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Investigation of a Pressurized Water Reactor (PWR) Spent Fuel Assembly under Complete Loss-of-Coolant Accident Conditions

BACKGROUND

This experimental program is being conducted at Sandia National Laboratories (SNL). The first phase of the program focused on axial heating and burn propagation in a single pressurized-water-reactor (PWR) 17-by-17 assembly and the second phase on radial and axial heating and zirconium-fire propagation, including effects of fuel-rod ballooning in a 1-by-4 assembly configuration.

The objective of this experimental program is to provide basic thermal-hydraulic data associated with a spent fuel pool (SFP) complete loss-of-coolant accident (LOCA). 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 accident code validation, primarily Methods for Estimations of Leakages and Consequences of Releases (MELCOR) or ATHLET-CD, and to reduce modeling uncertainties within the code.

This experimental program is directed by the US Nuclear Regulatory Commission (NRC) and is part of an international effort established with the Organization for Economic Co-operation and Development (OECD), including the following 13 countries: Czech Republic, France, Germany, Hungary, Italy, Japan, Norway, Republic of Korea, Spain, Sweden, Switzerland, the United Kingdom, and the United States, with the NRC as the operating agency.

TESTING APPROACH

The study was conducted in two phases. Phase 1 focused on axial heating and burn propagation. A single full-length test assembly was constructed with a prototypic fuel skeleton (see Figure 1) and zirconium-alloy-clad heater rods. As demonstrated in the previous study for boiling-water reactors (BWRs), the thermal mass of the compacted magnesium oxide (MgO) powder used to make the electric heater is an excellent match to spent fuel.

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

The assembly was characterized in two storage cells of different size. Phase 1 started with separate effect tests in which the assembly's hydraulic and thermal-hydraulic response was investigated. It 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.

MELCOR modeling results were used in all stages of testing. Pretest MELCOR modeling results were used to guide the experimental test assembly's 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.

Figure 2 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, allowing axial and radial radiative heat exchange. The test values are truncated beyond the time of ignition because of loss of instrumentation and noise in the remaining thermocouples. The MELCOR post-test prediction was within1 percent of the observed ignition test time. Figure 3 compares the volumetric flow between the experimental data and MELCOR. MELCOR captures the trend of the flow as the accident progresses and ignition occurs.

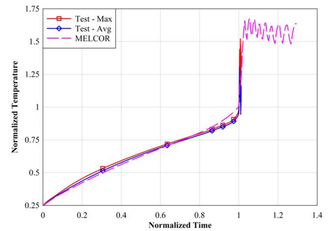

Figure 2. Cell 2 bundle temperatures as a function of time for the maximum test temperature (red squares), average test temperature (blue diamonds), and MELCOR.

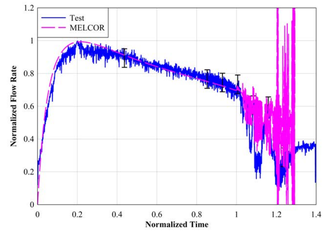

Figure 3. Induced flow rate within the Cell 2 assembly for the test (blue solid line) and MELCOR.

Phase 2 addressed axial and radial heating and burn propagation, including effects of fuel rod ballooning. Five full-length assemblies were constructed. The center assembly was of the same heated design as used in Phase 1. The four peripheral assemblies were unheated but highly prototypic, incorporating prototypic fuel tubes and end plugs. These boundary conditions experimentally represent a "cold neighbor" situation, which complements the bounding scenario that Phase 1 covered.

The peripheral fuel rods were filled with high-density MgO ceramic pellets, sized to precisely match the thermal mass of spent fuel. Similarly, this phase started with separate effect tests, including hydraulic and thermal/hydraulic measurements. Studies using this test assembly concluded with a fire test in which the center assembly was heated until ignition occurred, which eventually propagated axially and radially to the peripheral assemblies, as predicted. Fuel rods in two of the four peripheral assemblies were pressurized with argon, and fuel rods ballooned when the zirconium-alloy cladding reached a high enough temperature. The two peripheral assemblies without pressurized rods were used to compare and evaluate the effect of ballooning.

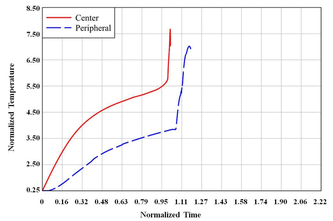

Figure 4. Peak cladding temperature in the center and peripheral assemblies during the ignition test.

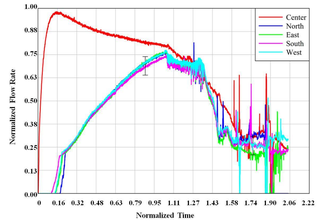

Figure 5. Measured flow rates in the center and peripheral assemblies during the ignition test.

Figure 4 gives the normalized peak cladding temperature as a function of normalized time for the center and peripheral assemblies. Both data series have been truncated because of the failure of the thermocouples at elevated temperatures. Figure 5 shows the normalized measured flow rates in the center and peripheral assemblies as a function of normalized time during the ignition test. The first major disturbance in the flow occurs after approximately 1.06 normalized hour and corresponds to the loss of electrical power in the center assembly. A sharp decrease in the peripheral assembly flow rates was recorded after 1.37 normalized hours, which coincides with the time when the ignition front had progressed across the entire cross-section of the peripheral assemblies. Debris was observed exiting the bottom of the inlet pipes and may be the cause of the erratic signals occurring after 1.58 normalized hours. MELCOR analysis for Phase 2 is ongoing.

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