CERL/ORNL RESEARCH AND DEVELOPMENT PROGRAMMES IN SUPPORT OF PRESTRESSED CONCRETE REACTOR VESSEL DEVELOPMENT.

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## INTRODUCTION.

Since the first prestressed concrete reactor vessels (PCRVs) were commissioned in France in 1960 there have been significant advances with respect with their design and development. The first of these was related to the "integral" design concept used at Oldbury-upon-Severn in which both the reactor and steam generators were housed within the same vessel. The "podded" vessel design followed at Hartlepool and Heysham in which the steam generators were located in seperate cylindrical cavities formed within the thickness of the vessel wall, and wire winding was utilised to apply hoop prestress. Current generation PCRV design in the UK is of the single cavity (Hinkley Point B) type, thus eliminating the complexity of the podded vessel approach. In the USA current generation PCRV design, as reflected by that developed by GA Technologies Inc. for a 2240 MW(t) HGTR-SC/C lead plant project, utilises an asymmetric cavity arrangement with an offset core. In support of the evolution of PCRV designs being developed both in the UK and the USA, research and developments programmes are being conducted at the CEGB Central Electricity Research Laboratories (CERL) and the Oak Ridge National Laboratory (ORNL) respectively.

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## CEGB PROGRAMME.

In the UK, recent work has focused on elevated temperature effects on concrete properties and instrument systems for PCRVs

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## ELEVATED TEMPERATURES. (Loose case)

PCRVs are designed for concrete operating temperatures of less than 100 C whereas the maximum gas temperature for a Magnox or Advanced Gas cooled reactor (AGR) is (cir) 650 C. Therefore research on concrete at elevated temperatures is of value in understanding the material behaviour both within and beyond normal operating limits. For example the study of the transient thermal strain behaviour of concrete provides data on the likely response during a hypothetical thermal excursion and the residual state of the material after such an event.

Studies, in collaboration with the Imperial College (University of London), have been made on a number of different PCRV concrete mixes in the temperature range of 20 to 600 C. Two rates of heating were used on unsealed samples at three different moisture states. The different loading conditions ranged from 0 (unloaded) to 1/3 of the ultimate cold compressive strength. All samples were at least 3 months old when put under load.

In this paper is not possible to discuss in detail, research which represents many years work. Comprehensive details are contained in



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the thesis of Khoury (1). However, the two most important properties - strain behaviour and strength, are discussed briefly.

Strain Behaviour.

When concrete is heated the total strain occurring consists of a number of components (2). These result from:

Thermal expansion
Changing moisture content
Chemical transformation
Cracking caused by differential expansion and physical deterioration of the concrete constituents
Temperature dependence of elastic properties
Steady state creep
Transient creep

When a number of concretes were tested, their behaviour was found to be a markedly different. Fig 1 shows the response of 4 mixes at a particular heating rate and load. The mixes were of similar strengths but contained different aggregate types. When however one looks at the load induced strain component (the total strain of a loaded sample less the total strain of its unloaded equivalent) a much closer correlation between the mixes appears (fig 2). This is particulary so at temperatures below 400 C. Using curves of this type it is then posible to look at the effects that load, moisture and heating rates have on the load induced strains.

From the figures, the dominance of the aggregate on the total deformation is clearly seen. However by building up a data bank of behaviour of aggregate types, it would be possible to reconstruct the likely behaviour of any new proposed mix. This nevertheless is in the future, at present there is a great deal of data still to be analysed which will be the subject of future papers.

The use of data derived from experiments using small samples has to be considered with care. In a structure such as a reactor vessel, the rate of heating and the moisture changes will vary considerably through the section, so then, will the load induced strains. Another important consideration is the fact that the strain data such as that described, is derived from load controlled experiments whereas a large redundant structure would likely to be strain controlled under thermal transient conditions. These points indicate the difficulties still remaining but at least information is becomming available which is improving the understanding of total behaviour and will help in formulating future research in this subject.

Compressive Strength.

Concrete mixes, similar to those used for the strain measurements, were investigated to study the effect of temperature on the compressive strength. Strengths were obtained on samples that had undergone one thermal cycle (residual strength) and others whilst the sample was still at temperature. Tests were also made on paste samples of the different cements or cement/pfa blends currently in use.

