WADC TECHNICAL REPORT 59-416
PART I

INVESTIGATION OF CREEP BUCKLING OF COLUMNS AND PLATES

Part 1: Elevated Temperature Properties of the Test Material Ti-7A1-4Mo Titanium Alloy

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FOREWORD

This report was prepared by New York University under USAF Contract No. AF-33(616)-5807. This contract was initiated under Project No. 7360, "Materials Analysis and Evaluation Techniques," Task No. 73604, "Fatigue and Creep of Materials." The work was administered under the direction of the Materials Laboratory, Directorate of Laboratories, Wright Air Development Center, with Lt. William H. Hill acting as project engineer.

This report covers work conducted from June 1958 through May 1959.

The authors wish to acknowledge the assistance and cooperation of the Metallurgical Engineering Research Group of New York University for heat treating of the specimen material. Especially they wish to thank Dr. Harold Margolin and Mr. Paul Farrar for their personal interest in this phase of the investigation.

ABSTRACT

As a first phase of an investigation of the Creep Buckling of Columns and Plates, materials properties tests were conducted on the sponsor chosen test material Ti-7Al-4Mo Titanium Alloy in both "as received annealed" and heat treated conditions. Bulk specimen material was heat treated according to the following schedule to obtain optimum creep performance: 1450°F-1 hr., furnace cool to 1050°F, air cool; reheat to 1050°F-24 hr., air cool. This phase of the investigation was necessary because of the paucity of published materials property data on this alloy, especially in compression.

A new technique for the collection of compression creep data from sheet specimens was developed in which both the short time stress-strain properties prior to creep and the creep data itself are autographically recorded.

The test results include values of the modulus of elasticity and 0.2 percent yield strength in both tension and compression at room temperature, 750°F, 850°F and 950°F. Compressive creep data were collected for a number of stress levels at 850°F and 950°F.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

W. J. Trapp

W. J. TRAPP
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I. INTRODUCTION

The major objectives of the experimental aspect of our Creep Buckling Investigation include the following:

1. To conduct materials properties tests on the sponsor chosen alloy, Titanium Alloy, Ti-7Al-4Mo. These include short time compression and tension stress-strain tests at several temperatures and compression and tension creep tests.

2. To conduct creep buckling tests in which end shortening and lateral deflection data are collected, both during initial loading and during creep.

The experimental data collected as a result of fulfilling items 1 and 2 above, will be used for comparison with both available theories and with our own theoretical analysis. The purpose here will be for indentifying the approach of greatest utility to airframe and missile designers and stress analysts.

In view of the paucity of materials property data available for Titanium Alloy Ti-7Al-4Mo, this report has been prepared and includes all data collected to date. It is anticipated that future reports, although primarily concerned with creep buckling, will contain additional materials property data collected as the needs of the program dictate.

The material was supplied by Titanium Metals Corporation in the annealed condition. A heat treatment suggested in reference 1 to give optimum creep performance was adopted after it was declared suitable by the sponsor. Complete processing data and details of the heat treatment are given later in this report.

A new method for autographic compressive creep recording was used in conjunction with our sheet compression testing method. In this new technique the stress-strain response of the specimen during the loading period prior to creep was recorded autographically until the predetermined creep stress was reached. Then autographic compressive deformation-time data were recorded for the creep test. All the data were recorded on a single 8-1/2 x 11 inch graph sheet.

Test data are presented herein in the form of tables and charts. The data include short time compressive and tensile moduli of elasticity and 0.2 percent yield strength values for heat treated Titanium Alloy Ti-7Al-4Mo at room temperature, 750°F, 850°F and 950°F. Compressive data were collected at room temperature and 750°F for annealed specimens. Compressive creep data at 850°F and 950°F for a number of stress levels are given in chart form. Average stress-strain curves and charts of tangent and secant moduli are also presented.

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II MATERIALS

1. Composition

Titanium Alloy Ti-7Al-4Mo had been ordered in two thickness of 3 inch wide strip: 3/16 in. and 3/8 in. The material was supplied in two heats as follows:

a) Heat M8307 3/8" x 3" x 6 ft. 3/16" x 3" x 64 ft.
b) Heat M8374 3/16" x 3" x 42 ft.

It had been anticipated that the material of heat M8307 would prove sufficient for our immediate needs, hence all specimens were prepared from this heat. The material of heat M8374 has been held in reserve for our future needs. Composition data supplied by the manufacturer, Titanium Metals Corporation, is given in Table 1 below:

Table 1. Composition of Titanium Alloy Ti-7Al-4Mo

Heat No.	N	C	Fe	Mo	Al	Titanium
M8307	.006	.028	.07	4.1	6.8	Remainder
M8374	.009	.027	.13	3.9	6.9	Remainder

2. Vendor Processing

Both heats were prepared from double melted 28" round ingots of approximately 6750 lbs. These were initially forged to 12" square and then to 4-1/4" square at an ingot forging furnace temperature of 2050°F. The forged billets were heated in a billet furnace at 1900°F and rolled to size. The finished flats were annealed at 1300°F for 2 hours, aircooled, and at 1200°F for 10 hours followed by a furnace cool to 700°F. They were then pickled and hot straightened. This processing information was supplied by Titanium Metals Corporation.

3. Heat Treating at New York University

Specimen material was delivered in 3-15 ft. random lengths. These were cut into 15 inch sections, the maximum size accommodated by the vacuum heat treating furnace, and marked. The heat treating pattern established provided for alternate 15 inch sections from the same length to be heat treated. This provision would allow later comparisons between heat treated properties and annealed properties to be made on adjacent sections of the same length.

The heat treatment employed was 1 hr. at 1450°F, furnace cool to 1050°F, air cool, reheat to 1050°F for 24 hrs., air cool. This particular heat treatment scheme was suggested in reference 1 as resulting in optimum creep performance and submitted to the sponsor for consideration. After sponsor approval of the schedule, the heat treatment was accomplished in a vacuum furnace by the Metallurgical Engineering Research Group of New York University.

An initial batch of 6 specimens was placed unrestrained in the tubular vacuum furnace and heat treated. Each of the heat treated bars when removed from the furnace showed curvature in the longitudinal direction. A careful examination revealed that the curvature in the sections was all in the same direction with reference to the originally annealed length. Machining tests indicated that residual stress was present in these heat treated pieces. This possibly arose from the straightening operation performed on the stock prior to shipment.

The results of a number of tests indicated that straight sections could be obtained by clamping the bars during the heat treating operation. Machining tests showed that this procedure also served to relieve some of the residual stresses. All subsequent heats were heat treated in the clamped condition.

Similar machining tests revealed the presence of residual stresses in the "as received-annealed" bars. This condition may also have been the result of the hot straightening operation performed by TMC.

The specimen preparation procedure, which is subsequently described, allowed for the preparation of flat specimens from both the heat treated and annealed stock although residual stress of undetermined magnitude may still have remained in the material.

III TESTING PROGRAM

1. Specimen Preparation:

A specimen sampling pattern encompassing pairs of the 15 in. long blanks taken from the same length was established. This is shown in Figure 1. Since an insufficient number of tension specimens could be prepared from this sampling pattern it was necessary to use additional blanks solely for the preparation of tension specimens.

Three sizes of creep buckling column specimens of cross-sectional dimensions 1/8 x 1/4 in. corresponding to $L/\rho = 100$, 60 and 40 were taken from the same size specimen blank. These are being used in our creep buckling column experiments. The dimensions and configurations of the creep buckling, tension and compression specimens are shown in Figure 2. The dimensions of the tension and compression specimens were governed by the capacities of our precision pneumatic testing machines which were used for the tests.

In the preparation procedure used, material was milled equally from the flat surfaces of the 3/16 in. thick blanks to a thickness of 1/8 inch. The creep buckling specimens were then cut from the blank. The thickness of the blank was further reduced to 1/16 in. by the same milling process to prepare the tension and compression specimens.

2. Short Time Compression Stress Strain Tests:

Compression specimens were installed in a jig which employed lateral guides to prevent buckling of the specimen below 3 percent compressive strain. The jig was then installed in a horizontal precision pneumatic testing machine of our own design shown in Figure 3.

A solid guide compression jig lubricated with molybdenum disulfide had been used for some of our early room temperature tests. Because of deterioration of the lubricant at temperatures above 750^{o}F, excessive friction resulted between guides and specimen. Ball bearing guides were then installed in our jig and used unlubricated, with a configuration for the ball guide similar to that described in reference 2. The friction evident in our previous tests with the solid guides was reduced to negligible values.

Photographs of the unassembled and assembled compression jig with a specimen installed are shown in Figure 4. The 1/16 in. diameter balls and bearing plates are constructed of stainless steel type 440 C hardened to Rockwell 57C. The ball retainers were fabricated of perforated type 304 stainless steel sheet. The perforation holes were enlarged to a diameter slightly smaller than that of the balls. The remaining parts of the jig are constructed of inconel. The ball spacing chosen allows for a minimum of 3 percent compressive strain without inter-ball buckling for specimen thickness greater than 0.020 inch.

Telescoping inconel tubing extensometers are used with contact points which fit into .005 inch deep by .0135 inch diameter holes, 2.00 inches apart on both of the longitudinal edges of the specimen. An accurately constructed drill jig is used to space the holes and to limit the depth. The contacts are held in position by means of Inconel X flat springs. The photograph in Figure 5 shows the extensometer installed on a compression specimen. This is only a mock up since in actual use the specimen would be installed in the compression jig. The relative change in position of the telescoping tubes is sensed by differential capacitors whose associated circuits transduce differential changes in capacitance to changes in voltage. A gas discharge tube device is employed for this purpose similar to that described in reference 3 and manufactured by the Decker Corporation and called, by them, a Delta unit.

The sensitivity of the devices currently employed is of the order of 0.4 mv/microinch/inch of strain in a two inch gage length. The response is linear for better than 0.050 in. of travel of the movable element, however, the current design allows modification for longer travel with linear response with a proportional sacrifice of sensitivity.

