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THE INSTALLATION AND OPERATION OF A CREEP TESTING MACHINE TO DETERMINE ITS OPERATING CHARACTERISTICS

BY

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A thesis submitted
in partial fulfillment of the requirements for the
degree Master of Science, Department of
Mechanical Engineering, South Dakota
State College of Agriculture
and Mechanic Arts

August, 1963

THE INSTALLATION AND OPERATION OF A CREEP TESTING MACHINE TO DETERMINE ITS OPERATING CHARACTERISTICS

This thesis is approved as a creditable, independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Adviser

Head of the Major Department

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The author wishes to thank Allis-Chalmers Manufacturing Company for supplying the stainless steel bar stock used for this study.

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INTRODUCTION

When designing any kind of structure or machine for high temperature operation, the engineer has to consider the effects of creep. In steam and gas turbines, for example, the rotor blades are subjected to high stresses by centrifugal force and to elevated temperatures by high pressure steam or hot gases. The combination of high stress and temperature causes a plastic deformation in the blades. This deformation, known as creep, occurs in all metals under the appropriate temperature and stress conditions, though some metals are more resistant to it than others.

It is practically undesirable to employ a design stress so low that no creep will occur; therefore, it must be accounted for in the design of the structure. The creep of a material can be accurately measured in a testing machine, but creep tests cannot be conducted for a length of time corresponding to the life for which a part is usually designed. The rate at which a material creeps over a certain test period is determined in the creep test; and, by the use of empirical relationships, this creep rate can be employed to deduce what the creep will be at the end of a desired time interval.

The purpose of this project was to install a creep-rate testing machine in the Mechanical Engineering Research Laboratory at South Dakota State College, and to determine its operating characteristics by conducting tests on a material with known creep properties.

REVIEW OF LITERATURE

Many authors have presented articles dealing with methods of creep testing and with the interpretation of creep data. Most creep data are obtained from constant load tests conducted on machines that apply a uniaxial tensile load to the specimen. Finnie and Heller (4) state that this is by far the most common type of creep test because it enables the creep properties of a material to be studied in the simplest possible manner. A machine, described by Marin (6) and Smith (8), that applies a constant, uniaxial load to the specimen is shown schematically in Figure I. When large deformations, which cause a marked reduction in the cross-sectional area of the specimen, are produced, another type of loading is desirable. Corresponding to the reduction in area, stress would increase with time if the applied load remained constant. The testing machine shown schematically in Figure II, described in a paper by Garofalo, Richmond, and Domis (5), has a loading mechanism designed so that the load will decrease with elongation; and a constant stress will be applied to the test piece as it deforms.

Some of the earliest work with creep and the interpretation of creep data was done by Andrade (1) who developed the creep-time relationship

$$\varepsilon = (1 + K_1 t^{1/3})\, e^{K_2 t} - 1 \qquad (1)$$

where K_1 and K_2 are material constants. Smith (8) proposed an equation of the form

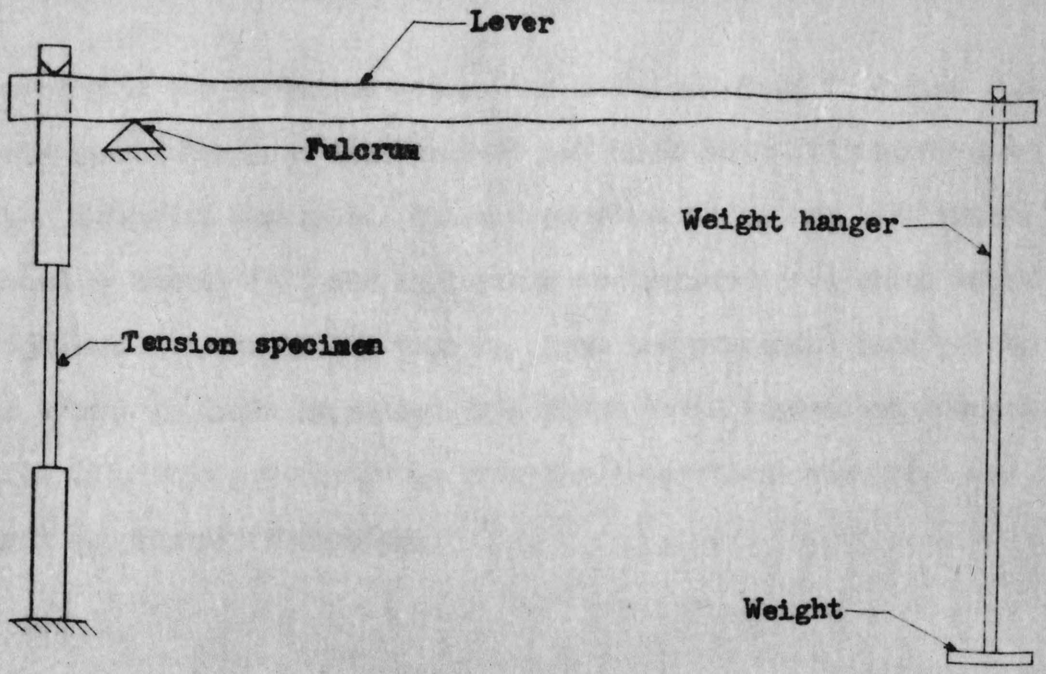

Figure I. Schematic diagram of constant load creep testing machine

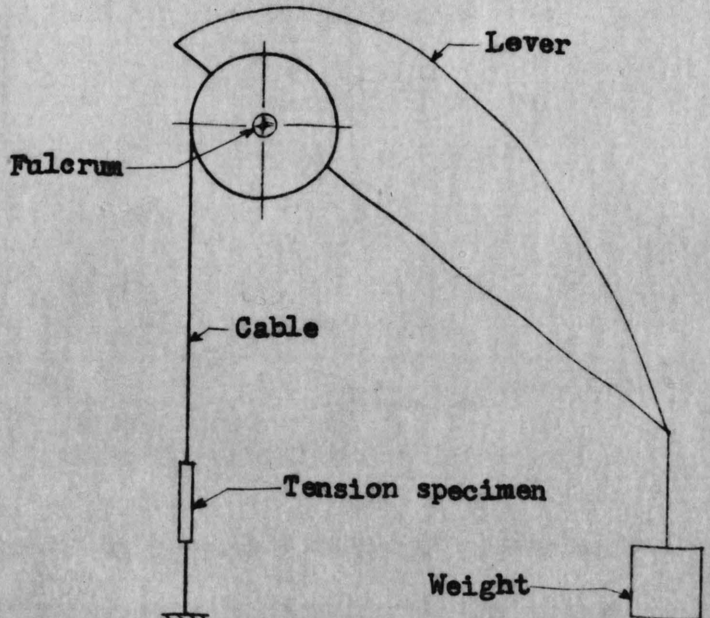

Figure II. Schematic diagram of constant stress creep testing machine

$$\varepsilon = K_1 + Ct \qquad (2)$$

by considering the schematic creep-time curve as shown in Figure III. This simple relation was also pointed out by McVetty (7) who used a slightly different approach. Other creep-time relations have been developed by Weaver (12) and by Tapsell and Prosser (10) which introduce additional terms to equation 2. From the practical standpoint, little advantage is to be gained from these extra terms; but according to Smith (8), they are desirable from the theoretical viewpoint if they can be properly evaluated.

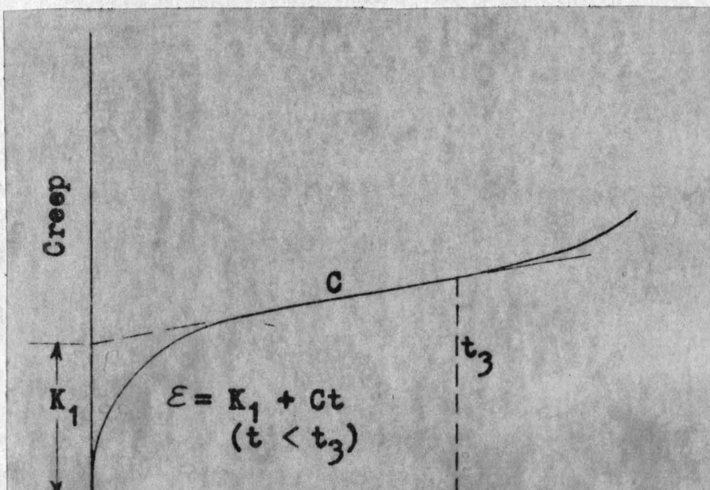

Figure III. Schematic creep-time curve

In order to provide a means of selecting a design stress based on the allowable creep deformation in the estimated life of the part, it is necessary to have an expression which relates the stress, creep, and time for a given operating temperature. This type of relation provides a means of extrapolating stress-creep-time information from the relatively short time of a creep test to the longer lifetime for which a part is designed. According to Marin (6), Smith (8), and Finnie and Heller (4), the most commonly used expression, called the log-log relation or power function, is

$$C = K_1(S/S_o)^n \tag{3}$$

where K_1 and n are material constants. This empirical equation was used by the ASME-ASTM* Joint Research Committee on Effect of Temperature on the Properties of Metals (2) to plot charts for the compilation of available creep data. Another stress-creep-time relationship mentioned by these authors is the exponential or semi-log equation

$$\mathrm{Log}_{10}\, C = K_1 + K_2 \frac{S}{S_o} \tag{4}$$

where K_1 and K_2 are experimental constants. Marin (6) states that this relation is more accurate when more extreme temperatures and stresses are involved.

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*American Society of Mechanical Engineers-American Society for Testing Materials.

CREEP THEORY

Definition of Creep

Creep is a slow, continuous deformation occurring at relatively high temperatures under essentially constant stress, even when this stress does not exceed the yield strength or proportional limit of the material (8)[1]. Although laboratory tests will appear to reveal a creep limit (a stress below which no creep would occur), there is no practical limit below which creep is absent, and this observation is attributed to the measuring apparatus not being sensitive enough to detect slow creep rates.

Characteristic Creep Curve

The creep curves for several different constant loads and for constant temperature, as obtained in conventional creep tests, are shown schematically, with linear coordinates, in Figure IV. The strain-time relation of creep forms a characteristic curve which deviates according to the combined effect of strain and temperature. These curves are considered to be comprised of four stages, or periods, as pointed out by Tapsell (9)[2], and are described in reference to Figure IV as follows:

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[1] G. V. Smith, Properties of Metals at Elevated Temperatures, McGraw-Hill Book Company, Inc.: New York, 1950, p. 95.

[2] H. J. Tapsell, Creep of Metals, Oxford University Press: London, 1931, p. 58.

