May 4, 2007

MEMORANDUM TO: Frank P. Gillespie, Director
Advisory Committee on Reactor Safeguards

FROM: Farouk Eltawila, Director ***/RA/*** C. Lui for
Division of Risk Assessment and Special Projects
Office of Nuclear Regulatory Research

SUBJECT: PROVIDING INFORMATION ON PHEBUS-FP FOR ACRS MEETING 543 - JUNE 6-8, 2007

Enclosed is the information on Phébus-Fission Product (Phébus-FP) Project for dissemination to members of the Advisory Committee on Reactor Safeguards (ACRS). The information is provided in advance of our briefing on the Phébus-FP Project - Status and Findings at the ACRS Meeting 543 scheduled for June 6-8, 2007. We look forward to our briefing on Phébus-FP.

Enclosure:
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Phébus-FP Project

The Phébus-FP facility

The layout of the Phébus-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 an 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 40MW Phébus driver core. The driver core is limited to about 29MW for the tests. Coupling between the driver core and the apparatus is an important feature of the test.

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 $10m^3$ 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. Condensers in the containment vessel simulate cold surfaces in a containment that will condense steam. The overall scaling factor is 1/5000 with respect to a 900MWe 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.

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 Phébus-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 the circuit and the 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 significant 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.

Enclosure

(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	Oct. 12, 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	Nov. 18, 2004
FPT-4	Late phase core configuration using rubble bed EdF fuel (38GWd/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