The output of the Delta unit is applied to a combination cathode follower-vacuum tube voltmeter and then to one channel of a Mosely Autograph Model 3 XY recorder. The desired strain scale is established on the recorder by the use of a mechanical calibrating device and the gain controls of the recorder.

Since the extensometer has a long linear range, calibration presents no special problem. A micrometer screw is used as the calibration standard. This is mounted in a jig which can be placed in the specimen position and which actuates the telescoping tubing in the same fashion as is done by the specimen in an actual test. The jig is shown in Figure 6. This device has been in operation for several years and has performed with great reliability. Tests have indicated that the calibration is stable within 1 percent for periods of several weeks.

Tests have established the low friction behavior of the loading cell of the testing machine. The load is sensed by measuring the pressure of the working fluid of the testing machine -- nitrogen gas. The pneumatic power supply of the testing machine has been equipped with a pressure transducer and the appropriate circuitry for use in autographic stress strain recording. The calibration standard is the 0.1 percent error pressure gage of the system. The proper stress scale on the autographic record is set using the known area of the specimen together with the machine pressure-load constant.

The pressure necessary to induce a known stress in the specimen is computed. The gain control of the recorder is adjusted after this pressure has been applied to the pressure transducer, to yield a convenient deflection of the recording pen. For high strength materials one half inch per 10,000 psi stress has been used. On the strain scale it has been convenient to use one half inch per 0.001 in/in strain. A block diagram of the autographic recording system is shown in Figure 7.

The horizontal arrangement of the testing machine results in significant advantages in spatial temperature distribution in the specimens in elevated temperature tests. Since significant chimney effects are avoided in the furnace it has been possible to limit spatial temperature variations in a three inch length to $\pm$ 2°F at temperatures up to 950°F. A Wheelco saturable reactor controller is used for temperature control. After a suitable stabilization period the temporal temperature variations remain less than $\pm$ 2°F. Chromel-alumel thermocouples are used for both control and temperature measurement. A Leeds and Northrop potentiometer is used for the actual measurement while a Wheelco recorder is employed for temperature monitoring. The temperature recording scheme has been included in the block diagram shown in Figure 7.

3. Compression Creep Tests

The same testing machine, compression jig, extensometer instrumentation and autographic recording apparatus used for the compression stress strain tests have also been employed in the creep studies with the addition of a time base. This timing device presents a long period saw tooth electrical function to the XY recorder. One cycle of this function drives the recording pen the entire chart length along the X axis after which it returns instantaneously to its starting point. Since in a creep test the strain is a monotonically increasing parameter, many time cycles can be recorded on a single 8-1/2 x 11 graph sheet with no ambiguity in the data. The result is a record of small physical size which displays the same resolution as a record many times its length. The mechanical-electrical scheme of this device is shown in Figure 8. In this present arrangement one sawtooth cycle corresponds to four hours. The timing device is included in the block diagram shown in Figure 7.

Since the procedure we employ is quite different from that employed in conventional dead weight creep testing it is described in detail below:

The specimen is installed in the compression testing machine.

The extensometers are attached, and a room temperature stress strain test to approximately 50,000 psi stress is performed, with the data recorded autographically. The furnace is positioned and the specimen is heated to the test temperature. During the heat up cycle the apparent thermal expansion strain is recorded as a function of time. This is accomplished by replacing the stress transducer connection to the X axis of the recorder with the output of a time base.

After soaking for 1/2 hour at temperature, by which time apparent thermal strain has stabilized to a constant value, the time base is disconnected and the stress transducer output is reapplied to the X axis of the recorder. A stress strain recording is then made up to the predetermined value of creep stress. At this time the stress transducer output is again removed from the recorder and replaced by the time base. At the same time the strain terminals are reversed to give a strain-time recording with the conventional directions on the chart for increasing strain and increasing time.

Shown in Figure 9 is such a recording. The room temperature stress strain test is clearly shown in the upper left. Applying the time base to the recorder input displaced the pen to A which corresponded to the time when the furnace was turned on. The specimen was heated to $844^{\circ}F$ (measured by potentiometer and also recorded separately) during which time the apparent thermal strain of the extensometer-specimen combination proceeded to point B. In the time scale shown, 2 inches on the chart correspond to one hour of elapsed time.

At B both thermal strain and temperature had been stabilized. The time base was then disconnected and the stress transducer was connected to the recorder. The recording pen was set manually to point B'. A stress strain test was then performed to 100 ksi corresponding to point C on the record. The time base then replaced the stress transducer on the X axis. The strain terminals were reversed and the pen was moved to C'. It should be noted that the pen was lifted for each resetting.

Creep occurred from point C' to point D (approximately four hours) and then the time base automatically lifted the pen returned the carriage to point D' and dropped the pen all within a time of less than one minute. Creep recording continued until point E for an additional four hours. The total creep time was then approximately eight hours.

4. <u>Short Time Tension Stress Strain Tests</u>

A precision pneumatic testing machine with a loading capsule arrangement similar to that employed on our compression testing machine was used for the tension tests. The specimen is pinned in universal motion loading clevises. The same pneumatic power supply and autographic recording system as previously described for the compression tests is used for tension as well. A photograph of the testing machine is shown in Figure 10.

The compression extensometer design was adapted for use in the tension tests. Our original extensometer which was designed to make only frictional contact with the flat sides of the specimen proved unsuitable for repeated long time operation. Excessive wear on the contact surfaces occurred after repeated installation and removal of the extensometer. The device employed in the current testing program is shown in Figure 11. Also shown in the photograph are the loading clevises. This extensometer design allows for the use of the same drill jig to space to .0135 inch diameter and .005 inch deep holes in the edge of the specimen for both compression and tension specimens.

IV TEST DATA AND DISCUSSION

The test data collected to date for both the heat treated and the annealed Titanium Alloy Ti-7Al-4Mo have been assembled in the form of tables and charts. The tables are given in this section while the charts will be found among the figures at the end of the report. It should be noted that all test results are for the longitudinal direction.

1. Short Time Compression

Short time compression data for the heat treated material at room temperature, 750°F, 850°F and 950°F are given in Table 2. Actual measured temperatures have been reported rather than the nominal values. Included in the table are room temperature modulus of elasticity values obtained from preliminary tests on specimens which were later tested at elevated temperatures. These modulus values obtained in tests to 50-60 ksi may be identified in the table since the corresponding yield strength values were not entered.

Analogous data for the annealed material at room temperature and 750°F nominally are given in Table 3.

The average values of compressive modulus of elasticity and 0.2 percent compressive yield stress with temperature are given in Figure 12 for both heat treated and annealed conditions. Average stress-strain curves for both heat treated and annealed material are given in Figure 13. The variation of tangent modulus with stress is given in Figure 14 while the variation of secant modulus with stress is given in Figure 15 for both the heat treated and annealed conditions.

2. Short Time Tension

Short time tension data for the heat treated material at room temperature, 750°F, 850°F and 950°F are given in Table 4. The average values of modulus of elasticity and 0.2 percent yield stress are given in Figure 12. Average stress strain curves are given in Figure 16.

3. Compression Creep

Creep results at several stress values are shown in Figure 17 for heat treated compression specimens at 850°F and in Figure 18 for 950°F.

4. Density

From micrometer measurements of the dimensions and from weight, as determined on an analytic balance, the density for both annealed and heat treated material was found to be 0.1605 lb/in^3.

5. Discussion

The results given in Figure 12 show that the heat treated specimens exhibit lower values of the 0.2 percent yield strength than the comparable "as received-annealed" specimens at room temperature. It should be noted however that:

1) The particular heat treatment employed was designed to achieve optimum creep performance and not high room temperature tensile or compressive strength. In this connection the heat treatment included no quenching.

2) The straightening operation performed by the manufacturer prior to shipment may have introduced some work hardening into the material, which could possibly affect the material properties.

As the creep buckling experimental investigation proceeds it is anticipated that additional data will be collected. This data collection will be dictated by the needs of the program but will include additional creep tests in both compression and tension.

V BIBLIOGRAPHY

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Table 2. Short Time Compression Properties of Heat Treated Titanium Alloy Ti-7Al-4Mo

Specimen No.	Temp. °F	E - 10^6 psi	σ_{cy} - ksi	Average Values Each Temperature E - 10^6 psi	Average Values Each Temperature σ_{cy} - ksi
A 324	RT	17.5	155		
A 463	RT	17.4	157		
A 422	RT	17.7	154		
A 423	RT	17.7	153		
A 424	RT	17.5	152	17.7	154
A 443	RT	17.6	---		
A 442	RT	17.8	---		
A 645	RT	17.8	---		
A 644	RT	17.7	---		
A 742	RT	17.9	---		
A 741	RT	17.9	---		
A 744	RT	17.9	---		
A 745	RT	17.9	---		
A 746	RT	17.9	---		
A 461	750	13.8	107		
A 326	750	14.0	104	14.0	106
A 325	750	14.4	108		
A 426	750	14.0	---		
A 322	840	13.4	98.2		
A 462	850	14.6	103		
A 641	850	13.8	100	14.0	101
A 621	850	14.3	102		
A 441	844	14.0	---		
A 443	844	14.2	---		
A 623	947	13.2	100		
A 643	943	14.4	100		
A 421	943	14.3	99.8		
A 442	954	13.6	---	13.8	99.7
A 645	948	13.9	---		
A 644	947	13.4	---		
A 742	947	13.5	---		
A 744	950	13.6	---		
A 745	947	14.0	---		
A 746	950	13.6	---		

Table 3. Short Time Compression Properties of Annealed Titanium Alloy Ti-7Al-4Mo

Specimen No.	Temp. °F	E - 10^6 psi	σ_{cy} - ksi	Average Values Each Temperature E - 10^6 psi	Average Values Each Temperature σ_{cy} - ksi
A 331	RT	16.4	160		
A 351	RT	16.5	159	16.4	159.4
A 332	740	13.4	109.3		
A 355	740	13.2	104	13.2	104
A 353	745	12.9	100.2		

