

An Assessment of RELAP/SCDAPSIM/MOD3.4 Using the Phebus FPT-2 Bundle Heating and Melting Experiment

By

J. K. Hohorst
Innovative Systems Software LLC
Idaho Falls, Idaho, 83404
jkh@srv.net

C. M. Allison
Innovative Systems Software LLC
Idaho Falls, Idaho, 83404
iss@cableone.net

Abstract – *The RELAP/SCDAPSIM/MOD3.4 code, designed to predict the behavior of reactor systems during normal and accident conditions, is being developed as part of the international SCDAP Development and Training Program (SDTP). RELAP/SCDAPSIM/MOD3.4 uses publicly available RELAP/MOD3.3 and SCDAP/RELAP5/MOD3.2 models, developed by the US Nuclear Regulatory Commission, in combination with (a) new models for fission product transport and deposition, fuel assembly behavior, and in-vessel melt retention, (b) advanced programming and numerical techniques, and (c) integrated graphics displays.*

Although the RELAP and SCDAP models have been successfully validated for a wide range of accident conditions using a variety of experiments and TMI-2, the results from ongoing research programs in Europe and Asia have indicated the need to continue to improve the accuracy of the models for:

- *Fuel behavior and fission product release from highly irradiated fuel bundles*
- *Quenching of hot damaged bundles*
- *Bundle heating, melting, and quenching in the presence of air*
- *In-vessel retention of melts under flooding conditions.*

As a result, SDTP members in Europe, Asia, Latin America, and the United States are developing improved models in each of these areas using special “SDTP-members-only” versions of RELAP/SCDAPSIM. The results of many of these model development activities have been presented in the public literature. However, these experimental models are now being implemented in the RELAP/SCDAPSIM/MOD3.4 version of the code for use by the general user community. This paper describes the assessment activities of this new version of the code using the Phebus FPT-2 experiment.

I. INTRODUCTION

The PHEBUS FPT2 experiment is part of the PHEBUS-FP program being conducted to investigate key phenomena that may occur during a LWR severe accident. The tests are conducted by IRSN, the nuclear research arm of the French Nuclear Safety Authority. The research program is supported by European Union (EU) member countries: Austria, Belgium, Finland, Germany, Italy, Netherlands, Spain, and the United Kingdom. The non-EU countries participating in the program are Canada, Japan, Korea, Switzerland and the United States. With the admission of Central and Eastern European countries to the EU, the participants in the program now represent a large fraction of the nuclear world.

The PHEBUS-FP program's primary mission is to verify the key phenomena occurring during a severe accident related to core melt progression and fission product release and transport⁶. Results from experiments have been used to develop and verify the computer models used in severe accident codes, such as MELCOR¹, ICARE², and RELAP/SCDAPSIM³. Results from the experiments have also been used to reduce the uncertainties in estimates of the source term. Results from the PHEBUS-FP program are being used to assess the accuracy of models in the RELAP/SCDAPSIM computer code.

The RELAP/SCDAPSIM code, designed to predict the behavior of reactor systems during normal and accident conditions, is being developed at Innovative Systems Software (ISS) as part of the international SCDAP Development and Training Program (SDTP)⁴. RELAP/SCDAPSIM/MOD3.4 uses the publicly available SCDAP/RELAP5/MOD3.2⁵ models, developed by the US Nuclear Regulatory Commission, in combination with proprietary (a) advanced programming and numerical techniques to allow users to run detailed 1D and multi-dimensional calculations reliably and quickly, (b) user options such as integrated 3D

graphical displays, and (c) advanced models such as the generalized 2D electrically-heated fuel rod simulator, fission product transport and deposition, and other structure models.

This paper will discuss the important features of the Phebus FPT-2 experiment, the development of the input deck used for ISS's assessment activities, and the results from a series of sensitivity studies on the effect of uncertainties and important boundary conditions, shroud thermal conductivity and axial peaking factors.

