Experiments on Ignition of Zirconium-Alloy in a Prototypical Pressurized-Water Reactor Single Fuel Assembly in a Spent Fuel Pool during a Complete Draindown

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ABSTRACT

This article summarizes an international effort to study zirconium-alloy fire propagation in pressurized-water reactor (PWR) spent fuel pools (SFPs) during accident conditions. This international effort was established with the Organization for Economic Cooperation and Development (OECD) including the following 13 countries: Czech Republic, France, Germany, Hungary, Italy, Japan, Norway, Republic of Korea, Spain, Sweden, Switzerland, United Kingdom, and the United States (with the U.S. Nuclear Regulatory Commission as the operating agency).

The experimental program was conducted at Sandia National Laboratories. The first phase of the program focused on axial heating and burn propagation in a single PWR 17×17 assembly, and the second phase focused on radial and axial heating and zirconium fire propagation, including the effects of fuel rod ballooning in a 1×4 assembly configuration.

The first two sections of this article summarize the background and objectives of the experiments. The subsequent sections describe the testing approach and results of the first phase of the experimental program. The second phase of the program is ongoing and OECD members continue to analyze the results.

KEYWORDS

Zirconium alloy fire propagation, spent fuel pool, loss of coolant inventory,

1. Introduction

In 2001, an evaluation of the potential accident risk in a SFP at decommissioning plants in the United States was performed. NUREG-1738, “Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants,” describes a modeling approach for a typical decommissioning plant with design assumptions and industry commitments, the thermal-hydraulic (T/H) analyses performed to evaluate spent fuel stored in the SFP at decommissioning plants, the risk assessment of SFP accidents, the consequence calculations, and the implications for decommissioning regulatory requirements. Some of the assumptions in the accident progression in NUREG-1738 were known to be necessarily conservative, especially the estimation of the fuel damage. The SFP accident research continued by applying best-estimate computer codes to predict the severe accident progression following various postulated accident initiators. The best-estimate computer code studies identified various modeling and phenomenological uncertainties that prompted a need for experimental confirmation.

In 2003, the U.S. Nuclear Regulatory Commission (NRC) undertook an experimental program to address thermal-hydraulic conditions and zirconium fire propagation during a complete draindown of a boiling-water reactor (BWR) SFP.

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

Through the SFPP Agreement, plans were implemented to conduct assessments of accident conditions that can arise in spent fuel pools and water reactor cores with complete loss of cooling water, resulting in fuel assembly heatup and zirconium-alloy ignition. These plans necessitate the production of data by means of experiments in specialized facilities located at the U.S. Sandia National Laboratories (SNL) facility, a government-owned/contractor-operated facility in Albuquerque, New Mexico. The experiments conducted thus far at SNL using prototypical materials and simulating fuel ignition phenomena have produced highly valuable data.

2. Objective

The objective of this project is to provide basic thermal-hydraulic data associated with SFP complete draindown. 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 is to facilitate severe accident code validation (primarily MELCOR or ATHLET-CD) and reduce modeling uncertainties within the codes.

3. Testing Approach

The study is being conducted in two phases. Phase 1, which is completed, focused on axial heating and burn propagation. Figure 1 shows a single full-length test assembly constructed with a prototypic fuel skeleton and zirconium-alloy clad heater rods. As demonstrated in the previous study for BWRs, the thermal mass of the compacted magnesium oxide (MgO) powder used to make the electric heater is an excellent match to spent fuel. The assembly was characterized in two different-sized storage cells. Phase 1 started with separate effect tests where the assembly hydraulic and thermal-hydraulic response was investigated. The experiment concluded with an ignition test to determine where in the assembly ignition first occurs and the nature of the burn in the axial direction of the assembly. The pool cell was completely insulated to model boundary conditions representing a “hot neighbor,” which is a typical bounding scenario.

