AMPTRACT: An Algebraic Model for Computing Pressure Tube Circumferential and Steam Temperature Transients under Stratified Channel Coolant Conditions

AMPTRACT: Modèle algébrique pour calculer les transitoires circonférentiels des tubes de force et de température de vapeur dans des conditions d'écoulement stratifié du caloporteur

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ERRATA SHEET

page 8, section 4.8, last paragraph should read:

For small convection to steam and radiation to calandria tube, the limiting pressure tube circumferential temperature may be expanded in powers of a small parameter to show that convection and radiation tend to flatten the parabolic temperature profile in eq. (15).

However, in the limit $t \longrightarrow \infty$, radiation cannot be ignored because the temperatures are generally high. Thus, the temperature distribution around the pressure tube circumference can never be strictly parabolic.

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Résumé

Dans un groupe de scénarios d'accidents hypothétiques d'un réacteur CANDU, on prévoit que certains canaux de combustible horizontaux connaîtront des périodes d'écoulement stratifié. À ce moment-là, les éléments combustibles supérieurs et une partie du tube de force sont soumis à une vapeur surchauffée et à un échauffement. L'écoulement stratifié du caloporteur peut entraîner un gradient de température circonférentielle autour du tube de force. À une température et une pression de canal suffisantes, le gradient température peut donner une déformation non uniforme (et localisée) du tube de force.

Par conséquent, il est nécessaire de déterminer la distribution circonférentielle de température du tube de force afin de calculer la déformation du tube de force et l'intégrité lors d'un écoulement stratifié. Le présent document présente un modèle algébrique, appelé AMPTRACT (Algebraic Model for Pressure Tube TRAnsient Circumferential Temperature), mis au point pour donner la distribution de température transitoire dans une forme fermée.

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L'AMPTRACT modélise les modes de transfert de chaleur suivants : l'irradiation provenant des extrémités au tube de force et de celui-ci au tube de calandre, la convection entre les éléments combustibles et le tube de force et la vapeur surchauffée, et la conduction circonférentielle entre la partie extérieure et la partie submergée du tube de force. On a recours à une méthode itérative pour résoudre les équations de masse et d'énergie dans une forme fermée pour les distributions de température de vapeur axiale et du transitoire de la gaine du combustible. On résout alors l'équation de conduction à une dimension pour obtenir la distribution de température du transitoire circonférentiel du tube de force dans un développement en série sinusoïdal.

Avec de longues périodes et en l'absence de convection et de rayonnement sur le tube de calandre, la distribution de température prévue du tube de force se réduit de la même façon en un profil parabolique. Dans ce cas on ne peut toutefois pas ignorer les rayonnements étant donné que les températures sont généralement élevées. La convection et les rayonnements tendent à aplatir la distribution parabolique.

On obtient une certaine conformité entre les distributions de température du tube de force et de pression prévues par l'AMPTRACT et celles observées dans les essais d'échauffement des tubes de force réalisés par les laboratoires de l'Établissement de Recherche Nucléaire de Whiteshell et de Westinghouse Canada.

AMPTRACT: An Algebraic Model for Computing Pressure Tube Circumferential and Steam Tempererature Transients under Stratified Channel Coolant Conditions

by P. Gulshani and C.B. So

Abstract

In a number of postulated accident scenarios in a CANDU reactor, some of the horizontal fuel channels are predicted to experience periods of stratified flow. During this time, the upper fuel elements and part of the pressure tube become exposed to superheated steam and heat-up. The stratified channel coolant condition can lead to a circumferential temperature gradient around the pressure tube. At sufficiently high temperature and channel pressure, the temperature gradient may result in non-uniform (and localized) pressure tube strain.

To study pressure tube strain and integrity under stratified flow channel conditions, it is, therefore, necessary to determine the pressure tube circumferential temperature distribution. This paper presents an algebraic model, called AMPTRACT (Algebraic Model for Pressure Tube TRAnsient Circumferential Temperature), developed to give the transient temperature distribution in a closed form.

AMPTRACT models the following modes of heat transfer: radiation from the outermost elements to the pressure tube and from the pressure to calandria tube, convection between the fuel elements and the pressure tube and superheated steam, and circumferential conduction from the exposed to submerged part of the pressure tube. An iterative procedure is used to solve the mass and energy equations in closed form for axial steam and fuel-sheath transient temperature distributions. The one-dimensional conduction equation is then solved to obtain the pressure tube circumferential transient temperature distribution in a cosine series expansion.

In the limit of large times and in the absence of convection and radiation to the calandria tube, the predicted pressure tube temperature distribution reduces identically to a parabolic profile. In this limit, however, radiation cannot be ignored because the temperatures are generally high. Convection and radiation tend to flatten the parabolic distribution.

Reasonable agreement is obtained between steam and pressure tube temperature distributions predicted by AMPTRACT and those observed in the pressure tube heatup tests conducted in experimental facilities at Whiteshell Nuclear Research Establishment and at Westinghouse Canada.

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AMPTRACT: AN ALGEBRAIC MODEL FOR COMPUTING PRESSURE TUBE CIRCUMFERENTIAL AND STEAM TEMPERATURE TRANSIENTS UNDER STRATIFIED CHANNEL COOLANT CONDITIONS

by

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1. INTRODUCTION

The core of a CANDU reactor consists of a large number of horizontal pressure-tube fuel channels connected via feeders to common headers above the core. Each pressure tube contains 37-element fuel bundles and is enclosed by a concentric calandria tube. The annular gap between the pressure and calandria tubes is filled with gas. The calandria tubes are surrounded by heavy water moderator. The pressure tubes provide a pressure boundary between the high pressure primary heat transport system and the low pressure, relatively cold moderator system.

In a number of postulated accident scenarios, some of the fuel channels at decay power levels are predicted to experience periods of low flow. During this period, the coolant boils and stratifies, exposing the upper fuel elements and part of the pressure tube to superheated steam. The exposed fuel elements and the surrounding pressure tube then heat-up due to reduced fuel cooling. At sufficiently high temperature and channel coolant pressure, the pressure tube may strain radially into contact with the relatively cold calandria tube, providing a path for heat transfer to the moderator. However, stratified channel coolant conditions can lead to a circumferential temperature gradient around the pressure tube. The resulting non-uniform and localized strain needs to be predicted to assess the pressure tube integrity.

To predict the pressure tube strain, it is necessary to predict:

(i) the channel thermohydraulic condition (i.e., the channel water level transient, steam flow rate, convective heat transfer coefficient, channel pressure etc.) for a given accident scenario,

(ii) steam, fuel and pressure tube temperature distributions given the thermohydraulic conditions,

(iii) mechanical response, i.e., non-uniform strain, of the pressure tube and compare the strain with that set by a failure criterion.

The above three requirements, which were identified some time ago[1], are weakly coupled and are addressed separately. An experimentally verified model[2,3] giving requirement (iii) has been developed at WNRE (Whiteshell Nuclear Research Establishment). Requirement (i) can be obtained using the general purpose thermohydraulic one-dimensional two-fluid computer code CATHENA[4] developed at WNRE. Simple two-fluid models[5,6] have also been developed to give the requirement (i) in specific accident scenarios.

CATHENA also models requirement (ii). A recent computer code, called SMARTT[7] has also been developed by the Ontario Hydro to model requirement (ii). This paper presents an algebraic model, called AMPTRACT, developed to give the pressure tube transient circumferential temperature distribution in an algebraic form, i.e., it models requirement (ii). AMPTRACT also solves for the steam flow rate, convective heat transfer coefficient and transient axial steam and fuel-sheath temperature distribution in closed form. Thus, AMPTRACT is an integrated model incorporating both channel thermohydraulic and temperature calculations. AMPTRACT provides a simple, flexible and inexpensive tool for the study of the parametric dependence of pressure tube temperature distribution. This paper presents a comparison of AMPTRACT predictions with those of the SMARTT code and with the results of experiments performed recently at WNRE.

