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Assessment of SCDAP Using the Full-Length High-Temperature FLHT-2 Test

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FLHT-2 실험결과를 이용한 SCDAP코드 평가

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Abstract

This paper assesses the models in the SCDAP code using the results of the FLHT-2 test. Calculations show that the SCDAP correctly predicts the temperatures, oxidation front movement, overall hydrogen generation and peak generation rate, internal fuel rod pressure, and cladding rupture due to ballooning. A comparison of the calculated results with measured data shows that two phase level is underpredicted, and that radiation heat transfer and autocatalytic reaction temperature of zircaloy are overpredicted. These models are recommended to be modified. The analysis also shows that the simulation of the gap in a fuel rod improves the code prediction on core damage progression.

요 약

FLHT-2 실험결과를 사용하여 원자력발전소의 중대사고발생시 노심의 거동을 해석하기 위한 전산코드인 SCDAP코드를 평가하였다. 계산결과에 의하면 코드는 실험시 측정된 노심의 온도경향, 총수소발생량 및 순간최대수소발생율, 그리고 연료봉내압과 피복재파열시간을 잘 예측하는 것으로 평가되었다. 그러나 이상유체높이와 복사열전달 및 zircaloy의 급격한 산화 시작 온도에 대한 모델은 수정되어야 할 것으로 평가되었다. 또한 핵 연료봉에서의 gap을 고려하여주는 것은 노심손상현상의 정확한 예측에 커다란 도움을 줄 수 있다는 것이 밝혀졌다.

1. Introduction

SCDAP (Severe Core Damage Analysis Package) code [1] is a computer code designed to characterize and quantify the fuel damage processes in a reactor core during a severe reactor accident. The code calculates the reactor transient characteristics such as core temperature, hydrogen generation, meltdown, and fission gas release. This code was mainly used to predict and analyze the PBF tests [2-5] conducted in Idaho National Engineering Laboratory (INEL). Recently TMI-2 [6], DF tests [7-8], and NRU tests [9] were also analyzed using this code.

The Coolant Boilaway and Damage Progression (CBDP) Program is conducted by Pacific Northwest Laboratory (PNL) as a part of US Nuclear Regulatory Commision (NRC) Severe Fuel Damage/Source Term (SFD/ST) Program. The CBDP program consists of in-reactor experiments using full-length (3.63 m) light-water reactor(LWR) fuel rods to determine fuel bundle behaviors and fission product release during simulated small loss-of-coolant accidents (LOCA) that result in a partially uncovered reactor core. As the coolant boils away and the fuel rods become uncovered, the temperature of the rods increases above design limits. As the temperature increases, the rods become damaged and potentially dangerous radioactive fission products are released from the fuel.

The Full-Length High-Temperature (FLHT) tests conducted in the NRU reactor are part of the CBDP program and provide data on bundle relocation, melt progression, hydrogen generation, and fission gas release at fuel temperatures as high as 2,700 K. The test data provide a basis for developing accident mitigation strategies, for evaluating postulated coolant boilaway accidents, for developing concepts for accident prevention and quantifying safety margins, and for developing, benchmarking, and validating computer codes such as SCDAP [1], MELPROG [10], and MELCOR [11].

The second test of the FLHT tests (FLHT-2) provides a valuable data base for validating severe accident analysis codes up to 2,500 K. This test was analyzed by PNL [9] using SCDAP/MOD 1/Version 18 (SCDAP-V18). According to the analysis, calculated peak temperatures agree with the data, and peak hydrogen generation rate and total amount of hydrogen generated agree with the data only if the calculation is artificially extended to include 5 minutes of accelerated oxidation. But, time increment from dryout to oxidation excursion is overpredicted.

SCDAP/MOD 1/Version 20 (SCDAP-V20), which is known as the latest version, was installed at KAERI in '1986. To assess the new version and to examine the importance of model changes made through the assessment of SCDAP code at KAERI, FLHT-2 test is analyzed.

This paper presents SCDAP analysis of the response of core in the FLHT-2 test. The subsequent sections of this paper contain model changes, input data for ŠCDAP implementation, comparison of calculations with measured data, and finally, some conclusions.

