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ANALYSIS OF THE BR2 LOSS OF FLOW TESTS

C. P. Tzanos and B. Dionne
Research and Test Reactor Conversion Department
Nuclear Engineering Division,
Argonne National Laboratory, Argonne IL 60439-4815 - USA

ABSTRACT

To support the safety analysis of the BR2 research reactor conversion to low- enriched uranium (LEU) fuel and extend the validation basis of the RELAP code for the safety analysis of the conversion of research reactors, the simulation of the BR2 tests A/400/1, C/600/3 and F/400/1 was undertaken. These tests are characterized by loss of flow initiated at different reactor power levels with or without loss of system pressure, reactor scram, flow reversal and reactor cooling by natural circulation. This work presents the RELAP analyses of these tests and comparison of code predictions with experimental measurements for peak cladding temperatures during the transient at different axial locations in an instrumented fuel assembly. RELAP simulations show that accurate representation of the pump coastdown characteristics, and of the power distribution, especially after reactor scram, between the fuel assemblies and the moderator/reflector regions are critical for the correct prediction of the peak cladding temperatures during these transients. Detailed MCNP and ORIGEN simulations were performed to compute the power distribution between the fuel assemblies and the moderator/reflector regions. With these distributions the predicted peak cladding temperatures are in a good agreement with experimental measurements.

1. Introduction

In 1963, a number of loss of flow tests were performed at the Belgian research reactor BR2 to demonstrate that the reactor can normally operate safely at the maximum heat flux of 400 W/cm^2, and to determine the maximum heat flux at which safe reactor operation can be maintained [1]. These tests are characterized by loss of flow initiated at different reactor power levels with or without loss of pressure. To support analyses to be performed with the RELAP code [2] for the safety analysis of the BR2 conversion from HEU fuel to LEU and extend the validation basis of the RELAP code for the safety analysis of the conversion of other research reactors to LEU fuel, the simulation of the BR2 tests A/400/1, C/600/3 and F/400/1 [3] was

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undertaken. This work presents the analysis of these tests with RELAP and comparisons of code predictions with experimental measurements. These tests present a number of challenges to a code like RELAP. They include a transient flow under loss of pumping power with or without loss of pressure, flow reversal driven by buoyancy, and heat transfer under forced and natural convection. For brevity, in this report these tests will be referred as Test A, Test C and Test F.

BR2 is a water-cooled thermal reactor moderated by water and beryllium. The core is located inside an aluminum pressure vessel, and at nominal conditions the vessel inlet and outlet pressure are 13.6 atm and 10.1 atm, respectively, while the inlet water temperature varies from 30 to 40°C. Normally, the coolant flows from the top of the core to the bottom. The beryllium moderator is a matrix of hexagonal prisms each having a central bore that contains either a fuel assembly, a control or regulating rod, an experimental device, or a beryllium plug. Each fuel assembly is composed of six concentric fuel plates divided by aluminum stiffeners into three sectors.

For the tests analyzed in this work the reactor was loaded with 14 fuel assemblies and operated at steady state at 24 MW for tests A and F, and at 36 MW for Test C. The fuel meat was composed of 90% enriched UAl_4 alloy. The cladding is aluminum. The main dimensions of the fuel plate are: active (fuel) length of 762 mm, active thickness of 0.5 mm, total thickness of 1.27 mm, and total length of 965 mm. Figure 1 shows a cross-section of a BR2 fuel assembly.

Cladding temperatures where measured on the outer surface of the outer plate (plate number six) of an instrumented assembly (assembly F346) at four axial locations relative to the fuel mid-plane: 300 mm (thermocouple TC11), 150 mm (thermocouple TC12), 0.0 mm (thermocouple TC13), and -150 mm from the center line. No temperature measurements are available for the location of -300 mm due to the failure of the thermocouple.