Section 2 of this paper describes briefly the WNRE channel heatup test facility and summarizes the results of two preliminary pressure tube heatup tests. In Section 2, the full-scale channel test facility at Westinghouse Canada is also briefly described. Section 3 presents an interpretation of the experimental results. Section 4 presents AMPTRACT assumptions, governing equations and their solutions. Limiting values of steam, sheath and pressure tube temperatures are also given in Section 4. A comparison of AMPTRACT predictions with those of SMARTT and with the results of WNRE tests is given in Section 5. Major conclusions and remarks are given in Section 6.

2. EXPERIMENTAL RESULTS

A series of four pressure tube circumferential temperature distribution experiments is being performed at WNRE. Two of these experiments have been completed. Preliminary results from these two tests are described below. A detailed description of the experiments and analysis of the results will be available when the series of experiments is completed[8].

The apparatus consisted of a 2.29 meter horizontal CANDU type channel (Figure 1). It was closed at one end ("inlet") and open to a vertical pipe (24.3 mm ID) at the other ("outlet"). In the channel, 36 indirect heaters were grouped into 3 different rings. These heaters together with a central tube formed a CANDU-type 37 element fuel bundle configuration. The linear heat capacity of a heater element is about six times smaller than that of a fuel element in a CANDU reactor fuel channel. The power distribution to the three rings of heaters are shown in Figure 2. Thermocouples were placed on the outside of the pressure tube to monitor its temperature distribution during the experiments. Their locations were different in the two tests (Figure 1). In the second test, thermocouples were also placed on the heater sheaths. The temperature of the fluid at the exit of the channel was also measured. The vertical pipe was connected to a surge tank so that the pressure in the channel could be kept relatively constant at 1 MPa during the experiment. The channel was immersed in a pool of water (23°C at 1 atm.) to simulate the moderator.

At the start of each test, the water in the pressure tube was heated slowly from room temperature. When the thermocouples at the top of the pressure tube registered saturation temperature (181°C), the power to the heaters was raised to a preset level (as shown in Figure 2). The experiment terminated when the heaters failed. In both tests the pressure tube was dry when this happened.

Figure 3 shows a typical circumferential temperature distribution measured around the outside of the pressure tube. Just before the power was raised, the temperature distribution varied from saturation at the top to subcooled at the bottom. The water inside the pressure tube should have a similar temperature distribution as the heat transfer across the pressure tube was low. As the power was increased, water boiled away gradually. The inside of the pressure tube became exposed to steam in succession from top to bottom. This is reflected in Figure 3 by the sequence of the sudden increase in temperature above saturation given by the thermocouple readings. The pressure tube strained as the temperature increased. When it came into contact with the calandria tube, heat transfer to the moderator water increased, and caused the pressure tube temperature to decrease.

The axial temperature gradients were relatively small compared to the circumferential temperature gradients. In general, the axial temperature distribution had a maximum in the middle of the channel.

Pressure tube circumferential temperature distribution was also measured some time ago in a series of standing start tests in the CWIT facility. This facility[5] has a header to channel to header configuration. The full-scale channel consists of a 6 m long pressure tube containing 37-element indirectly heated bundles. Thermocouples are placed around the pressure tube circumference and on the heater rods in two axial planes symmetrically on either side of the channel mid plane. The channel heat capacity is nearly equal to that of a CANDU reactor fuel channel. The result of one of these tests will be described in Section 5. The test procedure and the relevance of the tests to small loss of coolant accident with loss of Class IV power scenario in the CANDU reactor are described elsewhere[5].

3. INTERPRETATION OF WNRE EXPERIMENTAL RESULTS

In Figure 3 turnaround in some of the temperatures indicates pressure tube calandria tube contact. In a given ring and at a given time prior to contact with the calandria tube, the pressure tube temperature decreased from maximum at the top to the saturation temperature at the water level. Figure 3 shows that the upper parts of the pressure tube (i.e. upper thermocouples) are uncovered more rapidly than the lower parts. This indicates that the channel water level dropped relatively rapidly initially possibly due to the large volume of steam produced and the large axial steam flow which would pressurize the channel forcing some of the water out of the channel. With no makeup water to the channel, the level subsequently dropped gradually as the water boiled away uncovering in succession lower heater rods and lower parts of the pressure tube.

Figure 4 shows a typical steam temperature transient measured near channel outlet. Steam superheat of about 600°C or more was observed in spite of some heat loss to the surroundings near the channel outlet.

Figures 5 and 6 show the pressure tube circumferential temperatures at 300 and 400 seconds in rings 1 and 2 (Figure 1) in test 1. These temperature distributions are deduced from the measured temperatures like those in Figure 3. (Similar distributions were obtained in ring 3 and in test 2). Comparison of water level in Figures 5 and 6 shows that the water level axial profile was nearly flat possibly due to the short channel length (about 2.3 m) and, hence, small wall frictional pressure drop. Figures 5 and 6 show that the pressure tube (and heater rod sheath, not shown) temperature increased with distance from channel exit as expected since the steam flow rate and, hence, convective heat transfer coefficient (i.e., steam cooling) of the heater rods decreased. Temperatures in ring 3 (not shown) were, however, somewhat lower than those in ring 2 possibly due to heat losses at channel inlet.

The pressure tube in tests 1 and 2 was observed to strain radially into contact with the calandria tube as indicated by some of the temperature turnarounds in Figure 3. The top part of the pressure tube contacted the calandria tube first followed successively by the lower parts indicating non-uniform pressure tube strain due to temperature gradient around its circumference.

4. AMPTRACT: AN ALGEBRAIC MODEL OF PRESSURE TUBE TRANSIENT CIRCUMFERENTIAL TEMPERATURE

At each instant of time and in a given channel axial plane, AMPTRACT computes the steam temperature, the temperature of the exposed fuel elements in the outermost ring and the pressure tube circumferential temperature distribution for stratified channel coolant conditions. The model accounts for the most significant effects influencing the pressure tube temperature.

4.1 MODEL ASSUMPTIONS AND APPROXIMATIONS

AMPTRACT uses the following assumptions and approximations:

(i) At each instant of time and in a given axial cross-section, the exposed fuel elements are all assumed to be at the same temperature. This is a reasonable approximation for the range of temperature relevant to the study of non-uniform and localized pressure tube strain. (Inner elements eventually heatup to temperatures higher than those of the outer elements. However, this generally occurs at temperatures above that at which pressure-calandria tube contact is expected.)

(ii) The modes of heat transfer modelled are:

Conduction around the pressure tube circumference, radiation from the outermost (exposed) elements to the pressure tube and from the pressure to calandria tube, and convection between the fuel elements and the pressure tube and superheated steam. (Radiation from the calandria tube to pressure tube and from the pressure tube to the fuel elements is ignored because the calandria tube is relatively cold and peak pressure tube temperatures of interest are significantly lower than those of the fuel elements. Consistent with (i) above, radiation exchange among the fuel elements is ignored.)

(iii) The fuel element surfaces are considered black.

(iv) In calculating the total radiation from the fuel elements to the pressure tube, the number of outermost fuel elements is increased from the actual number to the number that would exist on the outermost ring if the elements were touching. The view factor from an outermost element to the pressure tube is taken to be 0.5.

(v) Radiation exchange between the pressure and calandria tube is calculated assuming isothermal, gray and diffuse surfaces.

(vi) Radiant energy is approximated by an expression linear in temperature.

(vii) Axial and radial conduction in the fuel element and pressure tube are ignored because of expected small axial temperature gradient and thin pressure tube. Nevertheless, the fuel and pressure tube temperatures vary with the axial distance along the channel because the steam temperature varies with this distance.

(viii) The pressure tube geometry (i.e. radius and thickness) and properties (density, specific heat and thermal conductivity) are assumed constant during heatup and evaluated at a representative temperature.

