ANALYSIS OF PRESSURE TUBE ELONGATION AND END SHIELD INTERACTIONS IN THE CANDU REACTORS

A. R. CAUSEY, S. R. MacEWEN
Atomic Energy of Canada Ltd., Chalk River Nuclear Laboratories,
Chalk River, Ontario KOJ 1JO, Canada

H. C. JAMIESON, A. B. MITCHELL
Ontario Hydro, 700 University Avenue, Toronto, Ontario M5G 1X6, Canada

ABSTRACT

Zirconium alloys change shape as a result of fast neutron irradiation-induced creep and growth. Growth is a change of shape which occurs in the absence of an applied stress. The zirconium alloy components of interest in CANDU* reactors are the horizontal pressure tubes, which contain the fuel bundles in pressurized heavy water coolant, and the calandria tubes, which separate the hot pressure tubes from the cold heavy water moderator in the reactor vessel. Depending on the particular reactor design the calandria tubes may, or may not, be rigidly attached to the reactor end shields. Movement of the stainless steel end fittings attached to each end of the pressure tube, which results from thermal and pressure expansion and from irradiation-induced elongation, can be limited by a yoke assembly.

Interpretation of the measured elongations of pressure tubes in operating CANDU reactors has required the development of a model to account for the interactions of the elongating pressure tubes with the reactor end shields and calandria tubes. Elongations of the Zircaloy-2 pressure tubes in units 1 and 2 of the Pickering Generating Station, measured periodically during 8 years of operation, are analyzed to determine the unconstrained tube elongation rates (i.e., the rates which would have been obtained in the absence of any interactions). These rates have been combined with measured metallurgical parameters, in an analysis proposed by Holt and Ibrahim, to obtain the creep and growth material constants of the pressure tubes. The forces, which are induced in the pressure tubes when their elongation is restricted by the end shields, are also calculated.

Material constants for the Zircaloy pressure tubes in the Douglas Point reactor are derived from the Pickering constants and from measured metallurgical parameters. Using these constants and structural details unique to the Douglas Point reactor, the model predicts elongation-time and elongation-flux behaviours which are in good agreement with the measured elongations of the Douglas Point pressure tubes.

---

*CANada Deuterium Uranium

1. Introduction

To exploit the advantages of natural uranium fuel in CANDU* reactors, we use neutron-economic zirconium-based alloys for core components; however, these alloys change dimensions under fast neutron irradiation [1]. The hexagonal close packed crystal structure of zirconium alloys, which limits the number of deformation modes, and the inherent crystallographic texture and Burgers vector, produced by tube forming processes, result in dimensional changes which are anisotropic. The schematic of a Pickering CANDU reactor in Fig. 1 shows the two main zirconium alloy structural components - pressure tubes and calandria tubes. The reactor vessel, two end shields, and calandria tubes form an integral assembly which contains the heavy water moderator, Fig. 1. Each calandria tube (at 340 K) is separated from its pressure tube by spacers in an inert gas annulus. The pressure tube, containing fuel bundles cooled by heavy water at 545 K, is joined to end fittings which slide on bearings inside each end shield, Fig. 2. Bellows between the end fittings and end shields seal the gas annulus, Fig. 2. One end fitting is fixed to its end shield. At the other end fitting, clearance between the yoke-nuts and yoke-plate, shown in Fig. 2, allows limited motion of the end fitting relative to the end shield. This end shield is fixed to the vault wall; movement of the other end shield deflects the annular rings of the reactor vessel.

Irradiation-induced creep and growth, as well as thermal expansion, of the pressure tube decreases the yoke-nut gap, Fig. 2, while elongation of the calandria tubes, by displacing the end shield, causes it to increase. Since the elongation rates of the pressure tubes are much higher than those of the calandria tubes the yoke-nut gaps will close. Continuing elongation induces a compressive stress in the pressure tube. The reactive force acts through the studs and end shields, inducing tensile stresses in the calandria tubes. The induced stresses increase the elongation rates of the calandria tubes and decrease those of the pressure tubes.

The Douglas Point reactor differs from the Pickering reactors in that its calandria tubes are attached to tubesheets which are not attached to the end shields, there are no annulus bellows on the fuel channels, and spring-loaded bolts around the perimeter of each end shield restrain their movement until a preload is exceeded.

This paper outlines a model [2] developed to account for the effects of the above interactions on the elongations measured on Pickering Generating Station units 1 and 2 and Douglas Point reactors. Elongation rates and induced-forces are determined for the Zircaloy-2 pressure tubes in the three reactors.

