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THE COLLEGE OF AERONAUTICS

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# Stress redistribution due to creep in Nimonic 90

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- by -

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## SUMMARY

The period covered by this report has been devoted to the design, construction development and calibration of a special apparatus to simulate the stress redistribution conditions occurring during the creep of a cooled turbine blade. The experimental assembly consists of two creep machines, each operating at a different temperature, so controlled that a load is shared between them, maintaining equal creep strains (and in consequence equal creep rates) in each specimen. The stress in each specimen and the creep strain of the pair are automatically measured and recorded by a specially developed unit. Some preliminary results on an aluminium alloy are presented.

## Contents

## 1. Introduction

The basic concept upon which this work has been based was suggested by Barnes in 1962(1). In particular this work sets out to provide answers to the three-bar problem described in that report; the three bars representing a model of actual turbine blade conditions.

The 'three-bar problem' arises from the geometry of the simplest array for stress-redistribution. This array (Fig. 1 after Barnes) consists of a rigid array of three bars, the cross-section of the middle one being equal to the sum of the cross-sections of the outer bars. These in themselves are identical, and are disposed symmetrically about the axis of the middle bar; the axes of all three bars being parallel. At their ends, all the bars are anchored to inflexible end pieces to which a force can be applied, such that the stress in each bar is equal if all three are at the same temperature.

If now the outer bars are heated to a higher temperature ($T_2$) than the inner bar ($T_1$) stresses are developed. The outer bars are put into compression and the inner bar in to tension, the magnitude of the tensile and compressive stresses being equal. Thus if we take the magnitude of these stresses to be x t.s.i., then if this and the temperature of the bars is high enough, and the time at temperature long enough creep will occur in the bars and the stress will relax. If the stress and temperature conditions are more severe relaxation may occur by rapid plastic flow as distinct from creep.

Now if an external load is applied such as would give a tensile stress y t.s.i. in all the bars when these are at the same temperature, the initial stresses would be $(y - x)$ t.s.i. in the outer bars and $(y + x)$ t.s.i. in the inner one. If now, for simplicity, it is assumed that $y > x$ i.e. $(y - x)$ is a small tensile stress, it can be seen that if the bars remain rigidly coupled, then the creep rate at $T_1$ under a stress of $(y + x)$ must equal the creep rate at $T_2$ under the stress of $(y - x)$. Should these conditions be met, then there is no reason for any redistribution to occur unless, as is probable, the primary, secondary and tertiary stages of creep are not identical for the given pair of conditions. For example, the ductility to rupture may be considerably lower at the lower temperature than at the higher i.e. the lower temperature bar may reach the tertiary stage when the higher temperature bar is still undergoing steady state creep. Under these conditions, if the bars remain rigidly coupled some stress redistribution must occur to decelerate the creep of the bar at $T_1$ and accelerate that of the bar at $T_2$.

Should the initial combinations of loads $(y + x)$ at $T_1$ and $(y - x)$ at $T_2$ not give identical creep rates some redistribution must occur immediately. This will be particularly so if $(y + x)$ exceeds the yield stress at $T_1$.

Although rigid coupling of the bars is assumed, it is not part of the assumption that the bar length is constant. In fact, the assembly will

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[1] N.G.T.E. Memorandum M.361 'A note on some aspects of the stress redistribution process in cooled turbine blades at steady high temperature running conditions'. J.F. Barnes.

undergo an overall creep rate, the value of which is not easy to predict. The simple assumption is often made that the rate will be that corresponding to y t.s.i. (i.e. the average stress) at

$$\frac{T_1 + T_2}{2} \quad \text{(i.e. the average temperature).}$$

Since from the engineering standpoint of predicting cooled turbine blade behaviour it would be of considerable benefit to be able to predict the overall creep rate from a knowledge of the initial thermal and loading conditions. From the engineering point of view therefore, the important parameters to be known are:-

1. The temperature of the coldest and hottest part of the structure. The temperature differential will give rise to the expansion stresses.
2. The relative cross-sectional areas of the hottest and coldest parts of the structure. In conjunction with the thermal expansion the ratio of these areas will affect the magnitude of the stresses.
3. Any variation in $\alpha$, the linear coefficient of expansion, in the temperature range in question. In addition the possibility of a phase change must be investigated i.e. if $T_2$ is above and $T_1$ below the $\alpha - \gamma$ phase transformation for a steel under test, some amelioration of the thermal stress conditions would be brought about.
4. The stress-strain curves at $T_1$ and $T_2$ for the proposed material under a strain rate comparable to the service loading conditions. In particular it is necessary to know if any combination of anticipated load will induce plastic flow.
5. If any stress arises from Points 1 - 3 this will relax with time due to creep. The rate of relaxation needs to be known.
6. The effect of an external stress will modify the behaviour during stress-redistribution. If plastic flow is induced there may be a very rapid redistribution.

In order to obtain definite experimentally determined information on points 5 and 6 rather than rely on calculations based on single stress, single temperature creep results, a special rig was constructed. This enables, by simulation, the changes in stress during redistribution to be measured together with the overall creep rate. Two independent creep tests are carried out simultaneously on identical specimens, at different temperatures. A total load is applied to the pair of specimens and this is automatically redistributed to maintain the same creep strain in both specimens i.e. as if both specimens were rigidly interlocked. The strain is also monitored.

Various combinations of loading conditions are possible with this simulation. Firstly it is possible to have two sequences of loading:

(a) The specimen-length comparator system is set before the specimens are heated. On heating and then loading the stress redistribution has to take into account changes in length due to thermal expansion.

(b) The comparator is set when the specimens have been stabilised at their testing temperature. Stress redistribution has only then to take into account differences in extension during loading and in the creep rate.

Since sequence (b) is simpler, this has been chosen for the work reported here. On loading three possible alternatives can be chosen:

(a) The initial stresses are equal. This simulates the service condition where due to prolonged heating the expansion stresses have relaxed completely and then an external stress is applied.

(b) The hotter specimen carries less than half the load. This is the condition $y > x$ discussed earlier. Stress redistribution during creep should occur, the rate of redistribution being dependent on the relative creep rates at the two temperatures, and the initial proportioning of the load.

(c) The cooler specimen carries less than half the load. Stress redistribution will, it is anticipated, be more rapid than (b) above. Some plastic flow in the latter specimen may interfere in the process.

Alternatives (b) and (c) simulate thermal stress or thermal stress plus applied stress conditions.

It can be seen that for the above three conditions that the same pair of temperatures, and the same average stress, could present three different patterns of redistribution. The overall creep curve may also in each case be expected to vary. These possibilities have been investigated in the work reported.

## 2, THE EXPERIMENTAL APPARATUS

This is shown in Figure 2.

The basic function of the apparatus is to measure the creep rates of the two specimens at the two temperatures, compare these rates and where necessary make a transfer of load from one specimen to the other to maintain equal creep rates. This has been achieved by using a volume of water as the combined total load, its redistribution being easily achieved by pumping. The direction of flow through the pumps is determined by an error signal derived from two identical linear displacement transducers mounted on the specimen extensometers.

## 2.1 The mechanical construction of the apparatus

Two standard 2-ton Denison tensile creep machines have been modified so that:

(a) The load may be applied simultaneously to the pair of machines, whilst still retaining the ability to load each machine independently. This independence is of considerable importance in the initial setting up of a test.

(b) The load may be continuously and smoothly transferred in either direction between the two machines. It was considered that a transference by increments of load was unlikely to be satisfactory.

The machines have been mounted alongside each other on a thick wooden platform attached to a rigid steel framework. The framework which carries the pumps, valves and some of the furnance controls, is mounted on anti-vibration feet. The whole assembly is contained within a special insulated room which is thermostatically controlled at 21°C. Entry to this room during a test is via an air trap double door. This precaution was found to be necessary as the brief opening of a door caused immediate changes in the strain readings.

The detailed modifications to the machines themselves have been as follows:-

a) The columns supporting the knife edges were lengthened and their separation increased. These modifications permitted the use of longer furnaces giving a more uniform temperature distribution. The extra diameter of furnaces has enabled the extensometers to be more easily accommodated.

b) The original weight loading system was replaced by a steel drum 15 ins. in diameter and 24 ins. in height with an approximate capacity of 10 gallons of water. Since these creep machines employ a lever ratio of 10:1 a full load of water exerts a pull on the specimen of 1000 lbs. The weight of the drum itself was counterbalanced by an extension arm mounted on the specimen side of the beam and carrying an adjustable weight. In actual operation this counterbalance weight was adjusted to balance both the drum and the residual water left in the drum below the outlet port. Thus the whole load may be removed from one specimen during the test and transferred to the other. Where such a situation is probable the maximum total load can, of course, only be 10 gallons of water. It is, however, possible to add extra fixed weights to the drums for any particular test.

c) A mechanism has been designed ensuring that the load is taken up simultaneously by both specimens. The handwheel on both machines has been replaced by a spring-loaded friction clutch driven by a cog and chain. This mechanism is shown in Figure 3.

During initial loading the clutches are disengaged allowing each machine to be adjusted independently to the point at which the load is just about to be taken up. The furnance is then put into position and allowed to warm up. The machines are then slightly re-adjusted to allow for the expansion and the clutches are then engaged. A common drive chain, driven by a handwheel, then applies the load simultaneously to each machine. The use of a friction clutch allows the two machines to be interlocked at precisely the right positions with no backlash.

## 2.2 The water-loading system

The system is shown diagrammatically in Figure 4. The two load drums are connected to each other by two flexible tubes. One tube extracts water from the bottom of tank A and by means of a pump transfers it to the top of tank B. The other tube transfers water in the opposite direction. Both pumps run continuously, the water flow being controlled by solenoid-operated valves placed between the pumps and the tube outlets. Water only flows into a tank while that particular valve is energised. The rate of flow of water can be adjusted by gate valves in the line. This adjustment is essential if hunting of the load is to be minimised. A water level indicator attached to each tank provides an approximate guide to the load in each tank; this feature being useful in the setting up of a test.

The solenoid valves (24 volt D.C.) are energised via a heavy duty relay from the transducer operated relays as described in Appendix 1.

## 2.3 Furnace construction

Three identical furnaces have been constructed according to the dimensions shown in Figure 5. The third furnace is maintained as a replacement should either of the specimen furnaces burn out.

The furnaces are wound with three zones. The two end windings of each furnace are controlled independently of the central winding as is shown in the diagram of the electrical system in Figure 6. The central winding is controlled by a C.N.S. saturable reactor-controller using a platinum resistance probe located adjacent to the outside of the heating tube (see Figure 5). The end windings are both controlled by an Ether-Transitrol Proportional on-off Controller. The control thermocouple (chromel-alumel) is fixed to the specimen grip. Current distribution between the upper and lower windings can be adjusted by a sliding resistance. The voltage to the end windings is adjusted by a Variac auto-transformer to give a duty cycle of approximately 90% on, 10% off. This minimises hunting effects.

With this system it is found that the temperature distribution over the gauge length can be held within ± 0.5°C over the temperature range 100 - 900°C. Distributions as low as ± 0.1°C have been obtained.

The specimen temperature is measured by a chromel-alumel couple tied to the gauge length. A new couple calibrated directly against International Fixed Points is used for each test. The output of a second thermocouple tied to the gauge length and another tied to the shoulder of each specimen is measured and recorded on a 4-way automatic potentiometric recorder.

## 2.4 Load cells

The load applied to each specimen is measured by a load cell positioned between the specimen and the loading screw. A linear displacement transducer mounted within the cell accurately measures the cell displacement. The design of the load cell is shown in Figure 7 and 7A. By adjusting the radius R in the main body, the sensitivity of the cell may easily be controlled. For the working range of these machines a radius of .312 ins. has been found satisfactory, giving a linear response over the range 0 - 1000 lbs.

Rods screwed into it's body connect the cell to the loading system. The lower rod is used to provide a housing for the transducer, and the displacement is measured between the upper and lower rods. Initial adjustment of the transducer position is easily achieved by adjusting the relative position of these rods. Once the required position is reached the rods are locked by means of the locking nut shown in Figure 7. The calibration of these cells is described in Section 3.

## 2.5 Extensometers

Two types of extensometer have been used, one an elementary pair designed and constructed at Cranfield, the other a more sophisticated pair purchased from the Mand Precision Engineering Co., Stourbridge. The former pair were used during the initial experimentation pending the delivery and subsequent modifications of the Mand pair. This elementary design however, proved successful in operation throughout the preliminary experiments and is therefore described below.

### 2.5.1 Initial extensometer. Figure 8.

Two $^1/_8$ ins. diameter silver steel rods were clamped to the upper specimen grip with one rod on opposite (180°) sides of the specimen. The lower specimen grip was machined from square section mild steel and ground on two opposite faces to provide flat, parallel surfaces for silver steel rollers. The rollers were inserted to ensure true axial movement of the rods relative to the lower grip. The end of one of the rods was in contact with the plunger of a linear displacement transducer clamped in a water jacket to the lower specimen grip.

This simple extensometer system has proved reliable in use at relatively low temperatures with soft alloys but, by virtue of its design, records the elongation of the whole specimen. Thus if appreciable deformation occurs in the shoulders or in the specimen grips the readings of the extensometer would be unreliable. Hence for high temperatures and harder material a more complicated design measuring only the gauge length elongation is required.

### 2.5.2 Mand Extensometers

These extensometers are illustrated in Figure 9. The extensometer locates on two ridges machined at the extremeties of the specimen gauge length (1 inch). Any movement apart of these ridges, i.e. extension occurring in the gauge length, is transmitted to linear displacement transducers by two pairs of arms. The outer pair of these arms is clamped on opposite sides of the upper ridge, the inner pair on the lower ridge. The pairs of arms are held together by springs. Hardened ground rollers inserted between hardened pads on the arms and ground flats on the specimen grips ensure axial movement. The transducers are mounted in water cooled jackets, on the inner pair of arms and initial adjustment can be made by means of the micrometer screws on the anvils mounted on the outer pair of arms.