As with the strain measurements, the aim was to determine the influence of the mix constitutents - the aggregate and cement paste, and the chemical and physical interaction of the two, on the strength changes.

Generally no mix lost more than 30% of its cold strength at temperatures less than 300 C. At this point the siliceous aggregate tended to deteriorate rapidly compared with the limestone or basalt material. Some of the mixes contained a cement/pfa blend and these pastes were shown to have very little deterioration below 600 C. Pfa had been shown previously to be beneficial to concrete in warm ( 150 C) moist conditions due to its hydrothermal reaction with otherwise potentially deleterious phases in the cement or aggregate.

INSTRUMENTATION.

The continuing policy of the CEGB is to obtain strain data from the operating PCRVs during their service life. All vessels built to date in the UK have had vibrating wire strain gauges embedded in the concrete during their construction. These gauges are then monitored during construction,prestressing and pressure testing, and during the vessels operating life.

One of the objects of the measurements is to confirm the vessel remains in a compressive state of stress during all phases of operation. For this, the stress has to be derived from measured strain - this strain being the sum of stress raising as well as non-stress raising components (ie elastic and creep strain). A more elegant solution is to measure stress directly in place of strain. This objective has eluded engineers for a long time in structures where creep strain is a significant component. In a concrete pressure vessel after, say 10 years, 75% of the total strain is a result of concrete creep.

At CERL, developments using the German Glotzl stress gauge have culminated in the installation of 10 gauges in the top slab of one of the Heysham I reactor vessels (3) and operational data from this installation is now becoming available.

The main problem with earlier installations using Glotzl gauges appeared to be the contact between the gauge and the parent concrete. During the heat of hydration cycle of a large pour of concrete, differential expansion between the gauge and the concrete resulted in the gauge sitting in a 'pocket' at the end of the cycle. In order to overcome this problem, a repressurising tube is included in the current design. After a suitable period from the concrete casting, this repressurising 'tail' can be used to increase the volume of the gauge until contact is reestablished. In the Heysham installation, because the repressurising tube came out at the top of the lift, this repressurising had to be done before the pouring of the next lift.

This was, perhaps, within 3 weeks of the first pour and as events proved this period was not long enough. For subsequent installations a considerably longer time has been recommended.

The result of not fully repressurising the gauge in a prestressed structure is that contact and therefore the registering of applied stress, is not made until sometime within the prestressing operation. From the first results obtained at Heysham, all the prestressing stresses were reading low and it was concluded that this lack of original contact was the cause. After allowing for a 'zero error' subsequent readings are as expected.

Fig 3 shows the stress and strain history at one of the gauge positions during the prestressing and the following 3 years to the proof pressure test. The stress measured at the end of prestress was 3 N/mm. The stress derived from both the strain gauge readings allowing for creep and the analysis, was about 9 N/mm. By using a 6N/mm offset, good correlation is obtained for subsequent readings, those taken during the proof pressure test for example. It is of interest to note from Fig 3, the relation between the stress variations and temperature in the 3 year period. From the data provided by the other gauges and analysis, this variation has been shown to agree with the thermal stress gradient across the top slab. It is encouraging to note that the gauge responds to small stress variations and augers well for subsequent measurements during operation.

Gauges of similar type are being installed in the latest four vessels being built in the UK (Torness in Scotland and the second stage at Heysham). In these installations a different layout has been adopted which enables the repressurising tail to be accessed at a much later stage. It is expected that this will eliminate the 'zero error' problem discussed.

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## ORNL PROGRAM*

The concrete development program at ORNL consists of generic studies designed to provide technical support for ongoing prestressed concrete reactor vessel-related activities, to contribute to the technological data base, and to provide independent review and evaluation of the relevant technology. Recent activities have been related to the development of properties for high-strength concrete mix designs for the PCRV of a 2240 MW(t) HTGR-SC/C lead plant project, and the development of PCRV model testing techniques.

