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OECD/NEA Sandia Fuel Project phase I: Benchmark of the ignition testing

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HIGHLIGHTS

- A unique PWR spent fuel pool experimental project is analytically investigated.
- Predictability of fuel clad ignition in case of a complete loss of coolant in SFPs is assessed.
- Computer codes reasonably estimate peak cladding temperature and time of ignition.

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ABSTRACT

The OECD/NEA Sandia Fuel Project provided unique thermal-hydraulic experimental data associated with Spent Fuel Pool (SFP) complete drain down. The study conducted at Sandia National Laboratories (SNL) was successfully completed (July 2009 to February 2013). The accident conditions of interest for the SFP were simulated in a full scale prototypic fashion (electrically heated, prototypic assemblies in a prototypic SFP rack) so that the experimental results closely represent actual fuel assembly responses. A major impetus for this work was to facilitate severe accident code validation and to reduce modeling uncertainties within the codes. Phase I focused on axial heating and burn propagation in a single PWR 17×17 assembly (i.e. "hot neighbors" configuration). Phase II addressed axial and radial heating and zirconium fire propagation including effects of fuel rod ballooning in a 1×4 assembly configuration (i.e. single, hot center assembly and four, "cooler neighbors").

This paper summarizes the comparative analysis regarding the final destructive ignition test of the phase I of the project. The objective of the benchmark is to evaluate and compare the predictive capabilities of computer codes concerning the ignition testing of PWR fuel assemblies. Nine institutions from eight different countries were involved in the benchmark calculations.

The time to ignition and the maximum temperature are adequately captured by the calculations. It is believed that the benchmark constitutes an enlargement of the validation range for the codes to the conditions tested, thus enhancing the code applicability to other fuel assembly designs and configurations. The comparison of lumped parameter and CFD computer codes represents a further valuable achievement.

Abbreviations: ATHLET-CD, Analysis of THermal-hydraulics of LEaks and Transients with Core Degradation; BIC, boundary and initial conditions; BWR, boiling water reactor; CFD, computational fluid dynamics; CYBL, Cylindrical Boiling; ID, inner diameter; LOCA, loss of coolant accident; MELCOR, methods for estimation of leakages and consequences of releases; PCT, peak cladding temperature; PRG, program review group; PWR, Pressurized Water Reactor; SFP, Spent Fuel Pool; S_{LAM}, laminar friction coefficient; Σk, form loss factor; H_2, hydrogen; MgO, magnesium oxide; UO_2, uranium dioxide; Zr, zirconium; Zry, Zircaloy; ZrN, zirconium nitride.

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1. Introduction

Spent fuel pools are robust structures with an extremely low likelihood of a complete loss of coolant under traditional accident scenarios. However, in the wake of the terrorist attacks of September 11, 2001, the SFP accident progression was reconsidered and reevaluated using best-estimate accident codes (Lindgren and Durbin, 2013). Recently, the Fukushima-Daiichi accident has renewed international interest in the safety of spent nuclear fuel stored in SFPs under prolonged loss of cooling conditions following the accident (Trégourès, 2015).

Separate and integral effect tests have been conducted since the 1980s to better understand the fuel behavior and degradation under accident conditions (Sehgal, 2012). Most of those experiments were focused on in-reactor conditions; however, a number of the tests, while not originally targeted at SFP accidents, provided valuable data and insights for application to SFP accident phenomenology. Fuel-degradation and fission-product-release phenomenology are relatively well known from severe accident studies; nonetheless, expected SFP-accident conditions differ from these and source term estimation is a challenge (more heterogeneous distribution of fuel assemblies, lower decay power, air-containing environment and lower pressure in SFP with respect to the reactor case).

One of the major differences is that fuel degradation in SFP accidents may occur in air environments, which accelerates zirconium alloy oxidation by nitriding and oxide layer breakup. Air also speeds up UO_2 fuel degradation and volatilization by oxidation, and may increase the release of e.g. ruthenium and otherwise less volatile fission products. The only integral tests specifically targeted for SFP loss of cooling accidents at the time this benchmark was launched, were conducted at Sandia National Laboratories, USA (2003–2006) (Lindgren and Durbin, 2013), partly within the OECD/NEA Sandia Fuel Project (2009–2013, subject of this paper). These are at the knowledge of the authors, the only integral tests specifically targeted for SFP loss of cooling accidents.

