C 3/3*

Comparison of the SCDAP Computer Code with Bundle Data Under Severe Accident Conditions

C.M. Allison, T.M. Howe

EG & G Idaho, Inc., P.O. Box 1625, Idaho Falls, Idaho 83415, U.S.A.

G.P. Marino

U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, MS 1130-SS, Washington, D.C. 20555, U.S.A.

Summary

The SCDAP computer code, which is being developed under the sponsorship of the United States Nuclear Regulatory Commission, models the progression of light water reactor core damage including core heatup, core disruption and debris formation, debris heatup, and debris melting. SCDAP is being used to help identify and understand the phenomena that control core behavior during a severe accident, to help quantify uncertainties in risk assessment analysis, and to support planning and interpretation of severe fuel damage experiments and data.

The first version of the code, SCDAP/MODO, has undergone extensive assessment over the past year. Comparisons between SCDAP calculations and data from the Severe Fuel Damage (SFD) Test Series being performed at the Idaho National Engineering Laboratory and the Hagen meltdown experiments being performed in Karlsruhe, West Germany, were essential parts of that assessment. Comparisons for two experiments, SFD Scoping Test (ST) and ESSI-2, are presented in this paper.

SFD-ST was a nuclear heated bundle test. The bundle consisted of 32 fuel rods arranged in a 6x6 array with the corner rods removed. The bundle inlet flow and fission power were varied during the experiment to obtain a slow heatup with nearly complete zircaloy oxidation prior to reaching the melting temperature of zircaloy. ESSI-2 was a single-rod, electrically heated experiment. This and other Hagen experiments studied meltdown phemomena under different heating and environmental conditions. ESSI-2 was a rapid heatup experiment, with limited oxidation and extensive melting of zircaloy.

Comparisons between SCDAP calculations and the experimental data showed good agreement. Calculated and measured bundle temperatures for SFD-ST were within 200 K for the entire bundle and within 20 K for maximum cladding temperatures. For ESSI-2, calculated and measured maximum cladding temperatures were within 50 K, and the extensive liquefaction and relocation that was calculated was in agreement with experimental results.

---

a. Work supported by the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, under DOE Contract No. DE-AC07-76ID01570.

1. Introduction

The Severe Core Damage Analysis Package (SCDAP) computer code is being developed at the Idaho National Engineering Laboratory under the sponsorship of the Office of Research of the United States Nuclear Regulatory Commission[1 - 3]. SCDAP models the progression of light water reactor core damage including core heatup, core disruption and debris formation, debris heatup, and debris melting. SCDAP is being used to help identify and understand the phenomena that control core behavior during a severe accident, to help quantify uncertainties in risk assessment analysis, and to support planning and interpretation of severe fuel damage experiments and data.

The first version of the code, SCDAP/MODO, was completed during the fall of 1982. SCDAP/MODO has undergone extensive assessment over the past year to determine the limitations and strengths of the code and its models. Two of the early assessment cases were comparisons of SCDAP calculations with data from both in-pile, nuclear heated experiments and out-of-pile, electrically heated experiments. The results of these comparisons, as presented in this paper, demonstrate the ability of SCDAP/MODO to accurately describe the early phases of damage progression up to and including geometry changes and material relocation.

2. Description of Experiments

The data for a nuclear heated bundle were taken from the Severe Fuel Damage Scoping Test (SFD-ST)[4]. This test, performed during October 1982, was the first in a series of experiments being conducted in the Power Burst Facility at the Idaho National Engineering Laboratory. The fuel bundle consisted of 32 zircaloy-clad UO_2 fuel rods arranged in a 6x6 array with the corner rods removed. The bundle was contained in an insulated shroud with a zircaloy liner intended to simulate the cladding of surrounding fuel rods in a typical PWR assembly. The fuel rods have a radial geometry typical of a 17x17 PWR assembly, but with an active fuel length of 0.914 m.

