SIMULATIONS OF MOLTEN ZIRCALOY/PRESSURE TUBE CONTACT EXPERIMENTS USING COMPUTER CODE WALLZ5 AND MINI-SMARTT-II

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ABSTRACT

An experimental program has been initiated to investigate the thermal-mechanical behaviour of a fuel channel when molten Zircaloy (Zr-4) from a fuel bundle flows onto a ballooned pressure tube. Eleven experiments were conducted to date, with various initial conditions .ie., internal pressure of 1 to 5 MPa, water subcooling of 18 to 26 °C, and Zr-4 melt of 19 to 88 g. In seven of these experiment, there were small deformations on the calandria tube located beneath the Zr-4 melt but they did not threaten the integrity of the fuel channel. This paper presents the results from these tests and some simulations results from computer codes WALLZ5 and MINI-SMARTT-II.

1.0 INTRODUCTION

During a postulated Loss of Coolant Accident (LOCA) scenario with impaired emergency cooling in a CANDU reactor, the fuel bundle can potentially heat up to and beyond the melting point of unoxidized zircaloy-4. There is a potential for end plates (Zr-4) and end caps of the fuel bundle to melt and flow onto surrounding pressure tube [1]. In such an event a localized hotspot can develop on the pressure tube/calandria tube surface which could lead to localized dryout.

A series of experiments have been conducted at Whiteshell Nuclear Research Establishment (WNRE) to study the thermal-mechanical behaviour of fuel channel when molten Zr-4 flowed onto a ballooned pressure tube [2]. The data from these experiments are used as input to the computer simulations of the transient thermal response of pressure tube and calandria tube using the computer codes WALLZ5 and MINI-SMARTT-II. These simulations are used to verify and validate the computer codes.

2.0 MATERIALS AND METHODS

2.1 Experimental Apparatus

Eleven experiments were performed by WNRE to date to investigate the above issue. A schematic of the experimental apparatus is shown in Figure 1.

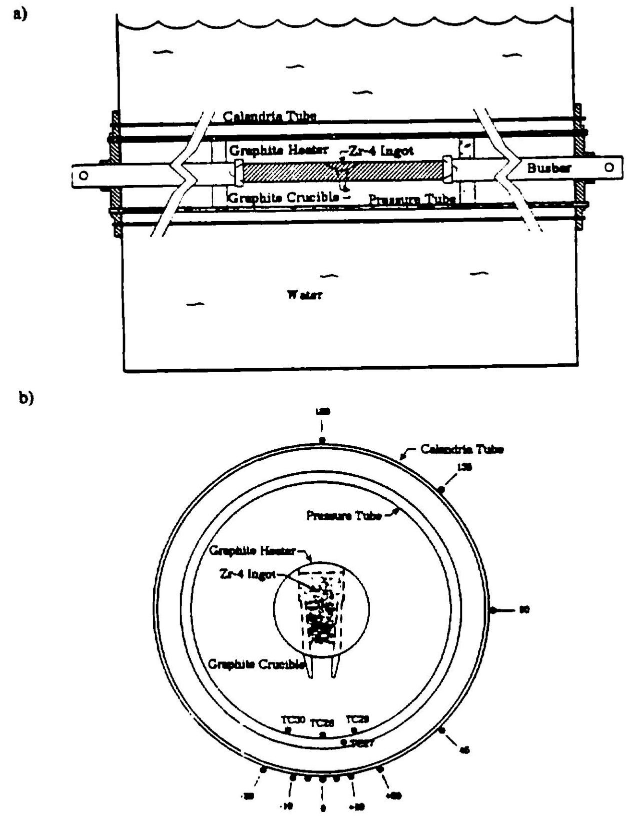

FIGURE 1: a) TEST APPARATUS AXIAL CROSS SECTION AND
b) CROSS SECTION CENTRELINE

Each experiment utilized a 1580 mm long section of Zr-2.5 Nb pressure tube mounted inside a 1730 mm long Zr-2 calandria tube. The calandria tube was submerged in heated, non-flowing water in a open tank and with at least 400 mm of water cover from the top surface of the calandria tube throughout the experiment.

The heater element was a 570 mm long and 38 mm in diameter graphite rod concentrically placed inside the channel assembly. A crucible was machined into the middle of the rod where it held a Zr-4 ingot. Power to the heater was supplied by a 5000 A D.C. power supply.

In Test 7, 8, and 9, a graphite pouring spout was extended from the crucible to within 4 mm of the inner surface of the pressure tube. The post-ballooning gap was designed to be small enough to allow the molten Zr-4 blob to be in thermal contact with both the pressure tube and the spout (hot graphite rod), hence resulting in higher pressure tube and calandria tube transient temperatures.