(ix) At each instant of time, the channel water level is assumed to have dropped rapidly to the level at that time. The rapid level drop from full channel occurs initially due to large volume of steam produced and the resulting channel pressurization which forces the water out of the channel.

In a reactor channel with sufficient inventory in the inlet feeder, the level would then remain essentially constant as the incoming water flow rate balances the steam generation rate. In the WNRE tests 1 and 2 described in Section 2, following the initial relative rapid drop, the water level dropped gradually as water boiled away because there was no makeup water to the channel. The gradual level drop causes different parts of the pressure tube circumference to uncover at different times and, hence, heatup for different durations. This effect increases the circumferential temperature gradient. For relatively long durations of heatup, this increase is negligible and AMPTRACT can be used to predict the temperature distribution in the tests. To improve the temperature distribution predicted by AMPTRACT for short durations in the tests, a given point on the pressure tube circumference is allowed to heatup only for the duration for which it was exposed.

(x) To compute the steam flow rate, steam superheat and convective steam cooling, an average channel void fraction and bulk boiling are assumed. The Heineman correlation[9] is used for the convective heat transfer coefficient. The average void fraction as well as the channel water level may be obtained from other models[5,6].

4.2 DERIVATION OF GOVERNING CONSERVATION EQUATIONS

With the assumption (vi), the pressure tube circumferential temperature is given by the following one-dimensional conduction equation (refer to table of nomenclature):

$$\frac{\partial}{\partial t} T_p = \alpha^* \frac{\partial^2}{\partial \phi^2} T_p + Q_{fr} - Q_{pr} + K_p \cdot (T_s - T_p) \qquad (1)$$

where K_p is a known constant. From the approximations (i) - (iv), the rate of radiation incident on a unit axial and circumferential length of the pressure tube from the fuel elements is given by

$$Q_{fr} = b_p T_f^4 \qquad (2)$$

where b_p is a known constant.

From the approximation (ii), (v) and (vi), the rate of radiation from a unit axial and circumferential length of the pressure to calandria tube is evaluated in the usual manner to be:

$$Q_{pr} \equiv \ell^3 T_f^{\,3} \cdot T_p \qquad (3)$$

In eq. (3) small radiation contributions from the calandria tube and the submerged part of the pressure tube have been omitted. Q_{pr} in (3) has been linearized in T_p by setting $T_p = \ell T_f$ where ℓ is a known "constant".

With the approximation (vi), the fuel-sheath temperature is given by the energy equation:

$$\frac{\partial}{\partial t} T_f = q - b_f \cdot T_f^{\,4} - K_f \cdot (T_f - T_s) \qquad (4)$$

where b_f and K_f are known constants and the partial derivative indicates that axial distance z is held constant.

The steam temperature is given by the energy equation for the steam phase:

$$\frac{\partial}{\partial t} (A_s \rho_s \bar{h}_s) = - \frac{\partial}{\partial z} (W_s \bar{h}_s) + K_s \cdot \alpha_s (\bar{T}_f - \bar{T}_s) \qquad (5)$$

where K_s is a constant and

$$\bar{h}_s \equiv h_s - h_g \;,\; \bar{T}_f \equiv T_f - T_{SAT} \;,\; \bar{T}_s \equiv T_s - T_{SAT}$$

In (5) the equation for mass conservation:

$$\frac{\partial}{\partial t} (A_s \; \rho_s) = - \frac{\partial}{\partial z} W_s + M_s \qquad (6)$$

has been used.

4.3 SOLUTION FOR STEAM FLOW RATE

Eq. (6) is integrated assuming bulk boiling, uniform channel power (assumption (x)) and slow level transient (assumption (ix)) for which the time derivative of the level in eq. (6) may be neglected. Eq. (6) then gives

$$M_s = \frac{Q_c}{\ell_o h_{\ell g}} \alpha_\ell, \quad W_s = \frac{Q_c}{\ell_o h_{\ell g}} \bar{\alpha} \cdot Z, \quad \bar{\alpha} \equiv \frac{1}{z} \int_o^z \alpha_\ell \, dz \tag{7}$$

4.4 SOLUTION FOR ZEROTH ORDER SHEATH TEMPERATURE

Eqs. (4) and (5) are solved iteratively. To begin the calculation, a zeroth order steam temperature:

$$T_{so} = \frac{1}{2} \left(T_f + T_{SAT}\right) \tag{8}$$

is assumed. Expression (8) is substituted in (4), the resulting equation is linearized in T_f and integrated to obtain the zeroth order sheath temperature:

$$T_{fo} = A_1 + B_1 \cdot e^{-a_o t} \tag{9}$$

where a_o, A_1 and B_1 are constants and the initial condition $T_{fo} = T_{SAT}$ is used.

4.5 SOLUTION FOR STEAM TEMPERATURE

For slow level transients (assumption (ix)), the void fraction in eq. (5) is replaced by its mean value. With the zeroth order sheath temperature in eq. (9) used for T_f in eq. (5), eq. (5) is integrated by the method of characteristics to obtain:

$$T_s = T_{SAT} + (T_{s\infty} - T_{SAT}) \cdot (1 - e^{-a_o t}) \tag{10}$$

where the limiting (i.e. $t \to \infty$) steam temperature is

$$T_{s\infty} \equiv T_{SAT} + \frac{\lambda}{z} \left(\beta z - 1 + e^{-\beta z} \right) \tag{11}$$

and λ and β are constants. The initial and boundary conditions used are:

$$T_s\ (t = 0) = T_{SAT}, \qquad T_s\ (t,\ z = 0) = T_{SAT}$$

4.6 SOLUTION FOR FIRST ORDER SHEATH TEMPERATURE

The steam temperature in eq. (10) is substituted into eq. (4) and the resulting equation is solved to obtain:

$$T_f = A_2 + B_2\ (z) \cdot e^{-at} \tag{12}$$

where a and A_2 are constants and B_2 is a function of z.

4.7 SOLUTION FOR PRESSURE TUBE CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION

Eq. (1) is solved below for T_p with T_s and T_f as given in eqs. (10) and (12) respectively subject to the initial and boundary conditions:

$$T_p\ (t = 0,\ z) = T_{SAT}, \qquad T_p\ (t,\ \phi = \phi_o) = T_{SAT} \tag{13}$$

Eq. (1) subject to (13) is solved using Duhamel's integral to obtain:

$$T_p\ (\phi,t) = T_{SAT} + \sum_{n=0}^{\infty} \Omega_n(t,z)\ \cdot \cos\ \left(\frac{2n+1}{2\phi_o}\ \Pi\phi\right) \tag{14}$$

where Ω_n is a function of t, z and n.

The infinite series in eq. (14) is rapidly convergent and generally only a few terms in the series is needed to give a pressure tube temperature accurate to within 10°C.

4.8 LIMITING PRESSURE TUBE CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION

In the limit $t \to \infty$ and for negligible radiation to the calandria tube and convection to steam, eq. (14) reduces to:

$$T_{p\infty} = T_{SAT} + C.\ \left(1 - \frac{\phi^2}{\phi_o^2}\right) \tag{15}$$

The parabolic profile (15) is identical to that obtained from a steady state derivation where all the heat generated in the fuel is assumed to be radiated to the pressure tube and where convection is ignored.

However, in the limit $t \to \infty$, radiation cannot be ignored because the temperatures are generally high. For small convection to steam and radiation to calandria tube, the limiting pressure tube circumferential temperature may be expanded in powers of a small parameter to show that convection and radiation tend to flatten the parabolic temperature profile in eq. (15).

5. COMPARISON OF AMPTRACT PREDICTIONS WITH EXPERIMENT

Steam and sheath axial and pressure tube circumferential temperature distributions predicted by AMPTRACT have been compared with those observed in the two WNRE pressure tube heatup tests described in sections 2 and 3. The pressure tube temperature distribution predicted by AMPTRACT has also been compared with that predicted by SMARTT in Reference 7.