2. Description of Model Changes

As a result of model assessment of SCDAP code carried out at KAERI since 1984 [12-14], a number of modifications to SCDAP-V20 are made to improve the code. Many of these are corrections of known bugs, but several items involve some significant modelling changes, particularly to the thermal hydraulic and heat conduction models.

2.1. Coolant Analysis Quasi-steady (COOLQS) Model

A model has been developed to account for the heat transfer to the shroud in the two phase region. The original COOLQS calculates the elevation of the two phase region without taking account of the heat transfer from the coolant to the shroud. This is true for the analysis of large scale severe accidents like TMI-2 because the shroud (reactor vessel wall) is very thin in comparison to the reactor core size. But for small scale experiments like PBF or FLHT tests where the number of fuel rods is limited, the heat transfer to the shroud may play an important role in the component temperature behaviors.

In fact, the code takes account of the heat transfer from the coolant to the shroud when it calculates shroud temperature distributions elsewhere in the code (HEATCN subroutine). But the amount of heat transfer to the shroud is ingored when the COOLQS calculates the level of the two phase region. Heat transfer to the shroud calculated in the

HEATCN subroutine is around 2000 W/m^2 for the FLHT-2 test. Therefore, COOLQS is modified so that the same amount of heat is to be bypassed to the shroud to conserve the heat in the two phase region.

It is also found that the equation used to calculate the change in the water inventory in a core during a time step does not conserve the coolant mass in the two phase region. The mass of water in the fuel bundle during a time step is calculated as follow:

Mass of Water at Present Time = Mass of water at previous Time + Mass In − Mass Out

The mass of water in the fuel bundle at present time is the mass of water up to the top level of two phase region at the end of a time step [15]. And the mass of water at previous time is the mass up to the top of two phase level at the beginning of a time step. During the test, the water level rapidly decreased because the core inlet flow was not sufficient to maintain a steady state steam generation. But in the prediction, the COOLQS calculates the masses of water for two different elevations (control volumes) and compares the mass difference to get steam generation rate (mass out). Therefore the mass of steam occupied by the water between the previous level and the present level is ignored.

In order to conserve the water mass in a core, the code is modified so that masses of water are calculated for a fixed elevation (same control volume).

2.2. Gap Model (HEATCN)

The SCDAP code can simulate any material layer in the fuel rod and shroud. Actually, the shroud is composed of many layers such as zircaloy liner, ZrO_2 insulator, helium gap, etc. And SCDAP code successfully simulates these layers and calulates temperature distribution with the HEATCN subroutine. The fuel rod is also composed of different layers such as UO_2, helium gap, and zircaloy cladding. The code, of course, simulates the gap in a fuel rod when it calculates internal pressure in other subroutine (FPRESS). However, the HEATCN does not simulate the helium gap and the code is forced to take the inside diameter of the cladding as the outside diameter of the fuel pellet when it calculates temperature distribution in a fuel rod.

The helium gap is well defined for a fresh fuel rod. As the fuel is burned up, however, the UO_2 pellet is crushed into small particles and they replace the gap. Therefore, when we calculate a test which uses pre-irradiated fuel rods, the method HEATCN assumed may be justified. But, in the FLHT-2 test, only the fresh fuel rods were used. Furthermore, when the fuel rod temperature is increased, the zircaloy cladding begins to expand and finally to balloon and the gap deformed plays important roles in the fuel rod temperature behavior.

For this reason, the HEATCN subroutine is modified to simulate gap by taking gap as a solid layer of gas and to calculate temperature distribution in a fuel rod using finite element method. Also the thermal properties of helium gas are chosen from the MATPRO [16] and are given as a function of temperature and pressure. It is also modified for code user to choose specific gap contents in the gap after the cladding has been ruptured. A typical gap gas which code user may choose varies from helium, and steam, to the mixture of hydrogen and other gases. However, the gas properties such as thermal conductivity, heat capacity, and density should be given to the input deck by a code user.

In the calculation of FLHT-2 test, hydrogen is selected as gap gas after cladding rupture [17].