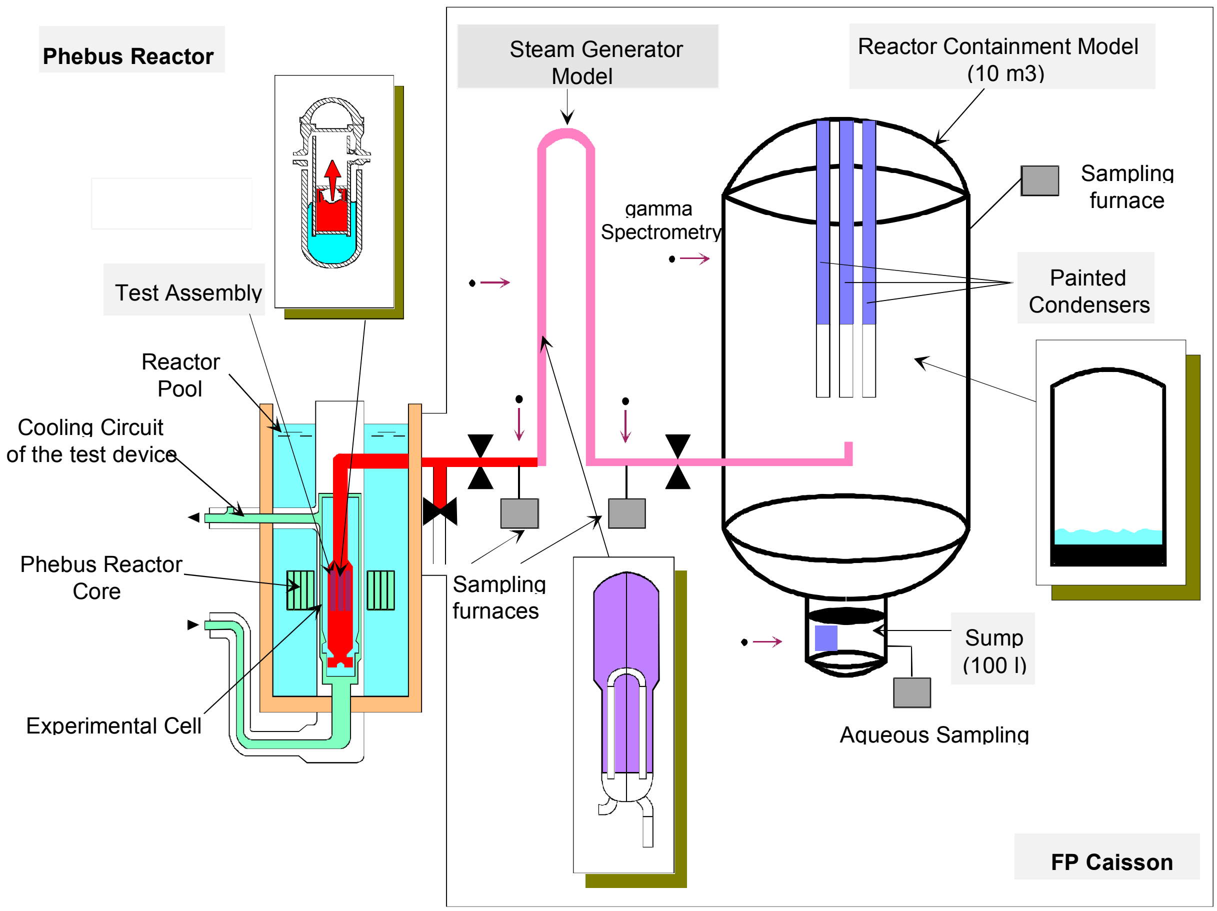

Fig. 1: Schematic view of the PHEBUS FPT-0 and FPT-1 experimental circuit

Phébus-FP Findings

Results from the PHEBUS-FP experimental program have provided a confirmation of the NRC's revised accident source term and have provided data for 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 Phébus-FP results indicated that radionuclide 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). There are low releases of refractory metal fission products (Ru, Mo, etc.) and oxide fission products (CeO_2, La_2O_3, etc.). Both radionuclide deposition in the reactor coolant system and revaporization from the reactor coolant system to the containment have to be considered. A brief discussion of Phébus-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_3I) Forms.

It has already been observed from the results of the FPT-0, FPT-1, FPT-2 test and preliminary results from the FPT-3 test, iodine released from the overheated reactor fuel transports as both a gaseous species and as particulate species. Cesium iodide is among the chemical forms of particulate iodine. In tests with silver-indium-cadmium control rods, cadmium iodide (CdI_2) is probably a more common form of particulate iodine. Phébus-FP results suggest 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 final results of the Phébus-FP tests.

Silver vaporized from control rod alloys in tests FPT-0, 1, and 2 transports to the containment sumps where it reacts 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 containment Phébus-FP tests is that atmosphere.

The FPT-2 test data show the effects of boric acid on the fraction of iodine in the gaseous state, either during initial release or during the subsequent revaporization from the reactor coolant system.

The FPT-3 test yielded remarkable results. In this test, most (~80%) of the iodine that entered the containment did so as a gaseous species. Current speculation is that boric oxide produced by the steam oxidation of the boron carbide control material of the test reacted with all elements such as cesium that are capable of forming particulate material with iodine. Despite the high initial inventory of gaseous iodine, the iodine concentration fell rapidly to the familiar steady-state concentration observed in the previous Phébus-FP tests. The rate at which the iodine concentration fell was faster by factors of 2 to 4 than the rate at which the particulate material concentration fell. The rate is much faster than would be expected if the gaseous iodine had to transport to the small surface area of the sump. Indeed, the sump was kept acid in the test (pH = 5) and late in the test the sump water was heated to near boiling to facilitate mass transport of molecular iodine from the sump to the containment atmosphere. Current speculation is that the gaseous iodine removal was occurring on the surfaces of the condensers in the containment. This removal was enhanced when there were higher fluxes of steam coming from the sump when it was heated. Chemistry within these water films was responsible for the development of the steady-state gaseous iodine concentration in the containment atmosphere. Increased steam flux from the evaporating sump in the later stages of the test perturbed the steady state by augmenting the condensation on the condensers and the attendant sweepout of the gaseous iodine.

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

The first two tests FPT-0 and FPT-1 indicate a 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 releases of refractory oxide fission products at high temperatures reached in such debris beds is as low as now predicted by accident analysis computer codes.

FPT-0 and FPT-1 tests have suggested a higher mobility (i.e., release from fuel) for refractory than had been anticipated especially for ruthenium (2% to 6% of bundle inventory).

1.3 Both Radionuclide 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, and 3 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 cesium was observed in FPT-0 and FPT-1, as assumed in the revised source term. Cesium release from the overheated reactor fuel transports as cesium molybdate (Cs_2MoO_4) rather than cesium hydroxide (CsOH). Any cesium hydroxide that reaches containment comes from the revaporization of cesium compounds deposited in the reactor coolant system model. 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.

Phébus Source Term Separate Effects Test

IRSN has launched a follow-on project known as the Phébus Source Term Separate Effects Test (Phébus-STSET). The Phébus-STSET project is a set of separate effects investigations to further understand some of the findings from the Phébus-FP project. The major elements of the Phébus-STSET project are the EPICUR tests of gaseous iodine behavior, the CHIP tests of fission product chemistry in the reactor coolant system, the MOZART tests of clad oxidation in air, the BECARRE tests of boron carbide oxidation in steam, and the VERDON tests of fission product release from irradiated high burnup and MOX fuels.

2. ASSESSMENT OF SEVERE ACCIDENT MODELING

The Phébus-FP results are being used to assess the adequacy of severe accident codes (e.g., MELCOR, SCDAP/RELAP5). A brief descriptions of the comparisons of MELCOR predictions and observations from the Phébus-FP tests are provided below:

2.1 Fuel Heatup

MELCOR models of fuel heat up to the runaway reaction with steam agree well with observations in the tests. Modest discrepancies in timing could be corrected by more detailed modeling of the non-prototypic shroud used in the tests to contain degrading fuel and limit radial heat losses.