The bundle inlet flow and power were varied during the experiment to obtain a slow heatup in steam with nearly complete zircaloy oxidation prior to reaching the melting temperature of zircaloy. The experiment instrumentation included thermocouples, failure indicators, and hydrogen and fission product monitors. However, all of the upper bundle fuel rod, inner shroud, and steam thermocouples failed during the experiment as maximum temperatures of 2400 K were reached.

The data for an electrically heated fuel rod were taken from the Hagen series of single-rod experiments (ESSI) conducted in Karlsruhe, West Germany [5]. The Hagen experiments were designed to study the meltdown phemomena of zircaloy-clad UO_2 fuel rods. Eleven single-rod tests were conducted using electrically heated tungsten rods encircled by UO_2 disks and zircaloy cladding. These 0.25-m-long, simulated fuel rods were placed in a steam atmosphere and enclosed in an insulated zircaloy shroud to reduce radiant heat losses. The data collected from the ESSI-2 experiment included experimental geometry, electric power, rod and shroud surface temperatures at the 0.14-m elevation, initial inlet steam temperature, and steam flow rates. These data were used in the following comparisons.

3. SCDAP Model

For both experiments, the geometry was initially described in SCDAP using representative components--fuel rods and shroud. Zircaloy oxidation, hydrogen generation, and fission product release were modeled for each component. Fuel rod ballooning and rupture, zircaloy and UO_2 liquefaction and relocation, and component fragmentation during reflood were also modeled.

The SFD-ST bundle was represented by four components--three fuel rods to represent each row of rods, and one slab to represent the shroud. The bundle boundary conditions were taken directly from the test. These included the time-dependent histories for inlet flow, bundle fission power, and shroud heat loss as indicated in Figure 1. The axial power profile, estimated from neutronic calculations prior to the test, was a chopped cosine, skewed to the bottom of the bundle, with the peak located at 25% of the fuel stack height. The peak axial power was 130% of the average bundle power.

The Hagen ESSI-2 bundle was represented by two components--a fuel rod and a shroud. The boundary conditions were taken directly from the test data and posttest analysis [6]. The axial power profile was relatively flat. The unheated structure below the bundle was simulated using an unheated length of fuel rod and shroud; the water-cooled structure above the bundle was not modeled. The inlet steam flow rate was constant at 0.38 g/s. The electrical power was varied with time as shown in Figure 2. The radiation heat transfer from the rod to the shroud, which was not measured, was calculated by SCDAP using measured shroud temperatures and SCDAP-calculated rod temperatures. The calculated radiation heat transfer is also shown in Figure 2. The uncertainty in boundary conditions was the dominant uncertainty in the comparisons between the Hagen experiments and the SCDAP calculations.

4. Results

Figure 3 shows the comparison between calculated and measured bundle temperatures. Three temperature comparisons are shown--(a) steam temperatures measured at elevations, relative to the bottom of the fuel stack, of 0.50 and 0.91 m; (b) cladding temperatures measured at varying radial positions within the bundle and elevations of 0.35, 0.50, and 0.70 m; and (c) shroud temperatures measured on the inner zircaloy liner at elevations of 0.35 and 0.70 m. The degree of shading in the symbols of Figure 3 represents the relative elevations of the results. The accurate calculation of steam temperatures indicates that the overall heat storage and heat removal within the bundle is consistent between experiment and calculations. Maximum bundle temperatures show excellent agreement between calculation and measurement. For the bundle as a whole, the agreement is within 200 K, going from a maximum of 200 K near the bottom third of the bundle to a minimum of 20 K near the top of the bundle where the highest temperatures were reached. The source of the larger overprediction of cladding temperature with decreasing elevation has not yet been determined, but may be due to several factors.

1. The axial power profile estimated from pretest neutronics calculations may not be accurate.
2. The axial variation in shroud heat loss, which was not known for these calculations, may also be influential.
3. The calculated two-phase region may be too small, resulting in an excessively rapid decrease in heat transfer coefficients with elevation since forced convection heat transfer coefficients are significantly smaller than two-phase heat transfer coefficients.