Experimental details regarding the thermocouples, their locations on the wall of the pressure tube and calandria tube to record the temperature data are given in Ref. [2].

2.2 Experimental Procedures

In all tests, the initial water surrounding the calandria tube was heated to about 95 °C and was held for 15 minutes to partially degas before being allowed to cool. The annulus between the pressure tube and the calandria tube was purged with argon or CO_2 gas. The purge flow was reduced to stagnation before the commencement of each test. Power to the heater element was ramped up to 50 kW and maintained at this level until the pressure tube ballooned into contact with the calandria tube. After the pressure tube had fully ballooned, power was then ramped up again until the Zr-4 ingot melted to produce a molten Zr-4 blob on the pressure tube. The experiment was terminated after any dryout patch caused by the molten Zr-4 had rewet.

2.3 Experimental Observations and Results

Table 1 summarizes the main results from tests conducted. Tests 1, 8, and 10 are excluded as no useful data was obtained.

Details of Tests 2 and 3 were presented in Ref. [1] and details of Test 6 was presented in Ref. [2]. Hence in this paper only results of Tests 4, 5 and 11 are presented.

TABLE 1: SUMMARY OF TEST RESULTS

Test	Pressure (MPa)	Subcool (C)	Max PT (C) a	Max CT (C) b	Dryout (s) c	Drop Size (g)	Deform (mm) d
2	3.0	24	760	800	16	19.1	< 0.5
3	3.0	20	725	900	21	19.1	< 0.5
4	5.0	26	700	765	14	18.7	< 0.5
5	3.0	18	765	1010	43	58.7	1
6	5.0	20	705	885	51	54.7	1.2
7	3.0	21	750	865	29	79.5	0.8
9	5.0	22	660	835	47	85.0	1.4
11	1.0	10	805	1295		70.9	

Notes

a) Maximum PT temperature prior to ballooning
b) Maximum CT temperature during Zr-4 transient
c) Duration of film boiling due to Zr-4 melt
d) CT defomation in a radial direction beneath melt

2.3.1 Test 4

The power to the experimental setup in this test was increased from 0 to 50 kW over a period of 130 s and held constant at this level for 90 s (Figure 2). During this period, the inner surface pressure tube temperature rose steadily to a maximum temperature of 700 °C prior to ballooning. Pressure tube made contact with the calandria tube at 197 s along the top and middle of the fuel channel and spread over the entire heated zone. After contact, temperature on the outer calandria tube reached a maximum of 520 °C and went into dryout for a period of 10 s.

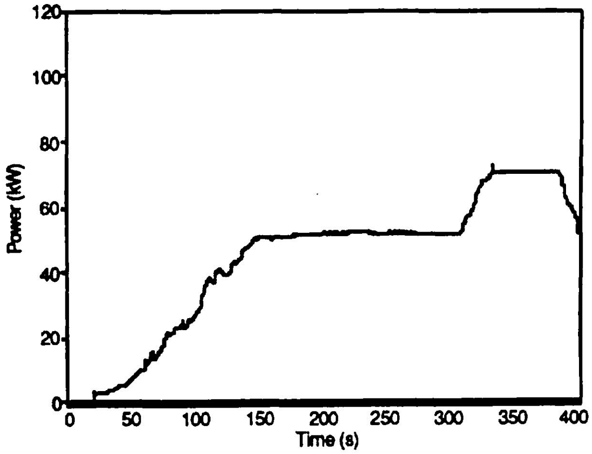

FIGURE 2: TEST 4, HEATER POWER HISTORY

As the calandria tube was in nucleate boiling, power was ramped up steadily to 69 kW. The average calandria tube temperature was 109 °C prior to the Zr-4 transient. At 335 s a molten Zr-4 blob dropped causing the calandria tube temperature to rise to a peak of 765 °C (Figure 3). The thermocouple on the pressure tube reached a maximum temperature of 1385 °C before it was destroyed (Figure 3). Dryout on the calandria tube lasted for a period of 14 s.

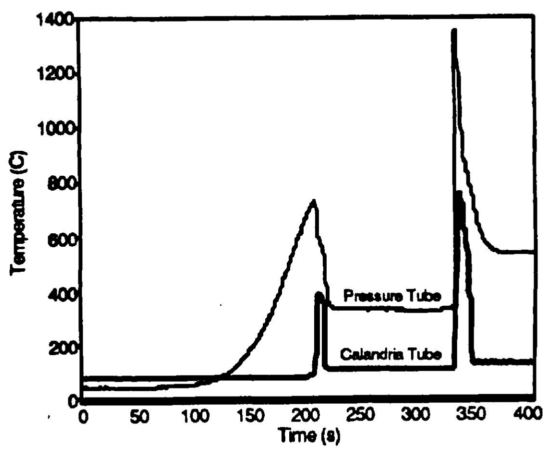

FIGURE 3: TEST 4, PRESSURE TUBE AN CALANDRIA TUBE TEMPERATURE HISTORY

After the fuel channel was disassembled, some minor dryout patches caused by pressure tube ballooning were evident on the calandria tube outer surface. A 20 mm diameter dryout patch was observed that was caused by the Zr-4 blob. As the channel was cut open, a Zr-4 blob of 18.7 g in weight, 8 mm thick, 35 mm long and 20 mm wide was found attached to the pressure tube which caused a slight dimple on the calandria tube.

