Development of a Model for Calculating Sheath Thermocouple Finning Losses for Application in In-Reactor Severe Fuel Damage Tests

by

L.C. Walters, J.W. DeVaal[1] and N.K. Popov[2]

Safety Thermalhydraulics Branch,
Reactor Safety Research Division
AECL
Whiteshell Laboratories
Pinawa, Manitoba
R0E 1L0

1 - Fuel Safety Branch, AECL, Chalk River Laboratories
2 - MMIR Project, AECL, Sheridan Park

ABSTRACT

The use of mechanical clamps to attach high-temperature thermocouples to the surface of CANDU®-type fuel elements has been developed as a means of improving the reliability of temperature measurements during in-reactor Severe Fuel Damage (SFD) tests. While helping to ensure good thermocouple-to-sheath contact, the clamps also result in fairly significant finning losses to the surrounding steam coolant. To quantify these losses (and thus relate the measured sheath thermocouple responses to the actual local sheath temperatures), a series of electrically heated simulation tests was performed at Whiteshell Laboratories in 1995 January. This paper presents the results of CATHENA simulations of these tests and the development of a heat transfer model for calculating the finning losses from the strapped sheath thermocouples.

1.0 INTRODUCTION

The Blowdown Test Facility (BTF), located in the NRU (National Research Universal) reactor at AECL's Chalk River Laboratories is used to perform in-reactor experiments to determine fuel behaviour and fission product release from CANDU-type fuel subjected to a range of postulated accident conditions. Data from these integral in-reactor tests are used to develop and validate computer codes and models used in performing safety and licensing analyses of CANDU power reactors.

One important aspect of performing BTF SFD tests is to relate the observed fuel damage and fission product releases to the fuel temperatures achieved during the test. To measure these temperatures reliably, specialized high-temperature rhenium-clad thermocouples are attached to the sheath of the previously irradiated fuel elements used in BTF tests. These thermocouples are installed in a hot cell with specialized tools and, once installed, must survive the test under steam cooling conditions where the volume-average fuel temperature is maintained at up to 2000 °C for as long as 20 minutes.

The use of rhenium-clad thermocouples and Zircaloy retaining clamps (or straps) are recent developments which reduce the likelihood of thermocouple failures and/or detachment from the sheath. This robust arrangement, however, results in fairly significant finning losses to the surrounding steam coolant during the test. To quantify these finning losses (and qualify the use of mechanical clamps), a series of three electrically heated fuel element simulator tests was conducted in the High Temperature Heat Transfer Lab at Whiteshell Laboratories in 1994 June and 1995 January as part of the instrument development program for the BTF tests. These tests are described in Section 2 of this paper.

In Section 3, the development of a model used for calculating the finning losses from the clamped thermocouples is described. The model was developed by constructing a CATHENA

CANDU® CANada Deuterium Uranium is a registered trademark of Atomic Energy of Canada Limited (AECL).

idealization of the heater test assemblies, including detailed wall model descriptions of the thermocouples and clamps. The model includes convective and radiative heat transfer from the clamps, convective heat transfer from the thermocouples, and contact heat transfer between the thermocouples and sheath, thermocouple and clamps, and the clamps and sheath.

As described in Section 4, simulations of two of the Whiteshell heater tests were conducted using the CATHENA model to obtain a better understanding of the thermalhydraulic phenomena observed in the tests, and to determine the solid-to-solid heat conductances between the clamp, thermocouple, and sheath. These sensitivity simulations addressed the effects of coolant mass flow rate, surface emissivities, and the effect of different values of contact heat transfer between the sheath, thermocouples, and the clamps used to attach the thermocouples to the sheath. The conclusions that could be drawn from performing the various sensitivity simulations are summarized in Section 5.

2.0 DESCRIPTON OF TESTS

2.1 Description of Test 1

The first test in the Whiteshell test series used an electrically heated Pickering-sized fuel element simulator contained within a quartz flow tube (Tiede and Moyer, 1994). With this arrangement the clamped thermocouple could be videotaped during the test, showing that the idea of using mechanical clamps was sound. The clamp remained relatively well cooled in the flowing steam and held the thermocouple in contact throughout the test.

In reviewing the results of the first test, it became apparent that the performance of the clamped thermocouple was strongly affected by the convective and radiative heat losses from the clamp. Also, while the test showed that the thermocouple remained in contact for the entire test, it recorded temperatures significantly lower than the actual local sheath temperature. Because of these observations, a second set of electrical heater tests was commissioned to obtain information on the survivability and finning losses of the strapped thermocouples under conditions more representative of BTF tests.

2.2 Description of Tests 2 and 3

Following the first test, a major objective of the second set of tests was to assess the performance of different types of thermocouples mechanically strapped to a BTF-typical Bruce-sized fuel element simulator (Tiede and Moyer, 1995). These heater tests, designated Tests 2 and 3, were conducted using a surrounding thermal shroud arrangement similar to that of an actual BTF fuel stringer (i.e., containing a NILCRA* liner). Data collected on the performance of the strapped thermocouples with this arrangement was thus fully representative of a BTF test.