3. FLHT-2 Test Analysis

In this section, general SCDAP predictions are summarized. The analysis also includes comparisons between the calculated results and measured

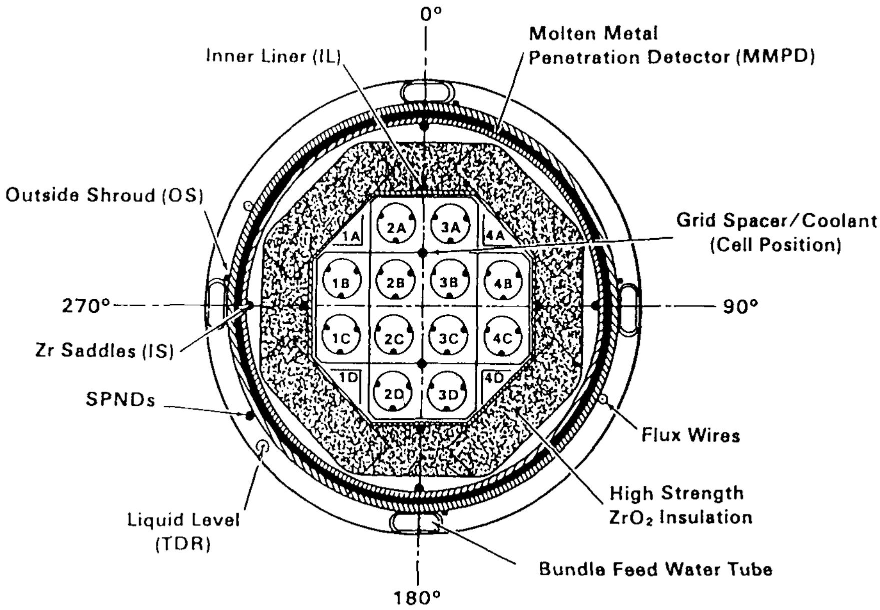

Fig. 1. Test Section of FLHT-2 Test.

data for level of two phase region, bundle temperatures, hydrogen generation rate, and fuel rod internal pressure. Input data to SCDAP is also briefly discussed.

3.1. Data Specification for SCDAP-V20 Calculations

The NRU FLHT-2 test train shown in Figure 1 consists of 12 zircaloy clad UO_2 fresh fuel rods, enclosed in an insulated shroud.

The test train is divided into two component groups; (1) 12 fresh fuel rods, (2) an insulated shoud. Each component group is divided into ten evenly spaced axial nodes and only the fissile length is considered. The fuel rod component at each axial node has six radial nodes, and the shroud has 19 radial nodes.

The input data used in the SCDAP-V20 calculations here is almost identical to the input data provided by PNL [9]. Exceptions from the data are as follows:

(1) 2500 K is chosen as the ZrO_2 cladding breach temperature.

(2) Helium inventory is adjusted to match the measured initial fuel rod internal pressure.

The first exception is necessary to simulate the breach of the cladding observed in the test (cladding breached at around 2,500 K). The SCDAP-V20 was updated so that ZrO_2 cladding breaches at a prescribed temperature (input data), whereas SCDAP-V18 calculates the breach as a function of stress of the cladding. This modification is made because breach calculation based on the stress is too complex because of geometry uncertainties and surface tension effects. Second exception is to match the initial conditions of the test. The helium inventory affects only the rod internal pressure.

The NRU reactor was scrammed at 825 s into the transient (SCDAP calculation time) and all the thermocouples installed at core structures showed the decrease in temperature. In the calculation, however, the reactor is assumed not to be scrammed until the end of calculation (1,000 s). PNL also prolonged the reactor shutdown time as the code failed to predict the autocatalytic reaction of zircaloy and the cladding breaches with the same shutdown time (825 s).

3.2. Comparison of SCDAP-V20 Results with Experiment

SCDAP code has three options (ASWLEV, Input card number 85) to calculate the level of two phase region and steam mass flow rate as follows:

(1) ASWLEV=0.0; code calculates the top elevation and steam mass flow rate.

(2) ASWLEV=1.0; elevation and steam mass flow rate are input

(3) ASWLEV=2.0; elevation is input and code calculates steam mass flow rate.