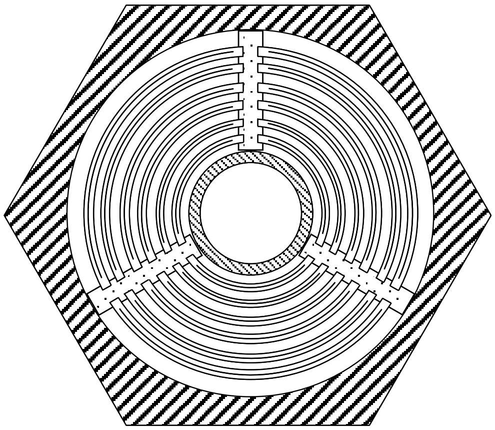

Figure 1. Cross-section of aBR2 fuel assembly

2. RELAP Model

A RELAP5-3D model (RELAP5-3D, Version 2.4.2ie) was developed that is based on an original RELAP model provided by BR2 [4]. This model simulates the primary system loop, the reactor vessel, the components inside the vessel, the shroud cooling system and the reactor pool. The primary system is represented by one loop, one pump, and one heat exchanger (primary and secondary side). The pressurizer is represented by a time dependent volume that sets the pressure boundary condition. The shroud cooling system provides heat removal by circulating water in the gap between a shroud surrounding the reactor vessel and the reactor vessel. The flow paths inside the reactor vessel include: one flow path for the instrumented assembly; one channel (RELAP channel) for the remaining fuel assemblies; one channel for the plugged assembly positions, the control rod flow paths, and the cooling path of the in-vessel irradiation (experiment) locations; and one channel for the by-pass flow (flow in the gap between assembly blocks, between assembly blocks and the reactor vessel, and through holes in the beryllium blocks).

The explicit simulation of each fuel plate in each sector of the fuel assembly requires a very long computation time. To determine the details needed to adequately model the instrumented assembly, initial simulations where performed with models where: (1) the whole assembly is represented by an average fuel plate; (2) in the instrumented sector, the instrumented plate and its neighboring plate were modeled explicitly, and (3) in the latter sector the instrumented plate and its two neighboring plates were modeled explicitly.

In case 2, the flow path to the instrumented assembly was split into three channels: one for the gap between the sixth fuel plate (outer fuel plate) of the instrumented sector and the Be block; one for the gap between the fifth and sixth plate of the instrumented sector; and one for the remaining of the instrumented assembly. In case 3, the flow path to the instrumented assembly was split into four channels: one for the gap between the sixth fuel plate of the instrumented sector and the Be block; one for the gap between the fifth and sixth plate of the instrumented sector; one for the gap between the fourth and fifth plate of the instrumented sector; and one for the remaining of the instrumented assembly. The simulations with these three models showed that for an accurate prediction of cladding temperatures in the peak fuel plate there is no need of a more detailed model that the three-plate model. The analyses presented in this work were performed with the three-plate model shown in Figure 2.

