August 21, 2000

MEMORANDUM TO: Samuel J. Collins, Director
Office of Nuclear Reactor Regulation

FROM: Ashok Thadani, Director **/RA/**
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER RIL-0004, "USE OF RESULTS FROM PHEBUS-FP TESTS TO VALIDATE SEVERE ACCIDENT CODES AND THE NRC'S REVISED ACCIDENT SOURCE TERM (NUREG-1465)"

This research information letter summarizes the insights from the PHEBUS-FP test results which has been used in part to validate severe accident codes, and the NRC's revised accident source term (NUREG-1465). The PHEBUS-FP integral tests provide insights and information on integral fuel degradation, fission product release, transport and behavior of fission products in a simplified model of a reactor coolant system and a reactor containment. PHEBUS-FP tests are performed in the PHEBUS-FP test reactor in Cadarache, France, in a program that receives support from NRC pursuant to a bilateral agreement.

Executive Summary

The PHEBUS-FP project is at the mid point of its experimental testing, as three out of six tests have been conducted. It is appropriate at this point to address how the PHEBUS-FP results are being used to assess the capability of severe accident codes. It is also important to reflect on the implications of PHEBUS-FP results for the NRC's revised accident source term (NUREG-1465). The PHEBUS-FP data is part of a set of tests used to assess the correctness of severe accident codes (MELCOR, SCDAP/RELAP5, VICTORIA) before new versions of codes are released. As a result, the modeling of core degradation with respect to fuel slumping has been improved in MELCOR. In addition, the PHEBUS-FP data has confirmed many of the important features of NUREG-1465, confirming that iodine is released predominantly as aerosols, with allowance for a small fraction (5%) in gaseous forms; and the position that pH control is required for containment sump to control gaseous iodine in the containment.

Overall, PHEBUS-FP integral data and its use has contributed to our confidence in severe accident codes and appropriateness of the NRC's revised accident source term. This research thus further confirms and supports regulatory actions recently completed and underway in connection with the revised source term; 1) rulemaking on use of the revised source term for operating reactors, and 2) licensing reviews of implementation of the source term on pilot plant applications. No new regulatory actions are recommended by the findings of this research.

Future research may bear on characterization of source terms for spent fuel pool accidents and may provide additional insights for improvement of reactor analysis.

Regulatory Issue

Analysis of severe accident progression and fission product release has become especially important as NRC modifies its reactor regulations to become more risk informed, thereby making NRC activities and decisions more effective, efficient, and realistic. Integral experiments such as PHEBUS-FP tests are especially useful for assessing the severe accident models (which were based on separate effect tests) for assessing Level 2 and 3 probabilistic risk analysis that support risk-informed regulation.

In addition, the NRC's revised accident source term is expected to be used in off-site dose analysis for nuclear power plants to support operational flexibility, remove unnecessary conservatism as well as for assessing the change in risk under Regulatory Guide 1.174. Some of the important features of the NRC revised accident source term (NUREG-1465) have been confirmed by results of the PHEBUS-FP tests. A brief background of the development of and description of the revised source term is provided in Attachment 1.

Method

The PHEBUS-FP Project consists of six tests, and three tests have been completed. The first test, FPT-0, was a "shake-down" test of the facility using only trace-irradiated fuel intended to verify the adequacy of the test procedures and instrumentation, and provided 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 test also provided information to better plan for the next test, FPT-1, which 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. Currently, the project is preparing for the next test, FPT-2, that will attempt to establish conditions for fuel degradation that involve less steam than in previous tests (i.e., FPT-0 and FPT-1). The intention is to have steam-starved conditions during at least a small portion of the test. Also, boric acid will be injected into the test section simulating the presence of boron during a PWR core degradation. This may alter the chemical forms of the fission products (cesium and iodine) that reach the containment vessel used in the test. For the two remaining tests, FPT-3 will use a boron carbide control rod (instead of a silver, cadmium, indium control rod), and in FPT-5, air will be injected into the test section to study the competition between fuel slumping and exposure of fuel to air. To date, only the final results of the FPT-0 test has been published. A brief description of the PHEBUS-FP facility and tests is provided in Attachment 2.

Findings

Results from the PHEBUS-FP experimental program have provided confirmation of the NRC's revised accident source term and have allowed assessment of the NRC's severe accident analysis codes such as MELCOR. A more detailed discussion of PHEBUS-FP findings is provided in Appendix 3.

