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August 5, 1994

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Project 679

Document Control Desk
U.S. Nuclear Regulatory Commission
Mail Station P1-137
Washington, DC 20555

Subject: Response to Request for Additional Material - CANDU 3 dated June 30, 1994

Reference: (1) AECLT letter (V. Snell) to NRC (D. Scaletti) dated July 19, 1994, ""Request for Additional Material - CANDU 3" dated June 30, 1994.

Gentlemen:

In reference 1 we supplied thirteen of the requested fifteen documents for your contract with Science and Engineering Associates, Inc.

Of the two remaining on your list we find that we must substitute the following documents.

Our best reference for the "Cold-Worked Zirconium - 2.5% Niobium Extended and Drawn Pressure Tubes" is the following:

1) CAN/CSA N285.6.1-88 "Seamless Zirconium Alloy Tubing for Fuel Channels."

This is part of the CAN/CSA - N285.6 Series 88, Material Standards for Reactor Components for CANDU Nuclear Power Plants, March 1988. This is not included since you already have the Canadian Standards.

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CANDU in the USA
A subsidiary of Atomic Energy of Canada

For the second document on your list (item no. 14) we have substituted the following more recent document.

2) Gillespie G. E. and R. G. Moyer "An Experimental Investigation of the Creep Sag of Pressure Tubes Under LOCA Conditions," Proceedings of the 5th Annual Canadian Nuclear Society Conference, Saskatoon, SK, 1984.

If there are any questions concerning the content of this letter, please contact me, or Louis Rib at (301)417-0047.

Sincerely,

Louis N. Rib
for Victor G. Snell, Director
CANDU 3U Safety and Licensing

Enclosures: As stated

cc: D. Scaletti w/ attachment

Proceedings from the 5th Annual Canadian Nuclear Society Conference, Saskatoon, SK, 1984

7051

AN EXPERIMENTAL INVESTIGATION OF THE CREEP SAG OF PRESSURE TUBES UNDER LOCA CONDITIONS

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ABSTRACT

During a postulated loss-of-coolant accident with impaired emergency cooling, the heat generated in the fuel will be transferred to the moderator. In the process, the pressure tube will heat and may deform into contact with its calandria tube. This paper describes experiments that were performed to investigate the sagging deformation of a pressure tube when a transient temperature is applied. The pressure-tube deflection and temperature were monitored. The contact between the pressure tube and calandria tube was observed, and the resulting type of boiling on the calandria-tube surface was noted, since this controls the rate of heat removal from the fuel channel. The experimental results were compared with computer predictions of the deformation. The computer models predicted the behaviour well.

INTRODUCTION

An important design feature of the CANDU-PHW reactor is that each horizontal fuel channel is surrounded by cool heavy-water moderator that can act as a heat sink during postulated loss-of-coolant accidents (LOCAs) with impaired emergency cooling. Under these conditions, the heat generated in the fuel is transferred mainly by radiation to the moderator. Because radiation is the principal mode of heat transfer, high fuel and pressure tube temperatures result.

At these elevated temperatures, the pressure tube may deform into contact with the surrounding calandria tube. If the internal pressure were high, the principal deflection of the pressure tube would be radially outwards (ballooning), and contact would occur completely around the circumference. If the internal pressure were low, the principal deflection would be downwards (sag) and contact would occur in a strip along the bottom. For intermediate pressure, both forms of deformation would occur; the sag and ballooning would cause initial contact on the bottom, and then the pressure would balloon the pressure tube into contact around the complete circumference.

The initial contact between the hot pressure tube and the cold calandria tube would result in a "spike" in the heat flux to the moderator. The magnitude of the spike would depend on the pressure-tube temperature at contact and the contact conductance between the pressure and calandria tubes. The magnitude of the spike would determine the boiling regime on the calandria-tube outer surface (either film boiling or nucleate boiling) and, thus, the fuel-channel temperatures.

A previous experimental investigation of heat transfer from the fuel channel to the moderator at high internal pressure [1,2] showed that the occurrence of film boiling on the calandria-tube surface could be accurately predicted for given pressure-tube heating rates and surrounding water temperatures. It also showed (i) that film boiling would be unlikely to occur at the moderator subcoolings expected in a CANDU-PHW reactor, (ii) that the heat transfer to the moderator would be sufficient to remove the heat generated in the fuel channels, and (iii) that the calandria tubes would not deform.