Table 4. Short Time Tension Properties of Heat Treated Titanium Alloy Ti-7Al-4Mo

Specimen No.	Temp. °F	E - 10^6 psi	σ_{ty} - ksi	Average Values Each Temperature E - 10^6 psi	Average Values Each Temperature σ_{ty} - ksi
A 32-T	RT	17.1	152		
A 42-T	RT	16.9	147		
A 52-T	RT	17.3	---		
A 44-T	RT	17.3	---	17.2	149.5
A 74-T	RT	17.2	---		
A 761-T	RT	17.1	---		
A 762-T	RT	17.6	---		
A 52-T	752	14.5	102		
A 64-T	752	14.3	100	14.4	101
A 44-T	852	13.4	98.7		
A 74-T	852	13.8	101	13.6	99.8
A 761-T	951	13.4	103		
A 762-T	952	12.8	101	13.1	102

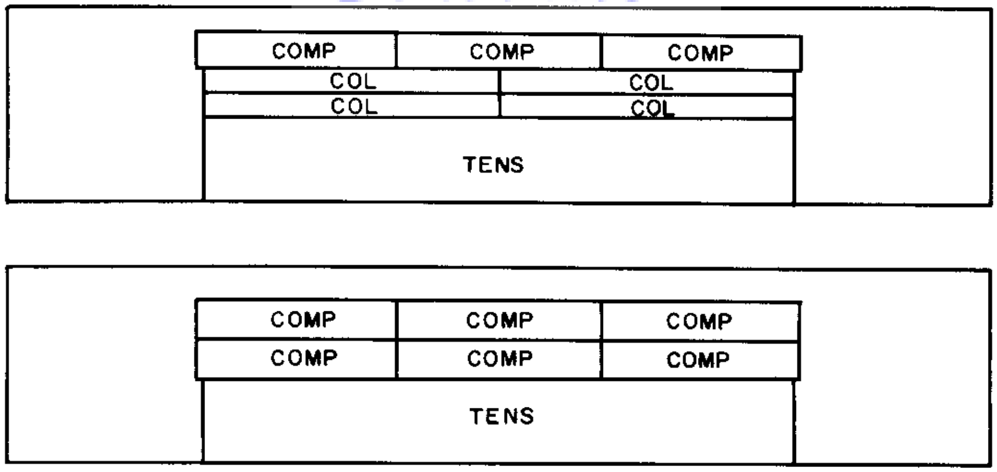


