Model for the Spread of Contact Between Pressure Tube and Calandria Tube

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INTRODUCTION

The assessment of the remaining life of the fuel channels in the earlier CANDU reactors in the Ontario Hydro system involves evaluation of the probability of formation of ZrH_x blisters on the Zr-2.5 wt% Nb pressure tubes (PT's) {Leger et al, 1988}. Such blisters can result in catastrophic rupture of the PT while the reactor is at power, as happened in the case of a Zircaloy 2 PT in Pickering A Nuclear Generating Station-Unit 2 (P2) in 1983 {Cheadle et al, 1987}.

The conditions necessary for the formation of the blisters are contact between the hot (570 K) PT and the cold (350 K) calandria tube (CT) and local H isotope concentrations in excess of some critical value related to the terminal solid solubility of H in Zr at the temperature of the contact point.

High D concentrations and axial concentration gradients were found near the outlet end of PT L09 in P3, and similar, but less severe D profiles were found in the in-situ analyses of channels in P3 and P4 {Lichtenberger, 1988}. Hence the extent of contact must be known at any given time to assess the probability of blister formation in a PT with a given D distribution. This information can be used in a probabilistic assessment of the reliability (PAR) of a given reactor core by a Monte Carlo technique {Leger et al, 1988}.

PT to CT contact occurs as a result of fuel channel sag {Sauve et al, 1989} due to irradiation creep. The concentric, horizontal PT and CT are separated by spacers (helical springs wrapped around the PT) at intervals along the length. In earlier reactors these were misplaced at some time after installation, so that, with time, the PT could sag down between the spacers and contact the CT. For any given set of spacer locations, the history of fuel channel sag and the development of the contact area between the PT and CT tube can be calculated using the computer code CDEPTH {Sauve et al, 1989}. CDEPTH is a finite element code and requires a large amount of memory and CPU time. Its use in the PAR is not practical because the Monte Carlo technique requires analysis of several thousand fuel channels. A closed form model describing the development of contact as a function of spacer location is required.

The determination of the time and location of initial contact as a function of spacer location has been the subject of other studies {Sakaguchi, 1987 and Badie and Holt, 1989} and relatively simple closed form algorithms are being developed. The subsequent spread of contact is dealt with here.

EXPERIMENTAL CONTACT DATA

Data have been obtained for spacer locations and for the extent and location of contact between PT and CT for 9 high powered fuel channels in P3, P4 and Bruce A Nuclear Generating Station, Unit 2 (B2). These are summarized in Table 1. For four channels the data were obtained from the post irradiation examination (PIE). For the rest, the data are from nondestructive examination of the channels, in-service, using CIGAR (Dolbey, 1986).

METHOD

CDEPTH was used to study the development of contact for sets of spacer locations giving a wide range of contact positions. Operating conditions corresponding to high powered channels in P3 at 100% power and in B2 at 88, 92 and 100% power were used with the CT and PT properties, geometries and loads for P3 and B2 respectively. The most recent models describing in-reactor deformation of PT's and CT's were used (Fidleris et al, 1985 and Causey et al, 1987). Based on the CDEPTH results, a closed form expression describing contact development was derived which was then fitted to the contact data.

RESULTS

Typical curves showing the spread of contact with time for a series of spacer positions are shown in Figure 1. As the length of the unsupported span in which the contact occurs decreases, the contact occurs later, and the initial rate of spreading decreases. As the length of contact increases, spreading occurs at an ever decreasing rate.

For data like that of Figure 1, the rate of spreading after some initial time, t_o, is related logarithmically to the length of the remaining unsupported half-span, Figure 2, ie:

$$d\ell/dt = -K\ell^n \qquad ....1$$

where: ℓ is the remaining length of the unsupported half-span and
t is time since contact
K and n are constants.

This relationship is probably controlled by creep, however, in the initial stages, the spreading rate may be higher than that given by Equation 1, and clearly has an elastic component, as illustrated by the spreading which occurs at zero time in the case of long unsupported spans, Figure 1.