2.3.2 Test 5

In this test, the power was increased to 50 kW over a period of 110 s and held at this level for 75 s (Figure 4). During this period, the pressure tube temperature rose steadily to a maximum of 765 °C prior to contact. Pressure tube/calandria tube contact began at 242 s along the top in the middle of the fuel channel and the spread over the heated zone. After contact, calandria tube temperature reached a maximum of 610 °C and caused dryout for a period of about to 21 s.

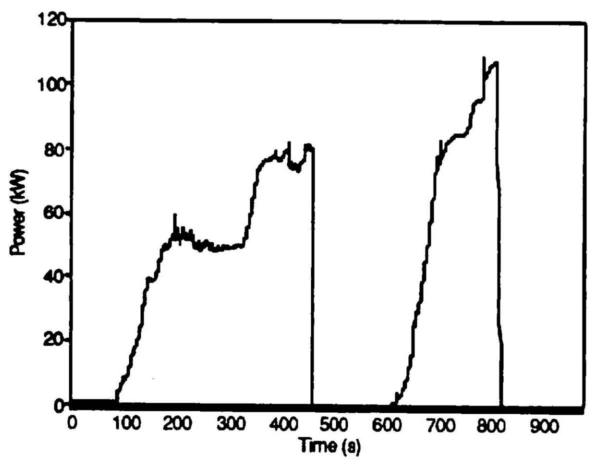

FIGURE 4: TEST 5, HEATER POWER HISTORY

As the calandria tube was still at nucleate boiling, the power was ramped up to 80 kW. At 460 s during the test, power was shut off by the over-current. Subsequently the power was increased again to 96 kW at about 600 s and a molten Zr-4 blob fell at 782 s. After the Zr-4 melted, the maximum temperature recorded on the calandria tube was 1010 °C (Figure 5). Again the thermocouple on the pressure tube was destroyed after a temperature of 1385 °C (Figure 5). A dryout period of 43 s was observed.

After the channel was disassembled, dryout patches on the top of the calandria tube caused by pressure tube ballooning were seen. There was a 35 mm diameter dryout patch on the bottom of the calandria tube caused by the Zr-4 melt. When the fuel channel was cut open a 58.7 g drop of Zr-4, 10 mm thick, 32 mm wide and 50 mm long, was found on the ballooned pressure tube and caused a dimple 32 mm in diameter and 1 mm high.

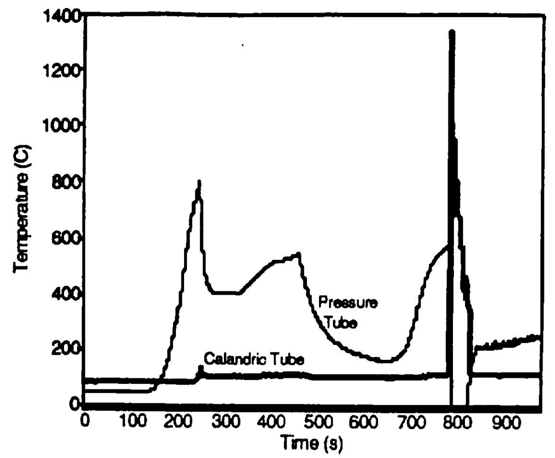

FIGURE 5: TEST 5, PRESSURE TUBE & CALANDRIA TUBE TEMPERATURE HISTORY

2.3.3 Test 11

The power in this test was increased from 0 to 60 kW over a period of 73 s and held constant at this level for 73 s (Figure 6). During this period, the pressure tube inner surface temperature rose steadily to a maximum of 825 °C prior to contact. Pressure tube made contact with the calandria tube at 177 s along the top and middle of the fuel channel and spread over the entire heated zone.