Figure 7 shows the pressure tube circumferential temperature distributions at various times predicted by AMPTRACT (solid curves) and SMARTT (dashed curves) in channel central plane for conditions given in Table 1. The agreement between the two predictions is good.

Figures 8-13 show the pressure tube circumferential temperature distributions observed (crosses) and predicted (solid curves and open circles) by AMPTRACT in rings 1, 2 and 3 in tests 1 and 2. Generally, the agreement between the observed and predicted temperature distributions is good at later times in the heatup as is seen at 400 second test time in Figures 8-10. At erlier times in the heatup, the predicted temperature distribution is more flat than that observed if the same duration of heatup is used in the model for each exposed point on the pressure tube circumference (compare predicted and observed distributions at 300, 200 and 150 second test times in Figures 8-13). In the test, however, there was no makeup water to the channel and, hence, the level, following the initial relatively rapid drop, fell gradually causing different points on the pressure tube circumference to be uncovered for different durations. Indeed, when these durations are used in AMPTRACT, the predicted distributions (open circles in Figures 8-13) agree well with those observed in the tests. This result shows that accident scenarios in which the channel water level falls gradually, as in boil-off process, give steeper temperature gradient around the pressure tube circumference. (Note that in most postulated accident scenarios in CANDU reactor, the feeder contains sufficient coolant inventory to supply the channel with makeup coolant. Thus, the coolant level in the channel remains essentially constant following the initial rapid drop.)

Figures 8-13 show that for a given water level, the peak pressure tube temperature decreases and, hence, the temperature distribution becomes more flat with distance from channel "inlet". This effect is due to steam cooling which increases with distance from channel "inlet" as the steam flow rate increases. Figure 14 shows AMPTRACT predicted top element sheath, peak pressure tube and steam temperatures and convective heat transfer coefficient versus distance from channel inlet in tests 1 and 2. Sheath and, hence, pressure tube temperatures decrease slowly with the distance as heat transfer coefficient increases. The steam temperature, however, increases rapidly with distance as steam with low specific heat continues to absorb fuel heat. This increase is not sufficient to cause the pressure tube temperature to increase with distance because of small convective heat transfer between the pressure tube and steam. Figure 14 shows that axial temperature gradient along the sheath and pressure tube is small supporting the model assumption (vi) in Section 4.1.

Figure 15 shows the observed (dashed curves) and predicted (solid curves) peak pressure tube and steam temperature transient in ring 1 in tests 1 and 2. The agreement between the observed and predicted pressure tube temperatures is good. The steam temperature is reasonably well predicted. The agreement between the observed and predicted steam temperatures improves when heat losses to the surrounding near the channel exist (where the steam temperature is measured) are accounted for. Figure 15 shows that, initially, the steam temperature is higher than that of the pressure tube. The pressure tube temperature, however, increases faster due to the increasing effect of radiation. Thus, after some time the pressure tube temperature exceeds that of steam with the result that the pressure tube transfers heat to steam. But, as was mentioned above, this heat transfer is small.

Figure 16 shows that there is also reasonably good agreement between the pressure tube circumferential temperature distribution measured (crosses) in and predicted (solid curve) by AMPTRACT for the CWIT standing start test 1146. The peak pressure tube temperature in test 1146 is nearly equal to that in WNRE test 1 (Figure 9) for the same duration of heatup inspite of higher (about twice) linear power in test 1146. This result is due to smaller (about six times) channel linear heat capacity in the WNRE facility.

Figure 17 shows that measured and predicted top element sheath temperatures decrease with axial distance as the steam temperature and heat transfer coefficient increase. The predicted pressure tube temperature near the channel mid plane is higher than the steam temperature and it decreases with axial distance. Beyond a certain axial distance, the steam temperature exceeds that of the pressure tube. Eventually, the steam temperature is high enough to cause the pressure tube temperature to increase. The measured pressure tube temperature is also higher closer to the channel exit supporting the prediction.

6. CONCLUDING REMARKS

AMPTRACT provides steam and sheath axial and pressure tube circumferential transient temperature distributions in algebraic forms. In the limit of large times, the pressure temperature distribution reduces to a parabolic profile expected from steady state heat transfer considerations. Second order effects such as convection to steam and radiation to the calandria tube tend to flatten the circumferential temperature profile.

Pressure tube temperature distributions predicted by AMPTRACT agree closely with those predicted by SMARTT for the conditions given in Reference 7.

Good agreement is obtained between pressure tube circumferential temperature distributions predicted by AMPTRACT and those observed in the WNRE tests when the appropriate heatup durations which account for gradually falling water level in the tests are used in AMPTRACT. It is predicted that accident scenarios in which the water level falls gradually, as in boil-off process, give steeper temperature gradients around the pressure tube circumference. The predicted steam temperature is also in reasonable agreement with that measured in the tests. These results show that the AMPTRACT model captures the major interactions.

AMPTRACT provides a simple, flexible and inexpensive tool for the study of the parametric pressure tube temperature distribution under stratified channel coolant conditions.

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TABLE OF NOMENCLATURE

A_s : Steam flow area.

h : Specific enthalpy.

h_g : Saturated steam specific enthalpy.

$h_{\ell g}$: Specific heat of vaporization.

ℓ_o : Channel length.

M_s : Steam mass generation rate per unit channel length.

n : Positive integer.

Q_c : Uniform channel power.

T : Temperature.

t : Time variable.

W_s : Steam mass flow rate.

z : Axial distance measured from the location where either $\alpha_s = 0$ or steam velocity vanishes.

GREEK SYMBOLS

α_ℓ : Liquid fraction

α_s : Void fraction

α^* A constant related to pressure tube thermal diffusivity

ρ : Density

ϕ : Azimuthal angle measured from the vertical.

ϕ_o : Azimuthal angle at water level.

SUBSCRIPTS

∞ : Limiting value

f : Fuel element

p : Pressure tube

s : steam.

TABLE 1

Channel Conditions Used in AMPTRACT For

Comparison of AMPTRACT and SMARTT Predictions

Time (s)	Average Channel Pressure (MPa)	Average Channel Power (kW)	Average Top Element Power (kW/m)	Average Channel Void	Final Channel Void
180	2.0	238.8	2.06	0.24	0.24
500	1.22	218.2	1.89	0.42	0.40
700	1.22	212.5	1.84	0.52	0.80