Defining the spread on one side of the initial contact (the contact half-length), S_o, at some short time, t_o, after contact, Equation 1 can be integrated to give an expression for the contact half-length at time t as a function of the time since contact, ie, for $t > t_o$:

$$S = \ell_o - (K't' + \ell_o'^m)^{1/m} \qquad ....2$$

where: ℓ_o is the initial unsupported half-span,
$m = 1 - n$,
$K' = -mK$ and
$t' = t - t_o$
$\ell_o' = \ell_o - S_o$.

For given fuel channel geometry, orientation and operating conditions the values of n and K were obtained from plots of spreading rate vs remaining unsupported half-span.

For the same set of spacer locations the spreading rate depended on operating conditions, but the exponent, n, was essentially the same. It varied from about 4.5 to about 6.7 depending on the location in the channel but was independent of the direction of coolant flow. The exponent was higher for spreading towards a spacer (average value of 6.2) than for spreading towards an end fitting (average value of 4.9). The ratio of the rate of spreading at the mid-range of each curve for P3 (100%) conditions to that for B2 (100%) conditions had an average value of 0.72. The ratio of the rates of spreading at 88% 92% and 100% power in B2 had average values of 0.87:0.92:1.00.

The initial contact half-length, S_o (arbitrarily taken at 3000 h after initial contact) varies approximately exponentially with ℓ_o, but with some curvature, Figure 3 and is adequately represented, for use in Equation 2, by:

$$S_o = A\ell_o^P + B\ell_o^{1.5} \qquad ....3$$

The initial spreading is different for Pickering and Bruce conditions and appears to be predominantly elastic. The magnitude of the initial spreading depends on whether the half-span in which it occurs is bounded by a spacer or an end fitting. There was little effect of channel orientation, direction of coolant flow or reactor power level.

SELECTION OF MODEL AND FITTING TO CONTACT DATA

The initial times and locations of contact for the nine measured contacts were taken from CDEPTH calculations for the appropriate channel configurations. From these and the measured contact data the 18 'observed' contact half-lengths, S', and initial unsupported half-spans, ℓ_o, and the nine times since contact, t, were calculated.

Due to irregularities and surface waviness in the PT and CT, the contact length is expected to develop incrementally with a characteristic length of increment, d. Hence the observed contact half-length, S', is expected to be shorter than that calculated for a continuously developing contact, S, by an average amount d/2, ie:

$$S = S' + d/2 \qquad ....4$$

Based on the PIE observations of contact, d is of the order of 0.1 m.

All the "measured" times since contact are greater than 3,000 h. Hence Equation 2 could be fitted to the data with S_o given by Equation 3, S related to S' by Equation 4 and t_o = 3,000 h. The fit was optimized to minimize the sum of the rms errors between the measured and calculated contact lengths and centers of contact. Because of the limited contact data available, it was necessary to limit the number of fitted parameters and eliminate some of the detail suggested by the CDEPTH calculations. Hence, the values of the spreading exponents and the relative rates of spreading in Bruce and Pickering were fixed at the average values given by the CDEPTH calculations.

The average rate of spreading towards spacers and towards end-fittings were fitted to the data. By dividing each channel into three regions - inlet, central and outlet - the fit was improved significantly with higher spreading rates in the outlet than in the inlet ends of the pressure tubes. This effect is due to the increase in the creep rate of the PT with temperature (Causey et al, 1987) and is expected from the CDEPTH calculations.

The difference between calculated and measured contact length, d/2, was set to 0.05 m, which appears to be physically reasonable. This was found to improve the fit, and was close to the "best fit" value. Derivation of an exact fitted value was not deemed justified on account of the small amount of data. The fitted values of the parameters are shown in Table 2, the relationship between measured and calculated extent of contact is shown in Figure 4 and the general characteristics of spreading curves calculated by the model are shown in Figure 5.

CONCLUSIONS

A closed form model has been derived to describe the spread of contact between PT's and CT's in CANDU reactor fuel channels. The form of the model was derived from a finite element beam model of the fuel channel and the parameters of the model were fitted to measure contact data for nine fuel channels. The model gives a good representation of the data and the fitted parameters reflect the effect of temperature on PT creep.