In normal operation, due to the nature of the comparator circuitry, only one transducer is operative. Pre-loading checks using both are however carried out for axiality of loading.

### 2.6 The Linear Displacement Transducers and Automatic Indicating Equipment

The transducers used both on the extensometer and within the load cells are standard Sogenique Type D linear displacement transducers[2]. They consist of two basic parts, an interpolating head and a reference shaft passing through this head to form a differential capacitor. The linear range of these transducers is from zero to 0.1 inches. With the indicator used for the apparatus the sensitivity is 1 part in $10^{-5}$ inches. The reference shaft which consists of two annular rings is fed with an alternating voltage and the voltage induced in the head corresponds to its position along the shaft. Since the head is wider than the ring elements the transducer acts as a differential capacitor interpolating to provide an analogue output related to displacement.

Cascaded voltage transformers are used in the a.c. bridge - indicator unit to balance the transducer output. The detection of the null point is indicated on a central reading meter. The tapping points of each of the voltage dividing transformers are connected to separate uni-selector switches. These switches are then automatically driven by the error signal from the out of balance bridge. Neon number tubes illuminated by the position of the uni-selectors display the displacement numerically. Print-out connections are available in parallel from these tubes. An Addo X number printing machine has been connected for this purpose.

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[2] Sogenique (Electronics) Ltd., Newport Pagnell, Bucks.

### 2.7 Programming and Control System

The basic requirements of the control system are as follows:-

a) Both loads and the specimen extension must be recorded at predetermined and accurately known times.

b) The difference in readings between the two strain transducers (hereafter called the error signal) must actuate the load transfer system. Due account must be taken of the sign of the difference if the strain rate equalizing system is to function.

c) As it would be extremely expensive to duplicate the transducer measuring bridge the one bridge must be able to work into both the load transducers and a strain transducer, returning automatically to the differencing system after measuring these three transducers. In order to prevent a serious departure from the equalized strain rate condition the time devoted to these three measurements should be as short as is feasible.

d) As the amplitude and polarity of the error signal is dependent upon the position of the uni-selector switches, these switches must be positioned to a preset point and locked there before the load transfer system can operate.

A detailed description of the circuitry which has been developed to fulfil these conditions is given in Appendix 2.

## 3. Furnace Testing

Considerable attention was paid to the design and construction of the furnance giving both close control of temperature and even distribution over the specimen gauge length and shoulders.

In assessing the performance of the furnace and controls calibrated thermocouples were attached, one to the centre of the gauge length and one to each shoulder. The controls were then adjusted so that the maximum variation between the three couples was within $\pm\frac{1}{2}$°C.

When this distribution (or better) had been achieved a record of the settings was made. This procedure was repeated at 50°C temperature intervals over the whole range of the furnace.

### 3.1 Calibration of Load Cells

The load cell, mounted in the working position, was directly calibrated by replacing the specimen and the specimen grips, by an N.P.L. certified 'C' ring, load cell. Preliminary calibration was carried out using a 0.0001" dial gauge to measure the deflection of the C ring (and thus load). This, however, tended to be insensitive at low loads. To overcome this difficulty the dial gauge was replaced by a type D Sogenique transducer. After re-calibration by the N.P.L. this modified C ring has been used to calibrate each load cell.* Periodic checks have been carried out on the calibration

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*The aluminium alloy results were obtained using the original calibration.

but no measurable changes have been recorded.

The load/deflection coefficient for the load cells is approximately $1 \times 10^{-5}$ ins/lb.

## 4. Experimental work on DTD 683

These experiments were performed mainly to test the equipment and to give experience in the setting up and conducting of tests. Thus they have been used in the development of the apparatus and improvements have been made during the series. The results therefore may not be completely comparable.

Two series of tests were carried out at two pairs of temperatures 200°C and 137°C; and 150°C and 93°C. The second pair were chosen so that they were in the same ratio on the absolute temperature scale as the first pair. It can be seen that some of these temperatures are above the ageing temperature and this must be expected to influence the results.

The experimental results are shown tabulated in figures 10, 11 and 12 and plotted in figures 13 to 23.

## Appendix 1

### Mechanism for operating the electromagnetic water valves

The automatic measuring and indicating equipment has been modified by the addition of two relays which are operated by the bridge unbalance. The two strain transducers are connected in anti-phase into the bridge through a special junction box. Any difference in the compared extensions produces a polarised error signal, which in turn operates one or other of the two relays. These relays then operate power relays energizing the water solenoids. At the true balance point neither relays nor solenoids are energized. The minimum error signal causing the relays to operate is given by a strain difference of $2 \times 10^{-5}$ ins. Overshoot of the load transfer system and consequent hunting is eliminated by throttling the water flow by the gate valves.

## Appendix 2

### Programming Equipment and associated control circuit

The circuit diagram is shown in Fig. A1.

The basic element of the programming unit is a 6 bank 12 way miniature uni-selector U.S.1 energised via a combination of 2 on/off gates controlled by synchronous clocks.

The master clock $T_1$, continuously running at 1 revolution per hour, operates for a period of 10 seconds, 12 contacts being spaced at 5 minute intervals on the clock face. The second clock $T_2$ making one revolution every 10 seconds operates via a single cam two microswitches M.S.1 and M.S.2 so positioned that M.S.2 operates 5 seconds after M.S.1.

To simplify the sequence of operations, consider the uni-selector U.S.1 at rest on position 4. (The uni-selector banks are connected so that positions 1 to 4 are repeated on 5 to 8 and 9 to 12).

When the operation of M.S.1 coincides with a continuous contact through the master clock and any of switches $S_2$ to $S_{13}$ a current pulse triggers the uni-selector, it will then continue to operate at 10 second intervals via contacts 5, 6 and 7 on bank 1, coming again to rest on position 8 until the sequence is repeated by the operation of the master clock contacts.

By use of switches $S_2$ to $S_{13}$ uniselector sequences can be programmed at a frequency of 5 minutes, and in any multiple thereof up to 60 minutes.

Switch positions 5, 6 and 7 on uni-selector bank 3 operate in turn relays RL6, RL7 and RL9, the contacts of which connecting via the 20 way socket to the Sogenique transducer junction box, connect into the measuring bridge Load Cell A, Load Cell B and Extensometer A. The closing of

Microswitch M.S.2, 5 seconds after M.S.1, operates via contacts 5, 6 and 7 on bank 4 relay RL2 the print command signal.

When the fourth pulse occurs the following sequence of operations takes place.

(1) Relay RL11 is energised via contact 8 on uni-selector bank 5.

(2) Capacitors $C_1$ and $C_2$ (already charged by the 1.5 volt cell via the normally closed contacts RL11/2), discharge through contacts RL11/1 to a transistor operated relay RL3 with a time constant determined by $C_1$ $C_2$ and the input resistance of the transistor circuit.

This time constant has been calculated to give a period of approximately 8 seconds.

(3) RL4 is energised by relay contacts RL3/1.

(4) RL4/3 contact is made energising Relay RL8.

(5) RL4/1 and RL4/2 are broken de-energising Relays RL9 and RL10.

(6) Relay RL8 connects through contacts RL8/1 transducer E to the measuring bridge.

This transducer mounted in an Invar frame within a cushioned block is set to give a reading of approximately 0.0500″ on the Indicator bridge.

The setting of this transducer is not critical providing it does not change during a test.

Connecting this transducer to the measuring bridge accurately positions the transformer tappings, used for bridge balance, at their mid position.

The error signal due to bridge unbalance is dependent upon the amplitude of the output signal from the balancing transformers. It is therefore necessary to precisely set this amplitude prior to connecting into the bridge the two strain measuring transducers.

(7) After the delay determined by $C_1$ and $C_2$, RL3 de-energises and operates the changeover contacts RL3/1, breaking the supply to RL4 and energising RL5.

(8) RL4 remains closed for a short period due to capacitor $C_3$.

(9) Contacts RL5/1 and RL5/2 break and disconnect the power supply from the uni-selectors driving the voltage dividing transformers within the Indicator Unit and thus locking them until a further sequence is initiated.

(10) Capacitor $C_3$ discharges through RL4 breaking contact RL4/3 and de-energies RL8 and thus disconnects the standard transducer from the measuring bridge.

(11) RL4/4 contacts break, and, being in parallel with contacts RL2/1, initiate a print command pulse which enables a check to be made of the stability of the standard throughout a test.

(12) Contacts RL4/1 and RL4/2 are made, energising RL9 and RL10, RL9 via contact 8 on Uniselector bank 2, and RL10 via contact 8 on bank 3. Relays RL9 and RL10 connect in antiphase the two strain measuring transducers into the Indicating bridge.

The whole system remains fixed in this position until a new sequence is initiated by the master clock.

Also connected into the Uniselector coil circuit is a manual/auto switch together with a push button, enabling any transducer to be selected independently of the master clock.

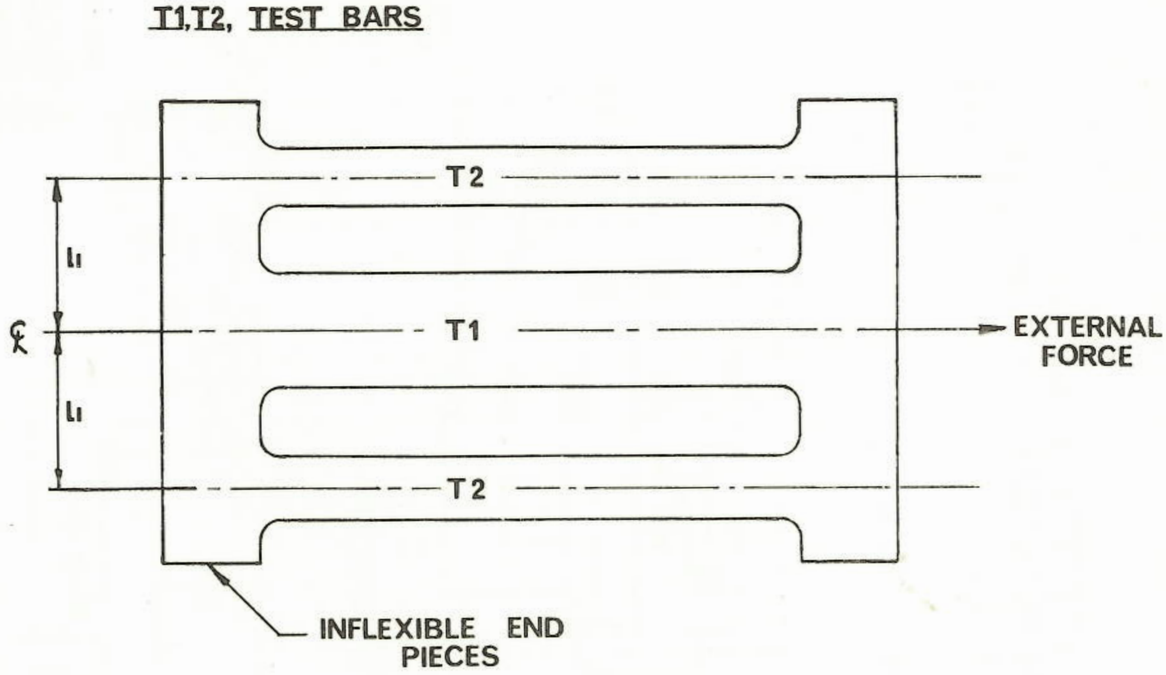
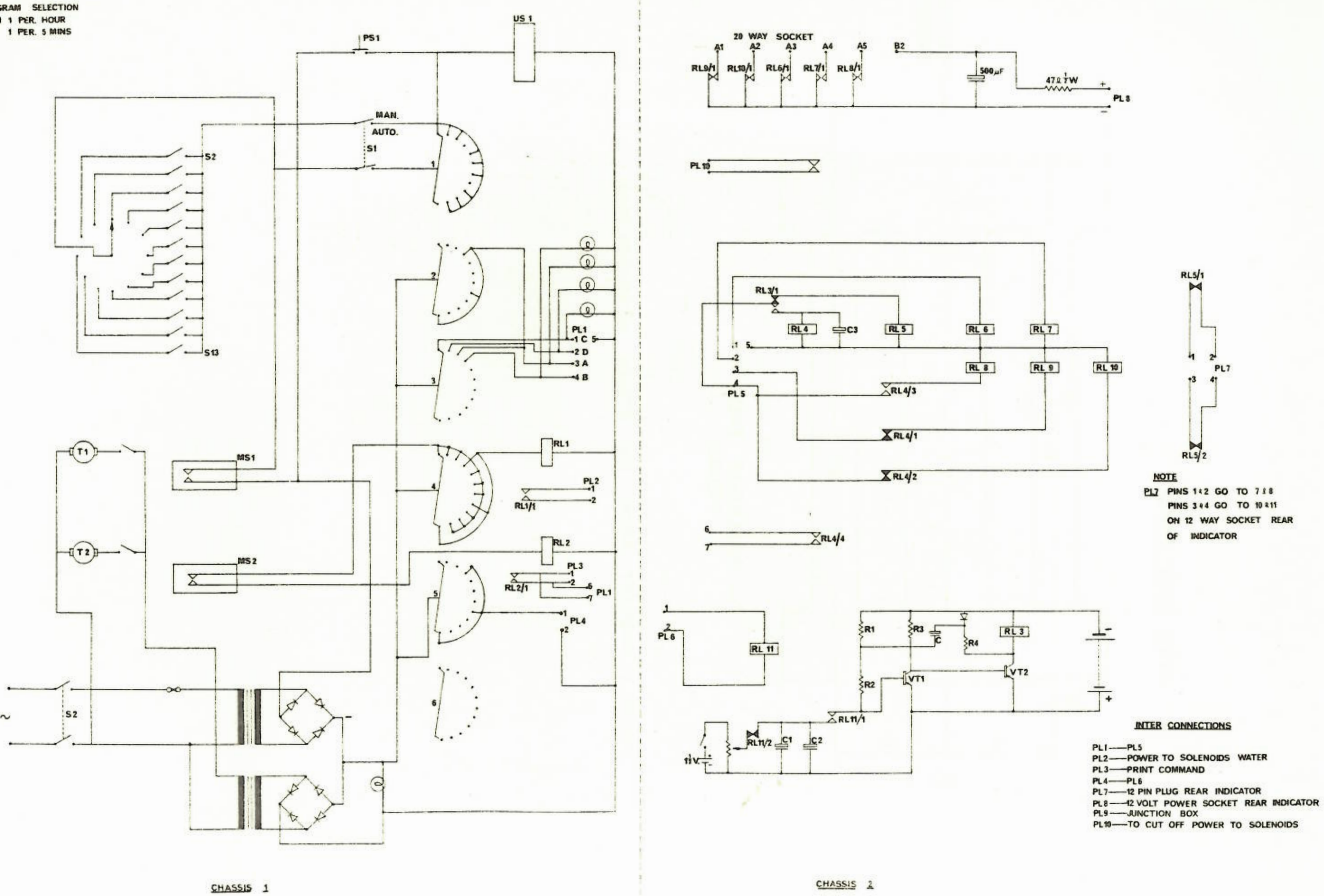