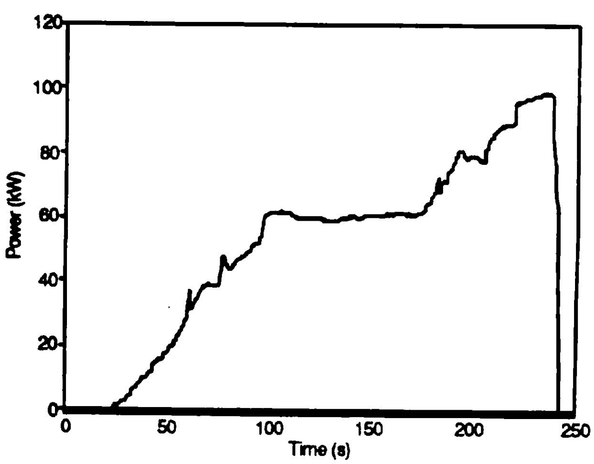

FIGURE 6: TEST 11, HEATER POWER HISTORY

As the subcooling in the test was low, after ballooning, the calandria tube continued to be in dryout state and the maximum calandria tube temperature reached 600 °C. The power was then increased steadily to 89 kW. During the same period the calandria tube temperature continue to rise steadily to a maximum of 780 °C prior to the molten Zr-4 transient. At 221 s a molten Zr-4 blob dropped. The maximum calandria tube temperature recorded was 1295 °C

3.5 s after the melt drop (Figure 7). After 16 s of molten Zr-4 contact, the fuel channel ruptured causing the test to terminated.

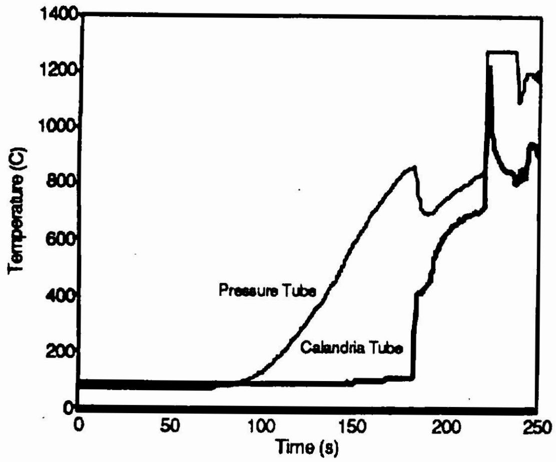

FIGURE 7: TEST 11, PRESSURE TUBE & CALANDRIA TUBE TEMPERATURE HISTORY

When the fuel channel was cut open, a 70.9 g Zr-4 melt was fused to the pressure tube. It caused deformation of 100 mm in diameter by 11 mm in height on the calandria tube.

3.0 WALLZ5 AND MINI-SMARTT-II CODES

This section provides a brief description of the two computer codes used for simulation of the experimental results.

3.1 Structure of WALLZ5 Code

WALLZ5 is a one-dimensional transient heat transfer model which simulates heat transfer from the pressure tube to the calandria tube and into the moderator. WALLZ5 can perform three types of transient analysis (pressure tube ballooning into contact with the calandria tube, molten Zr-4 contact with a ballooned pressure tube, and molten fuel contact with a ballooned pressure tube). Each analysis commences from the time contact is being made.

The main input parameters for WALLZ5 are moderator temperature, thickness of molten Zr-4 blob and contact conductance between pressure tube and calandria tube. After these values are initialized, the distance between nodes are computed. For each node, thermal conductivity and thermal diffusivity as a function of temperature are calculated. Finally the one-dimensional radial heat conduction equation and hence the wall temperature are solved.

In WALLZ5, the Rohsenow correlation is used to calculate the heat flux between the calandria tube and moderator at nucleate boiling. The Rohsenow correlation is defined as following :

$$q = \left[\frac{C_\ell (T_w - T_{sat})}{C_{sf}\, h_{fg}\, P_r^{1.7}} \right]^3 \frac{\mu_\ell h_{fg}}{\left(\frac{\sigma}{g(\rho_\ell - \rho_v)} \right)^{1/2}} \qquad (1)$$

where
- q = heat flux at wall temperature (kW/m^2)
- C_ℓ = specific heat of liquid (kJ/kg °C)
- h_{fg} = latent heat of vaporization (kJ/kg)
- P_r = Prandtl number of saturated liquid
- μ_ℓ = dynamic viscosity of liquid (kg/m•s)
- σ = liquid surface tension (kg/s^2)
- ρ_ℓ = liquid density (kg/m^3)
- ρ_v = vapour density (kg/m^3)
- g = acceleration due to gravity (m/s^2)
- T_w = wall temperature (°C)
- T_{sat} = moderator saturation temperature (°C)
- T_{mod} = moderator temperature (°C)
- C_{sf} = constant empirically derive from liquid rewets, heating surface, wall material, wall roughness, and pressure.