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TABLE 1
MEASURED CONTACT DATA FOR NINE CHANNELS

Channel	Inlet Spacer Location	Outlet Spacer Location	Inlet Extent of Contact	Outlet Extent of Contact	Time of Operation 1000's of h
B2P12	none	0.888	-1.54	-0.25	54.8
P3M12	-2.183	none	-1.06	1.90	104.5
P3L09	-0.803	2.573	0.18	1.37	104.5
P3Q16	-1.853	0.903	-0.85	-0.28	104.5
P4Q15	-1.113	2.393	-0.01	1.24	105.5
P3J09	-0.923	0.253	1.26	1.70	84.0
P4J09	-0.733	0.173	1.31	1.71	105.5
P3F07	-0.133	0.973	-1.64	-1.29	104.5
P4K10	-1.376	0.893	-0.44	-0.25	92.5

All dimensions in m from channel centerline

TABLE 2
CONSTANTS FOR LONG-TERM CONTACT SPREADING MODEL

For Pickering A at outlet end:		
spreading towards spacer:	n = 6.2	K = 1.389 x 10^{-3} ($m^{-5.2}$/1000h)
spreading towards E/F:	n = 4.9	K = 8.74 x 10^{-4} ($m^{-3.9}$/1000h)
For spreading at inlet end:	multiply K by 0.65	
For spreading at centre:	multiply K by 0.83	
For Bruce A at 100% power:	multiply K by 1.39	

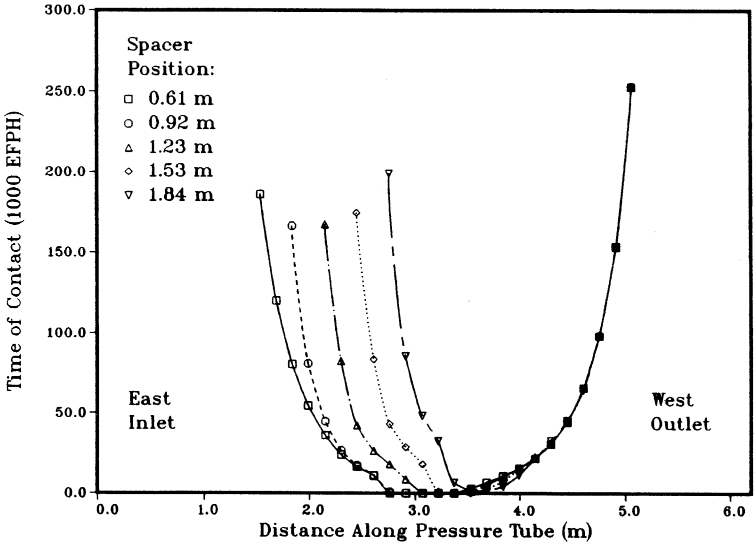

Figure 1: Contact Spreading Curves for Pickering Unit 3, West Outlet Channel

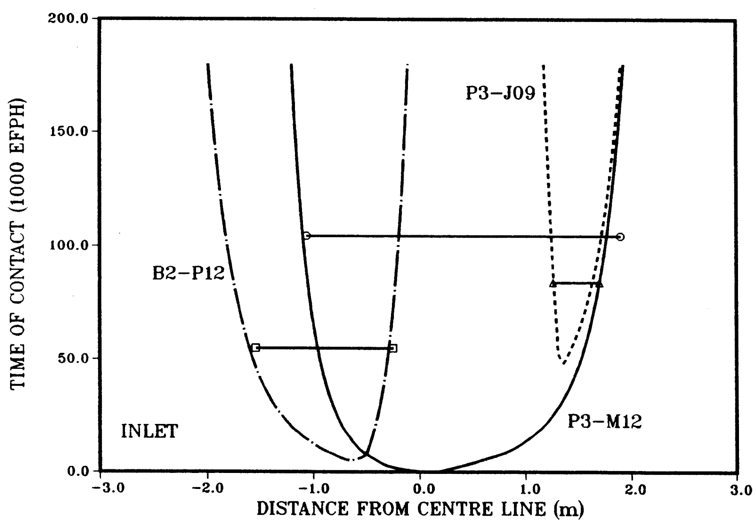

Figure 5: Spreading of Contact in Channels B2–P12, P3–M12 and P3–J09 (Horizontal Lines Represent Measurements)

