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FINDINGS AND USE OF RESULTS FROM PHÉBUS-FP TESTS TO VALIDATE THE NRC'S MELCOR SEVERE ACCIDENT CODE AND REVISED ACCIDENT SOURCE TERM (NUREG-1465)

Executive Summary

The French Institut de Radioprotection et de Sûreté Nucléaire (IRSN) is conducting and analyzing a suite of Phébus Fission Product (Phébus-FP) experiments. This international cooperative research program is primarily intended to develop experimental data for use in validating computer codes that are used to analyze severe reactor accidents. The U.S. Nuclear Regulatory Commission (NRC) is participating in this suite of experiments to obtain the experimental data needed to validate the agency's MELCOR integral severe accident analysis code, as well as models used to quantify the long-term development of gaseous iodine in a pressurized-water reactor (PWR) containment.

With the successful conduct of the last test, FPT-3, the Phébus-FP project has completed all five integral tests. The analysis and overall synthesis of the test results are still ongoing. However, it is now appropriate to address the Phébus-FP findings and how the test results are being used to assess the capability of the NRC's severe accident code. It is also important to reflect on the implications of Phébus-FP results for the NRC's revised "Accident Source Terms for Light-Water Nuclear Power Plants" (NUREG-1465). The Phébus-FP data are part of a set of tests used to assess the correctness of the NRC's –MELCOR code. As a result, the modeling of core degradation (with respect to fuel slumping, cesium transport, and behavior in the reactor coolant system) has been improved in the MELCOR code.

With regard to the NRC's revised accident source term, the Phébus-FP data have confirmed many of the important features of NUREG-1465 [e.g., iodine is predominantly released as an aerosol, with a small fraction (5%) in gaseous form]. However, the development of a steady-state gaseous iodine concentration observed in the Phébus-FP containment is not influenced by controlling the pH (either basic or acidic) of the Phébus-FP sump waters. Consequently, the results of the Phébus-FP tests indicate that controlling the sump pH may not significantly impact the development of a gaseous iodine concentration in the reactor containment in the immediate aftermath of an accident involving core degradation.

Overall, the Phébus-FP integral test data and the related analyses have contributed to the staff's confidence in the use of the MELCOR code for safety analysis and risk-informed decision-making. The test data have also bolstered confidence in the appropriateness of NUREG-1465 for use in design-basis dose assessment reviews (i.e., Regulatory Guide 1.183, "Alternative Radiological Source Terms for Evaluating Design-Basis Accidents at Nuclear Power Reactors"). The one exception to this bolstered confidence deals with the Phébus-FP findings concerning the need for pH control in the sump. The staff will undertake any necessary revision of NUREG-1465 in this regard once the confirmatory research has been completed.

Enclosure 1

Regulatory Issue

Analyses of severe accident progression and fission product release have become especially important as the NRC modifies its reactor regulations to become more risk-informed and performance-based. Integral experiments, such as the Phébus-FP tests, are especially useful in assessing the MELCOR code, which is used in Level 2 and 3 probabilistic risk assessments (PRAs) and in support of risk-informed regulation.

In addition, the NRC's revised accident source term is expected to be used in offsite dose analyses for nuclear power plants to support operational flexibility, eliminate unnecessary conservatism, and assess the change in risk under Regulatory Guide 1.174, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis." Some of the important features of the NRC's revised accident source term (NUREG-1465) have been confirmed by results of the Phébus-FP tests. Enclosure 2 briefly presents background information on the development and description of the revised source term.

Method

The Phébus-FP Project consisted of five integral tests, all of which have been completed:

- The first test, FPT-0, was a "shake-down" test of the facility, using only trace-irradiated fuel. As such, its purposes were to (1) verify the adequacy of the test procedures and instrumentation, and (2) provide information related to fuel degradation and fission product release, transport, and behavior in a simplified model of a reactor coolant system and a reactor containment.
- The second test, FPT-1, used intact fuel and cladding irradiated to 23 GWd/t.
- The third test, FPT-4, used fragmented fuel irradiated to 32 GWd/t and zirconia shards in a debris bed similar to those formed during the accident at Three Mile Island.
- The fourth test, FPT-2, was conducted with conditions for fuel degradation that involve less steam than in FPT-0 and FPT-1. The intention was to have steam-starved conditions during at least a small portion of the test. Also, boric acid was injected into the test section to simulate the presence of boron during PWR core degradation.
- Finally, FPT-3 used a boron carbide control rod (instead of a silver-indium-cadmium control rod).

Post test examinations and analyses of test results from both FPT-2 and FPT-3 are ongoing. Enclosure 3 briefly describes the Phébus-FP facility and tests.

Findings

The Phébus-FP tests have yielded information that confirms the MELCOR modeling used for reactor accident analysis and development of the alternative source term (NUREG-1465). The tests have also yielded new insights, including the following highlights:

A. Confirmation of the NRC's Revised Accident Source Term (NUREG-1465)

1. Cesium (Cs) is actually released from the overheated reactor fuel transports as cesium molybdate (Cs_2MoO_4), rather than cesium hydroxide (CsOH) as assumed in severe accident analyses conducted to date. Any CsOH that reaches the containment comes from the revaporization of cesium compounds deposited in the reactor coolant system (RCS). Materials (including Cs) that are transported from the RCS into the containment sump affect the pH of the water in the sump. The pH of the sump waters, in turn, affects the partitioning of iodine from the sump into the containment atmosphere as a gaseous species. Compared to hydrolysis of CsOH, hydrolysis of Cs_2MoO_4 is much less effective in raising the sump pH to inhibit iodine partitioning. Consequently, severe accident analyses need to reflect this change in the dominant chemical form of cesium that transports through the RCS to the containment.

