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L'ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

MEASUREMENT AND ANALYSIS OF PRESSURE TUBE ELONGATION IN THE DOUGLAS POINT REACTOR

Mesure et analyse de l'allongement des tubes de force dans le réacteur de Douglas Point

A.R. CAUSEY, S.R. MacEWAN, H.C. JAMIESON and A.B. MITCHELL

Chalk River Nuclear Laboratories   Laboratoires nucléaires de Chalk River

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Résumé

On a mesuré, au cours des six dernières années, l'allongement des tubes de force en alliage de zirconium employés dans les réacteurs CANDU**. Les conséquences de ces allongements, qui résultent d'un fluage et d'une croissance dus à une irradiation neutronique, ont été analysées récemment. Les taux d'allongement, précédemment inférés de nombreuses mesures d'allongement de tubes de force en Zircaloy-2 écroui employés dans les réacteurs de Pickering, ont été modifiés pour qu'ils s'appliquent aux tubes de force du réacteur de Douglas Point. Pour faire cette modification on a pris en considération les différences mesurées de texture et de densité de dislocation. En utilisant ces taux d'allongement et les données structurelles exclusives du réacteur de Douglas Point on a pu faire des analyses prédisant un comportement d'allongement en bon accord avec les allongements des tubes de force mesurés au cours des dix ans de fonctionnement de ce réacteur.

* Commission électrique ontarienne
** CANada Deutérium Uranium

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ABSTRACT

Elongations of zirconium alloy pressure tubes in CANDU** reactors, which occur as a result of neutron-irradiation-induced creep and growth, have been measured over the past 6 years, and the consequences of these elongations have recently been analysed. Elongation rates, previously deduced from extensive measurements of elongations of cold-worked Zircaloy-2 pressure tubes in the Pickering reactors, have been modified to apply to the pressure tubes in the Douglas Point (DP) reactor by taking into account measured differences in texture and dislocation density. Using these elongation rates, and structural data unique to the DP reactor, the analysis predicts elongation behaviour which is in good agreement with pressure tube elongations measured during the ten years of reactor operation.

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1. INTRODUCTION

Zirconium alloy pressure tubes in CANDU* reactors are elongating as a result of irradiation-induced creep and growth (1). An analysis of the consequences of pressure tube and calandria tube elongation in terms of the stresses induced in these core components and the displacement of the reactor end shields has been made previously (2,3). A computer code, ACCORD**, has been written to apply the general analysis to any specific reactor structure. Measured elongations of the pressure tubes in Units 1 and 2 of the Pickering Nuclear Generating Station (GS) have been analysed using this code (4), and the optimum value for the free elongation rate has been determined, from which the material dependent constants in the elongation rate equations for cold-worked Zircaloy-2 pressure tubes were calculated using a technique proposed by Holt and Ibrahim (5). In this report we present elongation measurement for the Douglas Point (DP) reactor. By taking into account structural differences between the DP and Pickering reactors (6), and differences in texture and dislocation density (7) of the Zircaloy-2 pressure tubes, we show that the elongation of DP pressure tubes can be described by material constants derived from those obtained (4) for the Pickering Units 1 and 2 pressure tubes.

2. DOUGLAS POINT REACTOR STRUCTURE

Figure 1 is a diagram, showing one of the 306 fuel channels in the DP reactor. The horizontal calandria vessel is penetrated by the calandria tubes, which are rigidly attached by rolled joints to the calandria tube-sheets. Each fuel channel assembly, which consists of a cold-worked Zircaloy-2 pressure tube and two type 403 stainless steel end fittings, passes through the end shields, concentric within a calandria tube. Each end fitting is supported on bearings in the end shields. The end shields, which are hung on rods attached to the roof of the reactor vault, are completely independent of the calandria shell and tube-sheets. The end shields are restrained from horizontal movement by an end shield ring assembly which consists of a series of spring-loaded bolts located around the perimeter of the end shield. The Belleville washers, which provide the spring load on the bolts, were originally set to prevent end shield motion until

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**Analysis of CANDU CORe Deformation

a preload of 1.56 MN (350,000 lbf) was exceeded. The effective spring constant for the two end shield ring assemblies acting in series is 27.3 MN/m (156,000 lbf/in). The end shields themselves consist of three layers of steel slabs, bolted together inside a shrink-fitted shell. For the purposes of analysis, the end shields can be considered to be rigid plates, free to move axially, or to tilt, to the extent allowed by the spring-loaded bolts.

Axial movement of the pressure tubes relative to the end shields, from thermal expansion, elastic extension, and irradiation creep and growth, is restricted by adjustable end-stops, Figure 1. The initial clearance gaps of the end-stops were defined to be 17.5 $\pm$ 0.6 mm with the reactor cold and depressurized, allowing 3.6 mm free axial movement once the reactor was at operating temperature and pressure. Irradiation-induced, axial elongation of the pressure tubes will cause the clearance gaps to decrease, and eventually to close. Further elongation causes an end load which induces a compressive stress in the pressure tubes. When a sufficient number of pressure tubes have closed their gaps, the total force exerted through the end-stops onto the end shields can exceed the preload defined by the Belleville washers, causing the end shields to move. The rate of end shield displacement will equal the average elongation rate of the end-loaded channels. This average rate will be less than the axial elongation rate of an unconstrained tube because the induced compressive stress will produce a negative creep rate which counteracts the positive elongation rate.

3. ELONGATION MEASUREMENT TECHNIQUES

Elongations of the pressure tubes in the DP reactor have been measured by three techniques; two make use of the fuelling machines, while the third involves measuring the clearance gap of the end stops. Clearance gaps are measured with a spring-loaded dial gauge between the outer face of the anti-torque collar and the end-stop, as illustrated in Figure 1.

Refuelling during full power operation is accomplished using two fuelling machines, one at each end shield, which contact the end fittings of any selected fuel channel. A specific channel is selected by motion of the carriage holding the fuelling machine head along horizontal tracks parallel to the end shield, and by vertical motion of the head itself. The planes defined by the horizontal and vertical motion of the two fuelling machine heads provide the reference for the first FM technique. With the FM technique, the displacements of the fuelling machine heads, from a fully retracted to the contact position, are measured using a linear potentiometer, and are combined to define the pressure tube elongation relative to the two reference planes.

For the second technique using the fuelling machines, the reference planes are defined by two theodolites, one at each reactor face. The planes defined by their vertical inclinations are approximately parallel to the two end shields, but are precisely parallel to each other. Scales on the heads of the fuelling machines intersect the reference planes when the fuelling machines are in contact with the end fitting. The position of the scale is measured using an optical micrometer on the theodolite.

The positions of the reference planes in both the FM and theodolite technique must be calibrated to obtain pressure tube elongations. Measuring the clearance gaps on selected channels is one method, while measuring the distance between the two theodolite stations provides another method, independent of other reactor components.

The techniques using the fuelling machines can measure all 306 channels in less than 6 hours, whereas 48 hours are required to measure all channels with the clearance-gap technique. In all cases, the raw data are corrected for temperature fluctuations in the pressure tubes and end fittings. The measuring error for the fuelling machine techniques is estimated to be ± 1.0 mm; for the clearance-gap technique the error is about ± 1.5 mm.

4. DATA ANALYSIS

Three sets of measurements involving all 306 pressure tubes, have been made at Douglas Point. The first set was made using the fuelling machines in March 1973 with the reactor at full power; the second set was made in January 1977, also using the fuelling machines, but with the reactor shutdown. The third set of measurements was made during the same shutdown period using the theodolite technique. Selected end-stop clearance gaps were measured at each of the above times. The elongation data from the theodolite scan are shown in Figure 2.

