials, ones that come in contact with FLiBe or FLiNaK molten salts or other related environments like high temperature steam etc., were considered in this PIRT. Focus of this PIRT was the metallic alloys, especially the ones that are permitted for the construction of elevated temperature Class A components by the ASME code. Degradation mechanisms considered in this PIRT included chemical degradation, mechanical degradation, radiation degradation, and synergistic effect of these mechanisms that may negatively impact operations or cause some safety concerns for the major structural components of FHRs. Main components which were considered included vessel and primary piping, primary heat exchangers, steam generator vessel, steam generator tubes, intermediate loop piping, valves and pumps. Welds in all structural components were identified as an important class of material, which varies in composition and properties, and needs more attention. Importance of impurity control in molten fluorides considered for FHR was highlighted throughout PIRT panel discussions. This paper gives a summary of important results from the PIRT panel discussions and report.

1. Introduction

The Fluoride High-Temperature Reactor (FHR) technology promises many benefits, including improved safety through passive safety systems and proliferation-resistant waste forms; improved economics through higher operating temperatures and thus higher operating efficiency; and a diversification of the nation's energy portfolio by expanding the role of nuclear power beyond baseload electricity to meeting peaking electricity demand and supplying industrial process heat. Several challenges remain before this class of reactors can be deployed, mostly related to its technological readiness. Material selection and identification of the possible degradation mechanisms for the selected materials in FHRs is important for the licensure and the safe operation of Fluoride High-Temperature Reactors (FHRs) Holcomb et al., 2013. In order to address this task, the Georgia Institute of Technology (GT) led integrated research project (IRP) hosted a Phenomena Identification and Ranking Table (PIRT) panel of internal and invited external experts to address degradation mechanisms and other materials related issues of importance to the FHRs. The PIRT panel for the FHR-IRP on Materials met on November 28–30, 2016 at Georgia Tech. The panel consisted of experts from different fields of materials science and engineering, mechanical behavior of materials, nuclear materials, and environmental degradation of materials participated in the PIRT. Two similar PIRT exercises were performed for the areas of Thermal Hydraulics Lin et al., (2018), and Neutronics (Rahnema et al., 2018) related phenomenon in FHRs.

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Table 1
List of panelists for the FHR Materials PIRT panel held at the Georgia Institute of Technology, Atlanta, GA on November 28 to 30, 2016.

Name	Organization
David Diamond *(Facilitator)*	*Brookhaven National Laboratory*
Preet M. Singh	*Georgia Institute of Technology*
Chaitanya Deo	*Georgia Institute of Technology*
Farzad Rahnema	*Georgia Institute of Technology*
Jinsuo Zhang	*Virginia Tech*
Graydon Yoder	*Oak Ridge National Laboratory*
Weiju Ren	*Oak Ridge National Laboratory*
James R. Keiser	*Oak Ridge National Laboratory*
Dane Wilson	*ThorCon Power*
T. L. Sham	*Argonne National Laboratory*
William Corwin	*Department of Energy, Nuclear Energy*
Vinay Deodeshmukh	*Haynes International*

Materials, ones that come in contact with FLiBe or FLiNaK molten salts or other related environments like high temperature steam etc., were considered in this PIRT. There is limited experience with molten salts, so identifying and ranking of the possible degradation mechanisms in these environments was the primary objective of this PIRT. Secondary objective was to rank the degradation mechanisms in more known environments, like in high temperature steam. Focus of this PIRT was the metallic alloys used in FHRs, and it was acknowledged that non-metallic materials like graphite, pyrolytic carbon, and ceramics require a separate PIRT exercise. There are a number of possible phenomenon that can degrade a metallic material over time. This may fall in the category of chemical degradation, mechanical degradation, radiation degradation, and synergistic effect of these mechanisms. Material property degradation may negatively impact operations or may cause some safety concerns for the major structural components of FHRs. Specific degradation mechanisms will depend on the material as well as the operational environment for that component.

This PIRT exercise was dedicated to identifying and ranking of the possible degradation mechanisms for metallic materials in FHR environments that may come in contact with FLiBe or FLiNaK molten salts or other FHR related environments like high temperature steam etc.. Names and affiliation of panelists are given in Table 1.