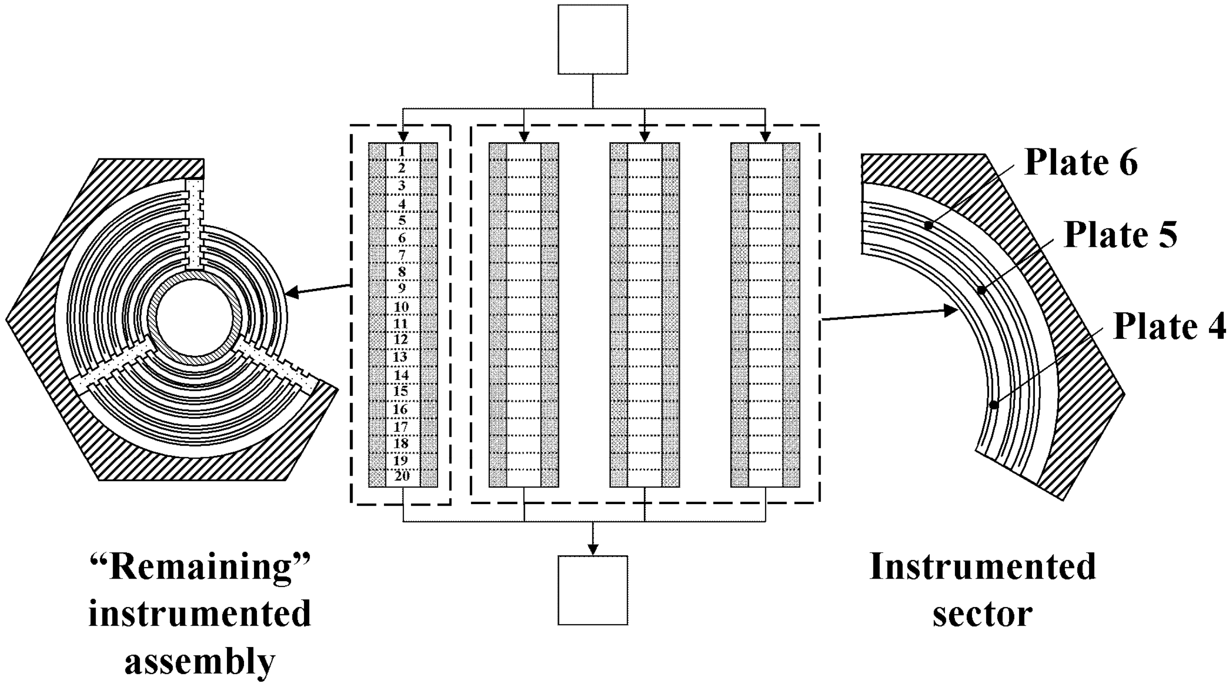

Figure 2. Three-plate RELAP model of the instrumented assembly

3. Results and Analyses

As mentioned earlier, tests A, C, and F where characterized by loss of flow with or without loss of pressure, and opening of the bypass valve ABV 1301. This valve establishes a flow path that connects the cold and hot legs of the primary system.

A set of pump homologous curves were provided by BR2, as well as a set of pump coastdown measurements (flow versus time) [3]. As shown in Figure 3, after about 12 s the homologous curves give a significantly higher flow that the measured data.

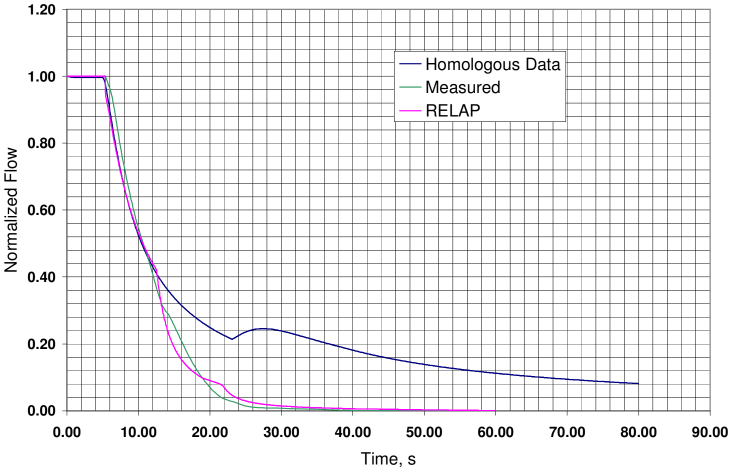

Figure 3. Pump coastdown

To improve the agreement between measured flow versus time and the flow predicted by the homologous curves, the pump friction torque was modified after 12 s. Even with this modification, the predicted flow nearly levels off to a higher flow than the measured flow after about 20 s. To generate a better match between predicted flow and measured flow after about 20 s, a valve was added in the primary system, which was closed after about 20 s at a rate that brought the predicted flow (Fig. 5, marked RELAP) to a good agreement with the measured flow. The homologous curves with the modified pump friction torque and the added valve were used for the prediction of the flow during the transient of tests A, C, and F.

3.1 Analysis of Test A

The drivers of the Test A transient were [3]: shutting off the power to the main pumps at 5.35s from the time of test initiation; reactor scram on a loss of flow signal at 7.7 s; and opening of the bypass valve ABV 1301. This valve started to open at 22 s and was completely open at 35.6 s.

During Test A, the clad temperature peaks immediately (see Fig. 4) after the pump is shut off, then it comes down significantly as the reactor power drops, and then a second peak is reached around the time when the flow in the fuel channels reaches a zero value and is reversed. Simulations with a varying slope of the pump coastdown curve at the initiation of pump coastdown show that the first peak of the cladding temperature is sensitive to the value of this slope.

RELAP simulations of Test A had been performed at BR2 [4] using the decay heat curve of the ANS79-1 standard [5]. The predicted clad temperature at the second peak was about 75°C higher than the measured temperature (Fig. 4). Simulations at ANL produced quite similar results.