Phase 2 will address axial and radial heating and burn propagation including effects of fuel rod ballooning. Five full-length assemblies will be constructed. The center assembly will be of the same heated design as used in Phase 1. The four peripheral assemblies will be unheated but highly prototypic, incorporating prototypic fuel tubes and end plugs. These boundary conditions experimentally represent a “cold neighbor” situation that complements the bounding scenario covered by Phase 1. The peripheral fuel rods will be filled with high-density MgO ceramic pellets sized to precisely match the thermal mass of spent fuel. Similarly, this phase will start with separate effect tests including hydraulic and thermal-hydraulic measurements. Studies using this test assembly will conclude with a fire test in which the center assembly is heated until ignition occurs, which eventually propagates axially and radially to the peripheral assemblies. Fuel rods in two of the four peripheral assemblies will be pressurized with argon so that these fuel rods will balloon when the zirconium-alloy cladding reaches a high enough temperature. The two peripheral assemblies without pressurized rods will be used to compare and evaluate the effect of ballooning.

Figure 1. Single fuel assembly for Phase 1 testing in construction stage.

4. Phase-1 Test Description

The test assembly in Phase 1 was constructed to represent a commercial 17×17 PWR fuel bundle. Figure 2 illustrates the various components comprising a typical 17×17 PWR assembly. The main structural component of the assembly is the core skeleton, which consists of 11 spacers attached to 25 guide tubes and 264 fuel rods passing through the spacers and held captive in the assembly by the top bus plates and bottom nozzle. For these tests, the top nozzle was replaced with a specially designed set of electrical bus plates to allow the application of power into the assembly.