2. ACCORD** Model of Fuel Channel-End Shield Intraction

The end shields are modeled [2] by rigid plates, one fixed and the other free to translate and tilt. Elastic-plastic members linking the plates, Fig. 3a, simulate pressure tubes, calandria tubes and end shield supports. Members are defined by their:

---

*CANada Deuterium Uranium

**Analysis of Candu Core Deformation

vertical position on the end shield, fast neutron flux, creep and growth rate, and initial gap. Attachment to the moveable end shield is modeled by a 'contact spring', whose spring constant can simulate any possibility from rigid attachment (e.g., calandria tubes) to an open gap. The pressure tube with an open gap followed by contact is described by a spring with a two-branch force-distance curve, Fig. 3b, with the discontinuity in the spring constant occurring at the critical force f_c when the gap closes. The end shield support members of the Pickering reactors, the annular rings and hanger rods (not shown), are modelled by one-branch springs. The spring-loaded end shield design of the Douglas Point reactor is modeled by a two branch force-distance curve with a high spring constant until the preload is reached followed by a low spring constant (related to the spring constant of the springs on the bolts).

The equation for each member relating x_i, the end shield displacement at elevation z_i, to the sum of the elastic, plastic and thermal elongations of that member is:

$$x_i = A_1 z_i + B_1 = - f_i \left[\frac{1}{KH_i} + \frac{\ell_o}{YA_o}\right] + \varepsilon_{I_i} + \Delta\ell_{T_i} + \Delta\ell_{P_i} \qquad \ldots(1)$$

where f is the axial force; KH is the contact spring constant ($KH = KH1$ for $f \leq f_c$, $KH = KH2$ for $f > f_c$); ℓ_o, Y, and A_o are the length, modulus, and cross-sectional area of the member; ε_I is irradiation-induced strain; $\Delta\ell_T$ and $\Delta\ell_P$ are the length changes resulting from thermal expansion and internal pressurization; A_1 and B_1 define the end shield tilt and displacement. The equilibrium conditions which are obtained from the initial total force and moment applied to the end shield by the weight of the moderator and fuel, are:

$$F_A + \sum_{i=1}^{NT} n_i f_i = 0 \qquad \ldots(2)$$

$$M_A + \sum_{i=1}^{NT} n_i z_i f_i = 0 \qquad \ldots(3)$$

where NT is total number of types of members and n_i is number of identical members at a given z_i.

Solution of the coupled eqs. (1-3), by a numerical technique [3], gives the initial forces in each member; differentiation of eqs. (1-3) defines the rate of change of each force and the end shield position.

The irradiation creep rate, $\dot{\varepsilon}_c$, and growth rate, $\dot{\varepsilon}_g$, which are assumed to be additive to define $\dot{\varepsilon}_I$ [4], are input in the form

$$\dot{\varepsilon}_c = (B\sigma_p + E \frac{f}{A_o}) \phi \qquad \ldots(4a)$$

$$\dot{\varepsilon}_g = (Ae^{-\phi t/\tau} + G) \phi \qquad \ldots(4b)$$

where ϕ is the fast neutron flux, σ_p is the hoop stress from pressurization of the tube, A and τ are constants for the transient growth term, and B, E, and G are steady-state constants which depend on texture, dislocation density and material.