2. Scope of PIRT exercise – Selection of materials and environments of relevance

Degradation mechanisms will depend on the materials used and the mechanical, chemical or radiation conditions. Therefore, as a starting point for the PIRT process, the panelists defined the AHTR design concept and its environmental parameters as the basis for the PIRT exercise. For this PIRT exercise the Oak Ridge National Laboratory (ORNL) pre-conceptual design for the AHTR was selected as the candidate design(Varma et al., 2012). During this process, panelists considered published literature in the field of materials performance and degradation in FHR related environments. This literature covers topics including effects of alloy composition, salt chemistry and impurities, radiation effects, processing related variables like cladding and welding, as well as individual degradation mechanisms considered in this PIRT report Delpech et al., 2010; Gibilaro et al., 2015; Ignatiev and Surenkov, 2013; Koger, 1972; Koger, 1973; Koger, 1974; Koger et al., 1974; Koger and Litman, 1968; Kondo et al., 2009; Kondo et al., 2009; Liu et al., 2013; McCoy and McNabb, 1972; Muralidharan et al., 2011; Olson et al., 2009; Sellers et al., 2014; Ren et al., 2011; Serp et al., 2014; Sohal et al., 2013; Wang et al., 2016; Williams et al., 2006; Ye et al., 2016; Zheng et al., 2015; Zheng et al., 2015. Since the publication of this PIRT report, papers have been published which addressed some phenomena identified as important.

Although different classes of materials (i.e. metallic alloys, carbonaceous materials like graphite, pyrolytic carbon, and ceramics like SiC and BC) will be used for different components of FHR and were discussed in this PIRT exercise, the main emphasis during the PIRT meeting was on the metallic materials and their degradation mechanisms. Panel acknowledged that a number of new commercial or model materials are available or may become available with time for the FHRs applications. However, code approval of structural materials is very important for their selection or usage for the AHTR applications. Therefore, the majority of metallic alloys considered during this PIRT exercise were the ones that are permitted for the construction of elevated temperature Class A components, contained in Section III Division 5 of the ASME Boiler and Pressure Vessel Code. Main components which were considered included vessel and primary piping, primary heat exchangers, steam generator vessel, steam generator tubes, intermediate loop piping, valves and pumps. Welds in all structural components were identified as an important class of material, which varies in composition and properties, and needs more attention.

Environments considered for the degradation phenomenon were based on the pre-conceptual AHTR reactor design parameters. Where the environmental parameters for a component were not available, important degradation mechanisms under extreme conditions were considered. A list of possible degradation mechanisms, including chemical degradation, mechanical degradation, thermal degradation, and radiation damage was listed and the effect of different environmental variables was summarized. Most of the important degradation mechanism were included for the panel discussion, but the list of phenomena may not represent every possible degradation phenomenon or their synergistic effects on the material behavior. This list may also include some phenomena which are deemed to have minimal impact on material degradation of selected classes of materials in FHR related environments.

3. PIRT process

Once the reactor design parameters and the scope of materials was defined, the following process was used to identify metallic material degradation phenomena, rank their importance in terms of their impact, and provide their level of understanding.

3.1. Step 1: Define the issue

Materials used in the FHR, ones that come in contact with FLiBe or FLiNaK molten salts or other related environments like high temperature steam etc., need to be capable of providing functionality with high reliability, to provide safe and economical operation.

3.2. Step 2: Define objectives of the PIRT

Objectives of this PIRT exercise were to determine the materials and their associated degradation mechanisms that might negatively impact operation of the FHR and determine new experimental databases, modeling, and detailed analyses that needs to be carried out. The initial focus was on structural materials, with secondary focus on core, control rod, and instrumentation materials. In this PIRT, 'operation' was defined to include normal operation as well as transients and accidents.

There is limited experience with molten salts, so identifying and ranking of the possible degradation mechanisms in these environments was the primary objective of this PIRT exercise. Secondary objective was to rank the degradation mechanisms in more known environments, like in high temperature steam. Degradation