II. Important Features of the Phebus FPT-2 Experiment

The FPT-2 bundle heating and melting experiment was performed in the Phebus facility, located at Cadarache, France, and operated by the French Atomic Energy Commission (CEA). The 21 rod experimental bundle consisted of a 5 by 5 rod array with the corner rods removed. Eighteen of the UO₂ – Zr clad fuel rods were previously irradiated in the BR3 reactor, burnup 32 GWD/tU. The remaining two bundle fuel rods were unirradiated. The remaining rod, centrally located, was a silver-indium-cadmium control rod with stainless steel cladding inside a Zircaloy guide tube. The test bundle was approximately 1 meter long and enclosed by an insulating shroud. The insulating shroud was a relatively complex structure with 4 vertical Zircaloy stiffeners on the inner surface, an inner thoria liner, a porous zirconia layer with a gap separating the two insulating layers (at higher temperatures the gap is closed), and an outside layer of Inconel. During the experiment, the oxidation of the Zircaloy stiffeners and the time dependent changes in shroud thermal resistance, due to bundle temperature changes were significant contributors to the overall uncertainties in the test boundary conditions.

The fresh fuel rods and the insulating shroud contained numerous thermocouples to measure the temperature history at various elevations and locations during the course of the experiment. The test facility also included an upper plenum region, a hot leg region connecting to a steam generator and a cold leg exiting into the containment. The system also included aerosol detectors and measuring devices to measure fission products released during the experiment.

As shown in Figure 1, the power was increased in a stepwise fashion during the 20,000-second experiment. Reactor power was increased over a period of a few seconds and then held constant at the new power until equilibrium was reached. Once equilibrium was attained the power was again increased. This process was continued until the desired experimental power was reached.

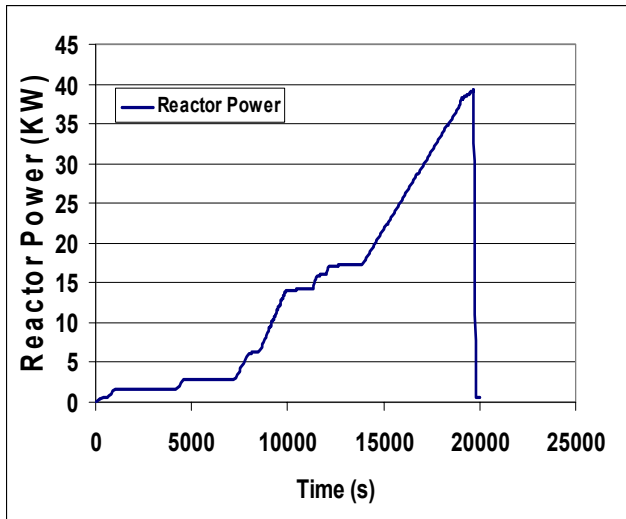


Figure 1. Bundle power

Steam flow into the lower portion of the bundle was held at 0.5 grams/sec for the duration of the experiment to create an extended period of steam starvation thus limiting the oxidation rate by steam availability. The steam inlet temperatures varied between 820 and 940 K.

As shown on Figure 2, the bundle temperatures increased as the power was increased with a rapid temperature excursion due to oxidation of the Zircaloy in the bundle prior to the bundle becoming steam starved. The rapid increase in temperature occurred during the power increase to 15 KW. From experimental measurements the majority of hydrogen produced during the experiment occurred during this oxidation transient. A small amount of hydrogen was released toward the end of the experiment. Measurements indicated the release of 120 grams \pm 14 grams during the experiment. The maximum experimental fuel bundle temperature was measured to be in excess of 2600 K, well below the melting temperature of the fuel and oxidized portion of the Zircaloy cladding, but above the melting points of the Zircaloy and control rod structural materials. The posttest examination of the bundle indicated the formation of a large molten pool, containing a mixture of fuel, control material and zircaloy, covering most of the lower half of the bundle during the experiment. The experiments using irradiated fuel performed in the Phebus facility at the Cadarache Center have shown fuel melting to occur at temperatures lower than expected.⁷