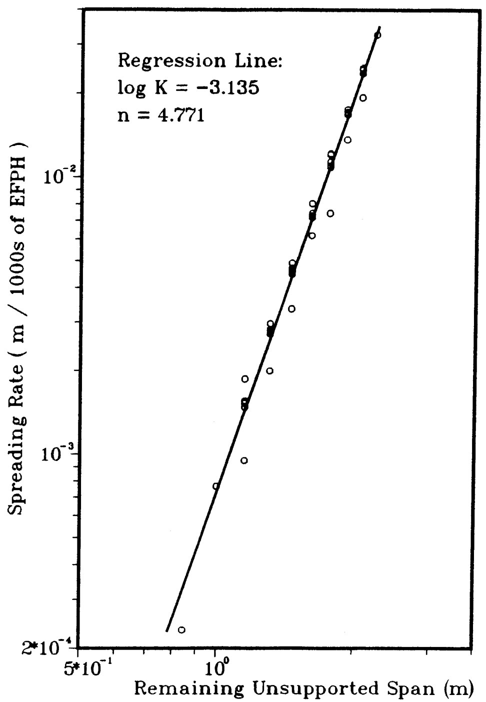

Figure 2: Spreading Rate vs. Remaining Unsupported Span in Pickering Unit 3 West Outlet Channel

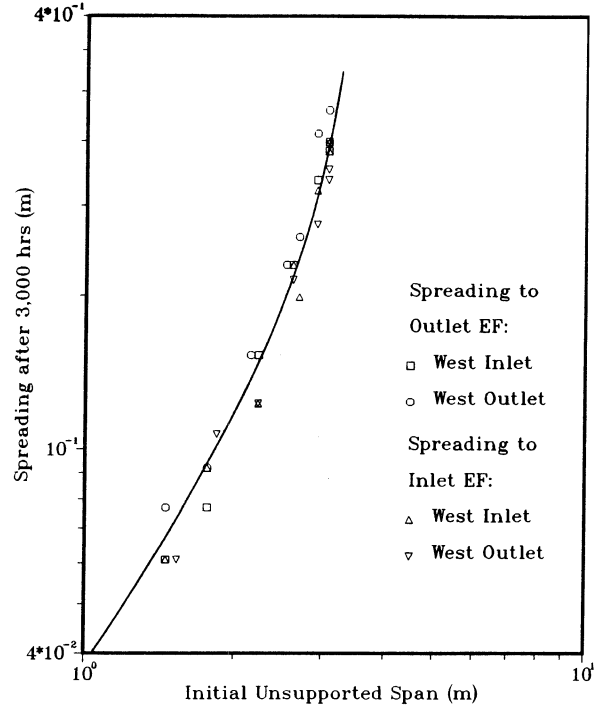

Figure 3: Initial Spreading of Contact toward an End Fitting in Pickering Unit 3 at 100% Power

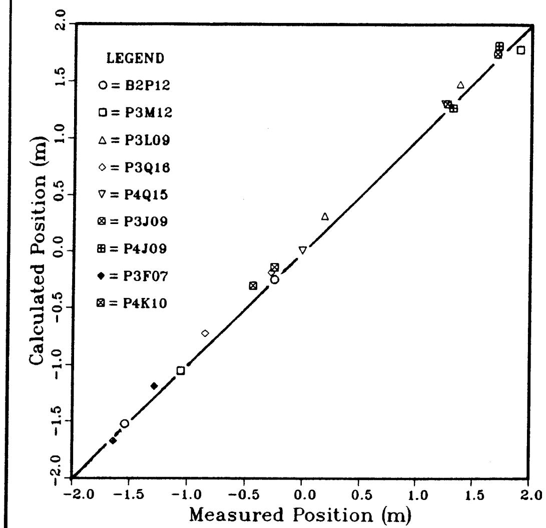

Figure 4 Comparison of Calculated Contact Points With Measured Contact Points.