2.2 Hydrogen Production

MELCOR models do an exceptionally good job of predicting the hydrogen production from the exothermic reactions of steam with the zirconium cladding on fuel. A comparison of MELCOR predictions to results obtained in the FPT-1 test is shown in Figure 1. This comparison adds confidence in the combination of chemical kinetics and mass transport limitations MELCOR uses to predict the oxidation of zirconium cladding by steam.

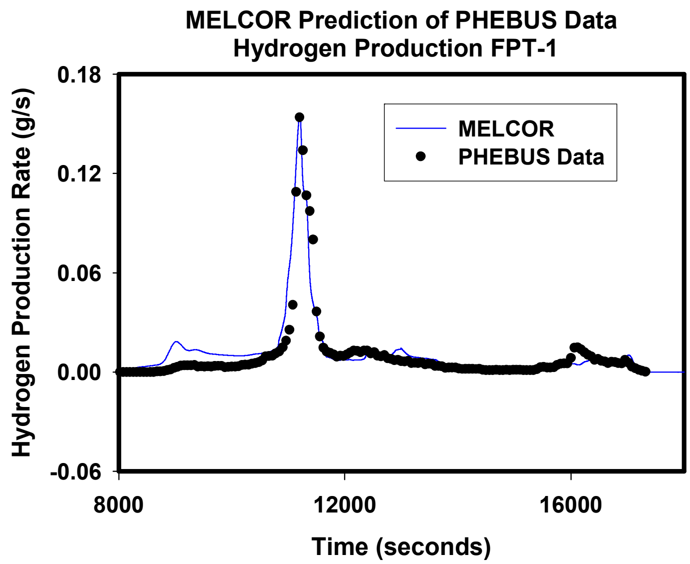

Figure 1. Hydrogen Production During Core Degradation

2.3 Ag-In-Cd Control Rod Modeling

The significant role of vapor and aerosols produced by the rupture of the Ag-In-Cd control rods in the Phébus-FP tests has made it apparent that a mechanistic models of control rod failure and material release were needed in MELCOR. These models have been added to the code.

2.4 Late Stage Core Relocation

Comparison of MELCOR predictions to the relocation of fuel from the core region once fuel melting begins and the magnitude of the molten fuel produced in the tests showed that improved modeling of melting and relocation was needed. In particular, relocation was observed to occur at lower temperatures than anticipated. Revised modeling has shown the overall core temperatures are lower in severe accidents and process of core degradation is more protracted.

2.5 Volatile Fission Product Release from Fuel

Initial comparisons of MELCOR predictions to observed releases of volatile fission products showed that MELCOR predicted well the overall releases but did not predict release rates particularly well. Insights from the Phébus-FP tests suggested that fission product speciation assumed in MELCOR needed revision as did some of the parameterization of the CORSOR-Booth modeling of the release process. These modification have produced admirable agreement of predictions with observations as shown in Figure 2.