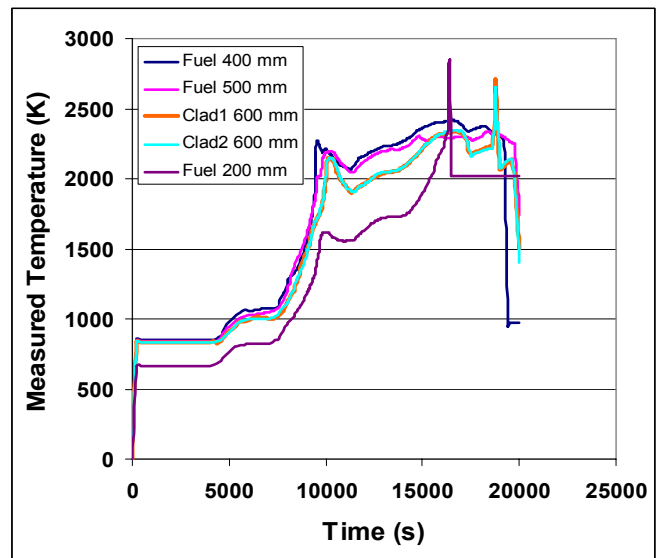


Figure 2. Measured bundle temperatures

III. Benchmark and Assessment Activities

ISS calculations of the FPT-2 experiment were performed as part of the European Union’s code benchmark activities. Benchmark activities were coordinated by the European Union’s Joint Research Center at Petten in the Netherlands. An input deck using the bundle configuration from the International Standard Problem 46 (ISP-46) calculations was initially used and modified to represent the FPT-2 experiment. ISP-46 was based on an earlier experiment, FPT-1, also performed in the Phebus reactor. The nodalization of the bundle used 12 axial nodes to model the active nuclear zone plus a small upper region of the fuel rod. The node center in the nodalization used for the calculation corresponded to the location of the bundle thermocouples. The insulating shroud was modeled as manufactured with all layers represented. This shroud model was identical to the model used by ISS for the ISP-46 International Standard Problem exercise. Figure 3 shows the nodalization of the bundle and a detailed representation of the shroud of the shroud model.

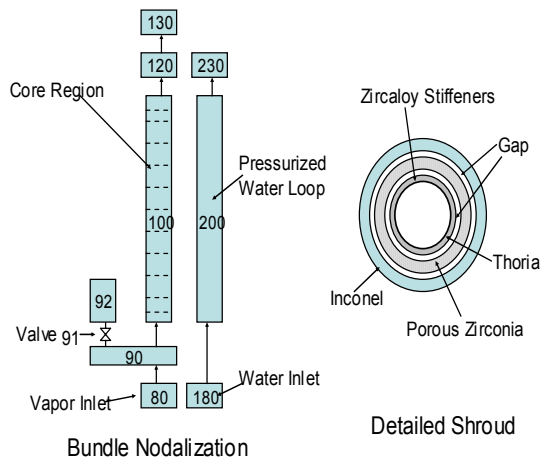


Figure3. Bundle and shroud nodalization used for the benchmark calculation.

Initial scoping calculations performed for the benchmark exercise used the initial recommended values for the axial power profile and thermal conductivity for the insulating shroud. IRSN also supplied an alternative shroud thermal conductivity and axial power profile. Additional calculations were performed using the alternative axial power profile and the IRSN recommended zirconia thermal conductivity. In addition, two additional scoping calculations were performed, one using the recommended zirconia thermal conductivity with the alternative axial power profile, the other using the alternative zirconia thermal conductivity with the recommended axial power profile. Table 1 in Section 4 shows the IRSN initially recommended and alternative shroud thermal conductivities along with several additional thermal conductivities that were used in the sensitivity studies discussed in this paper. A table has also been included in the nomenclature section listing the abbreviations used in the figures. Results from these calculations are shown in Figures 4 and 5.

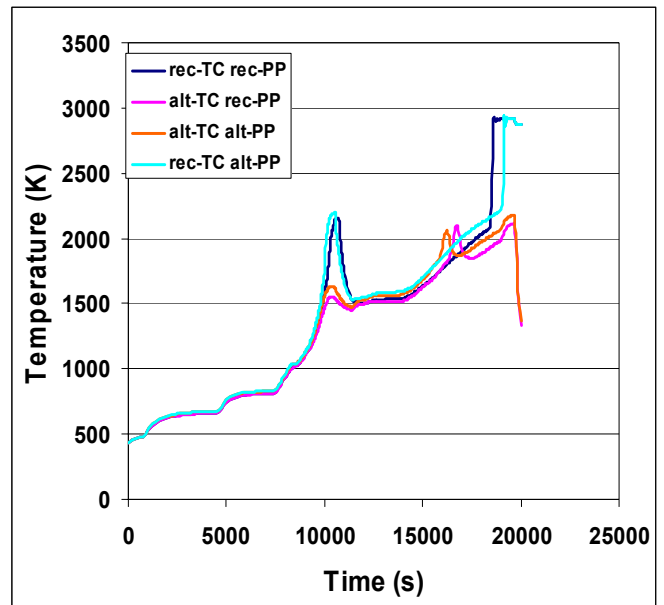


Figure 4. Calculated temperature at 200 mm elevation using recommended and alternative shroud thermal conductivity and axial power profiles.