Figure 4 shows the cumulative hydrogen generation during the experiment. This figure shows the measured hydrogen generation, including the contributions of high temperature material outside the bundle. The uncertainty estimates for these preliminary data may be as high as 40%. The figure also shows the calculated hydrogen generation for the bundle only, and for the bundle and surrounding structures. The latter is an upper-bound calculation which assumed that structural materials outside the bundle are at the same temperatures as the calculated cladding temperatures at the same elevations. The comparisons lead to two important points. First, the hydrogen generation rates are in good agreement early in the experiment before significant amounts of hydrogen were generated outside the bundle. Second, changes in the SCDAP SFD-ST model to include additional material unique to the apparatus are necessary and can potentially reduce the variation in calculated and measured hydrogen generation during the later stages of the heatup.

Although the degree and timing of UO_2 and zircaloy liquefaction have not yet been directly established, comparisons of calculations with the experimental behavior estimated from indirect measurements show good agreement. SCDAP calculated that liquefaction, the melting of zircaloy with subsequent dissolution of UO_2 by the molten zircaloy, began 195 minutes into the experiment. Enhanced fission product release due to the dissolution of the UO_2 was apparent during the experiment at 201 minutes. This would indicate that the calculated time of liquefaction was within 3% of the actual time. Posttest gross gamma scans of the bundle also indicate that calculated and actual percentages of bundle liquefaction during the experiment were within 10%.

Figure 5 shows calculated and measured cladding temperatures of the ESSI-2 fuel rod simulator at the 0.14-m elevation. After 14 minutes into the experiment, the measured and calculated temperatures are in excellent agreement. The calculated sharp temperature increase beginning at 12.5 minutes does not correspond to the measured temperatures and is the result of hot liquid zircaloy and UO_2 from the top one third of the rod freezing in a thin crust over the bottom two thirds of the rod. The temperature decreases as the crust cools, which is reflected in the calculated radiation heat loss shown in Figure 2. This effect does not show up in the measured results because the upper portion of the rod is apparently cooled by radiation to cold structures above the rod.

As the calculated heatup continues, the liquefaction and freezing fronts move down the rod. The zircaloy at the 0.14-m elevation melts at 14.3 minutes, and the resulting liquid zircaloy and dissolved UO_2 breach the oxide shell and flow downward slightly before 14.5 minutes. This removal of the zircaloy also terminates the cladding oxidation, significantly reducing the heatup rate at this elevation.

Although no direct measurements of zircaloy-UO_2 liquefaction and relocation were made, SCDAP calculations directly support the conclusions reached in the Hagen experiments; (a) maximum calculated temperatures did not exceed 2500 K as a result of the movement of liquid zircaloy into cooler regions of the rod; (b) maximum temperature, liquefaction, and freezing fronts started in the upper region of the rod and moved downward; and (c) extensive liquefaction of zircaloy and UO_2 occurred as a result of the rapid heatup.

5. Concluding Remarks

Comparisons of calculated and measured results for both the SFD-ST and ESSI-2 experiments demonstrate the ability of SCDAP/MOD0 to accurately describe early phases of damage progression up to and including geometry changes and material relocation.

Agreement between calculated and measured results, although in most cases very good, may be further improved by the reduction in the uncertainties in boundary conditions such as power and heat losses unique to the experimental hardware.

6. References

[1] ALLISON, C. M., et al., "Severe Core Damage Analysis Package (SCDAP) Code Conceptual Design Report," EGG-CDAP-5397, (April 1981).

[2] ALLISON, C. M., HOWE, T. M., "Conceptual Design of the Severe Core Damage Analysis Package", Trans. Amer. Nucl. Soc., 39, pp. 369-370 (1981).

[3] MARINO, G. P., ALLISON, C. M., MAJUMDAR, D., "SCDAP: A Light Water Reactor Computer Code for Severe Core Damage Analysis," Inter. Mtg. on Thermal Nucl. Reactor Safety, Chicago, IL, August 29 - September 2, 1982.