At film boiling the following heat flux equation is used:

$$q = 0.4\,(T_w - T_{mod}) \qquad (2)$$

3.2 Structure of MINI-SMARTT-II

The molten zircaloy/pressure tube contact code MINI-SMARTT-II was developed from the existing computer code MINI-SMARTT [3]. It is a two-dimensional heat transfer model which simulates circumferential wall temperature distribution. The code uses a concentric ring radiation model with a graded nodal scheme which improves the spatial convergence when a large heat flux is introduced at a very localized point on the pressure tube.

The modes of heat transfer in MINI-SMARTT-II are as follows :

- ring radiation from the outer fuel ring to the pressure tube;
- radial and circumferential conduction within the pressure tube;
- contact conduction between the molten zircaloy and the pressure tube;
- radiation and conduction across the gas gap between the pressure tube and the calandria tube and from the calandria tube into the moderator.

For ring radiation, the general heat flux equation used is :

$$q = \sigma \frac{\varepsilon_1 \varepsilon_2 (T_1^4 - T_2^4)}{\varepsilon_2 + (a/b)(\varepsilon_1 - \varepsilon_1 \varepsilon_2)} \qquad (3)$$

where σ = Stefan-Boltzmann constant (kW/m^2K^4)
ε_1 = emitting surface emissivity
ε_2 = receiving surface emissivity
a = radius of the emitting surface (m)
b = radius of the receiving surface (m)
T_1 = emitting surface temperature (K)
T_2 = receiving surface temperature (K)

The heat transfer coefficient (HTC) between calandria tube and moderator used during pool boiling is as follows :

$$HTC = 0.02648 \, (T_w - T_{mod})^2 \qquad (4)$$

where 0.02648 represents the heat flux from the Rohsenow correlation (Eqn. (1)) at saturation.

During the film boiling transient, the heat transfer coefficient is held as a constant.

$$HTC = 0.2 \ kW/m^2K \qquad (5)$$

3.3 Code Enhancements

In order to obtain comparable results from the two codes, a few changes were made to the existing WALLZ5 code. A correction was made in the calculation of heat flux from calandria tube to the moderator (Eqn. (2)). The equation should use the saturation temperature of the moderator (T_{sat}) instead of the actual moderator temperature when pool boiling occurred. The moderator saturation temperature is the temperature at which the moderator will starts to boil, thus causing the onset of pool boiling. This correction was also needed while solving for the calandria tube wall temperature. Secondly, heat radiation correlation (Eqn. (3)) between pressure tube and coolant was added to the code.

There were several modifications to MINI-SMARTT-II to enhance its accuracy. MINI-SMARTT-II was originally set to simulate molten Zr-4 thickness of 4 mm or less. Alteration of the pressure tube radial and circumferential nodalization and temperature ranges was necessary to incorporate molten Zr-4 blob of at least 11 mm in thickness as measured in the WNRE experiments. Secondly, the moderator temperature was replaced by the saturation temperature (T_{sat}) in the HTC equation (Eqn. 4) during pool boiling. Finally, the heat transfer coefficient between the calandria tube and moderator used during film boiling (Eqn. (5)) was changed to 0.4 kW/m^2K (same as in WALLZ5).

4.0 SIMULATION TESTS

Of the eleven experiments conducted by WNRE only six were used in the present simulations with WALLZ5 and MINI-SMARTT-II. In particular, Test 1, 8 and 10 did not produced any molten Zr-4 blob onto the pressure tube. For Test 7 and 9, the molten Zr-4 blobs were the largest ever to be produced in these test series. These tests were expected to produce higher calandria tube transient temperature, longer dryout period, and greater deformation than occurred in previous tests.

4.1 Initial Conditions

For each test, simulation were performed to predict the transient temperature of the calandria tube when the molten zircaloy melt made contacted with the pressure tube. The main experimental input parameters used in each test were molten zircaloy thickness and heat transfer coefficient between the pressure tube and calandria tube. The molten Zr-4 thickness used in Tests 2, 3 and 4 are 8 mm, in Tests 5 and 6 are 10 mm, and in Test is 11 mm.

4.2 Simulation Results

4.2.1 Test 2

Various simulations were carried out with the value of heat transfer coefficient as a parameter varying between 6.0 and 9.0 kW/m^2K. Results of these simulations with WALLZ5 along with the test results are shown in Figure 8. The calandria tube temperature transient generated by HTC of 8.0 kW/m^2K showed the closest agreement with the test. The agreement during the early part of the heat up phase was seen to be good. When the calandria tube temperature reached 600 °C, WALLZ5 began to over-estimate the test results and the simulation results eventually reached a steady state temperature of 960 °C.