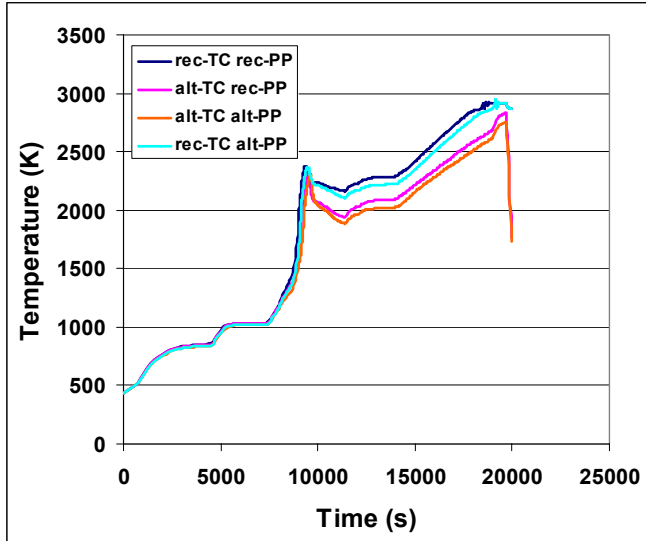


Figure 5. Calculated temperatures at 500 mm elevation using the recommended and alternative shroud thermal conductivity and axial power profiles.

As shown in Figures 4 and 5 when the recommended shroud thermal conductivity is used, temperatures in the bundle are calculated to be higher than when the alternative thermal conductivity is used. The alternative axial power profile provided by IRSN which lowered the power ratio at the middle nodes, the 400-600 mm elevations, from 1.736, 1.664, and 1.407 to 1.59, 1.56, and 1.3 did not effect the temperatures significantly. The thermal conductivity of the zirconia used in the insulating shroud plays a more significant role in determining the correct heat losses through the shroud.

Measured data from the FPT-2 and other severe accident experiments are used to assess the code. Assessment activities include comparing calculated results from a new version of the code to measured experimental values and to the predicted results from earlier version of the code.

To predict the melt progression in the test bundle accurately, the radial distribution of temperatures through the insulating shroud need

to be matched to the measured data. Due to bundle damage occurring during the simulated accident, there are uncertainties in the actual thermal conductivity of the shroud during the progression of the accident. Due to the effect of these uncertainties on the heat losses through the insulating shroud a series of sensitivity studies on the influence of changes in the thermal conductivity of the insulating material and the axial power profile within the band of uncertainty were performed. The next section describes these sensitivity studies and the results of these studies.

IV. Sensitivity Studies

A series of sensitivity studies were performed by varying the thermal conductivity of the porous zirconia shroud. The thermal conductivity of the remaining materials in the shroud was as given by the experimentalist with the exception of the gaps between the thoria inner liner and the porous zirconia and the zirconia and inconel. To represent the decreased gap size due to the relocation of bundle material, the thermal conductivity of the gases in the gap was increased approximately two orders of magnitude to represent the gap closure due to the absence of a gap closure model in RELAP/SCDAPSIM. Since the actual thermal conductivity of the shroud during the accident phase of the accident is uncertain, matching of heat losses through the shroud is the most common method used by analysts to predict accurate bundle temperatures and behavior. The matching of the heat losses is accomplished by varying the thermal conductivity of the insulating materials within an uncertainty band and comparing the predicted temperatures to the measured temperature of the inner and outer shroud.

A comparison of calculated bundle temperatures using the recommended or alternative axial power profile with the shroud thermal conductivities presented in Table 1 to the

measured data was performed. Thermal conductivities 1 and 2 are the original thermal conductivities suggested by IRSN, thermal conductivity 3 was the best thermal conductivity used for the insulating shroud in the analysis of ISP-46, and thermal conductivity 4 is the thermal conductivity that gave the best results for the FPT-2 experiment. Once a base deck has been developed for an experiment this deck is frozen and considered the best deck to be used for assessment calculations. This deck is then used to perform calculations with various versions of the code, old and new, to verify that changes and additions to the code have not changed the results.