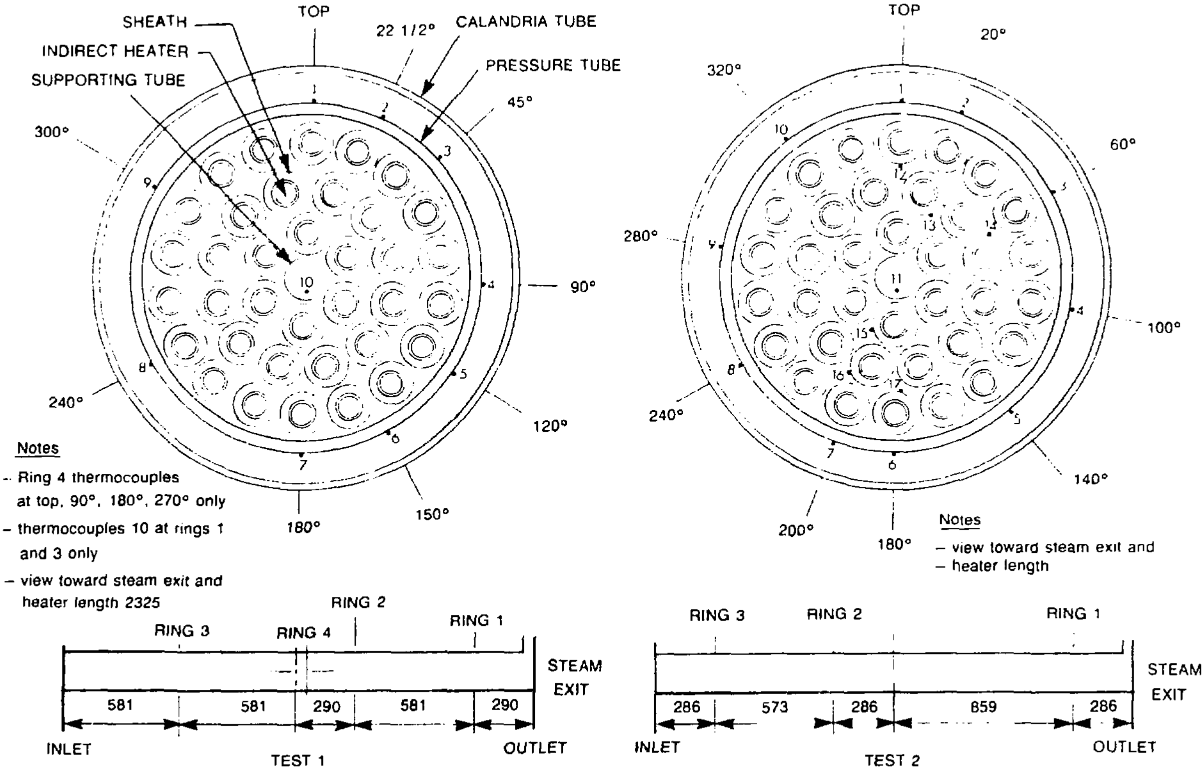


FIGURE 1 SCHEMATIC OF THE PRESSURE TUBE CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION EXPERIMENT FACILITY

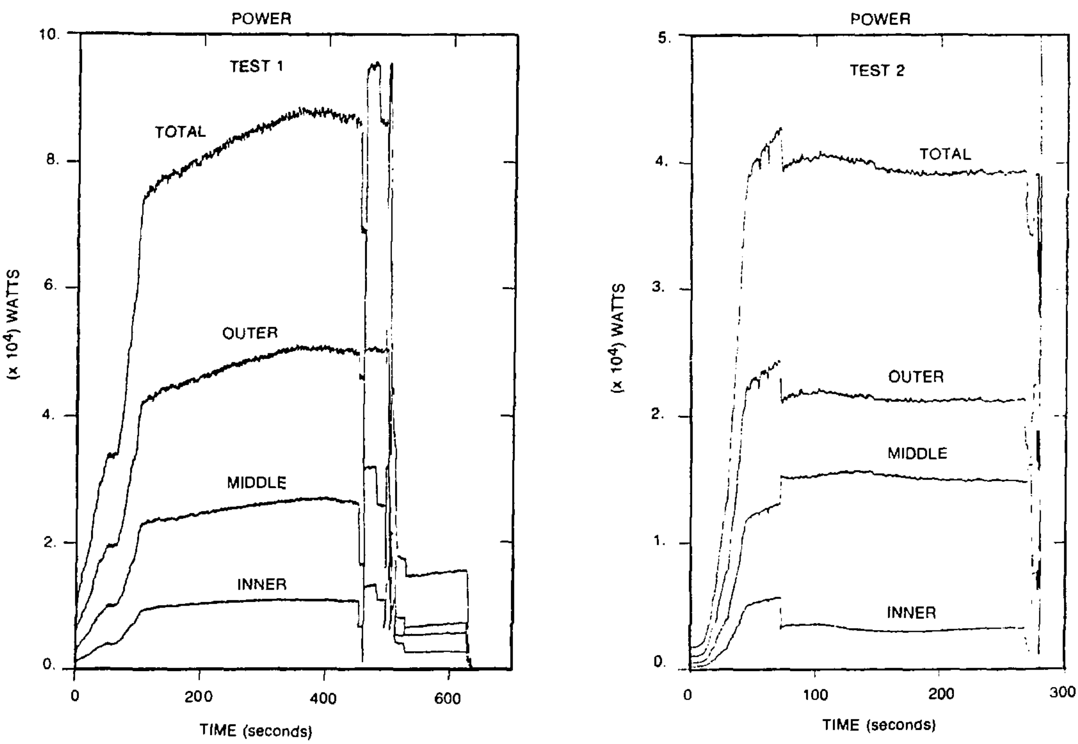


FIGURE 2 POWER INPUT TO INDIRECT HEATERS

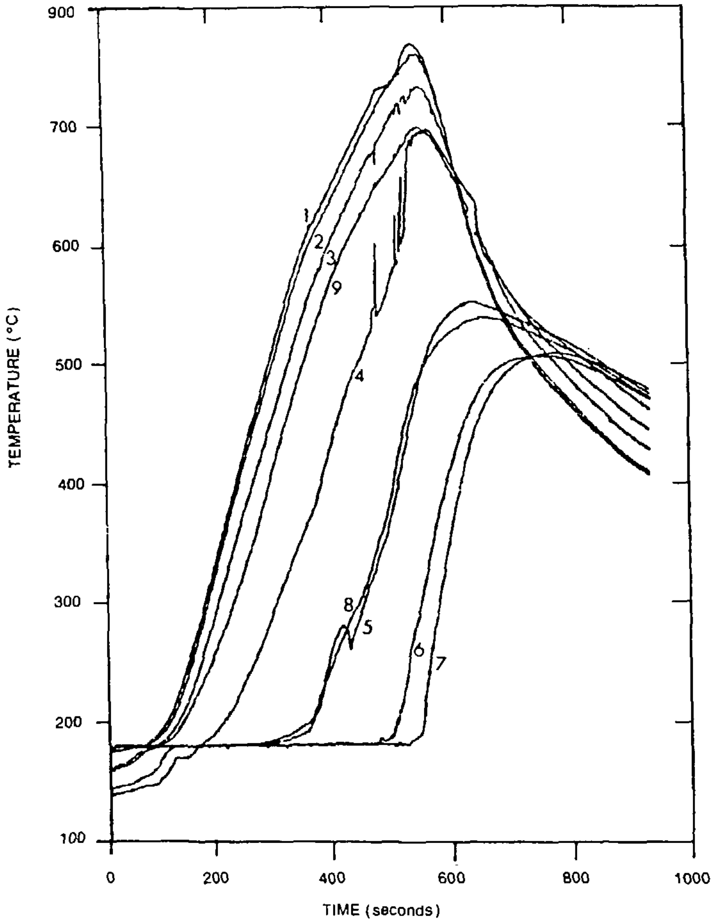


FIGURE 3 PRESSURE TUBE CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION MEASURED BY THERMOCOUPLES ON SECOND RING IN TEST 1 (NUMBERS ON CURVE CORRESPOND TO LOCATIONS SHOWN IN FIGURE 1)

