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INVESTIGATION OF THE COMPRESSIVE, BEARING, AND SHEAR CREEP-RUPTURE PROPERTIES OF AIRCRAFT STRUCTURAL METALS AND JOINTS AT ELEVATED TEMPERATURES

LUKE A. YERKOVICH

CORNELL AERONAUTICAL LABORATORY, INC.

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FOREWORD

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ABSTRACT

The establishment of the high-temperature mechanical properties of aircraft structural materials is a prerequisite to efficient design when elevated temperature service is expected. Normally these properties are determined from the conventional short-time tensile and creep-rupture tests and as such are not necessarily applicable for stress conditions other than tension. The present program was conducted to examine the high temperature strength and deformation characteristics of two high-strength airframe alloys when subjected to a variety of stresses under both short and long time loading. Specifically the object of the program was to determine the high-temperature tension, compression, bearing and shear properties of selected airframe alloys with the ultimate purpose of correlating tension behavior with behavior under the various other types of loads and applying these basic data to predict the behavior of riveted joints undergoing creep deformation in tension, bearing, and shear.

This report summarizes in tabular and chart form the high temperature properties of PH15-7 Mo stainless steel and 6Al-4V titanium alloy in tension, compression, bearing, and shear. In addition, correlations of the tensile creep-rupture properties with corresponding compression, bearing, and shear creep-rupture properties are presented.

The creep-rupture characteristics of doubler type riveted joints, which represent single units of a multiple riveted assembly, prepared from the test alloys are presented herein. Correlations between measured joint creep-rupture and predicted joint creep-rupture are also included.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Richard R. Kennedy

RICHARD R. KENNEDY
Chief, Metals Branch
Materials Laboratory

SUMMARY

Two aircraft structural alloys, PH15-7 Mo stainless steel and 6Al-4V titanium, each having high strength to weight ratios, have been investigated in the 700 to 900°F temperature region to establish their creep and rupture performances under the individual influence of tension, compression, bearing, and shear stresses. Results from this investigation indicate that the test alloys display creep properties under bearing and shear stresses quite similar to the normal creep behavior of metals in tension, i.e., deformation occurs in three characteristic creep rate stages. Except for slight variations, it is observed that creep-rupture correlations agree favorably with short-time strength correlations when the short-time characteristics are determined under a controlled strain rate of 0.5% per minute.

Within the rupture times of interest and particularly at the lower test temperature, both alloys exhibit creep-rupture stress sensitivity in bearing and shear as well as tension. At 700°F, for example, stress variations of several percent have a very profound influence on time to rupture. In addition at this lower test temperature, stresses considerably in excess of the yield strengths must be applied to produce rupture in less than 500 hours.

Doubler type riveted joints incorporating bearing and shear elements fabricated from the test alloys were creep tested at elevated temperatures to correlate joint creep-rupture properties with appropriate bearing and shear creep-rupture properties individually determined. Joints were designed to rupture preferentially by shear creep-rupture in the rivets or bearing creep-rupture of the riveted members. Results of the joint tests indicate that joint creep-rupture performance could not be predicted with reasonable precision when failure occurs by shear in the rivet. This generalization was found to exist for both PH15-7 Mo and 6Al-4V titanium joints at 800 and 900°F. On the other hand, it was observed that when joints were designed to rupture in bearing, the joint creep deformation characteristics as well as time to rupture were predictable from the basic bearing creep-rupture properties of the bearing element. Doubler type joints, utilizing C-110M titanium sheet and A-110AT titanium rivets, creep-rupture tested at 900°F demonstrate the agreement between actual and predicted performance for the case where the joint fails in bearing.

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INTRODUCTION

The elevated temperatures generated in supersonic airframes have created new design concepts to meet the structural strength and stability requirements associated with high speed flight. In some instances these design concepts have been reflected in the choice of unconventional structural materials while in others by the use of insulating measures which permit conventional airframe materials to be applied. In either case, however, there exists an awareness on the part of the design engineer that structural integrity depends to a great degree upon the creep behavior of those elements comprising the airframe structure and that the higher the operating temperature, the more critical the creep factor.

In the construction and assembly of airframe structural members, rivets and other mechanical fasteners which become integral to the primary structure are usually required to carry loads. The ability of joined members to sustain loads imposed upon them is in many cases dependent upon the strength characteristics of the element forming the joint and in some cases upon the stress condition created in the immediate joint area. When loads are transmitted through joints, complex and concentrated stress patterns arise which tend to promote failure in any of a number of ways. Notable among these are (a) excessive shear deformation or failure of the fastener, (b) excessive bearing deformation or failure of the fastened member, (c) excessive tensile deformation or failure of the fastened member between fasteners, and (d) fatigue failure in any of the elements initiated by loosening in the joint. In spite of these stress complexities, determinations of the shear and bearing characteristics of joints and or joint elements have provided sufficient guidance for satisfactory composite designs in the temperature range where the effects of creep are essentially unimportant.

Beside the structural materials problems which have resulted from aerodynamic heating, it has become apparent that certain conventional strength characteristics heretofore regarded as dictating the usefulness of structures are not necessarily useful. Instead, it is recognized that many of these same characteristics must be defined according to a specific creep process and particularly at the temperatures of interest. By way of illustration, Mordfin (1)* has demonstrated that tensile creep behavior could not be applied to predict the creep and rupture behavior of single-riveted joints undergoing combined shear and bearing deformation. Likewise, an investigation dealing with high temperature compression-creep behavior (2) disclosed that materials may display major differences in their creep behaviors under compression and tension stress. On the other hand, however, Mordfin and Legate (3) were able to correlate multiple-riveted joint creep and rupture behavior with corresponding shear and

*See bibliography

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bearing creep-rupture characteristics determined independently (4,). In view of these significant observations, it would seem that the creep behavior of materials under the individual influences of various types of stresses constitutes a very important phase in designing airframes for high temperature service. Accordingly, a program was initiated in which the high-temperature behaviors of single riveted joints were examined for possible correlation with the creep-rupture behaviors of the joint materials. Such a correlation could be used to predict the high-temperature deformation and rupture properties of riveted structures from the known characteristics obtained from simple tension, compression, bearing, and shear creep-rupture tests.

TEST MATERIALS AND PROGRAM

Under the sponsorship of the Materials Laboratory of the Wright Air Development Center, a test program has been conducted to determine the creep and rupture characteristics of two aircraft structural alloys when exposed to tension, compression, bearing, and shear stresses. These properties were determined to establish correlations with tensile creep-rupture behavior and to establish the relationship of the individual creep characteristics with those obtained from riveted joints fabricated from the same test alloys.

The test materials consisting of PH15-7 Mo stainless steel and 6Al-4V titanium alloy, both in sheet and bar form, were selected for this study because of their relatively high strength to weight ratios which render them somewhat attractive for airframe use. Both alloys were creep-rupture tested in the 700 to 900°F temperature range at various selected stress levels to produce rupture from a few to several hundred hours.

The PH15-7 Mo stainless steel was procured from Armco Steel Corporation as commercial grade in sheet and bar form. The sheet, 0.062-inch thick, was annealed at 1950°F and mill processed to a 2D finish. Bar PH15-7 Mo was annealed at 1950°F and centerless ground to 5/8-inch diameter. Certified chemical analyses along with the certified mechanical properties for the annealed and hardened condition as supplied by the producer follow:

	C	Mn	P	S	Si	Cr	Ni	Mo	Al
PH15-7 Mo Sheet	0.075	0.60	0.021	0.006	0.26	15.14	7.20	2.22	1.25
PH15-7 Mo Bar	0.071	0.56	0.019	0.011	0.46	15.22	7.21	2.36	1.05

		0.2% Y.S.	U.T.S.	% Elong. in 2 Inches	Hardness
Sheet	Annealed	46,400	128,500	33.5	85 R_B
	Condition TH 1050	202,800	210,000	7.0	45 R_C
Bar	Annealed		132,000		

The PH15-7 Mo alloy was creep tested after hardening which consisted of heating the annealed alloy to 1400°F for 1-1/2 hours, air cooling to room temperature and subsequently quenching in water below 60°F. Reheating at 1050 for 1-1/2 hours and air cooling renders the alloy in the TH 1050 condition and develops an ultimate tensile strength in excess of 200,000 psi.

The 6Al-4V titanium alloy was supplied by Mallory Sharon Titanium Corporation as commercial grade sheet and bar. The sheet, 0.062-inch thick, and bar, 1/2 inch diameter, were received in the hot rolled, vacuum annealed condition. Certified chemical analyses and mechanical properties supplied by the producer follow.

	C	N	Fe	Al	V	H_2 (a)
Sheet	0.03	0.01	0.18	6.08	4.00	41
Bar	0.04	0.01	0.23	6.35	3.86	25/45

		0.2% Y.S.	U.T.S.	% Elongation
Sheet	Longitudinal	117,400	138,200	12.0 (b)
	Transverse	131,900	138,100	12.0 (b)
Bar		133,600/144,400	138,000/145,000	13.3/15.6 (c)

(a) H_2 expressed in parts per million
(b) Measured over 2-inch test section
(c) Measured over 1-inch test section

Sheet 6Al-4V titanium alloy was tested in the heat treated condition which consisted of holding at 1725°F for 1/4 hour in an argon atmosphere, water quenching and subsequently reheating at 900°F for 8 hours followed by air cooling. In this heat treating operation, however, it became necessary to resort to a boiling water quench rather than the usual water quench to reduce the severe distortion tendencies exhibited by the alloy.

The 6Al-4V titanium alloy bar was tested in the vacuum annealed condition.

TEST SPECIMENS

Tension

Sheet tensile specimens, common to both the short-time and creep testing phases of the program, were machined from 16 x 1 inch blanks removed from the parent sheet such that loading was applied in the longitudinal direction. The finished specimens utilize a standard nominal test section 1/2-inch wide and 2 inches long centrally located in the 16-inch over-all length.

Bar tensile specimen, common to both the short-time and creep testing phases, were prepared from 5-1/2-inch blanks to a finished nominal diameter of 1/4-inch and a 2-inch long centrally located test section.

Specifications pertinent to the machining of the sheet and bar specimens are presented in Figure 1.

Bearing

Bearing specimens were prepared from 4-1/8 x 1-1/4-inch blanks removed from the parent sheet so that the bearing characteristics for the longitudinal direction were determined. The blanks were finish machined to 4 x 1-1/4-inch specimens by removing the metal edge below the bearing hole. For this series of tests, a 3/16-inch bearing hole diameter with an edge distance to hole diameter ratio of 1.5 was selected. Specifications for the bearing specimen are illustrated in Figure 2.

Shear

Specimens for shear testing were machined from the centers of the bar alloys so that shear load was applied in the transverse direction. Blanks 5/8-inch long and 1/2-inch diameter were finish machined to produce shear specimens 1/2-inch long and 1/8-inch in diameter. An illustration of the shear specimen, along with the appropriate machining specifications, is illustrated in Figure 3.

Compression

Sheet compression specimens were prepared from blanks removed from the parent sheet in such a manner as to determine compression characteristics in the longitudinal direction. These compression specimens were finish machined to 3/4 x 2-9/16-inch specimens with considerable care being taken to insure square corners and parallelism in opposite edges. Specifications for the sheet compression specimens are illustrated in Figure 4.

Short-Time Testing

The room and elevated temperature tensile, bearing, and shear characteristics of the test alloys were determined in a 60,000 pound hydraulic Universal testing machine. The machine is equipped with a strain pacer, operating in conjunction with a set of extensometers attached to the specimen, which permits stress-strain properties to be obtained under carefully controlled rates of strain at both room and elevated temperatures.

Creep Testing

Tension, bearing, and shear creep tests were conducted in conventional lever-loaded (10:1 ratio) creep machines of CAL design. Since these machines were primarily designed for tensile creep testing, special modifications in the loading system were necessary to adapt the equipment for bearing and shear creep testing as well.

Test temperature is maintained with a resistance-wound creep furnace provided with appropriate shunts to adjust temperature distribution in the top, middle, and bottom furnace sections as required. Regulation occurs through low or high voltage input to the furnace by a conventional potentiometric temperature controller. With this system of control and adjustment, the test temperature is maintained within limits of ± 3°F of the nominal test temperature over a specific gage length for the duration of the test. Temperature measurements are made at various selected positions on the test section by calibrated chromel-alumel thermocouples wired to the specimen at these positions and shielded from furnace radiation by asbestos cord. A precision potentiometer, accurate to within 0.5°F is used to indicate the test section temperature and to serve as a guide for temperature adjustment.

In tension creep testing, strain is measured by a set of extensometers attached to a two-inch gage section. These extensometers engage cantilever beams to which resistance strain gages are cemented. The displacement of the extensometers, which is a direct measure of the creep deformation, is transmitted to the cantilever pickup system and is detected as an unbalance in an electrical bridge circuit. Precalibration of the beams together with the bridge circuit permits convenient and accurate conversion of the generated bridge unbalance to creep strain. Continuous record of the strain is made on a Dynalog type strain recorder with a long time accuracy of 0.0004 in/in/div and a sensitivity of 0.00004 inch per inch.

In applying the basic tensile creep equipment for conducting bearing creep tests, special equipment modifications were required in the loading system to accommodate the bearing specimen. The modification consists essentially of a clevis of two hardened tool steel plates riveted to a spacer bar to maintain a total clearance between plates of 0.070-inch. A 3/16-inch hole was drilled and reamed in line through these plates. The bearing specimen is positioned between the plates and a hardened tool steel pin is inserted to fully engage the tool steel plates and the bearing specimen. The assembly, when secured into the creep testing machine, permits a bearing load to be applied to the specimen.

The effective bearing area is calculated as the product of the bearing hole diameter and the thickness of the sheet. Bearing hole deformation is measured by the displacement of the bearing pin with respect to the stress free corners of the bottom edge of the specimen. Two deformometer arms are attached to a stress free section of the specimen holder above the bearing pin hole. The other pair engage the bottom edge of the specimen. These four arms are used to generate a bridge signal which is conveniently converted to bearing hole deformation. The stress measuring system employed in the bearing creep program is capable of detecting deformations of 0.000016-inch which represents 0.009% of the bearing hole.

The test fixture for determining the shear characteristics of the test alloys is similar in design to the type employed in bearing testing. Like the bearing fixture, it too consists of a clevis to house the specimen and a blade to apply the shear load. The device is assembled by riveting two hardened and ground tool steel plates to a ground spacer bar such that the total clearance between the clevis and shear blade is 0.001 inch. One-eighth inch diameter holes were drilled and reamed in line through both plates as well as the tool steel shear blade, and these holes positioned sufficiently distant from the edges to make shear deformation in the fixture negligible. When the shear blade is placed within the clevis and the holes aligned, the test specimen is inserted to be loaded in double shear.

The strain measuring technique for determining shear strain is identical to that employed in the bearing test, and essentially shear strain is that displacement of the shear blade relative to a fixed and unstressed position of the clevis. Again, strains of 0.000016 inch or the percentage equivalent of 0.013% are capable of being detected.

The required modifications to the tensile creep test units which permit bearing and creep tests to be performed are discussed in detail, complete with illustrations in Reference 4.

TEST RESULTS

Short-Time Tension

The test alloys, both sheet and bar, were short-time tensile tested at room and elevated temperatures with the load applied parallel to the direction of working. These data provided a base line by which the short time properties under other conditions of loading may be correlated. In addition, they serve the very useful purpose of permitting stresses to be selected in the creep testing phases of the program.

PH15-7 Mo Stainless Steel Sheet

The short-time tensile characteristics for PH15-7 Mo stainless steel sheet were determined in duplicate at temperatures of 80, 700, 800, and 900°F. All tests were conducted at a constant strain rate of 0.5% per minute to the point of rupture. The results of these duplicate tests at the various temperature levels are summarized in Table 1 and typical stress-strain curves at each temperature are illustrated in Figure 5.

PH15-7 Mo Stainless Steel Bar

Duplicate short-time tensile tests on the PH15-7 Mo bar alloy were conducted at 80, 700, 800, and 900°F. Like the companion sheet alloy, all tests were performed at a constant strain rate of 0.5% per minute to rupture. The results of these series of tests are summarized in Table 2 and typical stress-strain curves at each temperature are illustrated in Figure 6.

6Al-4V Titanium Alloy Sheet

Short-time tensile properties of the heat treated 6Al-4V titanium alloy sheet were conducted in duplicate at 80, 700, 800, and 900°F. The results obtained for a constant strain rate of 0.5% per minute to rupture are presented in Table 3. Typical stress-strain curves at each temperature level are illustrated in Figure 7. It is worthy of notice that the short-time tensile behavior of the alloy appears to be somewhat insensitive to temperature in the 700 to 800°F region, at least for the 0.5% strain rate, since tensile strengths in the 111,000 to 116,000 psi range have been recorded for the duplicate tests at each temperature.

6Al-4V Titanium Alloy Bar

The short-time tensile properties of the 6Al-4V titanium alloy bar in the vacuum annealed condition were determined in duplicate at 80, 700, 800, and 900°F and at a constant strain rate of 0.5% per minute to rupture. Results of this series of tests are tabulated in Table 4 and typical stress-strain curves for the various test temperatures are presented in Figure 8. Unlike the heat treated sheet alloy, the vacuum annealed bar at room temperature displays an upper and lower yield point similar to low carbon steel. This deep-knee stress-strain characteristic, however, vanishes with increasing temperature and is non-existent at 700°F and above.