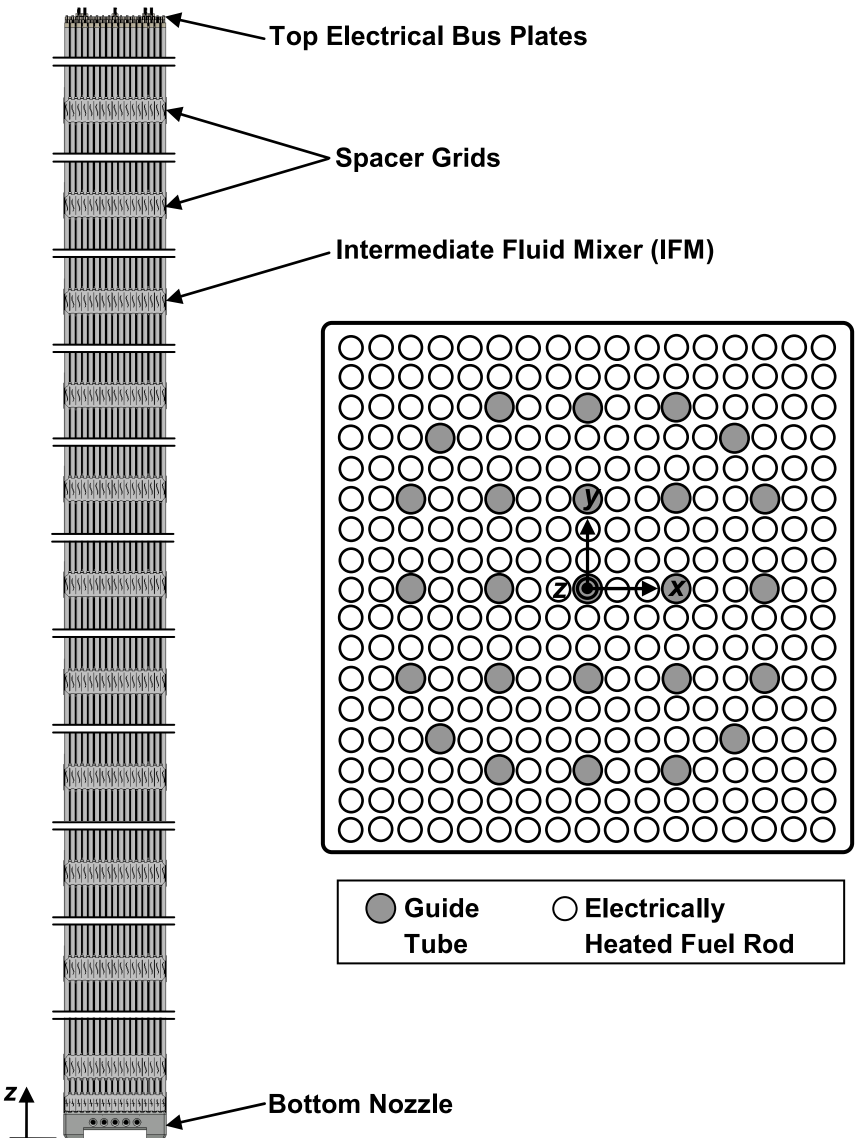

Figure 2. Various components in a typical 17×17 PWR fuel assembly.

Two storage cell sizes were fabricated for study in Phase I testing. Cell 1 had an inner dimension (ID) of 221.3 mm and was chosen to represent a common commercial size. Cell 2 had an inner dimension of ID = 223.4 mm and was chosen to match the cell size in the pool rack to be used in Phase 2 testing. A series of eight pre-ignition tests were conducted for each cell to determine the thermal-hydraulic response of the mock spent fuel assembly. MELCOR simulations were performed for each of these pre-ignition tests as well as for Cell 2 ignition tests.

A hot wire anemometer was used to measure the inlet flow rate to the test assembly with Cell 2. Laser Doppler anemometry measurements were made mid-bundle between the debris catcher and the first spacer in Cell 2 to provide average velocity profiles. Thermocouples were installed throughout the assembly to measure thermal response during heatup.

This article shows some results from the pre-ignition and ignition tests conducted for Cell 2, ID = 223.4 mm (8.796 in.). A final, destructive ignition test of the assembly in the Cell 2 configuration was conducted, representing a fuel bundle. Ignition of the Zircaloy inside the fuel bundle occurred. The exhaust gases of the ignition test were analyzed for nitrogen and argon to determine the significance of zirconium nitride formation.

5. Results

All stages of testing use MELCOR modeling results. Pretest MELCOR modeling results were used to guide the experimental test assembly design and instrumentation. MELCOR modeling results were also used to choose experimental operating parameters such as the applied assembly power. At each step in the testing, improvements were made to the MELCOR model to continually increase confidence in the modeling validity.

5.1 Cell 2 pre-ignition testing and analysis

Figure 3 shows a comparison of the average test and MELCOR temperature for all pre-ignition testing for a normalized height of z = 0.804 and a normalized time of t = 0.948 (just before ignition). Because of the sensitivity of these results, all data are presented in a normalized format. The normalization factors for time and temperature are defined by the first instance of ignition during the final, destructive test. The test and MELCOR model agree within 0.013 normalized temperature at all powers.

Figure 4 shows a comparison of the air flow rates for the pre-ignition tests and MELCOR at a normalized time of t = 0.948. The flow rates are all normalized by the maximum flow rate measured during the ignition test. The model agrees with the measured flow rate to within a normalized flow rate of 0.027 for all powers. Table 1 defines the hydraulic parameters representing the major and minor losses represented by the variables S_{LAM} and Σk, respectively. The values in Table 1 are obtained from curve fits to the pressure drop data as a function of the flow velocity through the bundle.

