The Strain Behaviour of Prestressed Concrete Reactor Pressure Vessels Over 20 Years Operation

Brian N. Grainger
Central Electricity Research Laboratory, Surrey, UK

1. INTRODUCTION

Construction of the prestressed concrete pressure vessels, (pcpv's) for the Magnox gas cooled reactors, at Oldbury Nuclear Power Station was started in 1962. The R1 vessel was prestressed in 1964, and had a proof pressure test in May 1966 prior to reactor start-up in October 1967. Events for R2 generally lagged by about eight months. These structures have therefore been under load for about 25 years, of which about 20 years have been under operational load. These were the first pcpv's in the UK to be used for nuclear containments and have been the subject of extensive research, both for concrete properties and their structural behaviour. (Hannant, 1967, Hornby et al. 1966, Carmichael and Hornby, 1973, Irving and Carmichael, 1969, Houghton Brown and Darton, 1968). Vibrating wire strain gauges (vwsg's) were built into the vessels during construction and have been regularly monitored to obtain a strain history of each vessel. An assessment of the strain behaviour of R1 vessel was made after 12 years operation (Hornby, 1979). A satisfactory comparison was obtained with predicted strains based on elastic analyses for prestress and internal pressure loads, combined with laboratory thermal creep and elasticity data.

This paper is based on work in support of a statutory Long Term Safe Review (LTSR) prepared by the Station for the regulatory authority, to validate the integrity of the plant for an operational life of up to 30 years. The R1 vessel strain behaviour is updated and reassessed, and data for R2 vessel is included. These regular results were obtained primarily with the vessels pressurised. Therefore, to reaffirm the linear response of the R1 vessel to internal pressure loading, a vessel strain monitoring exercise was undertaken during the 1986 scheduled biennial shutdown.

2. ANALYSES

2.1 Long Term Total Strain Behaviour

The philosophy of the Hornby (1979) assessment report on long term strain prediction has been retained, with the assumption of negligible thermal stress effects and no significant stress redistribution due to creep. The continuing modest thermal gradients in the vessels generally support these assumptions. The total strain has been determined by the superposition of elastic strains and creep strains, with allowance for a creep recovery strain upon initial start-up. (Hornby, 1979). The elastic analyses for prestress and internal pressure were performed using the BERSAFE 2-D finite element programmes, assuming the vessel is an axisymmetric body of revolution. For the 1979 analysis a prestress cable tension of 1793.5 kN was used and from statutory biennial surveillances, detailing tendon lift-off results, this load is still a realistic mean value.

The concrete elastic modulus used in the 1979 analysis was 43.1 GPa with a reduction to 35.3 GPa for the multi-penetrated standpipe zone. A value of 0.18 was used for Poissons ratio. A very small change in age dependent elastic properties of concrete occurs from ages 15 to 25 years and these would have little effect on the stress analysis. The elastic stresses and strains derived for the 1979 assessment have therefore been used. This makes comparison with the 1979 data more direct and any slight increase in the concrete stiffness represents a conservatism in the compressive strain prediction. Also as the concrete temperature levels have remained constant (±3°C) the updating of the predicted strain simply required a revised creep calculation for the further period of operation from 1979, i.e. from 5200 days to 8500 days. The specific thermal creep(s) formula (1) from the 1979 assessment was used. This is based on Hannant's (1967) creep test data on moisture sealed samples of laboratory cast Oldbury concrete, after adjustment to correlate with site concrete strengths (Carmichael and Hornby, 1973). The accuracy of a typical total strain prediction was assessed by Hornby (1979) to be ±18%. As the creep data has been further extrapolated it is considered that the potential variation has increased to ±25%.

$$s = 10.8 + [8.05 + 0.98(T-20)] \log_{10} \frac{(1+t)}{30} \quad \mu\varepsilon/\text{MPa} \qquad \ldots (1)$$

for concrete temperatures (T); $10°\text{C}<T<70°\text{C}$ and period under load $t(\text{days})>30$

3. INSTRUMENTATION

The embedded vwsg's (Strainstall type PC 657/2, 133 mm gauge length) were installed on two vertical sections 180° apart without boiler or blower penetrations (Fig. 1). The plucking coils of the vwsgs were used as electrical resistance thermometers (±2°C), and additional data was obtained from the 224 embedded vessel thermocouples during the 1986 R1 shutdown.

After 25 years service there are about half the R1 gauges and a third of the R2 gauges still functional. Age effects on the gauge factor are negligible as this is a function of fixed physical properties such as wire length, mass per unit length, elastic modulus and cross section area. Also long term relaxation of the gauge wire was eliminated by stabilizing the wire at temperatures far greater than service values (Hornby, 1981).