Short-Time Bearing

In determining the short-time bearing properties of the sheet alloy, all tests were conducted using a 3/16-inch diameter bearing hole and an edge distance to bearing hole diameter ratio of 1.5. Bearing stresses were developed by loading through a hardened shear pin whose diameter was adjusted to permit insertion into the 3/16-inch diameter bearing hole. Preliminary calculations of expected bearing strengths along with pilot bearing tests had demonstrated that for the 1.5D edge distance, a 3/16-inch bearing hole diameter was necessary to prevent shear failure in the load applying shear pin. All tests were performed at a constant strain rate of 0.5% per minute; i.e., the metal under the hole was deformed at the rate of 0.5% per minute rather than the hole itself. Earlier short-time bearing tests reported in reference 6 demonstrated that correlations with corresponding tensile properties are subject to large variations when strain rate control is not exercised.

PH15-7 Mo Stainless Steel Sheet

The short-time bearing characteristics of PH15-7 Mo sheet were determined at 80, 700, 800, and 900°F. The results of duplicate tests at each temperature are summarized in Table 5 along with the tensile-bearing correlation developed. The importance of conducting the short-time bearing tests at a strain rate equivalent to that in tension is indicated by the slight variations in the correlations regardless of temperature. There is, however, a tendency for the bearing strength to tensile strength ratio to increase slightly with increasing temperature which probably is of no practical significance. Typical bearing stress-hole deformation curves for the PH15-7 Mo sheet alloy at the selected temperatures are illustrated in Figure 9. In fixing the yield properties in bearing, 2.0% offset has arbitrarily been selected to define 2.0% permanent deformation of the 3/16-inch diameter bearing hole.

6Al-4V Titanium Alloy Sheet

Heat treated 6Al-4V titanium alloy sheet was tested at 80, 700, 800, and 900°F with the express purpose of correlating its bearing and tensile strength behaviors. The results of duplicate tests at the various temperature levels are summarized in Table 6. Table 6 in addition shows the strength relationship characteristic of the alloy at the test temperatures. As was the case for PH15-7 Mo sheet there appears to be a tendency for the strength ratio to increase and in this instance again, the variation is of no practical significance.

Typical bearing stress-hole deformation curves for 6Al-4V titanium alloy sheet at the test temperatures are presented in Figure 10.

Short-Time Shear

The short-time shear properties of the bar alloys were determined for 1/8-inch diameter specimens loaded in double shear. All tests were performed under constant strain rates of 0.5% per minute to establish the correlation of shear properties with appropriate tensile properties at both room and elevated temperatures.

PH15-7 Mo Stainless Steel Bar

Shear pin specimens 1/8-inch in diameter were loaded in double shear at 80, 700, 800, and 900°F. The results of duplicate tests at these temperatures are summarized in Table 7 along with the shear-tension property correlations found to exist. Since the shear tests were conducted under controlled strain rate conditions, a necessary feature of the test was the determination of strain as well as load, thus making it possible to construct shear stress-strain curves. Typical curves are illustrated in Figure 11 for each of the test temperatures. From these curves it is found that the elastic modulus in shear (generally determined from the torsion test and found to be approximately 0.4 of the elastic modulus in tension) ranges from 0.32 to 0.34 of the elastic modulus in tension. Elastic bearing deformation of the shear blade and specimen adapter plus slight bending of the shear specimen which cannot be separated from shear strain alone may account for the lower than accepted values for elastic modulus in shear.

6Al-4V Titanium Alloy Bar

Vacuum annealed 6Al-4V titanium alloy bar was short-time shear tested in duplicate at 80, 700, 800, and 900°F. Test results are presented in Table 8 which shows the shear-tension property correlations determined for this alloy. Typical shear stress strain curves at each test temperature are illustrated in Figure 12. Like the PH15-7 Mo bar, the elastic moduli in shear were determined and found to be less than the generally accepted 0.4 of the elastic moduli in tension.

TENSILE CREEP RESULTS

PH15-7 Mo Stainless Steel Sheet

Tensile creep tests on PH15-7 Mo stainless steel sheet were conducted in the temperature range of 700 to 900°F. At each of the test temperatures, the alloy was subjected to a series of static stresses to define the time and temperature relationship for various amounts of deformation and rupture. The results of the individual tests are presented in Table 9 and summarized in Figures 13 through 15 as conventional stress-time curves. Within the temperature range considered and more specifically at 700°F, it is significant to point out the stress sensitivity of the alloy. Short-time tensile tests at 700°F had established the 0.2% yield strength to be in the approximate range of 153,000 to 158,000. Creep specimens stressed at 152,000 and 155,000 psi were exposed for 3748 and 4721 hours respectively with no indication of rupture. In contrast, specimens stressed at the slightly higher stresses of 157,000 and 160,000 psi ruptured in 42 and 16 hours respectively.

PH15-7 Mo Stainless Steel Bar

The PH15-7 Mo bar was tensile creep tested at 800 and 900°F. Like the sheet alloy, selected static stresses were applied to define the creep and rupture behavior of the alloy within a time range. The results of individual tests are summarized in Table 10. Stress-time design charts showing the creep and total deformation behavior at 800 and 900°F are illustrated in Figures 16 and 17. In comparing equivalent rupture times for the sheet and bar, it is significant that the sheet develops a substantial rupture stress superiority at both 800 and 900°F. Since these alloys fall within the limiting specification in their chemical composition, the sheet superiority appears to indicate that the alloy exhibits a variation in heat treating response with section size which is not necessarily detectable by hardness measurement.

6Al-4V Titanium Alloy Sheet

A series of tensile creep-rupture tests were conducted on heat-treated 6Al-4V titanium alloy sheet at 700, 800, and 900°F. The results of the individual tests for various amounts of creep and total deformation are summarized in Table 11. Graphical representations of the deformation and rupture characteristics are illustrated in the stress-time charts of Figures 18 through 20. An interesting characteristic of this alloy is its creep and rupture superiority at 700°F compared with that at 800°F. At identical stresses of 95,000 psi, the specimen at 800°F required 37.5 hours to accumulate 5% creep and 75 hours to rupture while at 700°F 2850 hours were necessary to obtain 5% creep and rupture had not occurred after 3500 hours. This comparison is particularly interesting since the alloy exhibited a short-time tensile strength insensitivity in the 700-800°F temperature region.

6Al-4V Titanium Alloy Bar

The vacuum annealed 6Al-4V bar was tensile creep tested at 700, 800, and 900°F. Results of the individual tests are summarized in Table 12 for the selected stress levels. Stress-time design charts for various amounts of creep, total deformation and rupture are illustrated in Figures 21 through 23.

BEARING CREEP RESULTS

PH15-7 Mo Stainless Steel Sheet

Bearing specimens with 3/16-inch diameter holes and an edge distance to hole diameter ratio of 1.5 were exposed to a series of static stresses at 700, 800, and 900°F to correlate the bearing characteristics with appropriate tensile characteristics. The results of individual tests are presented in Table 13 and summarized in Figures 24 through 26 as conventional stress-time design charts for various amounts of bearing hole deformation and rupture. As was true in tension creep testing this alloy, it is again significant to observe its stress sensitivity at 700°F. To produce rupture in the 10 to 300-hour range under bearing loads, stresses between 89 to 96% of the ultimate bearing strength must be applied. At 800°F and particularly 900°F creep effects become more influential since stresses between 80 to 90% and 67 to 83% of the respective ultimate bearing strengths produce rupture in the same time range. At each temperature, however, the stresses are of sufficient magnitude to cause significant permanent deformation of the bearing hole upon application of the load.

For the particular boundaries employed in the bearing creep-rupture determination of PH15-7 Mo stainless steel sheet (i.e., 3/16-inch diameter hole and edge distance to hole diameter ratio of 1.5), correlations expressing bearing creep and rupture behavior to tensile rupture behavior have been made. Table 14 represents the correlation at 700, 800, and 900°F and various time levels in the 1 to 500-hour range. An item of particular interest in the rupture correlation is the decrease in ratios with increasing temperature. This trend is contrary to the short-time correlations presented in Table 5.

6Al-4V Titanium Alloy Sheet

Bearing specimens of 6Al-4V sheet utilizing 3/16-inch diameter bearing hole and an edge distance to hole diameter ratio of 1.5 were creep tested at 700, 800, and 900°F. The results of this series of bearing creep tests are summarized in Table 15 and graphically illustrated in Figures 27 through 29. A comparison of bearing rupture strengths with corresponding short-time bearing strengths indicates the stress sensitivity of the alloy throughout the test temperature range. It can be seen, for example, that stresses between 96 and 92% of the ultimate bearing strength at 700°F must be applied to produce rupture in the 10 to 300-hour range, whereas at 800 and 900°F stresses in the range of 90 to 75% and 75 to 55% of the ultimate bearing strength respectively are required.

Correlations of the bearing creep-rupture stresses and tensile rupture stresses in the 1 hour to 500-hour range at the test temperature are compiled in Table 16.

SHEAR CREEP RESULTS

PH15-7 Mo Stainless Steel Bar

Specimens prepared from PH15-7 Mo bar were exposed to shear stresses at 800 and 900°F. The shear-pin total deformation and creep characteristics of this alloy at the test temperatures are summarized in Table 17. Stress-time curves illustrating various amounts of creep, total deformation and rupture are presented in Figures 30 and 31.

The relationships of shear creep and rupture to tensile rupture for equivalent time periods in the 1 to 500-hour range, are summarized in Table 18.

6Al-4V Titanium Alloy Bar

The shear creep-rupture characteristics of 6Al-4V titanium alloy bar were determined at 700, 800, and 900°F for shear stresses which produced rupture in the range of a few to 500 hours. The results of these determinations are presented in Table 19 and are represented in terms of total shear deformation and shear creep-rupture as stress-time curves in Figures 32 through 34.

The relationships of the shear creep and rupture properties with the corresponding tensile rupture characteristics of this alloy in the 1 to 500-hour range are summarized in Table 20.

COMPRESSION CREEP RESULTS

PH15-7 Mo Stainless Steel Sheet

Compression creep tests were conducted on the PH15-7 Mo sheet alloy at 800 and 900°F. The results of these tests are compiled in Table 21 and illustrated graphically in Figures 35 and 36 along with the comparative tensile creep behavior displayed by the alloy. A correlation of compression creep stress to tensile creep stress for various amounts of creep deformation in the time range of 1 to 200 hours is presented in Table 22. The correlation indicates that at either temperature and within the time limits being considered, the alloy is slightly more resistant to creep in compression.

JOINT CREEP RESULTS

The joint creep-rupture phase of the test program was conducted on a doubler type joint configuration for which sheet and bar creep properties in tension, bearing, and shear had been determined. The joints were tested in their simplest forms (i.e., the minimum number of elements required to form the component) each of which may be said to represent a single unit of a multiple riveted assembly. The study was made with the primary objective of correlating joint creep-rupture behavior with the individual creep-rupture characteristics of the alloys involved and established under tension, bearing, and shear stresses at the corresponding test temperature. Essentially, the joints were designed to fail preferentially in some cases by bearing creep-rupture of the riveted sheet and in others by shear creep-rupture of the rivet. In all instances, however, stresses were sufficiently large to simultaneously cause significant deformation by both bearing and shear creep. This procedure was followed to compare the predicted and actual performances of the test joints with regard to time for creep and rupture as well as mode of rupture.

PH15-7 Mo Stainless Steel Sheet - PH15-7 Mo Stainless Steel Rivets

Doubler type joints utilizing all PH15-7 Mo stainless steel components in the TH 1050 condition were creep-rupture tested at 800 and 900°F. For this series of tests specimens were prepared with a combination of 3/16-inch rivets and bearing hole diameters. Consistent with the specifications for the bearing specimen, an edge distance to hole diameter ratio of 1.5 was employed in the joint design. The results of this series of tests are summarized in Table 23 and graphically compared in Figures 37 through 39 with the predicted joint creep behavior. The predicted behavior presupposes that each joint element stressed in bearing or shear undergoes creep deformation as dictated by the individual static bearing and shear creep tests. While the joints ruptured as predicted, neither time to rupture nor the creep behavior were predictable with reasonable precision. Instead, the comparison appears to indicate that the joint creep behavior depends in these cases on the shear creep behavior of a single rivet, and more specifically the weakest rivet. The degree of variation between the measured and predicted times to rupture of the joints at 800 and 900°F are shown in the following compilation.

Temp. °F	Shear Stress PSI	Time in Hours for Rupture Under Joint Shear	Individual Shear (1)
800	80,000	>950(2)	160
	(60,000	376.5	440
900	(62,000	158	210
	(64,000	42.5	95
	(66,000	5.5	40

(1) Basis for predicting mode and time for rupture.
(2) Test in progress, no indication of rupture after 950 hours.

Notable in the rupture comparison is the reversal in the joint behavior between 800 and 900°F. At 900°F the joint ruptured considerably earlier than predicted while at 800°F based on the single test, the joint showed no indications of rupturing after exposure for more than five times that predicted.

6Al-4V Titanium Alloy Sheet - 6Al-4V Titanium Alloy Rivets

Doubler type joints utilizing heat treated 6Al-4V titanium alloy sheet and vacuum annealed 6Al-4V rivets were creep tested at 900°F. The test specimens were prepared to fail in shear combining 1/8-inch rivets with 1/8-inch diameter bearing holes and an edge distance to hole diameter ratio of 1.5. The results of a series of four tests, each stressed at different levels are summarized in Table 24. Creep deformation curves for the individual tests are represented in Figures 40 and 41 comparing the predicted and measured behavior. Examination of the comparison indicates that joint creep occurs more rapidly than predicted from the static creep characteristics of the elements concerned and suggests that shear creep in the rivets may be accelerated by the joint forming process. In all cases, rupture of the joint had occurred as predicted, i.e., by rivet shearing; however, time to rupture was approximately half of the predicted time as shown in the following comparison.

Shear Stress	Time in Hours for Rupture Under	
PSI	Joint Shear	Individual Shear (1)
26,000	317.5	590
30,000	161.	260
35,000	56.5	110
40,000	25.3	53

(1) Basis for predicting mode and time for rupture.

C-110M Titanium Alloy Sheet - A-110AT Titanium Alloy Rivets

A series of creep-rupture tests for this combination was conducted at 800°F and compared with the bearing creep behavior of the C-110M alloy and the shear creep behavior of A-110AT reported in References 5 and 7.

The doubler type joint constructed from these alloys incorporated a 1/8-inch diameter bearing hole, 1.5 ratio of bearing hole diameter to edge distance and 1/8-inch diameter rivets. Based on this configuration specification and the known bearing and shear creep properties of the alloys involved which are summarized in references 5 and 7, a simple mechanics treatment of the bearing and shear stresses developed indicate that the joints would fail in bearing creep-rupture.

The results of this series of joint creep tests are summarized in Table 25. Creep deformation characteristics for the individual tests are represented in Figures 42 and 43 comparing the predicted and measured behaviors. Examinations of the curves indicate that the joints deform as predicted and that in this instance, the assumption that the sum of the creep deformations of each element is valid. Further it is observed that each joint had ruptured in bearing and time to rupture was predicted from the bearing rupture characteristics of the bearing element. Examples of the close agreement are illustrated by comparing the time for rupture of the joint with the time for rupture under bearing.

Bearing Stress PSI	Time in Hours for Rupture Under Joint Bearing	Time in Hours for Rupture Under Individual Bearing
50,000	267	270
54,000	165.5	190
70,000	55.7	52
85,000	21.5	20

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TABLE 1

SUMMARY OF SHORT-TIME LONGITUDINAL TENSILE CHARACTERISTICS OF PH15-7 Mo STAINLESS STEEL SHEET IN TH 1050 CONDITION

Temp. °F	0.2% Yield Strength PSI	Ultimate Tensile Strength PSI	Modulus of Elasticity x 10^6 PSI	% Elong. in 2 Inches
80	203,500	215,100	26.7	9.0
	196,800	217,000	29.5	9.0
700	153,600	169,400	23.7	11.0
	157,500	172,400	24.0	14.0
800	145,100	158,600	22.6	11.0
	140,500	154,900	23.1	16.0
900	121,000	130,500	22.0	11.0
	122,500	134,400	23.0	14.5

TABLE 2

SUMMARY OF SHORT-TIME TENSILE CHARACTERISTICS OF PH15-7 Mo STAINLESS STEEL BAR IN TH 1050 CONDITION

Temp. °F	0.2% Yield Strength PSI	Ultimate Tensile Strength PSI	Modulus of Elasticity x 10^6 PSI	% Elong. in 2 Inches
80	202,300	206,000	28.0	5.5
	201,200	207,500	27.7	5.5
700	162,200	172,000	26.4	7.5
	164,200	168,300	25.3	8.5
800	148,800	157,600	25.7	11.5
	147,200	151,600	25.1	11.0
900	127,200	128,200	23.6	12.5
	126,800	127,100	25.4	14.0

TABLE 3

SUMMARY OF SHORT TIME LONGITUDINAL TENSILE CHARACTERISTICS OF HEAT TREATED 6Al-4V TITANIUM ALLOY SHEET

Temp. °F	0.2% Yield Strength PSI	Ultimate Tensile Strength PSI	Modulus of Elasticity x 10^6 PSI	% Elong. in 2 Inches
80	132,300	150,200	15.5	9.0
	131,000	150,000	15.3	13.0
700	87,100	115,600	11.3	7.0
	85,900	115,800	12.1	10.5
800	90,500	116,000	10.7	11.0
	86,100	111,400	11.2	11.0
900	79,200	97,300	9.3	17.5
	78,800	96,850	10.3	17.0

TABLE 4

SUMMARY OF SHORT-TIME TENSILE CHARACTERISTICS OF VACUUM ANNEALED 6Al-4V TITANIUM ALLOY BAR

Temp. °F	0.2% Yield Strength PSI	Ultimate Tensile Strength PSI	Modulus of Elasticity x 10^6 PSI	% Elong. in 2 Inches
80	137,900* 137,400*	138,900 137,900	16.92 18.08	17.5 17.0
700	83,600 84,600	96,600 96,900	15.70 16.20	15.0 19.5
800	80,700 77,400	89,600 87,200	14.66 15.46	21.5 21.0
900	67,000 68,100	76,400 74,800	11.83 10.64	32.0 36.0

*Upper Yield Point - Specimens at room temperature exhibited upper and lower yield point characteristics.