FIGURE 1 SIMPLEST ARRAY FOR STRESS REDISTRIBUTION

T1 MOTOR TIMER 1 R.P. HOUR
T2 MOTOR TIMER 1 R.P. 20 SECS
MS1 } CAM OPERATED MICROSWITCHES
MS2 }
S2-S13 PROGRAM SELECTION
FROM 1 PER. HOUR
TO 1 PER. 5 MINS



NOTE
PL7 PINS 1 & 2 GO TO 7 & 8
PINS 3 & 4 GO TO 10 & 11
ON 12 WAY SOCKET REAR
OF INDICATOR

INTER CONNECTIONS

PL1——PL5
PL2——POWER TO SOLENOIDS WATER
PL3——PRINT COMMAND
PL4——PL6
PL7——12 PIN PLUG REAR INDICATOR
PL8——12 VOLT POWER SOCKET REAR INDICATOR
PL9——JUNCTION BOX
PL10——TO CUT OFF POWER TO SOLENOIDS

FIGURE A1 CIRCUIT DIAGRAM OF PROGRAMMING AND CONTROL EQUIPMENT

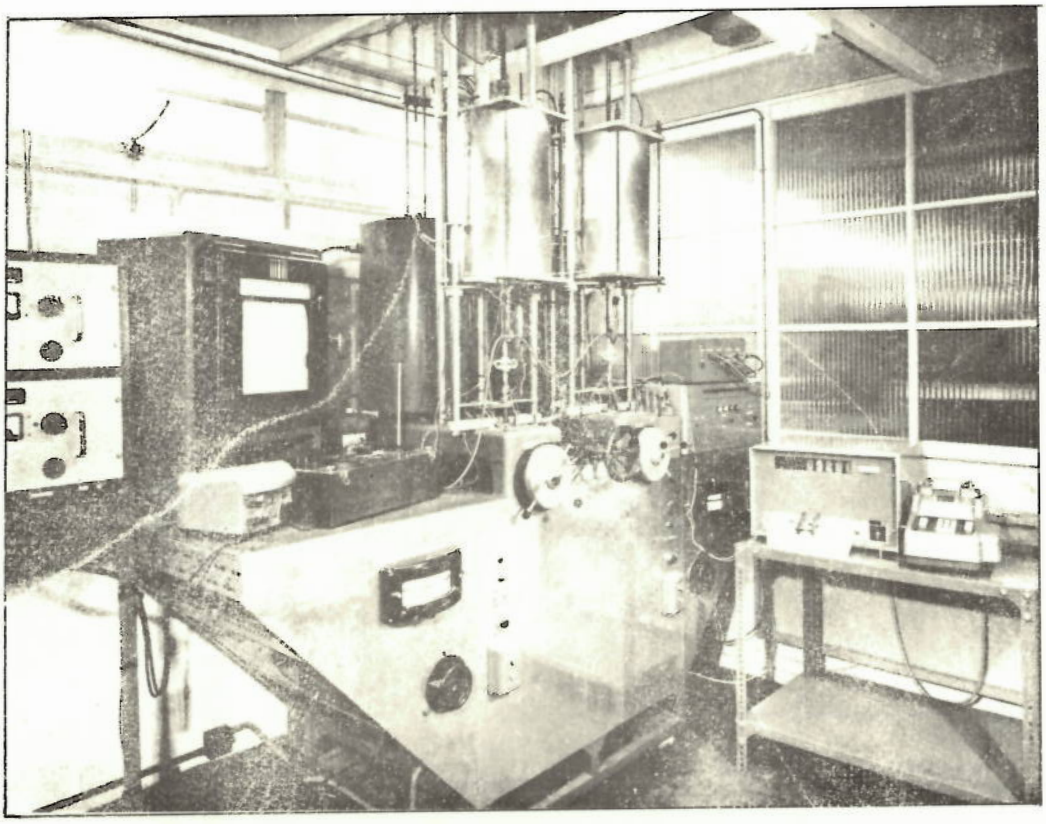


FIGURE 2 GENERAL VIEW OF EXPERIMENTAL APPARATUS

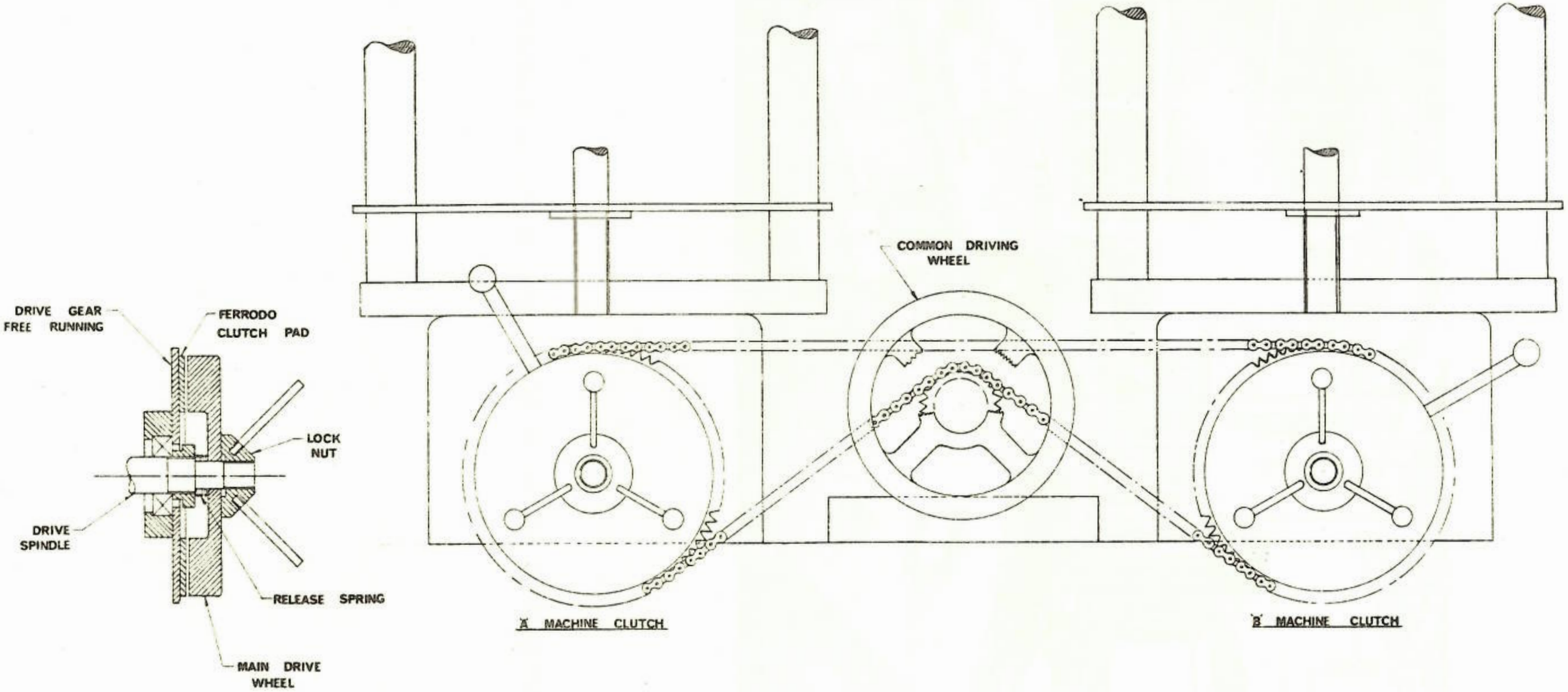


FIGURE 3 CLUTCH MECHANISMS SHOWING INTER-CONNECTIONS BETWEEN TWO MACHINES

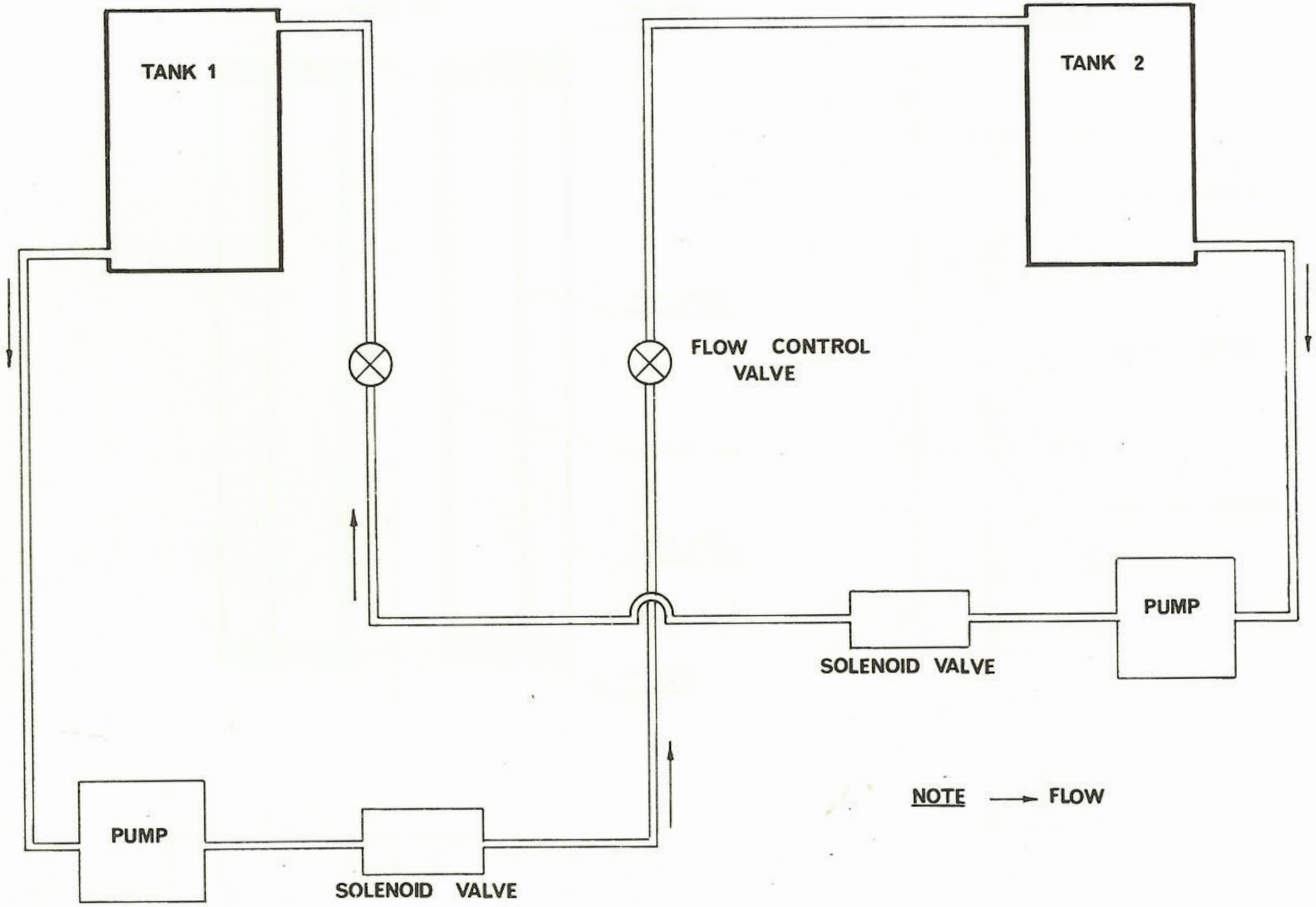


FIGURE 4 WATER LOADING SYSTEM

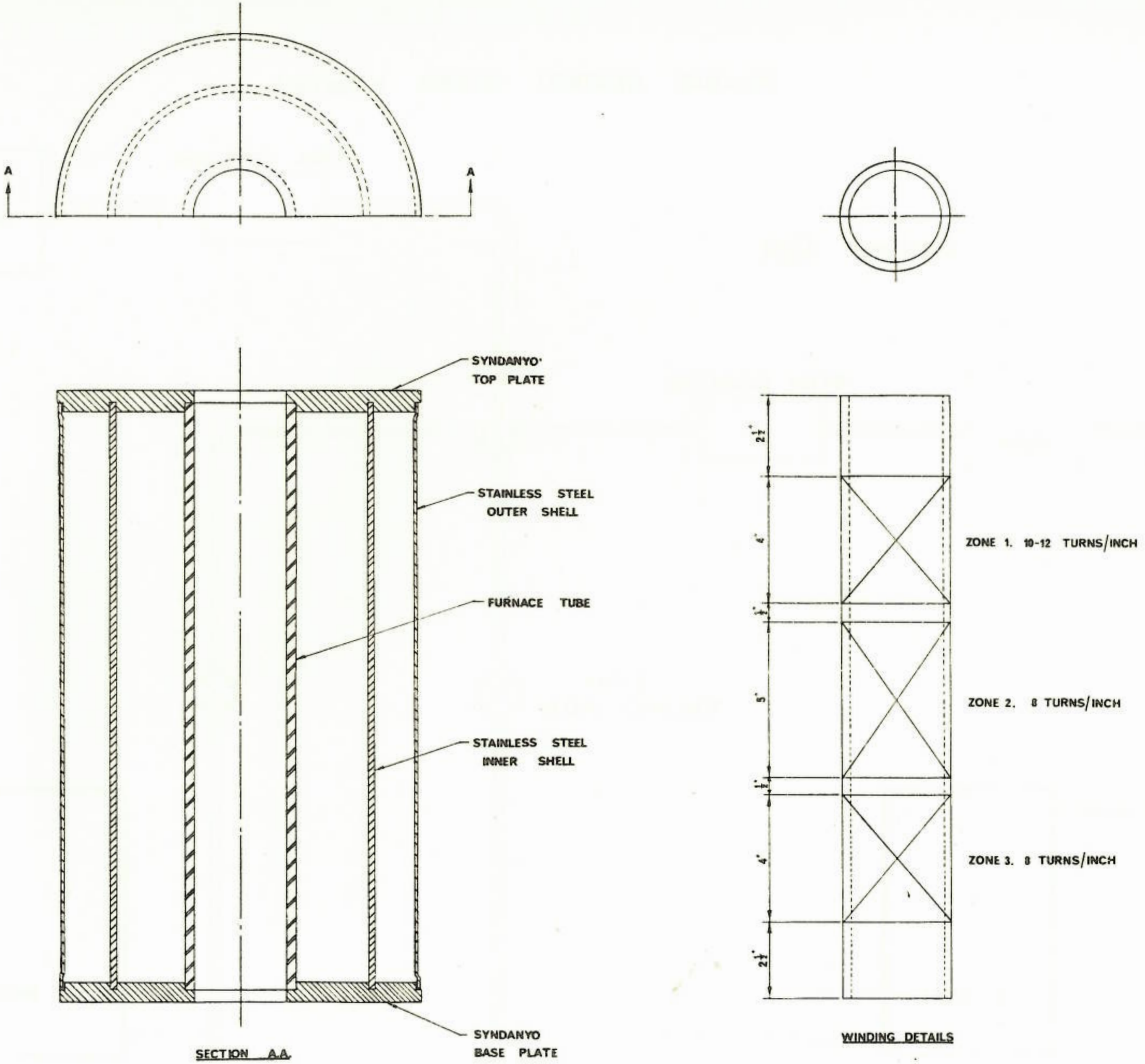


FIGURE 5 SPECIFICATION OF FURNACE CONSTRUCTION

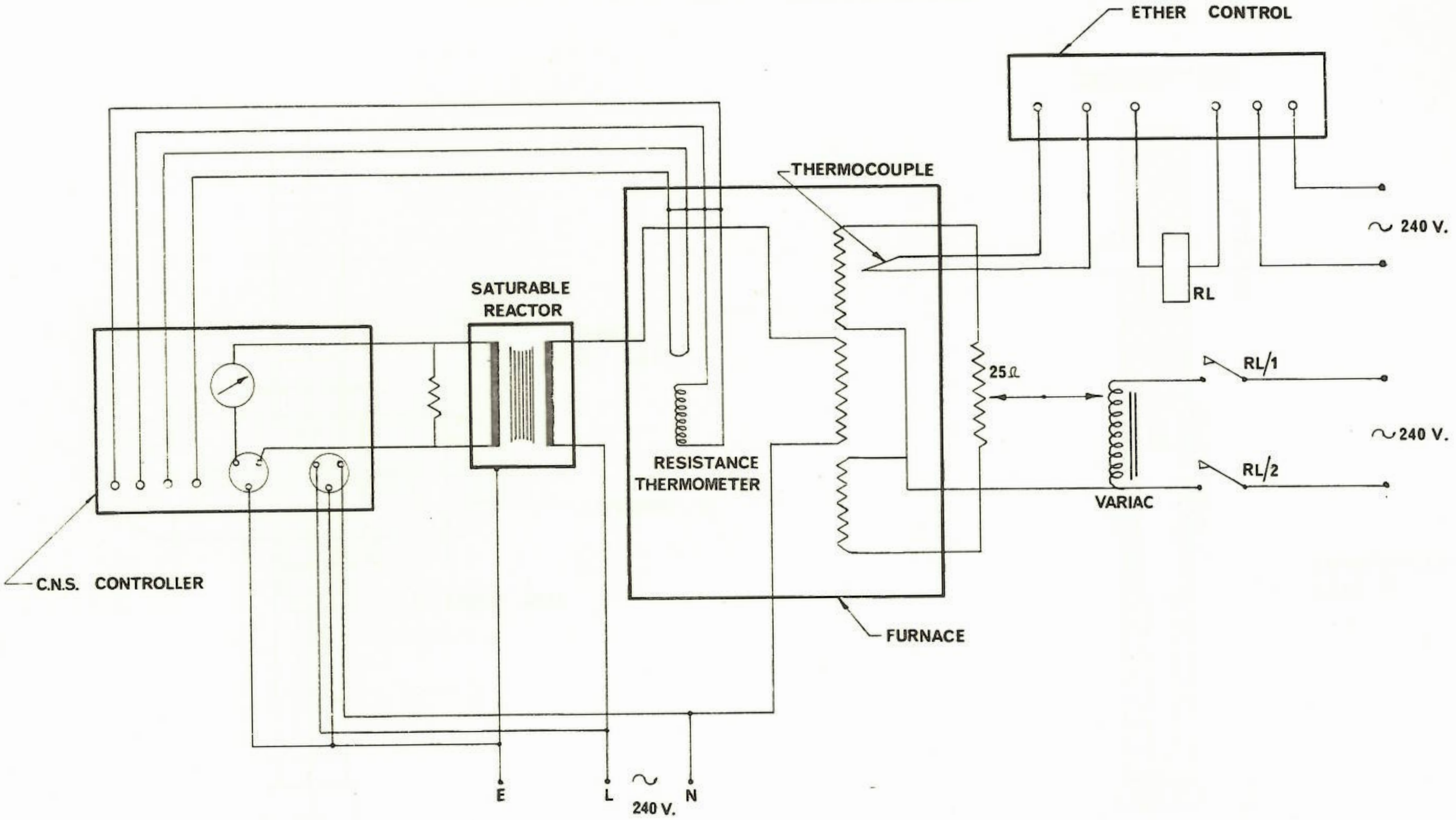
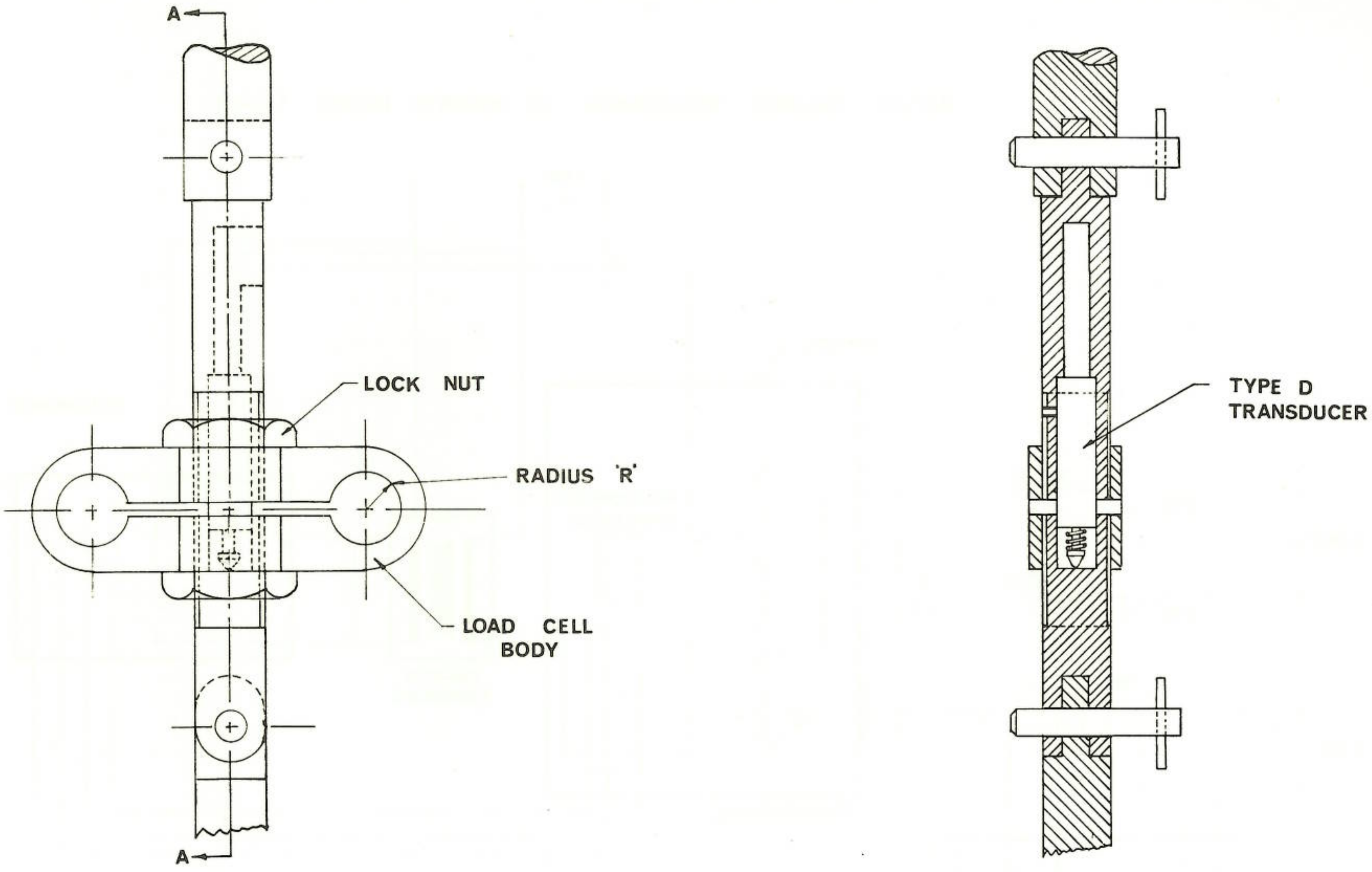


FIGURE 6 CIRCUIT DIAGRAM OF TEMPERATURE CONTROL SYSTEM



SECTION A.A.