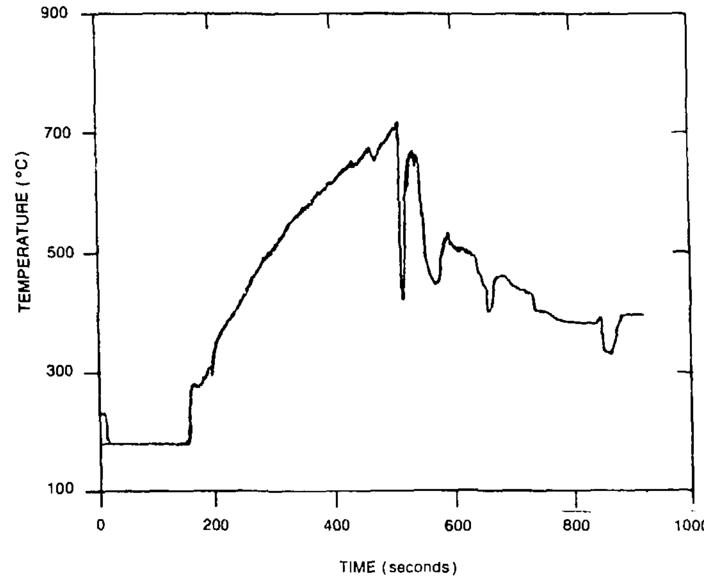


FIGURE 4 TYPICAL STEAM TEMPERATURE MEASURED NEAR CHANNEL OUTLET IN WNRE TESTS

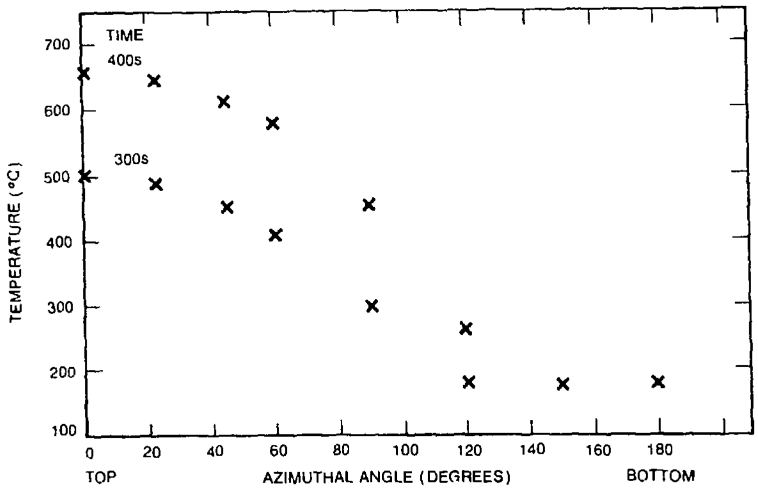


FIGURE 5 PRESSURE TUBE CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS MEASURED IN RING 1 IN WNRE TEST 1

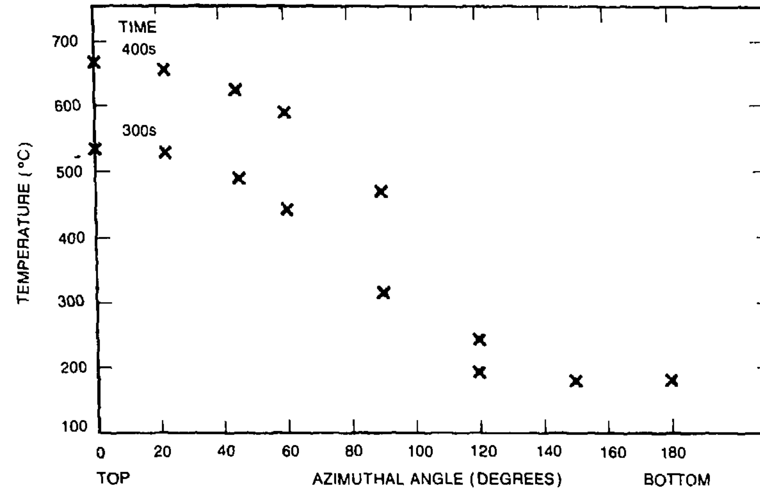


FIGURE 6 PRESSURE TUBE CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS MEASURED IN RING 2 IN WNRE TEST 1

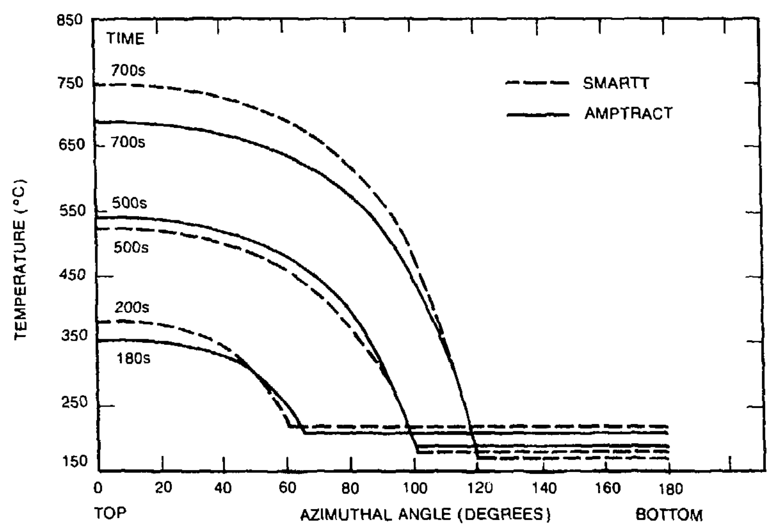


FIGURE 7 COMPARISON BETWEEN AMPTRACT AND SMARTT PREDICTED PRESSURE TUBE CIRCUMFERENTIAL TEMPERATURE

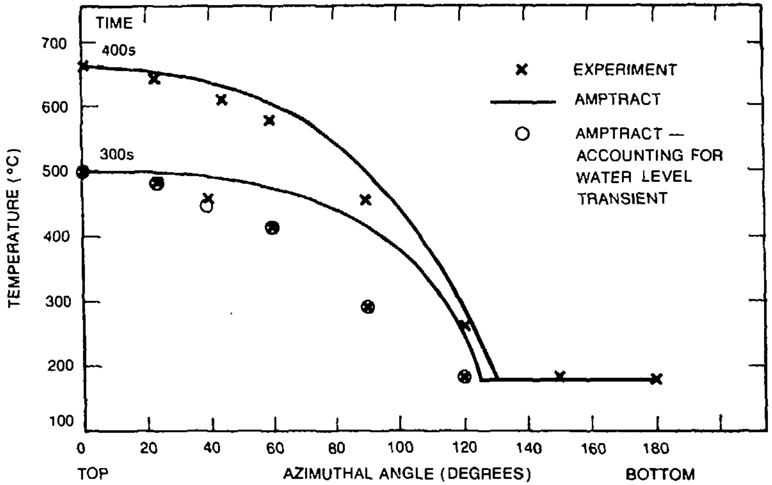


FIGURE 8 PRESSURE TUBE CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS IN RING 1 PREDICTED BY AMPTRACT AND OBSERVED IN WNRE CHANNEL TEST NO.1

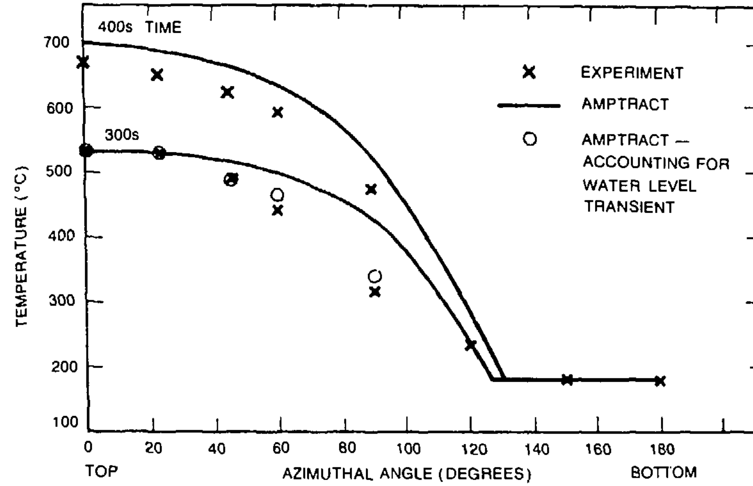
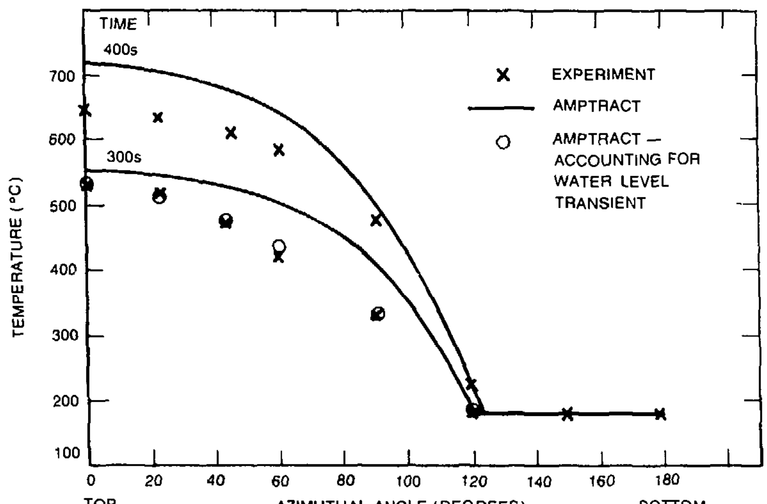