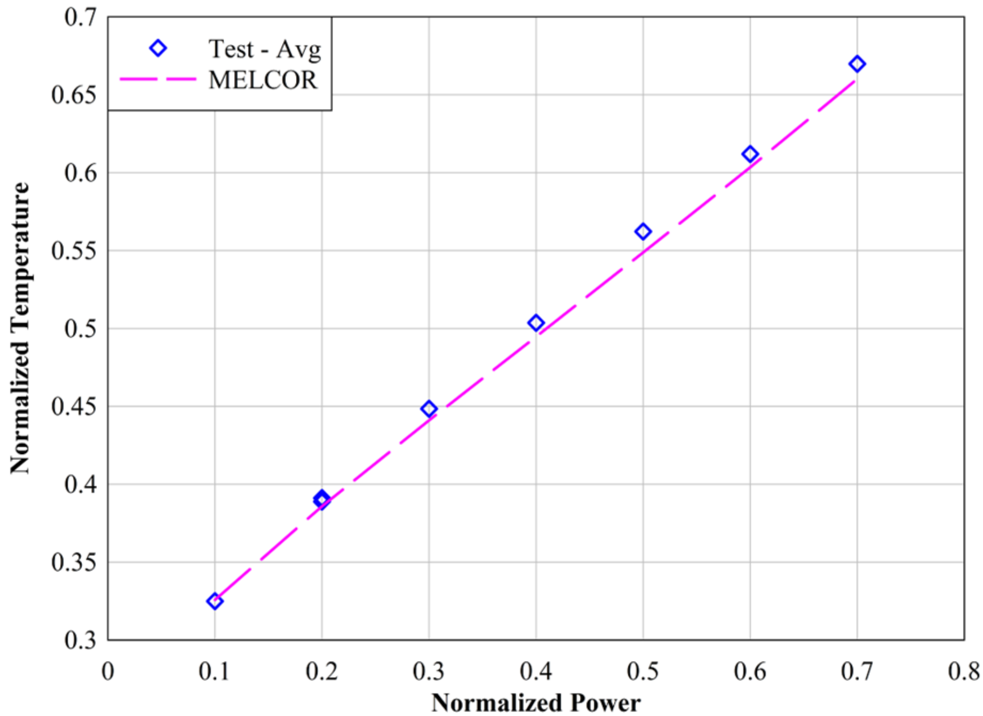

Figure 3. **Comparison of the average test (blue diamonds) and MELCOR (pink dashed) temperatures during pre-ignition testing for Cell 2 at a normalized height of z = 0.804 and a normalized time of t = 0.948.**

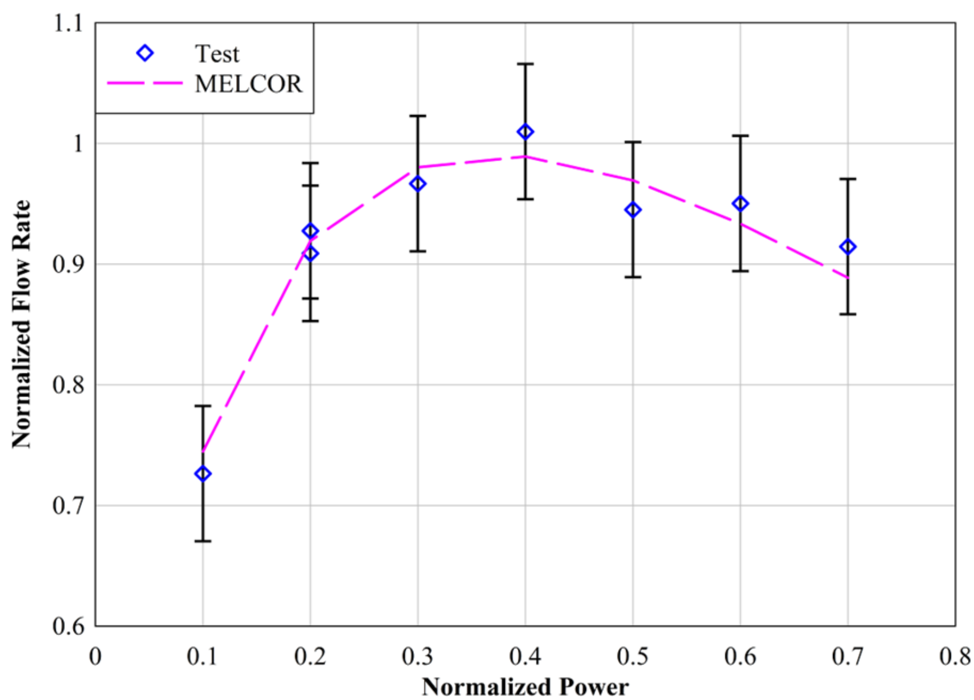

Figure 4. **Comparison of test (blue diamonds) and MELCOR (pink dashed) normalized flow rates during pre-ignition testing for Cell 2 at a normalized time of t = 0.948.**