TABLE 5

SUMMARY OF SHORT TIME BEARING CHARACTERISTICS OF PH15-7 Mo STAINLESS STEEL SHEET IN THE TH 1050 CONDITION FOR 3/16 INCH BEARING HOLE DIAMETER AND EDGE DISTANCE TO HOLE DIAMETER RATIO OF 1.5

Temp. °F	2.0% Bearing Yield Strength PSI	Ultimate Bearing Strength PSI	Average Ultimate Bearing Strength PSI	Avg. Bearing Strength / Avg. Tensile Strength
80	277,000 294,500	317,500 333,000	325,250	1.50
700	229,000 235,000	270,500 269,000	269,750	1.57
800	222,500 223,000	243,500 257,000	250,250	1.59
900	183,000 186,000	212,000 218,000	215,000	1.62

TABLE 6

SUMMARY OF SHORT-TIME BEARING CHARACTERISTICS OF
HEAT TREATED 6Al-4V TITANIUM ALLOY SHEET FOR
3/16 INCH BEARING HOLE DIAMETER AND EDGE DISTANCE OF 1.5D

Temp. °F	2.0% Bearing Yield Strength PSI	Ultimate Bearing Stress PSI	Average Ultimate Bearing Strength PSI	Avg. Bearing Strength / Avg. Tensile Strength
80	174,100	236,800	235,150	1.56
	169,700	233,500		
700	136,300	194,500	191,850	1.66
	134,900	189,200		
800	131,900	187,800	182,400	1.60
	133,300	177,000		
900	117,600	162,100	160,950	1.66
	113,100	159,800		

TABLE 7

SUMMARY OF SHORT-TIME SHEAR CHARACTERISTICS OF
PH15-7 Mo STAINLESS STEEL BAR IN TH 1050 CONDITION

Temp. °F	Shear Strength PSI	Average Shear Strength PSI	Average Shear Strength / Average Tensile Strength	Elastic Modulus in Shear x 10^6 PSI	Avg. Elastic Modulus in Shear x 10^6 PSI	Average Elastic Modulus in Shear / Average Elastic Modulus in Tension
80	125,500 124,900	125,200	0.61	9.27 9.63	9.45	0.34
700	101,000 108,000	104,500	0.61	8.18 9.01	8.59	0.33
800	94,400 95,600	95,000	0.61	7.85 8.34	8.10	0.32
900	80,300 77,600	78,950	0.62	8.33 7.87	8.10	0.33

TABLE 8

SUMMARY OF SHORT-TIME SHEAR CHARACTERISTICS OF VACUUM ANNEALED 6Al-4V TITANIUM ALLOY BAR

Temp. °F	Shear Strength PSI	Average Shear Strength PSI	Average Shear Strength / Average Tensile Strength	Elastic Modulus in Shear x 10^6 PSI	Avg. Elastic Modulus in Shear x 10^6 PSI	Average Elastic Modulus in Shear / Average Elastic Modulus in Tension
80	91,000 / 91,500	91,250	0.66	6.48 / 6.21	6.34	0.36
700	65,700 / 67,900	66,800	0.68	5.21 / 5.08	5.14	0.32
800	63,300 / 62,000	62,650	0.71	4.80 / 4.47	4.63	0.31
900	54,700 / 52,700	53,700	0.71	3.84 / 3.76	3.80	0.34

TABLE 9

TENSILE CREEP-RUPTURE CHARACTERISTICS OF PH15-7 Mo STAINLESS STEEL
SHEET IN TH 1050 CONDITION

Temp. °F	Stress PSI	% Elong. on Loading	Time in Hours for Deformation of 0.2% C	0.2% TD	0.3% C	0.3% TD	0.5% C	0.5% TD	1.0% C	1.0% TD	2.0% C	2.0% TD	3.0% C	3.0% TD	5.0% C	5.0% TD	Fracture Hours	Time of Test Hours	% Elong. in 2 In.	Specimen 399-A
700	152,000	0.80	1.0	OL	2.0	OL	2.5	OL	5.0	1.0	45.0	9.0	-	79.0	Test	Discontd.	3748	Hr. TD	3.68%	30
	155,000	0.81	1.2	OL	1.7	OL	2.0	OL	2.4	0.8	17.0	5.0	99.0	24.0	"	"	4721	Hr. TD	4.60%	28
	157,000	0.90	0.04	OL	0.1	OL	0.2	OL	0.7	0.06	2.9	0.9	6.4	3.3	17.1	11.8	42.0	42.0	13	29
	160,000	0.90	0.04	OL	0.1	OL	0.2	OL	0.7	0.06	2.9	0.9	4.8	3.2	8.9	7.1	16.0	16.0	12	27
800	140,000	0.78	1.0	OL	2.1	OL	3.0	OL	3.5	1.0	4.7	2.3	26.0	6.0	-	1080.0	1302.5	1302.5	8	22
	142,000	0.82	0.2	OL	0.3	OL	0.4	OL	1.0	0.2	2.6	1.2	9.6	3.4	-	-	32.0	32.0	8	26
	144,000	0.71	0.1	OL	0.1	OL	0.2	OL	0.2	0.1	1.6	0.7	3.8	2.3	9.6	7.6	17.0	17.0	9	25
	147,000	1.04	0.04	OL	0.05	OL	0.1	OL	0.2	OL	0.6	0.2	1.2	0.6	2.2	1.7	3.0	3.0	10	24
	A150,000	0.95	0.02	OL	0.03	OL	0.05	OL	0.1	OL	0.2	0.1	0.3	0.2	0.5	0.4	1.0	1.0	15	23
	B150,000	1.17	0.02	OL	0.04	OL	0.05	OL	0.1	OL	0.1	0.08	0.2	0.1	0.4	0.3	0.7	0.7	12	10
900	95,000	0.42	8.0	OL	40.0	OL	112.0	1.7	169.0	127.0	230.0	208.0	273.0	256.0	369.0	360.0	388.5	388.5	12	15
	105,000	0.44	0.9	OL	1.4	OL	6.0	0.4	93.0	28.0	122.0	114.0	134.0	129.0	148.5	146.0	163.0	163.0	14	17
	110,000	0.60	0.4	OL	0.6	OL	0.9	OL	35.0	0.5	66.0	55.0	73.0	69.0	78.0	78.5	83.0	83.0	15	18
	115,000	0.64	0.1	OL	0.2	OL	0.3	OL	0.9	0.2	3.8	1.7	6.2	4.9	8.3	7.8	20.5	20.5	11	20
	120,000	0.70	0.08	OL	0.1	OL	0.1	OL	0.4	0.1	1.4	0.6	2.4	1.7	3.4	3.1	4.0	4.0	15	19

C = Creep
TD = Total Deformation
OL = On Loading

TABLE 10

TENSILE CREEP-RUPTURE CHARACTERISTICS OF PH15-7 Mo STAINLESS STEEL BAR IN TH 1050 CONDITION

Temp. °F	Stress PSI	% Elong. on Loading	Time in Hours for Deformation of 0.2% C	0.2% TD	0.3% C	0.3% TD	0.5% C	0.5% TD	1.0% C	1.0% TD	2.0% C	2.0% TD	3.0% C	3.0% TD	5.0% C	5.0% TD	Fracture Hours	Time of Test Hours	% Elong. in 2 In.	Specimen 4C3-
800	125,000	0.503	3.5	OL	5.0	OL	7.0	OL	15.0	7.0	Test Discontd. 1500 Hours T.D. 1.85%									9
	130,000	0.551	0.3	OL	0.4	OL	0.9	OL	2.0	0.8	5.7	3.0	11.8	7.9	54.0	33.0	898.5	898.5	11.5	8
	131,000	0.558	0.1	OL	0.2	OL	0.3	OL	1.0	0.2	3.6	2.0	7.8	5.2	19.8	16.0	39.0	39.0	13.0	12
	133,000	0.641	0.05	OL	0.08	OL	0.1	OL	0.2	0.1	0.6	0.3	1.1	0.7	1.9	1.7	2.7	2.7	12.0	11
	135,000	0.593	0.1	OL	0.2	OL	0.3	OL	0.7	0.2	2.0	1.2	3.8	2.8	7.3	6.3	12.0	12.0	15.0	7
	145,000	0.784	0.05	OL	0.06	OL	0.09	OL	0.1	0.05	0.2	0.2	0.4	0.3	0.7	0.6	1.0	1.0	13.0	4
900	95,000	0.401	1.0	OL	1.2	OL	1.9	0.6	87.0	3.0	172.0	140.0	245.0	219.0	332.0	319.0	430.0	430.0	20.0	3
	100,000	0.435	0.7	OL	1.0	OL	1.5	0.3	4.0	1.9	52.0	20.0	92.0	77.0	131.0	125.0	164.0	164.0	17.0	1
	105,000	0.48	0.1	OL	0.1	OL	0.3	0.03	0.8	0.3	2.3	1.5	4.1	3.2	6.0	7.0	13.0	13.0	21.0	6
	115,000	0.62	0.03	OL	0.05	OL	0.07	OL	0.1	0.05	0.3	0.2	0.4	0.3	0.6	0.6	1.0	1.0	20.0	5
	108,000	0.49	0.1	OL	0.2	OL	0.3	0.01	0.8	0.3	1.8	1.4	3.3	2.5	10.2	7.5	58.0	58.0	15.5	10

C = Creep
TD = Total Deformation
OL = On Loading

TABLE 11

TENSILE CREEP-RUPTURE CHARACTERISTICS OF HEAT TREATED 6Al-4V TITANIUM ALLOY SHEET

Temp. °F	Stress PSI	% Elong. on Loading	Time in Hours for Deformation of 0.2% C	0.2% TD	0.3% C	0.3% TD	0.5% C	0.5% TD	1.0% C	1.0% TD	2.0% C	2.0% TD	3.0% C	3.0% TD	5.0% C	5.0% TD	Fracture Hours	Time of Test Hours	% Elon. in 2 In.	Specimen 401-
700	95,000	1.02	4.0	OL	12.0	OL	50.0	OL	200.0	OL	745.0	200.0	1360.0	735.0	2850.0	2140.0	Test discontinued 3500 hours. TD 7.07%			14
	110,000	3.20	1.5	OL	2.5	OL	4.0	OL	16.0	OL	58.0	OL	125.0	OL	270.0	48.0	489.0	489.0	15	1
	112,000	4.93	0.2	OL	0.5	OL	0.7	OL	3.0	OL	14.0	OL	33.0	OL	77.0	0.5	144.2	144.2	15	17
	114,000				Ruptured on loading														11.5	19
	120,000				Ruptured on loading														8.	7
800	85,000	1.21	2.0	OL	3.0	OL	7.0	OL	18.0	OL	52.0	12.0	86.0	45.0	150.0	112.0	278.0	278.0	14.	20
	90,000	1.01	1.0	OL	2.5	OL	8.0	OL	30.0	OL	56.0	30.0	77.0	56.0	114.0	95.0	187.0	187.0	11.	5
	95,000	1.86	0.3	OL	0.6	OL	1.2	OL	3.6	OL	11.3	0.3	20.0	4.5	37.6	21.3	75.0	75.0	16.5	8
	100,000	2.44	0.1	OL	0.2	OL	0.4	OL	1.0	OL	3.1	OL	5.9	0.5	12.4	4.6	25.0	25.0	15.	18
900	40,000	0.29	2.8	OL	7.0	0.1	23.0	3.0	88.0	50.0	189.0	165.0	253.0	236.0	339.0	329.0	441.0	441.0	12.5	23
	50,000	0.46	1.5	OL	3.0	OL	6.0	0.2	18.0	7.0	41.0	31.0	62.0	52.5	92.0	86.5	163.0	163.0	21.5	22
	55,000	0.46	1.0	OL	2.0	OL	4.5	0.1	13.0	5.3	31.0	22.5	46.0	39.0	70.0	65.0	170.0	170.0	27.5	21
	65,000	0.60	0.6	OL	1.0	OL	1.7	OL	4.2	1.2	8.8	6.0	13.1	10.7	20.5	18.4	51.5	51.5	30.0	16
	75,000	0.64	0.2	OL	0.4	OL	0.6	OL	1.3	0.5	2.9	1.8	4.5	3.5	7.2	6.5	27.0	27.0	19.5	6

C = Creep
TD = Total Deformation
OL = On Loading

TABLE 12

TENSILE CREEP-RUPTURE CHARACTERISTICS OF VACUUM ANNEALED 6Al-4V TITANIUM ALLOY BAR

Temp. °F	Stress PSI	% Elong. on Loading	Time in Hours for Deformation of														Fracture Hours	Time of Test Hours	% Elong. in 2 In.	Specimen 400-
			0.2%		0.3%		0.5%		1.0%		2.0%		3.0%		5.0%					
			C	TD	C	TD	C	TD	C	TD	C	TD	C	TD	C	TD				
700	80,000	0.64	0.4	OL	0.7	OL	2.2	OL	11.1	1.1	43.9	19.4	104.3	61.8	417.5	282.0	Test discontinued after 914 hours. TD 7.2%			19
	85,000	1.78	0.3	OL	0.6	OL	1.6	OL	3.0	OL	10.5	1.0	25.0	4.0	85.5	31.0	1322.5	1322.5	32.0	20
	90,000	3.39	0.2	OL	0.4	OL	0.5	OL	1.0	OL	3.5	OL	8.4	OL	27.0	2.3	202.5	202.5	29.0	21
	92,000	5.45	0.2	OL	0.3	OL	0.4	OL	0.9	OL	1.9	OL	3.5	OL	7.5	OL	52.0	52.0	26.0	23
	95,000	6.83	0.07	OL	0.1	OL	0.1	OL	0.3	OL	0.7	OL	1.3	OL	2.9	OL	5.5	5.5	20.0	22
800	60,000	0.49	4.7	OL	7.0	OL	15.0	0.5	35.0	15.0	100.0	65.0	173.0	137.0	340.0	296.0	1098.0	1098.0	38.5	1
	70,000	0.58	0.4	OL	0.6	OL	1.0	OL	2.0	0.8	4.7	3.2	8.2	6.2	18.3	15.1	147.0	147.0	38.0	4
	75,000	0.61	0.1	OL	0.1	OL	0.25	OL	0.5	0.1	1.5	0.8	2.6	2.0	6.2	5.0	72.0	72.0	34.0	5
	80,000	1.21	0.02	OL	0.05	OL	0.09	OL	0.2	OL	0.5	0.1	1.0	0.4	-	1.6	10.0	10.0	≥14.0	3
900	45,000	0.36	0.8	OL	1.6	OL	2.5	0.7	7.0	4.0	16.0	13.0	26.0	22.5	44.8	42.0	134.5	134.5	57.0	9
	50,000	0.41	0.4	OL	0.6	OL	1.3	0.2	2.5	1.7	6.8	6.0	11.0	10.2	19.9	19.1	65.5	65.5	52.0	8
	60,000	0.55	0.15	OL	0.2	OL	0.4	OL	0.8	0.3	1.9	1.3	3.1	2.4	5.5	4.8	22.5	22.5	41.0	7
	70,000	0.72	0.05	OL	0.06	OL	0.08	OL	0.1	0.02	0.2	0.1	0.3	0.2	0.6	0.5	3.2	3.2	38.0	6

C = Creep
TD = Total Deformation
OL = On Loading

TABLE 13

BEARING CREEP-RUPTURE CHARACTERISTICS OF PH15-7 Mo STAINLESS STEEL SHEET IN TH 1050 CONDITION
BEARING HOLE DIAMETER 3/16 INCH AND EDGE DISTANCE 1.5D