4. LONG TERM STRAIN MONITORING

4.1 Results

Results are available from 76 primary gauges (55 in R1, 21 in R2), which give 43 data sets after combining results from duplicated locations. The Table 1 lists measured and predicted strain changes between on-load (365 psig) and off-load (unpressurised) conditions. Similarly Table 1 lists measured and predicted total strains from start of prestress to the end of 1987 with the vessels on-load after about 20 years operation. The correlations are shown graphically in Fig. 2 and Fig. 3 respectively, with a ±25% creep tolerance band added to Fig. 3. A comparison of replicate results within and between vessels is about the same as within a vessel.

4.2 Discussion of Strain Histories

4.2.1 Effect of vessel pressure

There was generally good correlation between measured and predicted strain changes (Fig. 2), with the standard deviation between the two values of 17 με. Some of this will be the result of minor thermal stress effects as discussed later with reference to the blowdown results.

4.2.2 Total strain after 20 years operation

Over 60% of the measured values were within the predicted band. Note that instrumentation effects (gauge factor variation ±7% and temperature correction effects ±10 µε) have not been included in this tolerance band. The locations where correlation was poor are itemized on Fig. 3, with only six locations having compressive strains less than predicted. From a review of all strain histories the bulk of any differences between measured and predicted strains occurred during initial prestressing. The locations of, and reasons for, lack of correlation remain as described by Hornby (1979).

(a) difficulty in accurately modelling the complex prestressing system, particularly the 'radial' tendons in the end slabs.

(b) the as-built top cap prestress system was positioned 450 mm higher than the original design data used for the analysis.

(c) approximations used to model the base support to the vessel.

(d) localized cracking created during construction of the vessel as a result of thermal stresses from heat-of-hydration temperature regimes.

(e) the analysis assumes a monolithic structure of homogeneous isotropic material whereas in practice the vessel is a composite heterogeneous structure with multiple steel inclusions and penetrations.

(f) possible erroneous datum vwsg readings.

4.2.3 Strain history creep trends

The trend is of stable and gradually increasing compressive strain that is generally in good agreement with the predicted creep rates (e.g. Fig. 4 and Fig. 5). An exception is in the top centre of the top slab (gauges 61/62C) where creep is greater than predicted, but not excessive. Factors a,c,d and e all contribute to a less precise analysis of the top cap standpipe region, and also there may be some local thermal stress at this location which was not taken into account.

Two locations where nett tensile strain is indicated (20 µε), instead of the predicted compression, are in an area of the bottom slab which had local cracking during construction. Even in these locations the behaviour is stable with negligible change in tensile strain with time.

5. MONITORED SHUTDOWN 1986

The R1 vessel depressurisation can be characterized by two stages (Fig. 6);
1st Stage - an approximately exponential pressure drop to 180 psig as the reactor decay heat is removed via the boilers.
2nd Stage - corresponds to the blowdown operation at almost constant vessel temperature conditions, depressurisation approximately 16 psig/hour.
(The Station unit of vessel pressure (psig) has been retained in this paper);

Two periods of operation of the embedded pressure vessel cooling water (pvcw) system are shown in Fig. 6. This system is attached to the vessel liner and the standpipes and directly affects the vessel thermal regime and hence thermal stresses and strains, particularly in the top cap.

5.1 Blowdown Strain Results

The variation of load induced strain with decreasing vessel pressure was plotted for 64 vwsg's. The reference values (strain = 0) were taken at 365 psig just prior to reactor trip, and subsequent results were corrected for gauge temperature effects. For comparison with the 1986 shutdown strains the change of strain measured (Eadie, 1966) during depressurisation from proof pressure test (ppt) has also been plotted. A comparison between 'blowdown' strain response and ppt results was then made for each gauge by determining the rate of change of strain with decreasing vessel pressure (µε/psig). Typical responses for gauges where thermal stresses changes were minimal are shown in Fig. 7, and both Stage 1 and Stage 2 data were used for the strain response. Where thermal stresses significantly affected the strains (e.g. Fig. 8), only the Stage 2 data was included.

5.2 Discussion of Results

Vessel strain response to internal pressure loading is primarily a function of concrete elastic modulus. From a least squares fit of blowdown and ppt strains per psig internal pressure (Fig. 9), it was found that shutdown microstrain/psig = 0.92 x ppt microstrain/psig. This indicates that the concrete elastic modulus was about 9% greater during shutdown than during ppt.