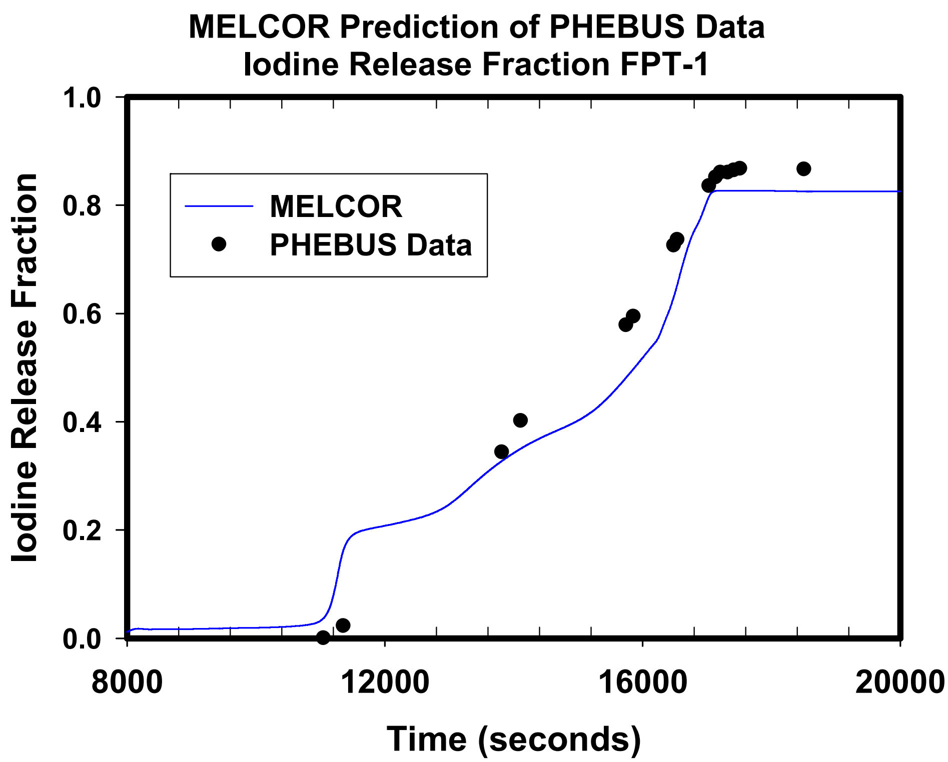

Figure 2: FPT-1 iodine release fraction

2.6 Volatile Radionuclide Speciation

Phébus-FP test suggest that CsOH may not be an important vapor or aerosol form of radioactive cesium in the reactor coolant system as assumed in the development of MELCOR. Rather, cesium molybdate may be an important chemical form that affects vapor deposition and revaporization. Similarly, Phébus-FP results show that silver vapor and aerosol from control rods can affect iodine speciation in the reactor coolant systems. Changes have been made to MELCOR to account for these findings.

2.7 Aerosol Formation in the Reactor Coolant System

Modeling of aerosol formation and growth in the reactor coolant system yields results that agree rather well with aerosol concentrations and particle size distributions measured in the tests.

These results are considered significant because they suggest rather complicated modeling of aerosol nucleation processes can be adequately described by simple approximations.

2.8 Aerosol Deposition in Steam Generators

Comparisons of aerosol mass deposited in the model steam generator tube of the Phébus-FP tests and code predictions show that codes, MELCOR and all other similar codes, over predict the deposition. Current thinking is that fully developed flow approximations for hydrodynamics in the codes may have to be modified to account for entrance effects in regions of high deposition.

2.9 Containment Thermal Hydraulics

The $10m^3$ containment model used in the Phébus-FP tests can be rather well modeled using a single MELCOR node. Very good predictions of the temperature, pressure, relative humidity and condensation rates are obtained with what might seem overly simple nodalization. These results add confidence to the large nodes used for MELCOR modeling of containment phenomena in reactor accidents.

2.10 Aerosol Composition

Aerosol modeling in MELCOR assumes that coagulation of aerosols occurs regardless of initial particle composition and size distribution. This assumption has been validated by the PHÉBUS-FP tests that show aerosols have rather uniform compositions and similar deposition rates.

2.11 Aerosol Sedimentation and Deposition

Comparison of predicted and measured rates of aerosol sedimentation and deposition in the containment model of the Phébus-FP test show the MELCOR modeling is quite satisfactory until aerosol concentrations fall to very low levels where measurements are difficult to make. This result is quite pleasing since the natural attenuation of aerosol concentration in the Phébus-FP tests is complicated by multiple deposition processes including gravitational settling, diffusiophoresis to condensers and thermophoresis from the heated containment walls.

2.12 User Effect

MELCOR has proved to be an useful tool for the prediction of severe nuclear reactor accidents. It is used in many countries. Code users have a variety of backgrounds and experience in the use of large integral codes. Code comparison exercises have shown that analysts modeling the same Phébus-FP test can get quite different results. This illustrates a strong “user effect” in the results obtained with MELCOR and demonstrates the importance of user training that has been provided by the MELCOR project.

2.13 Future Comparisons

Data from some of the later Phébus-FP tests (FPT-2 and FPT-3) are only now becoming available for comparison to code predictions. Additional validation of MELCOR modeling should be possible as these data are examined. Some important issues that will be addressed in the future include:

- Iodine chemistry modeling in the containment
- Effects of boron carbide control rods on the degradation of reactor fuel, fuel relocation and hydrogen production.
- Refractory radionuclide release during later stages of core degradation

Summary

Experimental data from Phébus-FP tests have provided valuable data to confirm the source term specified in NUREG-1465, and to validate the NRC MELCOR severe accident code.

The Phébus-FP tests revealed a number of unanticipated processes and phenomena including development of a steady state gaseous iodine concentration in the containment atmosphere despite no detectable partitioning of iodine from the sump in the containment model. The data was also used to confirm many of the important features of the NRC revised/alternative source term as specified in NUREG-1465. NUREG-1465 is used for design basis accident radiological consequence analysis in operating plants and in new standard reactor design certification reviews (10 CFR Parts 52 and 100).

The results from the Phébus-STSET Program will supplement the Phébus-FP findings and assist in refining the modeling of severe accident phenomena (e.g., iodine behavior, born carbide control rod degradation) in severe accident analysis. The MELCOR code is used for safety analysis and risk-informed decision making.

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