This paper describes two series of experiments performed to investigate fuel-channel behaviour when the fuel channel contains weights equal to the weight of the fuel, and has a temperature transient imposed on it similar to that expected in a LOCA with impaired emergency cooling. The results are compared with predictions made using the computer program CREEPSAG.

The first series was performed to determine the deflection rate of the pressure tube when subjected to a temperature ramp. The deflection of the pressure tube with time is compared with CREEPSAG predictions. The second series was performed to determine the initial contact temperature, investigate the development of the contact area, and determine the heat transfer to the surrounding water when sagging contact occurs.

THEORY

Fuel channel deformation is analysed using two separate one-dimensional computer codes: TRAN II [3] for the transverse creep, and CREEPSAG for the sag calculations. TRAN II has been described and shown to predict correctly the radial deflection of a pressure tube with an applied temperature ramp. The mechanisms and driving forces that act during longitudinal and transverse creep are very different. For bending, the stresses are low (less than 1 MPa) and the strains at which contact occurs are small (less than 1%). The small longitudinal strains required for sag are caused by the $\alpha \rightarrow \beta$ phase transformation under stress, whereas the large tangential strains (18%) required for circumferential contact are caused by grain-boundary sliding and dislocation creep. Since these two deformation mechanisms are independent, the resulting deflections can be considered separately and then added. The only coupling required is an updating of the moment of inertia caused by circumferential strain.

To analyse bending deflections of the pressure tube, CREEPSAG uses the idealization shown in Figure 1. The pressure and calandria tubes are assumed to be long thin beams with fixed ends (at their respective rolled joints) and interactive forces between them at the garter springs. These forces change with time, as the pressure tube deforms and supports less of the weight. In analysing the deflections of the tubes, the assumptions of simple beam theory were used. When the load is first applied, the stresses and strains are elastic and are described by

$$\kappa_o = \frac{M(x,t)}{EI} \; / \; t=o \qquad (1)$$

where κ_o is the initial curvature of the tube, x is the coordinate along the pressure tube, M is the bending moment, E is the elastic modulus, and I is the moment of inertia.

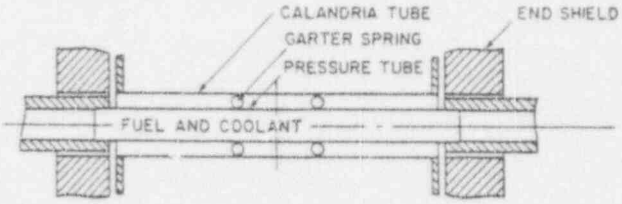

FIGURE 1: SCHEMATIC OF A FUEL CHANNEL

The plastic strain is calculated assuming the deformation is time dependent (creep). The longitudinal creep rate used in the analysis was determined experimentally by Shewfelt and Lyall [4], who expressed the creep rate in the following form

$$\dot{\varepsilon} = A\theta(t,T) \exp\left(-\frac{Q}{T}\right)\sigma \qquad (2)$$

where ε is the longitudinal strain, A is the creep correlation constant, θ is a hardening coefficient, t is time, T is temperature, Q is the creep activation energy, and σ is the longitudinal stress.

For convenience Equation (2) can be written as

$$\dot{\varepsilon} = B(x,t)\sigma \qquad (3)$$

Since plane sections remain plane

$$\frac{\varepsilon_{by}}{\varepsilon_{bc}} = \frac{y}{c}$$

where ε_{by} is the bending strain at y, ε_{bc} is the bending strain at c, y is the distance from the neutral axis, and c is the distance from the neutral axis to the extreme fiber of the tube. Differentiating this equation with respect to time and substituting Equation (3) yields

$$\frac{\sigma_{by}}{\sigma_{bc}} = \left(\frac{y}{c}\right) \qquad (4)$$

where σ_{by} is the bending stress at y and σ_{bc} is the bending stress at c. The rate of change of curvature (κ) of a tube due to creep is

$$\dot{\kappa}_c(x,t) = \frac{\dot{\varepsilon}_{bc}}{c} \qquad (5)$$

where x is the axial distance along the member, and t is time. The quantity $\dot{\varepsilon}_{bc}$ is given by Equation (3) and

$$\dot{\kappa}_c(x,t) = \frac{B(x,t)\sigma_{bc}}{c} \qquad (6)$$

The relationship between stress and moment at any given cross section is

$$M = \int_A \sigma_{by} y dA \qquad (7)$$

where M is the bending moment, and A is the area of the cross section.