### Development of High-Strength Concrete Mix Designs

Recent design optimization studies at GA Technologies Inc. have indicated that a significant PCRV size reduction can be effected by using 55 MPa (8000 psi) concrete in conjunction with large capacity [13.3 MN (1500 ton)] prestressing tendons (Ref.4). This can lead to substantial cost savings in both the PCRV and secondary containment. However, the use of 55 MPa (8000 psi) concrete for the PCRV design will involve incremental material and developmental costs since previous PCRV designs for the HTGR-SC plants (Fulton and Summit) were based on 45 MPa (6500 psi) concrete mixes. Results of a cost trade-off study at GA Technologies Inc. indicate that despite the incremental costs associated with the development of high-strength concrete mix designs there will still be a several millon dollar cost savings resulting from a reduced PCRV size (Ref.4).

In conformance with requirements outlined in Ref. 5, a testing program has been defined to develop high-strength concrete mix designs utilizing aggregate materials from four sources which are in close proximity to areas representing potential sites for an HTGR-SC/C plant (Ref.6). These sites have been identified as: Florida City/Turkey Point, Florida; Port Arthur, Texas; Pennsylvania/Delaware border area; and Blythe, California. The program is being conducted in three phases. Phase I involves: an evaluation of the suitability of admixtures, one cement, and aggregate materials from each of the above areas; development of 63.4 MPa (9200 psi) mix designs [Ref. 7 requires that the average compressive strength be at least 8.3 MPa (1200 psi) greater than the specified strength.]; and determination of strength and elastic properties at various ages and under different curing conditions. Phase II is concerned with an evaluation of the effect of elevated temperatures up to 316°C (600°F) on both sealed and unsealed specimens. Phase III involves a determination of the creep characteristics of concretes developed under Phase I when subjected to loadings representing 30%, 45% and 60% of their ultimate strength at

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temperatures to 71°C (160°F). Thermal properties and the effects of thermal cycling on strength and elastic properties will also be evaluated under this phase of testing. Activities are presently being conducted in Phase I of this program.

Model Testing Technique Development

Section III, Division 2 of the ASME "Code for Concrete Reactor Vessels and Containments" (Ref. 7) requires a model test whenever a model of a prototype with characteristics similar to those of current design has not been constructed and tested in accordance with code provisions, or if analytical procedures to predict ultimate strength and behavior in the range approaching failure are not established. Because the newer generation PCRV designs include an asymmetric cavity arrangement and offset core, existing model test data that were developed for single-cavity and symmetric multicavity PCRV designs may not meet the intent of the above requirements. Contingency plans are therefore being developed so that a PCRV model test can be conducted in a timely manner should it be established as a requirement for licensing.

Using results of a review of PCRV-related model tests (Ref. 8), it was established that two model testing areas may require some development: circumferential prestressing and leaktight liner systems. A test program has therefore been underway to establish satisfactory methods for circumferentially prestressing PCRV models ranging in size from 1:30- to 1:10-scale, and for lining the models so that they do not leak prematurely to terminate a test. Also associated with this activity was an evaluation of the performance of fibrous concrete.

Activities related to circumferentially prestressing the models were merely to identify a prestressed concrete pipe manufacturer who could apply prestress at a prescribed force level to models ranging in size from about 1- to 4-meters (3-to-13 ft) in diameter. Relative to the liner system, a design was developed which incorporated the use of a 12-gage AISI 1008 drawing quality steel in conjunction with a flanged head. (The flanged head eliminates the corner joint.)

To demonstrate the validity of the above concepts, a 1:30-scale single-cavity PCRV model was fabricated using the representative high-strength concrete [79.42 MPa (11520 psi)] mix design presented in Table 1. The model was tested by hydraulically pressurizing it until failure occurred in the head region at 24 MPa (3475 psi), Fig. 4. During the test both the liner and circumferential prestressing system functioned as designed, thus demonstrating the techniques developed.

An indication of the merit of fibrous concrete for PCRV application was provided by fabricating and testing a second 1:30-scale single cavity PCRV model using fibrous concrete (Table 1) of comparable strength [69.29 MPa (10050 psi)] to the plain concrete. The model was tested by hydraulically pressurizing it until failure occurred by rupturing twenty-three wraps of the circumferential prestressing wire at 27.72 MPa (4020 psi). Even though the circumferential prestressing had failed the liner remained leaktight and continued to contain pressure. As shown in Fig. 5, the head of the fibrous concrete model remained intact and the few cracks which occurred were relatively small and closed on depressurization. These results indicate that the shear strength of fibrous concrete is at least fifteen percent greater than plain concrete at comparable strength levels, and that fibrous concrete exhibits potential as a PCRV construction material.