The COOLQS [15] subroutine which calculates these variables uses simplified thermal hydraulic model (quasi-steady bioe-off model) to reduce calculational time at the sacrifice of accuracy. The second option (ASWLEV=1.0) is almost impossible to choose, because two phase level and steam flow rate are very difficult to measure. Code users may choose the third option mentioned above to avoid misinterpretation of thermal hydraulic boundary conditions in the core as far as the two phase (dryout) levels are known. But the second and third options can not be used in planning of a new test or in accident analyses of nuclear power plants. It is, therefore, preferable that the code correctly calculates two phase level and steam flow rate.

To assess the SCDAP code and the contributions of model changes, the following four cases are calculated:

Case A: ASWLEV=0.0, with model changes

Case B: ASWLEV=0.0, original code

Case C: ASWLEV=2.0, with model changes

Case D: ASWLEV=2.0, original code

In the following section, the code prediction for Case A is compared with the test results [18]. Later, the results of four different cases are, also, compared with the test results. The results of case D calculation are very similar to those of PNL analysis except fuel rod pressure. Therefore no comment is made on PNL analysis.

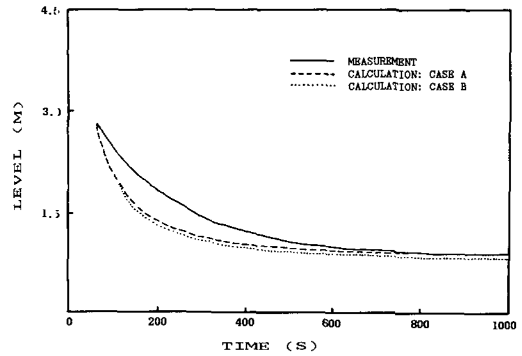

Fig. 2. Measured Dryout Front and Calculated Two Phase Mixture Level versus Time for FLHT-2 Test.

A. Comparison of Case A Calculation with Experiment

The measured dryout front decreased rapidly as the core inlet flow decreased from 9.45 to 1.26 g/s at 64 s into the transient (SCDAP calculation time). The two phase levels calculated by SCDAP code are noticeably lower than the measured dryout front at the initial stage. But the differences between the calculation and data become smaller as time passes by and the final levels are almost the same as seen in Figure 2.

It is thought that this initial difference is caused by the simplified quasi-steady boil-off model used in the COOLQS subroutine. The COOLQS subroutine initially assumes a steady state of core thermal hydraulics for given core inlet flow rate and heat generation rate of a core. It also assumes another instantaneous steady state whenever either core inlet flow rate or heat generation rate changes. And the void fraction and two phase level instantly change accordingly.

In the test, the core inlet flow rate was maintained at 9.45 g/s and the two phase level was stablized at an elevation of 284 cm at the beginning of the test. Then the core inlet flow rate decreased from 9.45 to 1.26 g/s at 64 s into the test. The calculation starts at 64 s and instaneous steady state for the core inlet flow of 1.26 g/s is assumed. A steady state may not be instantly

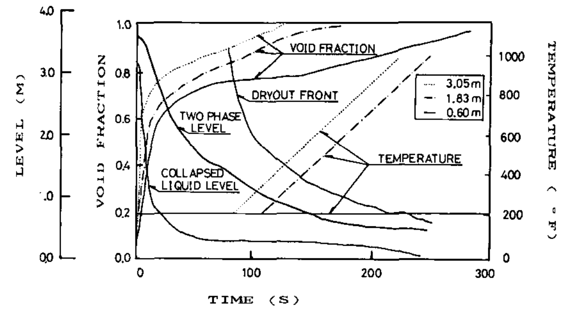

Fig. 3. Dryout Front, Void Fraction, and Wall Temperature Responses in Uncovery Test.