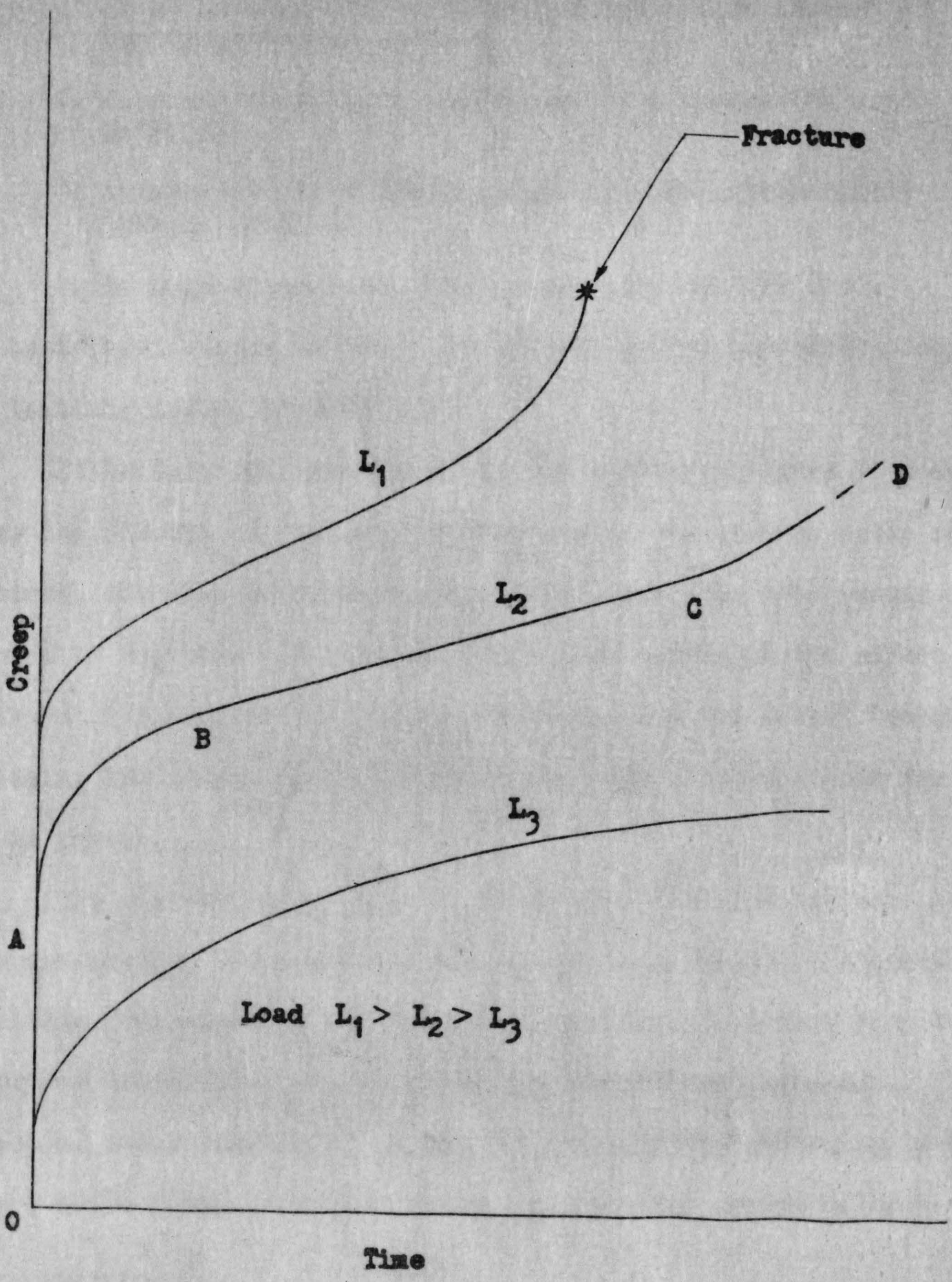

Figure IV. Characteristic creep-time curve

1. An initial, almost immediate, strain which occurs on application of the load (OA). This strain is composed of an elastic (recoverable) portion and an inelastic (non-recoverable) portion.
2. A strain which is characterized by a decreasing creep rate (AB).
3. A minimum rate of strain which is also substantially uniform (BC).
4. An increasing creep rate leading to fracture (CD).

The last three stages are known as primary creep, secondary creep, and tertiary creep, respectively.

It is inferred from the schematic curves in Figure IV that the lower the stress, the longer the time before the minimum creep rate is attained, and the longer the period over which this rate remains substantially constant. The curves could also represent the effect of different temperatures at constant stress, with the lowest temperature replacing the lowest stress on the first curve, and so forth for all of the curves.

The characteristic form of the creep-time plot has been generally ascribed to the interplay of two opposing forces; a strengthening resulting from strain hardening and a weakening resulting from the recovery or recrystallization[3] caused by temperature influence. The effect of strain hardening is held to outweigh the softening in primary creep, while during secondary creep the opposing forces balance each

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[3] These two terms refer to changes which are in the direction of returning the properties of a plastically deformed metal to its undeformed state. Recovery is only a partial return and recrystallization is a complete return to the original properties of the metal.

other. Similarly, the final stage of creep is considered to result from a predominance of softening. This concept is merely a descriptive explanation of the form of the creep curve, and no experimental evidence is available to support it. In fact, it has been pointed out[4] that if tertiary creep is caused by softening, then greater ductility should be expected in creep than in short-time tensile tests, which is contrary to actuality.

Theories of Plastic Flow

The power function (Equation 3) and the exponential function (Equation 4) are empirical relations and have no real physical significance, since neither can represent the zero creep rate corresponding to zero stress. However, both relations represent experimental data quite well over a wide range of minimum creep rates, which makes them useful for extrapolating creep-test data.

Several plastic flow theories have been advanced to give a physical explanation of the creep phenomenon, but none have been proven to be entirely adequate. The most widely accepted of these is the dislocation theory, which takes its name from the type of lattice defect illustrated in Figure V. Part (a) is a two-dimensional sketch of an edge dislocation, and part (b) shows the position of atoms before dislocation took place.

The dislocation is a local deviation from the regular, orderly arrangement of a perfect lattice. An edge dislocation is produced when either a row of atoms is removed from a lattice or a row of atoms

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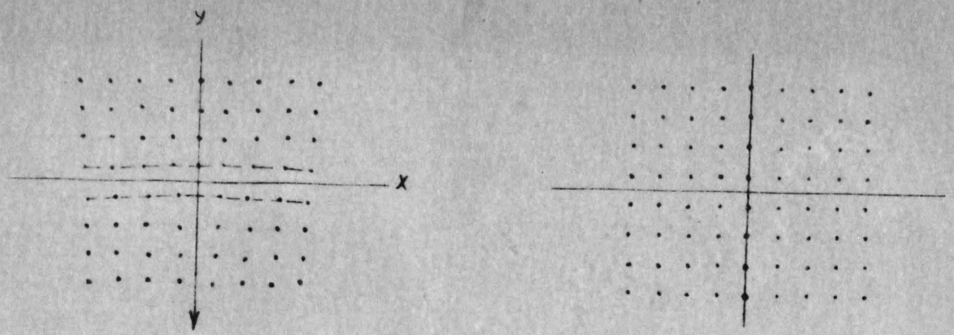
[4] Smith, op. cit., p. 100.

is displaced a unit (atomic) distance. Slip is produced when a dislocation is moved to the edge of the crystal. In edge dislocations the slip motion is in a direction normal to the line of the dislocation. A screw dislocation is produced when slip occurs in a direction parallel to the plane of the dislocation (Figure VI).

Dislocation theory resulted from the differences in magnitude between theoretical calculations and observed values of shear stress. The theoretical calculations were made for perfect crystals and gave much higher shear stress values than any observed for an actual crystal. For this reason, the concept was introduced that all crystals contain imperfections, namely dislocations, from which slip can start at a lower stress than if the crystal were perfect. As a result of factors inherent in the growth of any crystal from the melt, all real crystals will contain dislocations, and the number of dislocations may be increased by as much as twofold under the influence of external shear stress. The dislocations form lines which may or may not form a closed loop. If a dislocation line does not form a loop, it must end at the crystal surface.

As a material slips under an applied stress, a particular dislocation loop in the material may move. If it crosses another dislocation line, a resisting force is experienced, and a "jog" is created in each dislocation line. A jog can be introduced only when the number of atoms in the extra layer of atoms in an edge dislocation is reduced (Figure VII). The number of atoms in the extra layer is reduced by moving atoms out of the slip plane in a direction perpendicular to the slip motion. This motion, called "climb," must be



Row of atoms removed

(a)

Original position of atoms

(b)

Figure V. Two-dimensional sketch of an edge dislocation

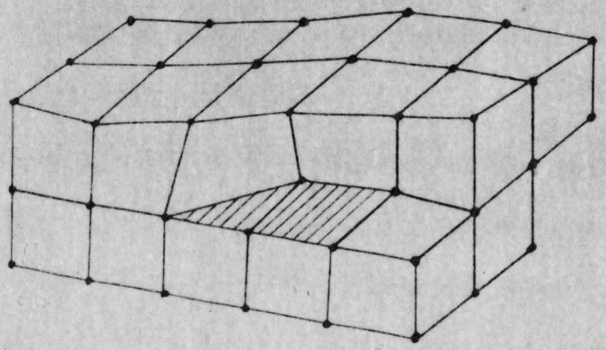


Figure VI. Three-dimensional sketch of screw dislocation

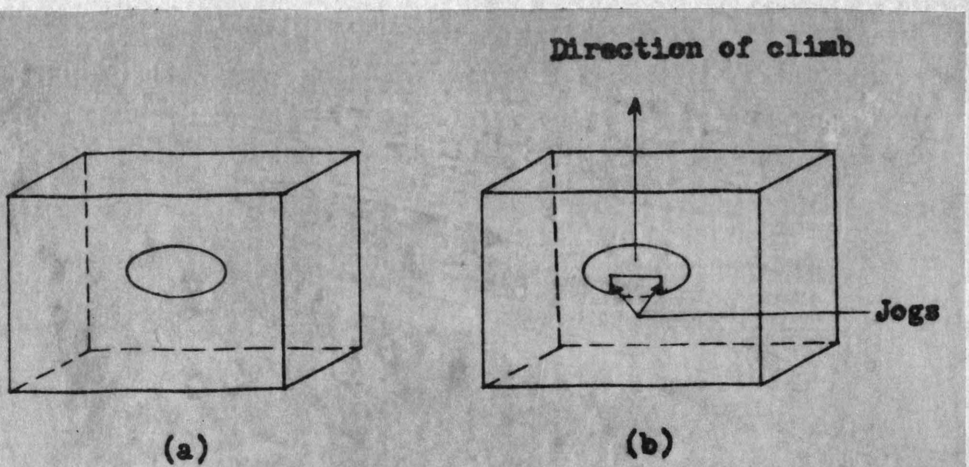


Figure VII. (a) A closed loop of pure edge dislocation in an otherwise perfect crystal. (b) Creation of two jogs in the dislocation loop by diffusion of several atoms out of the extra layer enclosed by the dislocation loop

accomplished by atomic diffusion, and, therefore, will be present only at sufficiently high temperatures.

The intersection of dislocations (forming jogs) and the motion of jogs (climbing) along the dislocations is the mechanism which is used to explain creep. Some dislocations are fixed in one place and cannot move about in the crystal. These sessile dislocations form obstacles which cause the movable dislocations to pile up in their slip planes. Although an applied tensile stress may not be sufficient to cause slip ordinarily, the stress created at the leading dislocation due to the pile up is sufficient to allow the leading dislocation to climb out of its original slip plane at a certain rate. The rate of climb is limited by the local equilibrium concentration of vacancies and their rate of motion, or in other words, by the rate of atomic diffusion. Once the dislocation has climbed to a certain height, which depends inversely upon the local internal stress, it has escaped, and shear may occur due to motion in a new slip plane.

The characteristic shape of the creep curve may then be said to be determined by the stress applied and the rate of climb of dislocation jogs. During primary creep the local internal stresses are only gradually building up in the process of dislocation movement, and the strain hardening process is steadily increasing. In the secondary creep stage, slip, created by climbing, is increasing at a rate just balanced by the strain hardening rate; thus, "steady-state" creep occurs. The material has reached its strain hardening limit and a brittle failure is imminent in the final stage.

A theory proposed by Smekal[5] followed the same lines as the dislocation theory. Smekal suggested that real crystals had flaws that would concentrate an applied stress and cause flow at a much lower stress than that theoretically calculated for an ideal crystal. Smekal considered the submicroscopic faults to be of a somewhat regular nature and to be a natural consequence of the crystalline growth. Since the exact nature of these defects is not known, Smekal's theory is not a satisfactory theoretical explanation of creep.

The Becker-Orowan theory[6] is based upon the statistical variations of energy in any small unit of volume in the crystal, due to the

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[5] Smith, op. cit., pp. 165-166.

[6] Smith, op. cit., pp. 166-167.

thermal vibrations of its atoms. With a given external stress, the local fluctuations at certain sites will result in sufficiently great shearing stress to cause slip. A sufficient number of these sites results in a noticeable slip. Because it is not made clear how this latter motion is to take place, the Becker-Orowan theory has not been widely accepted.

The reason for the lack of a completely satisfactory creep explanation is the presence of many variables that can affect creep properties. A slight difference in chemical composition, due to manufacturing inconsistencies, would cause two specimens of the same material to have measurably different creep rates. The previous history of a material being tested also affects its creep tendencies; an earlier heat-treating process or machining operation can create a great deal of change in the characteristics of a metal. These variables, along with the effects of stress and temperature, make it extremely difficult to derive a general equation that will explain creep under all conditions.

TEST EQUIPMENT

Testing Machine

The lever type creep testing machine (shown schematically in Figure I) used for this work applies a constant uniaxial load to the test specimen. Although there will rarely be situations in actual use wherein the load applied to a part is uniaxial and constant in time, it is nevertheless true that design data can be most conveniently taken from this type of test, and such tests do present a quantitative basis for design.

Constant loading is maintained by a mercury leveling switch and screw jack arrangement in the machine. The mercury switch is mounted on the lever arm and senses whether or not it is level. If the lever is not within ± 1 degree of being horizontal, the mercury makes a contact which starts the screw jack motor. The jack moves the lever arm up or down, as necessary, by acting through the specimen and specimen holding assembly. When a horizontal position is restored, contact is broken, and the screw jack motor is shut off.

Reasonably uniaxial loading is acquired by mounting the specimen holders to the machine through spherical yoke assemblies. The lower assembly is shown at the bottom of Figure XV, prior to mounting the specimen holder to it. The only non-axiality that results will be caused by friction in the yoke.

Furnace and Controller

A tubular, electrical resistance furnace was used to heat the specimen. To aid in making temperature adjustments along the specimen gage length, the furnace was wired to have three zones in its windings--designated as top, middle, and bottom.