Temp. °F	Bearing Stress PSI	% Bearing Hole Deformation on Loading	Time in Hours for Bearing Hole Deformation Expressed as Percent of the Diameter														Fracture Hours	Time of Test Hours	Specimen 399-A
			0.5%		1.0%		2.0%		3.0%		5.0%		10.0%		20.0%				
			C	TD	C	TD	C	TD	C	TD	C	TD	C	TD	C	TD			
700	240,000	4.23	0.50	OL	0.95	OL	2.0	OL	5.0	OL	24.0	0.2	125.0	34.0	317.0	260.0	331.5	331.5	13
	245,000	4.68	0.35	OL	0.50	OL	1.2	OL	3.0	OL	11.0	0.1	51.0	13.0	114.0	90.0	120.0	120.0	14
	250,000	5.83	0.14	OL	0.25	OL	0.3	OL	0.5	OL	1.9	OL	15.5	1.0	48.5	33.0	55.0	55.0	15
	257,000	6.50	0.03	OL	0.05	OL	0.2	OL	0.4	OL	1.4	OL	4.3	0.6	-	5.8	8.5	8.5	16
800	200,000	2.70	1.6	OL	1.90	OL	2.1	OL	3.1	1.0	10.0	2.2	588.0	50.0	-	-	725.0	725.0	4
	205,000	2.48	0.2	OL	0.45	OL	0.9	OL	1.8	0.1	6.9	1.4	50.0	18.7	95.9	90.4	104.5	104.5	12
	210,000	3.04	0.08	OL	0.15	OL	0.3	OL	0.6	OL	1.9	0.3	5.2	3.8	-	-	11.5	11.5	3
	225,000	3.78	0.05	OL	0.08	OL	0.1	OL	0.2	OL	0.5	0.08	1.6	0.8	2.3	2.2	2.5	2.5	2
900	145,000	2.48	0.3	OL	1.50	OL	14.2	OL	62.0	1.5	105.0	45.0	147.0*	131.0*	178.0*	171.0*	210.0	210.0	9
	165,000	2.67	0.2	OL	0.45	OL	0.9	OL	1.9	0.1	8.8	1.0	19.7	15.0	28.0*	26.3*	34.0	34.0	7
	180,000	3.05	0.1	OL	0.15	OL	0.3	OL	0.4	OL	1.4	0.2	4.7	3.0	9.5*	8.0*	10.5	10.5	6
	190,000	3.59	0.05	OL	0.10	OL	0.2	OL	0.3	OL	0.5	0.1	1.1	0.7	1.8	1.7	2.0	2.0	5

C = Creep
TD = Total Deformation
OL = On Loading
* = Extrapolated

TABLE 14

RATIO OF BEARING CREEP STRESS TO TENSILE RUPTURE STRESS
FOR PH15-7 Mo STAINLESS STEEL SHEET IN TH 1050 CONDITION
BEARING HOLE DIAMETER 3/16 INCH AND EDGE DISTANCE OF 1.5D

Temp. °F	Time in Hours	Bearing Creep-Tensile Rupture Stress Ratios for Bearing Hole Creep Deformation of					
		0.5%	1.0%	2.0%	5.0%	10.0%	Rupture
700	1	1.37	1.42	1.43	1.51	1.55	1.57
	10	-	1.37*	1.41*	1.51	1.54	1.58
	50	-	-	-	1.48*	1.56	1.59
	100	-	-	-	1.47*	1.54	1.58
	200	-	-	-	-	1.50	1.56
	500	-	-	-	-	1.47*	1.55
800	1	1.22	1.29	1.35	1.44	1.46	1.49
	10	-	-	1.26*	1.37	1.42	1.46
	50	-	-	-	1.33*	1.41	1.47
	100	-	-	-	1.31*	1.39	1.45
	200	-	-	-	-	1.36	1.44
	500	-	-	-	-	1.34	1.42
900	1	0.82*	1.23*	1.37*	1.48*	1.53*	1.56*
	10	-	1.03*	1.23	1.38	1.49	1.54
	50	-	0.91*	1.16*	1.35	1.41	1.45
	100	-	-	1.13*	1.33	1.37	1.41
	200	-	-	-	1.35*	1.37	1.42
	500	-	-	-	-	1.41*	1.46*

*Ratio calculated from extrapolated stress values.

TABLE 15

BEARING CREEP-RUPTURE CHARACTERISTICS OF HEAT TREATED 6Al-4V TITANIUM ALLOY SHEET
BEARING HOLE DIAMETER 3/16-INCH AND EDGE DISTANCE 1.5D

Temp. °F	Bearing Stress PSI	% Bearing Hole Deformation on Loading	Time in Hours for Deformation of 0.5% C	0.5% TD	1.0% C	1.0% TD	2.0% C	2.0% TD	3.0% C	3.0% TD	5.0% C	5.0% TD	10.0% C	10.0% TD	20.0% C	20.0% TD	Fracture Hours	Time of Test Hours	Specimen 401-
700	175,000	6.10	4.0	OL	15.0	OL	45.0	OL	100.0	OL	200.0	OL	462.0	145.0	711.5	590.0	850.5	850.5	13
	180,000	12.50	0.60	OL	1.0	OL	6.0	OL	14.0	OL	36.0	OL	92.0	OL	141.5	67.0	145.0	145.0	19
	182,000	14.22	0.40	OL	0.7	OL	2.0	OL	3.4	OL	7.2	OL	20.2	OL	27.9	9.6	28.0	28.0	10
	185,000	13.72	0.38	OL	0.9	OL	2.0	OL	3.2	OL	6.8	OL	14.9	OL	-	9.2	19.0	19.0	16
800	137,000	5.20	0.70	OL	1.5	OL	5.5	OL	14.5	OL	42.0	OL	125.5	38.5	233.5	192.0	286.0	286.0	27
	145,000	3.49	0.55	OL	1.0	OL	4.5	OL	9.7	OL	23.5	2.0	62.4	35.0	146.0	121.5	203.0	203.0	1
	150,000	5.30	0.45	OL	1.0	OL	4.5	OL	10.0	OL	26.5	OL	69.4	24.0	128.5	102.0	167.7	167.6	35
	157,000	6.15	0.30	OL	0.9	OL	2.5	OL	5.0	OL	10.5	OL	27.6	7.4	-	-	55.0	55.0	33
900	95,000	2.47	0.4	OL	1.0	OL	3.0	OL	5.0	0.5	14.0	3.5	37.0	26.0	74.0	66.5	113.0	113.0	22
	100,000	2.62	0.26	OL	0.6	OL	1.7	OL	3.8	0.35	8.6	2.5	21.0	14.3	41.1	36.7	62.0	62.0	18
	110,000	3.27	0.15	OL	0.3	OL	0.8	OL	1.3	OL	2.6	0.6	-	4.5	-	-	21.0	21.0	14
	120,000	3.47	0.09	OL	0.2	OL	0.5	OL	0.8	OL	1.7	0.3	4.0	2.4	7.4	6.4	10.0	10.0	15

C = Creep
TD = Total Deformation
OL = On Loading

TABLE 16

RATIO OF BEARING CREEP STRESS TO TENSILE RUPTURE STRESS
FOR HEAT TREATED 6Al-4V TITANIUM ALLOY SHEET
BEARING HOLE DIAMETER 3/16 INCH AND EDGE DISTANCE OF 1.5D

Temp. °F	Time in Hours	Bearing Creep-Tensile Rupture Stress Ratios for Bearing Hole Creep Deformation of					
		0.5%	1.0%	2.0%	5.0%	10.0%	Rupture
700	1	1.57	1.63	1.65*	1.67*	-	-
	10	1.48	1.51	1.57	1.62	1.64	1.68
	50	-	-	1.53	1.58	1.60	1.61
	100	-	-	1.51	1.56	1.57	1.60
	200	-	-	-	1.57	1.57	1.59
	500	-	-	-	1.55	1.56	1.60
800	1	1.18*	1.36*	1.55*	-	-	-
	10	-	-	1.13	1.53	1.58	1.63
	50	-	-	-	1.36	1.55	1.63
	100	-	-	-	1.28*	1.47	1.57
	200	-	-	-	-	1.43*	1.63
	500	-	-	-	-	-	1.62
900	1	-	-	-	-	-	-
	10	-	0.84*	0.98*	1.21*	1.34*	1.48*
	50	-	-	-	1.23	1.39	1.55
	100	-	-	-	-	1.49*	1.66
	200	-	-	-	-	-	-
	500	-	-	-	-	-	-

*Ratio calculated from extrapolated stress values.

TABLE 17

SHEAR CREEP-RUPTURE CHARACTERISTICS OF
PH15-7 Mo STAINLESS STEEL BAR IN TH 1050 CONDITION

Temp. °F	Shear Stress PSI	Inch Deformation on Loading	Time in Hours for Shear Pin Deformation of: 0.001 Inch C	0.001 Inch TD	0.005 Inch C	0.005 Inch TD	0.01 Inch C	0.01 Inch TD	0.02 Inch C	0.02 Inch TD	0.03 Inch C	0.03 Inch TD	0.04 Inch C	0.04 Inch TD	0.05 Inch C	0.05 Inch TD	Fracture Hours	Time of Test Hours	Specimen
800	77,000	0.012	0.5	OL	1.0	OL	6.0	OL	95.0	3.7	-	56.0	-	-		-	391.0	391.0	403-3
	80,000	0.012	0.3	OL	0.5	OL	6.5	OL	45.0	2.0	135.0	25.0	-	100.0	-	-	138.0	138.0	403-1
	83,000	0.014	0.2	OL	1.0	OL	8.0	OL	44.0	2.0	-	28.5	-	67.4	-	-	71.2	71.2	403-6
	85,000	0.016	0.1	OL	0.3	OL	1.4	OL	12.6	0.2	-	4.0	-	20.0	-	-	26.2	26.2	403-2
900	60,000	0.0084	0.1	OL	2.7	OL	114.0	0.2	332.0	160.0	425.5	354.0	-	430.0	-	-	434.5	434.5	403-8
	62,000	0.0095	0.09	OL	0.8	OL	5.3	0.1	90.0	6.7	192.5	70.0	-	193.5	-	-	-	-	403-9
	65,000	0.0096	0.06	OL	0.3	OL	1.9	0.07	17.3	2.2	43.5	18.4	58.0	44.2	-	58.5	69.0	69.0	403-7

C = Creep
TD = Total Deformation
OL = On Loading

TABLE 18

RATIO OF SHEAR CREEP STRESS TO TENSILE RUPTURE STRESS FOR PH15-7 Mo STAINLESS STEEL BAR IN TH 1050 CONDITION

Temp. °F	Time in Hours	Shear Creep-Tensile Rupture Stress Ratio for Shear Creep Deformation of					
		0.001 Inch	0.005 Inch	0.01 Inch	0.02 Inch	0.03 Inch	Rupture
800	1	0.51	0.54	0.61	-	-	-
	10	-	-	0.57	0.62	-	0.64
	50	-	-	-	0.62	-	0.64
	100	-	-	-	0.59	-	0.63
	200	-	-	-	0.58	-	0.61
	500	-	-	-	-	-	0.60
900	1	-	0.54	0.57*	-	-	-
	10	-	0.52*	0.57	0.61*	0.62*	0.63*
	50	-	-	0.56	0.59	0.61	0.62
	100	-	-	0.58	0.61	0.62	0.64
	200	-	-	0.59*	0.62	0.63	0.64
	500	-	-	-	0.63	0.64	0.66

*Ratio calculated from extrapolated stress values.

TABLE 19

SHEAR CREEP-RUPTURE CHARACTERISTICS OF VACUUM ANNEALED 6Al-4V TITANIUM ALLOY BAR

Temp. °F	Shear Stress PSI	Inch Deformation on Loading	Time in Hours for Shear Pin Deformation of														Fracture Hours	Time of Test Hours	Specimen
			0.001 Inch		0.005 Inch		0.01 Inch		0.02 Inch		0.03 Inch		0.04 Inch		0.05 Inch				
			C	TD	C	TD	C	TD	C	TD	C	TD	C	TD	C	TD			
700	65,000	0.0185	1.4	OL	32.0	OL	243.0	OL	-	2.0	-	323.0	-	-	-	-	366.0	366.0	402-13
	66,500	0.0181	1.5	OL	40.0	OL	163.0	OL	-	4.5	-	233.0	-	-	-	-	335.0	335.0	402-15
	67,000	0.0229	1.0	OL	12.2	OL	75.0	OL	342.0	OL	-	31.0	-	264.0			374.0	374.0	402-17
	68,000	0.022	1.1	OL	13.0	OL	-	OL	-	OL	-	-	-	-	-	-	16.2	16.2	402-14
	70,000	0.0222	0.4	OL	6.5	OL	-	OL	-	OL	-	-	-	-	-	-	7.0	7.0	402-12
800	55,000	0.0131	0.20	OL	12.0	OL	60.0	OL	171.0	26.0	-	155.0	-	-	-	-	183.5	183.5	402-6
	60,000	0.0165	0.08	OL	2.0	OL	12.3	OL	58.2	1.5	-	28.0	-	69.2	-	-	79.2	79.2	402-7
	61,000	0.0159	0.05	OL	1.5	OL	7.0	OL	18.2	2.0	-	13.0	-	-			19.0	19.0	402-11
	62,000	0.0192	0.04	OL	0.6	OL	3.0	OL	-	0.04	-	3.4	-	-	-	-	6.0	6.0	402-10
	65,000	0.0197	0.02	OL	0.07	OL	2.2	OL	-	0.02	-	2.2	-	-	-	-	3.0	3.0	402-9
	75,000	Ruptured on Loading																	402-8
900	27,500	0.004	2.10	OL	36.0	2.10	120.0	51.0	375.0	300.0	422.0	406.5	447.0	440.0	-	-	455.0	455.0	402-1
	35,000	0.005	0.40	OL	6.0	OL	20.0	5.7	57.0	39.0	86.4	74.0	102.3	95.0	-	107.8	109.5	109.5	402-2
	40,000	0.007	0.20	OL	2.0	OL	8.5	1.0	26.8	13.6	42.0	32.4	50.4	45.4	-	51.8	53.0	53.0	402-3
	47,500	0.011	0.09	OL	0.5	OL	2.2	OL	6.9	1.8	9.7	6.6	-	9.6	-	-	10.5	10.5	402-4

C = Creep
TD = Total Deformation
OL = On Loading

TABLE 20

RATIO OF SHEAR CREEP STRESS TO TENSILE RUPTURE STRESS
FOR VACUUM ANNEALED 6Al-4V TITANIUM ALLOY BAR

Temp. °F	Time in Hours	Shear Creep-Tensile Rupture Stress Ratios for Shear Creep Deformation of 0.001 Inch	0.005 Inch	0.01 Inch	0.02 Inch	0.03 Inch	Rupture
700	1	0.70*	-	-	-	-	-
	10	-	0.73	-	-	-	0.74
	50	-	0.71	-	-	-	0.74
	100	-	0.70*	-	-	-	0.73
	200	-	-	-	-	-	0.74
	500	-	-	-	-	-	0.75*
800	1	0.58*	0.70*	0.75*	-	-	0.77*
	10	-	0.70	0.74	0.77	-	0.79
	50	-	0.70*	0.76	0.79	-	0.80
	100	-	-	0.75	0.78	-	0.80
	200	-	-	0.75*	-	-	0.78
	500	-	-	-	-	-	0.79
900	1	0.40*	0.58*	0.68*	-	-	
	10	0.32*	0.51	0.62	0.71	0.73	0.75
	50	-	0.50	0.60	0.70	0.74	0.77
	100	-	0.52*	0.58	0.71	0.74	0.77
	200	-	-	0.58	0.72	0.73	0.76
	500	-	-	0.57*	0.72	0.74	0.75

*Ratio calculated from extrapolated stress values.