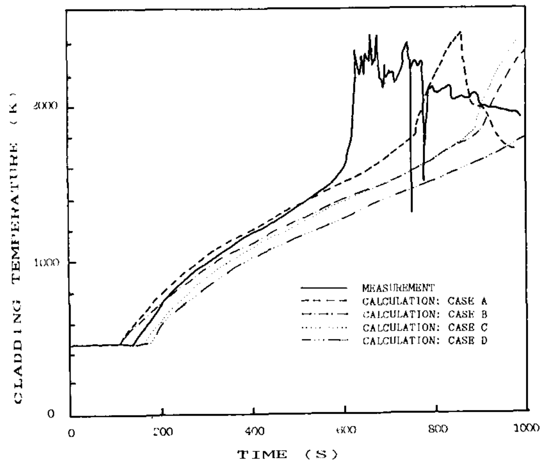

Fig. 4. Experimental Cladding Temperature at 213 cm Elevation and SCDAP Cladding Temperature Predictions at 200 cm Elevation versus Time for FLHT-2 Test.

achieved in the test and it is believed that the assumption of instantaneous steady state in the core results in the more rapid decrease of the two phase level in the calculation. Around 700 s into the test, however, a steady state seems to be attained in the test, and the code prediction on the two phase level is in good agreement with the data.

The COOLQS also assumes that dryout occurs as soon as a core is exposed to the superheated steam (above the top elevation of two phase region). In fact, small droplets may exist above two

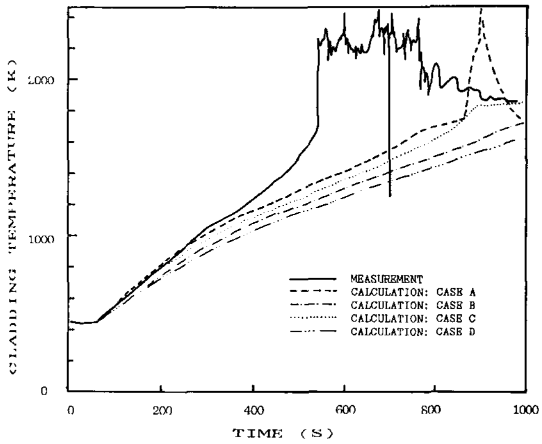

Fig. 5. Experimental Cladding Temperature at 274 cm Elevation and SCDAP Cladding Temperature Predictions at 272 cm Elevation versus Time for FLHT-2 Test.

phase level and they could delay the movement of dryout front [19], as shown in Figure 3. Furthermore, the void fraction for a fixed elevation in the two phase region is varying as time passes by. But the COOLQS assumes that the void fraction is always constant as far as inlet flow and heat generation rate are constant. A more sophisticated model which simulates varing void fraction observed in the test may improve the code prediction on two phase level but increases computing time.

The dryout level directly influences the core temperature predictions. As the code underpredicts the two phase levels, the core structure has earlier dryout than the measurement up to 148 s at the lower portion of the core. In terms of the rate of heat-up, SCDAP code reasonably well predicts the cladding temperatures during the slow heat-up stage, though the later rapid temperature excursion is not reproduced to such an extent in the calculation, as seen in Figures 4 and 5.

In the test, rapid temperature excursion started at 250 cm elevation when cladding temperature reached 1,700 K at 535 s into the transient. And the oxidation front moved axially upward and

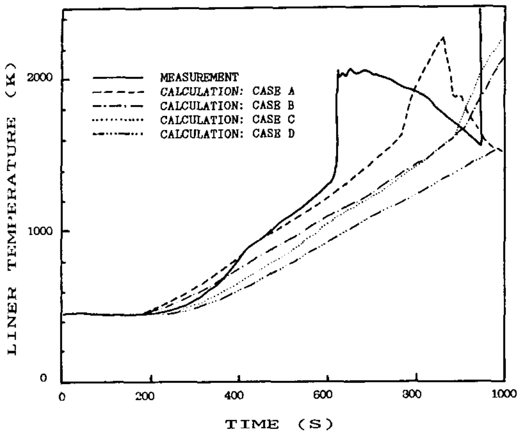

Fig. 6. Experimental Shroud Liner Temperature at 203 cm Elevation and SCDAP Shroud Liner Temperature Predictions at 200 cm Elevation versus Time for FLHT-2 Test.