Temperature control was achieved by a mechanical on-off controller wired into the testing machine electrical circuit. This circuit allows a small amount of current to flow through the furnace windings whether the controller is on or off. Sensing for the controller is by a chromel-alumel thermocouple located in the furnace windings.

Extensometer

Since the change in length due to creep is very slight from day to day, a microscope was used for making extension measurements. It is held by a mounting bracket in such a way that it may be sighted through a window into the furnace. Inside the furnace, an extensometer is mounted to the test piece so that two pieces of platinum will move relative to each other when the specimen elongates. The amount of elongation is measured by sighting the microscope on the platinum and determining how much relative movement has taken place by use of movable crosshairs visible through the microscope eyepiece.

PREPARATION FOR TEST

Preparations for testing were started by leveling the creep machine so that the specimen would be held exactly vertical. It was also necessary to balance the lever arm, with the weight hanger and upper spherical yoke assembly in place, so that it would rest horizontally on its knife-edge supports. These precautions were essential for proper specimen loading.

Three specimens of the dimensions shown in Figure VIII were machined from stainless steel bar stock for use in this work. The pieces were turned to a few thousandths oversize with a cutting tool and then polished down with emery cloth to the prescribed diameter (as measured with a micrometer). This gave the smooth, polished finish which was necessary to avoid creating stress raisers. The extensometer[7] was clamped to the 3/4 inch diameter shoulder of a specimen and the whole unit mounted in the machine as shown in Figure IX. With the extensometer clamped this way, it was possible to measure total elongation along the entire gage length.

With the specimen mounted as in Figure IX, three calibrated thermocouples[8] were attached to it at the top, middle, and bottom of the gage length. The thermocouple junctions were held firmly against the specimen by wrapping them with 14 gauge nichrome wire as shown in Figure X. Figure XI shows how asbestos string was wrapped around the

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[7] See Appendix B.

[8] See Appendix C.

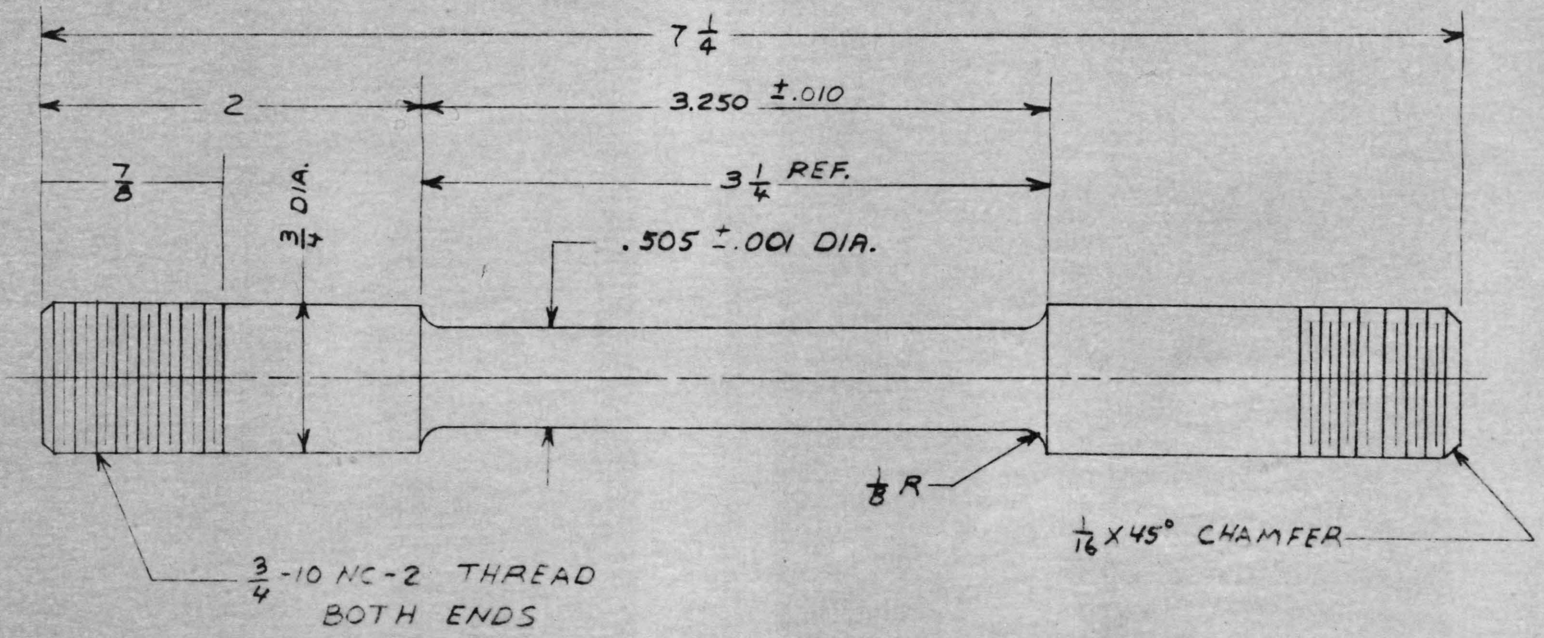

Figure VIII. Creep test specimen

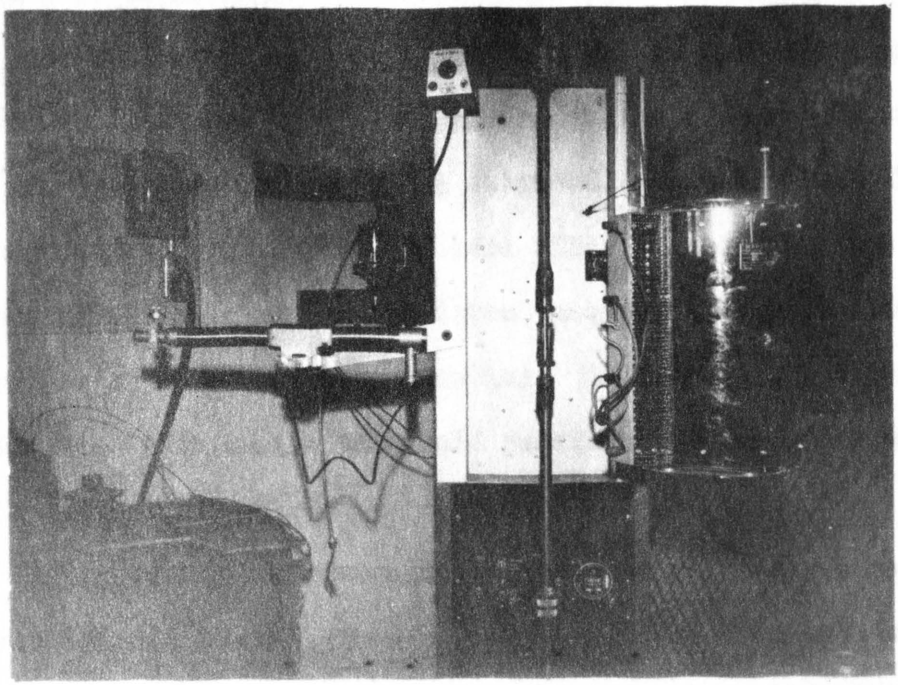

Figure IX. Specimen temporarily mounted in machine

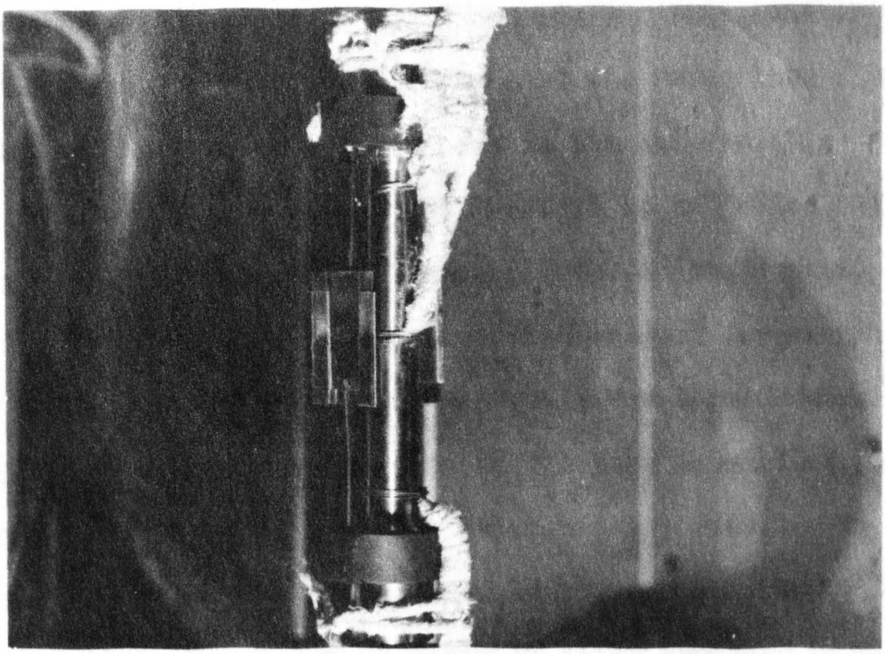

Figure X. Specimen, with thermocouples and extensometer in place, ready for testing junctions to avoid errors caused by radiation from the furnace wall. These last two Figures (X and XI) also show how the termocouples were wrapped with asbestos to prevent errors due to a short circuit.

Each thermocouple wire was attached to the terminal block and selector switch setup shown in Figure XII. This arrangement provided for temperature readings at all three junction locations with one potentiometer and one reference junction. A Leeds-Northrup Model 8662 potentiometer with an ice bath cold junction was used for temperature readings (Figure XIII).

After making the thermocouple connections, the top and bottom specimen holders (see Figure XIV) were unscrewed from the machine. The top specimen holder was then started into the furnace from the bottom, as shown in Figure XV, and pushed up through the furnace; this was done carefully so as to avoid bumping the extensometer or pulling the thermocouples loose. The whole unit was swung into place and the specimen holders were connected back to the machine (Figure XVI).

All thread engagements that were to be subjected to loading during the test were checked for proper thread engagement. The large nuts in the yoke assemblies were screwed on just far enough for all of their threads to make contact. All but a few threads were used when the specimen holders were screwed to the yoke assemblies, and at least 1/2 inch of thread was used when attaching the specimen to the holders. Powdered graphite was used in these last two locations to lubricate the connections for easier disassembly after exposure to elevated temperatures.