3. Results of Calculations and Measurements

3.1 Pickering Units 1 and 2

The pressure tubes in these reactors are ≈20 percent cold-worked Zircaloy-2 and the calandria tubes are nominally annealed Zircaloy-2. Pressure tube elongations have been determined by techniques [5] which measure the displacement of the end fitting relative to the end shield. Data from measuring the yoke-nut gaps on unit 1 at 29,600 h are shown in Fig. 4. The fuel channels are divided into 20 groups (the reactor is symmetrical about its vertical plane) with the mean flux, expressed as a percentage of that in the central tubes (1.84×10^{17} $n.m^{-2}.s^{-1}$ E>1 MeV), shown for each group. Figure 5 shows elongation as a function of full power time for the central, high flux tubes for both reactors. The slope of the line through the mean elongations up to 30,000 h gives an elongation rate of 2.7 mm/7000 h (7000 h is one year at 80% operating capacity); the rate above 30,000 h is 4.7 mm/7000 h. The dashed curve is elongation calculated with ACCORD using eq. (4) for the pressure tubes. The values of A and τ (-9.8×10^{-25} and 1.6×10^{21}) were chosen to give the best fit to the low time data in Fig. 5. Values of B, E and G (8.7×10^{-28}, 2.0×10^{-26}, and 5.6×10^{-25}, respectively) were obtained by optimizing a fit to the data for times > 30,000 h, combined with calculations involving the diametral strain rate as proposed by Holt and Ibrahim [4]. The observed negative intercept suggests that the pressure tubes initially shrank, from irradiation-induced relief of residual stresses [6]. They then elongated until about 17,000 h when the resulting closure of their yoke-nut gaps (initially about 6 mm) decreased their elongation rate. At 30,000 h, a mechanical adjustment, which opened the yoke-nut gaps on both reactors, reduced the end load and allowed an increased elongation rate after 30,000 h. The unconstrained steady-state rate, which is the rate that would be calculated for a closed-end internally pressurized tube (2:1 hoop stress (84 MPa) to axial stress ratio) with no applied end load (f = 0) using the above values for B, E, and G in eq. (4), is 5.0 mm/7000 h. This rate exceeds the observed rate of 4.7 mm/7000 h as a result of the compressive load exerted by the bellows decreasing the rate by about 0.3 mm/7000 h. Because there has been no measurable displacement of the end shields of the Pickering reactors up to 40,000 h, and because the elongation rates of calandria tubes are expected to be 5 to 10% of those of the pressure tubes, we have assumed that the constants A, B, E and G for the calandria tubes are negligible in the analysis.

The mean elongations of pressure tubes in the flux groups in Fig. 4 are plotted against per cent flux in Fig. 6 for 29,600 and 45,300 h. The calculated flux dependencies shown as bands in Fig. 6, are in good agreement with the measurements. The calculated compressive stress induced in a pressure tube with the average elongation rate builds up to 20 MPa at 30,000 h, and is removed when the gaps are reset, Fig. 7. Tube-to-tube variations in the elongation rate of ±30% (as estimated from texture and dislocation density variations [7]) could result in a stress in the fastest tube of 24 MPa at 30,000 h, Fig. 7. The calculated spread in elongations at a given time, obtained by combining the effects of this tube-to-tube variation in rates and a ±10% variation in initial yoke-nut gap sizes with reasonable estimates of the measuring errors [5], are consistent with the measured spread in elongations indicated by the ± 2 standard deviation bands in Fig. 5.

3.2 Douglas Point

The metallurgical structure of the cold-worked Zircaloy-2 pressure tubes in Douglas Point differs from that of the Pickering tubes. Holt [7] has determined the effect of texture and dislocation density on the constants B, E, and G, and values calculated for Douglas Point based on those of the Pickering tubes are 1.1×10^{-28}, 2.0×10^{-26}, and 5.9×10^{-25}, respectively. Values of A and τ (-8.4×10^{-25} and 1.6×10^{21}) were chosen to give the best fit to the Douglas Point data. Since the calandria tubes are not attached to the end shields, they are not involved in the analysis.

Calculated elongation versus time, and the mean elongations from 3 sets of measurements [8] similar to those illustrated in Fig. 4, are shown in Fig. 8. The tubes elongated freely, after an initial shrinkage like that of the Pickering tubes, up to 21,000 h before their initial yoke-nut gaps of about 4 mm were closed. At about 28,000 h the calculated pressure tube loading exceeded the end shield preload of 1.3 MN. By 40,000 h the end shield displacement rate equalled the elongation rate of the pressure tubes, 1.9 mm/7000 h. This calculated rate is in good agreement with the rate from the reactor data in Fig. 8, 2.0 mm/7000 h. The unconstrained steady-state elongation rate given by eq. (4) for $\sigma_p = 86$ MPa and $\phi = 1.57 \times 10^{17}$ $n.m^{-2}.s^{-1}$, is 3.2 mm/7000 h; end shield loading reduced this rate by 40%. The compressive stress induced in the pressure tubes increased rapidly above 21,000 h until the end shield preload was exceeded, and then decreased to an equilibrium level as the end shield displacement rate became constant, Fig. 9. The effect of a $\pm$ 20% variation in elongation rates, which is consistent with observed ± 2 standard deviation bands in Fig. 8, illustrates how the induced stress level depends on elongation rate of the pressure tube.

The predicted flux dependence of the elongation is in good agreement with the mean elongations of the low flux groups, as shown by the dashed lines in Fig. 10.