1. Confirmation of the NRC's Revised Accident Source Term

For the NRC's revised accident source term, the PHEBUS-FP results indicated that radionuclide releases to the containment are time dependent and further confirmed the NUREG-1465 prescription that iodine is released predominantly as an aerosol with allowance for a small fraction (5%) in gaseous form. Whether the allowance for 5% gaseous iodine (prescribed in NUREG-1465) is overly conservative will be evaluated by examination of the finalized results of the PHEBUS-FP tests. PHEBUS-FP data also confirms low release of refractory fission products (e.g., ruthenium, plutonium) as prescribed in NUREG-1465. Both radionuclide deposition in the reactor coolant system and revaporization from the reactor coolant system to the containment have to be considered. It was found that cesium (Cs) was not transported as cesium hydroxide (CsOH), as has been assumed in severe accident analysis, but as other chemical forms such as compounds of cesium and molybdenum (Cs-Mo). The prediction of the correct chemical form of Cs is important in determining the pH of the containment sump. In turn, the pH of the containment sump determines the partitioning of pool iodine to gaseous forms within the containment. The PHEBUS-FP finding supports the stipulation in NUREG-1465 that pH needs to be controlled in the containment sump to control gaseous iodine in the containment.

2. Assessment of Severe Accident Modeling

The PHEBUS-FP results are being used to assess the adequacy of severe accident codes (MELCOR, SCDAP/RELAP5, VICTORIA) before new versions of codes are release.

In terms of modeling of core degradation, the information obtained in the first two tests (FPT-0 and FPT-1) has been used to improve the modeling of fuel slumping in MELCOR. PHEBUS-FP results were also used to assess the SCDAP/RELAP5 modeling of core degradation. With respect to fission product release, transport, and behavior in the reactor coolant system, the FPT-0 and FPT-1 tests showed that Mo release may be much greater than presumed in existing models, and that Cs-Mo compounds are favored over CsOH, thereby affecting (reducing) the CsOH transport to containment pools. This effect will cause an unbuffered pool to be more acidic and consequently bias the partitioning of pool iodine to gaseous forms. In the containment, as observed in FPT-0 and FPT-1, the production of gaseous iodine in the containment sump water was low and was attributed to the formation of insoluble silver iodide in the sump water. MELCOR includes modeling of silver iodide in the containment sump.

Future information from PHEBUS-FP will provide additional data to assess the adequacy of severe accident codes as well as insights used to validate the modeling of air ingress in reactor and spent fuel pool accidents.

<u>Regulatory Application</u>

The results from the PHEBUS-FP tests and its use have confirmed the appropriateness of the NRC's revised accident source term, and contributed to our confidence in the use of MELCOR, SCDAP/RELAP5 and VICTORIA for severe accident analysis. In the future, it is expected that the PHEBUS-FP project will provide additional data on accident source terms, as well as assessment of NRC codes in modeling of severe accidents in general, and in particular the modeling of air-ingress in reactor and spent fuel pool accidents.

Attachments: As stated

cc w/atts.:
C. Paperiello, DEDMRS

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THE NRC'S REVISED ACCIDENT SOURCE TERM

Background:

Following the accident at Three Mile Island, the U.S. Nuclear Regulatory Commission (NRC) undertook a significant research effort to better understand reactor accidents that go beyond the design bases of U.S. nuclear power plants **[1]**. This effort was directed initially at obtaining a more realistic source term of radionuclides to be used in safety analyses of power plants. At the time, the so-called "TID-14844 source term" **[2]** was used for these safety analyses. This source term, which was devised in the 1960s, hypothesized that "severe" accidents would produce a source term of radionuclides to the containment of reactor composed primarily of noble gases and iodine in gaseous form. Events during the accident at Three Mile Island suggested that this prescription for radionuclides release to the containment might be overly conservative. Iodine released to the containment would not be entirely in gaseous form and assuredly the complete release of radioactive material to the containment was not instantaneous as was hypothesized in the safety analyses. The outcome of this aspect of the NRC research program has been a revised source term for use in reactor safety analyses **[3]**.

The effort to understand severe accident phenomena evolved with time to provide general technical support for the development of a technical understanding of severe accidents for probabilistic risk assessments. In this evolution, the undertaking built upon the mechanistic modeling of accident phenomena, loads on reactor containments and radionuclides behavior developed for the WASH 1400 study **[4]** of residual risks posed by the use of commercial power reactors. Support for the analysis of accident progression and fission product release has become especially important as NRC modifies it reactor regulations to become more risk informed.