For the purposes of data presentation and numerical analysis, we have divided the fuel channels into 34 groups, as shown in Figure 3. n_i/y_i defines the number of tubes of group i operating in a fast neutron flux which is y_i% of the maximum flux, (1.51 x 10^{17} $n.m^{-2}.s^{-1}$ E > 1 MeV). The flux groups are based on calculated channel powers with an estimated flux in the middle bundle of 2.0 x 10^{17} $n.m^{-2}.s^{-1}$. This subdivision, plus the fact that the reactor is symmetric about the vertical centre plane, results in 17 groups of tubes, as shown in Figure 3, defined by $2n_i$, y_i and z_i, the average vertical position.

The mean elongations and standard deviations for each group for each of the 3 sets of data analysed are listed in Table 1. The mean elongations at 41,100 h measured by FM and by theodolite agree reasonably well.

The mean elongations with scatterbands of ± 2 standard deviations, for tubes operating at 100% flux (groups 9 and 12) are plotted against full power time in Figure 4. The zero time intercept is -3.4 mm, and the apparent elongation rate between 22,500 and

41,100 h is 1.95 mm/7000 h. (7000 h is one year of operation with an 80% capacity factor.) The negative intercept suggests an initial, transient shrinkage occurring during the first several thousand hours of operation.

The effect of flux is shown in Figures 5a and 5b where the elongations of all groups are plotted against flux. The dashed lines are from the calculations to be described below. There appears to be a negative zero flux intercept and less elongation at high fluxes than would be extrapolated from the lower flux values. The scatter of the individual points about the line in Figure 5a for the 22,500 h data is greater than would be expected from the standard deviations listed in Table 1. Figure 5a shows that the points from channels above the horizontal center line of the reactor tend to have below average apparent elongations, while those from channels below the center line have higher than average elongations. This observation suggests a systematic variation of apparent elongation with channel position.

5. NUMERICAL RESULTS

The ACCORD code (3) is used to model the DP reactor structure, and being creep and growth material constants derived from those of the Pickering reactor pressure tubes (2), the elongation-time and elongation-flux behaviours are calculated for comparison with the observed DP behaviours. Equations for the irradiation creep rate, $\dot{\varepsilon}_c$, and growth rate, $\dot{\varepsilon}_g$, of the pressure tubes, which are assumed to be additive, are:

$$\dot{\varepsilon}_c = (B\sigma_p + E\,\frac{f}{A_o})\;K_c\;\phi \qquad \ldots(1)$$

$$\dot{\varepsilon}_g = A\phi e^{-\frac{\phi t}{\tau}} + G\;K_g\;\phi\;, \qquad \ldots(2)$$

where B, E and G are crystallographic texture constants, K_c and K_g are steady-state creep and growth material constants. A and τ are transient material constants, ϕ is fast neutron flux ($n.m^{-2}.s^{-1}$ E >1 MeV), t is time (h), σ_p is the hoop stress from pressurization of the pressure tube (MPa), f is axial end-load from the interaction of the tube with the end shields, and A_o is the cross-sectional area of the tube wall (m^2).

Values of these parameters for the Pickering Zircaloy-2 pressure tubes are listed in Table 2. Values for DP tubes were obtained from texture measurements (7), the DP design, and as follows. The dislocation density of DP tubes is about 85% of that of Pickering tubes, and Holt (7) has related the steady-state creep and growth rates to dislocation density through the empirical equations:

$$K_c \propto \rho^{0.16}$$

and

$$K_g \propto \rho^{0.82}$$

Values of K_c and K_g appropriate for DP have been calculated using the values found previously for Pickering units 1 and 2, and the above relations. The values of A and τ have not yet been related to any measurable, structural parameters, and consequently have been determined from the best fits to the data in question. The steady-state free elongation rate calculated using equations 1 and 2 and the constants in Table 2 for central zone tubes is 2.85 mm/7000 h, comprising about 0.5% creep and 99.5% growth.

We have assumed that friction between the end fittings and bearings does not contribute to axial loading during reactor operation. End shield distortions from thermal or loading effects have been neglected; these effects will be included in the future.

The elongation-time curves for group 9 and 12 tubes are shown in Figure 6; the measured elongations of Figure 4 are included for comparison. The calculated behaviour agrees quite well with the measurements at 41,100 h, while at 22,500 h it overestimates the apparent elongation. Table 3 lists the sequence of calculated times at which the pressure tubes with average material properties closed their clearance gaps and started to load the end shields. Figure 7 shows the total load on the end shields from pressure tubes which have the same elongation rates, as a function of time. About 160 tubes are pushing on the end shields when the total preload of 1.56 MN is exceeded at 27,000 h. Figure 8 shows the calculated variation of end load stress with time for pressure tubes in groups 9 and 12. The compressive stress increases rapidly after the tubes close their clearance gap until the preload is exceeded and the end shield starts moving. Then the compressive stress decreases slightly, and levels off after about 40,000 h at about 13 MPa. The elongation rate of these tubes at 40,000 h is approximately 1.9 mm/7000 h. This rate will vary with time, increasing when more pressure tubes in lower flux positions start pushing on the end shield and decreasing very gradually from the effect of the Belleville springs.

Figure 9 shows the displacement of the centre of the end shield during hot operation; when the reactor is shutdown there is no permanent displacement because the pressure tubes have thermally contracted. Calculated displacement at 41,100 h of 4.05 mm agrees fairly well with other calculations by Ontario Hydro. The long-term displacement rate of the end shield will be the same as that of the group 12 pressure tubes, viz 1.9 - 2.0 mm/7000 h.

At 22,500 h the 64 tubes in groups 9 and 12 that are pushing on the end shields have a calculated average compressive stress of 5.2 MPa. This would produce an elastic contraction of 0.34 mm in the pressure tube, and partly accounts for the over-prediction of elongation in Figure 6 at 22,500 h. FM measurements made while the reactor is operating underestimate the elongation of any pressure tubes which have closed their clearance gaps because of elastic contraction resulting from the end load.

The calculated elongation as a function of flux (dashed lines, Figures 5a and 5b) agree reasonably well with the measurements. The elongations for tubes in high flux positions (>85% maximum flux) are reduced because these tubes are end loaded as a result of interaction with the end shields.

The measurement error estimated for the fuelling machine techniques is insufficient to account for the ± 2 standard deviation error bands shown in Figure 6. Other sources of data variance are tube-to-tube variation in material properties, and the distribution of initial clearance gaps. The true variation in elongation rates from texture and metallurgical structure is presently unknown, particularly for the transient term. Therefore, to illustrate the possible effect, we will ignore the transient and estimate a ± 10% variation in steady-state elongation rates. Tubes in groups 9 and 12 were subdivided assuming a normal distribution of rates as shown in Table 4; the elongation-time behaviour is shown in Figure 10 for group 12. The spread of elongations at 22,500 h appears consistent with the estimated variation in steady-state elongation rates, but all tubes have been slowed down, as a result of end loading, to a similar rate by 41,100 h. However, the scatter in experimental elongations at 41,100 h is much larger than predicted by the variation in free steady-state elongation rates. Figure 11 shows the induced end load stresses which result in tubes in groups 12b to 12e having an elongation rate, equal to the displacement rate of the end shield, of about 1.9 mm/7000 h. The end load stresses at 44,000 h range from 2.7 to 18.7 MPa. At 22,500 h the end load stresses in groups 12d and 12e are 14.9 and 21.7 MPa respectively. Thus FM measurements would have underestimated the elongations of these tubes by 0.99 and 1.44 mm respectively. The fastest tubes in sub-groups 9e and 12e close their clearance gaps at 17,000 h and there is a more gradual build up of load on the end shield than when all tubes were considered to have the same elongation rates, as shown by the dashed line in Figure 7. At 22,500 h, it is calculated that 44 pressure tubes are pushing on the end shields, producing a total load of 0.49 MN (110,000 lbf).