The thermal shroud configuration used in Tests 2 and 3 also contained a small through-wall window located at the mid-plane elevation of the fuel sheath. This arrangement allowed a pyrometer to view the sheath surface directly beside the strapped thermocouple; thus yielding a direct measurement of the "true" local sheath temperature. The individual fuel element simulators constructed for Tests 2 and 3 consisted of electrically heated graphite filaments (or rods) placed inside alumina insulators which, in turn, were contained inside the Bruce-sized Zircaloy cladding. While separate heater assemblies were built for the two tests, the thermal shroud simulator was re-used.

The heater assemblies and surrounding thermal shroud were well instrumented, as shown in Figures 1 and 2. Internal heater temperatures were measured with pairs of thermocouples, designated TIFS's (for Temperature, Inside Fuel Sheath), located in grooves on opposite sides of the alumina pellets at the mid-plane of the top, middle and bottom bearing pads. These internal thermocouples were typically located axially near the external strapped thermocouples.

Three sheath thermocouples, designated TFS's (for Temperature, Fuel Sheath) were attached to the outside of each fuel element simulator with clamps. The sheath thermocouples were arranged with TFS01 strapped to the mid-plane of the top bearing pad, TFS02 strapped to the mid-plane of the middle bearing pad, and (for Test 2) TFS03 strapped to the mid-plane of the bottom bearing

---

* NILCRA is a partially stabilized transformation toughened ZrO_2 produced by Nilsen (USA) Inc.

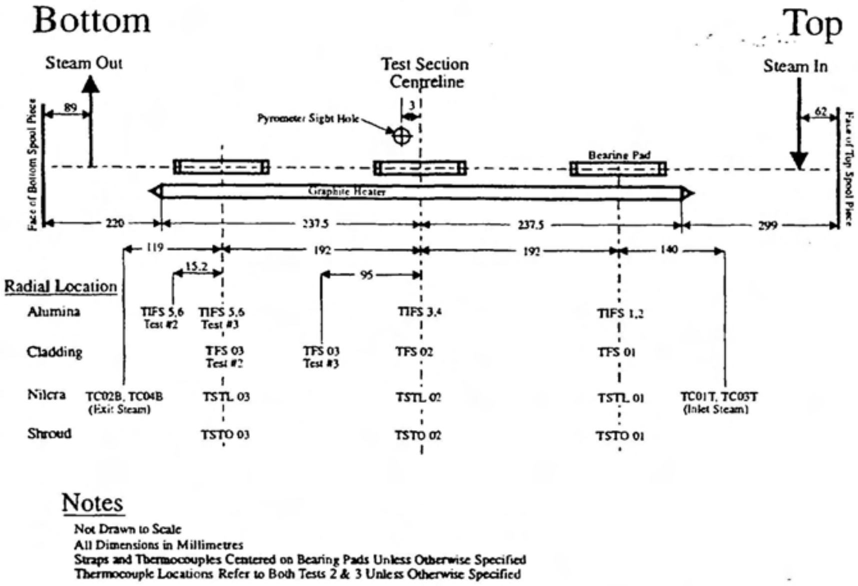

Figure 1: Whiteshell Heater Tests 2 & 3 Thermocouple Locations

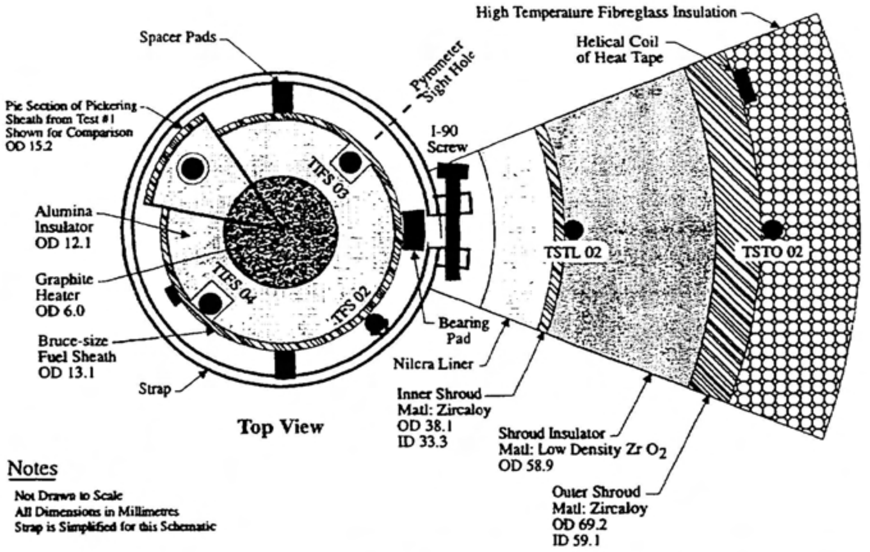

Figure 2: Whiteshell Heater Tests 2 & 3 Partial Cross-Section at the Middle Bearing Pad

pad. (For Test 3, the TFS03 thermocouple was moved to midway between the middle and bottom bearing pads as shown in Figure 1.)