The possible factors affecting concrete modulus include concrete age, current temperature, moisture content and irradiation. No direct Oldbury concrete elasticity test data is available to quantify age dependency over this 20 year period, but some strength data is available and the well documented strength/modulus relationships for moisture stable concrete can be used (e.g. CP110; 1972). Known strengths are 50 MPa at 28 days for water stored control cubes (Houghton Brown and Darton, 1958), and 77 MPa for equivalent on-site cube strength at 22 years as determined from cores from the outer face of the vessel wall. To obtain the concrete strength increase from 28 days to ppt (3 years) the CP110:1972 and Gonnerman and Lerch (1951) data give a factor of 1.24, i.e. ppt strength would be about 62 MPa. Then again from CP110:1972 the ratio of concrete modulus during blowdown to the modulus at ppt can be estimated to be 1.11 with an estimated variability of ±0.05.

The ppt was conducted with the vessel concrete at about 15°C whereas blowdown concrete temperatures were between 25°C and 38°C. Hannant (1967) gives modulus results for mature sealed Oldbury concrete samples at 27°C and 50°C when kept continuously loaded. Assuming linear dependence on temperatures between 15°C and 50°C the mean reduction in modulus as a result of temperature increase (15°C to 32°C) will be about 5%. The massive sections and modest temperatures in the Oldbury vessel precludes significant moisture loss from concrete. Similarly irradiation effects can be discounted, and so the nett effect of concrete temperature and age differences between ppt and the 1986 blowdown would be an increase in concrete elastic modulus of about 6%. This correlates with the comparison of ppt and blowdown strain responses, which suggests a 9% increase in stiffness over this 20 year period.

6. CONCLUSIONS

The strain histories support the assumption of minimal long term stress redistribution in these PCPV's with modest (<10°C) temperature differentials. The trends of stable continuing compressive creep, in line with predictions based on superposition of elastic and creep strains, indicate continuing compressive stress conditions that support further operation of the vessels under the existing surveillance programme.

The monitored blowdown of R1 vessel after 20 years operation, reaffirmed the response to decreasing vessel pressure was both linear and directly comparable to proof pressure test results, after allowances for concrete ageing and temperature differences.

7. ACKNOWLEDGEMENTS

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Table 1: Summary of Measured and Predicted Strains

Gauge	Pressure Strain (365 psig) με		Strain at 8500 days με		Temperature °C	
	Measured	Predicted	Measured	Predicted	Before s/up	After s/up
1C	-95	-115	115	45	17	24
3/4C	-25	-20	205	225	17	24
10C	-75	-88	-25	75	15	24
11/12C	-54	-56	150	177	20	28
13/14C	-17	-12	202	235	19	30
13/14AC	-8	-6	187	270	17	30
19C	-40	-50	325	280	24	37
25/26C	-115	-126	350	410	20	34
27/28C	-52	-76	350	330	20	37
33/34C	-165	-133	492	445	20	32
39C	-35	-28	300	345	22	33
42C	-15	-29	335	380	18	36
43/44C	-38	-16	169	310	20	28
45/46C	-50	-34	252	280	22	32
48C	-77	-48	297	210	25	35
50C	-85	-77	315	105	22	35
51/52C	5	21	225	385	20	26
61/62C	-2	-45	605	30	23	42
65/66C	35	16	378	420	18	32
67/68C	40	57	430	420	18	25
1/2R	-100	-101	145	70	17	24
9/10R	-45	-31	172	175	15	24
3V	50	43	30	-30	17	27
11/12R	38	34	440	471	20	28
13/14R	-25	-25	-15	-10	19	30
13/14AR	-140	-189	280	-85	17	30
13/14V	-75	-86	560	315	19	30
20V	-60	-57	780	630	19	20
22V	-55	-60	640	605	20	37
23/24V	-5	-29	537	530	18	30
26V	35	10	375	370	20	34
27/28V	-88	-101	560	580	20	37
29V	-110	-113	675	586	24	30
32V	-35	-45	600	540	22	37
33/34V	28	20	410	357	20	32
41V	-150	-160	730	530	18	36
43/44R	-33	-43	48	75	20	28
46R	20	12	330	220	22	35
47/48R	45	30	620	385	25	35
49/50R	50	13	280	285	22	35
51/52R	-62	-63	127	135	20	26
53R	-20	-30	170	245	20	26
56R	-25	-24	260	390	20	40

NOTES: Compression (+)ve
8500 days ≡ 20 years operation at end of 1987
C - Circumferential
R - Radial
V - Vertical