TABLE 21

COMPRESSION CREEP CHARACTERISTICS OF PH15-7 Mo STAINLESS STEEL SHEET IN TH 1050 CONDITION

Temp. °F	Stress PSI	% Deformation on Loading	Time in Hours for Deformation of 0.1% C	0.1% TD	0.2% C	0.2% TD	0.5% C	0.5% TD	1.0% C	1.0% TD	2.0% C	2.0% TD	Time of Test Hours	Deformation in 1-1/2 Inches	Specimen 399A-C
800	140,000	0.506	0.4	OL	1.5	OL	-	OL	-	-	-	-	80.0	0.99	9
	142,000	0.616	0.2	OL	0.8	OL	7.5	OL	-	3.5	-	-	120.0	1.40	12
	147,000	0.935	0.1	OL	0.2	OL	0.6	OL	1.6	0.04	-	1.8	35.0	2.37	11
900	95,000	0.352	1.5	OL	12.0	OL	-	32.0	-	-	-	-	48.0	0.63	6
	105,000	0.473	0.8	OL	1.3	OL	62.0	1.0	195.0	80.0	-	-	213.0	1.65	4
	110,000	0.522	0.4	OL	0.7	OL	2.4	OL	131.0	2.4	-	-	183.0	1.83	1
	115,000	0.572	0.3	OL	0.4	OL	1.7	OL	38.0	1.2	-	147.0	164.0	2.12	7
	115,000	0.516	0.1	OL	0.2	OL	0.9	OL	-	0.9	-	-	8.0	1.32	2
	115,000	0.616	0.04	OL	0.2	OL	1.3	OL	-	1.2	-	-	17.0	1.36	3

C = Creep
TD = Total Deformation
OL = On Loading

TABLE 22

RATIO OF COMPRESSION CREEP STRESS TO TENSION CREEP STRESS FOR PH15-7 Mo STAINLESS STEEL SHEET IN TH 1050 CONDITION

Temp. °F	Time in Hours	Compression Creep-Tension Creep Stress Ratios for Compression Creep Deformation of		
		0.2%	0.5%	1.0%
800	1	1.02	1.05	1.05
	10	-	1.05	1.05
	50	-	-	-
	100	-	-	-
	200	-	-	-
900	1	1.04	1.11	-
	10	1.03	1.10	1.09
	50	-	-	1.06
	100	-	-	1.07
	200	-	-	1.13

TABLE 23

SUMMARY OF JOINT CREEP-RUPTURE CHARACTERISTICS OF
PH15-7 Mo STAINLESS STEEL SHEET FASTENED WITH PH15-7 Mo STAINLESS STEEL RIVETS

Temp. °F	Bearing Stress PSI	Shear Stress PSI	Inch Deformation on Loading	Time in Hours for Deformation of 0.001 Inch C	0.001 Inch TD	0.005 Inch C	0.005 Inch TD	0.01 Inch C	0.01 Inch TD	0.02 Inch C	0.02 Inch TD	0.03 Inch C	0.03 Inch TD	0.04 Inch C	0.04 Inch TD	0.05 Inch C	0.05 Inch TD	Fracture Hours	Time of Test Hours	Specimen 399A-J
800	161,000	80,000	0.142	-	OL	1.0	OL	2.0	OL	21.0	1.5		18.0							17
900	123,500	60,000	0.010	0.2	OL	1.0	OL	8.5	OL	168.0	8.0	312.0	168.0	375.0	312.0	-	375.0	376.5	376.5	11
	128,000	62,000	0.011	0.1	OL	0.4	OL	1.7	OL	15.0	1.1	70.0	9.0	140.0	61.0	157.5	135.0	158.0	158.0	15
	133,000	64,000	0.010	0.09	OL	0.5	OL	1.4	OL	7.5	1.2	20.0	6.5	35.0	18.6	42.2	34.0	42.5	42.5	13
	138,000	66,000	0.013	0.05	OL	0.3	OL	0.8	OL	1.9	0.4	3.0	1.5	4.3	2.6	5.1	3.9	5.5	5.5	1

C = Creep
TD = Total Deformation
OL = On Loading

TABLE 24

SUMMARY OF JOINT CREEP-RUPTURE CHARACTERISTICS OF
6Al-4V TITANIUM ALLOY SHEET FASTENED WITH 6Al-4V TITANIUM ALLOY RIVETS

Temp. °F	Bearing Stress PSI	Shear Stress PSI	Inch Deformation on Loading	Time in Hours for Deformation of: 0.001 Inch C	0.001 Inch TD	0.005 Inch C	0.005 Inch TD	0.01 Inch C	0.01 Inch TD	0.02 Inch C	0.02 Inch TD	0.03 Inch C	0.03 Inch TD	0.04 Inch C	0.04 Inch TD	0.05 Inch C	0.05 Inch TD	Fracture Hours	Time of Test Hours	Specimen 401-J
900	41,500	26,000	0.0027	0.6	OL	2.0	0.6	10.0	6.0	39.0	30.0	70.0	61.0	102.0	93.0	132.0	124.0	Test in Progress		36
	47,500	30,000	0.0028	0.4	OL	3.0	0.7	13.0	6.5	40.0	32.0	69.0	61.0	95.0	88.0	117.0	112.0	161.0	161.0	11
	55,400	35,000	0.0051	0.2	OL	1.0	OL	3.7	1.0	11.5	7.1	22.5	16.8	32.0	27.4	39.0	35.7	56.5	56.5	8
	64,500	40,000	0.0084	0.04	OL	0.5	OL	1.4	0.5	4.8	2.0	9.4	5.6	14.2	10.0	19.0	15.0	25.2	25.2	2

C = Creep
TD = Total Deformation
OL = On Loading

TABLE 25

SUMMARY OF JOINT CREEP-RUPTURE CHARACTERISTICS OF
C-110M TITANIUM ALLOY SHEET FASTENED WITH A-110AT TITANIUM ALLOY RIVETS

Temp. °F	Bearing Stress PSI	Shear Stress PSI	Inch Deformation on Loading	Time in Hours for Deformation of: 0.001 Inch C	0.001 Inch TD	0.005 Inch C	0.005 Inch TD	0.01 Inch C	0.01 Inch TD	0.02 Inch C	0.02 Inch TD	0.03 Inch C	0.03 Inch TD	0.04 Inch C	0.04 Inch TD	0.05 Inch C	0.05 Inch TD	Fracture Hours	Time of Test Hours	Specimen
800	50,000	30,000	0.0047	0.2	OL	1.3	0.3	6.0	1.8	25.0	14.5	51.0	38.5	77.0	64.0	102.0	90.0	267.0	267.0	274-J-5
	54,000	33,600	0.0049	0.5	OL	2.9	0.2	8.5	3.0	19.0	13.5	28.5	24.0	37.4	33.0	45.7	46.0	165.5	165.5	274-J-15
	70,000	44,100	0.0168	0.2	OL	1.6	OL	3.8	OL	8.8	1.0	13.8	5.5	19.8	10.4	25.6	16.0	55.7	55.7	274-J-7
	85,000	54,000	0.0120	0.1	OL	0.7	OL	1.2	OL	2.9	0.9	4.4	2.5	6.0	4.0	7.4	5.6	21.5	21.5	274-J-9

C = Creep
TD = Total Deformation
OL = On Loading

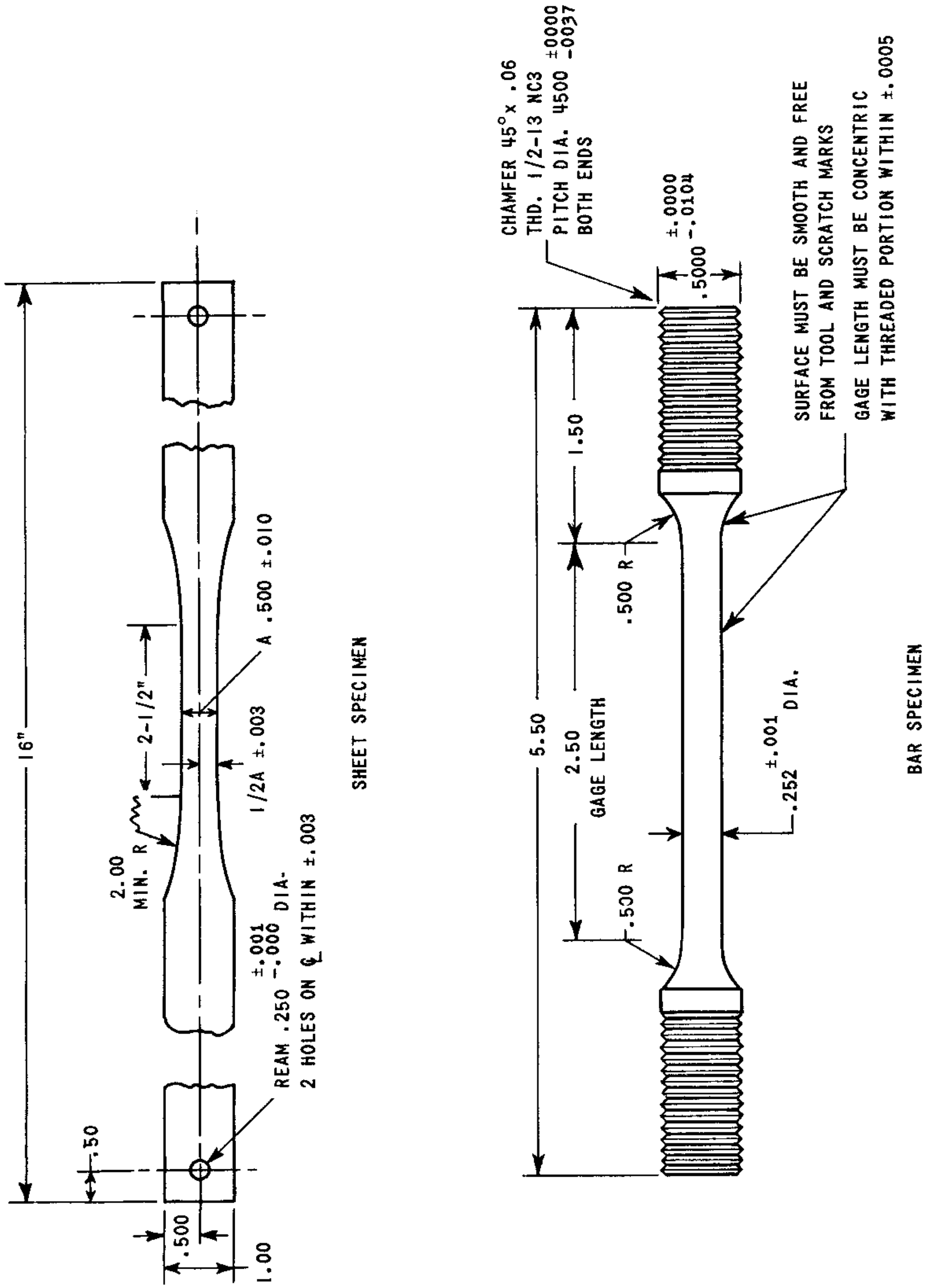


Figure 1 TENSILE TEST SPECIMENS

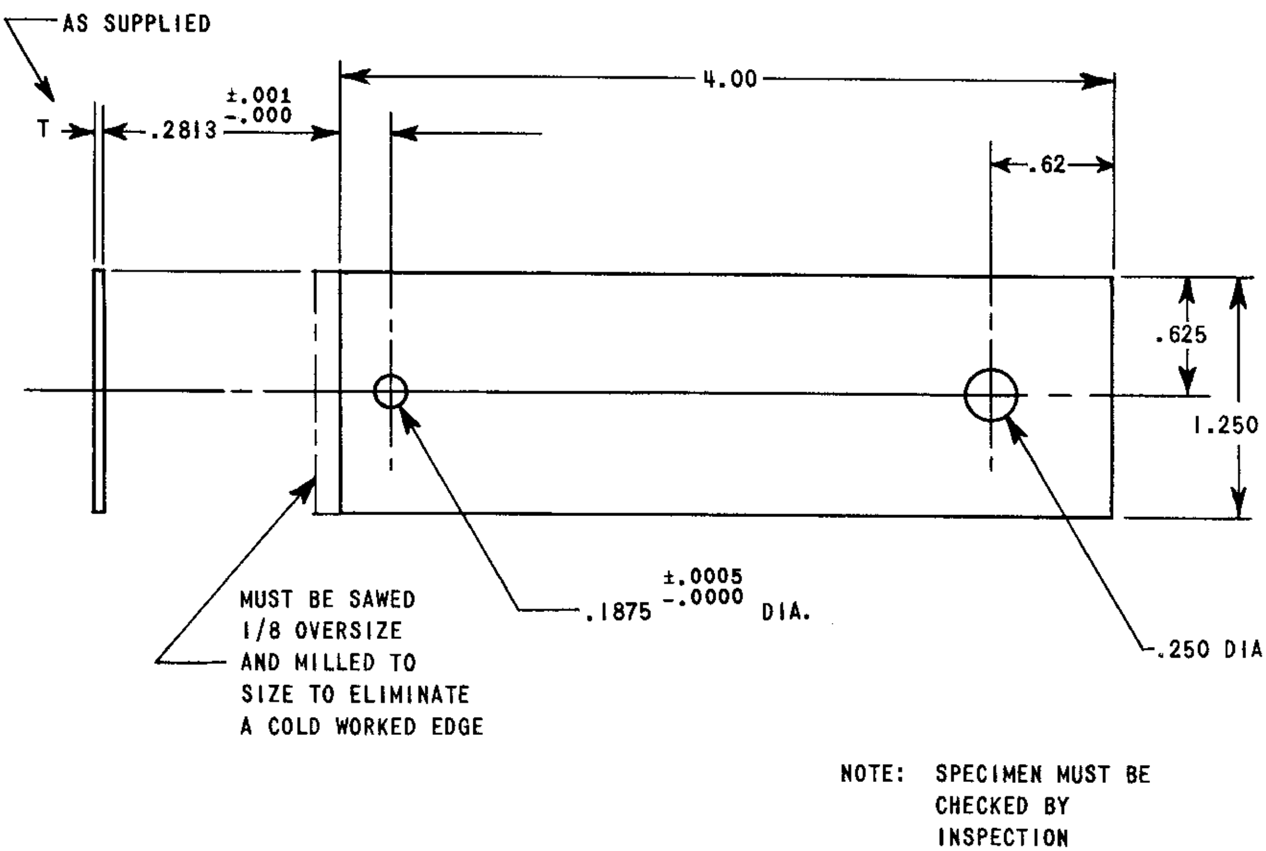


Figure 2 BEARING TEST SPECIMEN

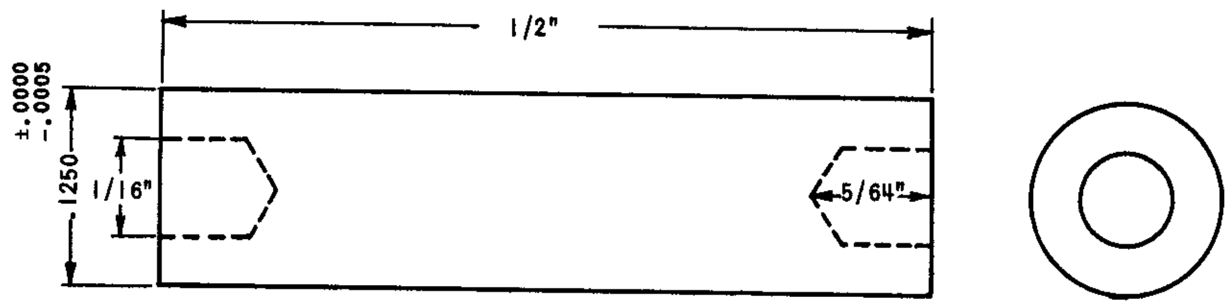
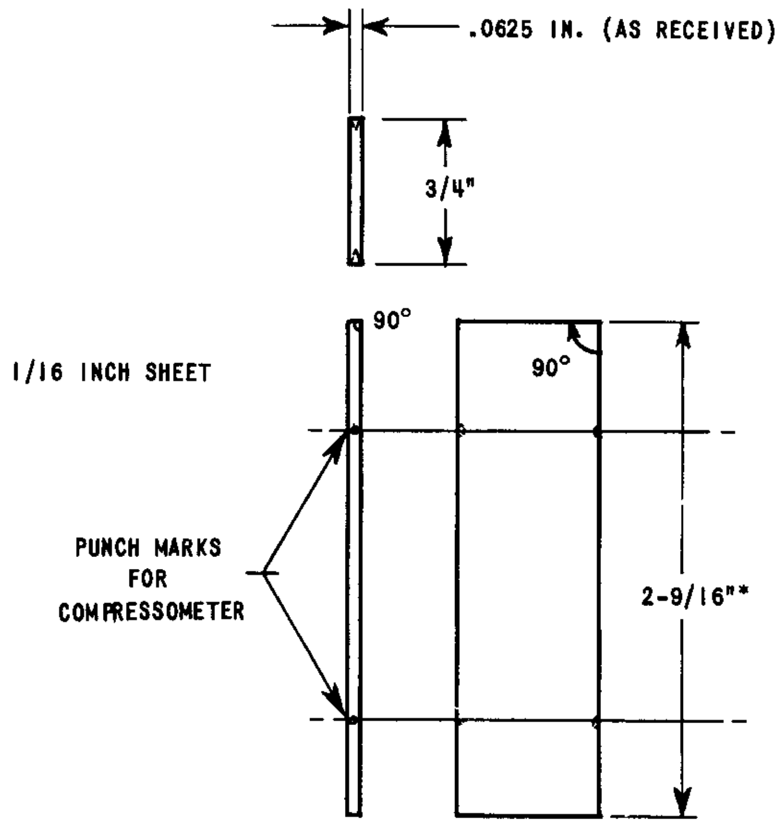


Figure 3 SHEAR TEST SPECIMEN



* INDIVIDUAL SPECIMENS WERE GROUND PARALLEL IN THIS DIMENSION TO 0.00025 IN.