Figure 12 considers the possible effects of variation in initial clearance gap. The curves are for tubes in group 12 whose initial gaps have been defined assuming a normal distribution about the mean of 17.5 mm, with a standard deviation of 0.6 mm, as shown in Table IV. At 22,500 h the variation in initial gaps of tubes with the same elongation rate has little effect on the elongations. However, by 30,000 h the elongations of the tubes directly reflect their variation in initial gaps, and retain the same difference with further elongation. The initial variation in gaps appears to account for about half the observed variation at 41,100 h. Both effects considered here predict no further spread in the scatterband of the elongation measurements as long as the tubes remain end-loaded. Collectively, the variation in material properties and initial clearances, and in measuring errors predict scatter in good agreement with the experimental data.

6. SUMMARY

The axial elongation rate deduced from an analysis of elongation of the Zircaloy-2 pressure tubes in the Pickering unit 1 and 2 reactors has been modified to apply to the pressure tubes of the Douglas Point reactor by taking into account textures and dislocation densities of the pressure tubes. Using this elongation rate, and structural data unique to the DP reactor, the ACCORD analysis predicts elongation behaviour in good agreement with measured elongations, for both the time and flux dependencies. The free, steady-state elongation rate, attained after about 40,000 h is 2.85 mm/7000 h, calculated from the value of 4.6 mm/7000 h found for Pickering units 1 and 2. Once the preload of 1.56 MN is exceeded at 26,800 h, approximately 160 tubes are being end loaded and slowed down by the end shields, producing a calculated elongation rate of 1.9 mm/7000 h by 40,000 h in good agreement with the measured rate. All pressure tubes that load the end shield will elongate at this rate, independent of their material properties. The end-load induced compressive stress will depend on the material property constants, and has been calculated to be 13 MPa for tubes elongating at the average rate. As a result of their common elongation rate, the difference in elongation between adjacent, end-loaded tubes, which affects coolant feeder pipe spacing, will not exceed the difference in their initial clearance gaps.

7. ACKNOWLEDGEMENTS

We wish to thank the staff of Douglas Point NGS and the personnel at Ontario Hydro Central Nuclear Services and Ontario Hydro Research Division who helped to make the pressure tube elongation measurements. Valuable discussions with P.A. Ross-Ross are gratefully acknowledged.

8. REFERENCES

1) V. Fidleris, Factors Affecting In-Reactor Creep of Zirconium Alloy Tubes, presented at the Conference on Reactor Materials Science, Alushta, USSR, May 29-June 1, 1978.

2) M.B. Carver and S.R. MacEwen, Appl. Math. Modelling, 2 (1978) 280.

3) S.R. MacEwen and A.R. Causey, Nucl. Tech. 44 (1979) 118.

4) A.R. Causey, S.R. MacEwen, H.C. Jamieson and A.B. Mitchell Measurement and Analysis of the Elongation of Zircaloy-2

Pressure Tubes in Pickering Units 1 and 2, to be published in Nuclear Engineering and Design, 1980.

5) R.A. Holt and E.F. Ibrahim, Acta Met., 27 (1979) 1319.

6) J.S. Foster, The Douglas Point Nuclear Power Station, Atomic Energy of Canada Limited, Report AECL-1587, 1962.

7) R.A. Holt, J. Nucl. Mater., 82 (1979) 419.

TABLE 1: Statistical Data Used in our Analysis of Elongations

Group	% Flux	Number of Tubes	22,500 h-FM		41,100 h-FM		41,100 h-Theodolite	
			Mean (mm)	s_T (mm)	Mean (mm)	s_T (mm)	Mean (mm)	s_T (mm)
1	52	6	1.46	0.75	3.49	1.10	4.45	1.01
2	66	16	0.97	0.45	4.74	1.07	5.54	1.10
3	56	22	0.51	0.45	3.92	0.79	3.90	0.76
4	76	12	1.34	0.49	6.53	1.01	6.35	1.15
5	89	24	1.63	0.63	7.30	1.48	7.83	1.38
6	51	10	1.51	0.56	4.44	0.84	4.27	0.58
7	65	16	1.93	0.95	5.58	1.48	5.55	1.39
8	89	24	2.65	0.65	8.00	1.76	7.57	1.45
9	100	32	2.90	0.79	8.28	1.27	8.46	1.27
10	64	16	2.33	0.57	6.04	1.50	6.08	0.81
11	88	24	3.19	0.60	7.50	1.48	7.84	1.07
12	100	32	3.23	0.61	8.18	1.27	8.10	1.05
13	53	22	1.25	0.62	4.92	0.92	4.36	0.96
14	72	12	2.16	0.49	6.77	0.93	6.36	0.81
15	84	24	2.36	0.61	7.07	1.22	6.89	1.22
16	61	8	1.08	0.53	4.95	0.91	5.08	0.93
17	51	8	0.54	0.54	3.94	0.59	3.86	0.62

TABLE 2: Parameters for the Creep and Growth Equations

Parameter	Pickering	Douglas Point
B	0.055	0.003
E	1.39	1.38
G	0.414	0.447
K_c	8.8×10^{-27}	8.6×10^{-27}
K_g	1.3×10^{-24}	1.14×10^{-24}
A	-1.1×10^{-24}	-7.3×10^{-25}
τ	1.0×10^{21}	1.5×10^{21}
σ_p	96 MPa	95 MPa
A_o	1.70×10^{-3} m^2	1.07×10^{-3} m^2
ℓ_o	6.07 m	5.28 m
ϕ_{max}	1.85×10^{17} n.m^{-2}.s^{-1}	1.51×10^{17} n.m^{-2}.s^{-1} E>1 MeV

TABLE 3: Contact Times for Pressure Tube Groups

Group	Number of Tubes	Time Clearance Gap Closed (h)
9	32	21,400
12	32	21,400
5	24	24,000
8	24	24,000
11	24	24,400
15	24	25,600

TABLE 4: Subdivision of Pressure Tube Group 12

Subgroup	Number of Tubes	Value	Steady-State Free Elongation Rate mm/7000 h	Initial Clearance Gaps (mm)
12a	2	mean -20%	2.28	16.3
b	8	mean -10%	2.57	16.9
c	12	mean	2.85	17.5
d	8	mean +10%	3.14	18.1
e	2	mean +20%	3.42	18.7