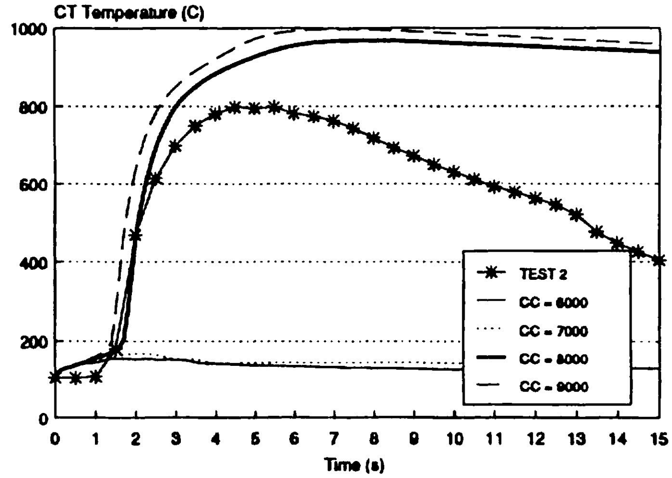

FIGURE 8: WALLZ5 AND EXPERIMENTAL CALANDRIA TUBE TEMPERATURE FOR TEST 2

The results of the experimental and simulation results using MINI-SMARTT-II are shown in Figure 9. Again the results produced by MINI-SMARTT when HTC was 8.0 kW/m^{2}K was seen to be in good agreement with the test. From the start of dryout to the peak temperature, the simulated results were consistence with the test values. During the rewetting phase, the simulated temperature transient showed reasonable agreement. Although at 15 s, the simulated temperature was about 150 °C higher than the test, this is mainly due to the difficulties in modelling the rewet transient.

From the results shown in this test, the heat transfer coefficient between the pressure tube and calandria tube is about 8.0 kW/m^{2}K. This value will be used throughout the simulations for the remaining tests.

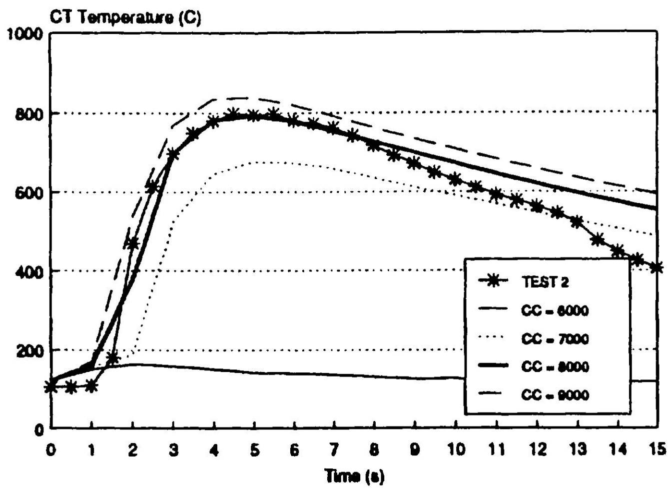

FIGURE 9: MINI-SMARTT-II AND EXPERIMENTAL CALANDRIA TUBE TEMPERATURE FOR TEST 2

4.2.2 Test 3

Results from Test 3 and the simulations using WALLZ5 and MINI-SMARTT-II are shown in Figure 10. Although the measured maximum test temperature was at 800 °C because of an amplifier clipping, the estimated maximum temperature probably was higher. There was good agreement between the test results and the simulated data while HTC was at 8.0 kW/m^{2}K. The WALLZ5 simulation indicated that the steady state temperature was around 1000 °C.

Figure 10 shows that the results of simulation using MINI-SMARTT-II using HTC of 8.0 kW/m^{2}K are in good agreement with the test both during heat up and rewet transient. The simulated peak temperature was close to 900 °C. At 15 s, the simulated temperature was only about 50 °C higher than the test result.

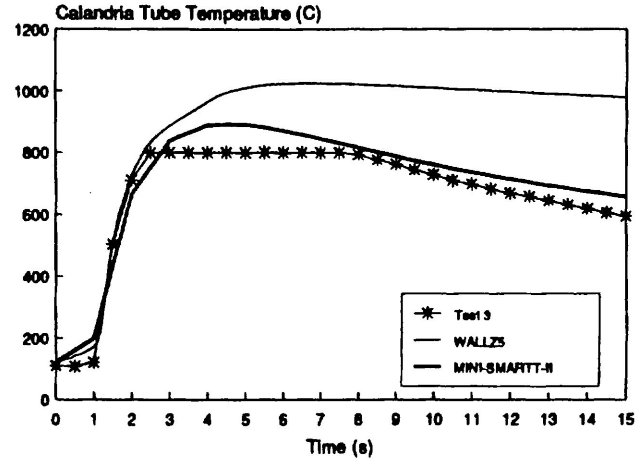

FIGURE 10: SIMULATED AND EXPERIMENTAL CALANDRIA TUBE TEMPERATURE FOR TEST 3

4.2.3 Test 4

Results from Test 4 and the simulations using WALLZ5 and MINI-SMARTT-II are shown in Figure 11. In this test the timing of dryout predicted by WALLZ5 and MINI-SMARTT-II while using HTC of 8.0 kW/m^{2}K were about 1 s later than the test. This small discrepancy in timing reflects the non-uniform strain on the pressure tube during the ballooning transient. There was good agreement between the test and simulated heat up temperature during the initial dryout transient. The steady state temperature predicted by WALLZ5 was about 150 °C higher than the test result.