More details of these tests are provided in Ref. 9.

Table 1. Mix designs for PCRV models

| Material | Quantity, kg/m³ | |
|---|---|---|
| | Plain | Fibrous |
| Type II Cement | 529 | 521 |
| Fly Ash | 69 | 68 |
| Sand (oven dry) | 621 | 612 |
| Coarse Aggregate[a] | 943 | 928 |
| Water | 239 | 236 |
| Fibers[b] | 0 | 88 |
| Admixture | 1360 mℓ | 1360 mℓ |

[a] 19-mm maximum size for plain concrete.
9.5-mm maximum size for fibrous concrete.

[b] Grade 1008 steel, 50 mm length, 0.5 mm diameter, collated with hooked ends.

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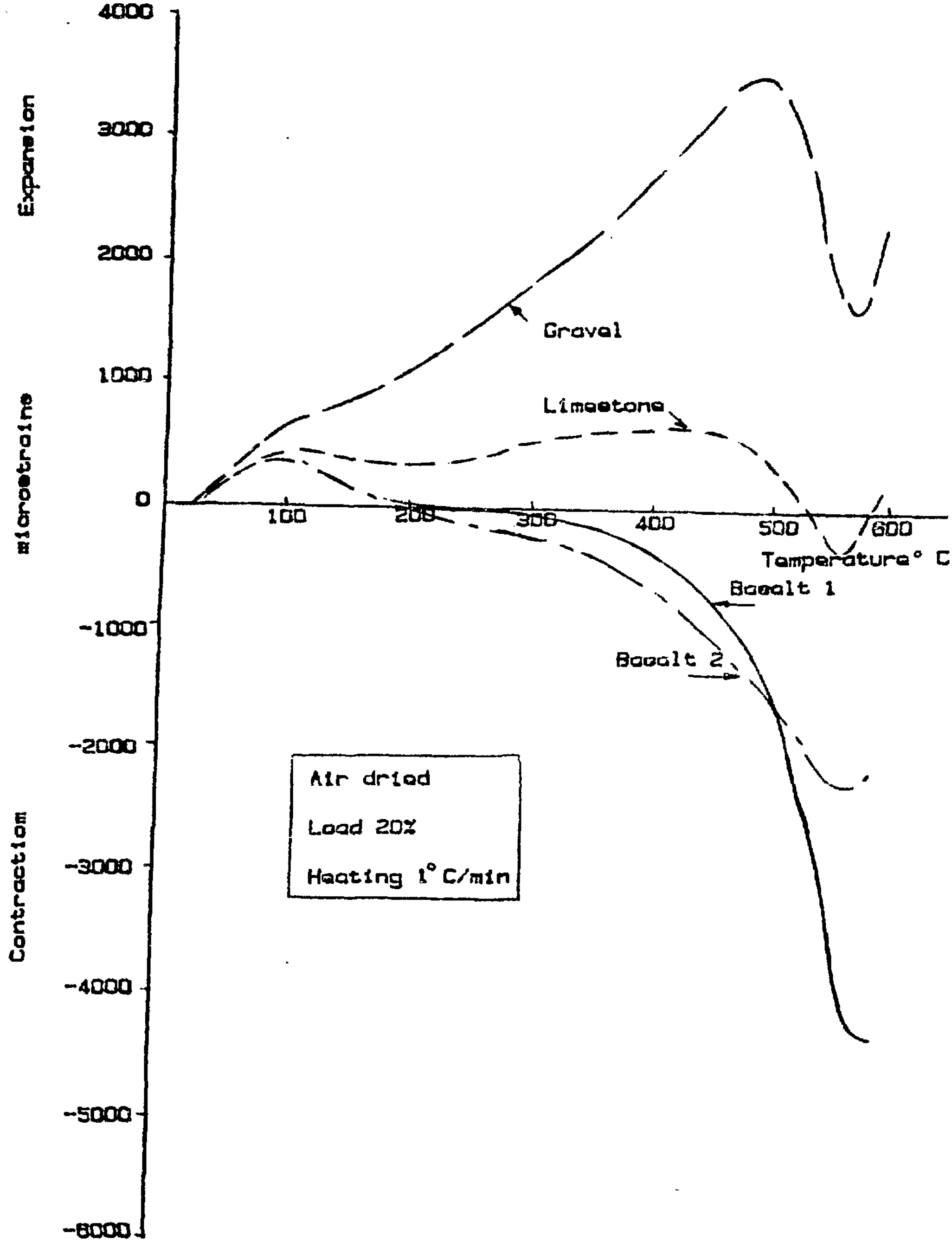


FIG. 1. TOTAL STRAIN OF 4 CONCRETES ON FIRST HEATING.