Figure 4 COMPRESSION TEST SPECIMEN

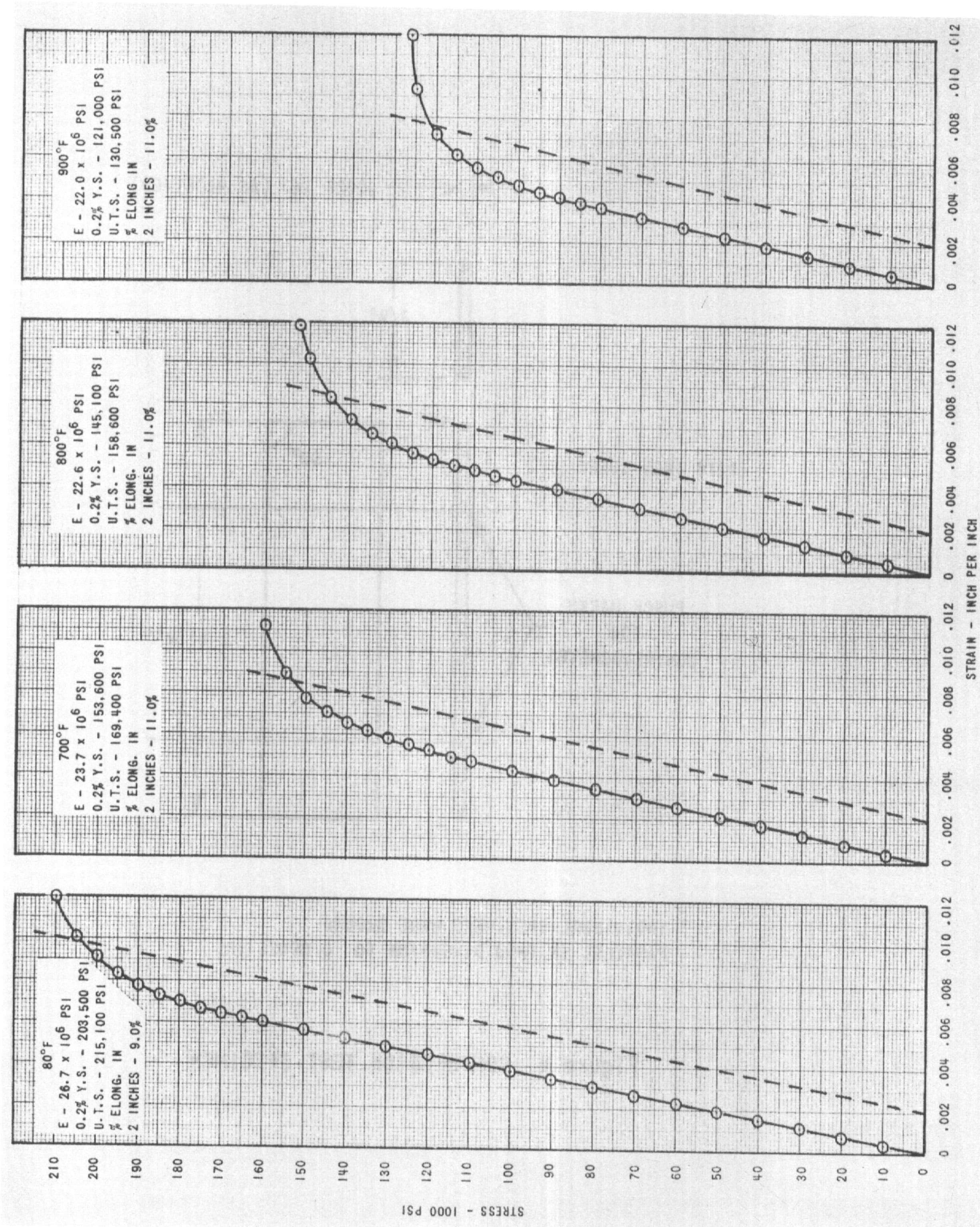


Figure 5 SHORT-TIME TENSILE STRESS-STRAIN CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL SHEET IN TH 1050 CONDITION AT ROOM AND ELEVATED TEMPERATURE

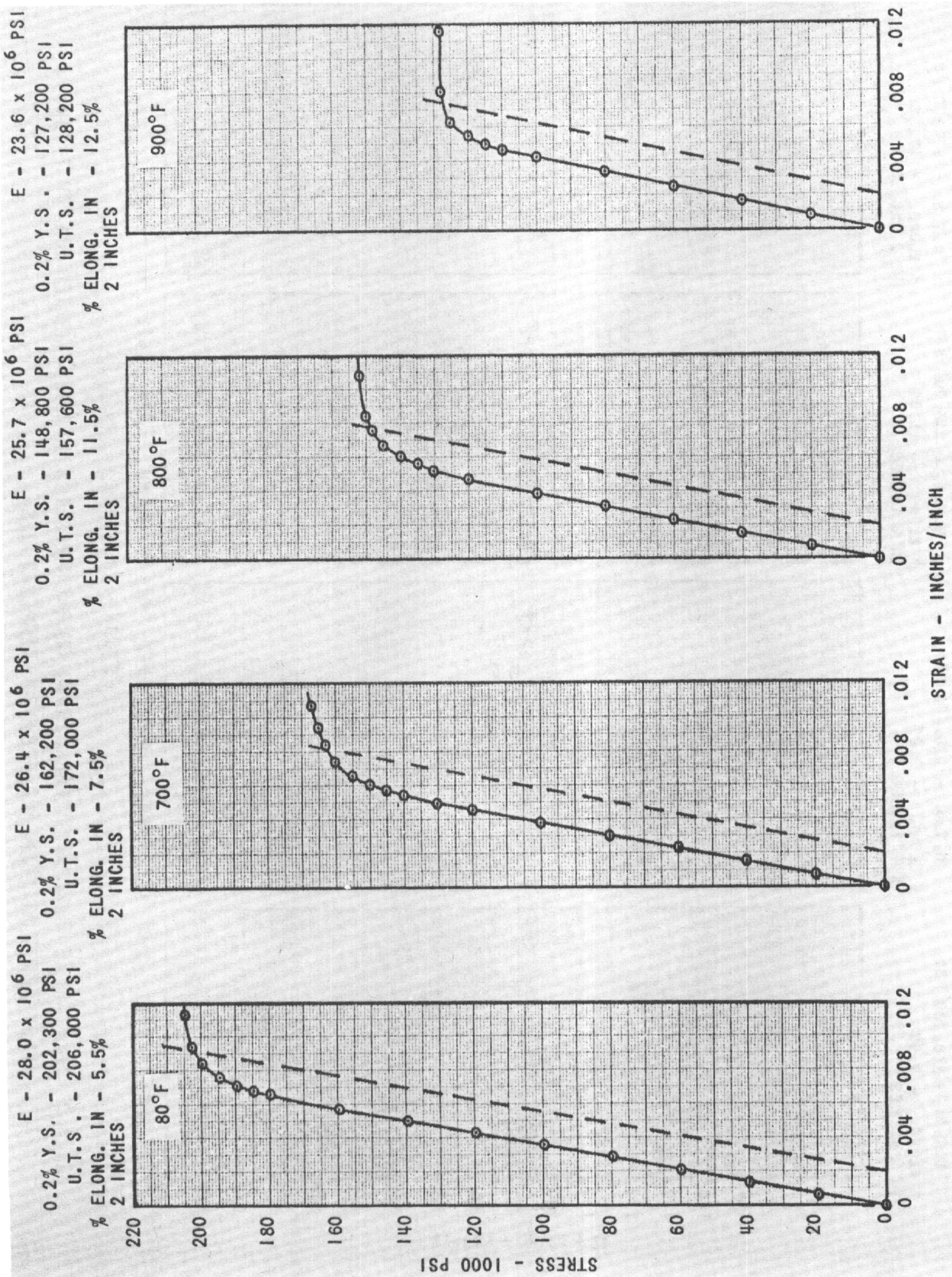


Figure 6 SHORT-TIME TENSILE STRESS-STRAIN CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL BAR IN TH 1050 CONDITION

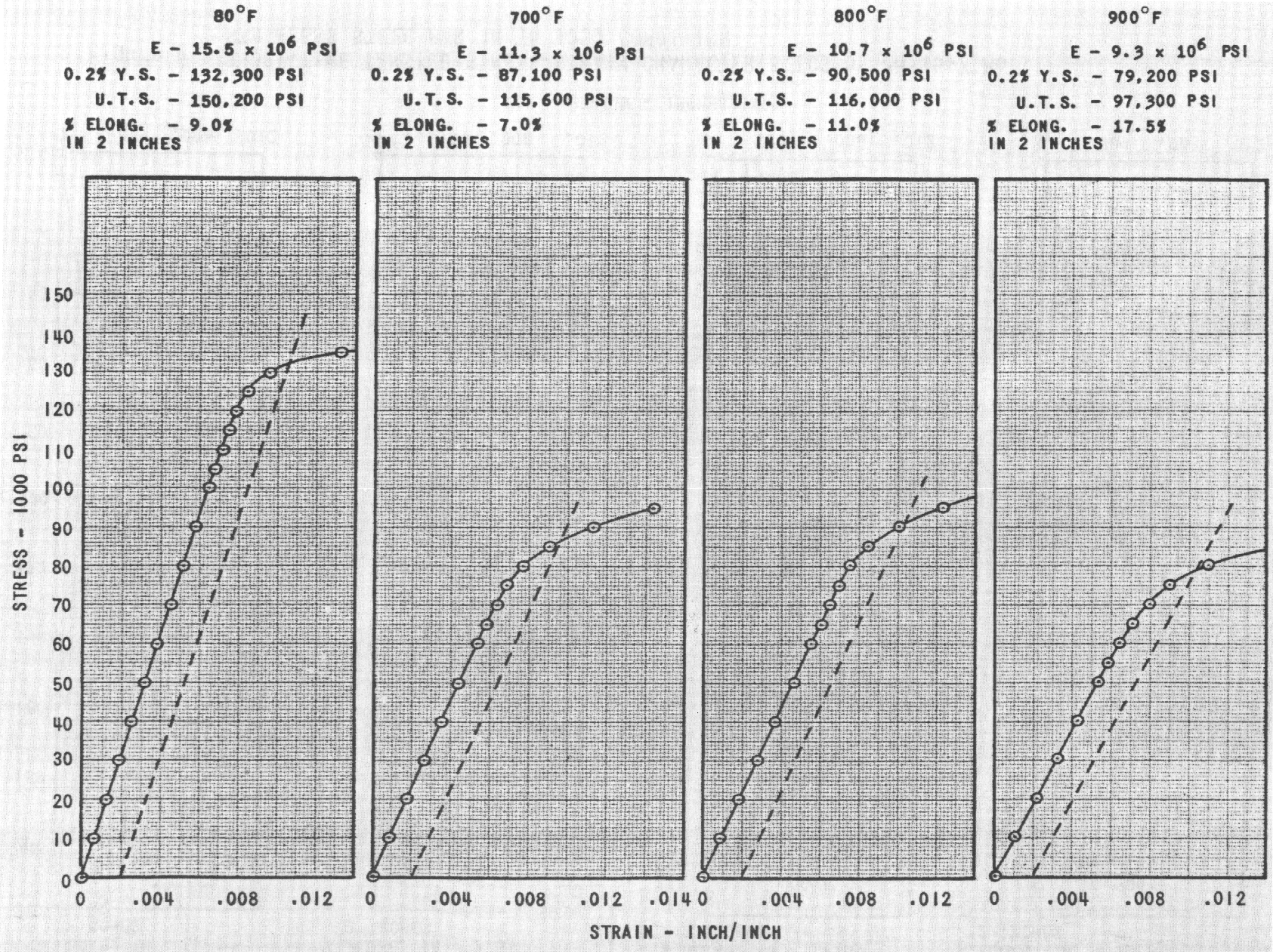


Figure 7 SHORT-TIME TENSILE STRESS-STRAIN CHARACTERISTICS OF HEAT-TREATED 6AL-4V TITANIUM ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURES

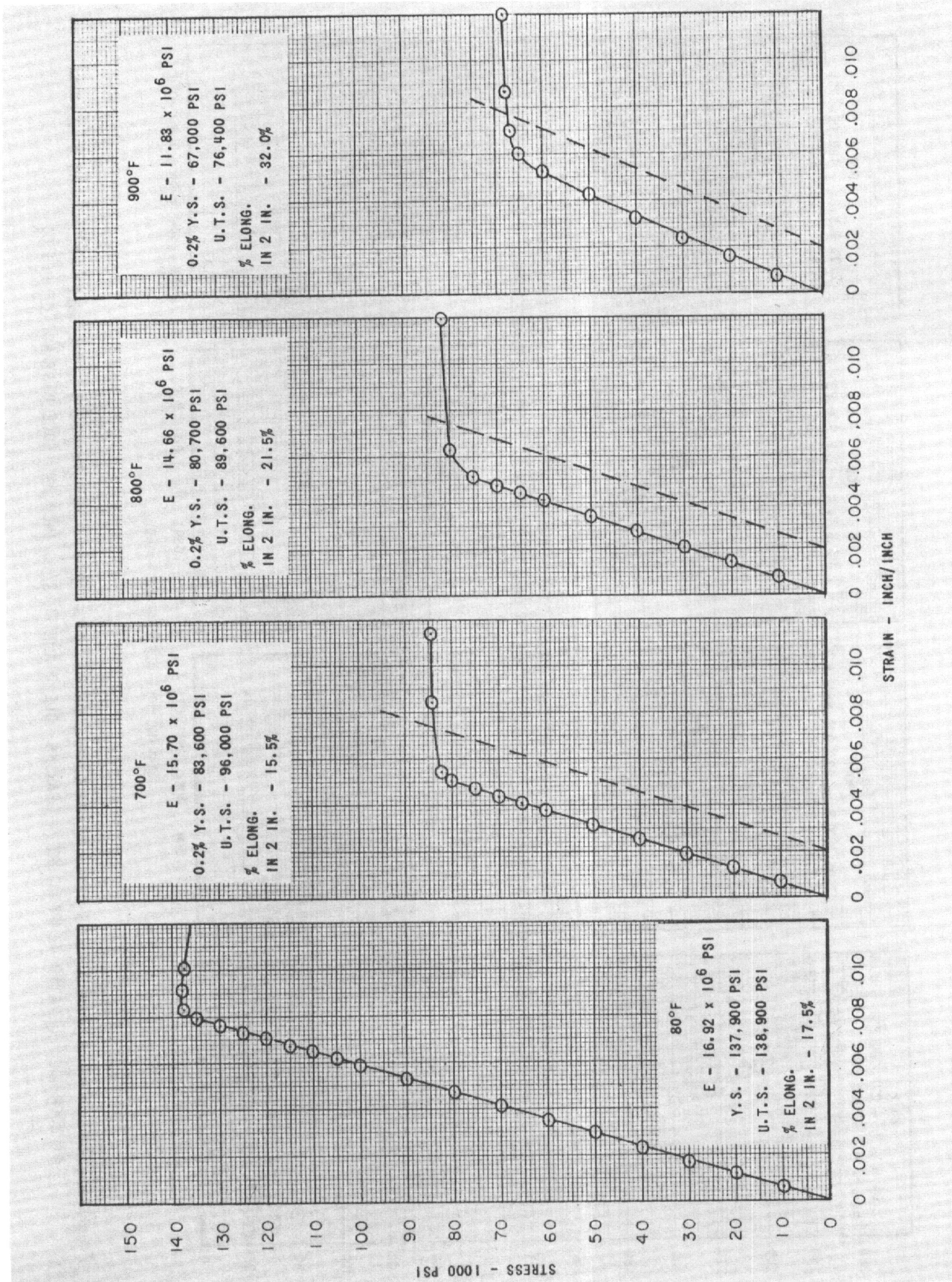


Figure 8 SHORT-TIME TENSILE STRESS-STRAIN CHARACTERISTICS OF VACUUM ANNEALED 6AL-4V TITANIUM ALLOY BAR AT ROOM AND ELEVATED TEMPERATURE

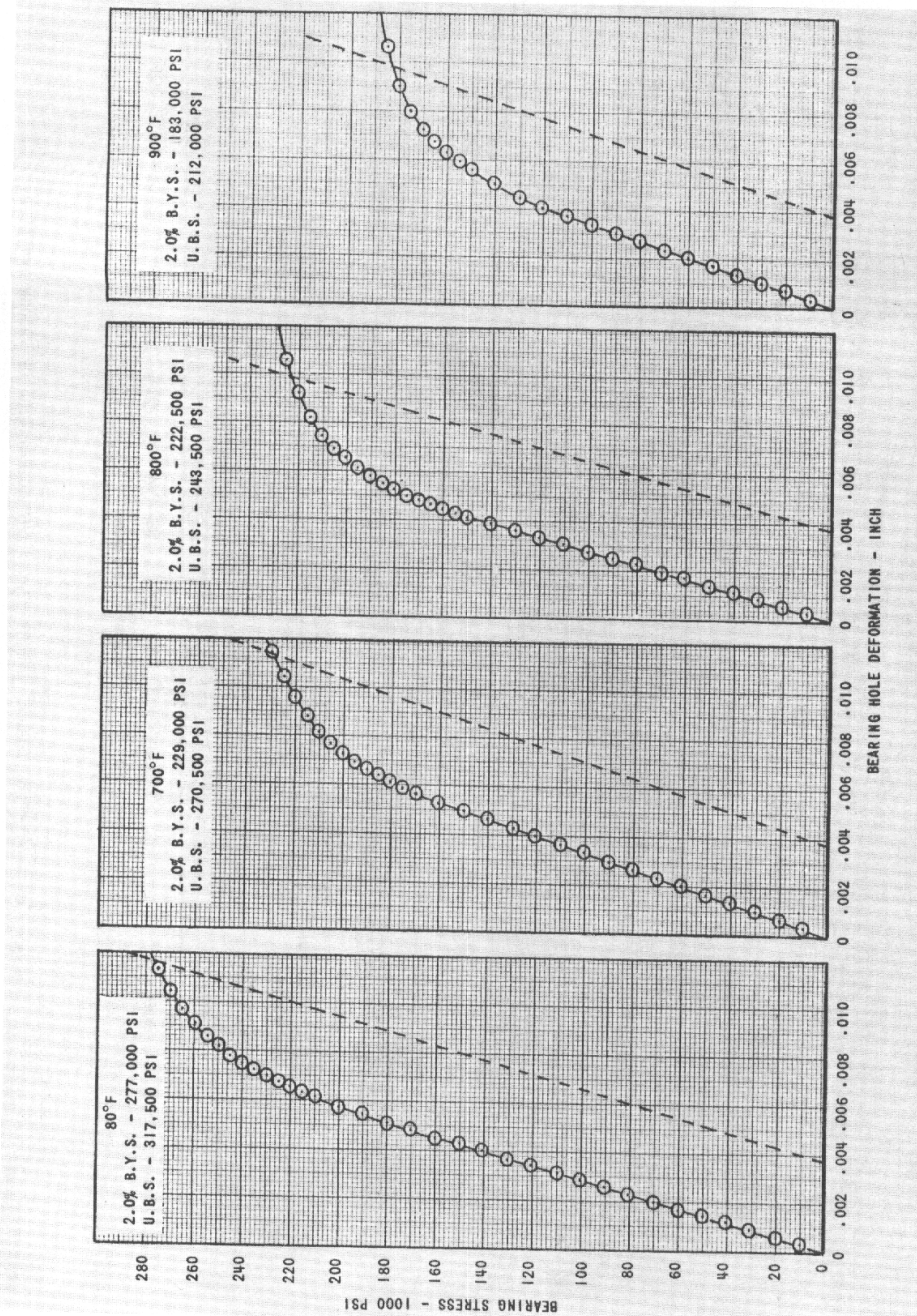


Figure 9 SHORT TIME BEARING STRESS-DEFORMATION CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL SHEET IN TH 1050 CONDITION AT ROOM AND ELEVATED TEMPERATURE - BEARING HOLE DIAMETER 3/16 INCH AND EDGE DISTANCE OF 1.5 D.