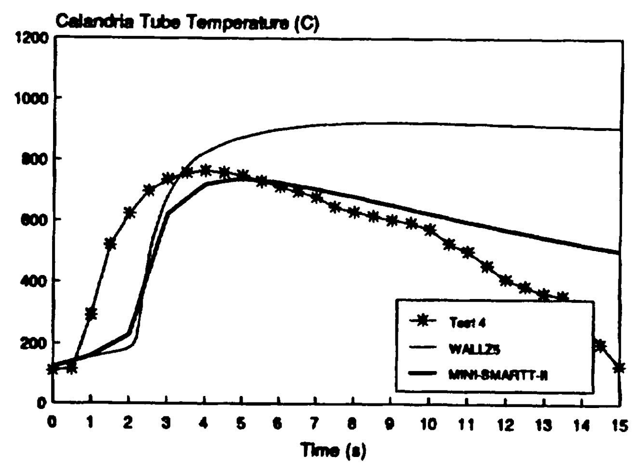

FIGURE 11: SIMULATED AND EXPERIMENTAL CALANDRIA TUBE TEMPERATURE FOR TEST 4

In MINI-SMARTT, the simulated calandria tube temperature showed good agreement with the test when HTC was about

8.0 kW/m^{2}K. The simulated heat up rate and peak temperature also showed good agreement with the test. Because of the difficulty in rewet modelling, the simulated temperature was at 550 °C after 15 s into dryout while the test had finished the rewet transient.

4.2.4 Test 5

Results of simulations from WALLZ5 along with the test results and MINI-SMARTT-II are shown in Figure 12. There was strong agreement between the results and the simulated calandria tube temperature when HTC of 8.0 kW/m^{2}K was used. From the start of dryout to the peak, the simulated temperature from WALLZ5 was extremely close to the test. Although the steady state temperature occurred past the test peak, the difference in peak temperature was about 100 °C.

As regard to the simulation of MINI-SMARTT-II, the agreement between the test and the simulated results from HTC of 8.0 kW/m^{2}K is good. During the rewet transient, the decline in temperature rate between the simulated result and the test was extremely close (the simulated temperature was only about 50 °C higher throughout the transient).

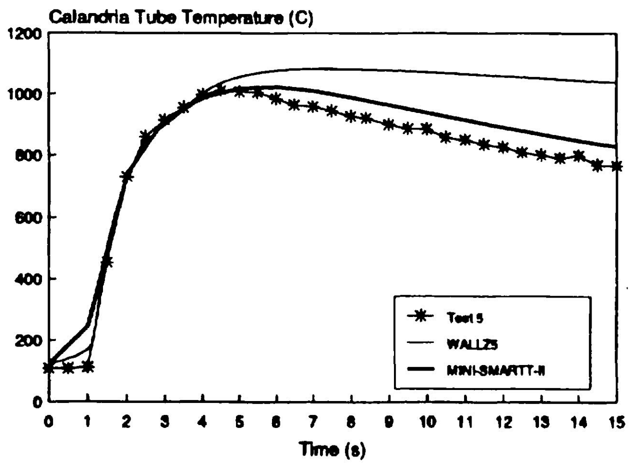

FIGURE 12: SIMULATED AND EXPERIMENTAL CALANDRIA TUBE TEMPERATURE FOR TEST 5

4.2.5 Test 6

Results from Test 6 and the simulations using WALLZ5 and MINI-SMARTT are shown in Figure 13. There was good agreement between the test and the simulated data while HTC was at 8.0 kW/m^{2}K. Although the simulated steady temperature from WALLZ5 was about 150 °C higher than the test, the transient heat up phase was reasonable close to the test results.

There was good agreement between the test and the simulation of MINI-SMARTT-II using HTC of 8.0 kW/m^{2}K. The difference in peak temperature between the test and the simulation was about 100 °C. During the rewet transient, the simulated temperature was again over-estimated the test by about 100 °C.