Substituting Equation (4) into (7) yields

$$M = \frac{\sigma_{bc} I}{c} \qquad (8)$$

From Equations (6) and (8)

$$\dot{\kappa}_c(x,t) = B(x,t)\left(\frac{M(x,t)}{I}\right)$$

For a quasi-straight tube

$$\kappa(x,t) = \frac{\delta^2 y}{\delta x^2}$$

The deflection of the tube is found by adding the elastic curvature to the inelastic curvature, and then by integrating the resulting curvature of the tube twice, giving

$$Y(x,t) = \int_o^x \int_o^x \left\{\frac{M(x,t)}{EI} + \int_o^t \frac{B(x,t)\, M(x,t)}{I}\, dt\right\} dxdx \qquad (9)$$

The CREEPSAG program solves for the elastic support forces at the garter springs and ends of the tube, and numerically integrates Equation (9). Constant temperature is used during each time step in the integration, with the temperature increased upon completion of each time step.

EXPERIMENTS

Series One

The same experimental apparatus design was used for all experiments. Figure 2 is a schematic. It consisted of a 3-metre long pressure-tube segment with rolled joints at both ends. The pressure tube contained a ring of 26 equally spaced heating elements (consisting of tantalum ribbon, alumina insulators and zirconium sheathing), an intermediate ring of insulating fire brick, and cylindrical tungsten weights at the center. The combination of weights, fire brick, and heating elements had the same weight per meter as CANDU-PHWR fuel bundles. The pressure tube was surrounded by a 30-mm air gap and then by solid insulation. In three tests, a garter spring, supported by springs with the stiffness of a calandria tube, was added to the apparatus. Thermocouples were spot-welded to the surface of the pressure tube to record the temperature. Quartz push rods, connected to the core of LVDTs (linearly varying differential transformers), contacted the pressure tube to record deflections.

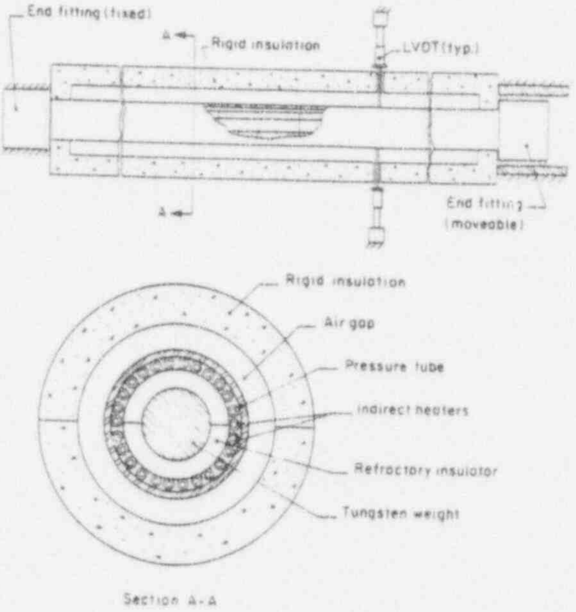

FIGURE 2: TEST SECTION SCHEMATIC

The experiments were performed by heating the pressure tube to 350°C and holding at this temperature for 10 minutes to heat the internal weights. The power was then varied to obtain a linear temperature ramp at the center plane of the pressure tube.

Table 1 lists the experiments performed. Temperatures were measured at the top, bottom and sides of the pressure tube at 5 axial locations. There was a steep temperature gradient near each rolled joint, but the temperature was nearly uniform over the central 2.6 m, except for experiment 1.6, where an axial temperature gradient was imposed.

TABLE 1: TEST SERIES-ONE CONDITIONS

Expt	Temp. Ramp °C/s	Garter Springs		LVDT Loc. m	Temperature °C	
		No.	Location m		Measured	Predicted
1.1	3.0	0	-	1.5	820[1]	800
1.2	2.7	0	-	1.5	810	830
1.3	3.3	1	1.5	1.0	890[2]	880
1.4	3.1	1	1.5	1.0	820[2]	940
1.5	2.8	1	1.5	1.0	860[2]	890
1.6	3.0[3]	0	-	1.5	890[1]	870

[1] Deflection is 20 mm

[2] Deflection is 10 mm

[3] Varied from 2.8 to 3.4 along the tube

The experiments were simulated using the computer code CREEPSAG. Table 1 shows that when garter springs were not used, the temperatures at a given deflection were well predicted. Figure 3 compares the measured central deflections of experiment 1.2 with the predicted deflections. The figure shows that the predicted deflection is accurate at large deflections. The discrepancies in the initial deflections are caused by the creep law used. In the experiments used to determine the correlation, very little strain was measured below 700°C [4].