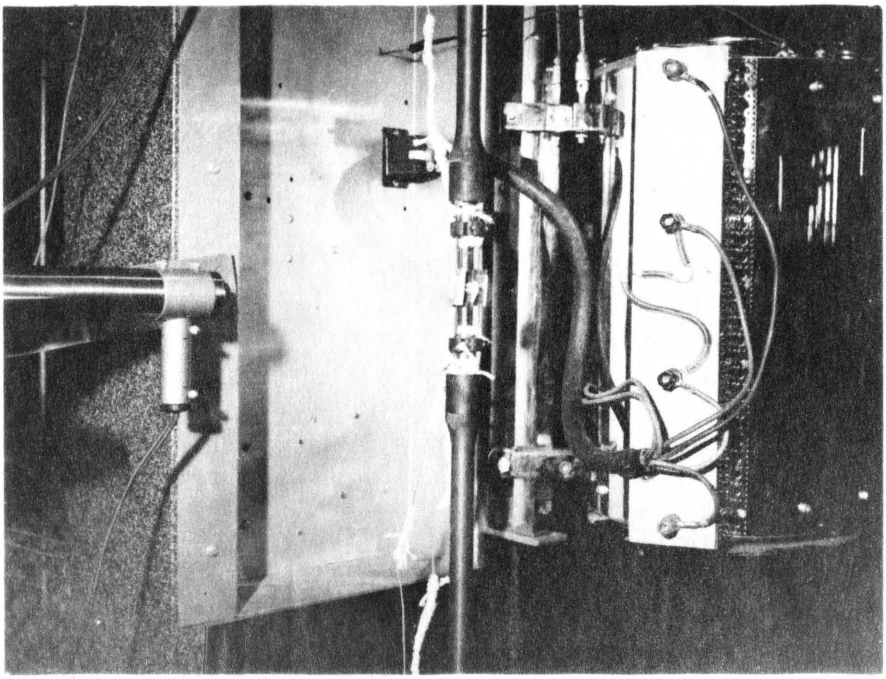

Figure XI. Asbestos string used to minimize errors

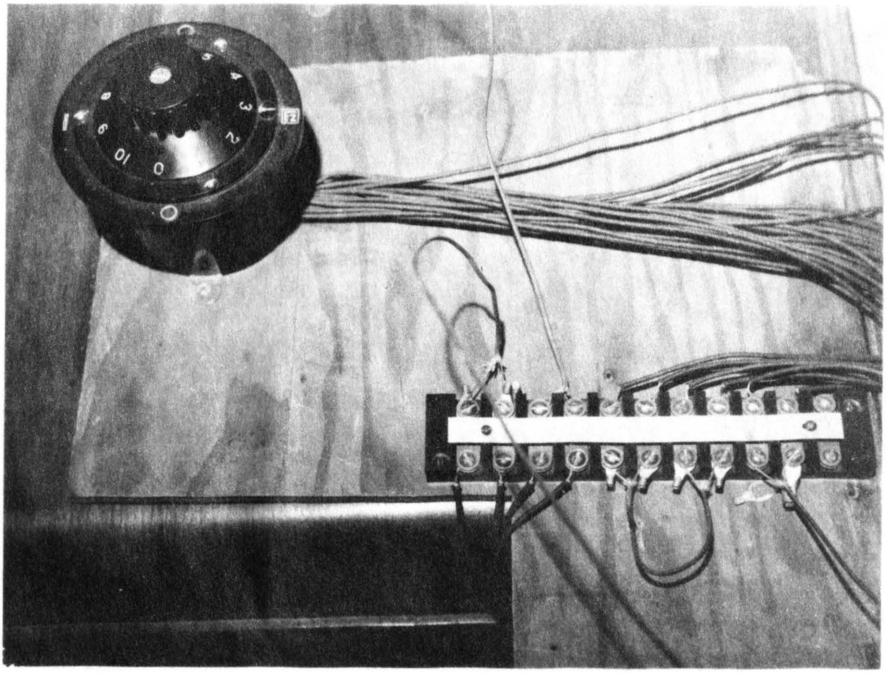

Figure XII. Terminal block and selector switch

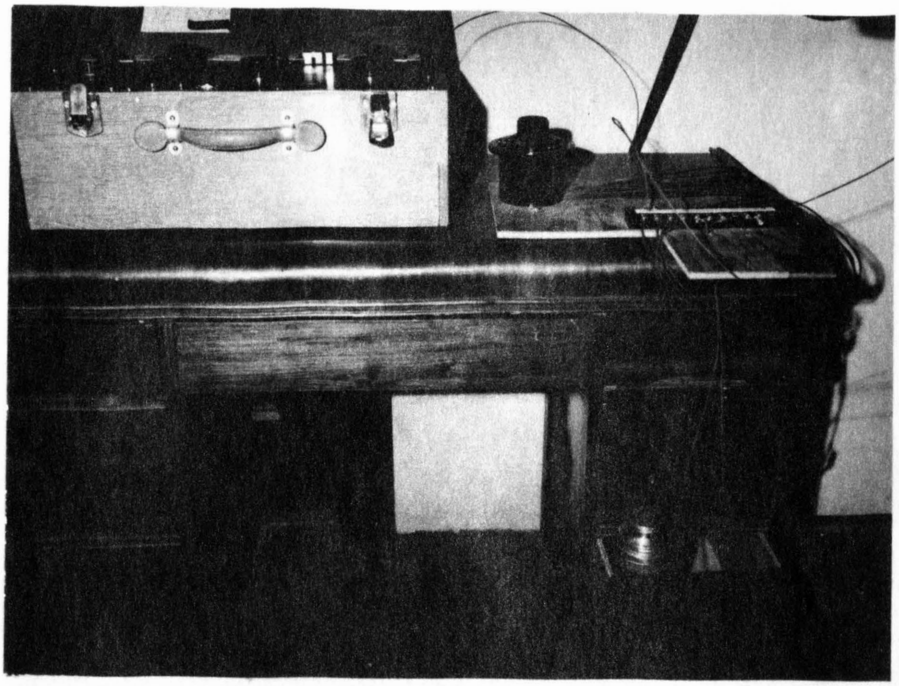

Figure XIII. Temperature reading apparatus

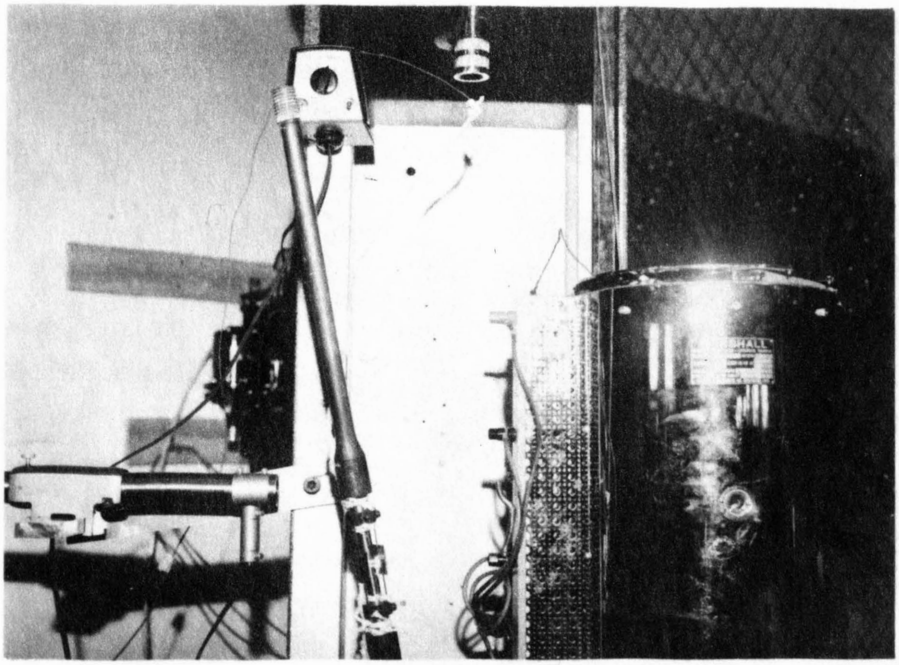

Figure XIV. Specimen holder unscrewed from machine

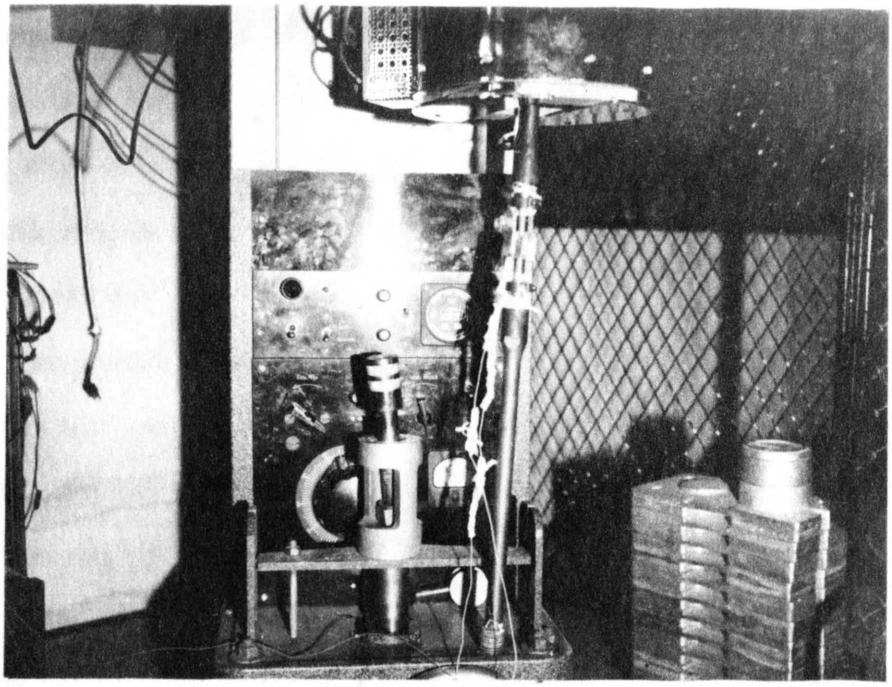

Figure XV. Inserting specimen into the furnace

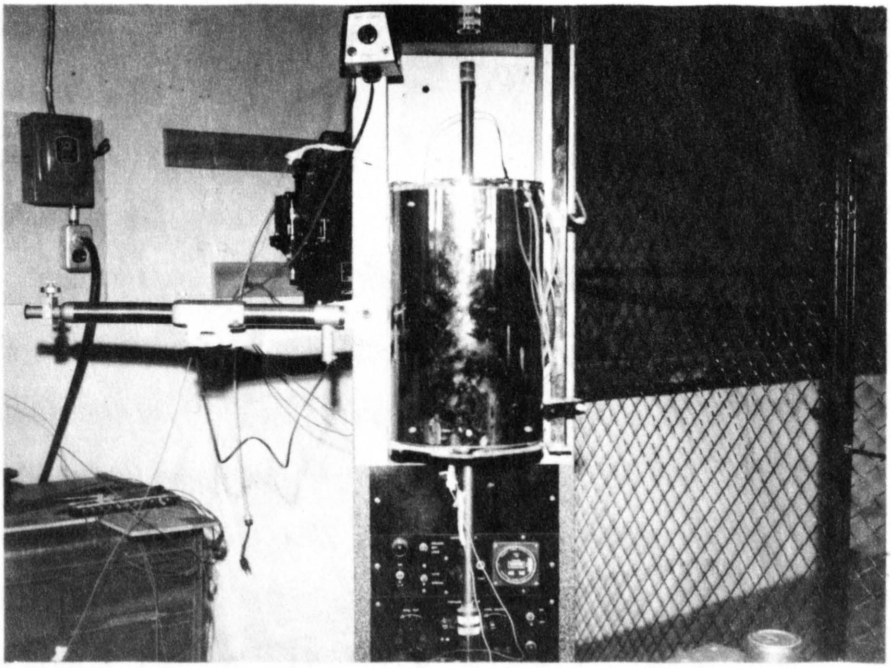

Figure XVI. Mounting specimen for test

The furnace was set in a position that would allow centering the specimen an equal distance from the open ends, and would make the extensometer visible through the windows at its middle. A shunt was needed across the middle furnace winding (see Figure XI) to maintain a constant temperature along the specimen gage length. Adding a shunt where there was none originally cools the area shunted and warms the other two areas. Lengthening a shunt already present warms the area affected and cools the others; shortening a shunt has the opposite effect. It was necessary to make several changes in the shunt to obtain the proper temperature distribution.

The temperature controller was mounted so as to be level across the top by hanging it on a wall near the machine (Figure XVII). The galvanometer needle was set to zero by the zero adjustment knob, and the internal bridge was balanced against the dry cell by the balance adjustment knob. The two bottom wires in Figure XVII connect into the testing machine circuit; the top wire is a chromel-alumel wire which connects to the sensing thermocouple at a terminal on the furnace.

Another microscope mounting bracket, similar to the one supplied with the machine, was made so that elongation readings could be taken from both sides of the furnace. Before the microscope could be used for extension measurements, it had to be adjusted so that its internal light source and its lens focused on the same point. This was done by clamping one mounting bracket to a table, as shown in Figure XVIII, and focusing the microscope onto a piece of paper. A cross was drawn on the paper and illuminated with a flashlight; the paper was then moved around until the center of the cross was visible at the center of the microscope image. By moving the bulb around inside the illuminator, the internal light source was focused on the same point and held in place by tightening the illuminator clamp screws.