As indicated previously, the two tests examined the response of different types of sheath thermocouples; where 1.0 mm-diameter K-type stainless steel clad thermocouples were used for TFS01, TFS02 and TFS03 in Test 2, and high-temperature C-type thermocouples were used in Test 3. (A 1.8 mm-diameter Westinghouse Hanford rhenium-clad thermocouple was used for TFS01 in Test 3, while a smaller diameter (1.1 mm) rhenium-clad French CEA thermocouple was used for TFS02, and a 1.0 mm-diameter Zr/Ta-clad Idaho Falls thermocouple was used for TFS03.)

The arrangement of thermocouples on the thermal shroud simulator was chosen to reflect the arrangement typically used for a BTF test. Thermocouples were located in grooves behind the NILCRA liner at the top, middle, and bottom bearing pad locations (designated TSTL01, TSTL02 and TSTL03, respectively), and on the outside surface of the thermal shroud (designated TSTO01 through TSTO03).

Pairs of upstream and downstream coolant thermocouples, designated TC01T and TC03T (for Top), and TC02B and TC04B (for Bottom) were installed into the central flow channel at the top, and through drilled holes in the NILCRA liner below the heated element. To ensure that condensation of the supplied steam flow would not occur during the tests, a helical coil of trace heating was wound around the outside of the shroud and a blanket of high-temperature insulation was then placed over the shroud.

The individual tests were performed by establishing a steam flow over the fuel element simulator and then increasing the electrical power supplied to the heater in steps. The exit coolant mass flow rate in both of these tests was uniform and was measured (by condensate weight gain) to be about 4.1 g/s. In Test 2, a small purge flow of helium was used to clear the downstream condenser coils during the test, but (after ensuring the condenser coils were installed laying flat) this was found not to be needed in Test 3 and, thus, was not used. The experimental assembly was disassembled after Test 2, and its instrumented heater rod removed and replaced with the higher-temperature instrumented heater rod for Test 3. The primary objectives for Test 3 were to examine the response of the higher-temperature and larger-diameter thermocouples, and to determine the effects of operating at higher test temperatures (which could cause damage to the NILCRA liner).

3.0 SIMULATION OF TESTS

The results of Tests 2 and 3, and the post-test state of the instrumentation, confirmed that the idea of using mechanical clamps to attach the sheath thermocouples was effective; but, due to finning losses, they did record temperatures significantly lower than measured by optical pyrometry (i.e., about 150°C to 200°C lower). As a result, it was decided to use the clamp design proven in these tests for attaching the sheath thermocouples installed in the BTF-105A test (DeVaal et al., 1996). Following the successful use of this attachment technique in the BTF-105A test, it was also further decided to develop a CATHENA model for calculating the behaviour of the strapped thermocouples for use in pre-test planning and piloting of the BTF-105B test.

3.1 The CATHENA Code

The CATHENA code (Hanna, 1997) was developed by AECL at Whiteshell Laboratories primarily for the analysis of postulated LOCA events in CANDU reactors. CATHENA uses a non-equilibrium two-fluid representation of two-phase fluid flow in piping networks. The liquid and vapour phases may have different pressures, velocities and temperatures. Interface mass, energy and momentum transfer are specified using constitutive relations that have been obtained either from the literature or developed from separate effects experiments. The code uses a staggered-mesh, one-step, semi-implicit, finite-difference solution method, that is not transit time limited. The extensive wall heat transfer package includes radial and circumferential conduction, solid-solid contact conductance, thermal radiation and the zirconium-steam reaction. The heat transfer package is general and allows the connection of multiple wall surfaces to a single thermalhydraulic node. The CATHENA code includes models required for complete reactor loop simulations, such as pumps, valves, a pressurizer, break discharge models, separator models and an extensive control system modeling capability.

3.2 CATHENA Idealization

Two separate, but similar, CATHENA idealizations were used to model Whiteshell heater Tests 2 and 3. The main differences between these two idealizations were in the input boundary conditions. These boundary conditions consisted of the measured experimental data (i.e., the inlet coolant temperatures, heater power, inlet mass flow rate and outer shroud temperatures) from each heater test.

In both idealizations, the model of the fuel element simulator consisted of a graphite rod, and surrounding alumina insulators and Zircaloy fuel sheath, as shown schematically in Figure 3. The outer diameter of the heater (i.e., the sheath) is 13.08 mm. The sheath thermocouples (TFS01, TFS02 and TFS03) were modelled as thin rods of stainless steel with a 2 mm diameter. The clamps holding the thermocouples in place were modelled as 5 mm wide by 0.5 mm thick circumferential Zircaloy bands. The NILCRA thermal shroud liner (20.54 mm ID, 33 mm OD) and Zircaloy outer shroud (33.02 mm ID, 68.58 mm OD) were also modelled in the idealizations.