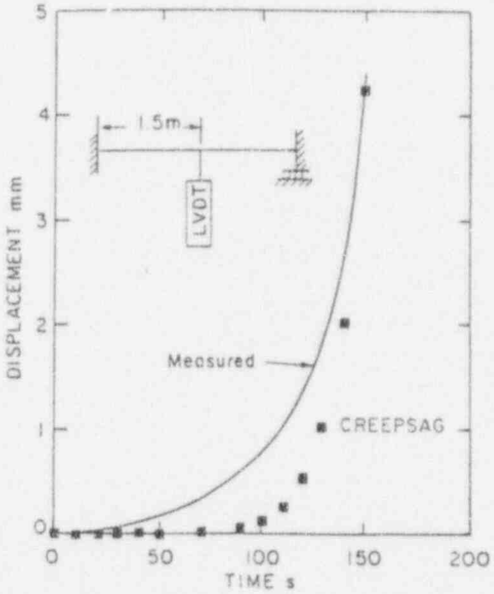

FIGURE 3: DEFLECTIONS DURING EXPERIMENT 1.2

Figure 4 compares the deflections measured for experiment 1.4 with CREEPSAG predictions. The actual deflections are more rapid than predicted, since the pressure tube deformed locally at the garter spring, and the garter spring also deformed.

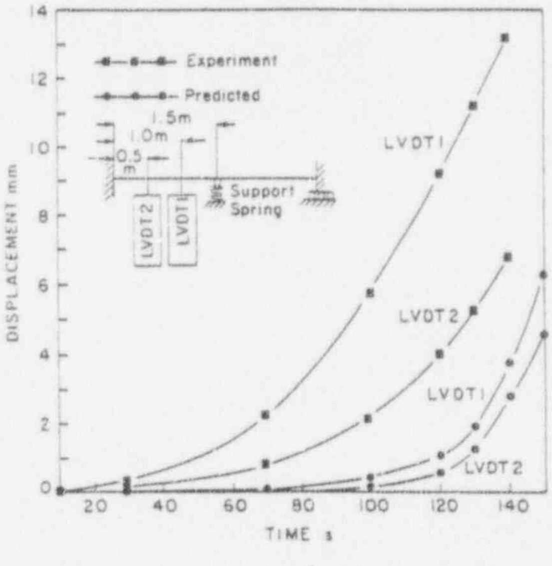

FIGURE 4: DEFLECTIONS DURING EXPERIMENT 1.4

Table 2 compares the deflections measured during experiment 1.6 with those predicted using CREEPSAG. The deflections were taken at 212 seconds, when the maximum deflection would cause the two tubes to be close to contact. The maximum deflection is larger than the distance between the tubes, since the calandria tube will deflect elastically. This comparison demonstrates that CREEPSAG models well the deflection of a tube with an axial temperature variation.

TABLE 2: DEFLECTIONS DURING EXPERIMENT 1.6

LVDT Axial Location m	Temperature °C	Deflection mm	
		Measured	Predicted
0.55	870	8.3	8.8
1.04	830	17.0	22.0
1.44	780	15.7	17.2
1.93	670	10.0	8.3
2.43	640	4.3	2.6

Series Two

For this test series, the outer insulation shown in Figure 2 was removed and the pressure tube assembly was placed inside a calandria tube, which was surrounded by water, as shown in Figure 5. Thermocouples were not spot-welded to the bottom of the pressure tube, since they would disturb any contact with the calandria tube. In the series-one experiments, the azimuthal temperature gradients were small, so for series two we assumed that the bottom temperature was equal to the side temperature. The development of the contact between the tubes was monitored by LVDT probes, which were attached to the calandria tube in a line along the bottom and inserted about 01.1 mm inside the calandria tube. When the pessure tube was close to the calandria tube, it contacted the probes. When the probes stopped moving, contact was assumed.