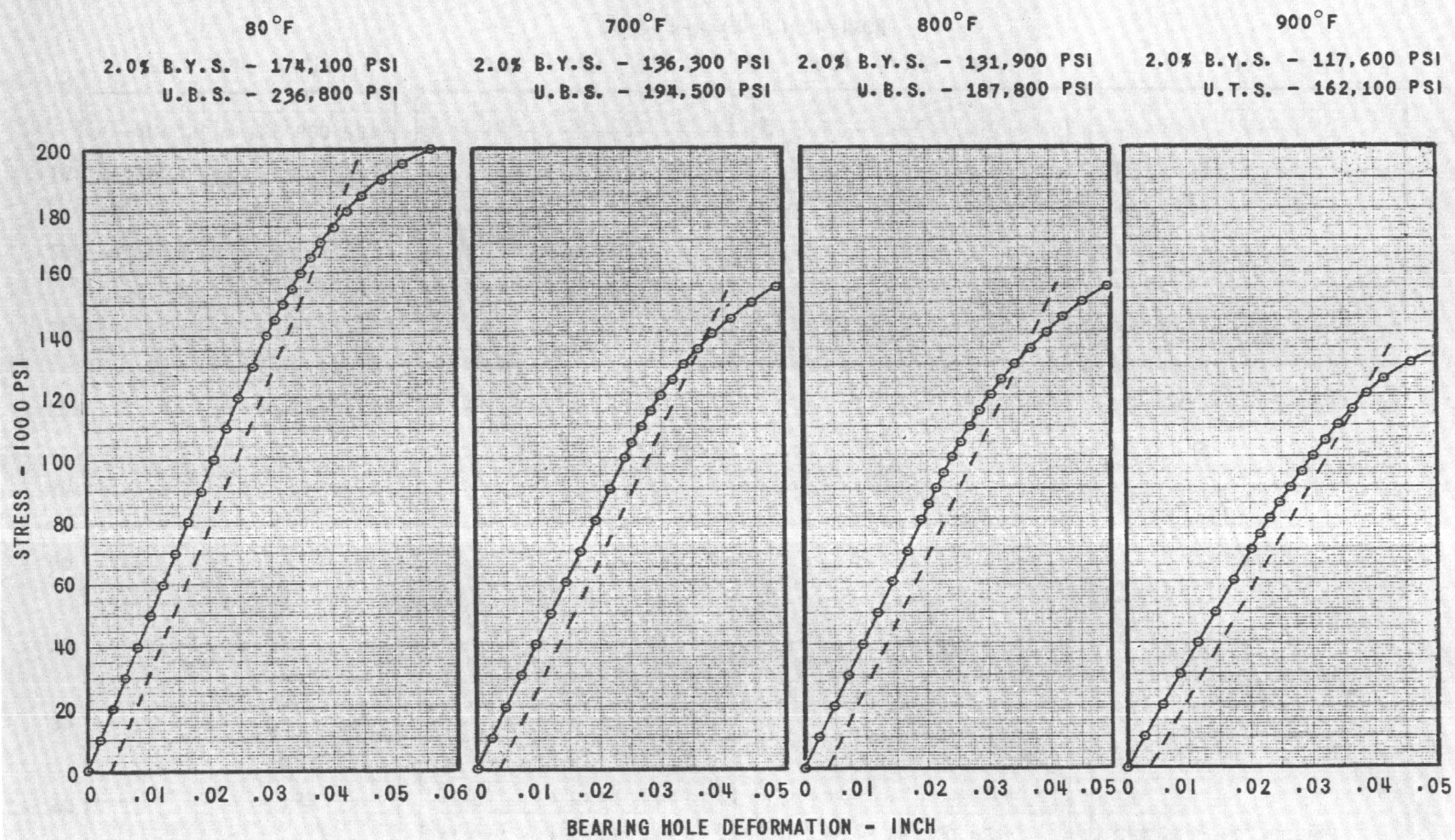


Figure 10 SHORT-TIME BEARING STRESS-DEFORMATION CHARACTERISTICS OF HEAT-TREATED 6AL-4V TITANIUM ALLOY SHEET AT ROOM AND ELEVATED TEMPERATURE - BEARING HOLE DIAMETER 3/16 INCH AND EDGE DISTANCE OF 1.5 D.

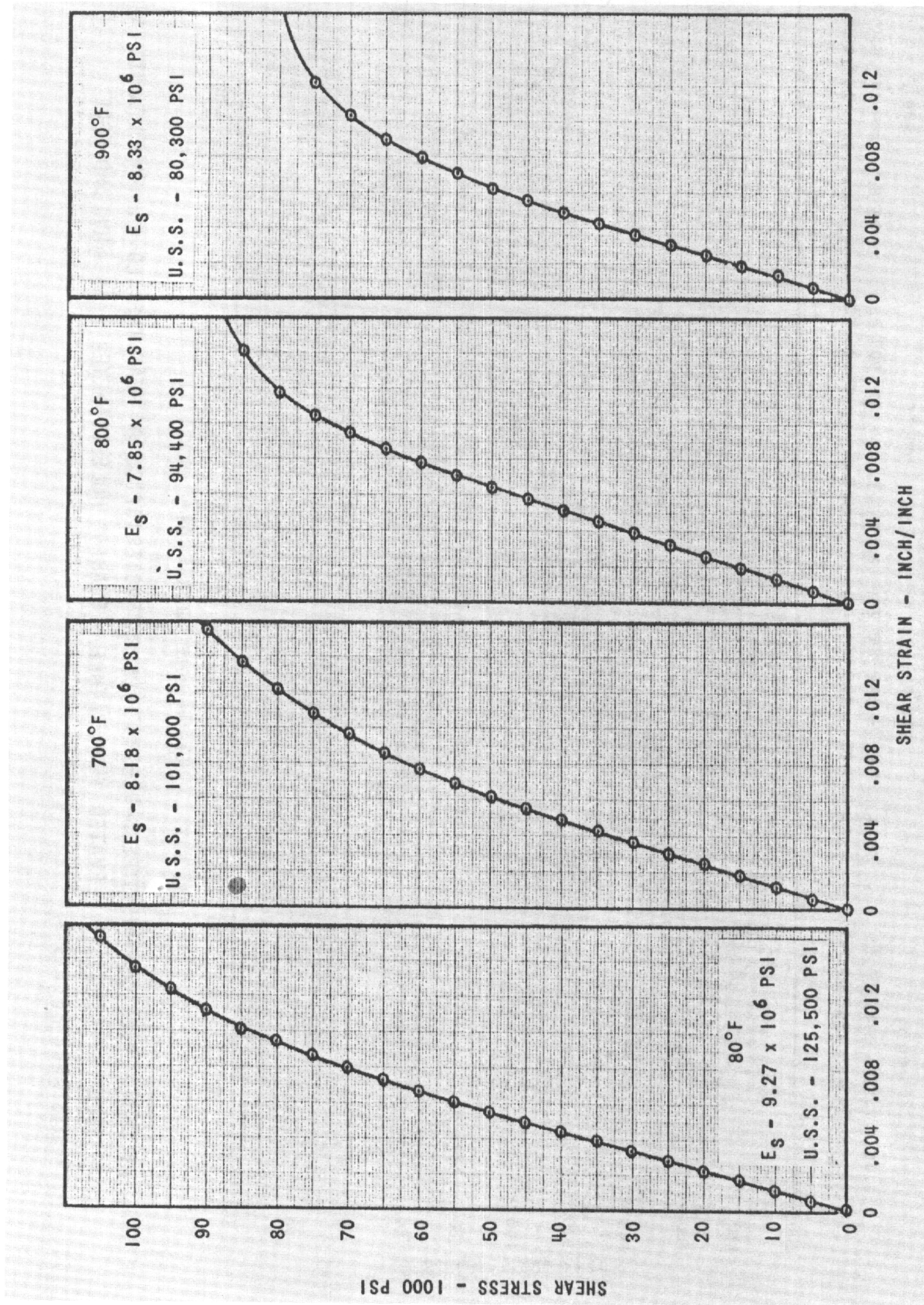


Figure 11 SHORT TIME SHEAR STRESS-STRAIN CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL BAR IN TH 1050 CONDITION

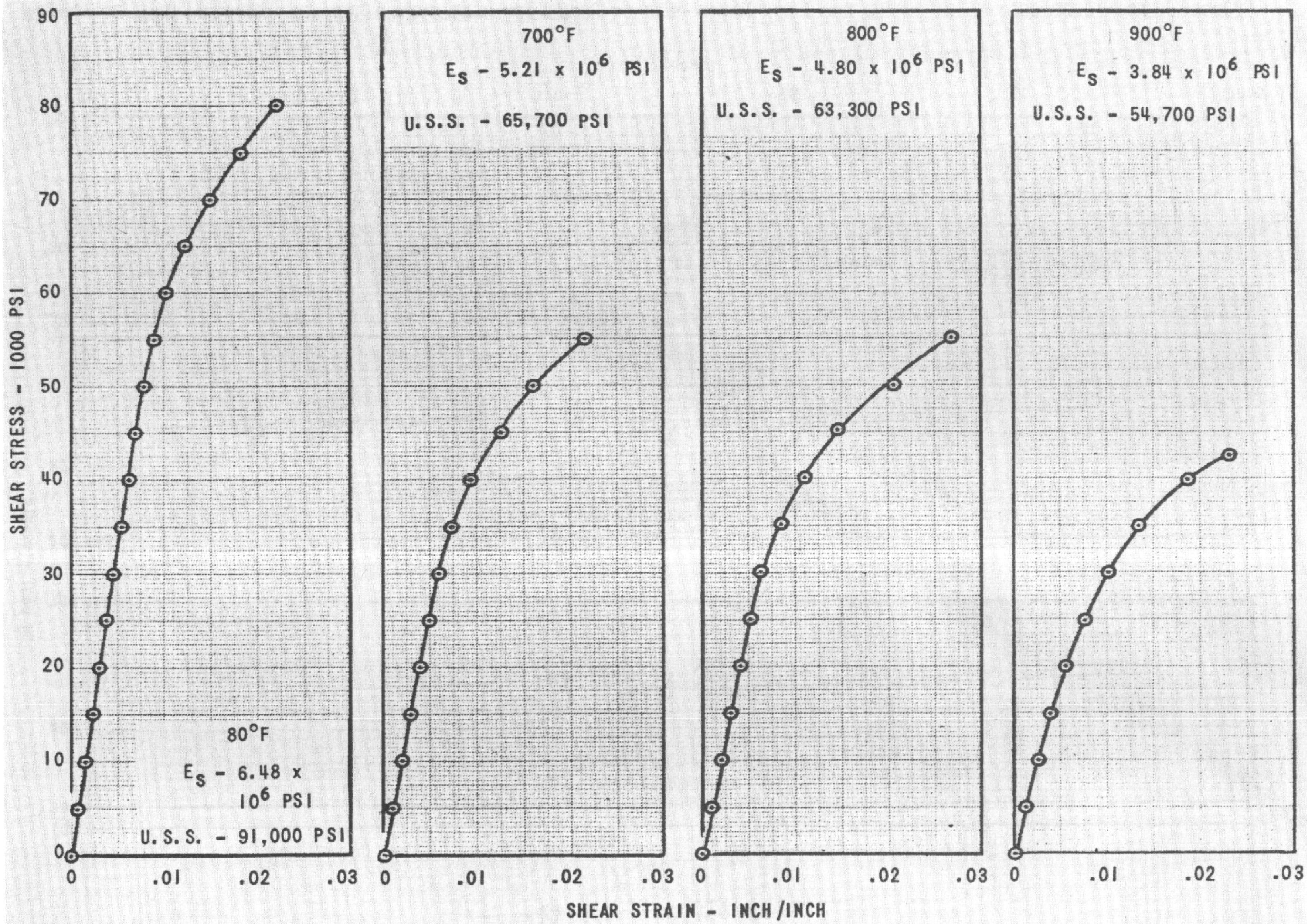


Figure 12 SHORT-TIME SHEAR STRESS-STRAIN CHARACTERISTICS OF VACUUM ANNEALED 6A1-4V TITANIUM ALLOY BAR

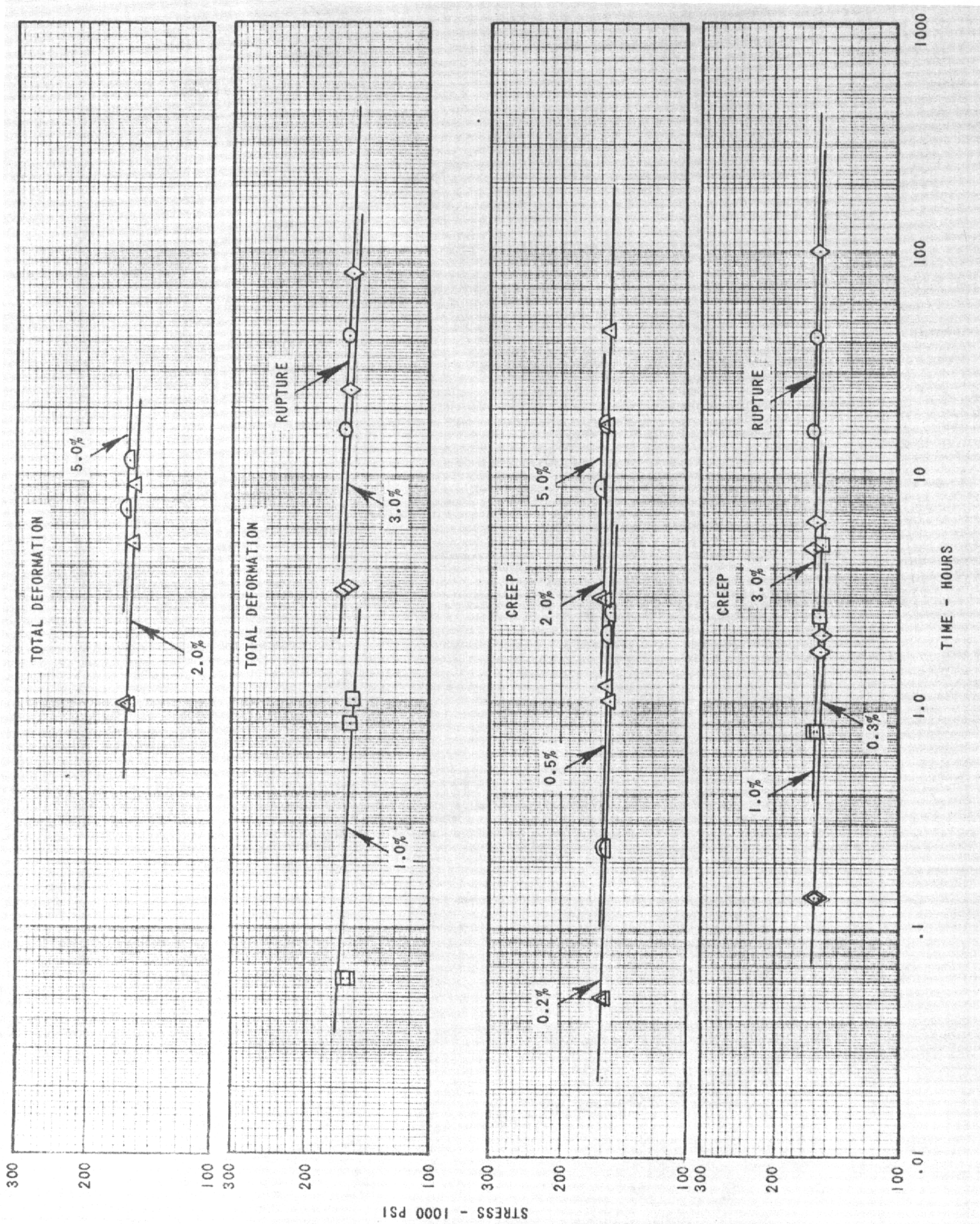


Figure 13 TENSILE CREEP-RUPTURE CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL SHEET IN TH 1050 CONDITION AT 700°F