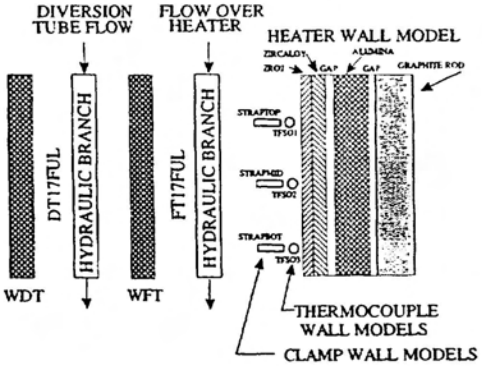

Figure 3: CATHENA Idealization of the Whiteshell Heater Test Wall Models

The flow boundary condition at the top of the test section was initially used to specify the coolant flow over the heater rod. In reality, while the coolant flowing in this annulus between the heater rod and the inside surface of the NILCRA liner represents the vast majority of the total input flow, there can also be leakage flow through the grooves in the outer surface of the NILCRA liner and through the small gap (0.01 mm) between the NILCRA liner and the inner wall of the thermal shroud. This path (designated DT, for the Diversion Tube flow) was modelled in the idealizations by an annulus where a diversion flow (or liner tube flow) was also established using a flow boundary condition.

Heat transfer wall models were incorporated in the idealizations for the heater rod and surrounding pipe components, the thermocouples, and the clamps (or straps), as shown in Figure 3. Solid-solid contact heat transfer models were used in the idealizations to account for heat conduction between each pair of contacting solid surfaces. Specifically, contact heat transfer was modelled between the heater rod surface (i.e., the sheath) and the clamps, the heater surface and the thermocouples, and the clamps and the thermocouples. The heat transfer coefficient for all of these contact models was initially chosen (based on previous experience) to be 2 kW/m^2°C. The percentage of the area assumed to be in contact between the surfaces varies in each of these contact models. For the heater and each clamp, 0.5% of the area of the clamp was initially specified to be in contact. For the heater and thermocouples, 1.5% of the area of the thermocouple was initially specified in contact, and for the clamps and the thermocouples, 0.3% of the area of the thermocouple was specified in contact.

Radiation heat transfer was expected to be an important portion of the total heat transferred from the heater outwards to the thermal shroud. Consequently, radiation models between the heater surface and the NILCRA liner, and between the NILCRA liner and the clamp were included. The emissivity of the outer wall of the sheath was initially set at 0.80, while 0.85 was specified for the inner wall of the NILCRA liner and for the outside surface of the strap. Radiative heat transfer between the thermocouples and the sheath, and between the thermocouples and the strap was not modelled, because of the small surface area of the thermocouples.

4.0 DISCUSSION OF RESULTS

A series of sensitivity simulations of the Whiteshell heater tests was conducted with CATHENA (MOD 3.5b/Rev.0). A summary of the most important boundary conditions and assumptions used in these simulations is shown in Tables 1 and 2. The primary objective of these simulations was to understand the effects of varying input parameter values on the predicted temperatures. Parameters chosen for evaluation were the inlet mass flow rate and distribution, surface emissivities, and the contact areas and conductances between the sheath, thermocouples and clamps. Other parameters were considered, such as the heater power (see Figure 4), but the uncertainties in the other chosen parameters were assessed to be significantly higher. In particular the measurement uncertainty in the inlet mass flow rate (±15%) and the indeterminate split between the central channel and liner tube flow received the most attention.

In the first simulations, the effects of varying the flow over the fuel, modifying surface emissivities, and allowing leakage behind the NILCRA liner were examined. As expected, when the inlet mass flow rate was decreased, the predicted sheath temperatures increased. It was also found that when the inlet mass flow rate (measured 4.1 g/s) was split between the central flow tube (3 g/s) and the liner tube (1.1 g/s), better agreement was obtained between the predicted and measured shroud liner and sheath temperatures. A period of flow stagnation observed in Test 3 in the period from 1700 s to 1718.5 s, as shown in Figure 5, was also modelled.