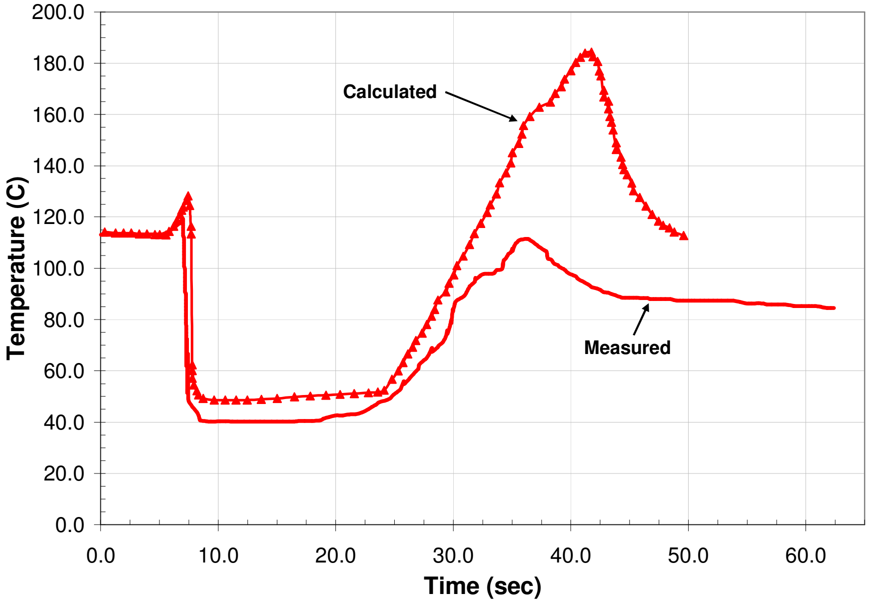

Figure 4. Measured and predicted cladding temperature for TC14 (initial RELAP simulation)

Simulations with significant perturbations in the flow coastdown curve, the fuel channel heat transfer coefficient, and in the heat removed by the shroud cooling system had a minor impact on the predicted temperature for the second peak. In small reactor cores, a significant fraction of the photons generated by radioactive material in the fuel plates are transported and absorbed in the moderator/reflector region. RELAP simulations using a rough estimate of the decay heat split between fuel plates and the moderator/reflector region gave a good agreement between predicted and measured peak cladding temperatures. Based on these results, MCNP and ORIGEN simulations (see Ref. 6) were performed to determine the heat generation in the fuel and in the moderator/reflector regions after reactor scram. Table 1 shows the power split among the different reactor regions at steady state and at different times during the transient as determined from the MCNP and ORIGEN simulations. The fraction of heat generated outside the fuel is significant and increases with the transient time. At steady state about 96% of the heat is generated in the fuel, at 0.1 s after reactor scram this fraction is 82% and at 50 s is 72%.

Table 1. Power split at steady-state and during the transient of test A

Region	**Steady-state**	**Transient**		
		0.1 s	25 s	50 s
Fuel	0.959	0.824	0.744	0.718
Beryllium hex	0.026	0.112	0.163	0.180
Other	0.015	0.064	0.093	0.103

MCNP and ORIGEN were also used in the analysis of tests C, and F and similar splits were obtained as in test A.

In the original RELAP model provided by BR2, the instrumented assembly was represented by an average fuel plate, and five axial nodes where used in the active (fuelled) region of the fuel plate. Before proceeding to the final analysis, a number of sensitivity analyses were performed with the "average-plate" model and the above mentioned rough estimate of the decay heat split between fuel plates and the moderator/reflector region. These sensitivity analyses showed that: (1) the use of twenty axial nodes in the instrumented and the average assembly would predict the peak cladding temperature with an uncertainty of less than 3.3°C, and (2) the correction of the flow to match the measured flow coastdown and the exact timing of opening the bypass valve had no significant effect on the predicted cladding temperature at the time of the second peak. In the analysis of tests A, C, and F twenty axial nodes were used in the instrumented and the average assembly.

Figure 5 shows measured and predicted temperatures for Test A.