FIGURE 9 PRESSURE TUBE CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS IN RING 2 PREDICTED BY AMPTRACT AND OBSERVED IN WNRE CHANNEL TEST NO.1



TEST 1 CONDITION
CHANNEL PRESSURE = 1 MPa
CHANNEL POWER = 42 kW

FIGURE 10 PRESSURE TUBE CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS IN RING 3 PREDICTED BY AMPTRACT AND OBSERVED IN WNRE CHANNEL TEST NO.1

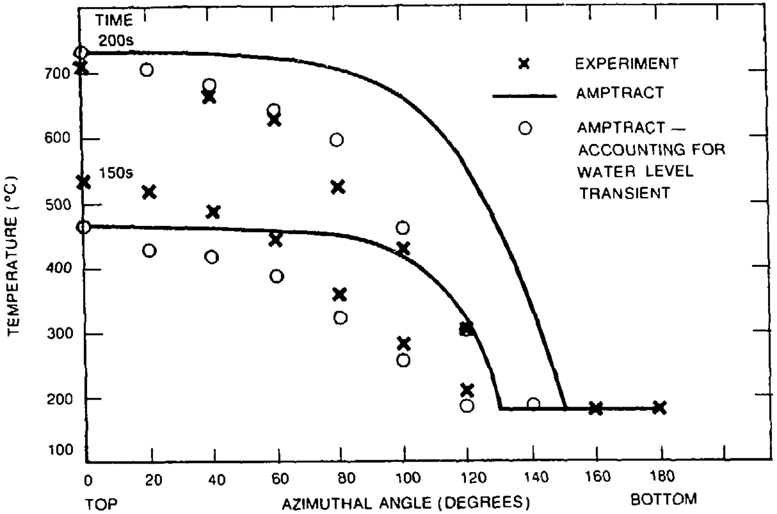


FIGURE 11 PRESSURE TUBE CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS IN RING 1 PREDICTED BY AMPTRACT AND OBSERVED IN WNRE CHANNEL TEST NO. 2

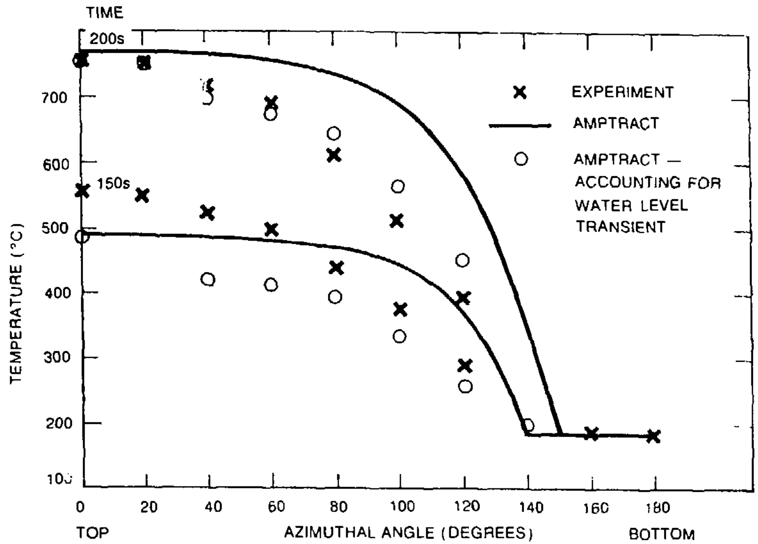
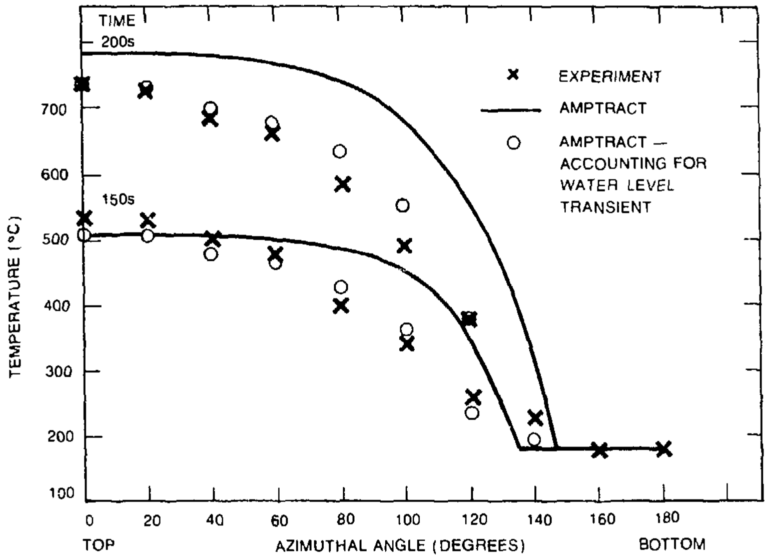


FIGURE 12 PRESSURE TUBE CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS IN RING 2 PREDICTED BY AMPTRACT AND OBSERVED IN WNRE CHANNEL TEST NO.2



TEST 2 CONDITION
CHANNEL PRESSURE = 1 MPa
CHANNEL POWER = 80 kW

FIGURE 13 PRESSURE TUBE CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS IN RING 3 PREDICTED BY AMPTRACT AND OBSERVED IN WNRE CHANNEL TEST NO.2

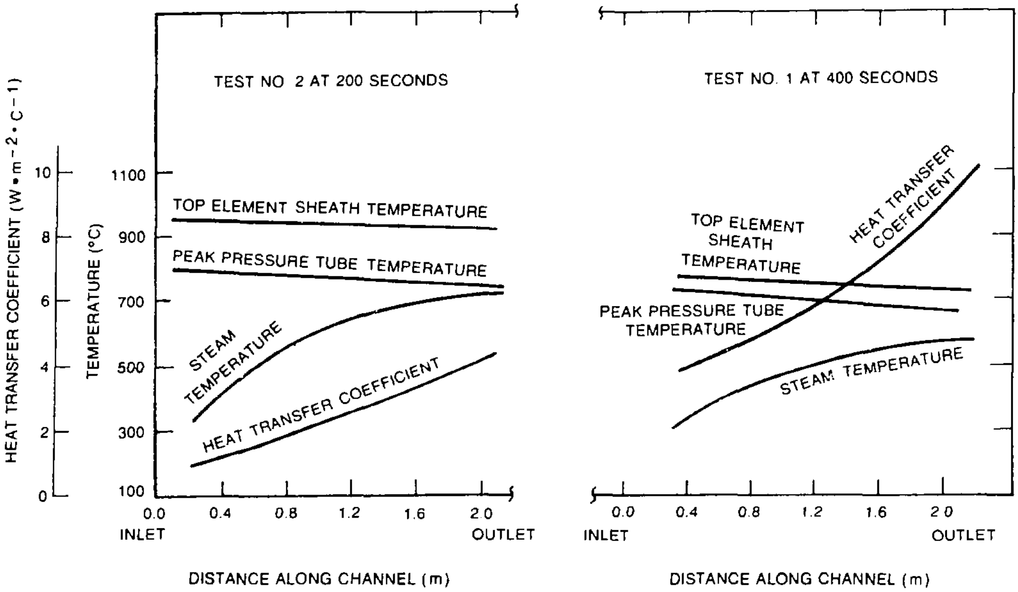


FIGURE 14 PREDICTED TOP ELEMENT SHEATH, PEAK PRESSURE TUBE AND STEAM TEMPERATURES AND HEAT TRANSFER COEFFICIENT ALONG THE CHANNEL IN WNRE TESTS 1 AND 2