The objectives of the research by NRC are to develop computer models of accident processes and fission product release that could be used to make predictions for the wide range of accident conditions considered in risk assessments. NRC has developed detailed, mechanistic models of individual severe accident processes (e.g., VICTORIA) along with development of a systems-level model, MELCOR, that addressed all important phenomena in an integrated, but less detailed, manner. Modeling detail in the systems-level code is determined to a significant extent by findings from the models of individual phenomena and, especially, from the comparison of model predictions to results of separate experiments.

The revised source term:

Based on phenomenological and analytic severe accident research, the NRC has formulated a revised accident source term for use in reactor regulatory analyses. This revised source term, often called the NUREG-1465 source term, provided a more realistic description of radionuclides releases to the containment in a severe reactor accident. Distinct source terms are specified for PWRs and BWRs. There are releases to the containment of fission products in 8 element categories that occur during four phases of an accident - fuel cladding rupture, fuel degradation, core debris/concrete interactions and late phase revaporization processes. Some important features of the source term are:

Attachment 1

Attachment 1

- releases to the containment are time dependent
- all radiologically important elements are considered
- iodine is specified to be released predominantly as metal iodide particles, but a fraction (5%) is also specified to be gaseous (HI, I_2, CH_3I, etc.)
- both radionuclides deposition in the reactor coolant system and revaporization of the deposited materials have been considered in developing the description of release to the containment
- rather small fractional releases of the refractory metal fission products (Ru, Mo, etc.) and the refractory oxide fission products (CeO_2, La_2O_3, etc.) are prescribed.

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3. L. Soffer et al. (1995), “Accident Source Terms for Light-Water Nuclear Power Plants,” NUREG-1465, U.S. Nuclear Regulatory Commission, Washington, D.C.

4. U.S. Nuclear Regulatory Commission (1975), “Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants,” WASH-1400, (NUREG-75/014).

PHEBUS-FP Program

(A) The PHEBUS-FP facility

A layout of the PHEBUS-FP facility is shown in Figure 1. The test device consists of a bundle of 20 fuel rods and 1 control rod of one meter in height, surrounded by insulating ceramic shroud is fitted into a pressure tube. The test device is inserted into a pressurized water loop, located at the center of the 40 MW PHEBUS driver core.

The upper plenum above the test bundle is connected to a horizontal pipe simulating the hot leg and cold leg sections of the reactor coolant system, and a single inverted U-tube simulating a PWR steam generator. The outlet of the U-tube is connected to a 10 m^3 vessel simulating the containment building of a reactor. The containment vessel includes scaled painted surfaces and a water-filled sump to investigate iodine behavior in the containment. The overall scaling factor is 1/5000 with respect to a 900 MWe French PWR. The facility is instrumented to allow measurement of fission product release, deposition in the primary circuit and release to the containment, and behavior in the containment. Extensive post-test examination of the test bundle, circuit and containment are carried out after each test.

(B) Conduct of Test

Before a test (except FPT-4), test fuel from the BR3 reactor (a Belgian reactor that use 1 m-long fuel rods) is re-irradiated in the PHEBUS-FP in-pile section for up to two weeks using the existing pressurized water loop in order to generate a sufficient inventory of short- and medium-lived fission products. The loop is then slowly blown down with simultaneous reduction of the reactor power, with the in-pile section isolated from the loop. After these steps, testing may begin. During the test phase, the in-pile section is connected to a circuit and containment vessel.

During the test phase, the in-pile fuel bundle is heated by fission power from the driver-core at a rate typical of a severe accident up to temperatures at which the fuel is damaged. The test bundle is pushed to conditions in which fission product release takes place, and control rods and structural materials are vaporized, producing sufficient quantities of aerosols. The fuel bundle will be damaged to the extent necessary not only to release fission products, but also to study the mechanical behavior of the fuel during extensive degradation.

The released fission products are swept by a flow of steam and H_2 into the circuit that simulates the primary cooling system up to the point of pipe break. Then the flow enters the containment vessel.