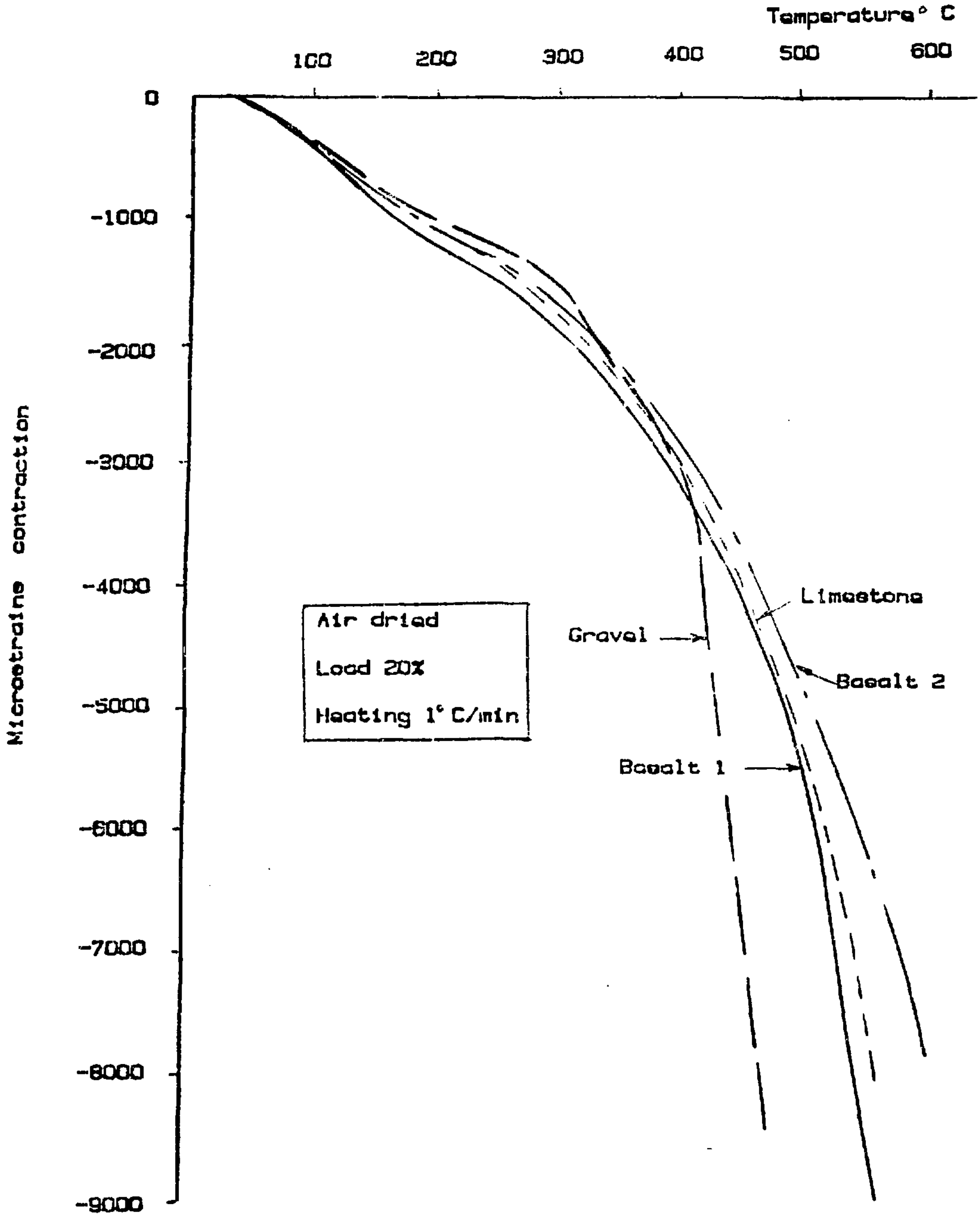


FIG. 2. LOAD INDUCED STRAIN OF 4 CONCRETES ON FIRST HEATING.