FIGURE 7 LOAD CELL CONSTRUCTION

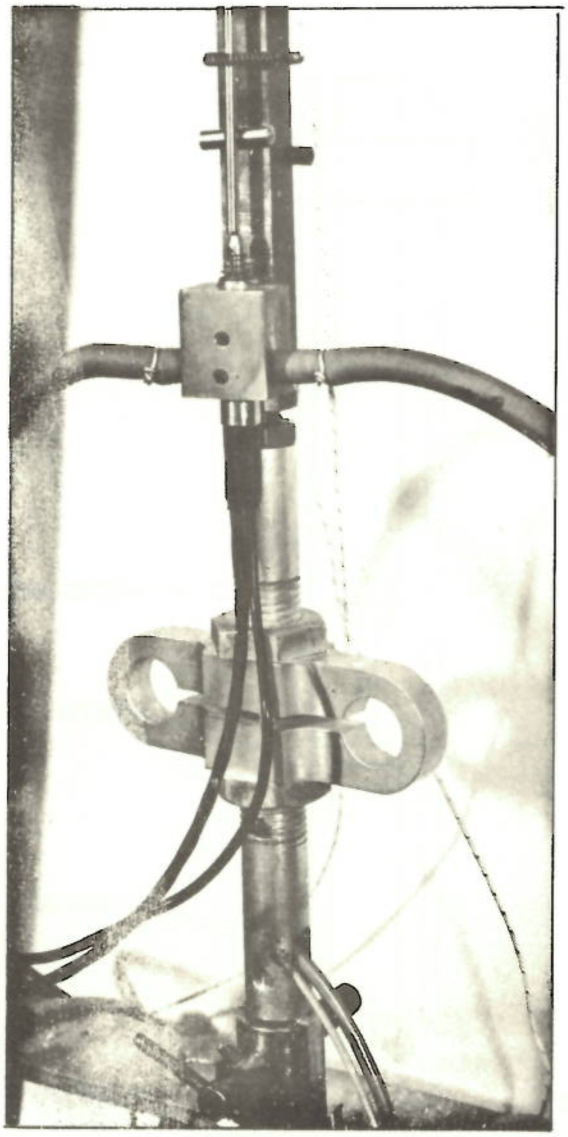


FIGURE 7A ACTUAL LOAD CELL IN POSITION

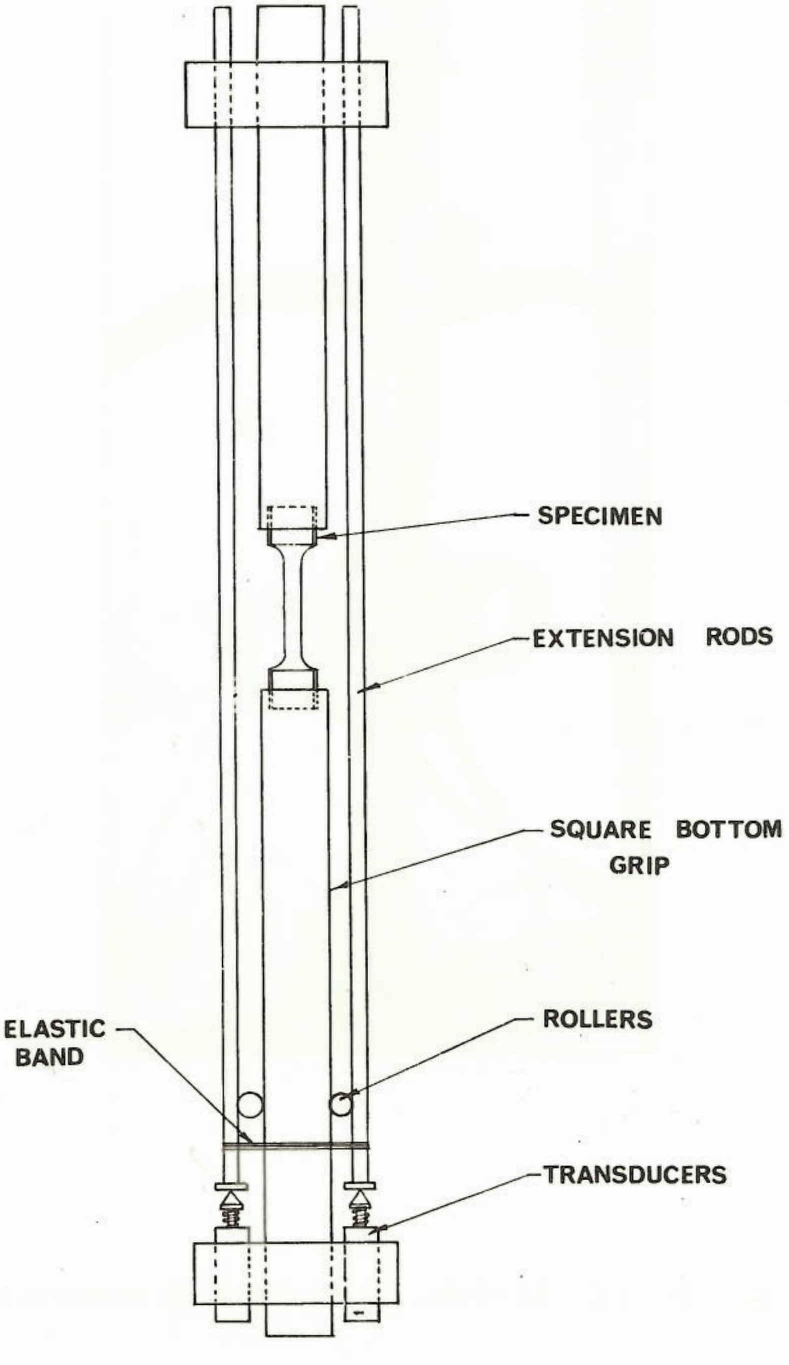
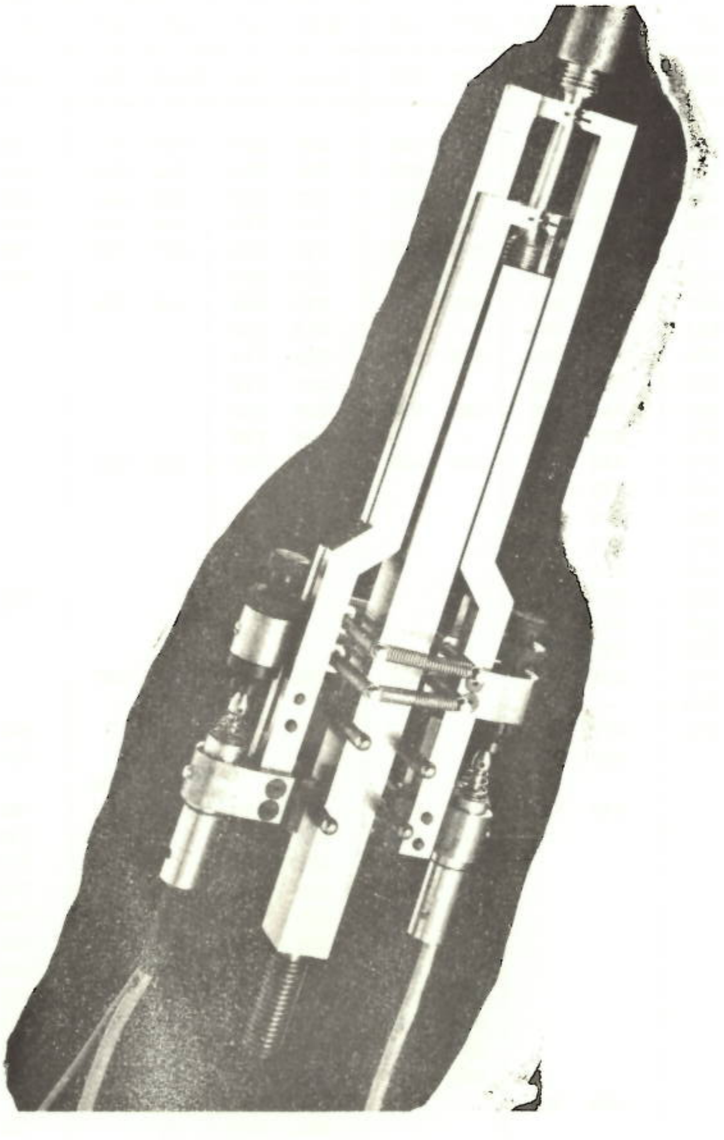


FIGURE 8 INITIAL EXTENSOMETER



9 MAND EXTENSOMETER SHOWING POSITION OF TRANSDUCERS

LOAD REDISTRIBUTION

| Test No. | 7 | | 8 | | 9 | | 13 | | 15 | | 18 | | 19 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M/C | A | B | A | B | A | B | A | B | A | B | A | B | A | B |
| Temp. $^{o}$C. | 200 | 137 | 200 | 137 | 200 | 137 | 200 | 137 | 150 | 93 | 150 | 93 | 150 | 93 |
| Time Mins. | Load | lbs. | Load | lbs. | Load | lbs. | Load | lbs. | Load | lbs. | Load | lbs. | Load | lbs. |
| 0 | 603 | 603 | 745 | 493 | 493 | 745 | 306 | 930 | 610 | 610 | 743 | 496 | 780 | 780 |
| 5 | 624 | 578 | 611 | 631 | 387 | 853 | 596 | 620 | 989 | 234 | 882 | 359 | | |
| 10 | 607 | 594 | 607 | 640 | - | 861 | 557 | 659 | 986 | 241 | 872 | 369 | 220 | 1340 |
| 15 | 597 | 605 | 592 | 653 | - | - | 544 | 673 | 982 | 244 | 868 | 375 | 233 | 1327 |
| 20 | - | - | 588 | 657 | 362 | 879 | 532 | 686 | 977 | 250 | 862 | 381 | 243 | 1317 |
| 25 | 567 | 634 | 578 | 664 | - | | 525 | 694 | | | 858 | 386 | 250 | 1310 |
| 30 | 567 | 637 | 574 | 667 | 352 | 886 | 520 | 699 | 968 | 262 | | | 267 | 1293 |
| 35 | 560 | 643 | 566 | 669 | - | | 516 | 700 | | | | | | |
| 40 | 555 | 650 | 555 | 689 | 346 | 890 | 508 | 710 | | | | | | |
| 45 | 550 | 655 | 551 | 692 | - | | 502 | 716 | | | | | | |
| 50 | 538 | 667 | 544 | 699 | 391 | 894 | 496 | 722 | | | | | | |
| 55 | 535 | 670 | 537 | 706 | - | | 488 | 730 | | | | | | |
| 60 | 531 | 676 | 535 | 709 | 335 | 902 | 490 | 727 | 953 | 281 | | | | |
| 65 | 528 | 678 | 530 | 715 | | | | | | | | | | |
| 70 | 525 | 680 | 526 | 719 | | | | | | | | | | |
| 75 | 524 | 681 | 520 | 726 | | | | | | | | | | |
| 80 | 520 | 686 | 514 | 731 | | | | | | | | | | |
| 90 | 515 | 692 | 507 | 736 | | | | | | | 827 | 419 | 247 | 1313 |
| 100 | 510 | 695 | 504 | 743 | | | | | | | | | | |
| 110 | 508 | 699 | 497 | 749 | | | | | | | | | | |
| 120 | 502 | 704 | 491 | 755 | 316 | 919 | 462 | 756 | 948 | 287 | | | | |
| 135 | 495 | 710 | - | - | | | | | | | | | | |
| 150 | 492 | 715 | 477 | 770 | | | | | | | 809 | 443 | 221 * | 1339 |
| 180 | | | 468 | 779 | | | 456 | 764 | | | 794 * | 452 | 216 * | 1344 |
| 195 | | | | | | | | | 931 | 300 | | | | |
| 240 | | | 449 | 796 | 300 | 933 | 437 | 785 | | | 784* | 463 | 225 * | 1335 |
| 300 | | | | | 293 | 942 | 423 | 793 | | | 783 * | 469 | 228 * | 1332 |
| 360 | | | | | 294 | 936 | 420 | 799 | | | 768 * | 482 | 228 * | 1332 |
| 420 | | | | | 297 | 940 | 409 | 812 | | | 758 * | 490 | 222 * | 1338 |
| 480 | | | | | 284 | 950 | 400 | 818 | | | 756 * | 493 | 224 * | 1336 |
| 540 | | | | | 281 | 949 | 396 | 825 | | | 752 * | 499 | 226 * | 1334 |
| 600 | | | | | 271 | 959 | 396 | 825 | | | 746 * | 504 | 220 * | 1340 |
| 720 | | | | | 269 | 963 | 385 | 835 | | | 760 * | 498 | 219 * | 1341 |
| 900 | | | | | 262 | 967 | 379 | 841 | | | 743 * | 505 | 221 * | 1339 |
| 1080 | | | | | 260 | 974 | 375 | 845 | | | 737 * | 516 | 230 * | 1330 |
| 1200 | | | | | 274 | 969 | 372 | 848 | | | 729 * | 522 | | |
| 1250 | | | 359 | 885 | | | | | | | | | | |
| 1440 | | | | | | | 361 | 860 | | | 724 * | 522 | | |
| 1800 | | | | | | | 350 | 871 | | | | | | |
| 2160 | | | | | | | 343 | 877 | | | | | | |
| 2400 | | | | | | | 341 | 879 | | | | | | |
| | | | | | | | | | Operator error indicates that A results should be B and vice versa | | * Add: 30 mins to reading. | | * Add: 30 mins to reading. | |

FIGURE 10

CREEP STRAIN. INS. Gauge Length 1.5"

| Test No. | 7 | 8 | 9 | 13 | 15 | 18 | 19 |
|---|---|---|---|---|---|---|---|
| Time Mins. | | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | .00599 | .00287 | .01288 | .00661 | .00906 | .00767 | |
| 10 | 605 | 302 | 1304 | 679 | 912 | 772 | .00184 |
| 15 | 604 | 304 | | 698 | 916 | 777 | 184 |
| 20 | 615 | 310 | 1316 | 704 | 915 | 787 | 185 |
| 25 | 625 | 286 | | 708 | | 790 | 185 |
| 30 | 629 | 293 | 1333 | 712 | | 790 | 185 |
| 35 | 632 | 311 | | 722 | | | |
| 40 | 637 | 327 | 1344 | 719 | | | |
| 45 | 626 | 342 | | 725 | | | |
| 50 | 627 | 351 | 1362 | 735 | | | |
| 55 | 633 | 361 | | 737 | | | |
| 60 | 635 | 369 | 1367 | 749 | 902 | | |
| 65 | 640 | 378 | | | | | |
| 70 | 646 | 391 | | | | | |
| 75 | 653 | 404 | | | | | |
| 80 | 653 | 405 | | | | | |
| 90 | 660 | 415 | | | | 820 | 187 |
| 100 | 667 | 432 | | | | | |
| 110 | 681 | 438 | | | | | |
| 120 | 697 | 452 | 1412 | 782 | 920 | | 188* |
| 135 | 700 | | | | | | |
| 150 | 704 | 476 | | | | 831 | |
| 180 | | 495 | 1443 | 831 | | 853* | 188* |
| 195 | | | | | 925 | | |
| 240 | | 546 | 1469 | 831 | | 877* | 186* |
| 300 | | 585 | 1490 | 848 | | 867* | 188* |
| 360 | | | 1505 | 863 | | 883* | 185* |
| 420 | | | 1529 | 878 | | 897* | 186* |
| 480 | | | 1540 | 885 | | 897* | 186* |
| 540 | | | 1556 | 898 | | 901* | 185* |
| 600 | | 690 | 1580 | 907 | | 917* | 185* |
| 720 | | 718 | 1601 | 913 | | 892* | 188* |
| 900 | | | 1648 | 942 | | 919* | 181* |
| 1080 | | 798 | 1690 | 979 | | 914* | 186* |
| 1200 | | | 1685 | 995 | | 907* | |
| 1250 | | | | | | 940* | |
| 1440 | | 829 | | .01023 | | | |
| 1800 | | | | 1052 | | | |
| 2160 | | | | 1083 | | | |
| 2400 | | | | 1110 | | | |
| 2880 | | | | | | | |
| 3000 | | | | | | | |

* Add: 30 mins. to readings (Test 18)

* Add: 30 mins. to readings (Test 19)