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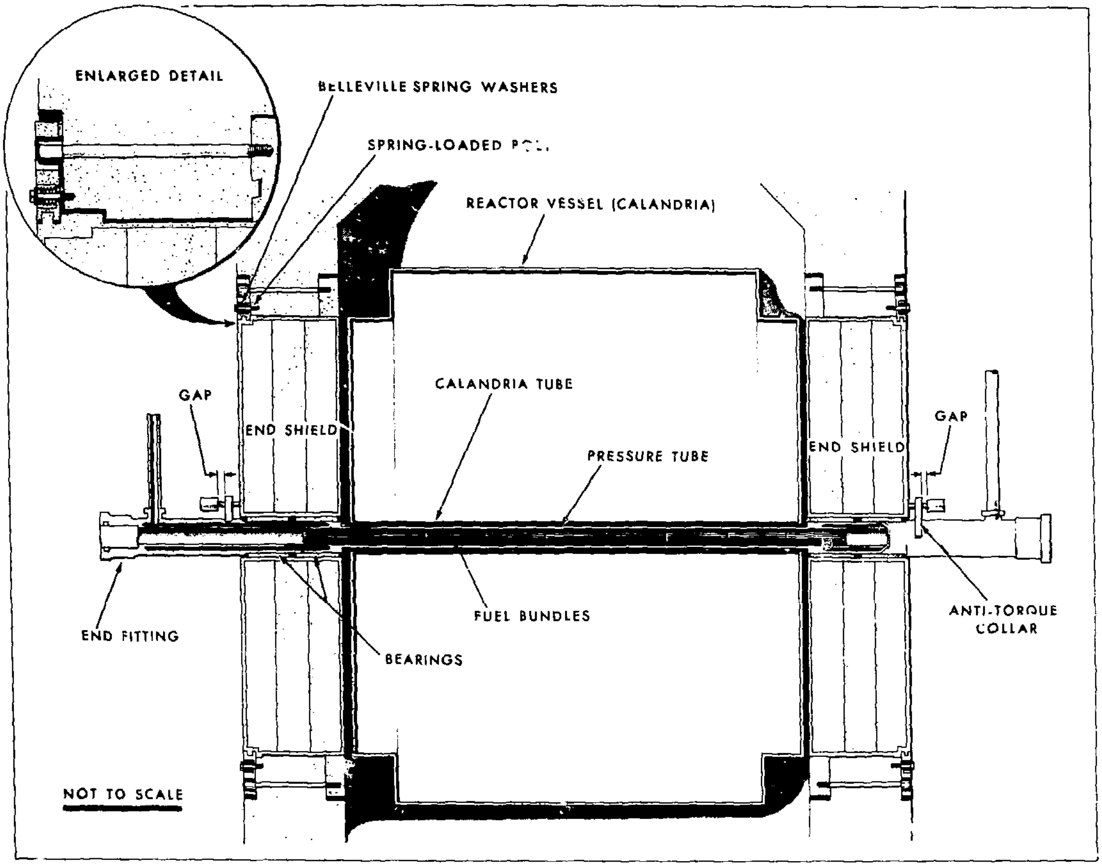

FIGURE 1: Simplified diagram of core components in the Douglas Point reactor.

Channel Elongation (mm)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A								3.5	4.4	6.3	4.2	4.8	3.7							
B						4.1	4.8	4.9	5.6	7.1	6.7	5.2	5.5	3.3	4.4					
C				3.0	4.0	3.2	3.6	5.7	5.7	7.1	6.2	6.6	5.7	5.2	4.2	3.8	3.1			
D			3.6	4.8	5.2	5.4	7.1	7.8	8.8	9.0	7.4	7.7	7.0	7.1	6.4	3.6	3.6	2.1		
E			3.8	5.3	5.9	6.8	8.0	5.6	10.0	8.3	8.4	7.0	6.0	7.1	4.8	6.0	4.1	3.5		
F		3.2	4.6	6.2	8.7	8.1	8.5	6.7	9.8	4.3	9.1	9.4	9.3	8.7	4.9	6.9	5.6	4.8	3.3	
G		4.4	5.4	7.6	6.3	7.8	9.4	8.5	9.6	9.8	7.2	9.1	8.9	9.0	5.9	6.8	5.7	1.4	3.1	
H	3.5	3.7	7.3	6.2	8.2	7.9	7.1	7.5	5.7	7.5	7.0	6.5	6.5	8.1	9.6	9.5	5.5	4.7	5.3	4.5
J	4.0	4.4	5.5	8.7	9.7	6.9	8.5	9.4	7.0	8.9	11.2	9.4	8.9	9.0	9.1	9.7	7.8	7.2	5.4	4.4
K	4.2	5.2	8.1	7.3	9.0	—	10.1	9.8	7.5	9.1	9.4	9.4	9.1	7.2	6.7	7.4	5.0	6.6	4.4	2.9
L	4.8	6.6	6.9	9.2	6.8	6.5	9.1	6.6	5.4	9.2	8.0	9.2	8.7	6.3	8.7	7.3	7.0	6.2	5.1	4.2
M	3.7	5.8	7.3	7.0	6.4	8.4	6.6	6.7	6.7	7.6	7.8	8.7	7.9	8.8	7.4	8.3	6.9	7.3	5.2	4.5
N		5.4	6.3	8.6	8.8	8.9	8.4	9.3	7.6	8.1	9.8	8.8	8.8	8.5	9.7	8.5	6.7	6.8	5.3	
O		4.7	6.3	7.9	7.8	6.9	7.7	7.5	9.0	8.6	7.4	9.5	8.5	8.7	7.7	7.1	7.4	6.5	5.0	
P		4.5	3.8	6.3	5.6	8.4	7.3	7.5	7.4	8.7	7.1	8.0	8.1	7.2	7.3	6.5	6.3	4.8	3.8	
Q			4.2	6.3	5.5	6.6	6.0	7.3	6.7	7.3	8.0	7.2	6.8	7.5	6.0	5.5	4.9	5.3		
R			2.5	5.8	5.4	6.3	2.3	7.3	6.4	6.5	6.9	6.3	6.0	5.4	6.2	5.3	3.1	3.3		
S					3.8	3.7	3.2	5.5	5.6	6.0	4.7	5.8	5.4	4.4	5.1	4.2				
T						3.8	4.0	2.9	3.6	3.6	5.1	4.2	3.8	3.7	3.7					

THEODOLITE DATA

FIGURE 2: Theodolite data at 41,100 h.

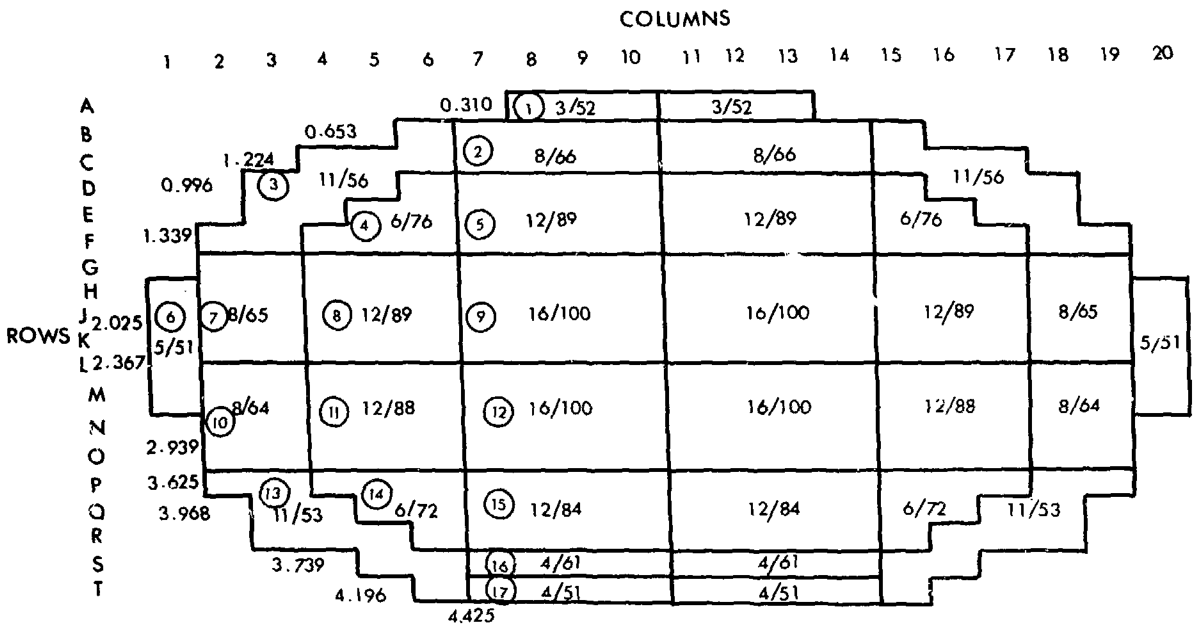

FIGURE 3: Flux distribution of DP reactor with tube groups and locations.