FIGURE 1 TEST SPECIMEN SAMPLING PATTERN

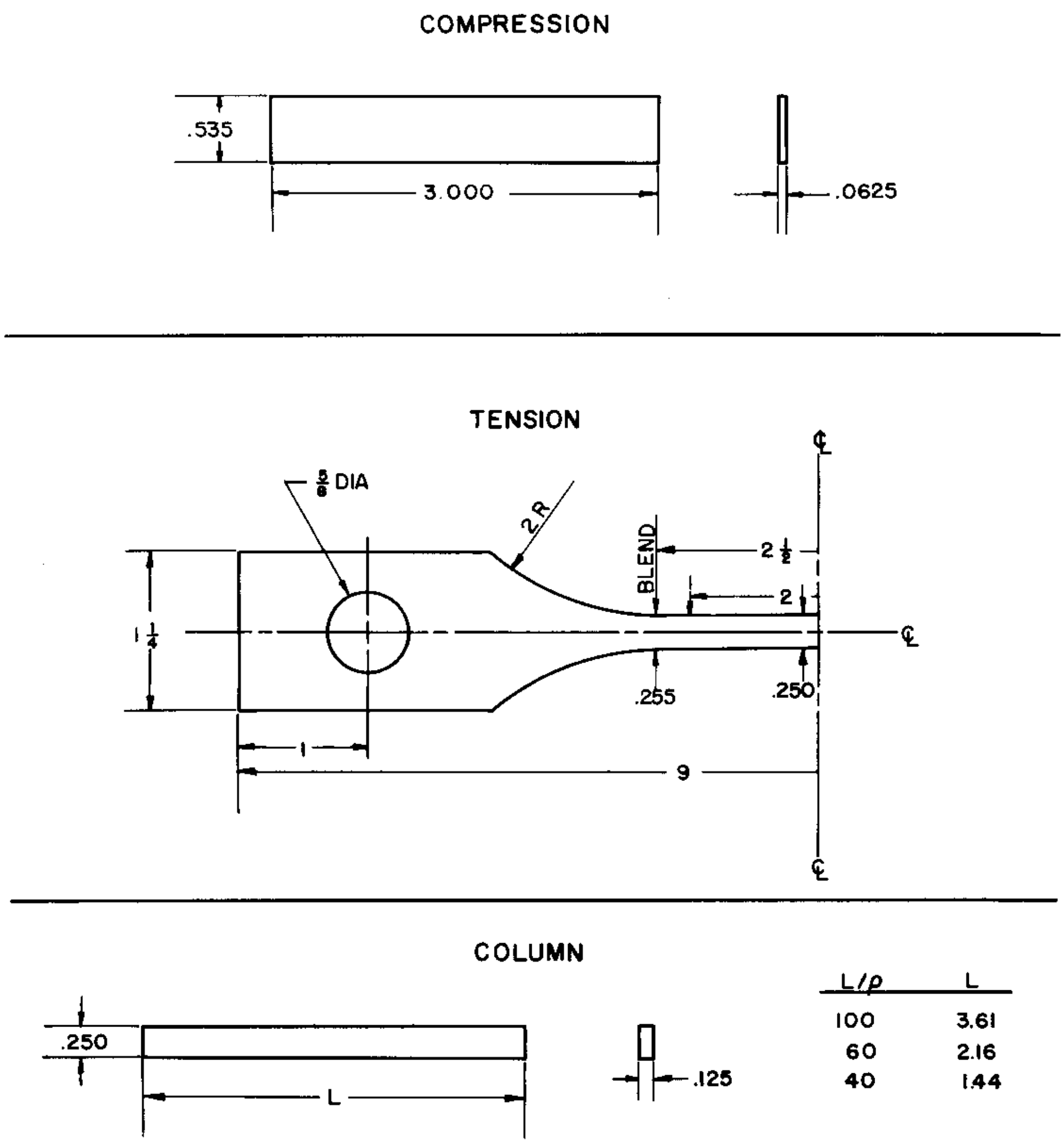


FIGURE 2 SPECIMEN CONFIGURATIONS AND DIMENSIONS

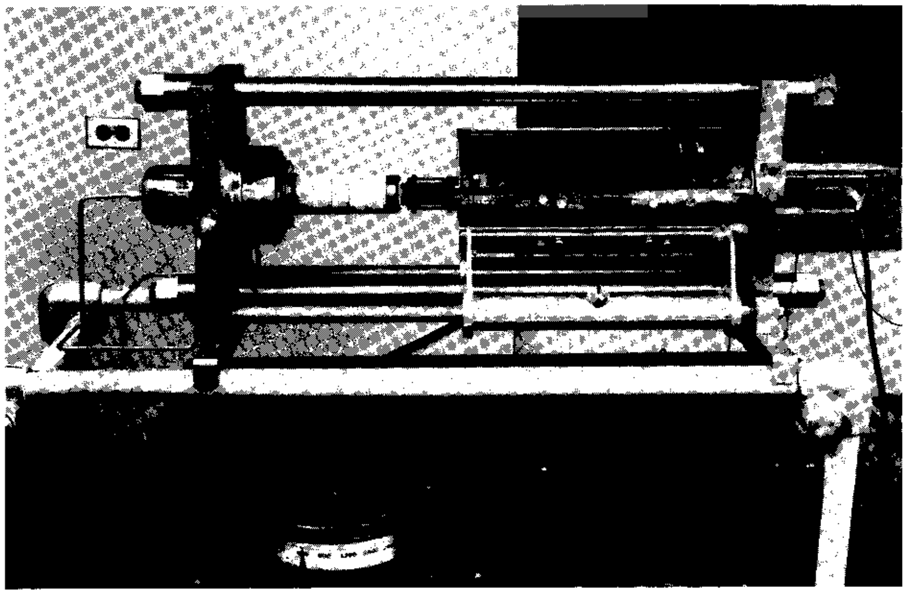


FIGURE 3 PRECISION PNEUMATIC COMPRESSION TESTING MACHINE

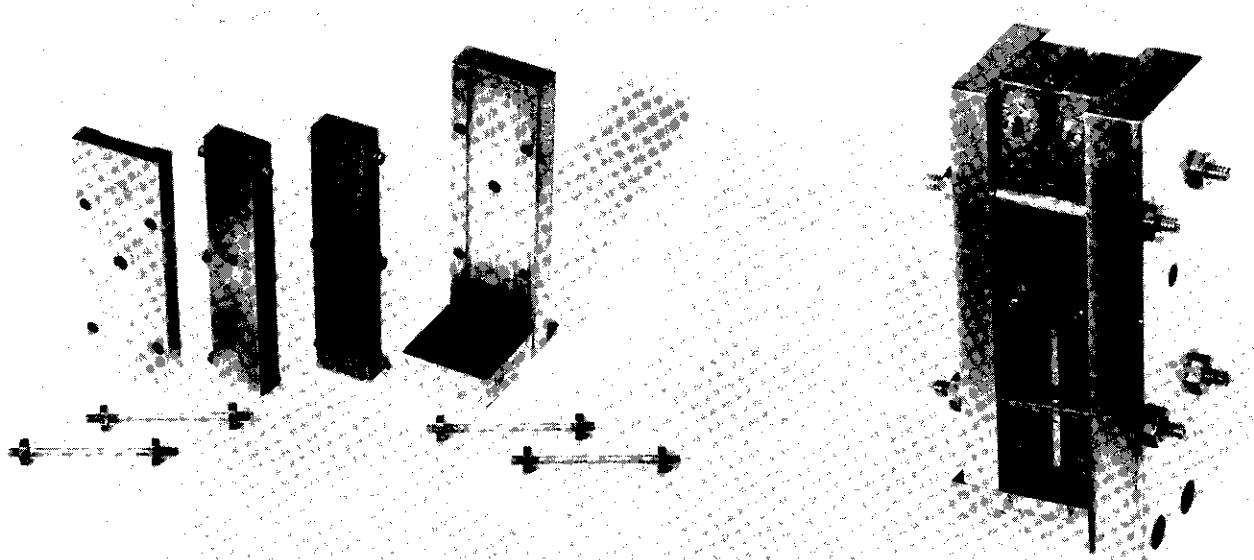


FIGURE 4 BALL BEARING GUIDE COMPRESSION JIG

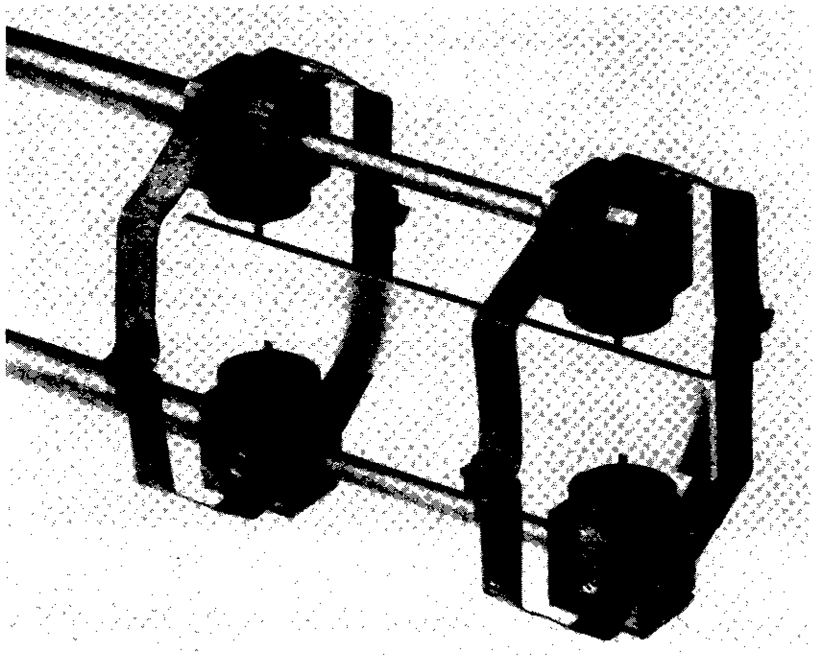


FIGURE 5 MOCK UP OF COMPRESSION EXTENSOMETER ON SPECIMEN

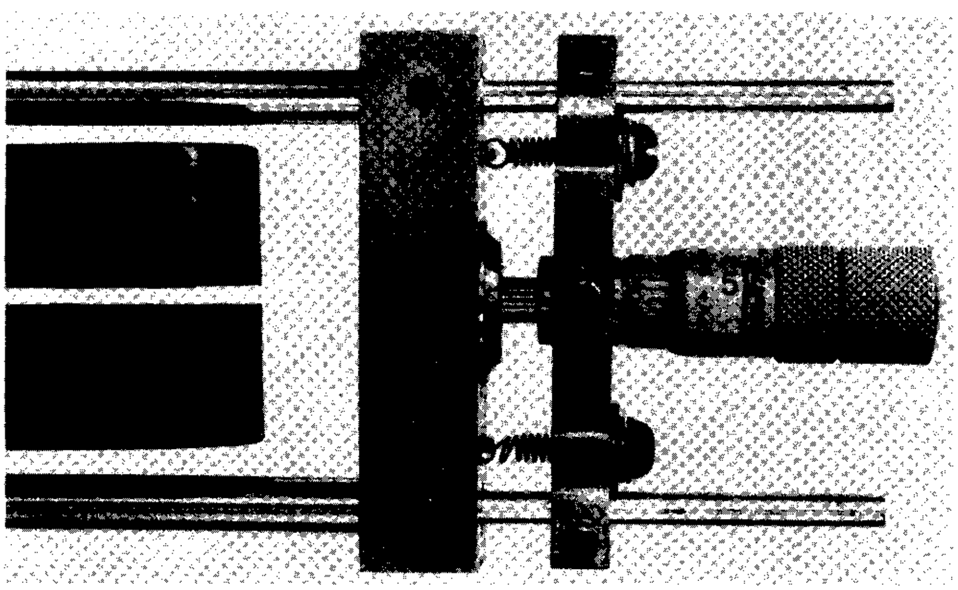


FIGURE 6 STRAIN CALIBRATION JIG

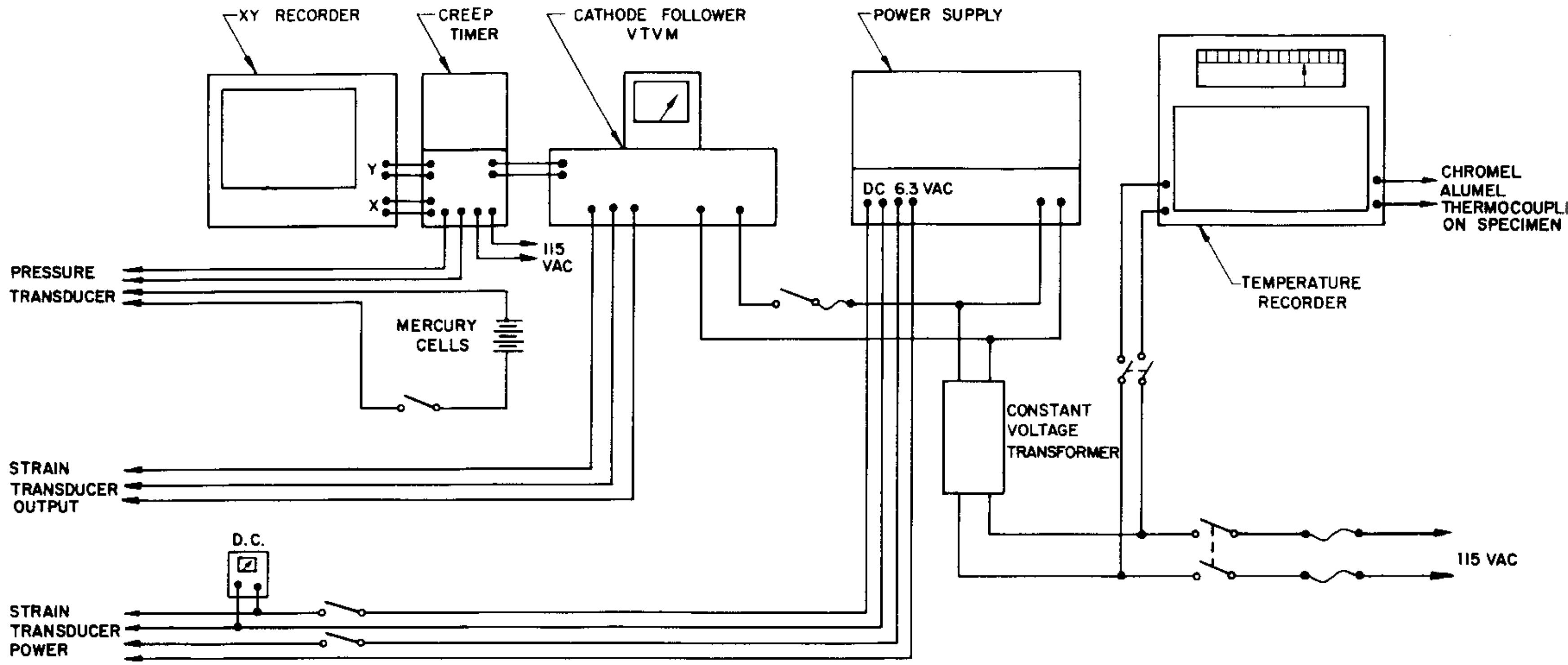
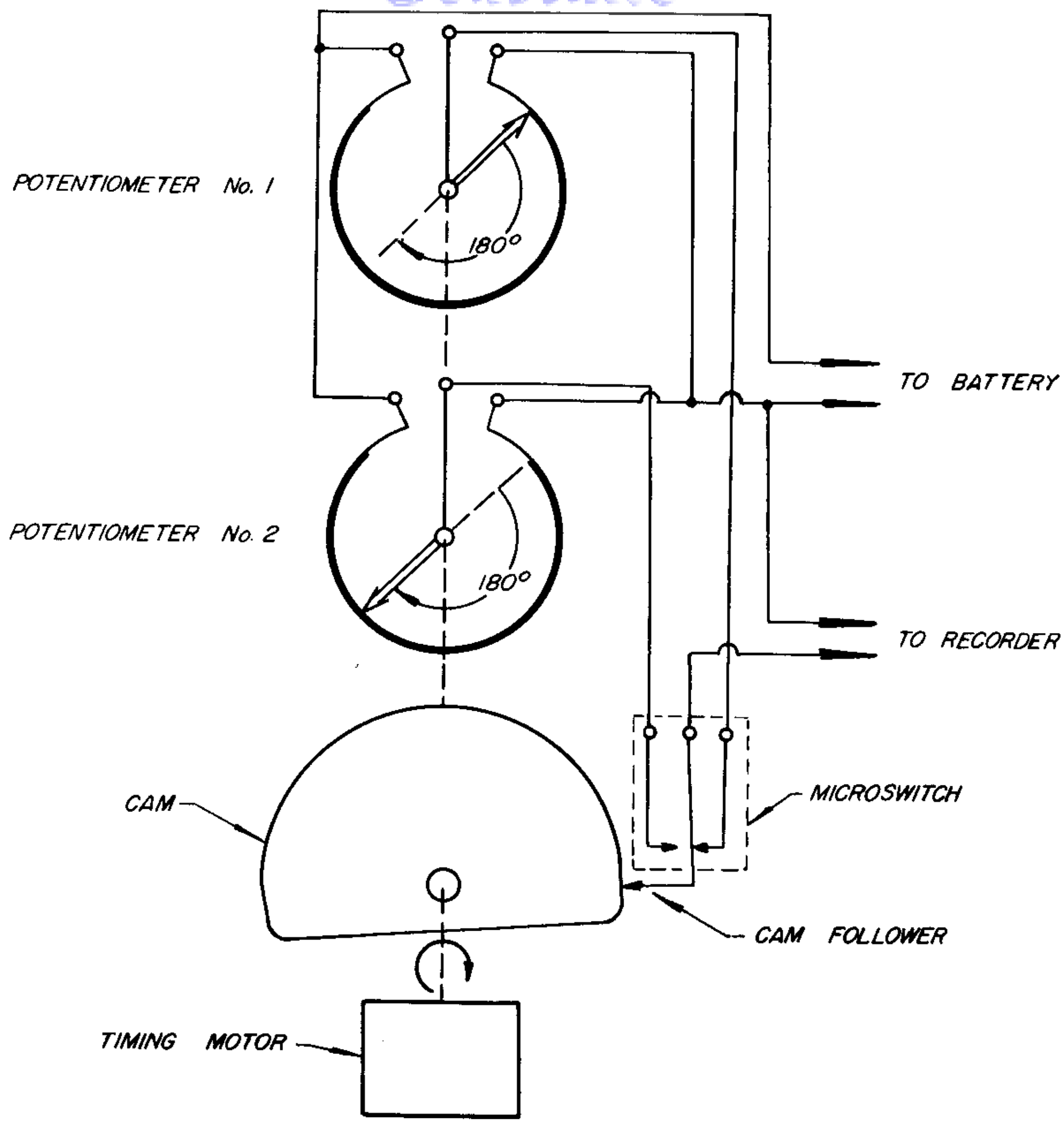