The sensitivity calculations reported in this paper employed the thermal conductivities listed in Table 1 with three different axial power profiles. Two of the power profiles were suggested by IRSN and the other power profile was that used for the ISP-46 (FPT1) calculation. Figure 6 shows the three axial power profiles used to develop a dependable FPT-2 input deck to be used for the verification and for the verification and assessment of models in RELAP/SCDAPSIM.

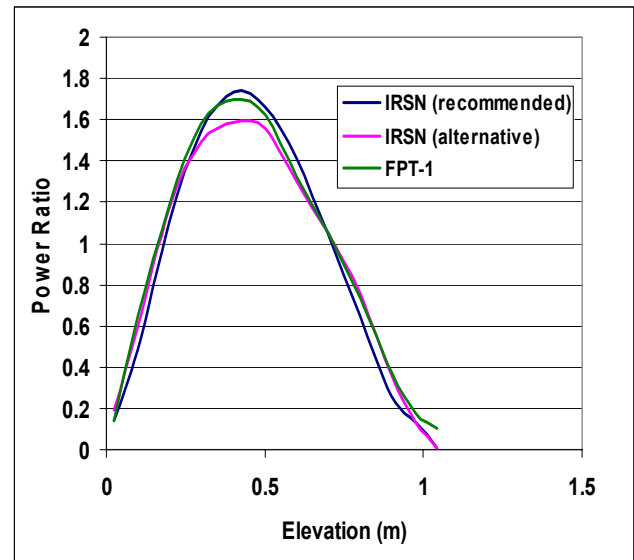


Figure 6. Axial Power Profiles used for sensitivity studies

Figures 7 and 8 show the calculated and measured temperatures of the shroud at two elevations in the bundle, one near the bottom, 100 mm and the other in the upper central portion, 800 mm, for each of the above thermal conductivities with various axial power profiles.

Table 1 – Thermal Conductivities

Temperature	300	500	700	878	1073	1173	1248	1700	2100	2500
Thermal Conductivity 1 (rec)	.65	.60	.59	.59	.54	.56	.58	1.12	1.47	2.3
Thermal Conductivity 2 (alt-rec)	.74	.70	.69	.68	.62	.61	1.03	1.98	2.56	3.07
Thermal Conductivity 3 (fpt1)	.23	.23	.30	.33	.58	.64	.78	3.0	3.2	4.0
Thermal Conductivity 4 (fpt2)	.22	.22	.29	.32	.56	.64	.78	2.0	2.5	3.0

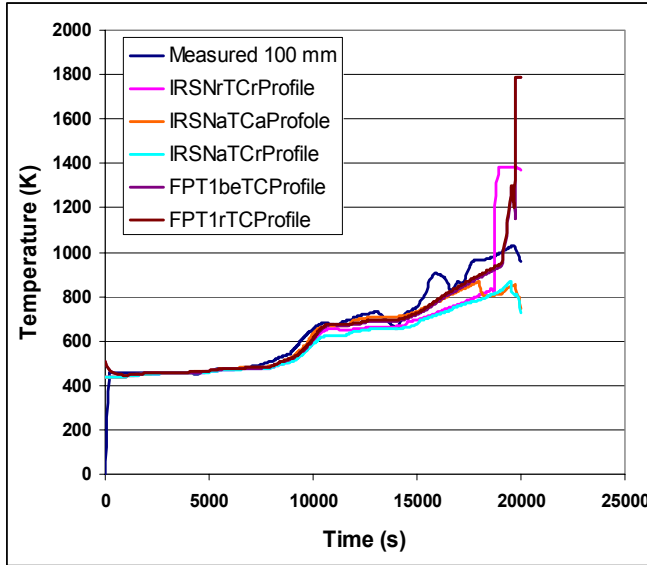


Figure 7. Calculated and measured shroud temperatures at the 100 mm elevation in the bundle at various thermal conductivities and axial power profiles.