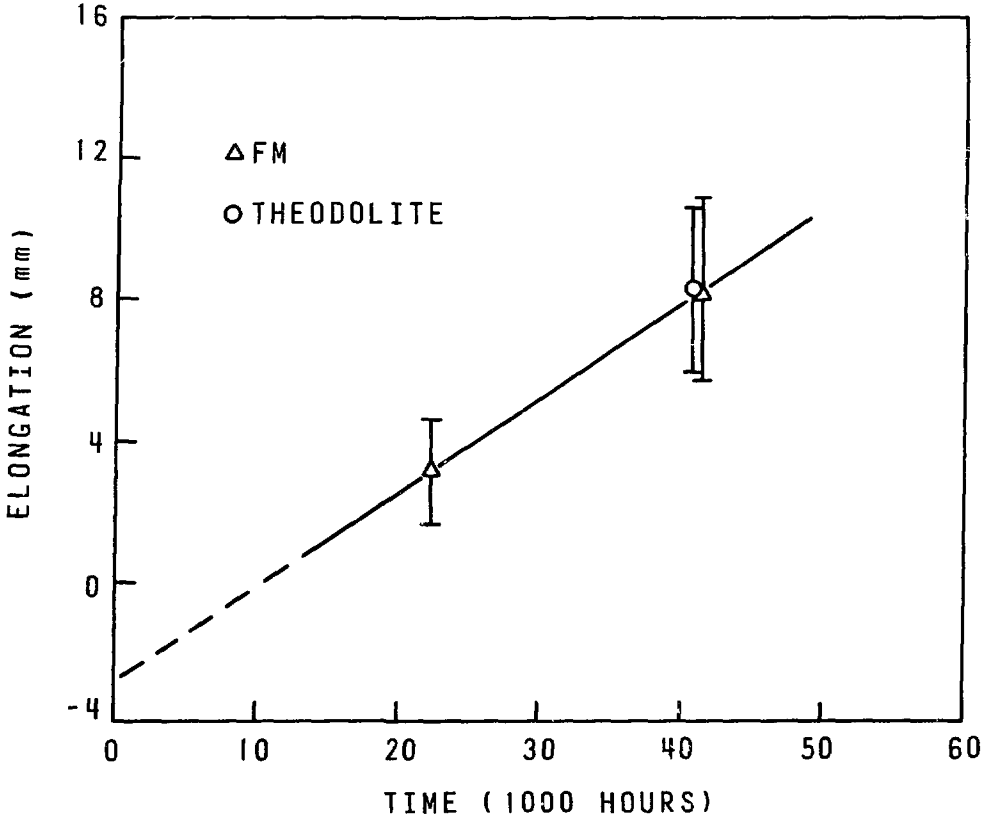

FIGURE 4: MEAN PRESSURE TUBE ELONGATIONS WITH ± 2 STANDARD DEVIATION SCATTERBANDS FOR HIGH FLUX TUBES.

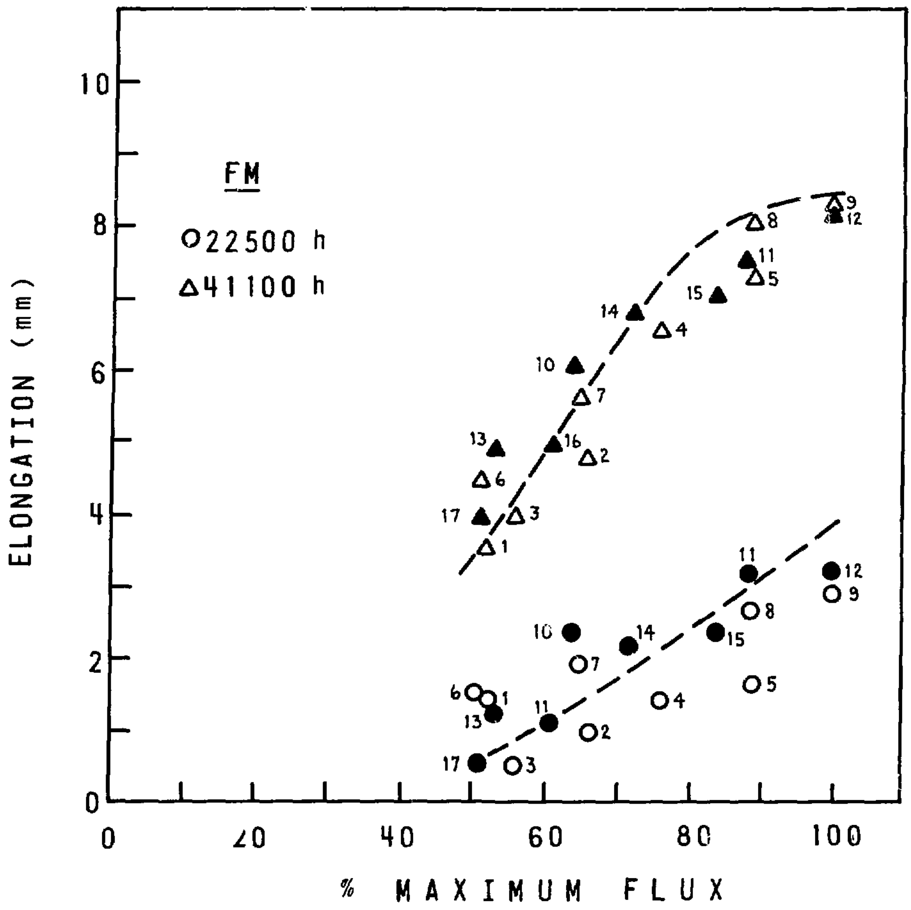

FIGURE 5a: MEAN ELONGATION AS A FUNCTION OF PERCENT FLUX FOR FM MEASUREMENTS; SOLID SYMBOLS DENOTE GROUPS LOCATED BELOW THE HORIZONTAL CENTRE LINE OF THE REACTOR WHILE OPEN SYMBOLS DENOTE THOSE ABOVE; NUMBERS REFER TO GROUPS IN FIGURE 3. DASHED LINES ARE CALCULATED BEHAVIOUR.