(C) Test matrix

No	Objective	Fuel bundle	Primary circuit	Containment vessel	Date
FPT-0	Degradation and fission product (FP) release from *fresh fuel*	fuel degradation and FP release under steam rich condition	FP chemistry and behavior	Aerosol behavior and deposition Radiochemistry of iodine at sump pH = 5	Dec. 2, 1993
FPT-1	Same as FPT-0 but with *pre-irradiated fuel* (23GWd/tU)	Same as FPT-0	Same as FPT-0	Same as FPT-0	July 26, 1996
FPT-2	Same as FPT-1	Same as FPT-1under steam starved condition	Same as FPT-0 with boric acid injection	Same as FPT-1, H_2 recombiner, sump pH = 9	2000
FPT-3	Same as FPT-1, but with B_4C control rod	Same as FPT-2	Same as FPT-0	Same as FPT-2	2002-2003
FPT-4	Late phase core configuration using rubble bed EdF fuel (33GWd/tU)	release and transport of less volatile FPs and refractory materials	Used integral filters in test device, thereby bypassing the primary circuit and containment vessel.		July 22, 1999
FPT-5	Same as FPT-1 with air ingress	fuel degradation and FP release under air conditions	Same as FPT-1	Same as FPT-1 & FPT-2	2005

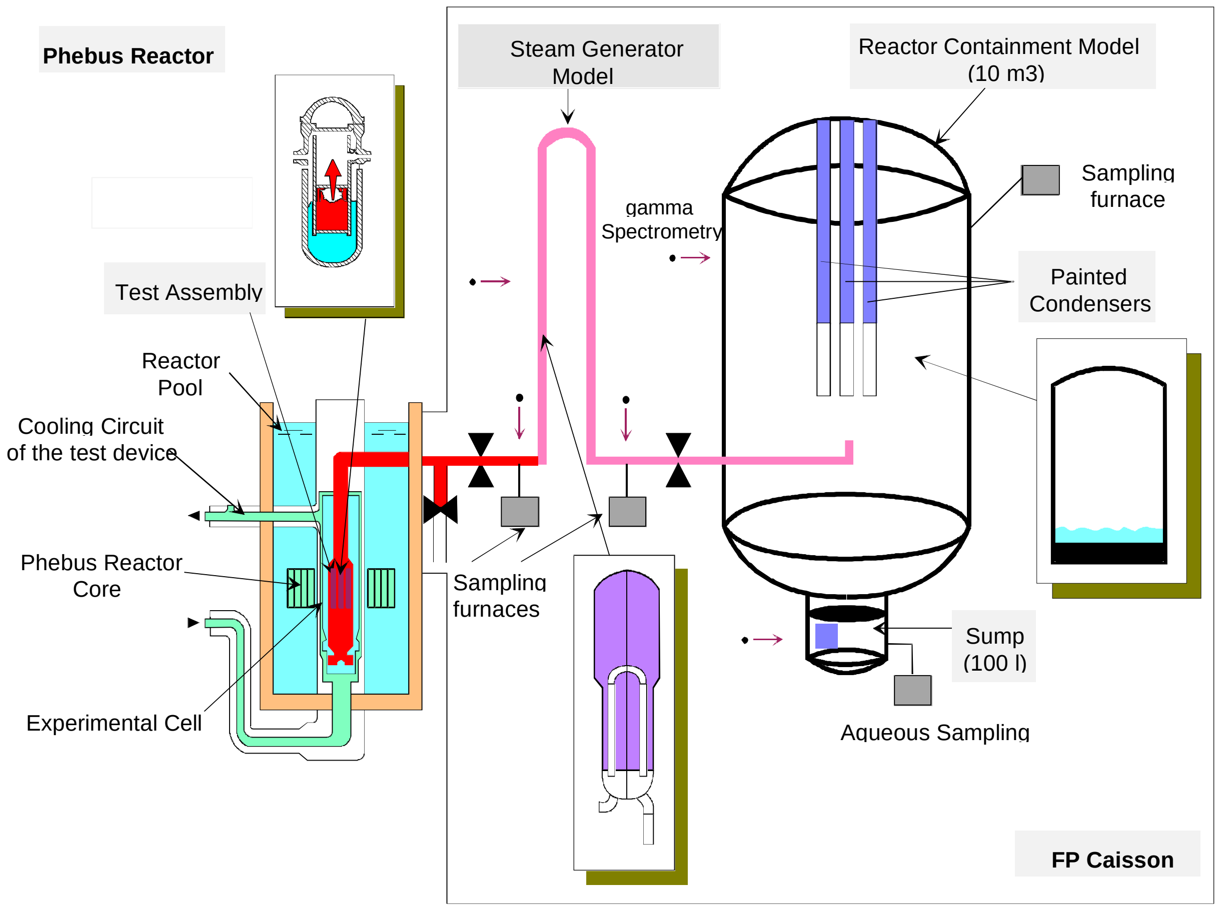

Fig. 1: Schematic view of the PHEBUS FPT-0 and FPT-1 experimental circuit

PHEBUS-FP FINDINGS

Results from the PHEBUS-FP experimental program have provided a confirmation of the NRC's revised accident source term and have provided assessments of the NRC's systems-level accident analysis codes such as MELCOR.