This paper is heavily based on the OECD/NEA Sandia Fuel Project, an international NEA project to study thermal-hydraulics and fire characteristics of Pressurized Water Reactor (PWR) spent fuel assemblies when cooling water in the storage pool is totally lost. This project was proposed by U.S. Nuclear Regulatory Commission (USNRC) and endorsed by the NEA in 2008. Fifteen organizations from the following thirteen member countries participated to the project (OECD/NEA, 2009-2013) from July 2009 to February 2013: Czech Republic, France, Germany, Hungary, Italy, Japan, Norway, Republic of Korea, Spain, Sweden, Switzerland, United Kingdom, and the United States (with the USNRC as the operating agent).

The USNRC had previously developed computer codes for the analysis of spent fuel response to a range of accident conditions. In the absence of prototypic validation data, the inputs were specified using available geometric data and textbook correlations. The codes were subsequently used for a variety of studies to characterize the response of spent fuel in casks and spent fuel pools to accident conditions (Durbin and Lindgren, 2013b; Durbin et al., 2016; Lindgren and Durbin, 2013). With the generation of the thermal-hydraulic data in the recent BWR-SFP and PWR-SFP experimental programs, a higher degree of confidence can be developed on the appropriateness of the models in the codes and the accuracy of the results.

Both the BWR-SFP experimental program (Lindgren and Durbin, 2013) and the PWR-SFP one (Cardoni, 2010; Durbin et al., 2013a, 2016; Durbin and Lindgren, 2013b), addressed thermal-hydraulics and zirconium fire propagation during a complete drain-down of SFPs, under BWR and PWR anticipated geometry and conditions. The accident conditions of interest for the SFP were simulated in a full-scale prototypic fashion (electrically-heated, prototypic assemblies in a prototypic SFP rack) so that the experimental results closely represent actual fuel assembly responses. A major impetus for this work was to facilitate code validation and reduce modeling uncertainties within the codes and identify code model limitations. In fact, substantial analytical efforts underneath both programs in the form of: experimental design analysis, pre-test predictions and post-test analysis. The focus of this paper is the last one in the form of an open benchmark exercise (i.e. calculations were developed after the observation of the experimental data).

The main purpose of the analytical exercise is to investigate how the fuel might deteriorate in case of a loss of cooling/coolant accident, in particular when all the coolant has been lost and air has access to fuel rods and chemical reactions can drive the heat-up of cladding. The key focuses being (i) how long it would take to reach temperatures that trigger fuel damage and (ii) the main phenomena dominating fuel behavior. In particular, this paper summarizes the comparative analysis regarding the final destructive ignition test of the phase I cell 2 of the project. The objective of the benchmark is to evaluate and compare the predictive capabilities of computer codes relative to the ignition testing of PWR fuel assemblies. Nine institutions from eight different countries were involved in the benchmark calculations.

2. Experimental program

2.1. OECD/SFP experimental program

In May 2009, 12 Organization for Economic Cooperation and Development (OECD)/Nuclear Energy Agency (NEA) countries and USNRC signed an agreement called the "OECD/NEA Spent Fuel Pool Project – An Experimental Programme and Related Analyses for the Characterization of Hydraulic and Ignition Phenomena of Prototypic Water Reactor Fuel Assemblies." The signatories, jointly with USNRC, defined an experimental test matrix, experimental conditions, and parameters to be investigated in the Sandia Fuel Project.

The objective was to perform a highly detailed thermal-hydraulic characterization of full-length commercial fuel assembly mockups to provide data for the direct validation of severe accident codes. Code predictions based on previous results indicated that fuel assemblies can ignite and radially propagate in a SFP complete drain-down (Lindgren and Durbin, 2013). Hence, qualified data obtained in representative fuel configurations were needed to confirm these results. The proposed experiments focused on thermal-hydraulic and zirconium fire phenomena in PWR assemblies and supplement earlier results obtained for BWR assemblies.

The ignition is due to the very exothermic oxidation of zirconium alloy with air. Zirconium oxidation in air releases more heat than in steam and forms non-protective oxide scales. It is believed that code validations based on both the PWR and BWR experimental results will considerably enhance the code applicability to other fuel assembly designs and configurations. This is needed because SFP analyses rely on simulation tools that were developed mainly for analysis of reactor core accidents.

The project was conducted in two phases. Phase I (subject of the comparative analysis investigated in this paper) focused on axial heating and burn propagation. A single full length test assembly was constructed with zirconium alloy clad heater rods. As demonstrated in the previous BWR study, the thermal mass of the compacted MgO powder was used to make the electric heated rods an excellent match to spent fuel in terms of heat capacity. The assembly thermal-hydraulic characteristics were measured in two different sized storage cells and concluded with an ignition test identified as Cell 1 and Cell 2. The ignition test determined