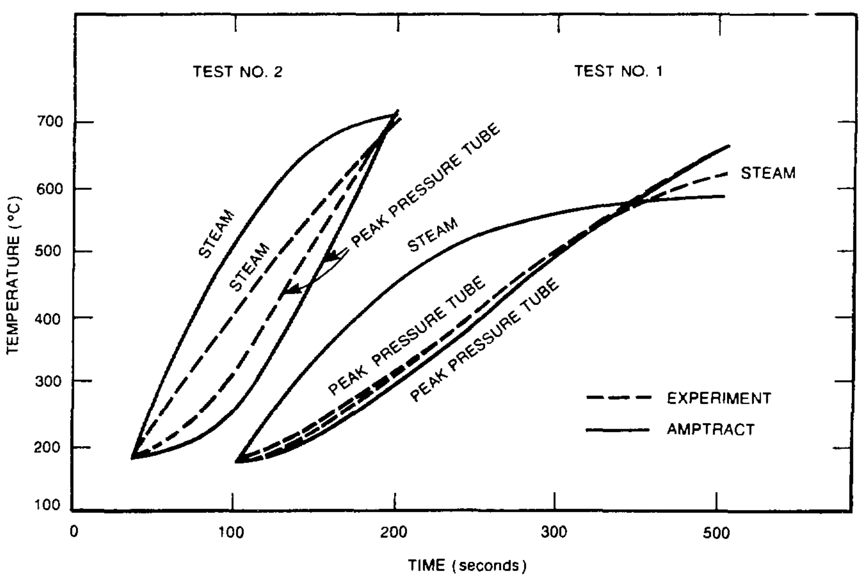


FIGURE 15 STEAM AND PRESSURE TUBE TEMPERATURE TRANSIENTS AT TOP OF CHANNEL IN RING 1 IN WNRE CHANNEL TESTS 1 AND 2

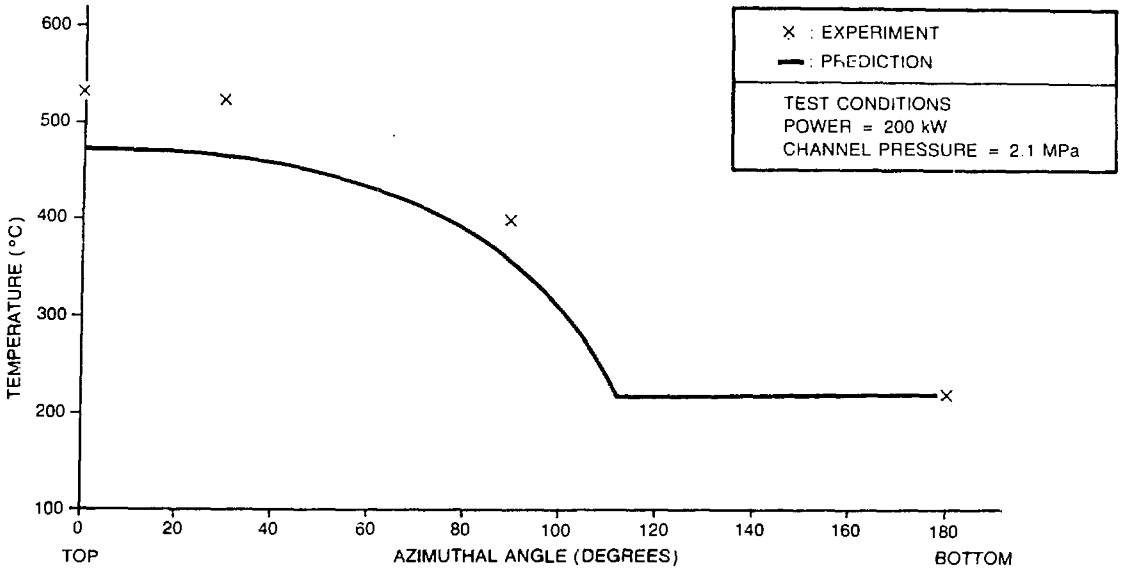


FIGURE 16 PRESSURE TUBE CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION AT 300 SECONDS FOLLOWING BOILING IN CHANNEL AND 0.75 m DOWNSTREAM OF MIDDLE OF CHANNEL IN CWIT HIGH PRESSUE STANDING START TEST 1146 (BOTTOM CHANNEL)

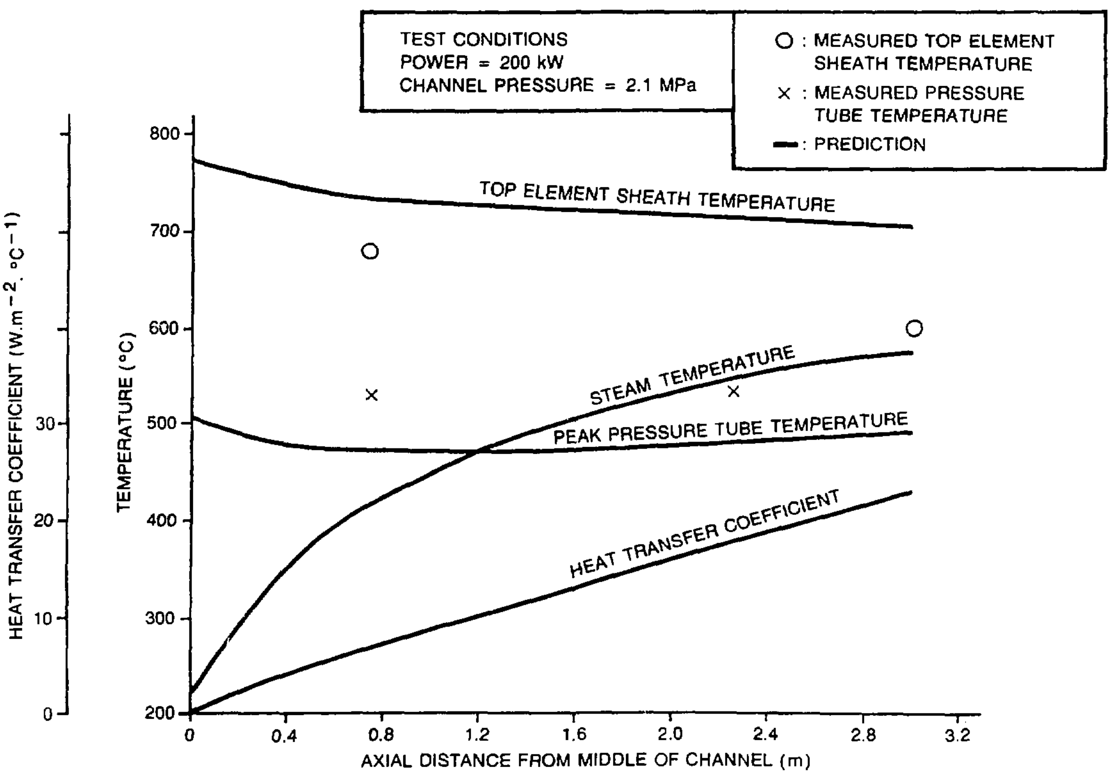


FIGURE 17 MEASURED AND PREDICTED TEMPERATURES AND HEAT TRANSFER COEFFICIENT ALONG THE CHANNEL AT 300 SECONDS FOLLOWING BOILING IN CHANNEL IN CWIT HIGH PRESSURE STANDING START TEST 1146 (BOTTOM CHANNEL)

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