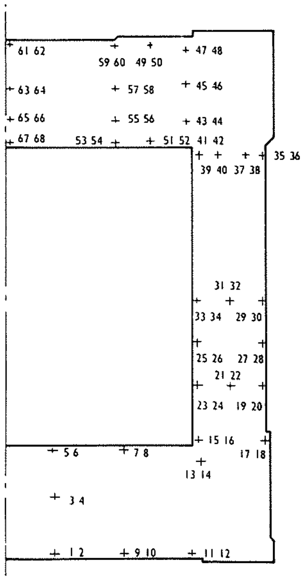

FIG. 1 VIBRATING WIRE STRAIN GAUGE LAYOUT

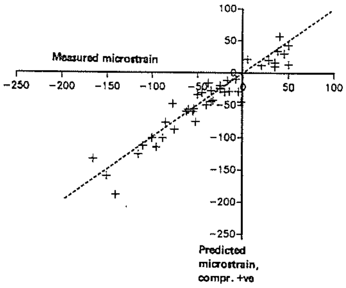

FIG. 2 CORRELATION OF PREDICTED AND MEASURED STRAIN UPON VESSEL PRESSURISATION

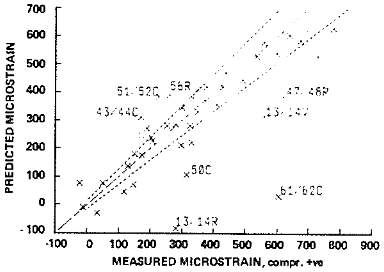

FIG. 3 CORRELATION OF MEASURED AND PREDICTED STRAIN ON LOAD AFTER 20 YEARS OPERATION

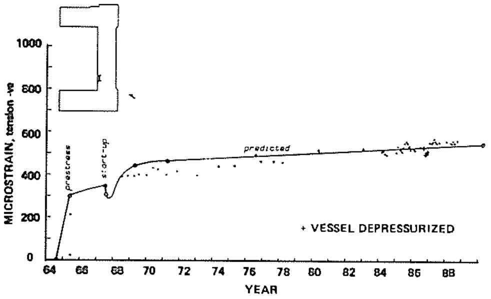

FIG.4 OLDBURY R1 (B) GAUGE G23/V

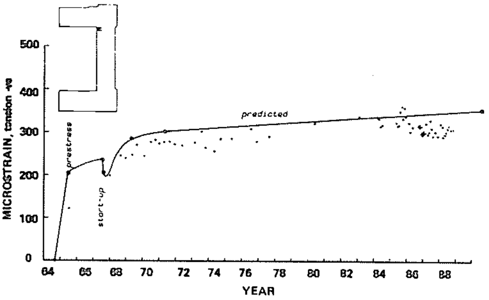

FIG. 5 OLDBURY R1 (G) GAUGE G42/C

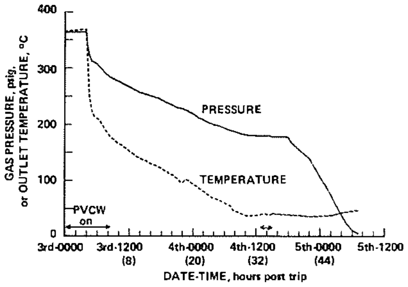

FIG. 6 OLDBURY R1 BLOWDOWN
OCTOBER 1986

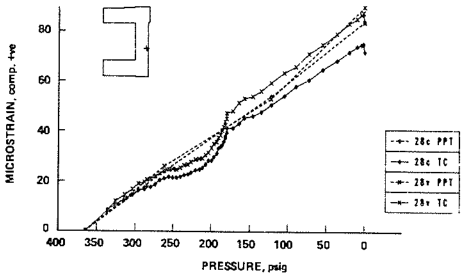

FIG. 7 OLDBURY R1 BLOWDOWN

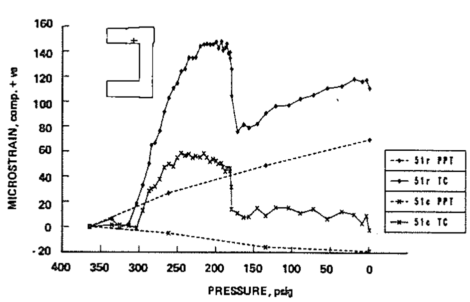

FIG. 8 OLDBURY R1 BLOWDOWN

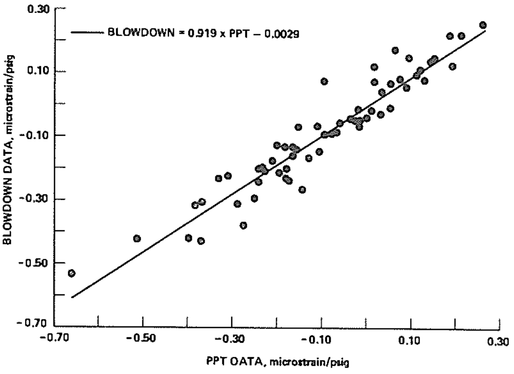

FIG. 9 OLDBURY STRAIN SLOPES