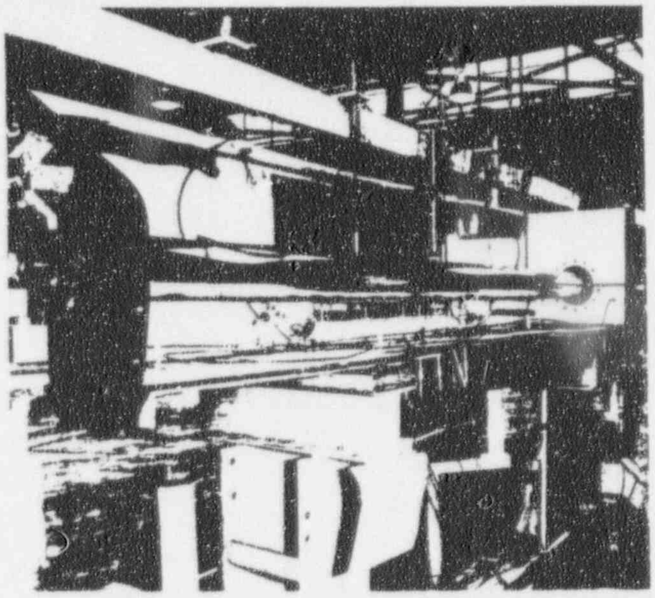

FIGURE 5: APPARATUS USED IN SERIES TWO EXPERIMENTS

Table 3 lists the experiments performed, and the measured and predicted pressure tube temperatures at initial contact. Experiments 2.1 and 2.2 did not involve garter springs, and the contact temperatures were well predicted. In experiments 2.3 and 2.4 the garter springs buckled, and there were large local deformations at the garter spring (similar to those in series one). The resulting total displacement at each garter spring was 3.64 mm and 3.05 mm in experiment 2.3, and 3.97 mm and 4.02 mm in experiment 2.4. If the tubes are concentric, the gas gap is 8.3 mm; thus the localized deflections at the garter springs were up to half the distance between the tubes. The timing of the local deflection is not known and may have occurred after the initial contact. Thus, it should not be considered, in analysing contact, unless a more detailed analysis, which models the local deformation, is performed.

TABLE 3: TEST SERIES-TWO CONDITIONS

Expt.	Temp. Ramp °C/s	Garter Springs		Contact Temp. °C		Water Temp. °C
		No.	Spacing m	Meas.	Pred.	
2.1	2.7	0	-	780	770	-
2.2	3.9	0	-	700	770	90
2.3	2.9	2	1.2	810	850	91
2.4	3.8	2	1.0	870	920	93
2.5*	2.4	2	1.0	940	900	93

* 25-mm long solid spacers used to prevent garter spring crushing

Figure 6 shows the movement of the short LVDT probes used to indicate contact in experiment 2.2. When the maximum deflection is reached, contact is assumed. Table 4 lists the time at which the LVDTs indicated contact. In the experiments with garter springs, the development of the line of contact in the central 600 mm was quite rapid (within about 10 s). The pressure tube did not contact the calandria tube within 100 mm of the garter springs in these experiments. When 25-mm spacers were used instead of garter springs (experiment 2.5), it took three times as long for the contact to develop. This difference in laydown time may be caused by the local deformation at the garter springs, which reduces the curvature of the pressure tube required for initial contact.