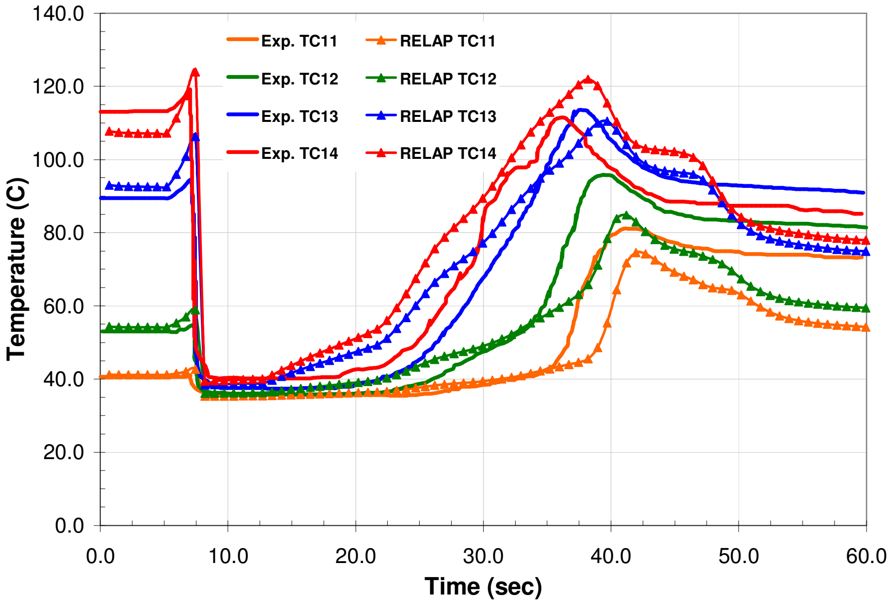

Figure 5. Measured and predicted cladding temperature for all TCs in test A

As mentioned earlier, the cladding temperature peaks immediately after the pump is shut off, and then a second peak is reached around the time when the flow in the fuel channels reaches a zero value and reverses. The predicted maximum peak cladding temperature (TC14) is 10.5°C higher than the measured value, and the maximum discrepancy between predicted and measured temperatures at the time of the second peak is 11°C (TC12). The predicted time of the second peak is about 2 s longer than the measured time.

3.2 Analysis of Test C

The test series C/600 is characterized by a steady state peak heat flux of 600 W/cm^2, total loss of flow without loss of system pressure, reactor scram, flow reversal and reactor cooling by natural convection. This series represents the highest heat flux tests performed in the experimental program of 1963 at BR2. The drivers of the Test C transient were: opening of the bypass valve; reactor scram at 6.55 s from the time of test initiation; and shutting off the power to the main pumps at 6.65 s. The bypass valve started to open at 6.52 s and was completely open at 21.7 s.

Figure 6 shows measured and predicted temperatures for Test C.