2. Iodine released from the overheated reactor fuel transports in both gaseous and particulate forms, with cesium iodide (CsI) among the chemical forms of particulate iodine. However, tests with silver-indium-cadmium control rods, suggest that cadmium iodide (CdI_2) is a more common form of particulate iodine.

3. Silver vaporized from control rod alloys in tests FPT-0, -1, and -2 transported to the containment sumps, where it reacted with any dissolved iodine species to form insoluble AgI or $AgIO_3$. These reactions of silver limit the dissolved iodine concentration of the sump waters to very small levels that are insufficient to support substantial partitioning of iodine from the sump into the Phébus-FP containment atmosphere, regardless of the sump pH.

4. With respect to the behavior of iodine in containment, the most important observation is that, in tests FPT-0, -1, -2, and -3, a steady-state iodine concentration developed in the Phébus containment atmosphere, and that steady-state concentration persisted for days (up to 96 hours). (Test FPT-4 was a debris bed test, which did not involve iodine transport to the containment.) The steady-state gaseous iodine concentration in containment was independent of the Phébus containment sump pH in the range of pH=9 (basic) to pH=5 (acidic). Iodine that reached the sump had no further involvement in the development of the steady-state gaseous iodine concentration in the atmosphere. In addition, in the tests with silver-indium-cadmium control rods (FPT-0, 1, and 2), iodine in the sump either precipitated as a silver salt (FPT-0 and FPT-1) or was effectively sequestered as a result of high pH (FPT-2).

   The steady-state gaseous iodine concentration indicates that there were sources and sinks of gaseous iodine operating simultaneously at equal rates. However, the integral nature of the Phébus-FP tests makes it difficult to identify the nature of those sources and sinks. Whatever processes were taking place were doing so independent of the pH in the sump. The most likely region of the containment that could involve both sources and sinks would be the condensers in the Phébus containment. The condensers simulate the surfaces of structures and equipment that will be present in reactor containments. The pH of water films on these condensers are not affected by buffers placed in the sump. Moreover, the water films that affect iodine chemistry in the atmosphere may, in fact, be water condensed in the pore structure of the surface materials. Such pore waters can interact with the atmosphere and may be acidified by air radiolysis or gaseous products of cable radiolysis. In addition, pore waters probably cannot interact directly with spray droplets; however, the Phébus tests did not examine spray effects.

While the Phébus sump is readily accessible to its containment atmosphere, varying the pH of the sump did not alter the development of a steady-state gaseous iodine concentration in the containment atmosphere. This suggests that controlling the pH of sumps in reactor containments may not prevent the development of a gaseous iodine concentration in the reactor containment in the immediate aftermath and at least 96 hours into an accident involving core degradation. However, without a more mechanistic understanding of the sources and sinks of gaseous iodine in the Phébus tests, the magnitude of the steady-state gaseous iodine concentration that may develop in reactor containments under accident conditions cannot be predicted confidently. Enclosure 4 presents a more detailed discussion of the Phébus-FP findings.

B. Assessment of Severe Accident Modeling

The Phébus-FP results are currently being used to assess the adequacy of the MELCOR code. For modeling core degradation, the information obtained in the first two tests (FPT-0 and FPT-1) has also been used to improve the modeling of fuel slumping in MELCOR. With respect to modeling fission product release, transport, and behavior in the RCS, as previously discussed, the Phébus-FP tests revealed that cesium is released from the overheated reactor fuel transports as Cs_2MoO4, rather than CsOH. Consequently, severe accident analyses need to reflect this change in the dominant chemical form of cesium that transports through the RCS to the containment. MELCOR also models CsOH resulting from revaporization of cesium compounds deposited in the RCS. In addition, the MELCOR code includes the ability to model silver iodide in the containment sump. However, the overall modeling of iodine behavior in the containment will be revised once the analysis of the related separate effects experimental data (from Phébus-STSET and CSNI BIP) has been completed. The iodine models should also be subjected to peer review to provide the credibility that they can be scaled and used to quantify iodine behavior in PWR containments.

Regulatory Application

Overall, the Phébus-FP integral test data and the related analyses have contributed to the staff's confidence in the use of the MELCOR code for safety analysis and risk-informed decision-making. The test data have also bolstered confidence in the appropriateness of NUREG-1465 for use in design-basis dose assessment reviews (i.e., Regulatory Guide 1.183). The one exception to this bolstered confidence deals with the Phébus-FP findings concerning the need for pH control in the sump. The staff will undertake any necessary revision of NUREG-1465 in this regard once the confirmatory research has been completed.

The results of the Phébus-FP tests indicate that controlling the sump pH may not significantly impact the development of a gaseous iodine concentration in the reactor containment in the immediate aftermath of an accident involving core degradation.