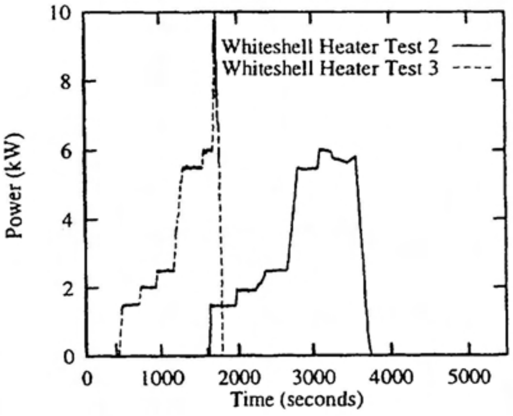

Figure 4: Heater Powers

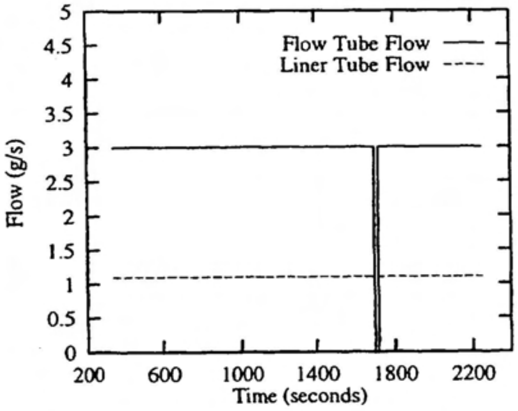

Figure 5: Inlet Mass Flow Rate

Because of different uncertainties in the measured data and the availability of a "true" sheath temperature via pyrometry at the heater mid-plane, a hierarchy of importance in fitting to the measured test data and a minimum acceptance criterion were developed. In this regard, the temperatures taken to be the most important were those measured at the mid-plane elevation (i.e., thermocouple TFS02), the "true" sheath temperature from the pyrometer, the internal alumina temperatures measured at the mid-plane (i.e., TIFS03, TIFS04), and the mid-plane NILCRA liner temperature (i.e., TSTL02). The chosen minimum acceptance criterion required that these five temperatures all be predicted within ±50°C. This criterion was believed to be reasonable given the uncertainties in the various measured temperatures, and desire to control the BTF-105B test within this margin.

Based on comparisons between the measured and calculated mid-plane temperatures, the best results for Test 2 were obtained with the conditions for Simulation 8 (see Table 1), whereas for Test 3 the best results were obtained with Simulation 9 (see Table 2). Note that Test 3, which did not use a helium purge flow, was performed under conditions most similar to the conditions expected in the BTF-105B test.

Figures 6, 7, 8 and 9 show a comparison of the measured and calculated alumina temperatures obtained in Simulation 8 of Test 2 and in Simulation 9 of Test 3. The general agreement between the calculated and measured temperatures is quite good. In Simulation 8 of Test 2, however, the alumina temperatures were overpredicted except for the middle bearing pad (i.e., TIFS03, TIFS04; see Figure 6). In Simulation 9 of Test 3, the alumina temperatures at the top bearing pad (i.e., TIFS01, TIFS02) were overpredicted, whereas the middle bearing pad temperature (i.e., TIFS03, TIFS04) was predicted well, and the bottom bearing pad (i.e., TIFS05, TIFS06) was underpredicted (see Figures 7, 8 and 9 respectively).

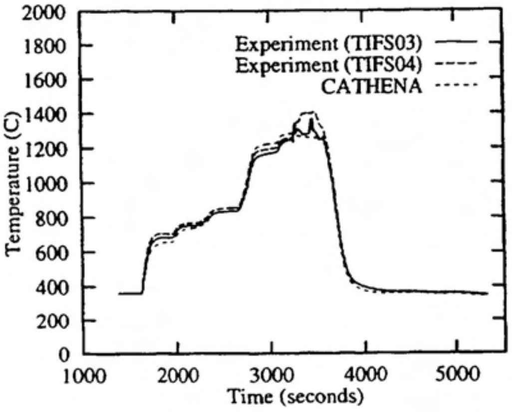

Figure 6: Alumina Temperatures-Mid Bearing Pad (Whiteshell Heater Test 2, Simulation 8)

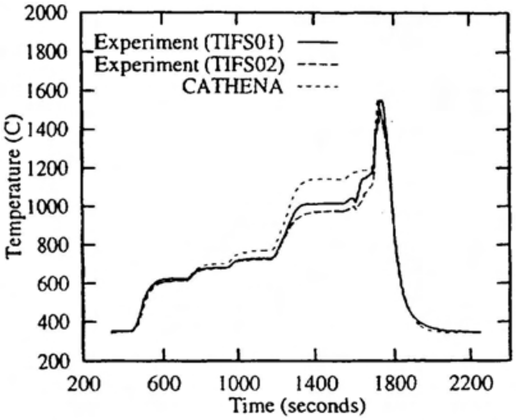

Figure 7: Alumina Temperatures-Top Bearing Pad (Whiteshell Heater Test 3, Simulation 9)

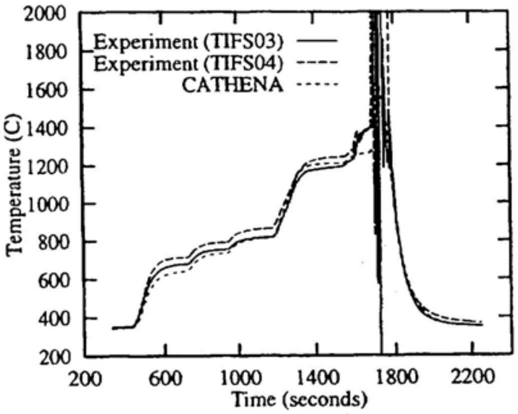

Figure 8: Alumina Temperatures-Mid Bearing Pad (Whiteshell Heater Test 3, Simulation 9)