1. CONFIRMATION OF THE NRC REVISED ACCIDENT SOURCE TERM

For the NRC's revised accident source term, the PHEBUS-FP results indicated that radionuclides releases to the containment are time dependent and further confirm the prescriptions that iodine is released predominantly as metal iodide particles, but a fraction (5%) is specified as gaseous ($HI, I_{2,}$ CH_3); low releases of refractory metal fission products (Ru, Mo, etc.) and oxide fission products (CeO_2, La_2O_3, etc.). Both radionuclides deposition in the reactor coolant system and revaporization from the reactor coolant system to the containment have to be considered. A brief discussion of PHEBUS-FP findings with respect to the revised source term assumptions is given below.

1.1 Iodine is Released Primarily as an Aerosol but Includes a Small Fraction of Gaseous ($HI, I_{2,}$ CH_3) Forms.

It has already been observed from the results of the FPT-0 test and preliminary results from the FPT-1 test that it was prudent to include in the iodine source term some allowance for a fraction of the iodine entering the containment in a gaseous form. Whether the allowance for 5% gaseous iodine (assumed in NUREG-1465) is overly conservative will be evaluated by examination of the finalized results of the PHEBUS-FP tests. In the containment, as observed in FPT-0 and FPT-1, the production of gaseous iodine by radiolytic oxidation reactions involving iodine ions in the containment sump water was low, attributed to the formation of insoluble silver iodide in the sump water. Both tests have provided good data on the steady state concentrations of gaseous iodine that showed a level of 0.1% of the bundle inventory, and it appears to be mostly of organic iodine.

The FPT-2 test will provide data to show whether boric acid in the reactor coolant system affects the fraction of iodine in the gaseous state, either during initial release or during the subsequent revaporization from the reactor coolant system. Release of boron oxides to the reactor coolant system from the degradation of boron carbide control materials planned for the FPT-3 test will provide data on the effects of boron on iodine chemistry in the context of accidents at boiling water reactors.

1.2 Low Releases of Refractory Metal Fission Products and Oxide Fission Products.

The first two tests FPT-0 and FPT-1 indicate low releases of refractory metal fission products (Ru, Mo, etc.) and oxide fission products (CeO_2, La_2O_3, etc.) as assumed in NUREG-1465. The planned analysis of the release from debris beds of fuel (the FPT-4 test), much like those observed to develop during the accident at Three Mile Island will provide data to ascertain whether the release of refractory oxide fission products at high temperatures reached in such debris beds is low.

The planned FPT-5 test on the effects of air intrusion into the reactor coolant system is expected to indicate whether the revised source term should account for larger releases of refractory metal fission products such as ruthenium (Ru) and molybdenum (Mo). FPT-0 and FPT-1 tests have suggested a higher mobility (i.e., release from fuel) than had been anticipated especially for ruthenium (2% to 6% of bundle inventory).

1.3 Both Radionuclides Deposition in the Reactor Coolant System and Revaporization from the Reactor Coolant System to the Containment have to be Considered.

The FPT-0, 1, 2, 3, and 5 tests are to provide the chemical and physical forms of deposits in the reactor coolant system, as well as the late release caused by revaporization from the reactor coolant system to the containment. Limited revaporization of tellurium and ruthenium was observed in FPT-0 and FPT-1, as assumed in the revised source term. In FPT-0 and FPT-1, it was found that cesium (Cs) was not transported as cesium hydroxide (CsOH), as assumed in severe accident analysis, but as other chemical forms such as compounds of cesium and molybdenum (Cs-Mo). The prediction of the correct chemical form of Cs is important for aerosol transport in the reactor coolant system (because of the temperature dependency of the chemical forms), as well as in determining the pH of the containment sump. In turn, the pH of the containment sump determines the partitioning of pool iodine to gaseous forms within the containment. This supports the stipulation in NUREG-1465 for pH control at values of 7 or greater in the containment sump to keep the total gaseous iodine no more than 5% of the total iodine released.