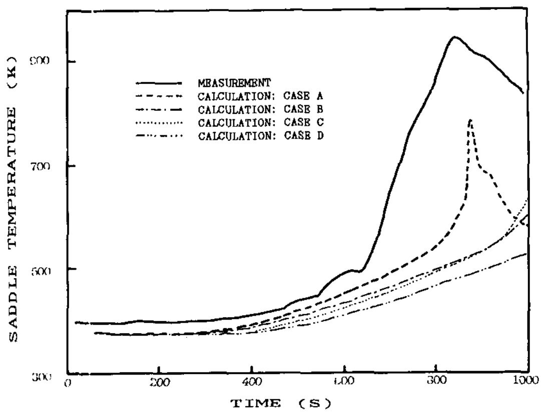

Fig. 7. Experimental Saddle Temperature at 203 cm Elevation and SCDAP Saddle Temperature Predictions at 200 cm Elevation versus Time for FLHT-2 Test.

then downward to the lower portion of the bundle. But the code predicts the rapid temperature excursion at 200 cm elevation when the cladding temperature reaches 1,853 K at 718 s. The time cladding temperature reaches 1,700 K is, however, around 670 s, that is 135 seconds later than the measured data. The oxidation front predicted by the code first moves axially upward and then downward as obseved in the test. The time increment from dryout to rapid oxidation excursion in the test was 466 seconds, whereas it is 627 seconds in the code prediction. The time increment from dryout to 1,700 K is, however, 580 seconds and is in reasonable agreement with the data (466 seconds). The maximum temperatures measured and calculated are around 2,500 K in both cases.

The calculated cladding temperature at the elevation of 200 cm, although dryout occurs earlier in the calculation, has the same tendency as the measured temperature data up to 1,400 K. But rapid temperature excursion mainly caused by the autocatalytic reaction of zircaloy with oxygen is not well reproduced in the calculation. It is thought that radiation heat transfer in the superheated region is overestimated, and that the autocatalytic reaction temperature is too high in the code.

Recent study reveals that the oxidation rate of zirconium discontinuousely changes at 1,789 K [20]. But the code assumes that it changes at 1853 K, and the oxidation rate is lower than the measured data. Also, results of many in-pile tests show that the autocatalytic reaction starts below 1,700 K. In fact, many oxidation experiment were conducted at atmospheric pressure, but most of the severe accident experiments were conducted at high pressure (13 atm for FLHT-2 test). Therefore, it is questionable whether high system pressure affects oxidation process. Only one observation was made on the influence of high system pressure on the oxidation phenomena [21] up to now. More studies are needed on this subject.

The SCDAP predictions on shroud liner and saddle temperatures have the same tendencies as the cladding temperature responses as seen in Figures 6 and 7. During the early slow heat-up stage, the calculated temperatures are in good agreement with the data. But the later rapid temperature excursion is not well predicted in the calculation. As the saddle temperature is affected by the shroud liner temperature, the rapid temperature excursion in the saddle is not timely repro-

Table 1. FLHT-2 Hydrogen Generation Data

	Noncondensable Flowmeter	Mass Spectrometer	Conductivity Meter	Experimental Range
Peak Hydrogen rate(mg/s)	207	180	110	110-207
Total Hydrogen Produced	44	40	39	39- 44

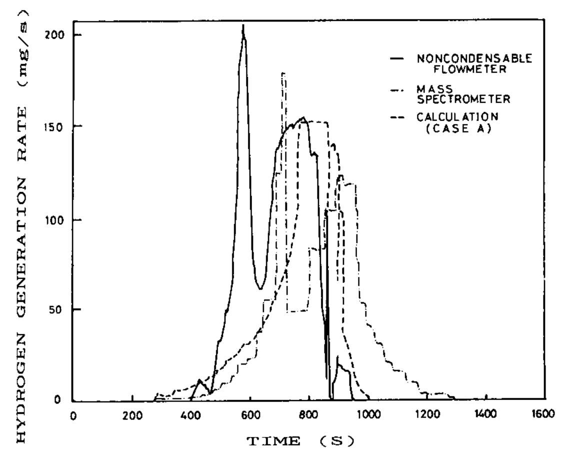

Fig. 8. Comparison of Measured and Calculated Hydrogen Production Rates Versus Time in FLHT-2 Test.