Table 1. Summary of Assembly Hydraulics for Storage Cell 2

Description	Cell 2
Inner Dimension, mm (in.)	223.4 (8.79)
Flow Area, m^2 ($in.^2$)	0.0283 (43.86)
Hydraulic Diameter $D_{H,}$ (in.)	11.6 (0.45)
S_{LAM}	146
$\sum k$	24.8

5.2 Cell 2 ignition testing and analysis

Phase 1 of the Spent Fuel Pool Project concluded with the ignition of the test assembly in the Cell 2 configuration. This test was conducted on March 1, 2011.

MELCOR calculations were run with current best practice modeling parameters and sensitivity coefficients for the analysis of severe accidents with the exception of radiative exchange factors. These exchange factors were adjusted based on the discretization of the model. Exchange factors should be based on standard expressions for simple geometries, where possible, or on experimental data or detailed radiation calculations for complicated geometries involving intervening surfaces such as for radiation between “representative” structures in cells containing a number of similar structures (e.g., fuel rod bundles). In the absence of this information, exchange factors should be treated parametrically to examine the effects of radiation on the course of a calculation. The values for exchange factors are user- defined input and can range from zero to unity. The baseline values for the MELCOR model are the default value for both axial and radial exchange factors.

Figure 5 compares normalized temperatures as a function of time for the experimental maximum and average temperature and the peak cladding temperature predicted by MELCOR. The MELCOR input model was configured with 12 axial nodes and 1 radial node allowing axial and radial radiative heat exchange. The test values are truncated beyond the time of ignition due to loss of instrumentation and noise in the remaining thermocouples. The MELCOR post-test prediction was within 1 percent of the observed ignition test time.

Figure 6 compares the volumetric flow between the experimental data and MELCOR. MELCOR captures the trend of the flow as the accident progresses and ignition occurs.