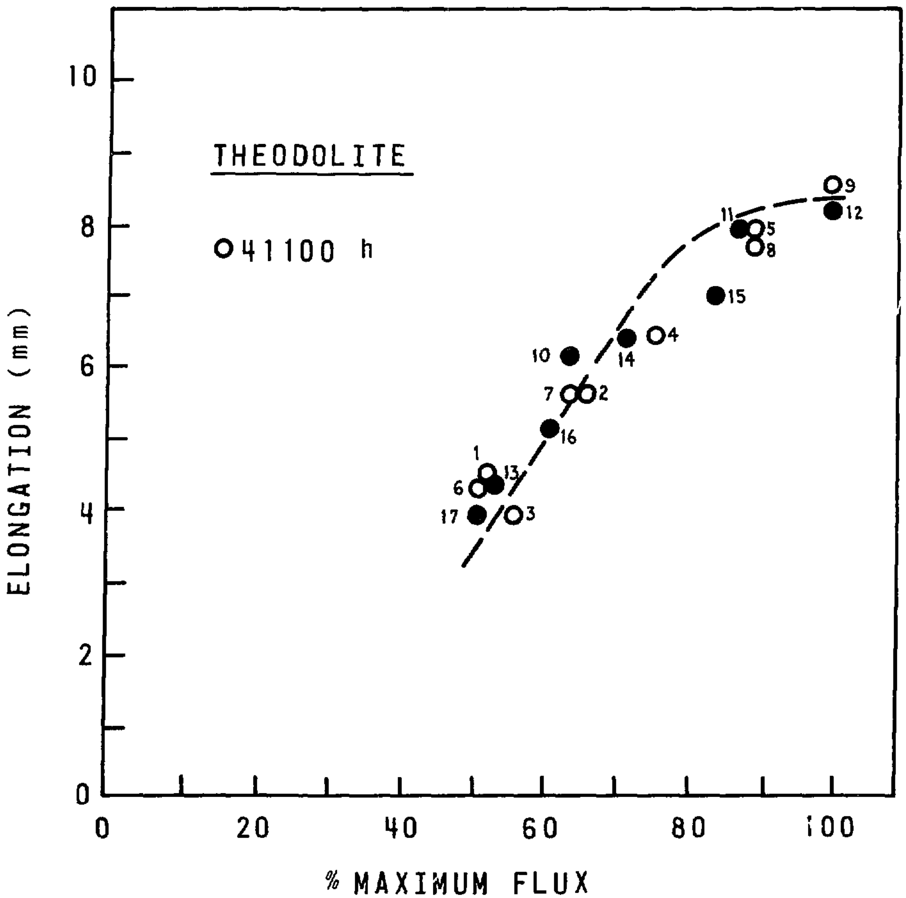

FIGURE 5b: MEAN ELONGATION AS A FUNCTION OF PERCENT FLUX FOR THEODOLITE MEASUREMENTS; SOLID SYMBOLS DENOTE GROUPS LOCATED BELOW THE HORIZONTAL CENTRE LINE OF THE REACTOR WHILE OPEN SYMBOLS DENOTE THOSE ABOVE; NUMBERS REFER TO GROUPS IN FIGURE 3. DASHED LINES ARE CALCULATED BEHAVIOUR.

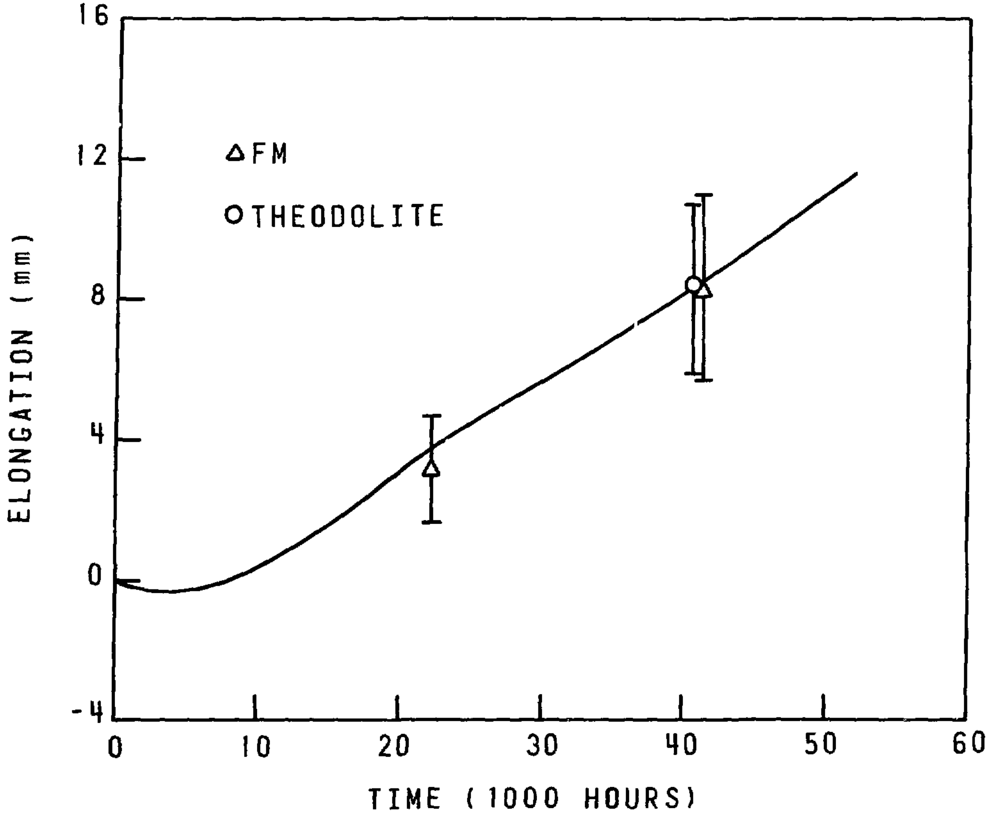

FIGURE 6: CALCULATED PRESSURE TUBE ELONGATION WITH TIME, FOR GROUPS 9 AND 12.

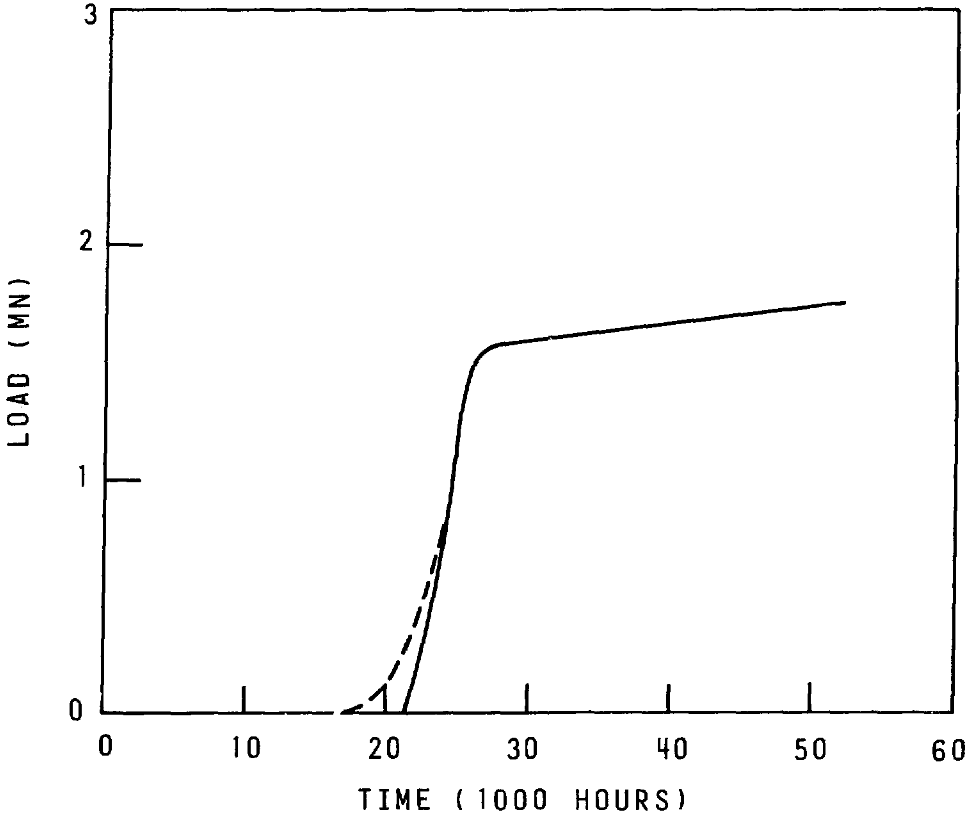

FIGURE 7:

LOAD ON END SHIELD AS FUNCTION OF TIME; SOLID LINE-, ALL TUBES WITH SAME RATES; DASHED LINE- TUBES IN GROUPS 9 AND 12 ARE GIVEN DIFFERENT ELONGATION RATES.

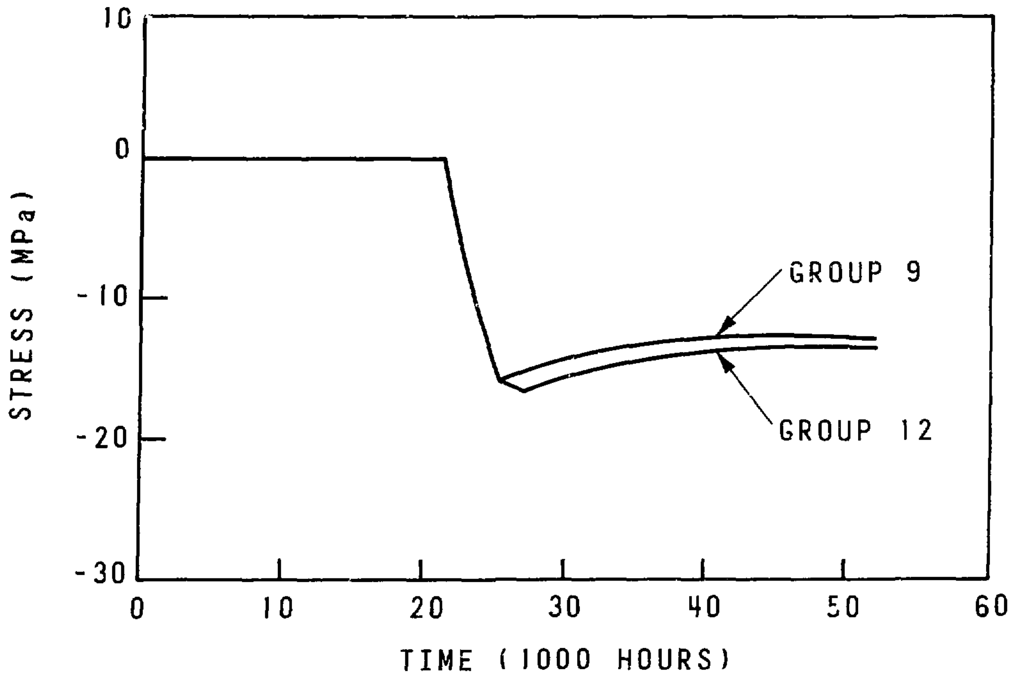

FIGURE 8: COMPRESSIVE END STRESSES IN GROUP 9 AND 12 PRESSURE TUBES.

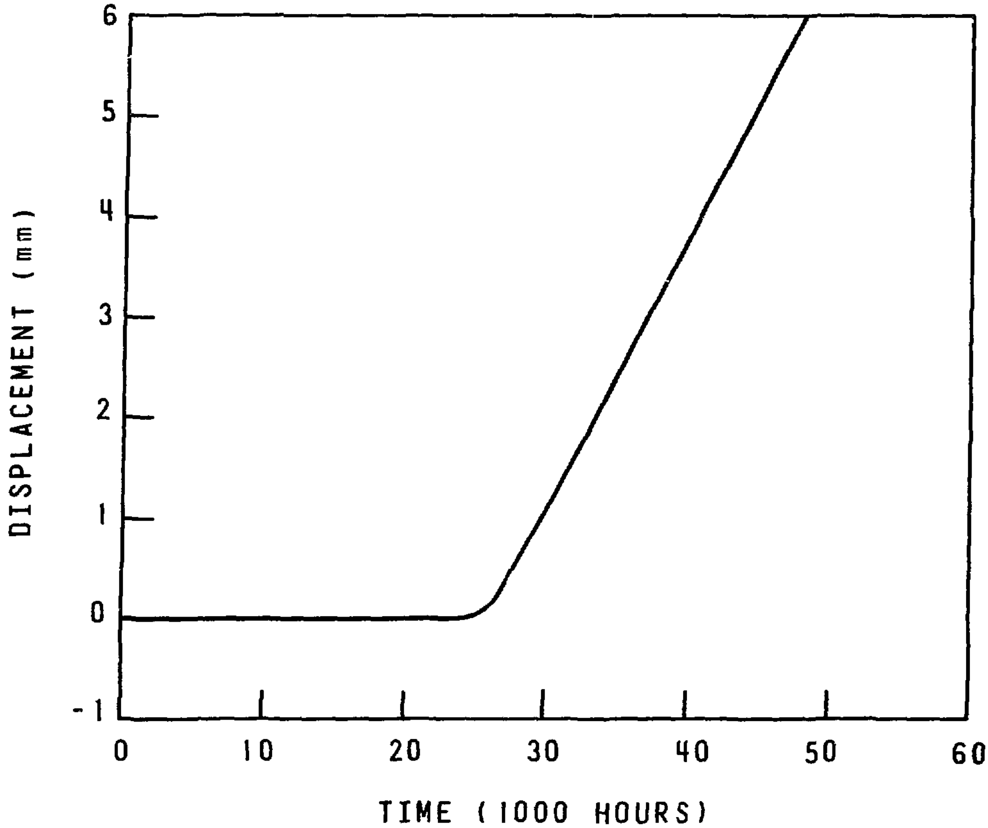

FIGURE 9: DISPLACEMENT OF CENTRE OF END SHIELD WITH TIME DURING OPERATION.