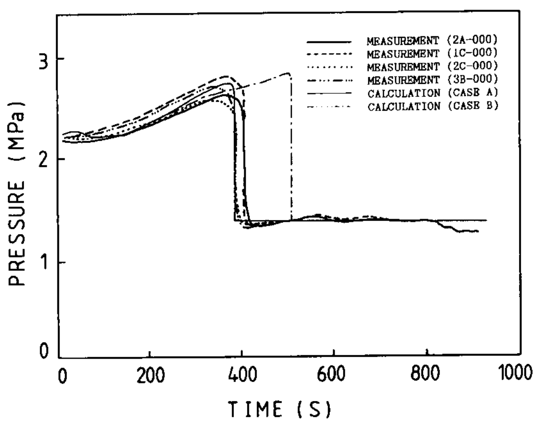

Fig. 9. Comparison of Measured and Calculated Fuel Rod Internal Pressure Responses versus Time in FLHT-2 Test.

duced, as shown in Figure 7.

Total amount of hydrogen released during the FLHT-2 test was 39-44 g, according the measurement (Table 1). In the SCDAP calculation, the total amount of hydrgoen produced is 37 g. The calculated total amount of hydrgoen is in good agreement with the data, considering that zircaloy sources in instrument hardline carriers and in unfuelled cladding [9] are not modelled in the calculation. The calculated peak hydrogen generation rate is 152 mg/s and is in good agreement with the measured data (110-207 mg/s), as shown in Figure 8.

The fuel rod cladding in the test was ruptured between 389 and 418 s when the cladding temperatures were around 1,255 K and maximum fuel rod internal pressures were 2.58-2.83 MPa. SCDAP-V20 predicts very large ballooning at an elevation of 236 cm. The calculated rupture time, temperature, and pressure are 378 s, 1,250 K, and 2.77 MPa, respectively, and are in good agreement with the measured data (Figure 9).

According to the preliminary analysis, little evidence of axial fuel relocation was observed in the test [22]. In the calculation, however, 4.1% of total UO_2 volume is melted and relocated.

B. Comparison of Four Different Calculations with Experiment

In this section, the effect of model changes on the HEATCN and COOLQS subroutines, and of options for the two phase level calculation are compared with the test data. The comparison of calculations with measurement is divided into the following four areas; two phase level, temperature response, hydrogen generation rate, and fuel rod internal pressure.

Two Phase Level

Figure 2 compares the calculated two phase levels for Cases A and B to the measured dryout front. Model changes to the COOLQS subroutine seem not to give significant improvement to the code predictions. However, the calculated two phase levels with the model changes (Case A) are slightly higher than those of the orginal code (Case B) and the final levels are in good agreement with the data. The simple assumptions used in the COOLQS subroutine should be modified, as mentioned before (see Section 3.2.A).

Temperature Response

A comparison of calculated cladding temperatures at 200 cm elevation with the measured data is shown in Figure 4. The claculations for Case A and Case B, where two phase level is calculated by the code, predict earlier dryout than the test data. After cladding dryout, the temperatures calculated with the gap model (Case A) increase more rapidly than those of original code calculation (Case B) and are in excellent agreement with the measured temperatures up to 1,400 K.

In the test, rapid temperature excursion started at around 535 s when temperature exceeded 1,700 K at 250 cm elevation, whereas Case A calculation indicates that it starts at 718 s when temperature reaches 1,853 K at 200 cm elevation. For Case B, the starting time (970 s) is much later than that of Case A. The temperature responses predicted for Cases C and D have the same tendency and the results of Case C calculation are in better agreement than Cases B and D predictions, as shown in Figure 4.

For the elevation of 272 cm (Figure 5), calculated dryout time is almost identical to the data. In the early stage, the code predictions with the gap model (Cases A and C) show good agreement with the measured cladding temperature up to 1,000 K. But above 1,000 K, the calculated temperatures for four different cases are much lower than the data, though Case A prediction is slightly better than the other predictions. It seems that radiation heat transfer is overpredicted in the code.