FIGURE 11

## CREEP TESTS ON DTD 683 - Gauge Length 1.5"

| Test No. 28<br>Load 10 t.s.i.<br>Temp. $137^{o}$C | | Test No. 29<br>Load 10 t.s.i.<br>Temp. $200^{o}$C | | Test No. 30<br>Load 12 t.s.i.<br>Temp. $137^{o}$C | | Test No. 31<br>Load 8 t.s.i.<br>Temp. $200^{o}$C | |
|---|---|---|---|---|---|---|---|
| Time Mins. | Creep Strain ins. | Time Mins. | Creep Strain ins. | Time Mins. | Creep Strain ins. | Time Mins. | Creep Strain ins. |
| 1 | .003795 | 1 | .003075 | 1 | .003510 | 1 | .001350 |
| 2 | 3795 | 2 | 3105 | 2 | 3540 | 2 | 1350 |
| 5 | 3795 | 3 | 3135 | 3 | 3570 | 7 | 1410 |
| 13 | 3840 | 4 | 3135 | 4 | 3600 | 12 | 1410 |
| 18 | 3870 | 5 | 3135 | 5 | 3600 | 17 | 1410 |
| 23 | 3915 | 8 | 3180 | 15 | 3705 | 22 | 1410 |
| 28 | 3840 | 13 | 3240 | 20 | 3720 | 27 | 1410 |
| 33 | 3840 | 18 | 3300 | 25 | 3735 | 87 | 1410 |
| 38 | 3840 | 23 | 3345 | 30 | 3765 | 147 | 1425 |
| 43 | 3840 | 28 | 3405 | 35 | 3780 | 207 | 1425 |
| 48 | 3855 | 33 | 3480 | 40 | 3780 | 267 | 1425 |
| 53 | 3840 | 38 | 3555 | 45 | 3825 | 327 | 1425 |
| 58 | 3855 | 43 | 3600 | 50 | 3810 | 387 | 1425 |
| 63 | 3900 | 103 | 4050 | 110 | 3795 | 447 | 1440 |
| 128 | 3945 | 103 | 4485 | 230 | 3840 | 507 | 1470 |
| 188 | 3900 | 223 | 4890 | 350 | 3930 | 567 | 1590 |
| 248 | 3900 | 283 | 5250 | 470 | 4020 | 627 | 1680 |
| 308 | 3915 | 343 | 5670 | 590 | 4110 | 687 | 1740 |
| 428 | 3960 | 403 | 5985 | 710 | 4155 | 747 | 1800 |
| 488 | 3975 | 468 | 6345 | 830 | 4170 | 807 | 1875 |
| 608 | 3990 | 523 | 6690 | 950 | 4200 | 867 | 1965 |
| 668 | 4005 | 583 | 7080 | 1070 | 4230 | 927 | 2055 |
| 728 | 4020 | 643 | 7410 | 1190 | 4185 | 987 | 2145 |
| 908 | 4035 | 703 | 7770 | 1310 | 4395 | 1047 | 2235 |
| 1028 | 4050 | 763 | 8130 | 1430 | 4245 | 1167 | 2400 |
| 1208 | 4095 | 823 | 8550 | 1550 | 4260 | 1287 | 2610 |
| 1328 | 4095 | 883 | 8865 | 1670 | 4245 | 1407 | 2760 |
| 1448 | 4125 | 943 | 9315 | 1790 | 4185 | 1527 | 2955 |
| 1568 | 4155 | 1003 | 9780 | 1910 | 4245 | 1647 | 3150 |
| 1688 | 4215 | 1123 | .010800 | 2030 | 4335 | 1767 | 3390 |
| 1868 | 4215 | 1243 | 12015 | 2150 | 4365 | 1887 | 3555 |
| 2048 | 4230 | 1363 | 13350 | 2270 | 4470 | 2007 | 3750 |
| 2228 | 4260 | 1483 | 15000 | 2390 | 4440 | 2187 | 4095 |
| 2408 | 4260 | 1603 | 16515 | 2570 | 4485 | 2367 | 4395 |
| 2588 | 4245 | 1723 | 18720 | 2750 | 4605 | 2547 | 4785 |
| 2768 | 4245 | 1843 | 20820 | 2930 | 4650 | 2727 | 5205 |
| 2948 | 4350 | 1963 | 23565 | 3110 | 4755 | 2907 | 5685 |
| 3128 | 4380 | 2143 | 28395 | 3290 | 4695 | 3087 | 6210 |
| | | 2323 | 35205 | 3470 | 4485 | 3207 | 6510 |
| | | 2503 | 48660 | 3650 | 4500 | 3387 | 7035 |
| | | 2623 | 66765 | 3830 | 4575 | 3567 | 7530 |
| | | 2743 | .120360 | | | 3747 | 8040 |
| | | | | | | 3927 | 8610 |
| | | | | | | 4107 | 9315 |
| | | | | | | 4167 | 9585 |