4. Summary

The analysis of the interaction of elongating fuel channels with a moving end shield is based on rational assumptions concerning the reactor structure and rigorous mathematics describing the interactions of the various components. The general nature of the analysis, particularly the concept of a multi-branch spring force-distance curve, allows calculations for different CANDU designs with simple changes of input parameters. This has been demonstrated by the excellent agreement between calculated and observed elongation-time and elongation-flux behaviour of the Douglas Point pressure tubes. The creep and growth parameters were derived, through consideration of the metallurgical structure, from the corresponding parameters obtained from the analysis of the Pickering measurements.

Elongation rates for pressure tubes can be defined by eq. (4). The calculated unconstrained steady-state elongation rate of pressure tubes of the Pickering units 1 and 2, after the transient has decayed and structure interactions are accounted for, is 5.0 mm/7000 h. This rate agrees very well with predictions by Holt [7] from analyses of the effect of metallurgical structure on the elongation of Zircaloy-2 pressure tubes in the Hanford N-reactor and Winfrith SGHWR. When used in ACCORD, eq. (4) defines the complete elongation-time and elongation-flux behaviour of the Pickering pressure tubes, including: initial shrinkage, discontinuous change in elongation rate at 30,000 h, and the effect of end-loads, from closure of yoke-nut gaps and from the bellows.

References

[1] FIDLERIS, V., "Summary of Experimental Results on In-Reactor Creep and Irradiation Growth of Zirconium Alloys", Atomic Energy Review, 13, pp. 51-80 (1975).

[2] MACEWEN, S.R., CAUSEY, A.R., "Analysis of the Interaction of Fuel Channels with the End Shields in CANDU Reactors", accepted for publication in Nuclear Technology.

[3] CARVER, M.B., MACEWEN, S.R., "Numerical Analysis of a System Described by Implicitly-defined Ordinary Differential Equations Containing Numerous Discontinuities", Appl. Math. Modelling, 2, pp. 280-286 (1978).

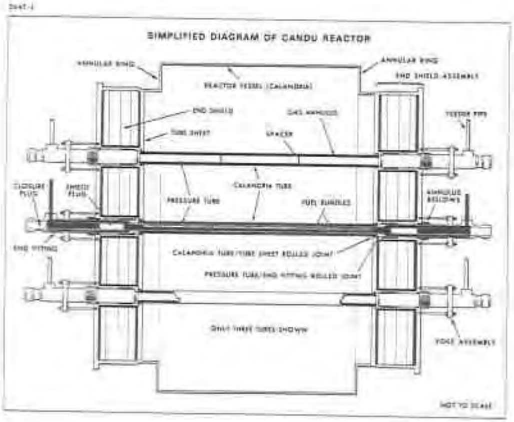
[4] HOLT, R.A., IBRAHIM, E.F., "Factors Affecting the Anisotropy of Irradiation Creep and Growth of Zirconium Alloys", accepted for publication in Acta Met.

[5] CAUSEY, A.R. MACEWEN, S.R., JAMIESON, H.C., MITCHELL, A.B., "Mesurement and Analysis of the Elongation of Zircaloy-2 Pressure Tubes in Pickering G.S. Units 1 and 2", to be published.

[6] FIDLERIS, V., "Factors Affecting In-Reactor Creep of Zirconium Alloy Tubes", Conference on Reactor Material Science, Alushta, USSR, May 29-June 1, 1978.

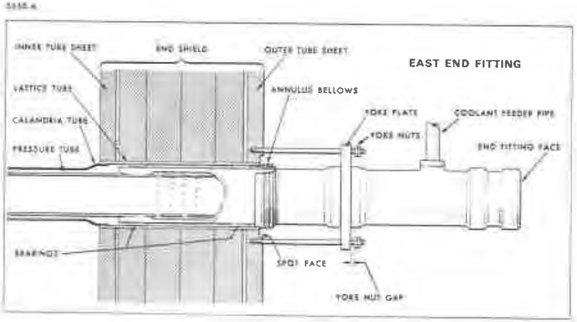
[7] HOLT, R.A., "Effect of Microstructure on Irradiation Creep and Growth of Zircaloy Pressure Tubes in Power Reactors", accepted for publication in J. Nucl. Mat.

[8] CAUSEY, A.R., MACEWEN, S.R., JAMIESON, H.C., MITCHELL, A.B., "Measurement and Analysis of Pressure Tube Elongation in the Douglas Point Reactor", to be published.