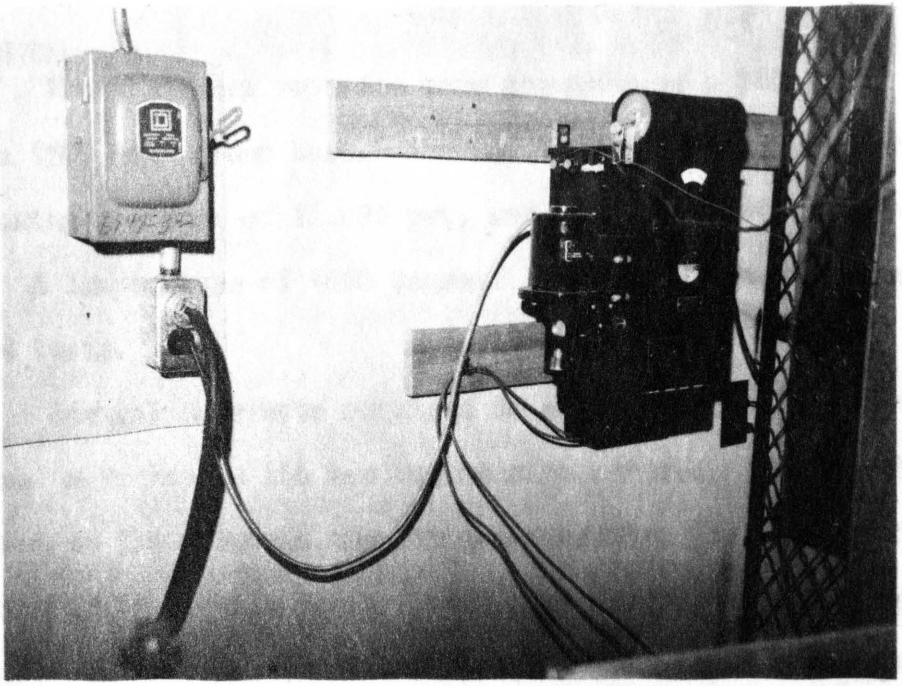

Figure XVII. Temperature controller

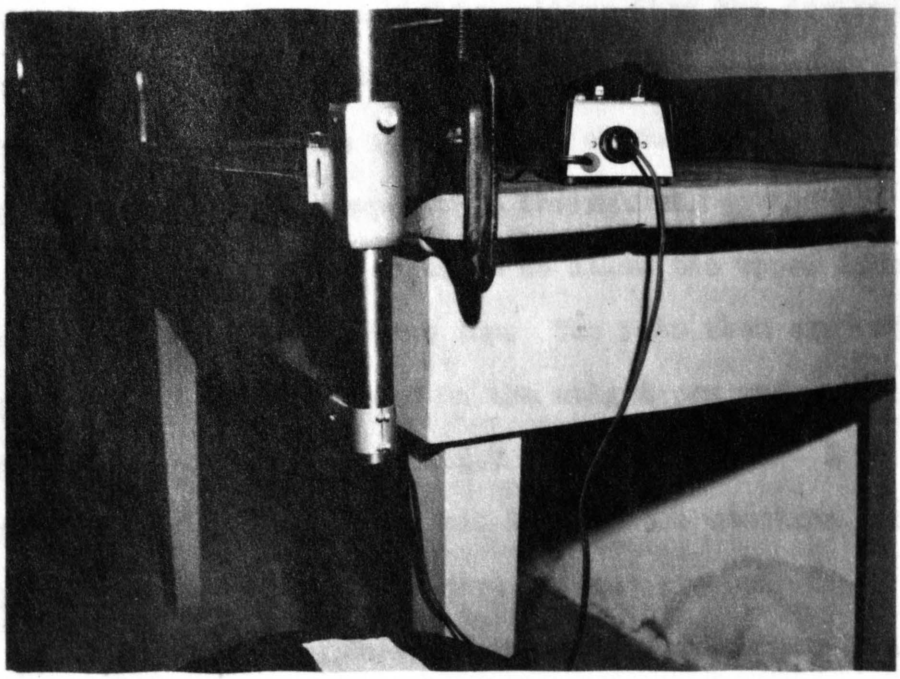

Figure XVIII. Microscope clamped to table

TEST PROCEDURE

The test work reported here consists of a 760 hour, a 1000 hour, and a 1500 hour creep test. The 760 hour and the 1000 hour tests were run using a stress of 10,000 psi, and the last test was run at 15,000 psi. A temperature of 1000 degrees Fahrenheit was maintained in all three tests.

Several days were required to get the proper temperature settings. A Variac on the testing machine controls the amount of current allowed to flow through the furnace windings. It was found that a setting of 45 on this Variac gave a very nearly constant specimen temperature of 1000 degrees Fahrenheit when the temperature controller dial was set at 1012 degrees. Because the control element is located in the furnace windings, a higher setting than the desired specimen temperature is needed on the controller. With the desired temperature settings established, the specimen was allowed to heat up for 24 hours to gain an equilibrium temperature throughout.

The screw jack was adjusted to allow the upper spherical yoke to contact against the machine top. The yoke then supported the weights when they were placed on the weight pan and prevented unwanted shock loads from being transmitted to the specimen. Each pound of weight added was equal to 200 psi load on the specimen, and enough weights were used to give the desired test stress.

By following a prescribed switching procedure, the machine automatically applied loading to the specimen. As soon as the lever arm reached a horizontal position, the loading mechanism (screw jack) automatically shut off. At this time the timer was started, and the initial microscope readings were taken on both sides of the extensometer. The first microscope readings gave references from which elongation could be determined.

Under magnification, little bright specks and other surface variations could be detected on the platinum extensometer. One of these variations, close to the boundary between movable pieces, was chosen on each part of the extensometer as a reference point. The reference points picked were as close together as possible and were near the intersection of the stationary cross hairs. This cross hair intersection was focused on another point which was used as a reference for locating the microscope at the same place each time a reading was taken. After picking reference points, the microscope mounting brackets were not moved. The microscope had a thumbscrew clamp on its base that allowed it to be moved from one bracket to the other so that readings could be taken on both sides of the extensometer.

For taking readings, the filar eyepiece was rotated until the micrometer dial was on top of the microscope, then clamped securely so it would not turn during the test. The micrometer dial was turned until the double hairline went beyond one of the reference points; then it was turned the opposite way until the top hairline touched the point. The micrometer reading was noted and turning continued, keeping track of the number of turns, until the other point was contacted. Here, the micrometer was read again, and the distance between references was determined and recorded. As the test proceeded, the distance between references increased or decreased, depending on the direction of relative motion between extensometer parts. The amount of this change gave the exact amount of deformation in the specimen.

Heat losses were kept at a minimum by wrapping spun glass insulation around the specimen holders where they entered the furnace. On the third test, a clamp was used to hold the upper furnace and covers snug against the specimen holder, and it was found that a smaller temperature gradient resulted when this was done.

Microscope readings were taken every several hours at first; but after steady-state creep began, readings were taken every one or two days. Whenever elongation was measured, the three junction temperatures were also read and recorded. Temperature readings had to be taken at least every other day to keep check on the controller. Balance of the Wheatstone bridge circuit in the controller had to be watched very carefully, especially after the battery had been used for a period of time; because whenever the bridge got out of balance, it changed the control temperature.

When a test was finished, the furnace and timer were shut off and the load-unload switch was changed from the "load" to "unload" position. The machine compensates automatically for contraction of the specimen while it cools. After the specimen cools down, it is removed from the test apparatus, and the diameter is measured in three places, with a micrometer, to check for reduction in area.

Figures XIX and XX show the machine, with all components in place, as it looked during the last test.

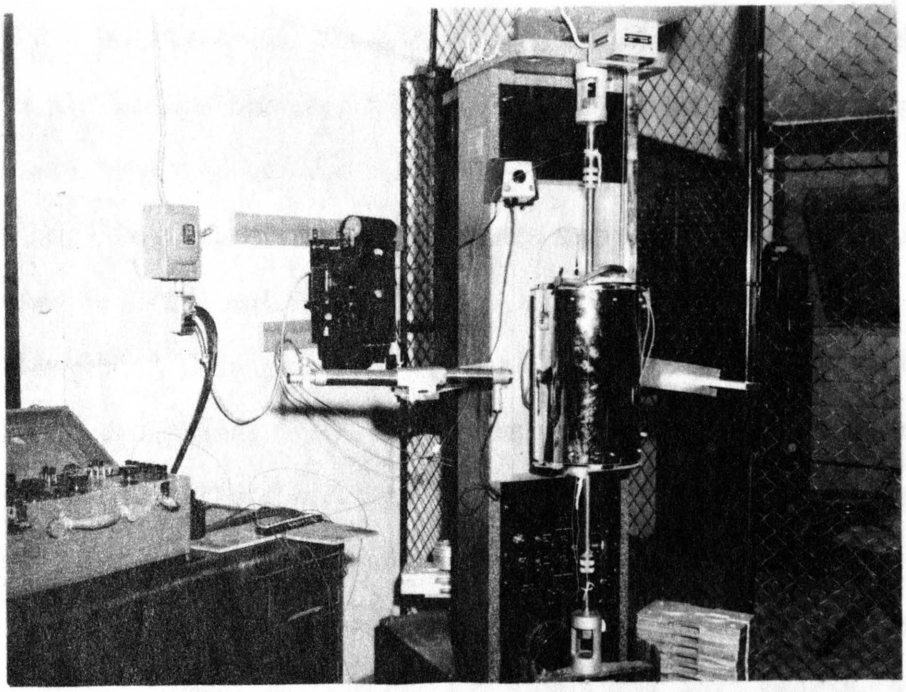

Figure XIX. Left three quarter view of creep machine

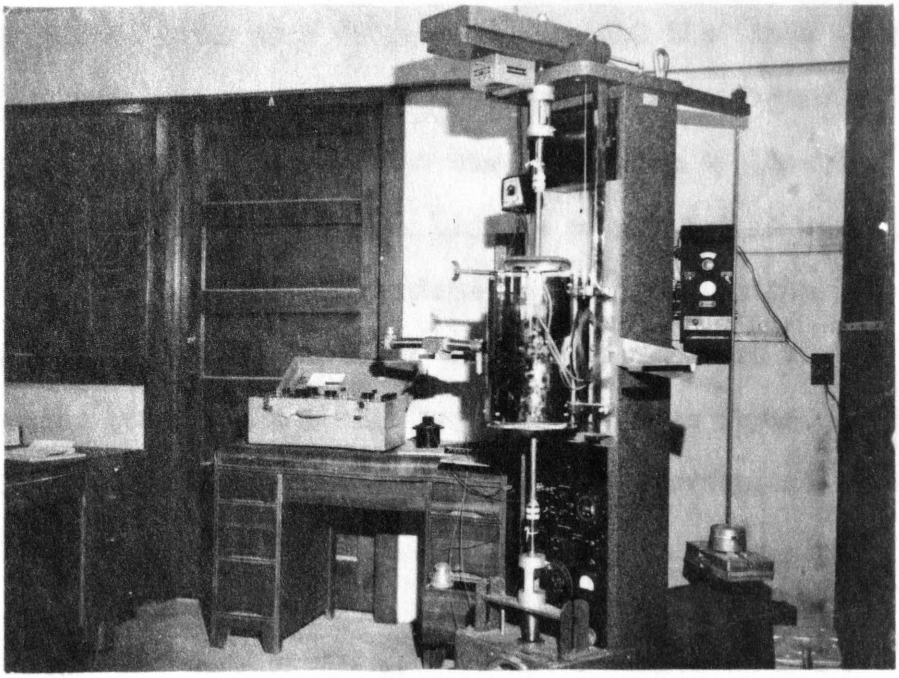

Figure XX. Right three quarter view of creep machine

RESULTS

The first test was stopped after 764.8 hours due to inconsistencies in the elongation readings. Upon disassembly of the apparatus, it was found that the top extensometer bracket had come loose and was not holding. Because of this, the creep data in Table 1 are known to be in error and will not be considered as valid results.

Elongation data given in Tables 1, 2, and 3 are the distances, at the times indicated, between reference points in ten thousandths of an inch units. The first left and right extensometer reading averages listed in Table 2 and Table 3 were used as the reference distances for plotting the creep curves in Figure XXI. The mean difference between these references and subsequent right and left reading averages gave the amount of elongation that had occurred up until the later time. By plotting the mean differences against the times at which they were determined, the characteristic creep curves in Figure XXI were constructed. The immediate strain occurring upon application of the load is not shown in these curves because no provisions were made to measure it. The tertiary creep stage is not shown, either, because the stresses and temperatures used in these tests were not high enough for it to present itself in the relatively short times reported here. Primary and secondary creep, however, are readily recognizable in the two curves presented in Figure XXI.

Table 1. Creep Data for Test at 1000 degrees Fahrenheit and 10,000 psi--First Test

Time (hours)	Temperature (degrees F) Bottom	Middle	Top	Elongation (inches x 10^4) Left	Right
.5	999.7	999.0	1000.0	213.0	163.2
16.4	997.3	997.0	999.0	214.5	165.2
27.9	993.5	993.5	996.0	215.1	166.1
44.6	1023.0	1013.0	1004.5	215.5	171.9
72.2	1009.5	1006.0	1003.0	225.4	163.7
95.0	1024.7	1014.5	1004.5	227.3	171.3
118.7	1013.3	1008.3	1006.0	245.7	173.4
141.7*	1013.7	1008.7	1006.0	247.5	171.5
165.7	999.0	998.0	998.5	247.6	170.0
192.0	1000.0	999.7	1001.0	250.0	170.9
238.8	997.7	997.3	998.0	252.7	170.0
433.0	995.0	995.0	996.5	251.4	170.0
486.5	1001.0	1000.5	1001.5	252.1	169.7
500.8	1000.0	1000.0	1001.5	252.1	172.5
524.8	993.5	995.0	998.5	251.7	173.5
550.0	994.5	995.5	997.5	250.9	173.6
573.9	994.0	995.0	998.0	251.7	175.8
600.3	991.3	993.0	996.5	249.6	181.7
620.8	991.0	991.7	994.7	250.9	182.0
645.4	992.0	994.5	997.0	251.9	181.2
665.3	996.5	996.5	998.5	250.3	177.2
696.3	997.7	997.7	1000.0	248.5	176.4
720.2	997.3	997.3	1000.0	262.5	187.3
764.8	991.7	994.0	998.0	261.4	180.0

*The temperature controller was reset at this point.