FIGURE 12

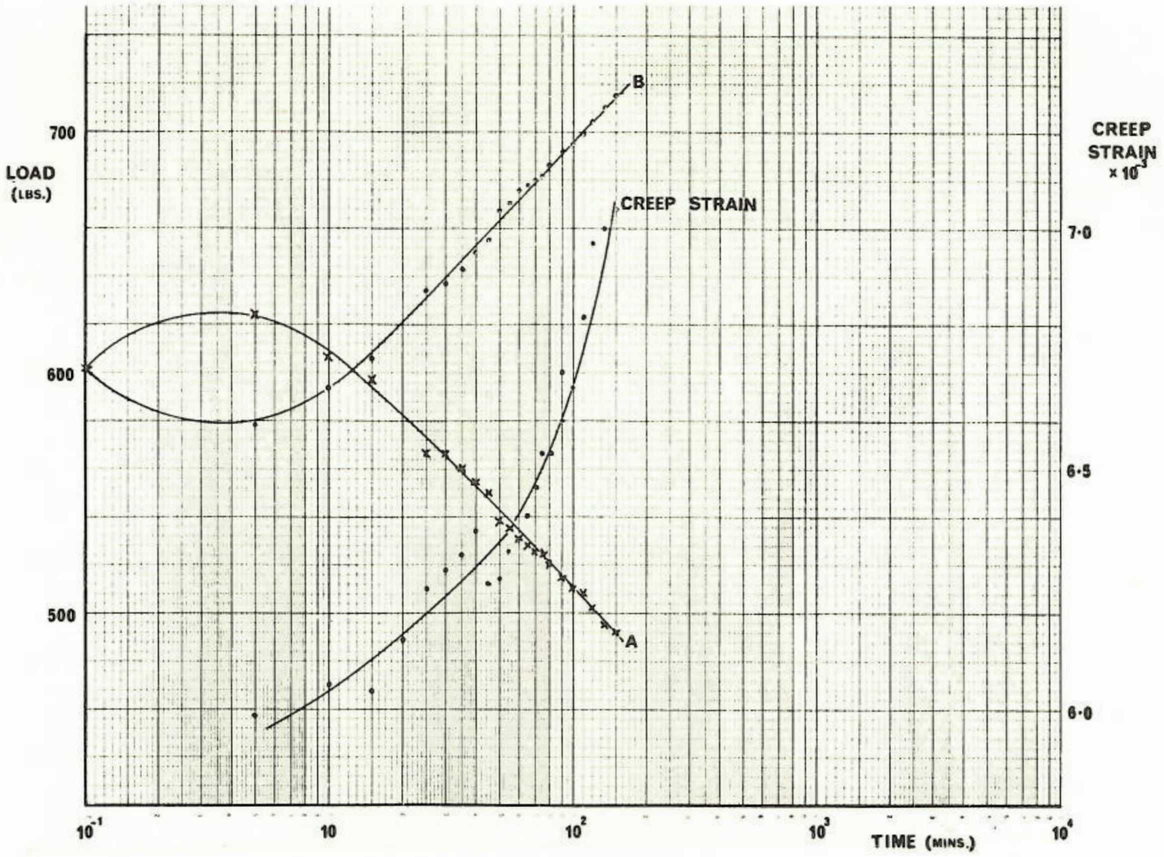


FIGURE 13 COMBINED TEST No. 7 AT 200°C AND 137°C

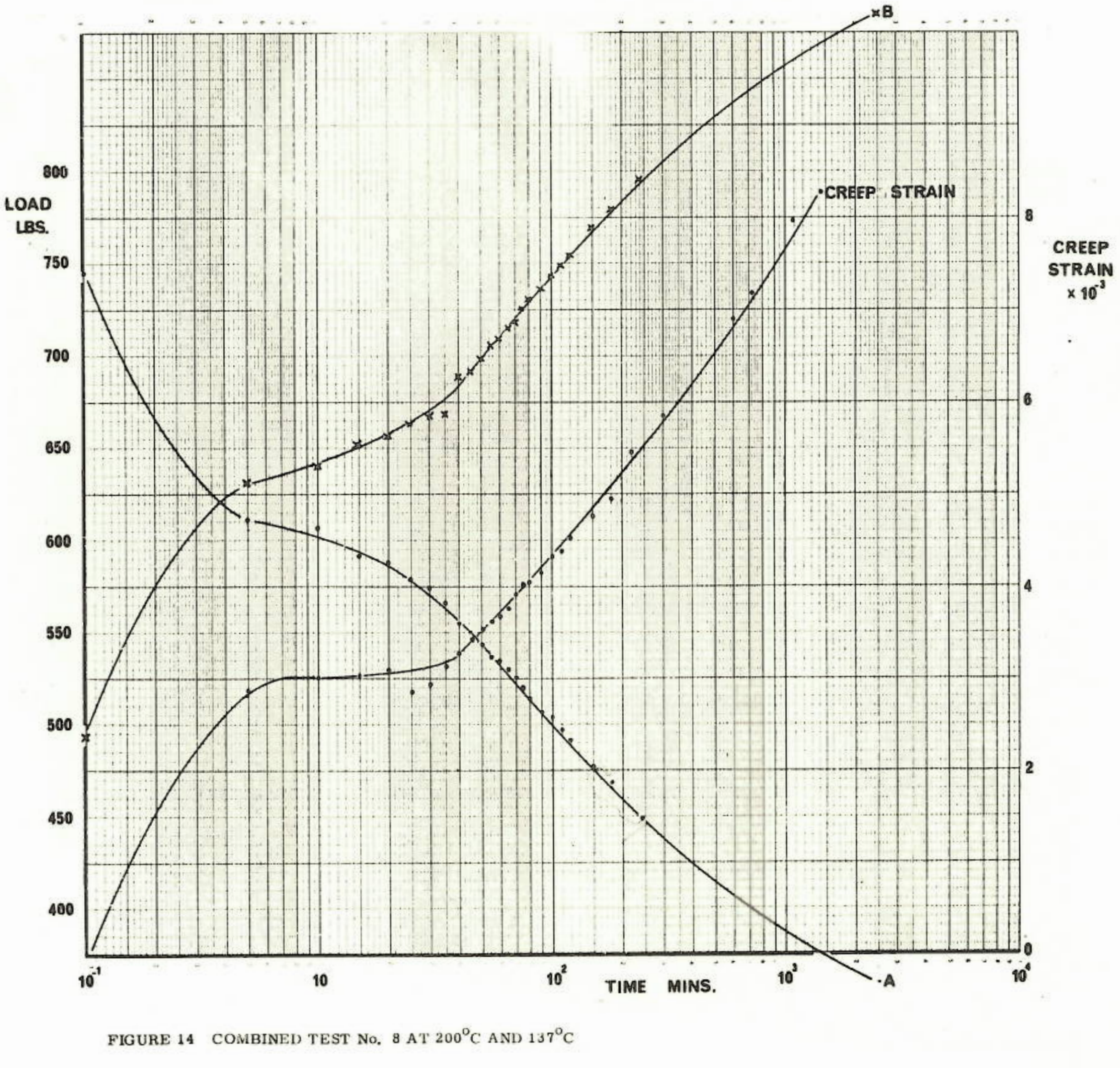


FIGURE 14 COMBINED TEST No. 8 AT 200°C AND 137°C

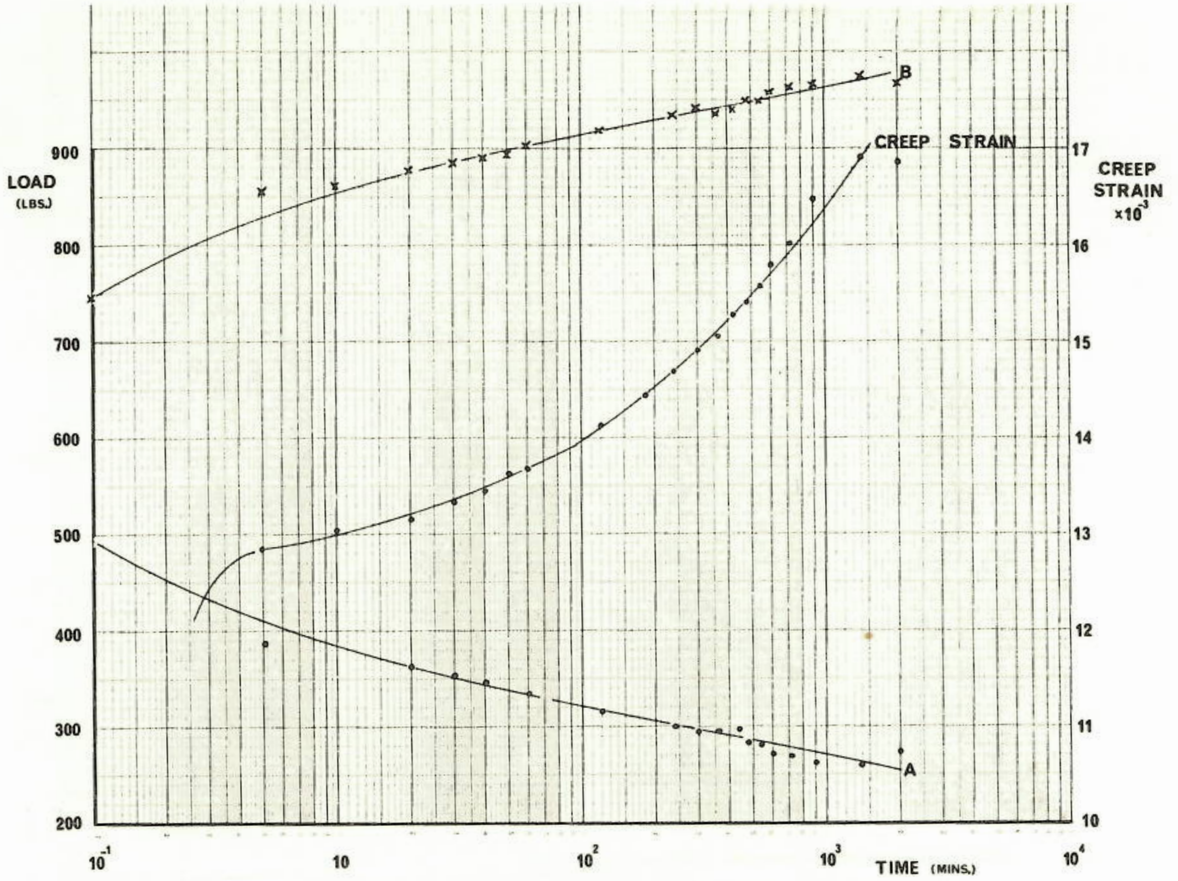


FIGURE 15 COMBINED TEST No. 9 AT 200°C and 137°C

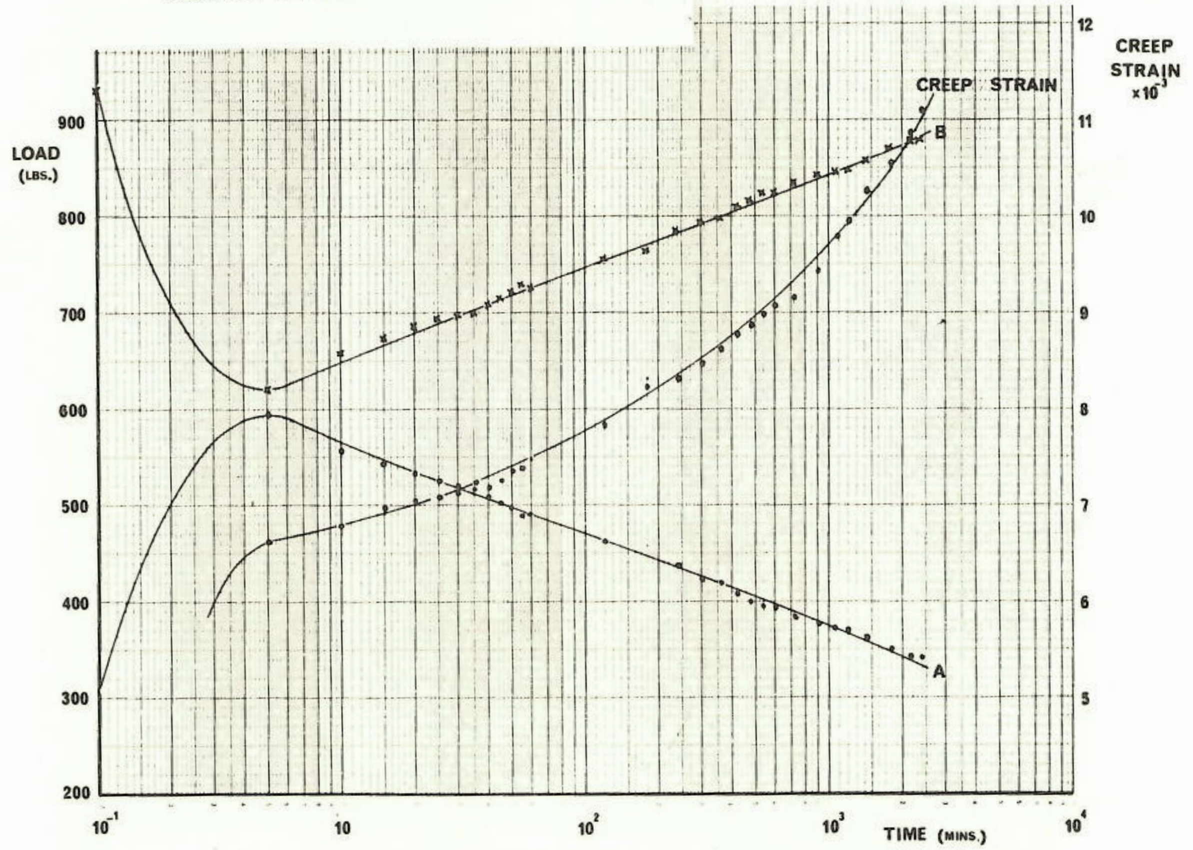