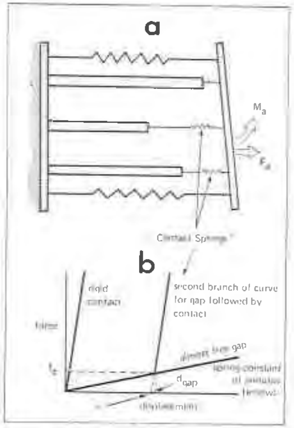
1

1. Simplified diagram of the core components in a Pickering type CANDU reactor.



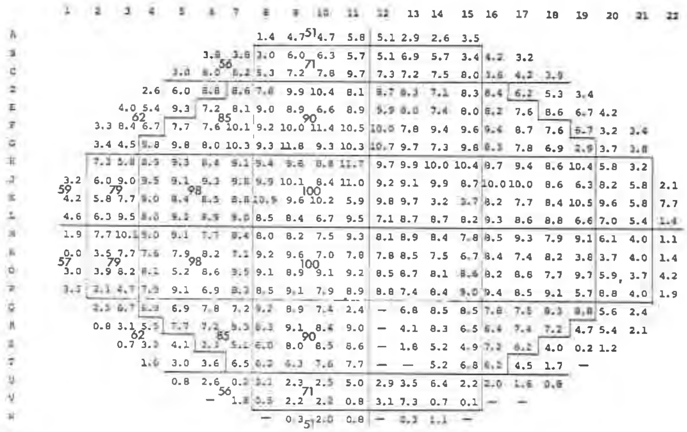
2

2. Diagram of the end fitting-fuel channel assembly, yoke assembly, and end shield.



3

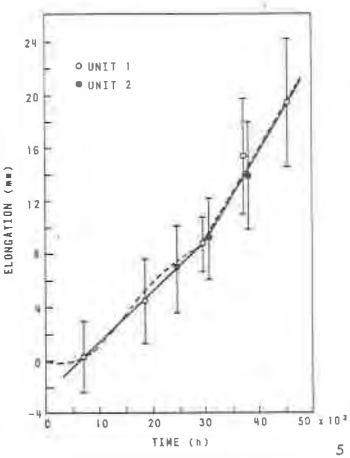
3. Model schematic showing different members with contact springs and the associated force-distance curves.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A								1.4	4.7	4.7	5.8	5.1	2.9	2.6	3.5							
B						3.8	3.8	3.0	6.0	6.3	5.7	5.1	6.9	5.7	3.4	4.2	3.2					
C					3.0	8.0	8.2	5.3	7.2	7.8	9.7	7.3	7.2	7.5	8.0	3.6	4.2	3.9				
D				2.6	6.0	8.8	8.6	7.8	9.9	10.4	8.1	8.7	8.3	7.1	8.3	8.4	6.2	5.3	3.4			
E			4.0	5.4	9.3	7.2	8.1	9.0	8.9	6.6	8.9	5.9	8.0	7.4	8.0	8.2	7.6	8.6	6.7	4.2		
F		3.3	8.4	6.7	7.7	7.6	10.1	9.2	10.0	11.4	10.5	10.5	7.8	9.4	9.6	9.6	8.7	7.6	6.7	3.2	3.4	
G		3.4	4.5	9.8	9.8	8.0	10.3	9.3	11.8	9.3	10.3	10.7	9.7	7.3	9.8	8.3	7.8	6.9	2.9	3.7	3.8	
H		7.3	5.8	8.5	9.3	8.4	9.1	5.4	9.6	8.8	11.7	9.7	9.9	10.0	10.4	8.7	9.4	8.6	10.4	5.8	3.2	
J	3.2	6.0	9.0	9.5	9.1	9.3	9.8	9.9	10.1	8.4	11.0	9.2	9.1	9.9	8.7	10.0	10.0	8.6	6.3	8.2	5.8	2.1
K	4.2	5.8	7.7	9.0	8.4	8.5	8.8	10.5	9.6	10.2	5.9	9.8	9.7	3.2	3.7	8.2	7.7	8.4	10.5	9.6	5.8	7.7
L	4.6	6.3	9.5	8.0	9.2	8.9	9.0	8.5	8.4	6.7	9.5	7.1	8.7	8.7	8.2	9.3	8.6	8.8	6.6	7.0	5.4	1.4
M	1.9	7.7	10.1	9.0	9.1	7.7	8.4	8.0	8.2	7.5	9.3	8.1	8.9	8.4	7.8	8.5	9.3	7.9	9.1	6.1	4.0	1.1
N	0.0	3.5	7.7	7.6	7.9	8.2	7.1	9.2	9.6	7.0	7.8	7.8	8.5	7.5	6.7	8.4	7.4	8.2	3.8	3.7	4.0	1.4
O	3.0	3.9	8.2	8.1	5.2	8.6	3.5	9.1	8.9	9.1	9.2	8.5	6.7	8.1	8.6	8.2	8.8	7.7	9.7	5.9	3.7	4.2
P	3.5	2.1	4.7	7.5	9.1	6.9	8.3	8.5	9.1	7.9	8.9	8.8	7.4	8.4	9.0	9.4	8.5	9.1	5.7	8.8	4.0	1.9
Q		2.5	6.7	8.9	6.9	7.8	7.2	9.2	8.9	7.4	2.4	—	6.8	8.5	8.5	7.8	7.5	8.3	8.8	5.6	2.4	
R		0.8	3.1	5.5	7.7	7.2	5.5	6.3	9.1	8.4	9.0	—	4.1	8.3	6.5	6.4	7.4	7.2	4.7	5.4	2.1	
S			0.7	3.3	4.1	2.3	5.1	6.0	8.0	8.5	8.6	—	1.8	5.2	4.9	7.2	6.2	4.0	0.2	1.2		
T				1.6	3.0	3.6	6.5	6.2	6.3	7.6	7.7	—	—	5.2	6.8	6.5	4.5	1.7	—			
U					0.8	2.6	0.2	3.1	2.3	2.5	5.0	2.9	3.5	6.4	2.2	2.0	1.6	0.6				
V						—	1.8	0.5	2.2	2.2	0.8	3.1	7.3	0.7	0.1	—	—					
W								—	0.3	2.0	0.8	—	2.3	1.1	—							