FIGURE 7 AUTOGRAPHIC RECORDING SYSTEM-SCHEMATIC



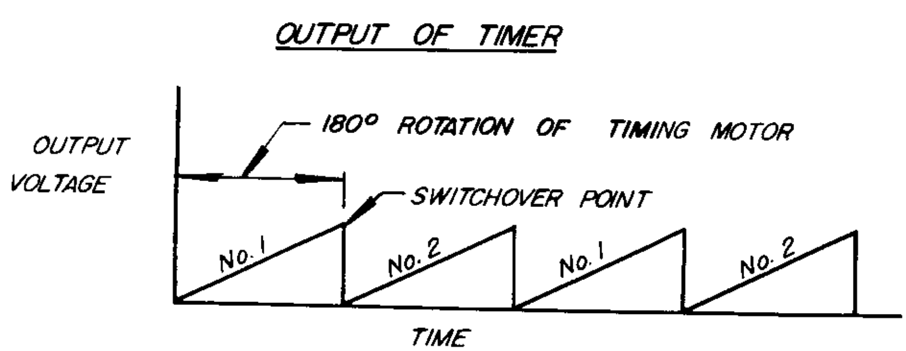


FIGURE 8 CREEP TIMER-SCHEMATIC

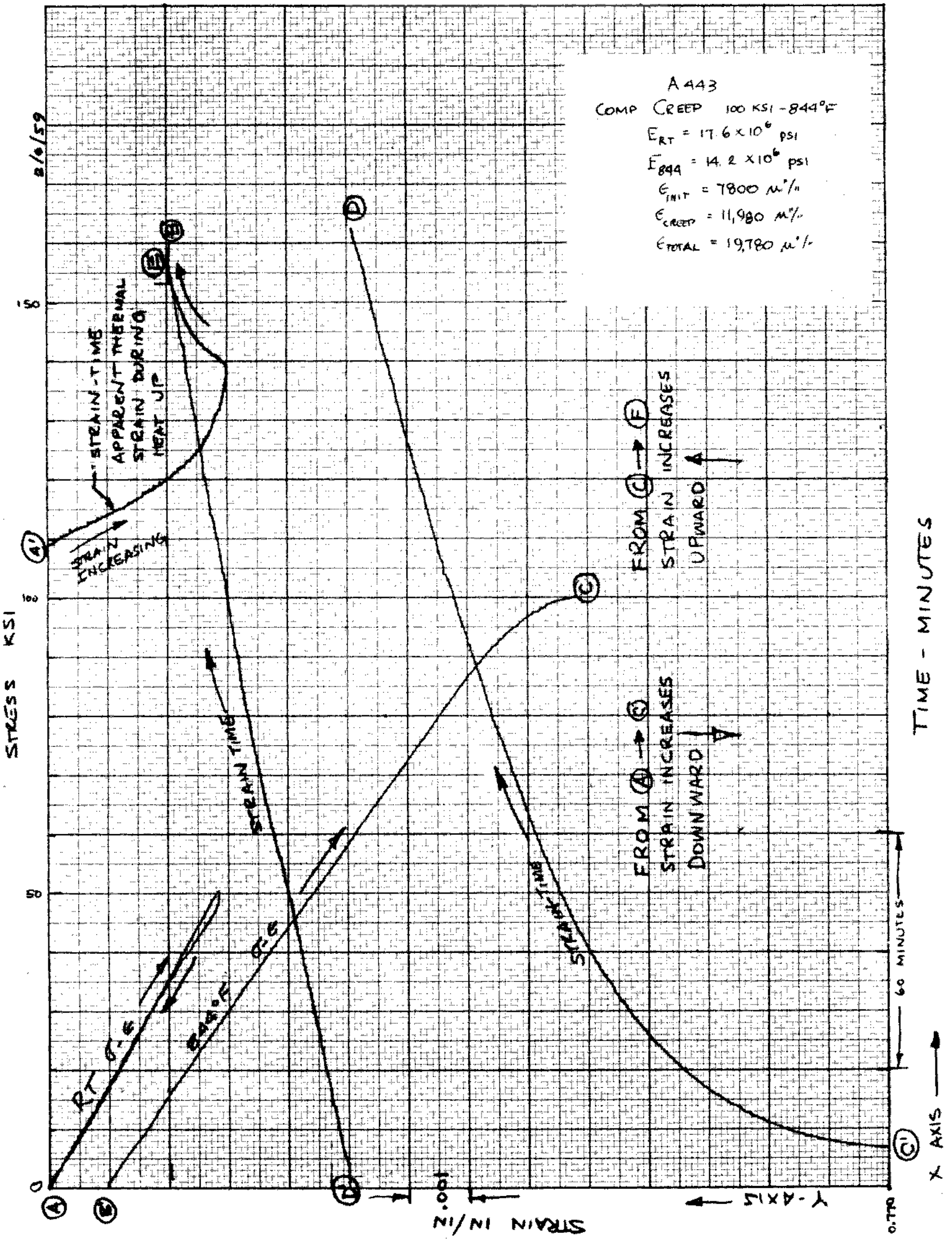


FIGURE 9 SAMPLE AUTOGRAPHIC CREEP RECORD FOR COMPRESSION SPECIMEN AT 844°F AND 100 ksi STRESS

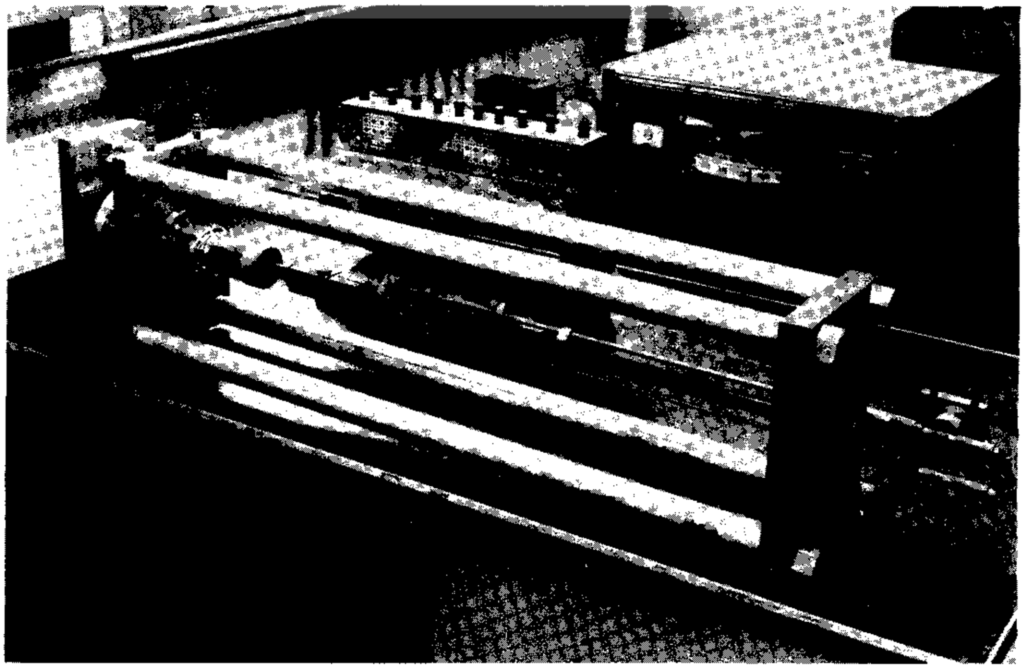


FIGURE 10 TENSILE TESTING MACHINE. FURNACE HAS BEEN REMOVED TO SHOW DETAILS OF SPECIMEN INSTALLATION

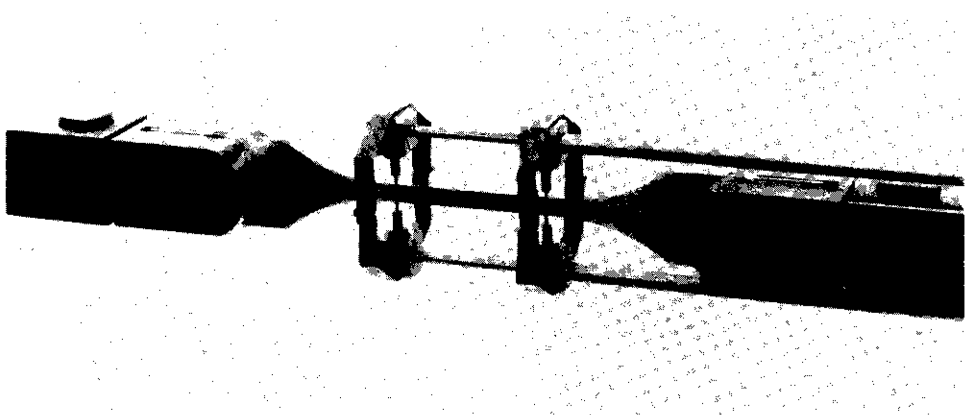


FIGURE 11 TENSILE SPECIMEN WITH EXTENSOMETER INSTALLED IN PIN JOINT LOADING CLEVISES

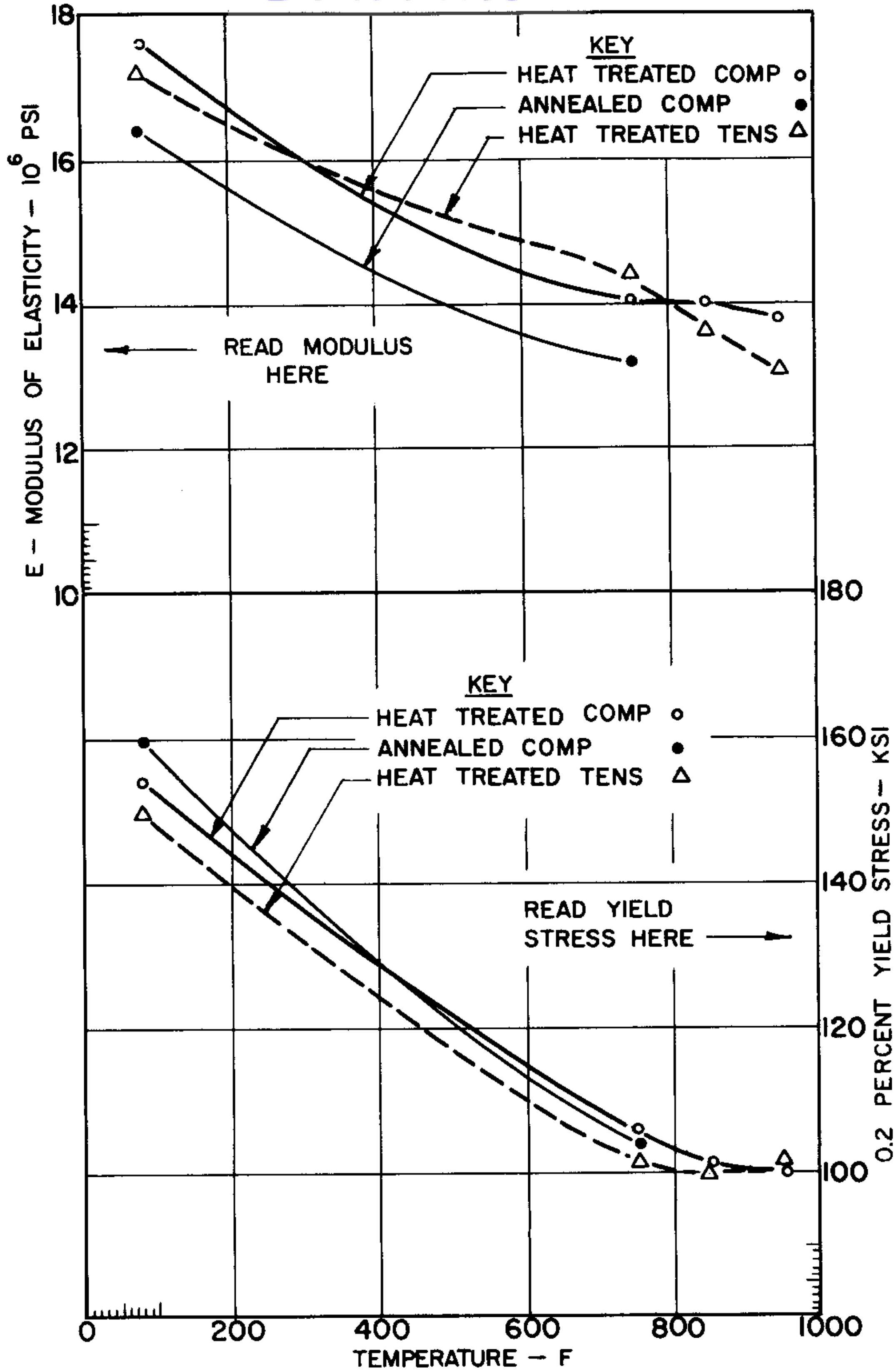


FIGURE 12 ELASTIC MODULUS AND 0.2 PERCENT YIELD STRENGTH WITH TEMPERATURE FOR TITANIUM ALLOY Ti-7Al-4Mo IN TENSION AND COMPRESSION

