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Simulation of the PHEBUS FPT-1 experiment using MELCOR and exploration of the primary core degradation mechanism

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ABSTRACT

Core degradation evaluation of probability, progression and consequences of a core degradation accident is critical for evaluation of risk as well as its mitigation. However, research and modeling of severe accidents to date are limited, and their accuracy in predicting severe accident consequences is still insufficient. It is therefore important to explore the mechanisms of core degradation and to develop mitigation measures for severe accidents. PHEBUS FPT1 is a typical and classic core degradation experiment. MELCOR is a world famous severe accident analysis code developed by Sandia National Lab that has seen wide application, a broad user base, and a number of supporting experiments. The PHEBUS experiment was simulated using MELCOR in this paper. Experimental data on, thermal power and steam mass flow rates are used to determine average pressure, energy distribution, molten mass, temperature of the fuel, and hydrogen generation. Data from the PHEBUS experiment and Cho's calculations are used to compare the average pressure, several fuel temperatures and the hydrogen generation rate. The results confirm the validity of MELCOR's simulation of the PHEBUS experiment. The temperature distribution of the core is provided. These results are used to determine the mode and behavior of core degradation with the intent of building a foundation for further research.

1. Introduction

The core degradation process is a critical factor in the progression of a severe accident. The process of core degradation provides the initial conditions for subsequent phenomena within and outside of the containment vessel, which often include events which compromise the containment and provide hydrogen source terms (Hofmann, 1999). What's more, core degradation inevitably constitutes a grave threat to the safety of a nuclear power plant and the public surrounding it (Gaunt et al., 2012). However, studies on severe accidents have been insufficient to accurately predict their consequences (Sehgal, 2012). In the simulations of Fukushima core degradation, MELCOR and MAAP are in agreement about most key parameters, but not in hydrogen generation prediction (Wachowiak, 2014). As a consequence, it is necessary to conduct further research into the core degradation process and to identify and develop mitigation measures that can be deployed under severe accident conditions.

Several notable international experiments have been undertaken to expand research on core degradation. For example, a series of CORA experiments on severe accidents which study severe fuel damage were done by KFK in Germany (Firnhaber et al., 1993). Another investigation of core degradation called COBE was done by JRC in Italy (Shepherd et al., 2001). An experiment called COLOSS was undertaken by FZK in Germany to simulate core loss during a severe accident (Homann et al., 2003). PHEBUS FPT-1 is yet another important core degradation experiment done by IRSN in France. The overall objective of PHEBUS is to study the transport and behavior of fission product releases from the fuel, bundles, structures and control rod materials, using a scaled reactor circuit and containment building (Leskovar, 2002). PHEBUS provides a suitable model of core degradation mechanisms.

MELCOR is an integrated severe accident analysis code developed by Sandia National Lab (Gauntt et al., 2001). The main objective is to establish a basis for future severe accident analyses for actual reactors using MELCOR. A number of MELCOR models can be validated against data from PHEBUS. The earliest MELCOR

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analysis on PHEBUS is done by Cho in 1999, using MELCOR 1.8.4 (Cho et al., 1999). Several years later, a simulation of the PHEBUS FPT1 experiment with MELCOR 1.8.5 was done by Leskovar (Leskovar, 2002). More recently, the results from the PHEBUS FPT1 test for a severe accident and the lessons learned with MELCOR were made by Park (Park et al., 2006). In 2007 the PHEBUS experiment was also mentioned by Buck (2007) in his modeling of late-stage core degradation in light water reactors. Meanwhile, a preliminary analysis of the PHEBUS FPT3 experiment using severe accident codes was done by Repetto (Repetto et al., 2007). A significant analysis of PHEBUS-FP results for plant safety applications was performed in Switzerland (Birchely and Guntay, 2013). Most recently, the simulator version MELCOR-RAIM was used for analysis of PHEBUS in Korea (Kim et al., 2013). All of these developments in modeling the PHEBUS experiment using MELCOR provide a basis for this investigation.

2. Brief introduction of PHEBUS FPT1

PHEBUS, which was intended to study the performance of in-pile experiment, was done in France to solve international standard problem (ISP) 46. The purpose of PHEBUS was to identify the key physical phenomena associated with a severe accident in pressurized water reactors (PWRs). The experiment modeled core degradation, fission product releases and transport, and included dominant physical and chemical behavior. The typical low-pressure loss-of-coolant accident (LOCA) was successfully demonstrated by PHEBUS FPT1 in a steam-rich atmosphere in July 1996. That experiment provided a body of vital knowledge important for understanding the core degradation process of PWRs.