Table 2. Creep Data for Test at 1000 Degrees Fahrenheit and 10,000 psi--Second Test

Time	Temperature (degrees F.)			Elongation (inches x 10^4)							
				Left				Right			
(hours)	Bottom	Middle	Top	One	Two	Three	Av.	One	Two	Three	Av.
0.3	1003.2	1004.0	1003.2	171.9	172.1	172.0	172.0	35.4	35.4	35.6	35.5
18.8	1000.7	1001.3	1001.2	157.1	157.7	158.0	157.6	25.2	24.5	25.0	24.9
47.0	998.7	999.5	999.0	156.1	155.9	155.4	155.8	25.0	24.8	24.6	24.8
69.5	1002.7	1004.0	1003.2	156.6	155.8	156.0	155.8	25.4	25.4	24.8	25.2
113.0	1003.2	1004.7	1004.7	155.8	155.3	154.8	155.3	25.6	25.2	24.9	25.2
138.6	1004.2	1005.0	1005.2	155.3	155.0	154.7	155.0	24.9	25.2	24.9	25.0
166.5	999.0	1000.0	999.7	155.2	155.0	154.8	155.0	24.6	24.7	25.3	24.9
187.7	998.7	999.5	999.3	155.2	154.9	155.0	155.0	25.2	25.0	24.4	24.9
212.7	1001.7	1003.0	1002.7	154.9	154.2	154.0	154.4	24.9	24.8	24.8	24.8
252.5	999.0	1000.0	1000.0	143.3	143.7	143.2	143.4	24.8	24.6	24.6	24.7
287.5	1000.7	1001.3	1002.0	143.4	143.0	143.0	143.1	24.4	24.1	24.2	24.2
301.3	1000.7	1001.3	1001.7	143.5	143.5	142.7	143.2	24.6	23.6	24.2	24.1
329.3	999.7	1001.0	1001.2	143.4	143.0	142.7	143.0	24.0	23.9	24.0	24.0
353.6	1000.7	1002.0	1002.0	141.0	144.0	142.7	142.6	22.8	22.6	22.6	22.7
376.6	1001.7	1002.3	1002.3	141.2	142.7	143.0	142.3	22.2	22.9	22.1	22.4
419.5	1002.7	1003.5	1003.2	140.1	143.4	143.2	142.2	22.1	22.3	22.4	22.3
451.3	1003.7	1004.2	1005.0	142.1	140.5	143.0	141.5	21.9	22.4	22.1	22.1
473.8	1004.2	1004.7	1005.0	142.8	142.6	142.1	142.5	22.1	21.5	22.2	21.9
498.9	1005.3	1006.0	1006.2	142.2	142.3	142.0	141.8	21.4	22.1	21.6	21.7
522.4*	997.7	998.7	998.7	142.0	141.2	139.0	140.7	21.5	21.2	21.9	21.5
549.0	997.7	998.7	998.7	139.9	140.3	142.0	140.7	22.3	21.2	21.9	21.8
593.5	1000.0	1001.0	1001.2	140.5	142.0	140.5	141.0	21.2	21.2	21.6	21.3
622.0	1002.0	1003.0	1002.7	141.3	141.9	141.6	141.6	20.7	21.7	21.0	21.1
642.0	1002.0	1003.0	1002.7	148.0	147.7	148.0	147.9	23.5	23.6	22.6	23.2
666.6	996.4	997.5	997.7	140.6	140.8	140.4	140.4**	14.1	13.5	14.0	13.7**
690.0	997.7	998.7	998.7	140.1	140.2	140.0	140.1	11.2	12.8	11.3	11.8
720.0	996.4	997.0	996.4	140.7	141.8	142.2	141.6	12.7	12.6	12.7	12.7

Table 2. (continued)

Time (hours)	Temperature (degrees F.)			Elongation (inches x 10^4)							
				Left				Right			
	Bottom	Middle	Top	One	Two	Three	Av.	One	Two	Three	Av.
755.8	1002.0	1003.0	1002.7	140.2	139.8	139.7	139.9	12.4	12.6	12.7	12.6
785.0	995.2	996.0	996.0	141.2	139.5	140.8	140.5	11.8	13.3	11.7	11.9
810.6	994.4	995.5	995.2	140.8	139.5	139.2	139.8	11.0	11.4	11.2	11.2
833.6	996.0	996.7	996.7	140.1	140.0	139.1	139.7	11.6	11.9	12.0	11.8
857.9	995.5	996.7	996.2	140.8	139.3	139.1	139.7	11.1	11.8	11.9	11.6
883.1	998.7	999.5	999.3	140.0	140.0	139.1	139.7	11.8	11.4	11.6	11.6
923.6	1000.0	1001.0	1001.2	139.2	140.1	139.0	139.4	11.3	11.5	11.1	11.3
952.7	1001.2	1002.0	1002.0	139.3	139.5	139.1	139.3	11.2	11.3	10.9	11.1
976.4	1001.7	1002.3	1002.3	139.2	139.4	139.3	139.3	11.5	12.0	10.7	11.4
1025.8	999.0	1000.0	999.7	138.7	139.4	139.4	139.2	11.5	11.1	11.1	11.2

*The temperature controller was reset at 498.9 hours.

**A new reference distance was chosen due to rotation of the filar eyepiece.

Table 3. Creep Data for Test at 1000 Degrees Fahrenheit and 15,000 psi--Third Test

				Elongation (inches x 10^4)							
Time	Temperature (degrees F.)			Left				Right			
(hours)	Bottom	Middle	Top	One	Two	Three	Av.	One	Two	Three	Av.
0.5	998.2	996.7	995.2	356.3	356.1	356.0	356.1	91.1	90.7	90.8	90.9
7.0	999.3	999.5	1000.0	336.8	337.1	337.0	337.0	110.4	109.2	110.2	109.9
19.7	999.0	999.0	999.3	324.5	324.9	324.0	324.5	119.0	120.0	120.0	119.7
45.9	998.7	998.7	999.3	313.4	313.9	312.9	313.4	129.1	129.6	129.0	129.2
75.0	997.2	998.0	998.7	304.0	304.0	305.0	304.3	136.4	136.2	136.0	136.2
98.2	996.7	997.5	998.2	302.8	302.9	303.3	303.0	137.9	137.5	137.6	137.7
117.9	997.7	998.3	998.7	300.0	300.5	300.3	300.3	140.5	141.4	141.2	141.0
147.5	1000.0	1000.5	1001.2	299.0	298.9	298.5	298.8	143.6	143.6	143.5	143.6
189.5	990.7	990.7	991.7	296.2	296.0	295.8	296.0	146.5	146.1	146.8	146.5
221.0*	1005.0	1005.0	1005.7	293.2	294.2	294.1	293.8	147.6	147.7	147.8	147.7
296.5**	1001.2	1001.3	1002.0	288.2	288.3	288.2	288.2	151.3	150.8	150.4	150.8
318.6	999.0	999.5	999.7	286.9	288.0	287.9	287.6	152.2	152.3	151.3	151.9
362.3	1002.7	1003.0	1003.7	285.3	284.9	285.0	285.1	155.7	156.0	155.8	155.8
408.4	1001.2	1001.7	1002.3	280.9	281.9	281.1	281.3	159.3	160.0	158.5	159.3
454.2	998.2	998.7	999.0	280.0	279.3	279.3	279.5	161.0	161.3	161.0	161.1
507.6	998.2	998.7	999.0	275.5	276.0	276.2	275.9	162.0	162.6	162.3	162.3
545.8	999.0	999.5	1000.7	272.8	271.8	272.8	272.5	164.7	164.5	164.5	164.6
602.9	997.2	997.5	998.7	270.4	270.0	270.4	270.3	166.4	166.1	166.5	166.3
651.4	996.7	997.5	998.2	267.3	267.4	268.4	267.7	170.6	170.0	169.8	169.9
693.0	996.0	996.7	996.7	269.4	269.4	269.2	269.3	171.0	170.5	170.4	170.6
742.0**	996.7	997.0	998.2	264.4	264.1	262.8	264.1	171.6	172.4	172.6	172.2
799.5**	1002.3	1003.0	1003.2	261.3	263.4	263.9	262.8	175.1	174.5	173.3	174.3
860.0**	999.0	999.5	999.7	258.2	258.5	258.7	258.5	177.5	178.5	178.4	178.1
939.0	998.2	998.7	999.0	256.4	256.2	256.7	256.4	180.7	181.0	180.0	180.6
987.8	999.0	999.0	999.7	255.4	254.6	254.1	254.7	182.0	182.0	182.1	182.0
1040.0	1001.7	1001.7	1002.3	253.8	253.8	254.3	254.0	184.8	184.9	185.0	184.9

Table 3. (continued)

				Elongation (inches x 10^4)							
Time	Temperature (degrees F.)			Left				Right			
(hours)	Bottom	Middle	Top	One	Two	Three	Av.	One	Two	Three	Av.
1100.0	1000.7	1001.0	1002.0	253.6	253.9	253.6	253.7	186.0	186.0	186.5	186.2
1148.5	999.0	999.0	1000.0	252.4	252.4	251.5	252.1	187.3	187.4	188.1	187.6
1227.7	998.7	999.0	1000.0	250.0	249.6	249.8	249.8	190.5	189.2	190.2	190.0
1275.6	999.7	999.5	1001.2	243.1	243.7	243.3	243.4"	190.6	190.6	191.0	190.7"
1322.1	999.7	1000.0	1000.7	241.9	241.5	242.3	241.9	193.4	194.0	194.2	193.9
1370.7	1002.3	1002.3	1003.2	240.4	240.0	240.2	240.2	193.8	193.2	193.5	193.5
1442.5	999.7	1000.5	1001.2	237.7	237.4	237.9	237.7	195.5	196.0	195.5	195.7
1486.0	1002.3	1003.0	1004.2	236.7	236.6	236.8	236.7	197.6	198.3	196.9	197.7
1540.0	999.7	1000.5	1001.2	235.0	234.9	235.6	235.2	198.6	198.7	198.6	198.6

*A new battery was installed in the controller before this reading was taken.

**The controller was reset before these readings were taken.

"The light in the microscope was refocused at this point.

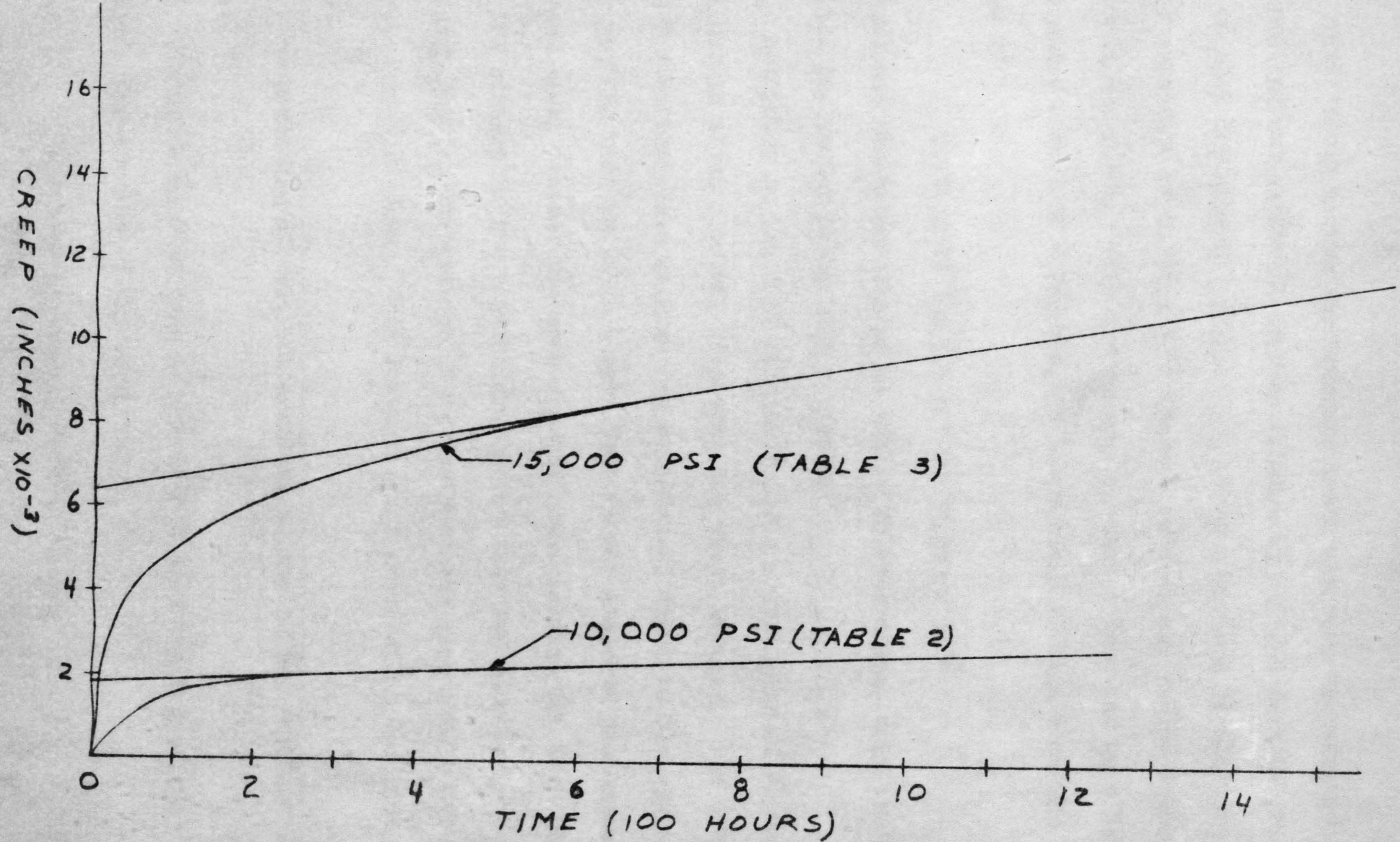

Figure XXI. Creep-time curves from data in Tables 2 and 3

Only those elongation readings taken when the temperature of the specimen was within ±2 degrees Fahrenheit of 1000 degrees were used to plot the curves. Eshbach (3) gives a minimum coefficient of linear expansion of 0.711×10^{-5} inches per inch per degree Fahrenheit for stainless steel. With a specimen 3.5 inches long and an allowed temperature change of 4 degrees, it is possible to have a change in length of

$$0.711 \times 10^{-5} \times 3.5 \times 4 = 9.954 \times 10^{-5}$$

or about one ten thousandth of an inch. In some cases, this is more than the day to day change due to creep.