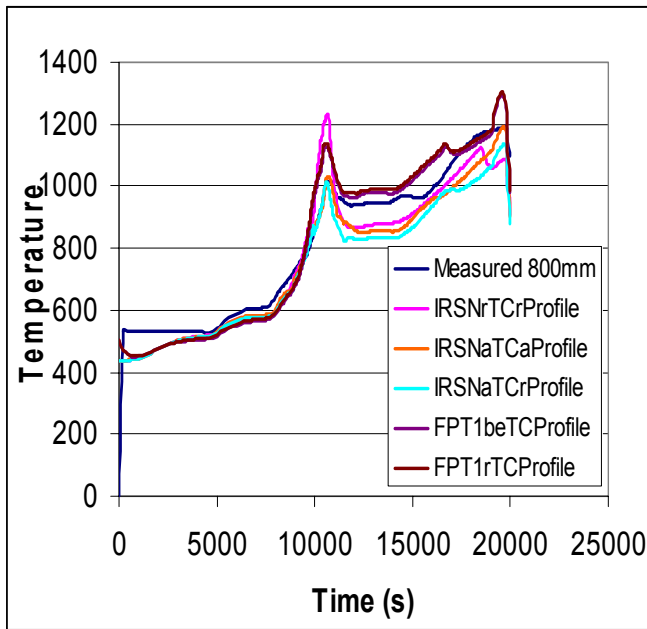


Figure 8. Calculated and measured shroud temperatures at the 800 mm elevation in the bundle at various thermal conductivities and axial power profiles.

Matching the measured temperatures radially and axially through the shroud indicates that the

heat losses have been predicted correctly. From the above two figures it can be seen that the alternative thermal conductivity and alternative axial power suggested by the experimentalists gave the best results for the heat losses through the shroud.

Figures 9 and 10 show calculated and measured temperatures in the bundle at two elevations in the bundle. Looking at the figures and comparing the results from the calculations to the measured temperatures it can be seen that the calculations using the alternative IRSN thermal conductivity and power profile predict the best temperature agreement with the measured data during the heat up phase of the accident.

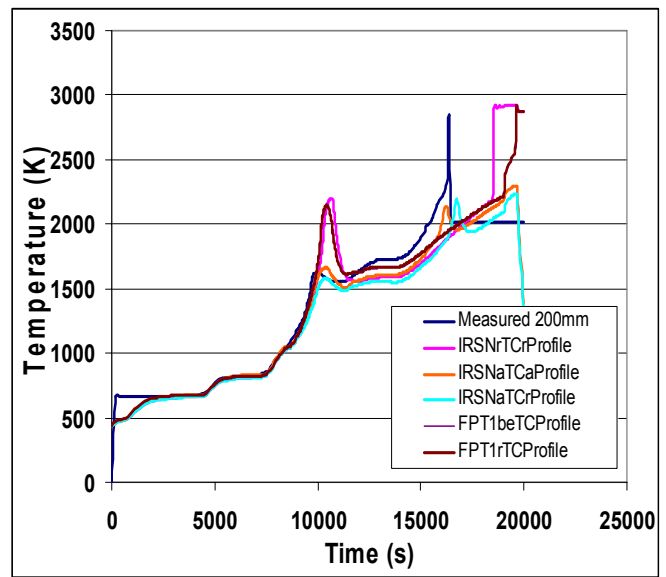


Figure 9. Calculated and measured temperatures at the 200 mm elevation in the bundle.

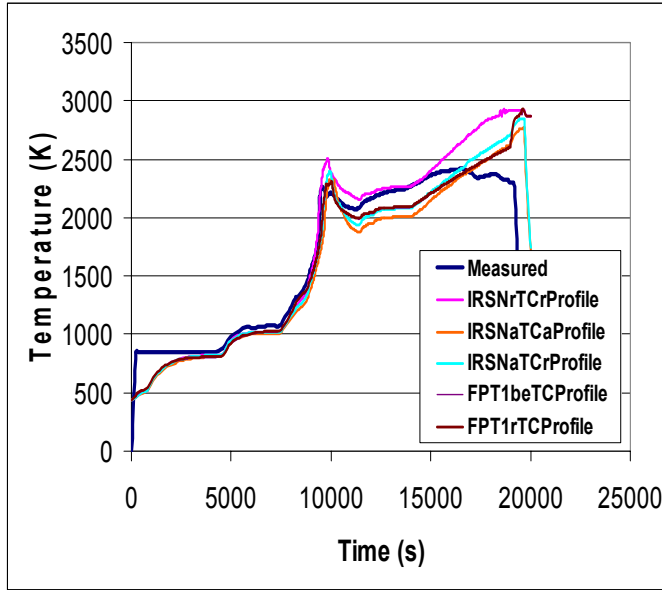


Figure 10. Calculated and measured temperatures at the 400 mm elevation in the bundle