[4] GRUEN, G. E., BUESCHER, B. J., "Severe Fuel Damage Scoping Test Performance" Twenty-first ASME/AIChE National Heat Transfer Conference, Seattle, WA, July 24-28, 1983.

[5] HAGEN, S., "Out-of-pile Experiments on the High Temperature Behavior of Zry-4 Clad Fuel Rods," 6th Inter. Conf. on Zirconium in the Nucl. Industry, Vancouver, Canada, June 28 - July 1, 1982.

[6] Personal communications with S. Hagen, Karlsruhe, West Germany.

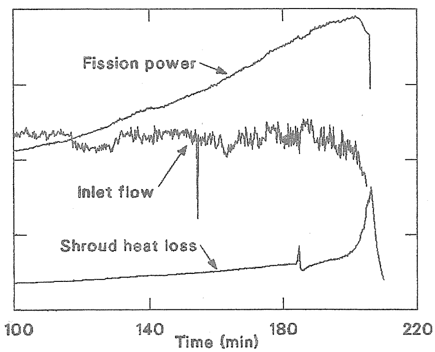

Figure 1. Measured power, flow, and heat loss bundle boundary conditions for SFD-ST.

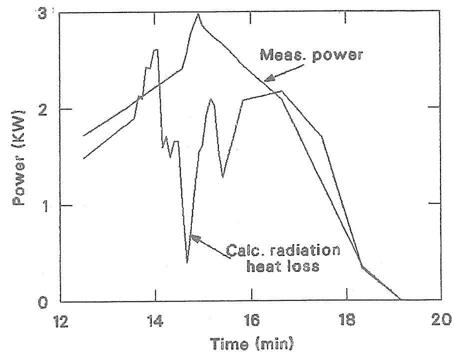

Figure 2. Measured power and calculated radiation heat loss from fuel rod to shroud for ESSI-2.

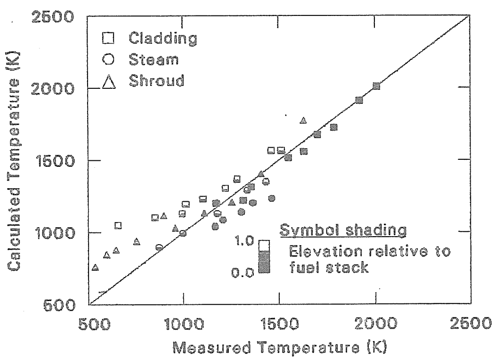

Figure 3. Comparison of calculated and measured bundle temperatures for SFD-ST.

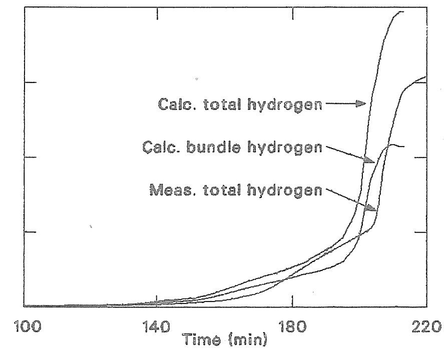

Figure 4. Measured and calculated hydrogen generation for bundle and other experimental structures for SFD-ST. Results have been divided by maximum calculated total hydrogen generation.

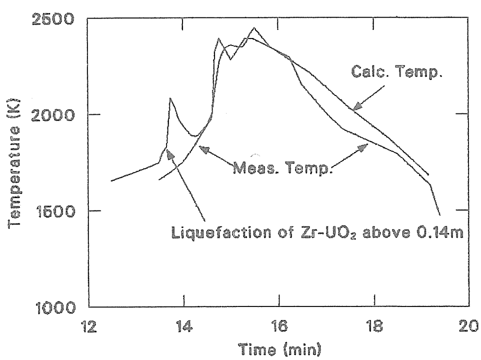

Figure 5. Measured and calculated fuel rod temperature at 0.14 m for ESSI-2.

C 3/3*