According to the ASTM standards (11), a variation of ±3 degrees is allowable without unduly affecting the creep results. The data in Table 2 show that this maximum was exceeded 13 times in the second test, and the data in Table 3 show that it was exceeded six times in the last test. There were some drastic deviations in the last test due to a low battery on the controller. It is also recommended in the ASTM standard that the temperature along the specimen gage length not vary by more than 3 degrees. This limit was not exceeded in the last two tests.

No reduction of area was detected in any of the specimens tested.

The minimum creep rate is determined by the slope of the straight line portion of the creep curve, or by

$$C = \frac{\varepsilon}{t \times \text{gage length}} \times 100. \qquad (5)$$

For 10,000 psi stress and 1000 degrees Fahrenheit, the creep rate was found to be

$$\frac{0.00008}{3.25} \times 100 = 0.025 \text{ per cent per 1000 hours.}$$

At 15,000 psi stress and 1000 degrees, the creep rate was

$$\frac{0.00336}{3.25} \times 100 = 0.103 \text{ per cent per 1000 hours.}$$

These values are plotted on log-log paper in Figure XXII.

Taking the logarithm of both sides of Equation (3) results in

$$\log_{10}C = n \log_{10}\left(\frac{S}{S_o}\right) + \log_{10}K_1 \qquad (6)$$

which represents a straight line on a log-log plot. The value of n is determined by the slope of the straight line in Figure XXII and K_1 is determined by the intercept on the "y" axis where "x" = $\log_{10}(\frac{S}{S_o}) = 0$, or $\frac{S}{S_o} = 1$. Taking

$$S_o = 10{,}000 \text{ psi}$$

gives a value of

$$K_1 = 0.025.$$

The slope of the straight line in Figure XXII is

$$n = 3.5.$$

Now Equation (3), or Figure XXII, can be used to find what the minimum creep rate would be for other applied stresses. Once C is determined, the lifetime for a desired strain can be found by

$$t = \frac{\varepsilon}{C}. \qquad (7)$$

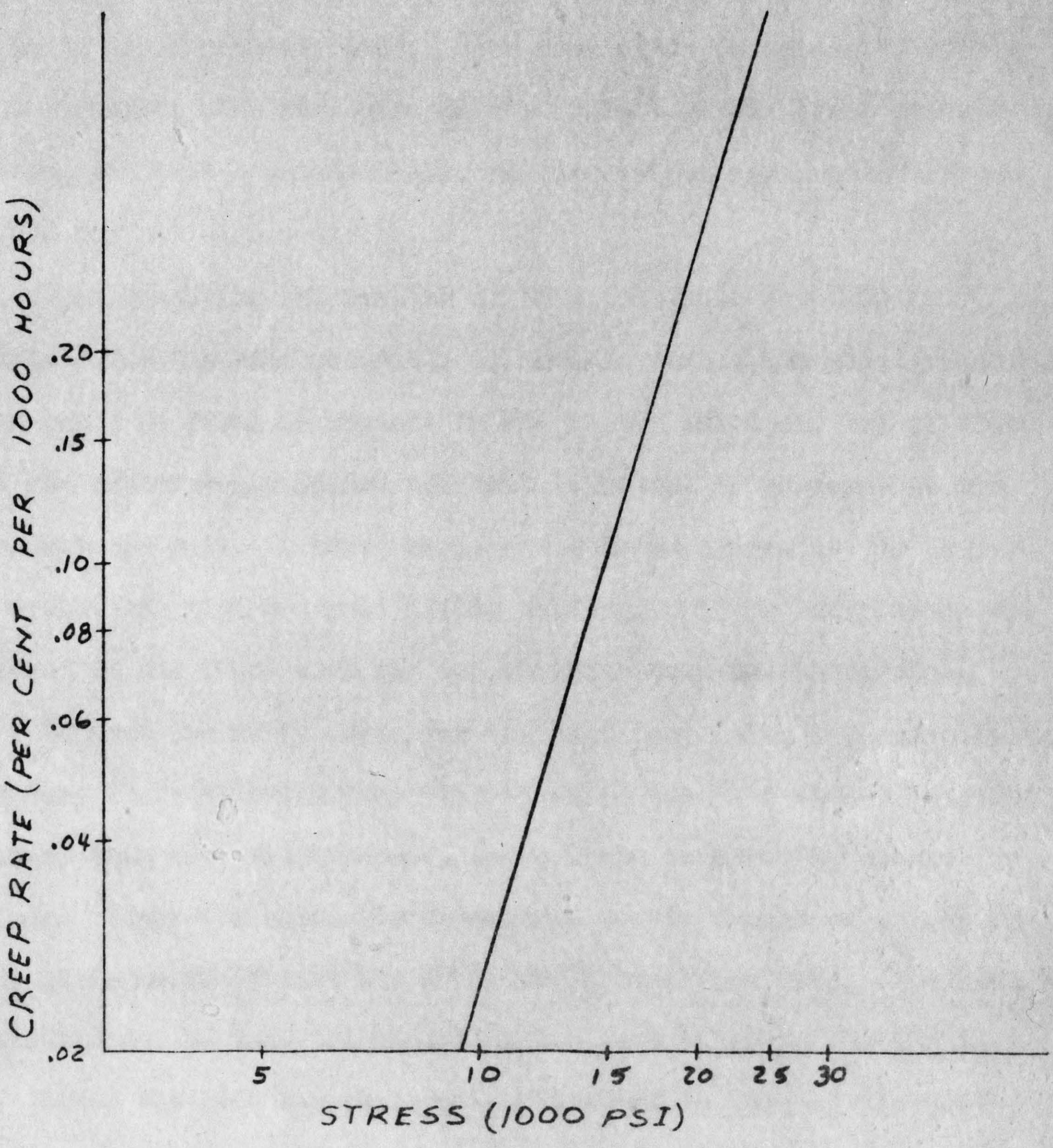

Figure XXII. Creep rate-stress relation for stainless steel

RECOMMENDATIONS AND CONCLUSIONS

The qualitative results of this test indicate that the South Dakota State College creep testing apparatus will give satisfactory results if it is properly used. This conclusion is supported by the fact that curves with the shape of the characteristic creep curve were obtained, and that a substantially higher minimum creep rate was determined for the higher stress.

Upon comparing the results of this test with the data in Appendix D for the same material, it is seen that a quantitative error does exist. No error is present in the 10,000 psi test, but an error of 34 per cent for the 15,000 psi test is noted, as compared to the Allis-Chalmers data. A small error could be explained by the temperature deviations that occurred during testing, but the large error encountered in the final test has to originate from something else.

Because the creep curve for the last test takes the characteristic shape, it is believed that this error is due to a higher temperature or stress than what was intended, rather than an error in elongation readings. Since the stress is determined by the amount of weight applied, it is unlikely that the error would stem from this. A possible explanation may be that the thermocouples were in error for the last test. Since the same temperature was involved in both of the tests, it was thought that the same set of thermocouples could be used for both. New thermocouples were used for the 10,000 psi test, but they had been cooled and reheated when used for the 15,000 psi test. It is possible that this cooling and reheating, even though the same specimen temperature was used, changed the thermocouple characteristics so that they should have been recalibrated. To avoid this possibility, it is recommended that new, calibrated thermocouples be used for each specimen tested.

Since the controller battery had to be replaced during the 15,000 psi test, it is possible that some error could have resulted from that. It is recommended that a new battery be installed at the start of each test, or a standard cell be purchased for the controller. Also, for creep data to be considered accurate, three or more tests should be run at each set of conditions. This would involve a period of between one and two years when only one machine is available on which to do test work.

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APPENDIX A

Nomenclature

ε	Creep deformation, creep strain inches
C	Minimum constant creep rate $\frac{d\varepsilon}{dt}$
L	Load or stress psi
S	Stress psi
S	An arbitrary constant psi
t	Time hours
K_1, K_2, n	Material constants, not necessarily the same for each equation

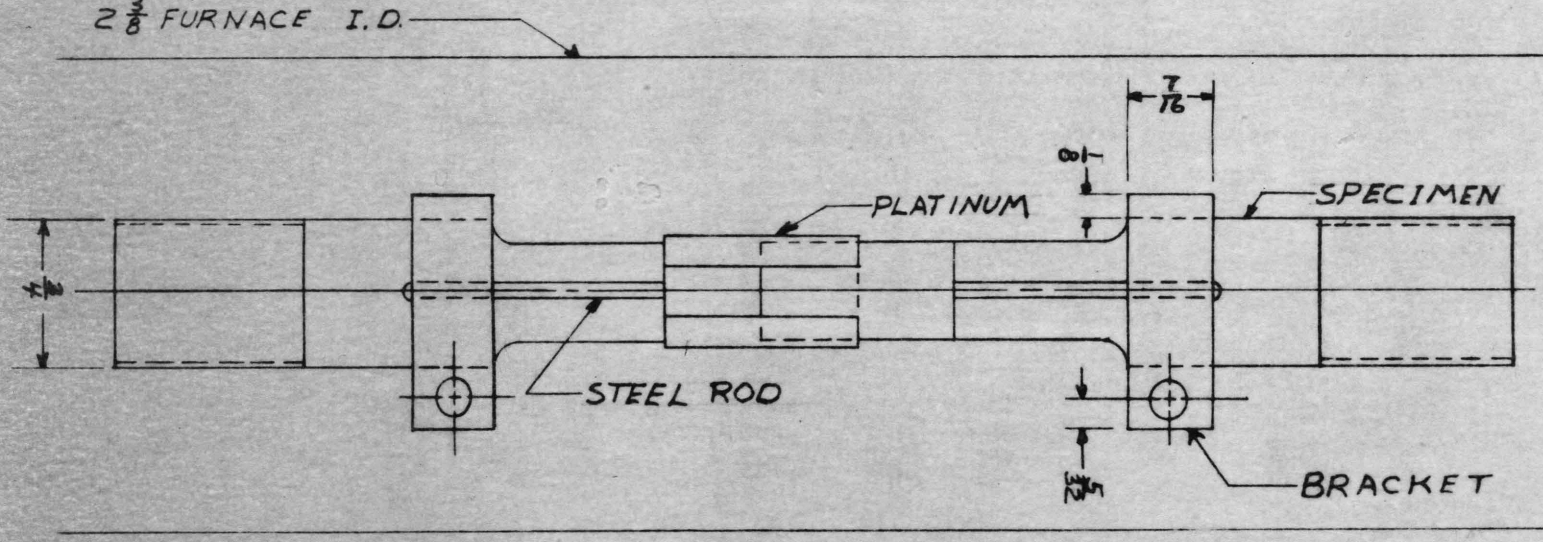
APPENDIX B

Method Used for Making Extensometer

Figures XXIII and XXIV are the working drawings used to make the creep extensometer. Figure XXIII is a layout of how the specimen and extensometer would fit into the I. D. of the tubular furnace.