The fuel assembly of PHEBUS FPT1 is shown in Fig. 1. Due to the limitations on experimental conditions, the number of bundles is relatively small. As shown in this figure, there are 21 bundles in

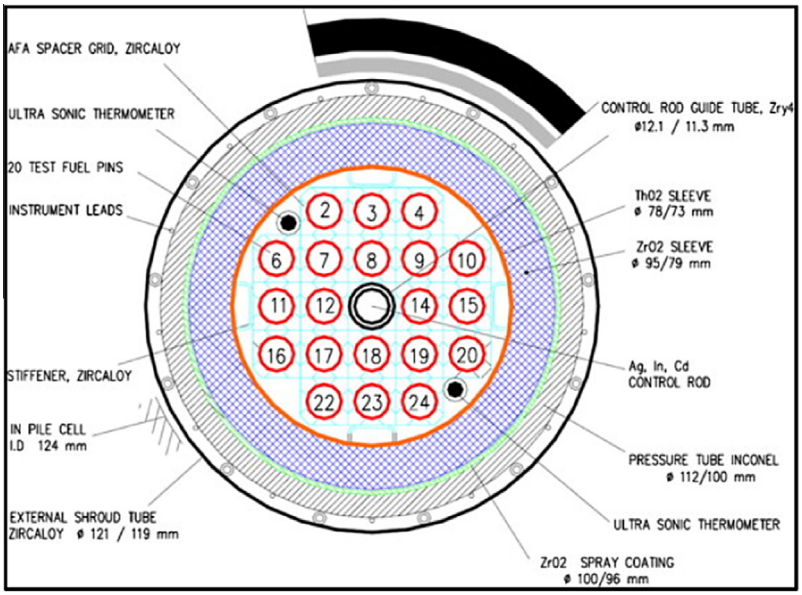

Fig. 1. Fuel assembly scheme (March and Teisseire, 2013).

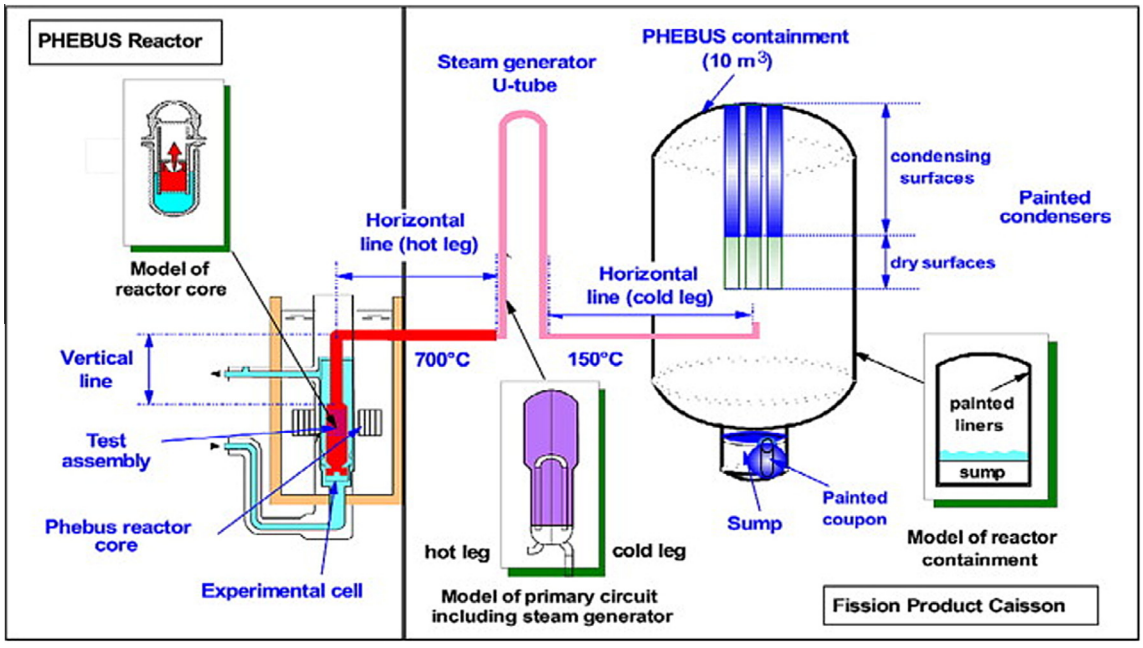

Fig. 2. System schematic of PHEBUS FPT1 (Clement and Zeyen, 2013).