2. ASSESSMENT OF SEVERE ACCIDENT MODELING

The PHEBUS-FP results are being used to assess the adequacy of severe accident codes (MELCOR, SCDAP/RELAP5, VICTORIA) before new versions of codes are released.
The information from FPT-0 and FPT-1 has been used to improve the modeling of fuel slumping in MELCOR 1.8.4. Similarly, it has been learned that, in accidents involving silver-indium-cadmium control blades, the reaction of CsI to form water-insoluble AgI must be modeled to accurately predict the behavior of iodine in reactor containments.

2.1 Core Degradation

Based on FPT-0 and FPT-1, improvements in core degradation modeling of cladding oxidation and fuel collapse were implemented into MELCOR 1.8.4. In the prior MELCOR 1.8.3, the model for cladding oxidation correctly recognized the existence of the outer oxide layer that forms over the underlying metal cladding, and the oxidation models correctly accounted for the reduction in oxidation rate associated with the formation of the oxide layer. Upon reaching the melting temperature of the metallic Zr, however, the MELCOR 1.8.3 relocation model presumes that the rod/clad geometry would be lost. At this point, (T~2100K) the molten Zr metal would be released to drain to cooler regions of the core, whereupon oxidation and hydrogen generation would cease and the fuel material would be converted to a particulate rubble, which could also relocate downward. This treatment generally led to a too-rapid core slumping. In MELCOR 1.8.4, this treatment was modified to allow molten Zr (i.e., Zr metal that was above 2100K) to remain in place behind the outer oxide shell and the fuel rod was allowed to remain intact above 2100K. The molten Zr was allowed to remain in place until a temperature of 2400K was reached, at which point it was assumed that the hot molten metal would breach the retaining oxide layer and subsequently drain. The fuel rods were allowed to remain standing until 2800K after which the UO_2/ZrO_2 monotectic reaction was assumed to cause the rod to collapse to form rubble. These changes led to a remarkable improvement in comparisons to test data such as the DF tests (SNL), PBF tests (INEL), FLHT tests (AECL), and CORA tests (FZK).

PHEBUS-FP results were also used to assess the SCDAP/RELAP5/MOD3.2 modeling of core degradation. SCDAP/RELAP5 has been and continues to be used to perform calculations to support the evaluation of the potential for steam generator tube rupture as a result of severe accidents in operating pressurized water reactors.

FPT-4 test will indicate whether modeling of fission product release from debris beds must be included in the code. The results of FPT-5 will indicate whether the code must make allowances for the possibility of air intrusion into the reactor coolant system following vessel penetration by core debris to predict adequately the severe accident source term, especially the releases of refractory metal fission products such as ruthenium. In addition, it is expected the results from FPT-5 will provide insights on the modeling of air ingress in reactor and spent fuel pool accidents as well.

2.2 Fission Product Release, Transport and Behavior in the Reactor Coolant System

Concerning fission product behavior, the FPT-0 and FPT-1 tests showed that Mo release may be much greater than presumed in existing models, and that Cs-Mo compounds are favored over CsOH, thereby affecting (reducing) the CsOH transport to containment pools. This effect will cause an unbuffered pool to be more acidic and consequently bias the partitioning of pool iodine to gaseous forms. As mentioned earlier, this supports the stipulation in NUREG-1465 for pH control at values of 7 or greater in the containment sump to keep the total gaseous iodine no more than 5% of the total iodine released.

Analysis of FPT-1 with MELCOR and VICTORIA codes has confirmed the adequacy of the codes in modeling of fission product release and deposition in the reactor coolant system. It is expected that the results of the PHEBUS-FP tests will provide additional data for the selection of parameters in the modeling of fission product releases from the fuel and answer the question of whether aerosol nucleation needs to be explicitly modeled in a systems-level accident analysis code like MELCOR. Results from the tests will indicate whether the limited fission product speciation adopted in the MELCOR code is adequate.

2.3 Fission Product Behavior in the Containment

In the containment, as observed in FPT-0 and FPT-1, the production of gaseous iodine by radiolytic oxidations reactions involving iodine ions in the containment sump water was low and was attributed to the formation of insoluble silver iodide in the sump water. MELCOR includes modeling of silver iodide in the containment sump. Other PHEBUS-FP tests (e.g., FPT-3) will provide a different mix of materials (e.g., boron carbide) expected to be transported to the containment sump that may affect the amount of gaseous iodine in the containment. Hence, it is anticipated that the results of the PHEBUS-FP test will provide a good indication of whether the existing iodine chemistry model in MELCOR is adequate for predictions of iodine chemistry under reactor accident conditions.

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