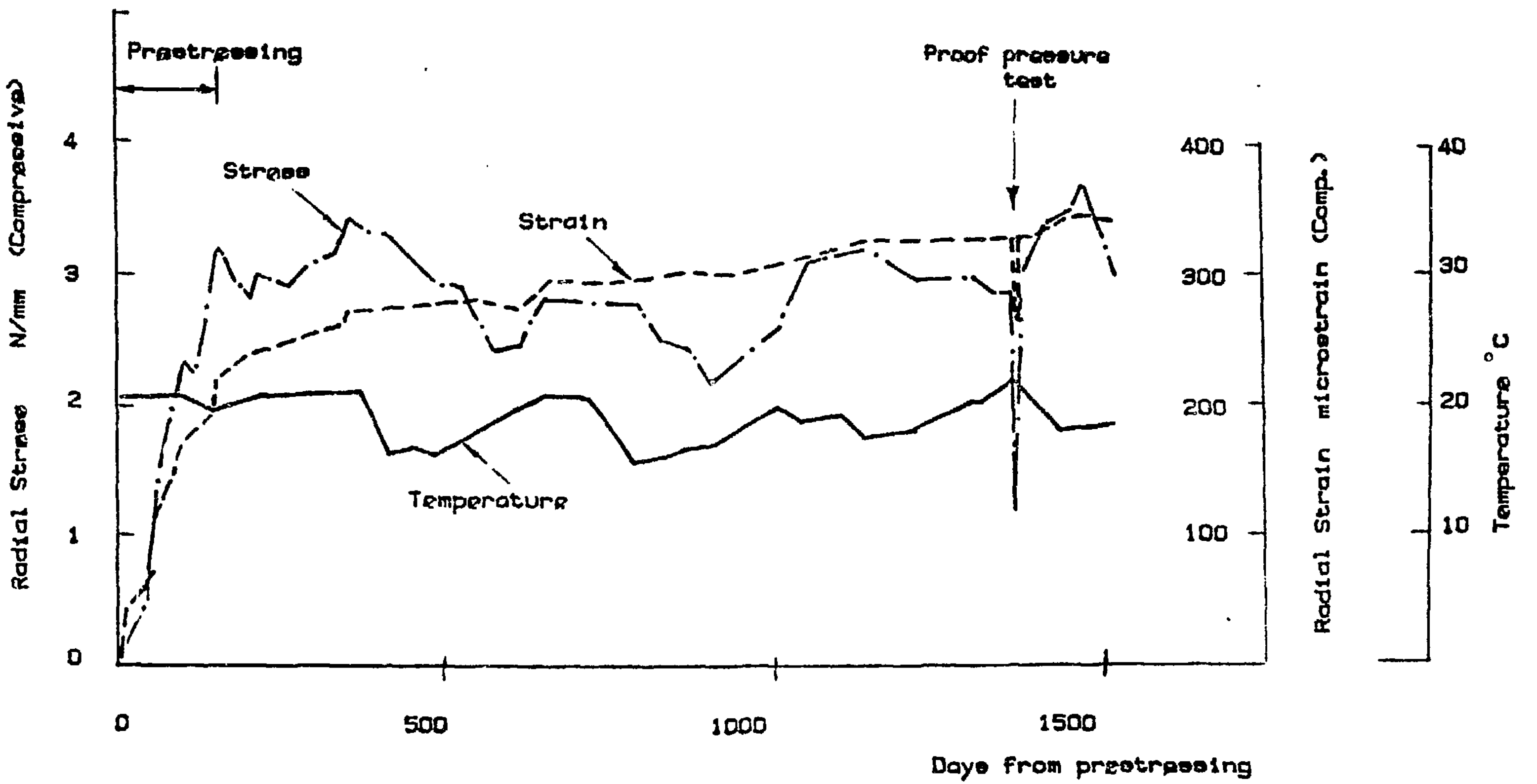


FIG. 3. STRESS STRAIN AND TEMPERATURE VARIATIONS AFTER START OF PRESTRESSING