The extension measuring parts were made of platinum because it resists oxidation and will remain bright to reflect light back into the microscope. Figure XXV shows the pieces which made up the extensometer, along with a specimen. The platinum was made into the configuration shown at left in Figure XXV from a 1 inch by 3 1/2 inches by .010 inch platinum strip. The lengthwise dimensions are all 1 inch; the pieces that slide on the inside are 5/8 inch wide, and the other pieces are bent from a 1 inch square in such a way that the parts can move freely with respect to each other. Cutting the platinum to these dimensions left a small piece on which to test spot-welding techniques.

The platinum was spot-welded to a 1/16 inch diameter stainless steel rod (acquired by cleaning the flux off of a welding rod), with care being taken to axially align the platinum and rod. The free end of this rod was then welded into 1/16 inch holes drilled in the bracket as shown in Figure XXIV. Stainless steel material was used to make the bracket, and it has the particular dimensions that it does because the only material readily available had a 1 3/16 inch diameter.



NOTE: ALL DIMENSIONS ARE INCHES

Figure XXIII. Layout drawing used for making the extensometer

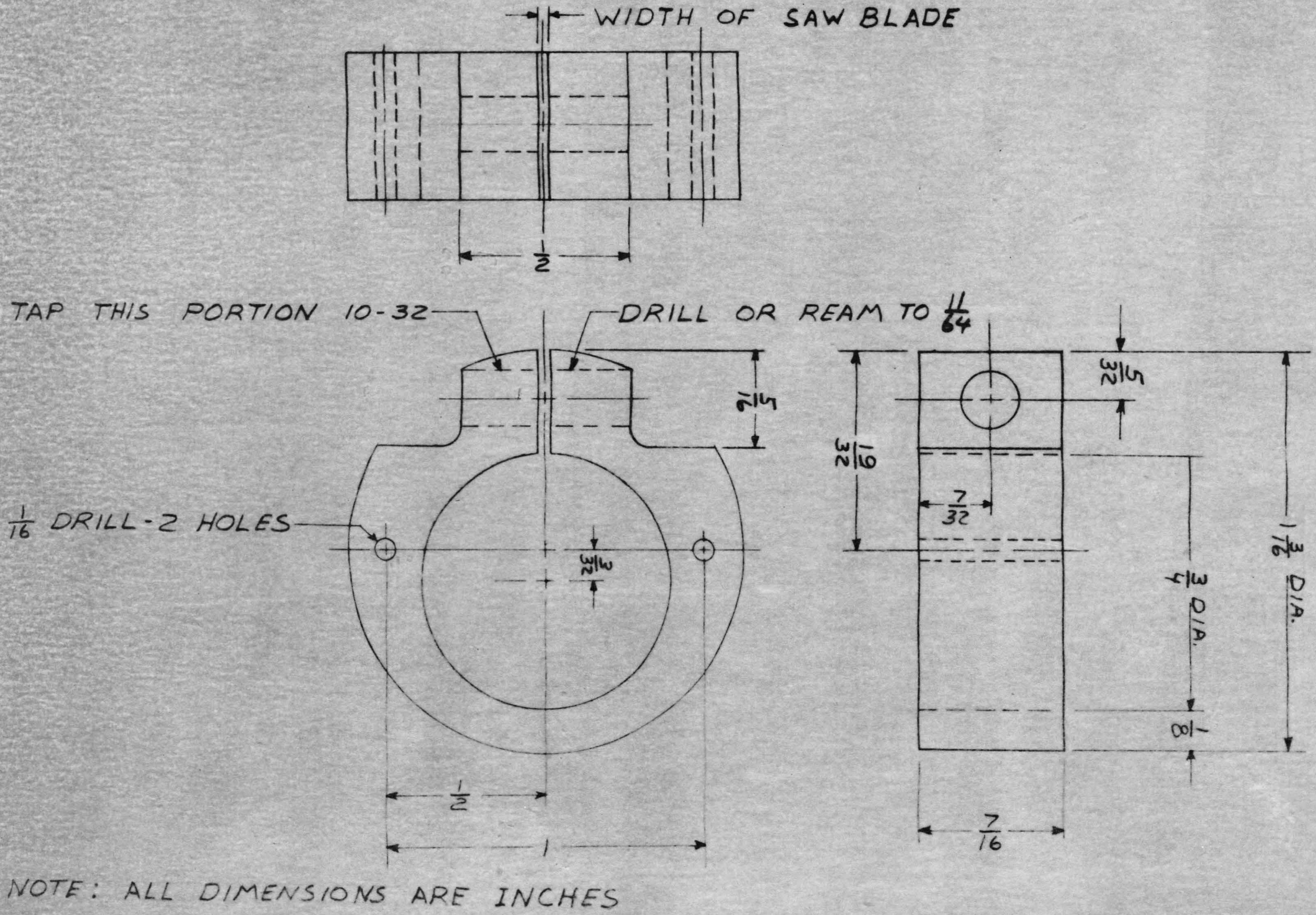


Figure XXIV. Extensometer bracket

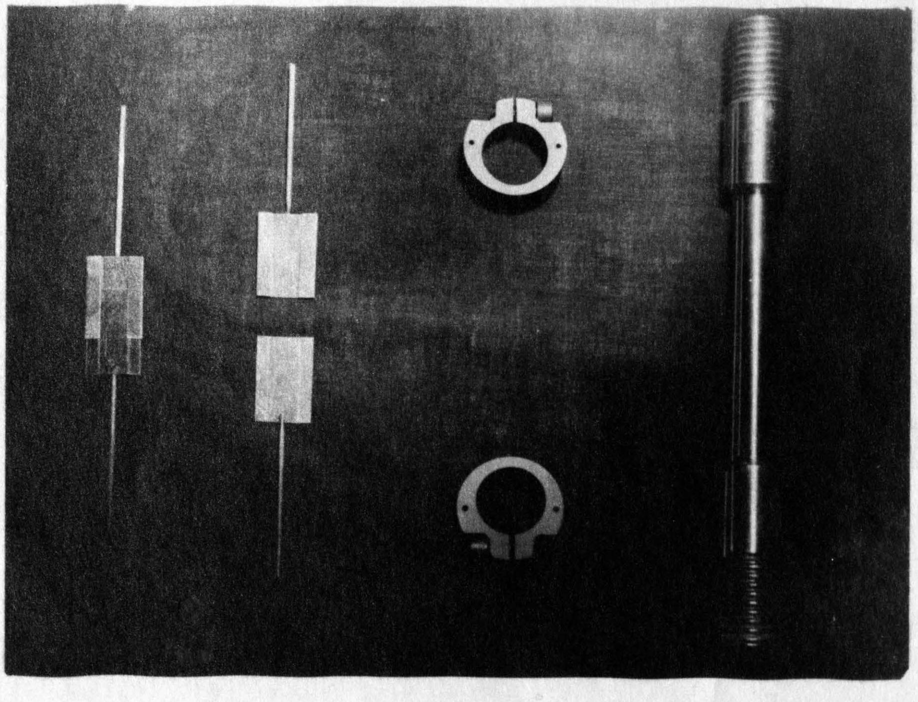


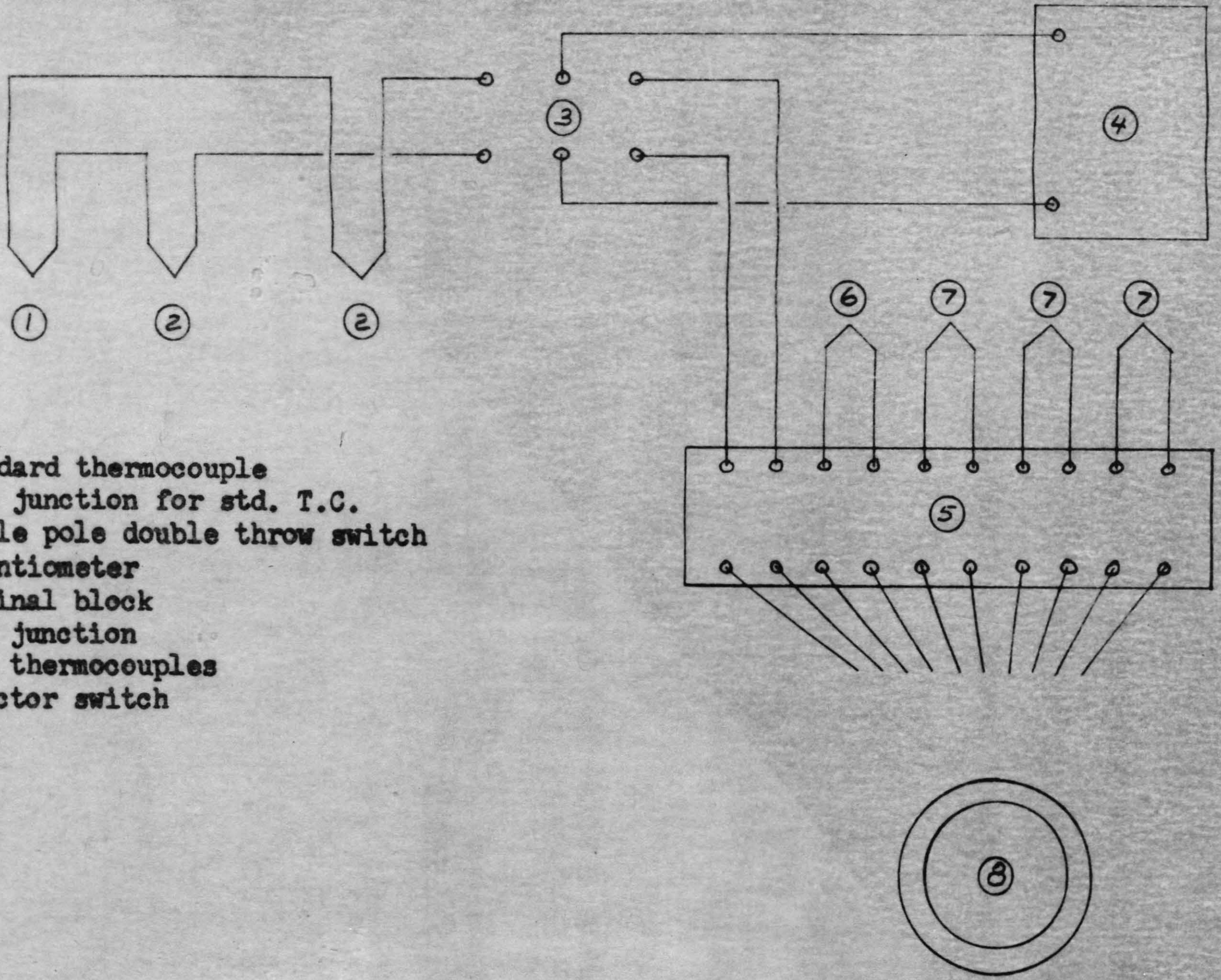
Figure XXV. Parts used in making up the extensometer

APPENDIX C

Method Used for Making and Calibrating Thermocouples

The thermocouples were made from 20 B&S gauge chromel-alumel duplex thermocouple material. This consists of a chromel wire and an alumel wire, each covered with a different color of fiberglas insulation, and both covered with an over-all insulating layer. The insulation material was scraped off of both wires for a distance of about 2 inches from the ends to be joined, and all foreign material was removed from the bare wires. These wires were twisted tightly together and dipped into a borax welding flux; then, using a small acetylene torch, they were heated until the twisted joint formed a bead.

A thermocouple calibration furnace with a standard thermocouple, and instructions for operating this equipment, are in the Mechanical Engineering Laboratory, EH 106. Figure XXVI is a schematic diagram showing how to set it up for calibrating three couples at a time. The powerstat was set on 50 and allowed to warm up for several hours, which gave a temperature very close to 1000 degrees Fahrenheit. A comparison between the standard temperature and the temperatures recorded by the test thermocouples gave the amount of correction to be applied at this temperature.



1. Standard thermocouple
2. Cold junction for std. T.C.
3. Double pole double throw switch
4. Potentiometer
5. Terminal block
6. Cold junction
7. Test thermocouples
8. Selector switch

Figure XXVI. Thermocouple calibration diagram

APPENDIX D

Mechanical Properties of ACM-1418 Stainless Steel as Given by Allis-Chalmers Manufacturing Company

ACM-1418 is the Allis-Chalmers designation for this material, which corresponds closely with AISI-403 stainless steel. Two samples of this material had the following room temperature mechanical properties:

Tensile strength, psi	110,500	113,000
Yield strength, psi at 0.01%	81,250	87,500
Elongation, %	21	22
Reduction of area, %	68	69
Izod impact, ft. lb.	94-96-95	102-98-101
Brinell hardness	235	248

Specific creep data on individual tests at 1000 degrees Fahrenheit were as follows:

Stress psi	Duration hours	Creep rate % per 1000 hours
15,000	1512	0.077
10,000	1679	0.025
6,000	1467	0.007