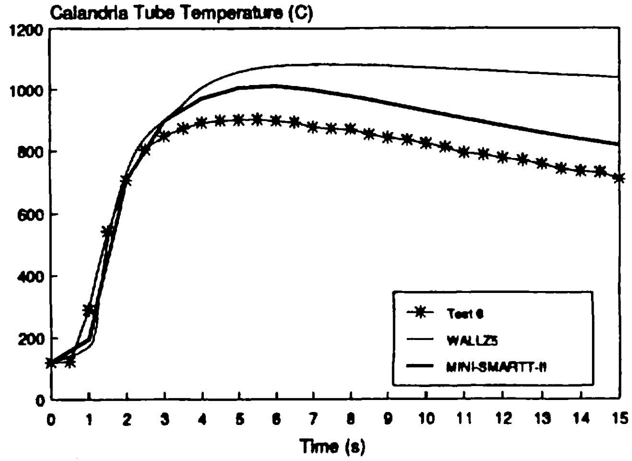

FIGURE 13: SIMULATED AND EXPERIMENTAL CALANDRIA TUBE TEMPERATURE FOR TEST 6

4.2.6 Test 11

Results from Test 11 and the simulations using WALLZ5 and MINI-SMARTT are shown in Figure 14. During the initial heat up phase to peak, the results using HTC of 8.0 kW/m^{2}K showed good agreement with the test. The thermocouple on the calandria tube was destroyed after reaching the peak, thus the simulated temperatures after this point are irrelevant.

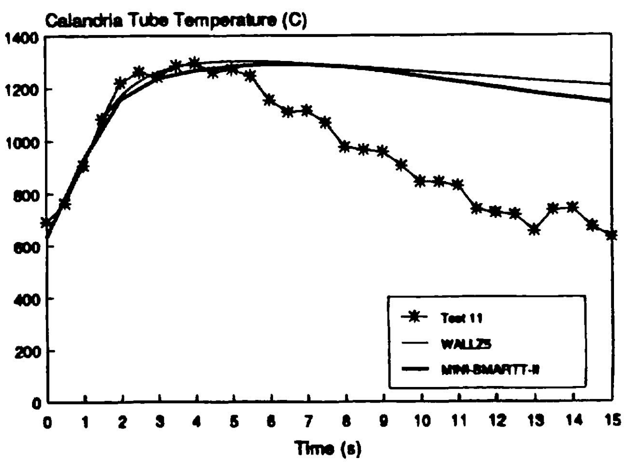

FIGURE 14: SIMULATED AND EXPERIMENTAL CALANDRIA TUBE TEMPERATURE FOR TEST 11

5.0 CONCLUSIONS

Test 11 was the only experiment where the heat stored in the molten Zr-4 melt (11 mm in thickness) caused the fuel channel severely deformed and ruptured. The low subcooling, 10 °C, on the calandria tube restricted the transfer of heat to the moderator thus caused the fuel channel temperature to rise significantly and resulted in the rupturing of the channel. The consequence of this condition was also evident in the result of Test 10 although no molten Zr-4 was produced.

The results from six WNRE experiments were used in the simulations with both WALLZ5 and MINI-SMARTT-II. The initial value of heat transfer coefficient between the pressure tube and calandria tube during the molten Zr-4 transient was predicted by both codes to be about 8.0 kW/m^2K.

During the initial heat up transient, both codes indicated good agreement with the experiments. Rewet modelling was not encoded into WALLZ5 and the steady state temperature over-estimated the peak by about 100 to 150 °C. MINI-SMARTT-II showed good agreement with the actual peak. The rewet transient temperature predicted by MINI-SMARTT-II showed reasonable agreement with the experiment. Although the rewet temperature were higher than the actual this was due to the difficultly in modelling of the rewet transient.

Overall MINI-SMARTT-II was shown to be a better model in simulating the experimental calandria tube temperature. Although WALLZ5 does not include a model for rewetting, it is a much simpler and faster code to use, and it is well suited to predict peak temperature when only the initial heat up transient temperature is being investigated.

6.0 REFERENCES

[1] D.B. Sanderson, K.W. Demoline, K.E. Locke, and A.P. Muzumdar, "Experiments to Determine the Thermal-Mechanical Response When Molten Zircaloy-4 Flows onto a Ballooned Pressure Tube ". Proceedings of the Tenth Annual CNS Conference, Ottawa, Ont., pp. 9-26 to 9-30, June 1989.

[2] M.J. Brown, D.G. Litke, Q.M. Lei, and D.B. Sanderson, "Molten Zircaloy-4/Ballooned Pressure Tube Interaction Experiments", AECL, 1990. Proceedings of the Twelve Annual CNS Conference, Saskatoon, Saskatchewan, June 1991.

[3] D.B. Reeves, G.H. Archinoff, G.H. Locke, and A.P. Muzumdar, "Development of the MINI-SMARTT Code For Analyzing Fuel Element/Pressure Tube Contact", CNS/ANS International Conference on Simulation Methods in Nuclear Engineering, Montreal, October 1986.