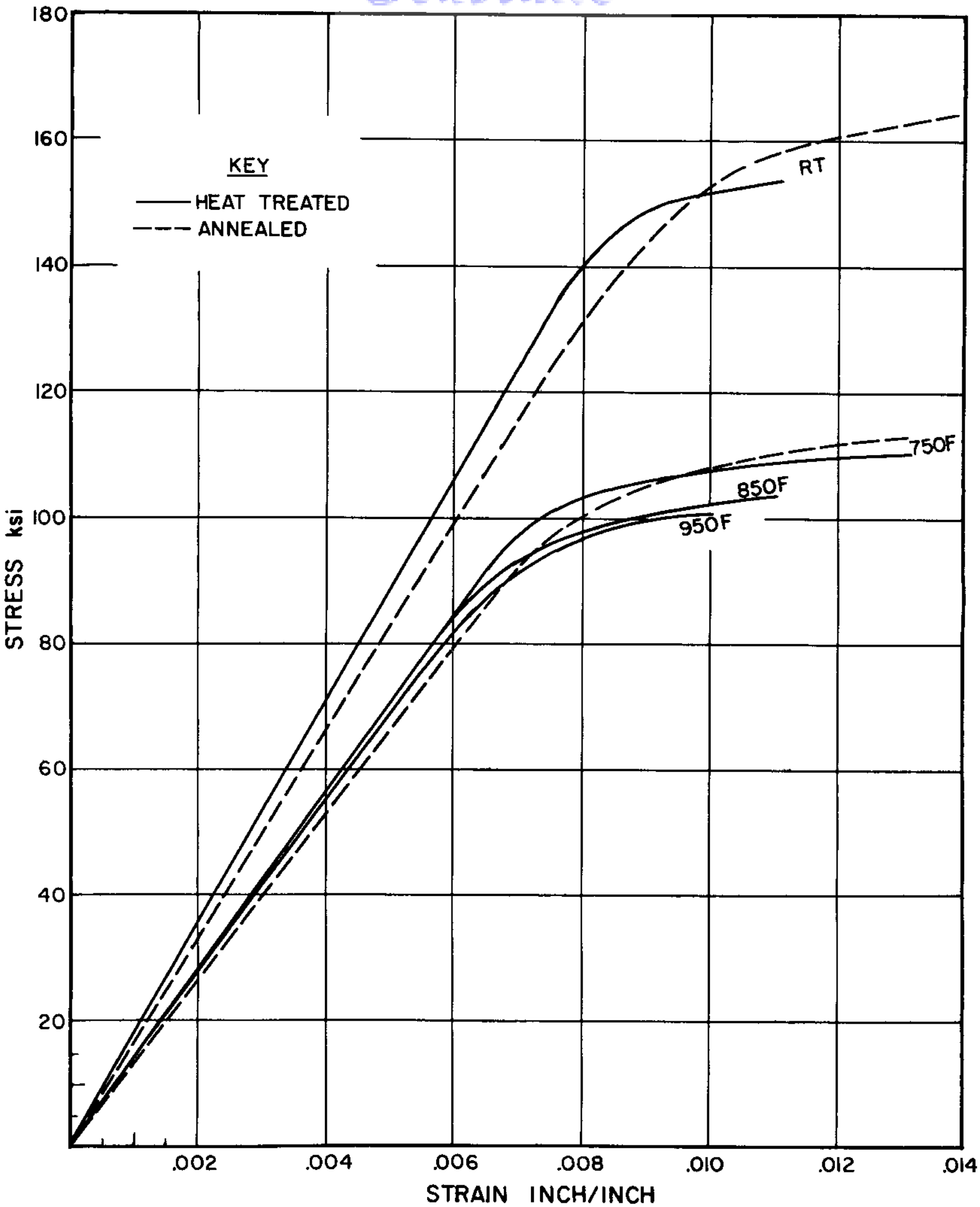


FIGURE 13 AVERAGE COMPRESSIVE SHORT TIME STRESS STRAIN PROPERTIES OF HEAT TREATED AND ANNEALED TITANIUM ALLOY Ti-7Al-4Mo

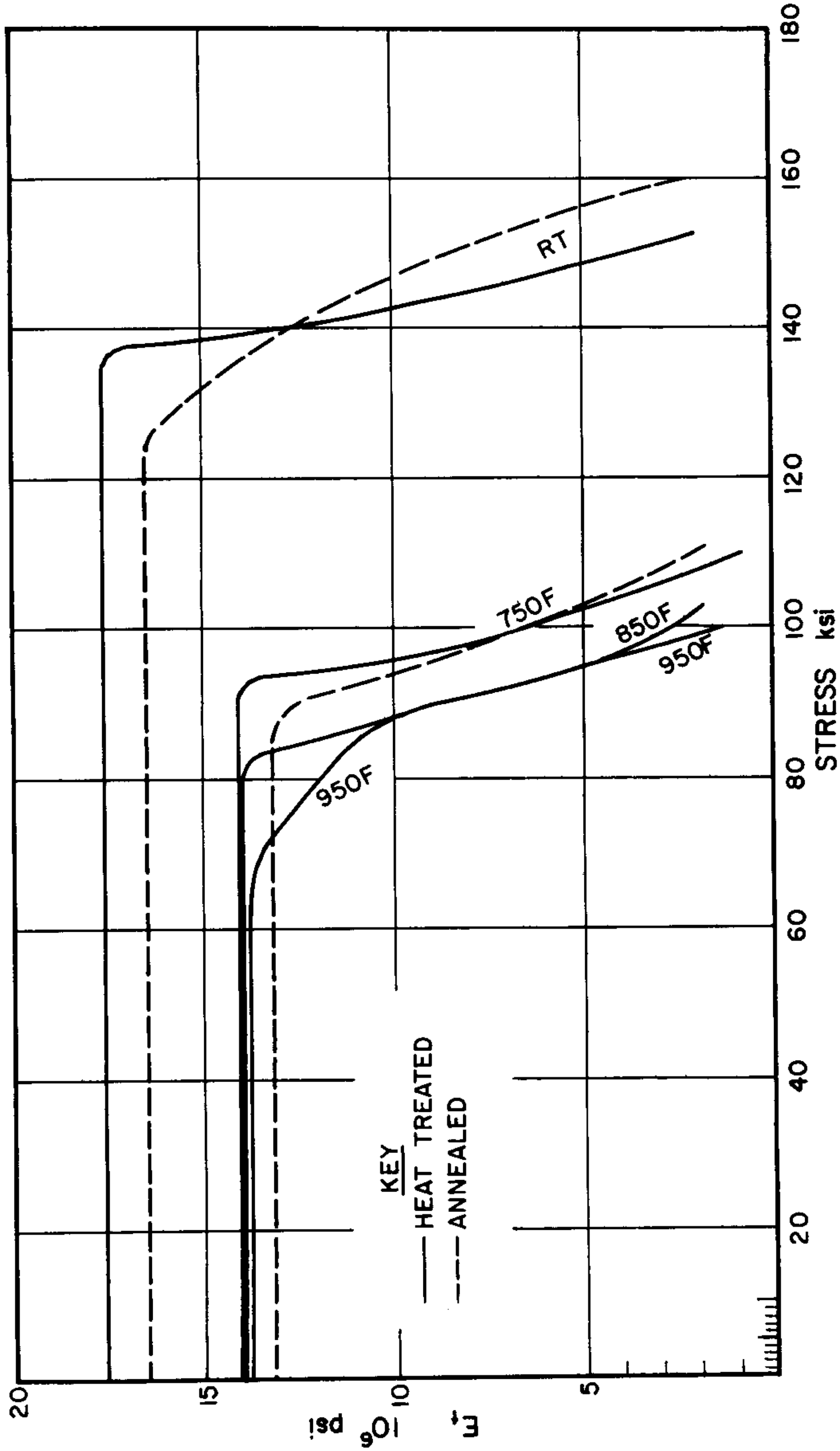


FIGURE 14 COMPRESSIVE TANGENT MODULUS WITH STRESS FOR HEAT TREATED AND ANNEALED TITANIUM ALLOY Ti-7Al-4Mo