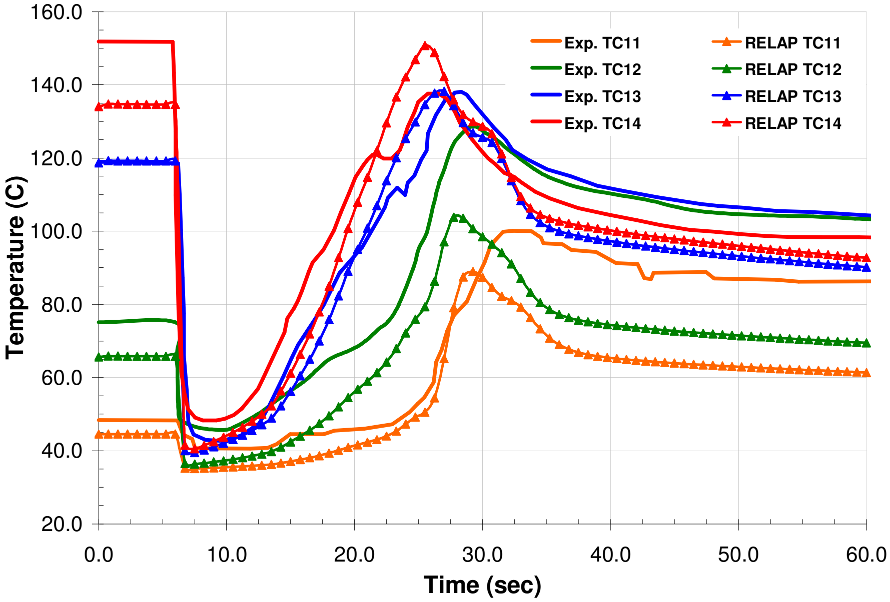

Figure 6. Measured and predicted cladding temperature for all TCs in test C

At steady state, the maximum discrepancy between predicted and measured temperatures is 17.7°C at the location of thermocouple TC14. The maximum discrepancy between predicted and measured temperatures at the time of the peak is about 14.4°C, also at the location of thermocouple TC14. RELAP predicts that the location of TC14 reaches the maximum peak cladding temperature of 150.9 °C, while the experimental measurements show that the maximum peak cladding temperature of 137.5°C is reached at the location of thermocouple TC13. At the latter location the discrepancy between predictions and measurements is only 1.1 °C. RELAP predicts that the peak temperature is reached a little earlier than the measured time. The maximum discrepancy between predictions and measurements is 2.8 s.

3.3 Analysis of Test F

Test F is characterized by a steady state peak heat flux of 400 W/cm^2, total loss of flow with loss of system pressure, reactor scram, flow reversal and reactor cooling by natural convection. The drivers of the Test F transient were [3]: shutting off the power to the main pumps at 10.2 s from the time of test initiation; reactor scram at 11.1 s; opening of the depressurization valve; isolation of the pumps; and opening of the bypass valve. The depressurization valve, which opens to the reactor pool, started to open at 11.1 s and was completely open at 17.45 s. The pump isolation valve upstream of the pumps started to close at 18.6 s and was completely closed at 47.7 s, and that downstream of the pumps started to close at 18.45 s and was completely closed at 45.15 s. The bypass valve started to open at 26.45 s and was completely open at 42.35 s.

Figure 7 shows the pressure at the top of the active fuel during the transient. It drops sharply during depressurization from 1.22 MPa to 0.16 MPa.

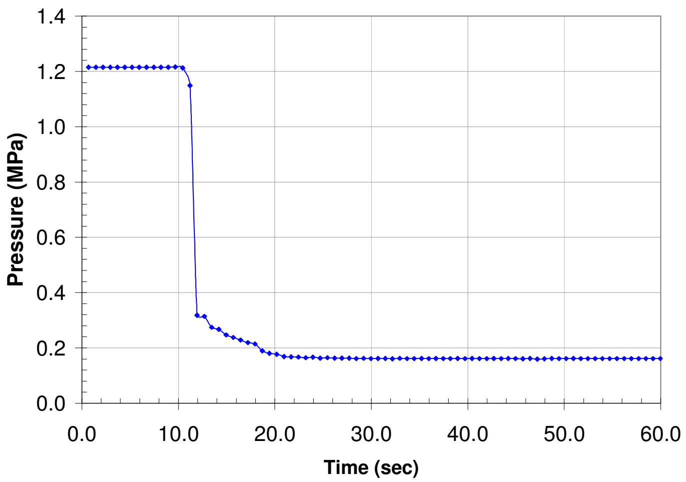

Figure 7. Pressure at top of active fuel in test F

Figure 8 shows measured and predicted temperatures for Test F.