FIGURE 16 COMBINED TEST NO. 13 AT 200°C and 137°C

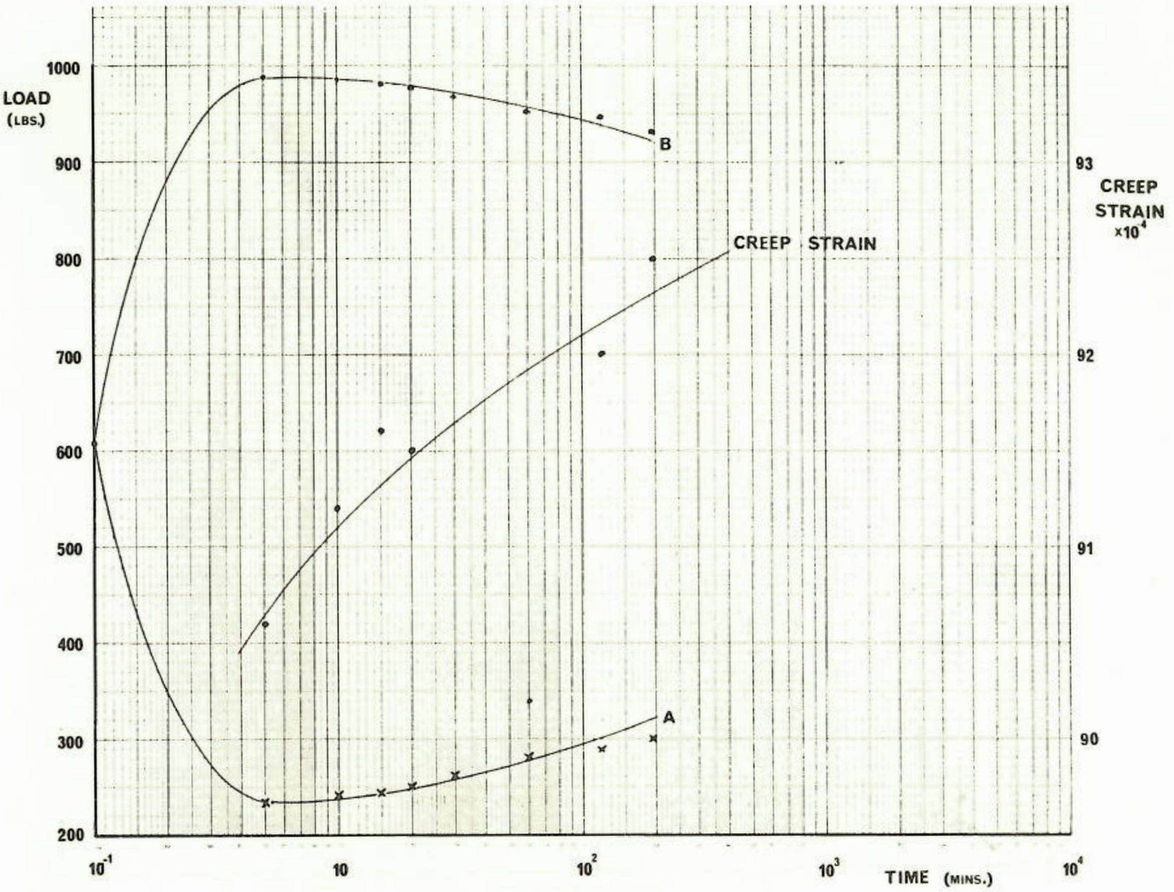


FIGURE 17 COMBINED TEST No. 15 AT 150°C and 93°C

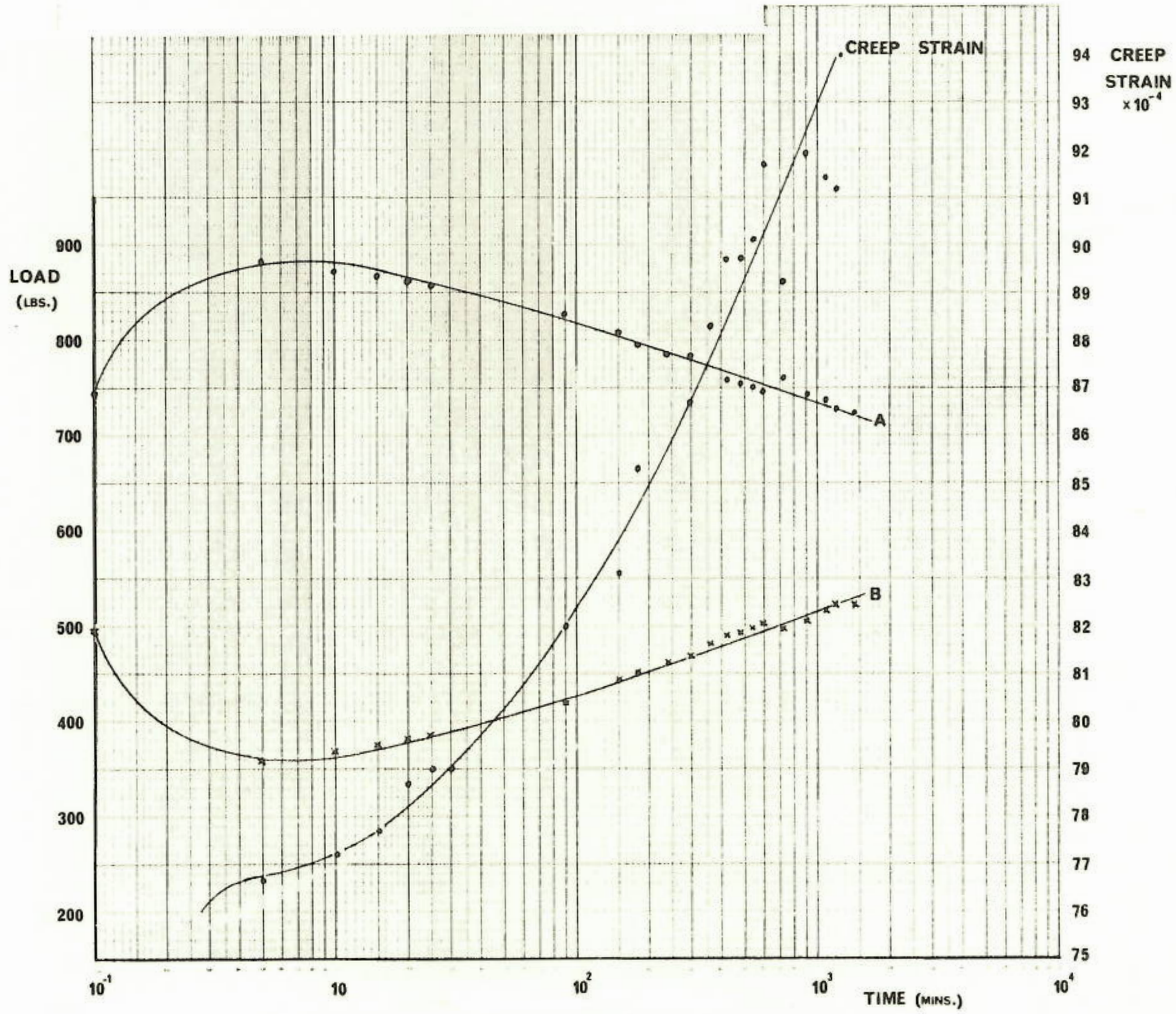


FIGURE 18 COMBINED TEST No. 18 AT 150°C and 93°C

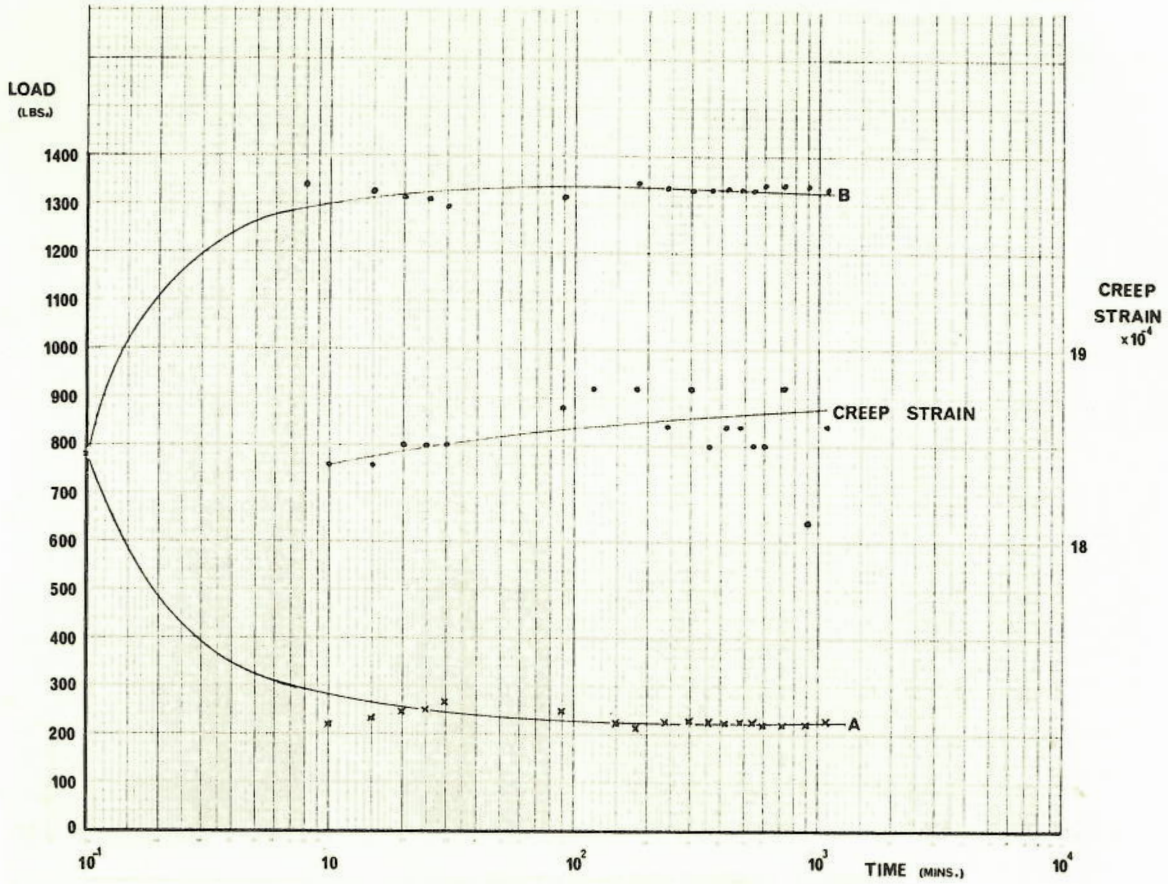


FIGURE 19 COMBINED TEST No. 19 at 150°C and 93°C

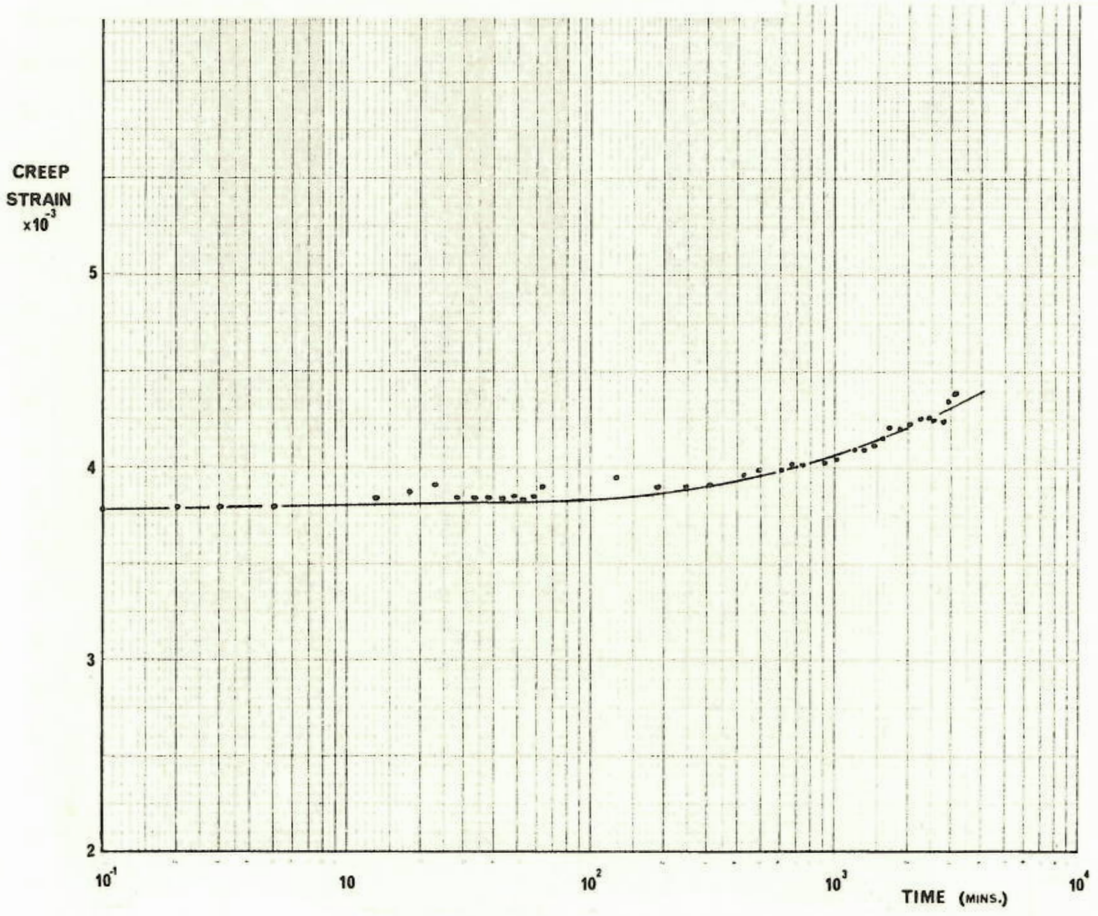