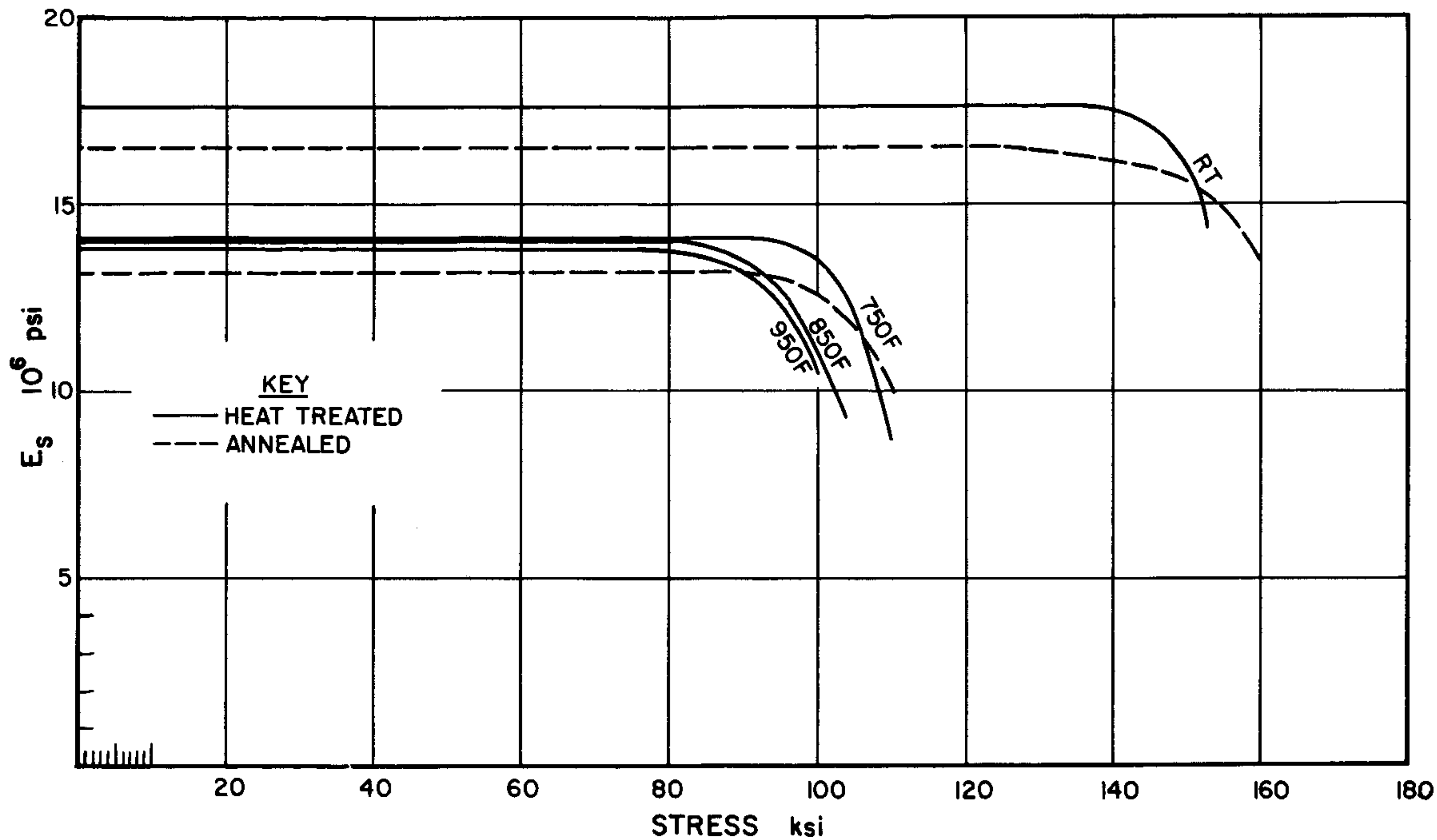


FIGURE 15 COMPRESSIVE SECANT MODULUS WITH STRESS FOR HEAT TREATED AND ANNEALED TITANIUM ALLOY Ti-7Al-4Mo

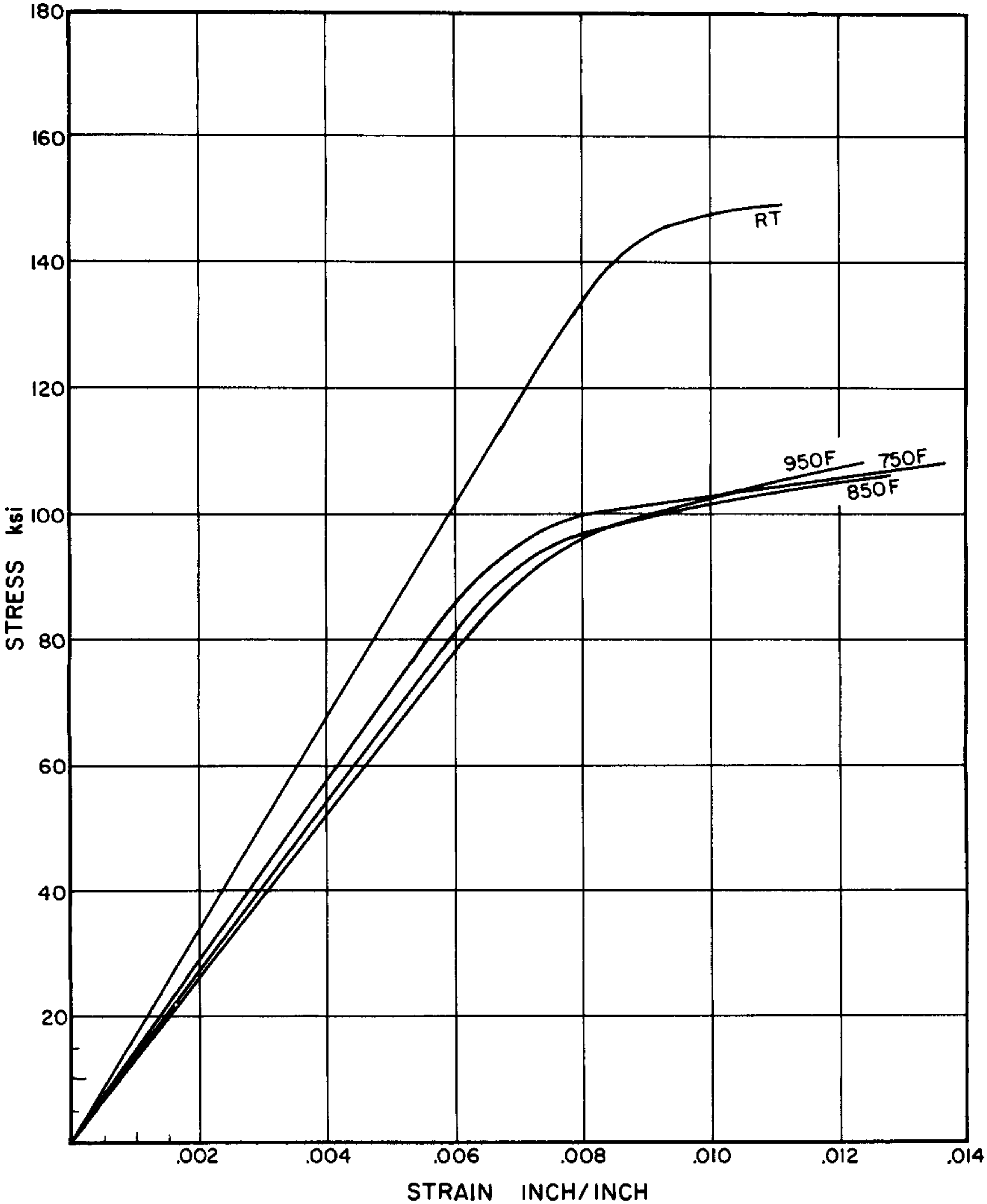


FIGURE 16 AVERAGE TENSILE SHORT TIME STRESS STRAIN PROPERTIES OF HEAT TREATED TITANIUM ALLOY Ti-7Al-4Mo