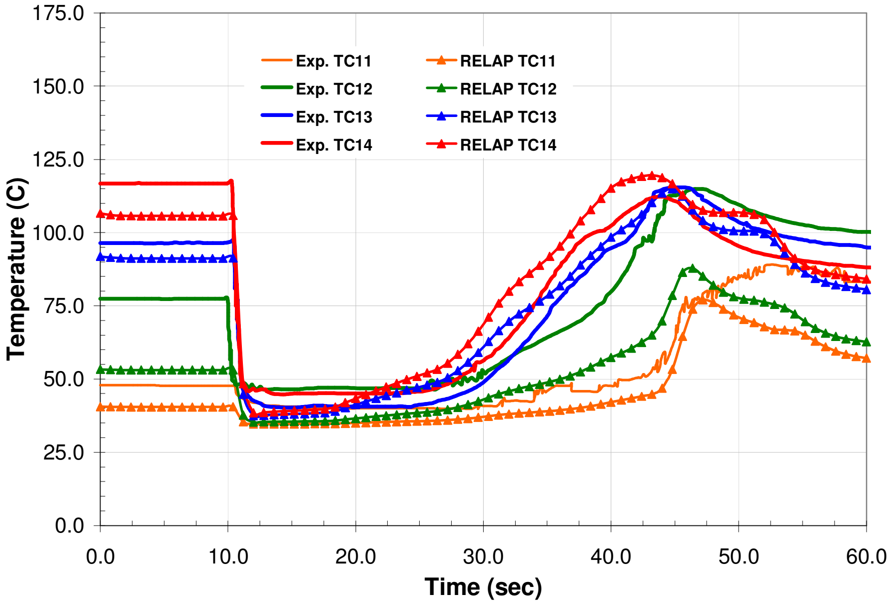

Figure 8. Measured and predicted cladding temperature for all TCs in test F

At the location of TC11, the cladding temperature remains near the peak value much longer than in the other thermocouples and for some time, after the peak, it is nearly equal to that in TC14, although the power at TC14 is about eight times higher. This, as well as the time trace of this thermocouple, indicate that most likely TC11 failed near the time of the peak.

This test was performed at the same power as Test A. At steady state the temperatures of thermocouples TC11, TC13 and TC14 for Test F are much closer to those for Test A, than for TC12. Also, although the power at TC12 is much lower than at TC13 and TC14, after the peak, where a quasi-steady-state is reached, the temperature given by TC12 is higher than that of TC13 and TC14. Most likely TC12 had also failed at the time of Test F.

At steady state, the maximum discrepancy between predicted and measured temperatures is 18.8°C at the location of thermocouple TC14. The maximum discrepancy between predicted and measured temperatures at the time of the peak is 7.4°C, also at the location of thermocouple TC14. RELAP predicts that the peak temperature is reached a little earlier than the measured time. The maximum discrepancy between predictions and measurements is 0.6 s.

The water saturation temperature at 0.16 MPa is 113.2 °C. Thus, for a short time around the time of the peak some nucleate boiling may have taken place at the surface of the cladding at the locations of TC13 and TC14.

4. Summary and Conclusions

To support the safety analysis of the BR2 research reactor conversion to LEU fuel and extend the validation basis of the RELAP code for the safety analysis of the conversion of research reactors from HEU fuel to LEU, the BR2 tests A, C, and F were analyzed with RELAP. These tests are characterized by loss of flow initiated at different reactor power levels with or without loss of system pressure, reactor scram, flow reversal and reactor cooling by natural circulation.

During Test A, the clad temperature peaks immediately after the pump is shut off, then it comes down significantly as the reactor power drops, and then a second peak is reached around the time when the flow in the fuel channels reaches a zero value and reverses. The RELAP simulations show that the value of the first peak is sensitive to the slope of the pump coastdown curve at the initiation of pump coastdown, while that of the second peak is sensitive to the power distribution between the fuel assemblies and the moderator/reflector regions. Test A simulations where performed with power distributions computed from detailed MCNP and ORIGEN analyses that provide the decay heat distribution between the fuel and moderator/reflector regions. With these distributions the agreement between computed and measured peak cladding temperatures is good.

At steady state, the maximum discrepancy between measured and predicted cladding temperatures is 6°C. At the first peak, the maximum discrepancy between measured and predicted cladding temperatures is 9°C, while this discrepancy for the peak cladding temperature of the instrumented plate is only 3.7°C. The maximum discrepancy between predictions and measurements for the time of the second peak in cladding temperatures is about 2 s. The predicted maximum cladding temperature at the time of the second peak is 10.5°C higher than the measured temperature and the maximum discrepancy between predicted and measured temperatures at the time of the second peak is 11°C.

In Test C, at steady state, the maximum discrepancy between predictions and measurements is 17.7°C at the location of thermocouple TC14. At the time of the second peak, the maximum discrepancy between predicted and measured temperatures is 14.4°C, also at the same location. RELAP predicts that the peak temperature is reached a little earlier than the measured time. The maximum discrepancy between predictions and measurements for the time of the peak is 2.8 s.

In Test F, at steady state, the maximum discrepancy between predicted and measured temperatures is 18.8°C at the location of thermocouple TC14. The maximum discrepancy between predicted and measured temperatures at the time of the peak is 7.4°C, also at the location of thermocouple TC14. The maximum discrepancy between predictions and measurements for the time of the peak is 0.6 s.

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7. References

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