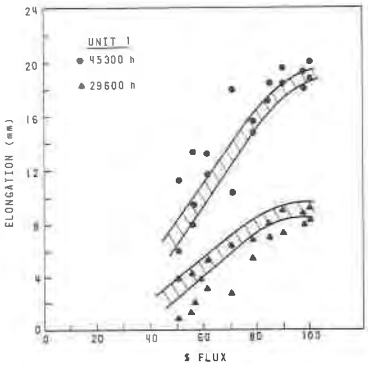
4

4. Set of typical pressure tube elognations (mm) from yoke-nut gap measurements on Pickering unit 1 at 29,600 h, divided into groups with average percentage flux shown.



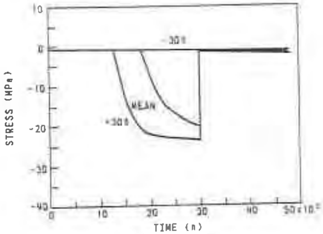
5

5. Elongation as a function of time with calculated behaviour given by the dashed line; scatterbands are ±2 standard deviations.



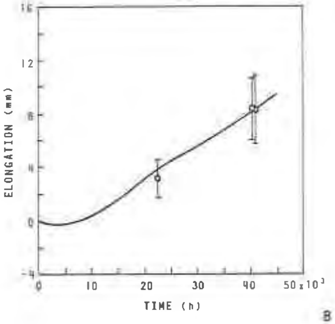
6

6. Elongation as a function of flux at given times with the calculated behaviour given by the bands.



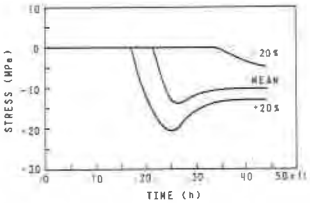
7

7. Calculated induced-stresses in Pickering pressure tubes with different elongation rates.



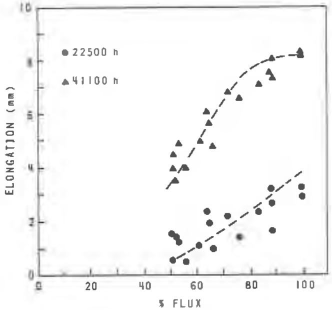
8

8. Calculated elongation as a function of time for Douglas Point reactor compared with measured mean elongations; scatterbands are ±2 standard deviations.



9

9. Calculated induced-stresses in Douglas Point tubes with different elongation rates.



10

10. Elongation as a function of flux at given times with calculated behaviour given by the dashed lines.