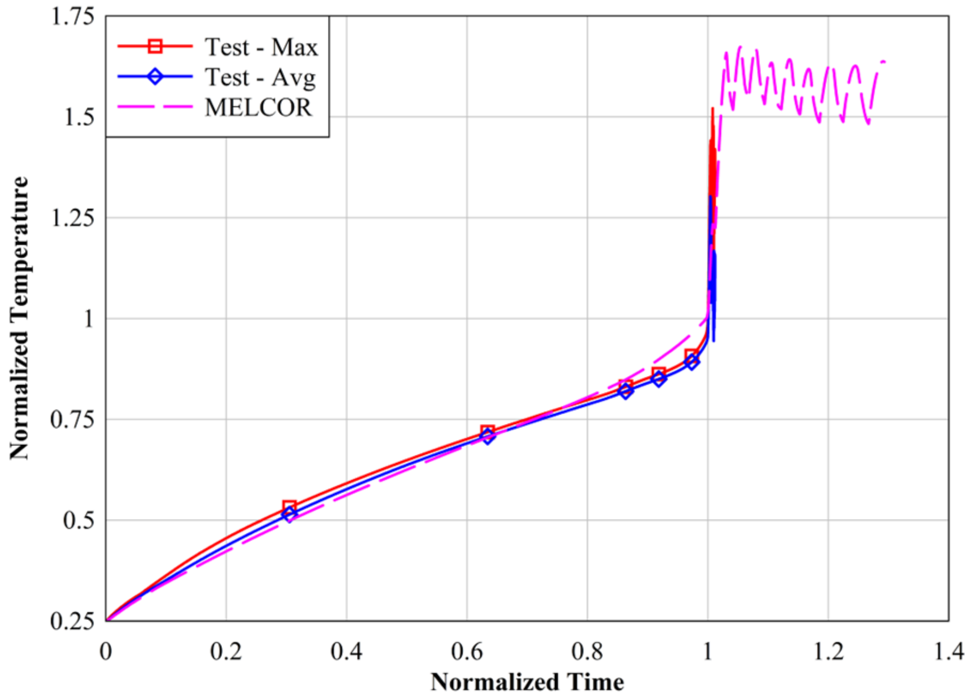

Figure 5. Cell 2 bundle temperatures as a function of time for the maximum test temperature (red squares), average test temperature (blue diamonds), and MELCOR (pink dashed).

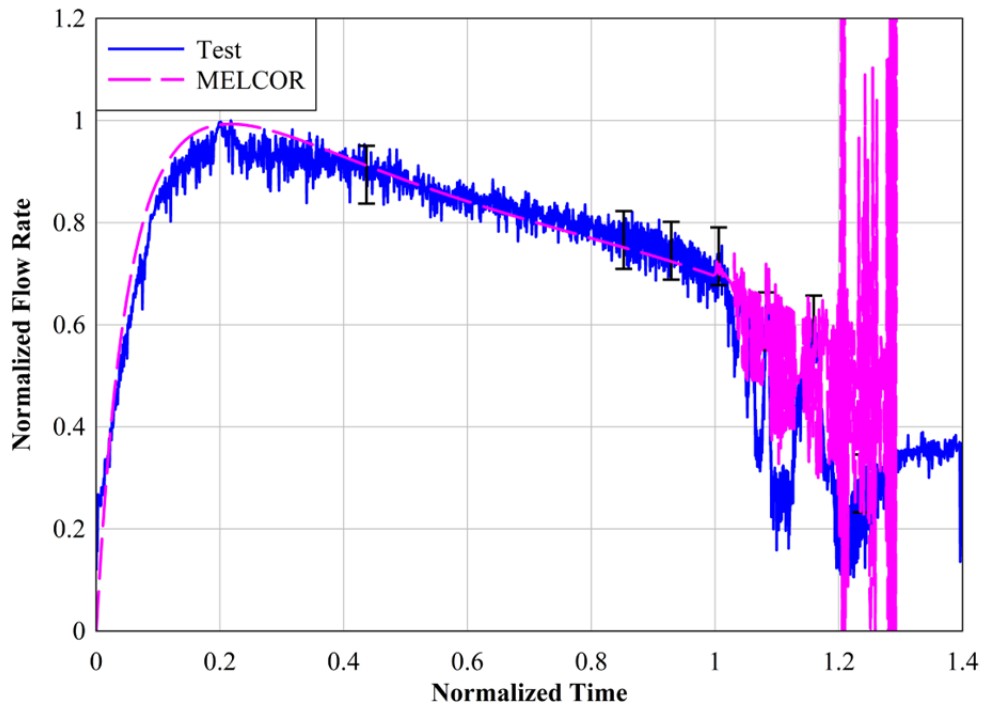

Figure 6. Induced flow rate within the Cell 2 assembly for the test (blue solid) and MELCOR (pink dashed).

6. Summary

Testing of a single full-scale 17×17 PWR fuel assembly for Phase 1 of the Spent Fuel Pool Project has been successfully completed. The prototypic fuel assembly was constructed to measure the thermal-hydraulic response of fuel under complete draindown scenarios. Testing included a pre-ignition series and concluded with a final destructive ignition experiment.

A MELCOR model using 12 axial and 1 radial nodes was created to simulate the tests. The MELCOR results and Cell 2 pre-ignition experimental values were within 1.33 percent of normalized temperature for all test powers.

The time to ignition was captured by MELCOR to within 1 percent of the observed time for the power at which the ignition test was conducted. The MELCOR maximum temperature was within 5 percent of the maximum test temperature for times prior to ignition.

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