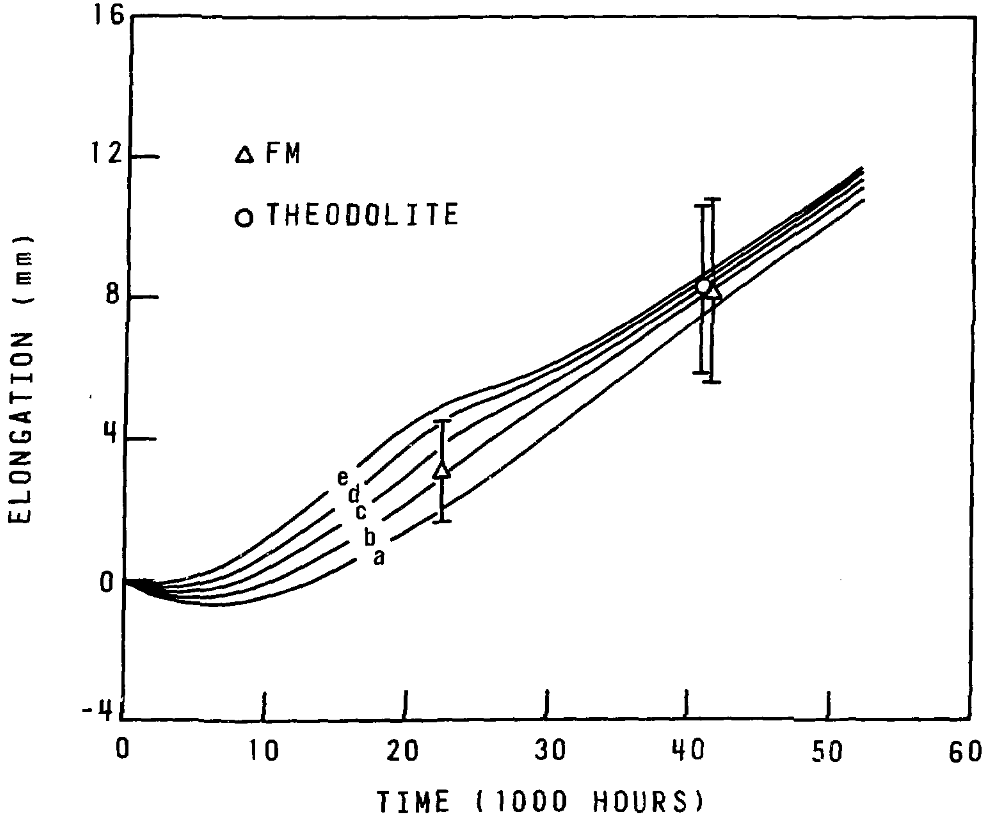

FIGURE 10: EFFECT OF DIFFERENT STEADY-STATE ELONGATION RATES IN TUBES IN GROUP 12.

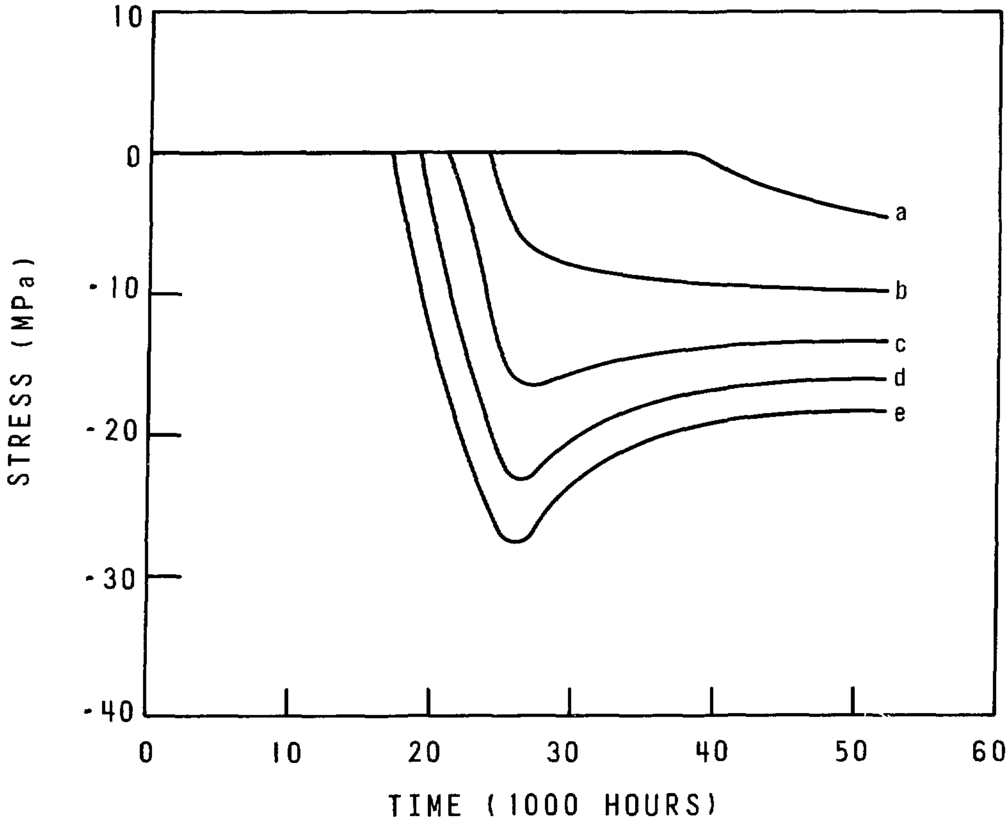

FIGURE 11: COMPRESSIVE END STRESSES IN GROUP 12 PRESSURE TUBES WITH DIFFERENT ELONGATION RATES.

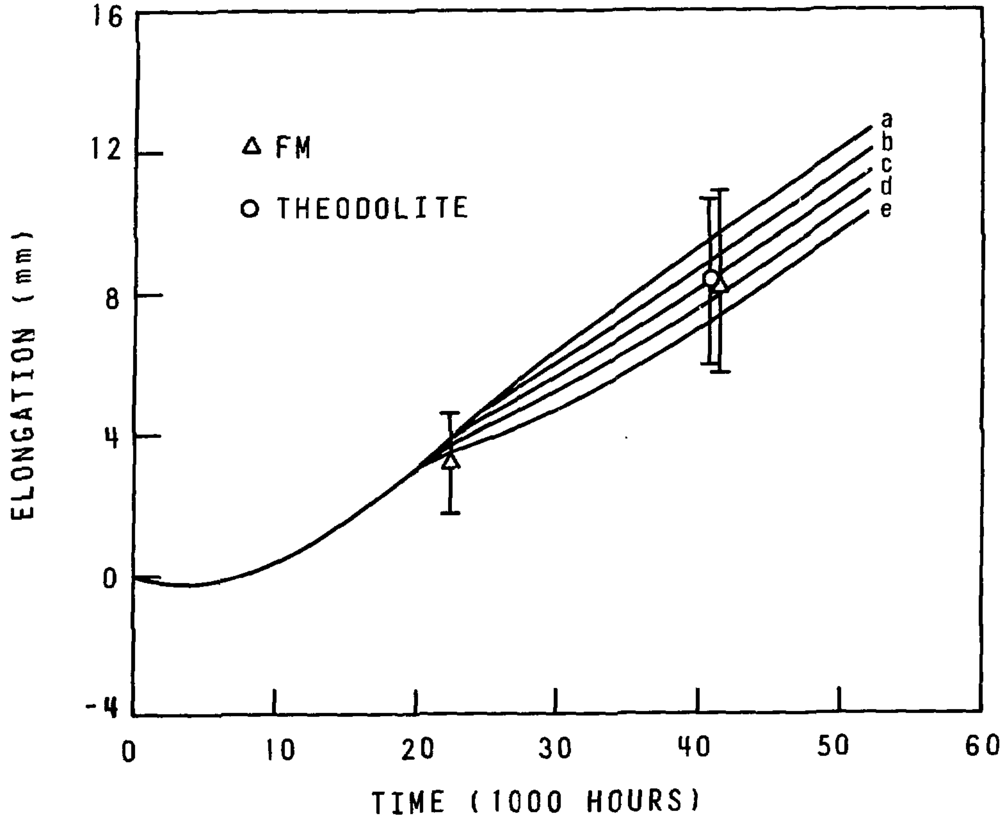

FIGURE 12: EFFECT OF INITIAL CLEARANCE GAP ON ELONGATION WITH TIME.

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