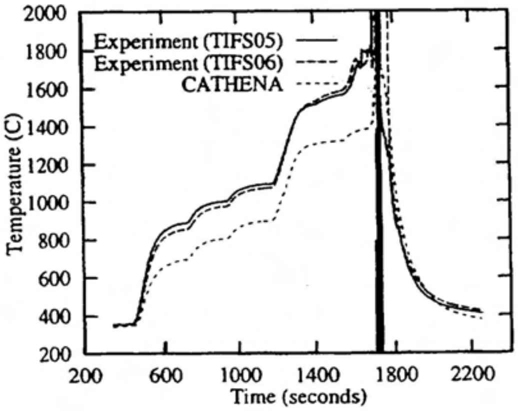

Figure 9: Alumina Temperatures-Bottom Bearing Pad (Whiteshell Heater Test 3, Simulation 9)

The outlet coolant temperatures for both tests, shown in Figures 10 and 11, are underpredicted; however the agreement is slightly better for Test 2. This lack of agreement suggests that the downstream coolant thermocouples may have been heated by line-of-sight radiative losses from the heater and/or by the presence of axial conduction at the bottom of the heater.

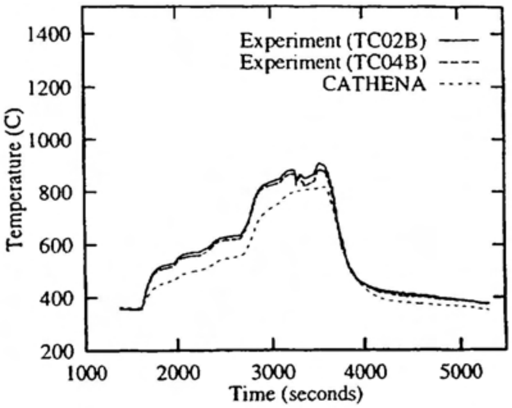

Figure 10: Outlet Coolant Temperatures (Whiteshell Heater Test 2, Simulation 8)

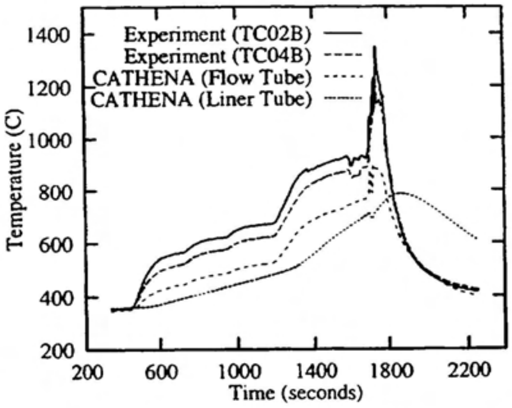

Figure 11: Outlet Coolant Temperatures (Whiteshell Heater Test 3, Simulation 9)

For both tests, the NILCRA liner temperature profiles are generally overpredicted at high temperatures (see Figures 12 and 13).

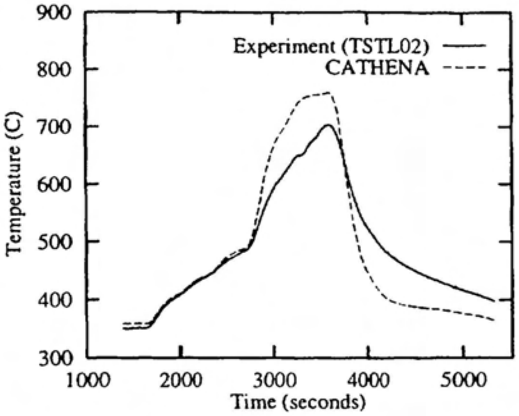

Figure 12: Nilcra Liner Temperatures-Mid Bearing Pad (Whiteshell Heater Test 2, Simulation 8)

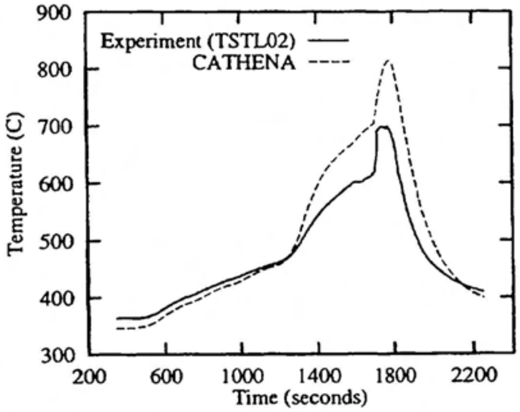

Figure 13: Nilcra Liner Temperatures-Mid Bearing Pad (Whiteshell Heater Test 3, Simulation 9)

Figures 14, 15 and 16 show comparisons of measured and calculated sheath temperatures. For Test 2, the sheath temperatures at the thermocouple sites were well predicted. However, the sheath temperature at the pyrometer site was overpredicted (indicating that the pyrometer may have been focused on part of the clamp during this test), as shown in Figure 14. For Test 3, as a result of the modifications to the heat conductances (in Simulations 7 and 9), the sheath temperatures at the thermocouple sites increased by approximately 100°C. As a result, the sheath thermocouple and pyrometer temperatures were well predicted.