The simulation of gap in fuel rods seems to improve the code predictions on temperature response as well as on hydrogen generation and fuel rod internal pressure, as mentioned in this paper. The improvement may be attributed to the following facts: First, the calculated fuel pellet temperature in the two phase region with the gap model is higher than that of the original model because of inferior thermal conductivity of helium, whereas the cladding temperatures are the same (steady state assumption in the two phase region). Next the fuel volume assumed with the gap model is smaller by 4 % than that of the original model, because the original code assumes that the outside diameter of the fuel pellet is the inside diameter of the cladding. This difference results in higher volumetric heat generation rate with the gap model. Higher power density and temperature of fuel pellet, and lower heat capacity of helium than that of UO_2 increase the temperatures of fuel rods and of cladding more rapidly when the core is exposed to the superheated steam. Also higher fuel rod temperatures increase rod pressures and hydorgen generation rates more rapidly.

Calculated temperature responses of shroud liner and saddle have the same tendencies as the cladding temperatures responses (Figures 6 and 7). The existance of fuel gap increases the fuel rod temperature more rapidly and the higher cladding temperature influences shroud liner and saddle temperatures as well.

Hydrogen Generation Rate

The amount of hydrogen and peak hydrogen generation rate measured during the FLHT-2 test by oxidation of cladding, shroud liner, and instrument hardline carriers were 39-44 g and 110-207 mg/s, respectively. The total amount of hydrogen produced and peak hydrogen generation rate predicted by Case A calculation are 37 g and 152 mg/s, respectively. These results are in good agreement with the data, considering that zircaloy sources in the carriers and in the unfuelled cladding (15 % of total zircaloy) are not modelled in the calculations.

For Cases B, C, and D, oxidation is not finished until the end of calculation time (1000 s). Therefore, it may not be meaningful to compare the calculated total amount of hydrogen with the data. However, the total amounts of hydrogen produced until 1,000 s for Cases B, C, and D are 25.4, 32.4, and 14.2 g respectively. These results are caused by the difference in the onset time of rapid oxidation. For Case B, rapid oxidation is predicted to start at 920 s, that is 162 seconds later than Case A prediction. And oxidation onset time for Case C is earlier by 100 seconds than that of Case B, though dryout occurs ealier in Case B. Simulation of gap in a fuel rod apparently improves the code prediction on hydrogen generation rate.

Fuel Rod Internal Pressure

The test results show that fuel rods were ruptured between 389-418 s into the test and that maximum pressure and rupture temperature were between 2.58-2.83 MPa and 1,255 K, respectively. In the calculations, fuel rods rupture at 236 cm elevation and the rupture temperatures are around 1,250 K in four different cases. But the rupture pressures and rupture times vary from case to case.

Best agreement for rupture time is obtained in Case A calculation. The predictions on rupture time and maximum pressure for Case A are 378 s and 2.77 MPa, respectively. The rupture pressures calculated for the other cases are almost the same (2.82-2.88 MPa), but rupture times vary from 465 s for Case C, 504 s for Case B to 608 s for Case D.

In conclusion, simulation of gap in a fuel rod improves the code capabilities to simulate core damage progression. Also when the code is forced to calculate the two phase level, better agreement is attained, though earlier dryout of core structure is predicted.

4. Conclusions

The comparison of SCDAP/MOD 1/Version 20 calculations with the results of the FLHT-2 test has shown that the code reasonably well predicted the temperature response during the temperature excursion, hydrogen generation rate, the movement of oxidation front, and the fuel rod cladding rupture.

SCDAP-V20 calculations show that some attention should be paid to the simplified thermal hydraulic model in calculation of two phase level. When the code is forced to calculate the level, the top level of two phase region decreases more rapidly than the data and it causes earlier heat-up of the core. Modification of the code to allow varying void fraction may improve the code predictions.

The rapid temperature excursion of zircaloy cladding and liner is not reproduced to such an extent in the calculation. Modifications on radiation heat transfer and on autocatalytic reaction temperature of zircaloy with oxygen are needed.

The modification on core thermal hydraulic model does not give significant improvement on prediction of two phase level, though later stage level is in good agreement with the data. The gap model seems to improve the code capability to correctly predict the core response during severe core damage accidents. Simulation of gap in a fuel rod is recommended.

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