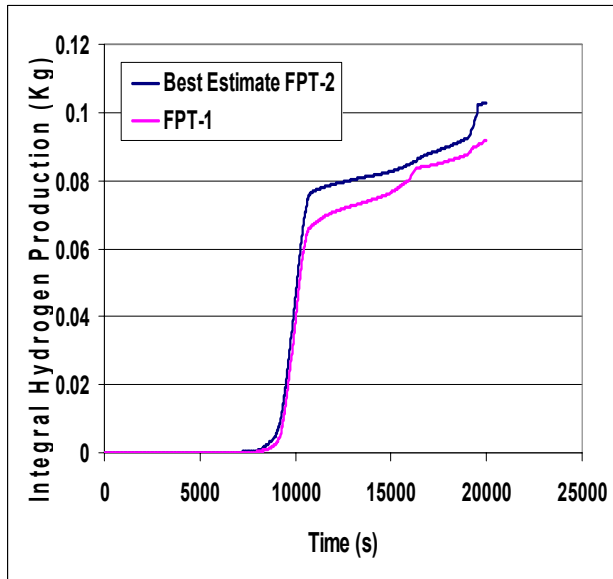


Figure 11. Predicted Hydrogen form best estimate case and the one using the thermal conductivity and axial power profile from ISP-46.

Figure 11 shows the predicted hydrogen production from the best estimate case and the one using the thermal conductivity and power profile from the FPT-1 analysis. Curve 1 shows the predicted hydrogen production using the

ISP-46 zirconia thermal conductivity and ISP-46 axial power profile. This curve shows the production of 102 grams where as the best estimate case, curve 2, shows the production of 92 grams hydrogen, both values are within the experimental error in hydrogen release measurement when the excess hydrogen produced during the formation of the molten pool and oxidation of the shroud zircaloy is excluded. The initiation of zircaloy oxidation occurs at approximately the same time during the accident.

V. Conclusions

The assessment of RELAP/SCDAPSIM using the FPT-2 experiment has shown that the code can predict the progression of the experiment. Calculated results fall within the experimental uncertainties considering the large uncertainties in the shroud thermal conductivity and axial power profile. Assessment results indicate that at this time no major modeling changes need to be made to code, with the exception of the lower molten pool formation in the presence of highly irradiated fuel as noted in the abstract and which has been presented in an earlier published paper.

Sensitivity results indicated that the variation in shroud thermal properties was the dominant contributor to overall variability in the predicted results. The differences in shroud thermal properties had the most direct impact on bundle temperature response, in particular the peak bundle temperatures. The shroud properties also indirectly affected the rate of hydrogen production because of the strong feedback between oxidation and temperature. In the two cases, shown in Figure 11, the best estimate case and case using the slightly different shroud thermal conductivity from FPT-1, the higher bundle temperatures obtained from the FPT-1 properties showed the production of a greater quantity of hydrogen.

The participation in the Phebus program has had very beneficial impact on the improvement of future training activities for ISS, development of improved code models, the improvement of code user guidelines and manuals, and the assessment and verification of code models. Improved user guidelines that reflect the lessons learned from ISP-46 calculations have already been prepared and improvements from the FPT-2 benchmark participation are in progress. PHEBUS program has had an impact on the user options and models being developed for future releases of RELAP/SCDAPSIM. One example is the development of a model that considers the lower formation temperature of a molten pool when irradiated fuel is present in the bundle.

ACKNOWLEDGEMENTS

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NOMENCLATURE

Properties represented in Figure	Abbreviation
IRSN recommended Thermal Conductivity	Rec-TC
IRSN alternative Thermal Conductivity	Alt-TC
IRSN recommended power profile	Rec-pp
IRSN alternative power profile	Alt-pp
IRSN recommended Thermal Conductivity and recommended power profile	IRSNrTCrProfile
IRSN alternative Thermal Conductivity and alternative power profile	IRSNaTCaProfile
IRSN alternative Thermal Conductivity and recommended power profile	IRSNaTCrProfile
FPT1 best estimate Thermal Conductivity and power profile	FPT1beTCProfile
FPT1 recommended Thermal Conductivity and power profile	FPT1rTCProfile

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