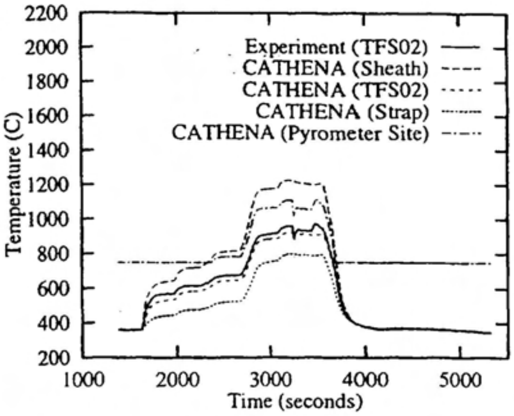

Figure 14: Sheath Temperatures-Mid Bearing Pad (Whiteshell Heater Test 2, Simulation 8)

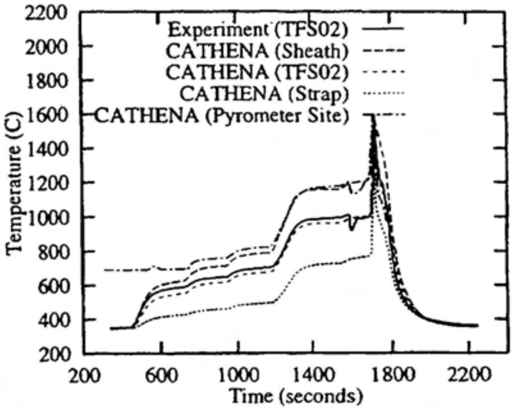

Figure 15: Sheath Temperatures-Mid Bearing Pad (Whiteshell Heater Test 3, Simulation 9)

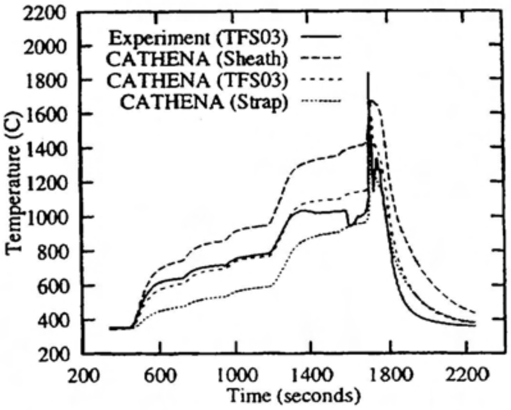

Figure 16: Sheath Temperatures-Bottom Bearing Pad (Whiteshell Heater Test 3, Simulation 9)

Figures 15 and 16 show the mid-plane and lower bearing pad sheath temperatures in Test 3. These figures show that good agreement was obtained, except around the time of element failure (at ~1600 s), when the changes in the internal heater temperature were not captured. Interestingly, the measured sheath temperature at location TFS03 (bottom bearing pad) stabilized in the period from ~1300 s to 1600 s, which was not predicted. This is believed to be indicative of an incipient failure (i.e., a decrease in contact) of the clamp at the lower bearing pad.

5.0 CONCLUSIONS

CATHENA simulations and analysis of Whiteshell heater Test 2 and Test 3 are presented in this paper. The simulations were used to gain an understanding of the effects of the thermocouple-to-sheath, thermocouple-to-clamp and clamp-to-sheath heat transfer and inlet mass flow rate on the predicted sheath temperatures. The best agreements between the measured and predicted sheath temperatures were obtained for the conditions specified in Table 1 for Simulation 8 of Test 2, and as specified in Table 2 for Simulation 9 of Test 3.

Of these two tests and simulations, the one believed to be most applicable for modelling the upcoming BTF-105B test is the Test 3 Simulation 9 case. (The reasons for choosing this test and simulation are that a helium purge flow was not used when this test was performed, the pyrometry data is believed to be more trustworthy than in Test 2, and this test went to higher sheath temperatures than did Test 2.) As a result, it has been decided to use the clamp and thermocouple models and the wall model conductances as chosen for the Test 3 Simulation 9 run in future CATHENA simulations of BTF tests.

An important outcome of this work was that good agreement could be obtained with the test data by using fixed values of contact conductance (i.e., it has been determined that the contact condition does not change significantly during heating). Given these results, the modeling developed in this paper will be useful in calculating the internal temperature distribution within BTF fuel elements where measured sheath temperatures and fuel power information are known.