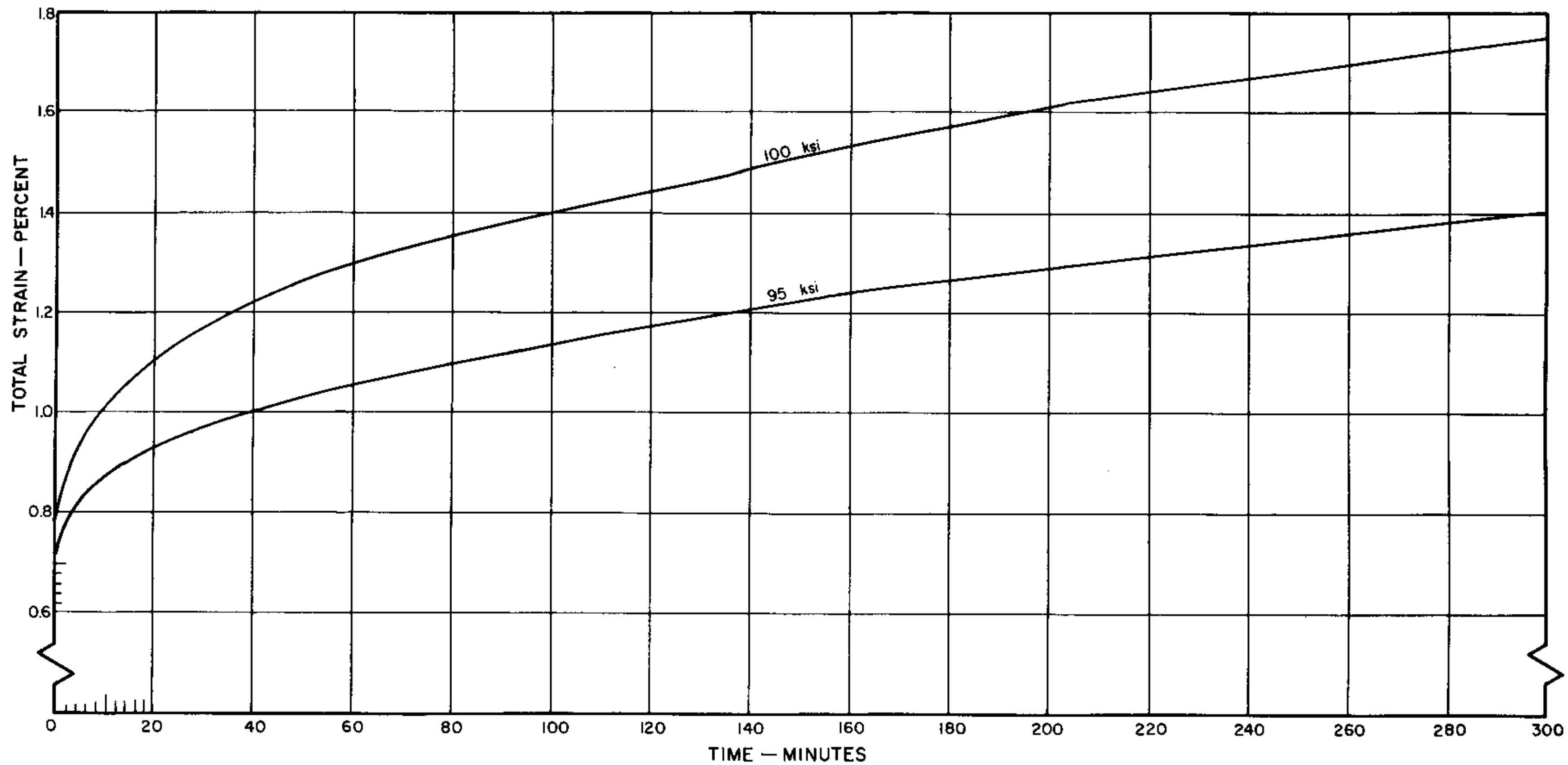


FIGURE 17 COMPRESSIVE CREEP RESULTS FOR HEAT TREATED TITANIUM ALLOY Ti-7Al-4Mo AT 850°F

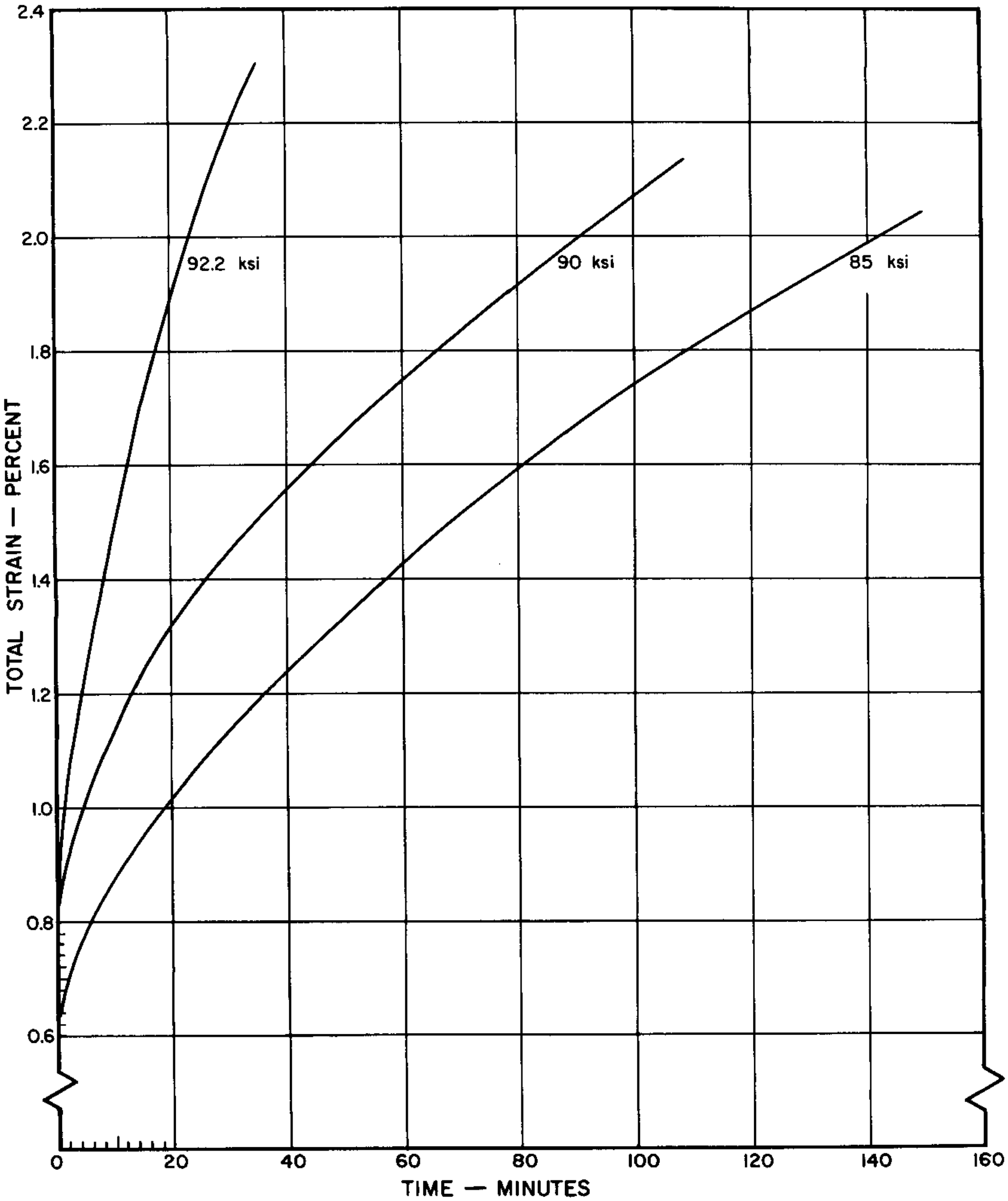


FIGURE 18 COMPRESSIVE CREEP RESULTS FOR HEAT TREATED TITANIUM ALLOY Ti-7Al-4Mo AT 950°F. AVERAGE CURVES SHOWN