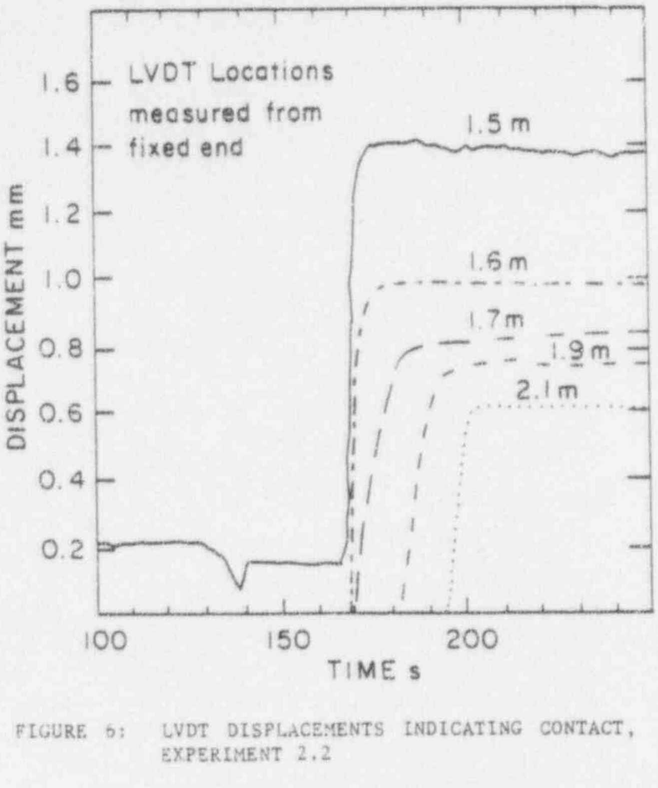

FIGURE 6: LVDT DISPLACEMENTS INDICATING CONTACT, EXPERIMENT 2.2

In performing an analysis of the heat transfer to the moderator after contact, the area of the contact patch is required to calculate the head flow. To measure the width of contact, two LVDT's were mounted at an angle of 15° from the bottom of the tube at the center (1.5 m). As seen from Table 4, these indicated contact, but contact did not occur at the same time as at the bottom. Our only other indication of contact width was the width of oxide patches formed during film boiling on the surface of the calandria tube. To obtain this indication, the temperature of the water surrounding the calandria tubes was set much high than in an operating reactor. With this low subcooling, some patches of film boiling occurred for short times. The time that the film boiling patches existed was short since the heat in the film boiling area was conducted to adjacent areas on the calandria tube with nucleate boiling on the surface. The maximum width of a film patch was 20 mm, which is equivalent to 20°. This is less than the 30° included angle of the LVDTs.

TABLE 4: LAYDOWN IN TEST SERIES-TWO

Location m	Time from Initial Contact, s Experiment Number				
	2.1	2.2	2.3	2.4	2.5
0.9	6	30	G.S.[2]	-	-
1.0	-[1]	-	-	G.S.	G.S.
1.1	-	17	*[3]	*	*
1.2	0[4]	-	52	-	-
1.3	-	6	-	14	32
1.4	0	5	10	4	2
1.5	0	0	6	0	0
1.6	0	1	2	8	14
1.7	-	10	0	14	36
1.8	0	-	10	-	-
1.9	-	20	70	*	*
2.0	-	-	*	G.S.	G.S.
2.1	-	-	G.S.	-	-
1.5+15°	0	9	188	16	2
1.5-15°	0	3	*	0	2

[1] Indicates no LVUT at location
[2] G.S. is garter spring
[3] * indicates contact did not occur
[4] 0 indicates initial contact

CONCLUSIONS

The pressure tube will deform and contact its calandria tube when heated. Local deflection of the pressure tube at the garter springs causes the contact to occur earlier than predicted using beam analysis only. Thus, the computer code CREEPSAG overestimates the contact time and temperature. This results in an overprediction of the heat stored in the pressure tube at the time of contact. This is because the stored heat controls the initiation of film boiling and thus the rate of heat removal from the pressure tube.

The contact patch between garter springs was 800 mm long and of the order of 20 to 30 mm wide; i.e. ~ 6% of the calandria tube area between the garter springs. Thus, when there is no internal pressure most of the heat to the moderator is transferred through the gas gap by radiation and conduction.

The film boiling that occurred, quenched in all cases. During the experiments the water temperature was hotter than that used in operating reactors. This increased water temperature makes film boiling more likely and quenching of the film patches slower. The film boiling patches that did occur all quenched while the power was on. Since the film boiling patches quenched in these experiments under conditions more severe than expected during a LOCA, it can be concluded that sagging contact will not cause failure of the calandria tube.

ACKNOWLEDGEMENT

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The authors wish to acknowledge the technical assistance given by G.H. Archinoff, P.D. Thompson, and E. Kohn.

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[2] G.E. Gillespie, R.G. Moyer and P.D. Thompson, "Moderator Boiling on the External Surface of a Calandria Tube in a CANDU Reactor During a Loss-of-Coolant Accident", Proceedings of the International Meeting on Thermal Nuclear Reactor Safety, Chicago, Illinois, 1982 August. Nuclear Regulatory Commission, NUREG/CP-0027, 1983, pp. 1523-1533.

[3] R.S.W. Shewfelt, D.P. Godin and L.W. Lyall, "Verification of a High- Temperature Transverse Creep Model for Zr-2.5 wt%Nb Pressure Tubes", Atomic Energy of Canada Limited Report, AECL-7813, 1984.

[4] R.S.W. Shewfelt and L.W. Lyall, "A High-Temperature Longitudinal Strain Rate Equation for Zr-2.5 wt% Nb Pressure Tubes," to be published.