ACKNOWLEDGEMENTS

BTF tests (and instrument development for these tests) are jointly sponsored by AECL and the Canadian nuclear utilities (Ontario Hydro, Hydro Quebec and New Brunswick Power) through the cost-shared COG (CANDU Owners Group) program. The authors wish to thank COG for supporting the BTF program and for funding these particular instrument development tests. The work of R.W. Tiede and other members of the Containment Analysis Branch at Whiteshell Laboratories in performing the experiments described in this paper is also gratefully acknowledged.

REFERENCES

R.W. Tiede and R.G. Moyer, "Re: Strap Test #1 for BTF-105 Cladding Surface Instrumentation," Unpublished Proprietary Document, Atomic Energy of Canada Limited, 1994 June.

R.W. Tiede and R.G. Moyer to J.W. DeVaal, "Re: Strap Tests 2 & 3 for BTF-105 Cladding Surface Instrumentation," Unpublished Proprietary Document, Atomic Energy of Canada Limited, 1995 March.

B.N. Hanna, "CATHENA: A Thermalhydraulic Code for CANDU Analysis," Nuclear Engineering and Design, NED-97-549, Accepted for Publication.

J.W. DeVaal, J.D. Irish, L.W. Dickson, S.T. Craig, M.G. Jonckheere and L.R. Bourque, "Preliminary Results of the BTF-105A Test: An In-Reactor Instrument Development and Fuel Behaviour Test", to be presented at the 5th International Conference on CANDU Fuel, Toronto, Ont., Sept. 21-24, 1997.

Table 1: Summary of Boundary Conditions for the Whiteshell Heater Test 2 Simulations

	General	Inlet Mass Flow Rate g/s	Liner Tube Mass Flow Rate g/s	Emissivity of NILCRA Liner	Heat Contact Conduct. KW/m^2°C		Area of solid-solid contact m^2		
					T-Sh	T-St	T-Sh	T-St	St-Sh
Simulation 1		5.0	0.0	0.85	2.0	2.0	4.7E-08	9.4E-09	1.4E-07
Simulation 2		4.1	0.0	0.85	2.0	2.0	4.7E-08	9.4E-09	1.4E-07
Simulation 3		4.1	0.0	0.4	4.0	2.0	4.7E-08	9.4E-09	1.4E-07
Simulation 4	Removed radiation	4.1	0.0	0.4	4.0	2.0	4.7E-08	9.4E-09	1.4E-07
Simulation 5	Replaced radiation	2.0	0.0	0.4	4.0	2.0	4.7E-08	9.4E-09	1.4E-07
Simulation 6		2.1	2.0	0.4	8.0	2.0	4.7E-08	9.4E-09	1.4E-07
Simulation 7		3.0	1.1	0.4	8.0	2.0	9.4E-08	9.4E-09	1.4E-07
Simulation 8		3.0	1.1	0.4	8.0	1.0	9.4E-08	9.4E-09	1.4E-07
Simulation 9		3.0	1.1	0.4	16.0	4.0	9.4E-08	9.4E-09	1.4E-07

Note T-Sh is the contact between the thermocouple and the sheath
T-St is the contact between the thermocouple and the strap (or clamp)
St-Sh is the contact between the strap (or clamp) and the sheath

Table 2: Summary of Boundary Conditions for the Whiteshell Heater Test 3 Simulations

	General	Inlet Mass Flow Rate g/s	Liner Tube Mass Flow Rate g/s	Emissivity of NILCRA Liner	Heat Contact Conduct. KW/m^2°C		Area of solid-solid contact m^2		
					T-Sh	T-St	T-Sh	T-St	St-Sh
Simulation 1		5.0	0.0	0.85	2.0	2.0	4.7E-08	9.4E-09	1.4E-07
Simulation 2		4.1	0.0	0.85	2.0	2.0	4.7E-08	9.4E-09	1.4E-07
Simulation 3		4.1	0.0	0.4	4.0	2.0	4.7E-08	9.4E-09	1.4E-07
Simulation 4	Removed radiation	4.1	0.0	0.4	4.0	2.0	4.7E-08	9.4E-09	1.4E-07
Simulation 5	Replaced radiation	2.0	0.0	0.4	4.0	2.0	4.7E-08	9.4E-09	1.4E-07
Simulation 6		2.1	2.0	0.4	8.0	2.0	4.7E-08	9.4E-09	1.4E-07
Simulation 7		3.0	1.1	0.4	8.0	2.0	9.4E-08	9.4E-09	1.4E-07
Simulation 8		3.0	1.1	0.4	8.0	1.0	9.4E-08	9.4E-09	1.4E-07
Simulation 9	Stalled the flows between 1700s and 1718.5s	3.0	1.1	0.4	16.0	4.0	9.4E-08	9.4E-09	1.4E-07

Note T-Sh is the contact between the thermocouple and the sheath
T-St is the contact between the thermocouple and the strap (or clamp)
St-Sh is the contact between the strap (or clamp) and the sheath