FIGURE 20 TEST No. 28 LOAD 10 t. s. i. TEMPERATURE 137°C

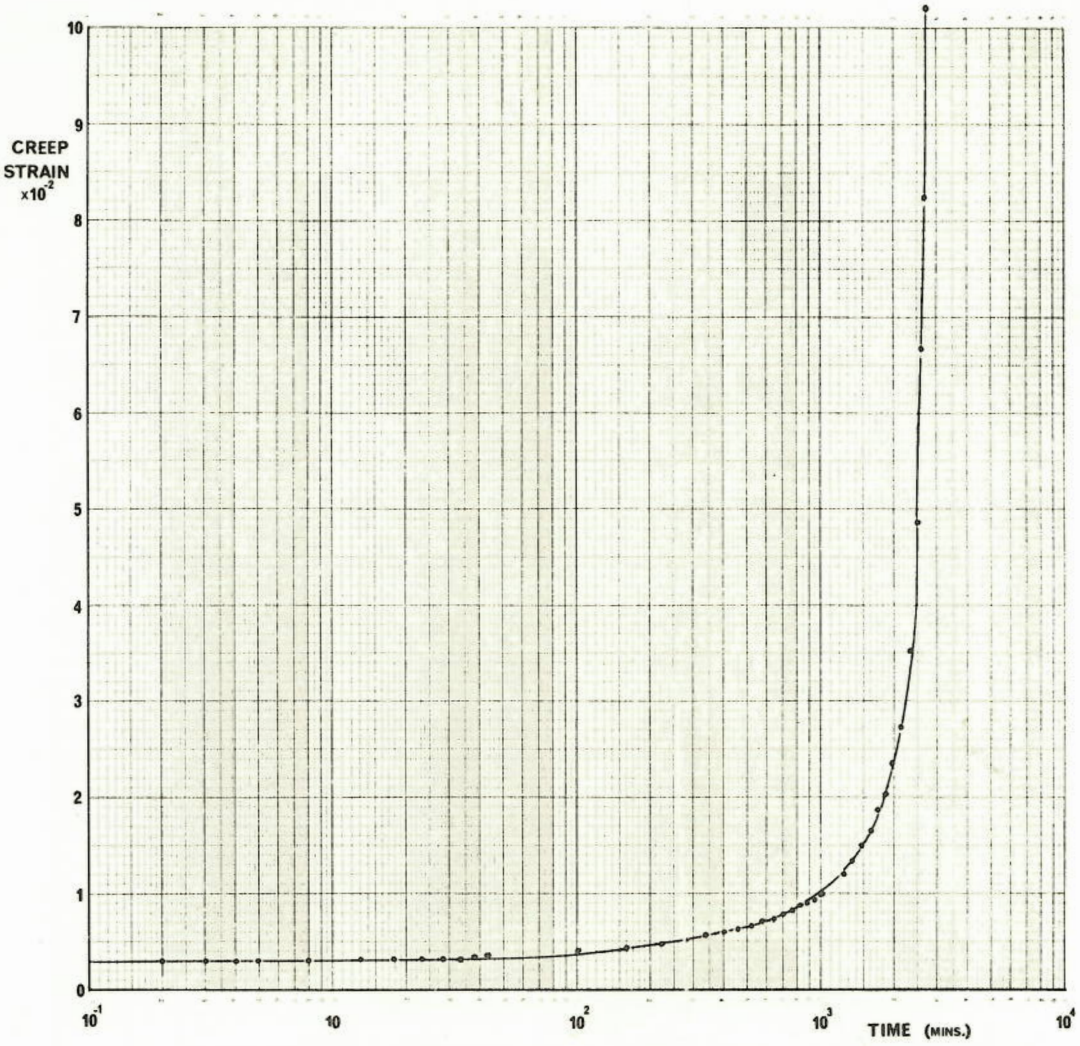


FIGURE 21 TEST No. 29 LOAD 10 t. s. i. TEMPERATURE 200°C

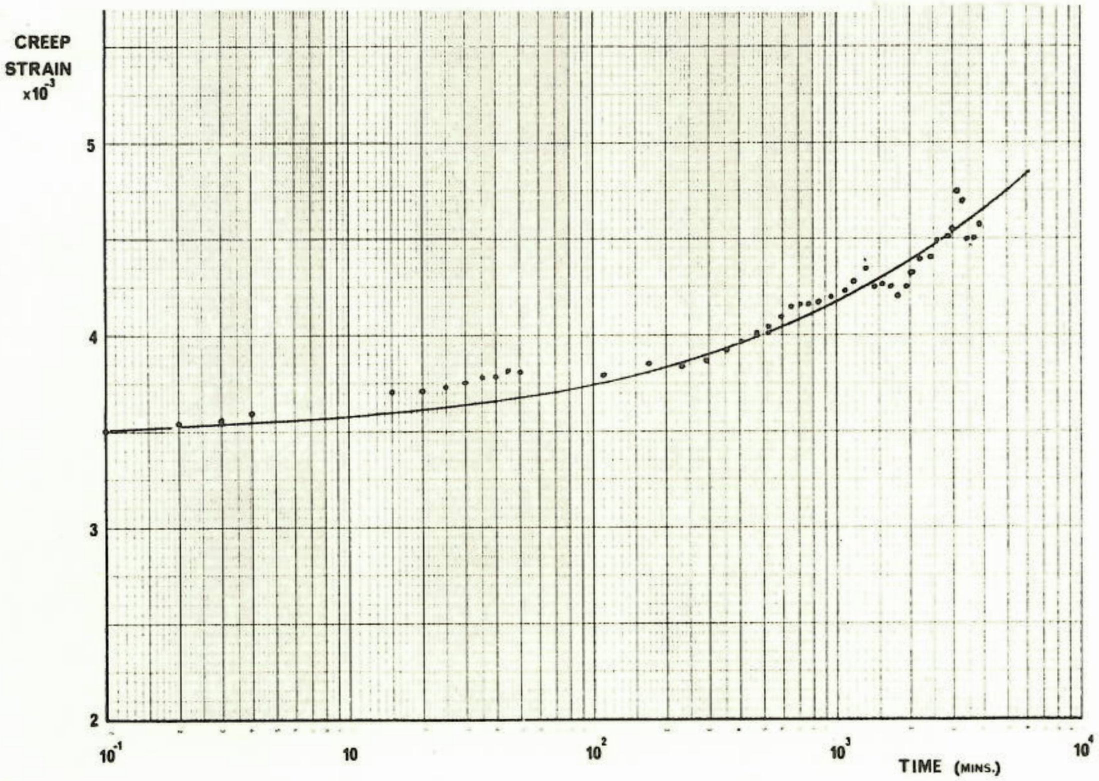


FIGURE 22 TEST No. 30 LOAD 12 t. s. i. TEMPERATURE 137°C

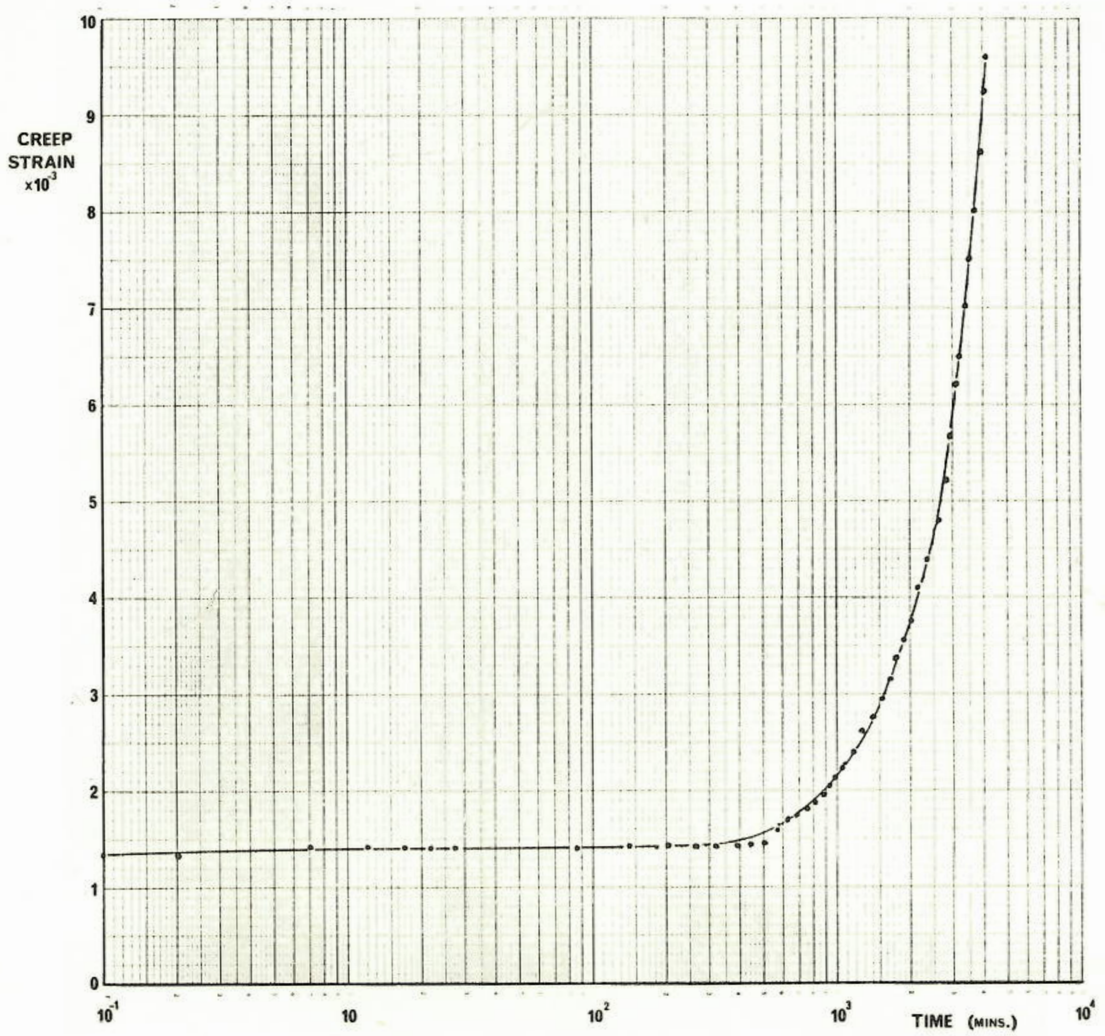


FIGURE 23 TEST No. 31 LOAD 8 t. s. i. TEMPERATURE 200°C