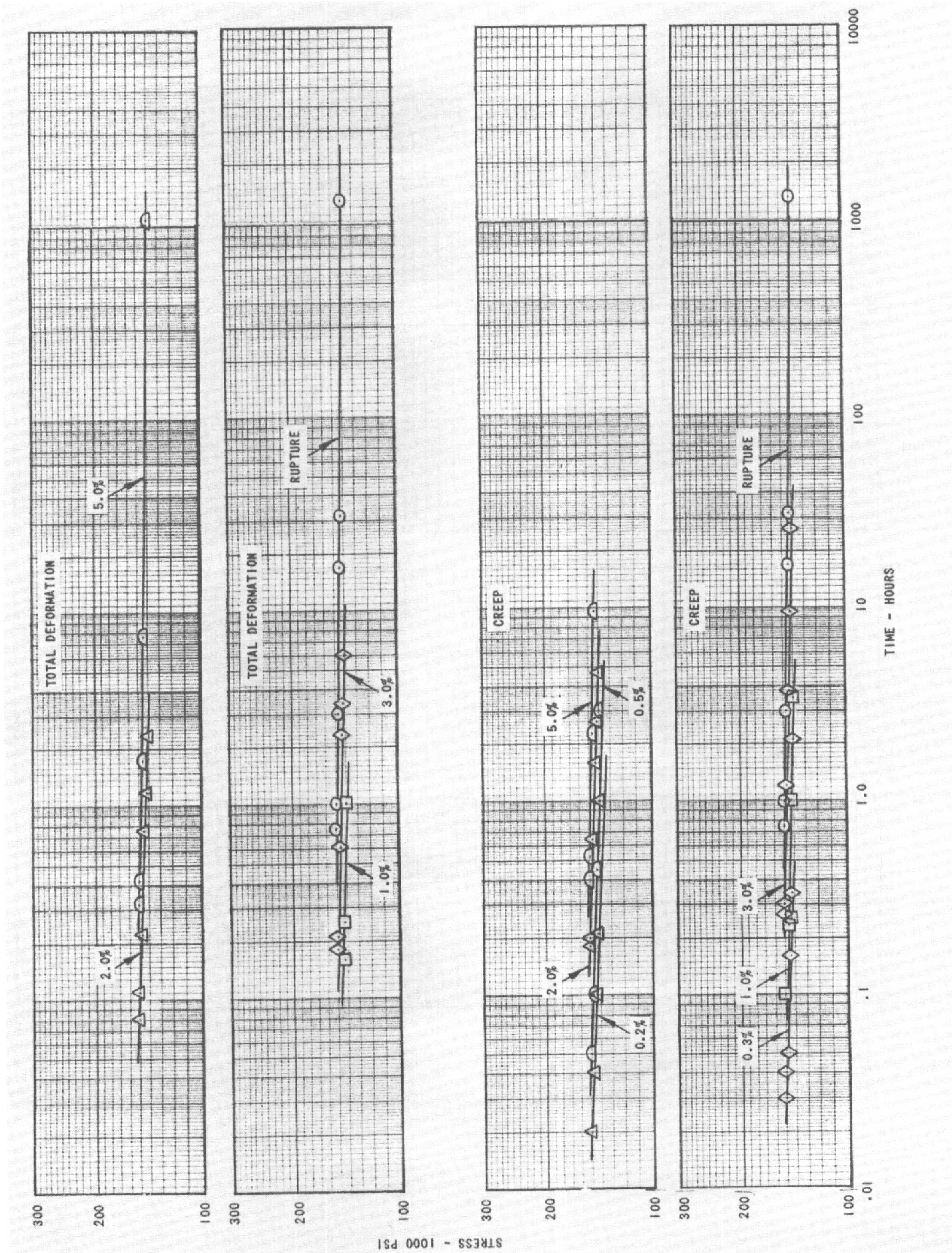


Figure 14 TENSILE CREEP-RUPTURE CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL SHEET IN TH 1050 CONDITION AT 800°F

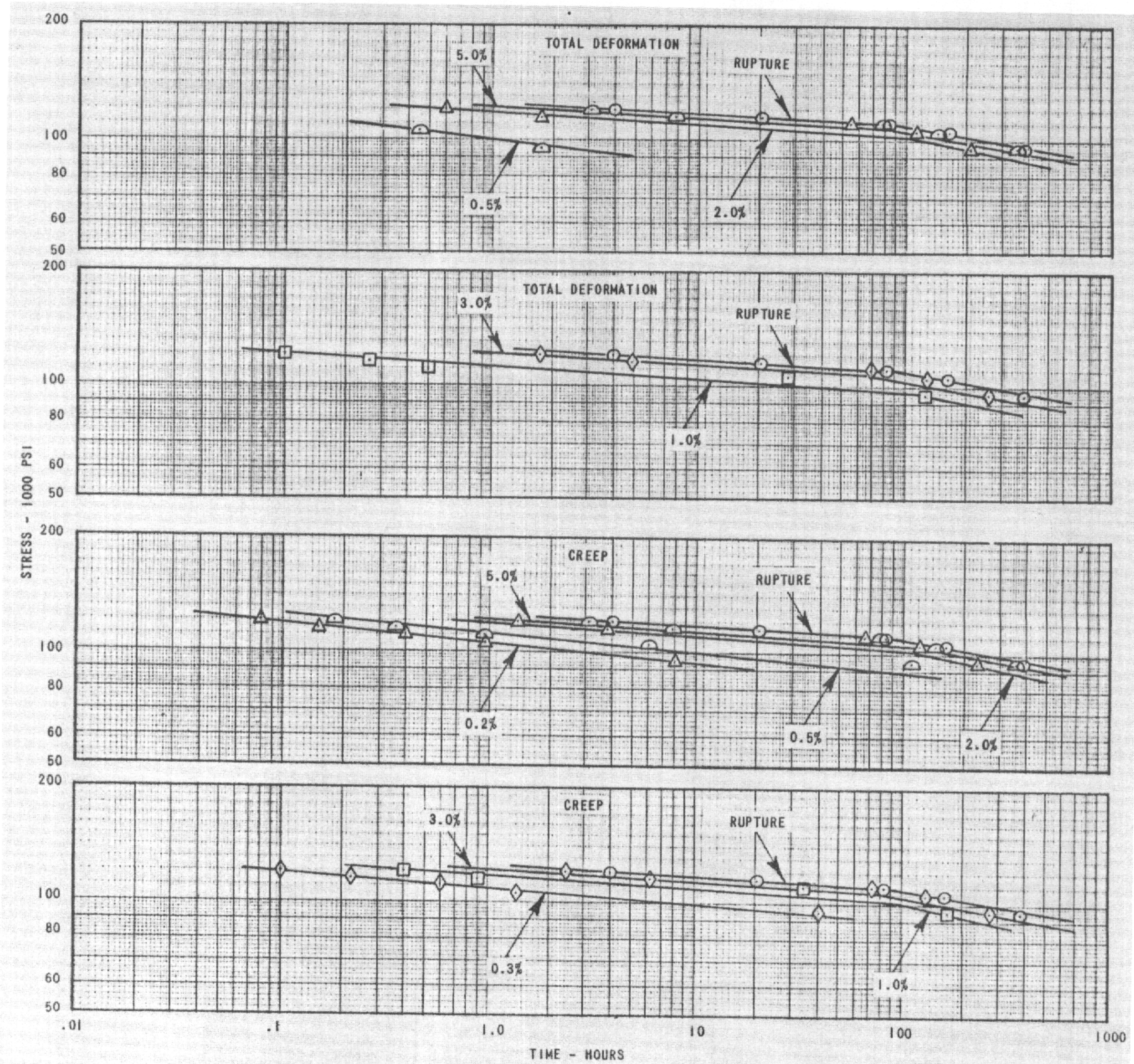


Figure 15 TENSILE CREEP-RUPTURE CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL SHEET IN TH 1050 CONDITION AT 900°F

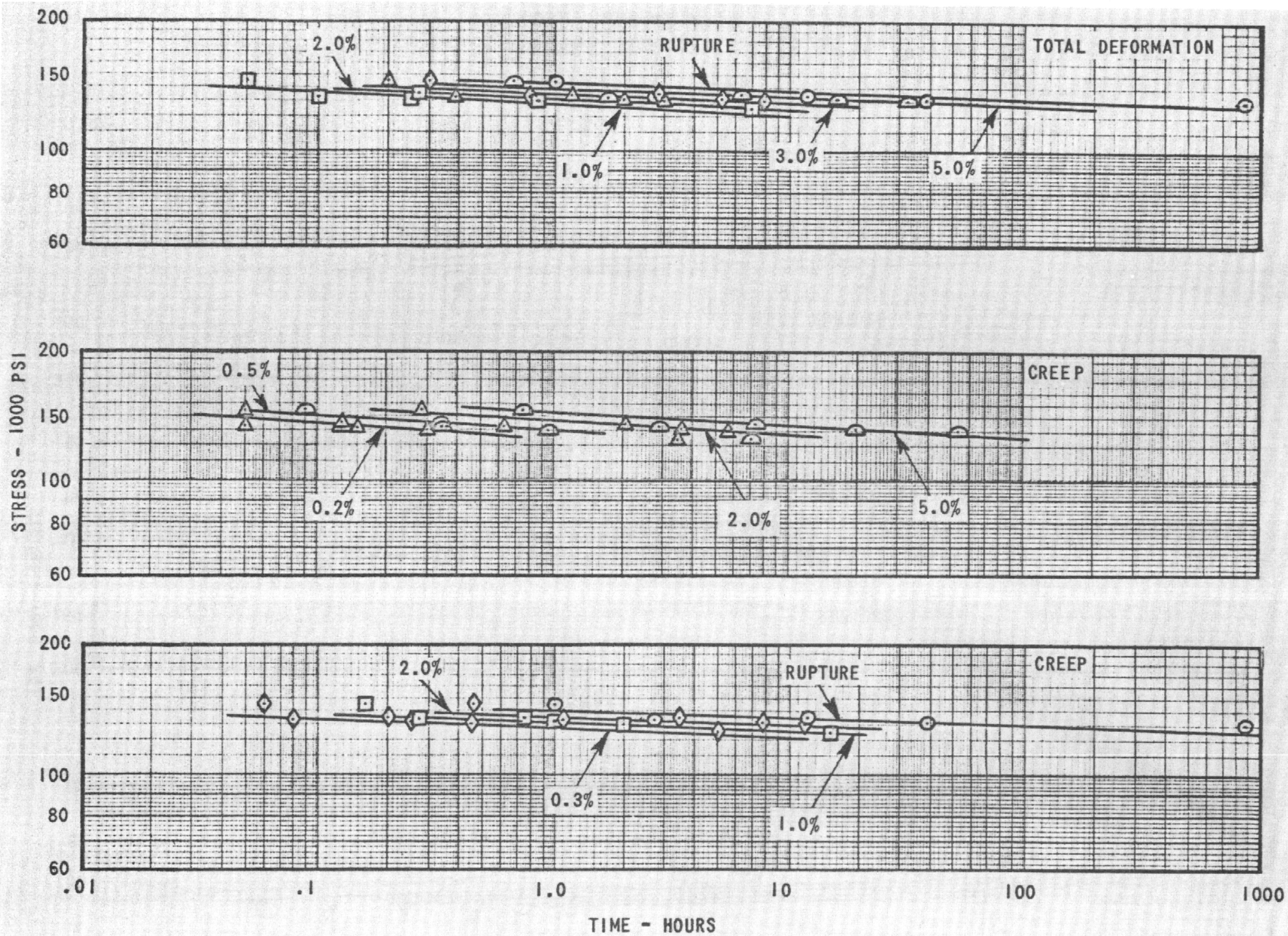


Figure 16 TENSILE CREEP-RUPTURE CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL BAR IN TH 1050 CONDITION AT 800°F.

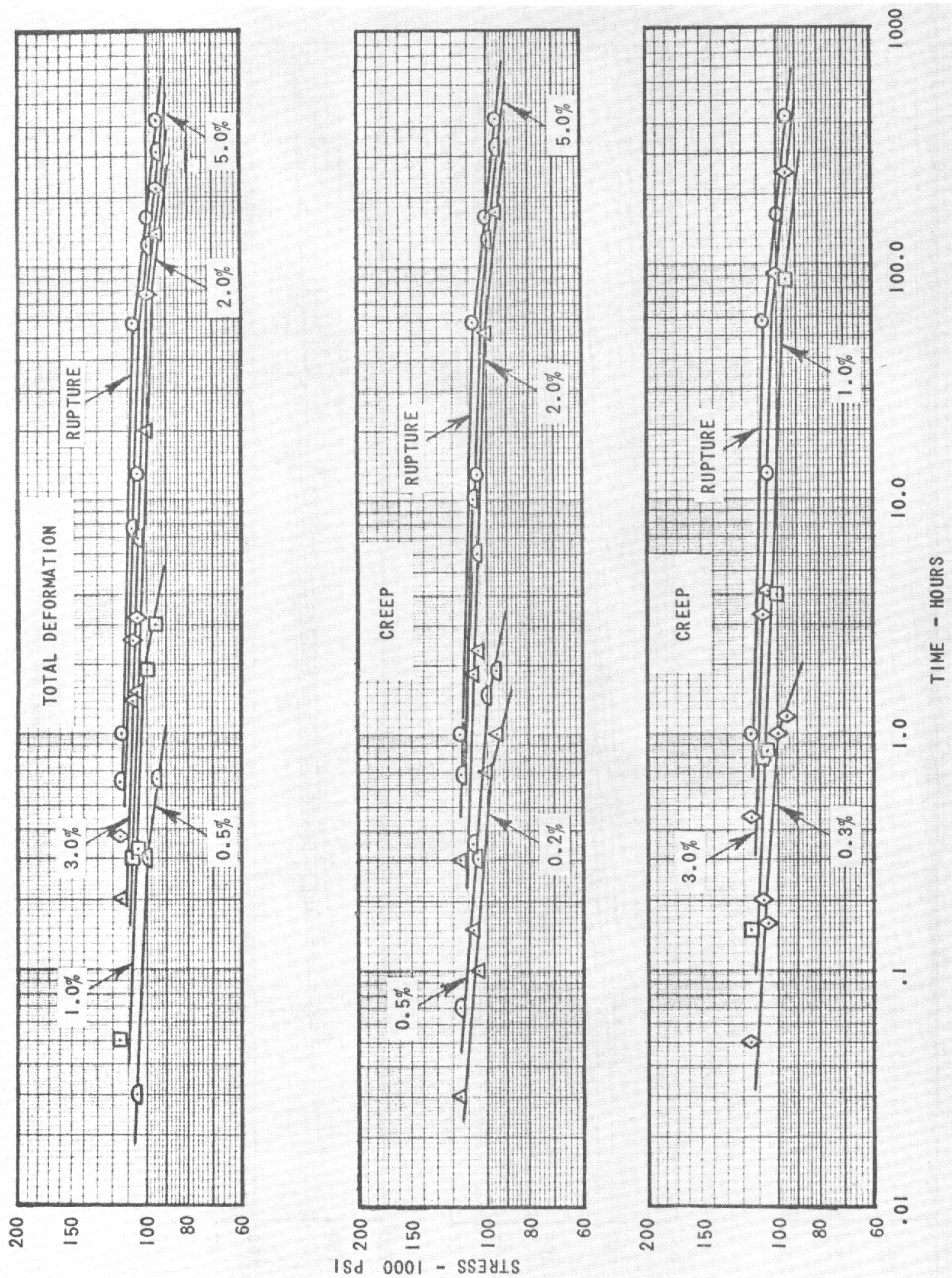


Figure 17 TENSILE CREEP-RUPTURE CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL BAR IN TH 1050 CONDITION AT 900°F

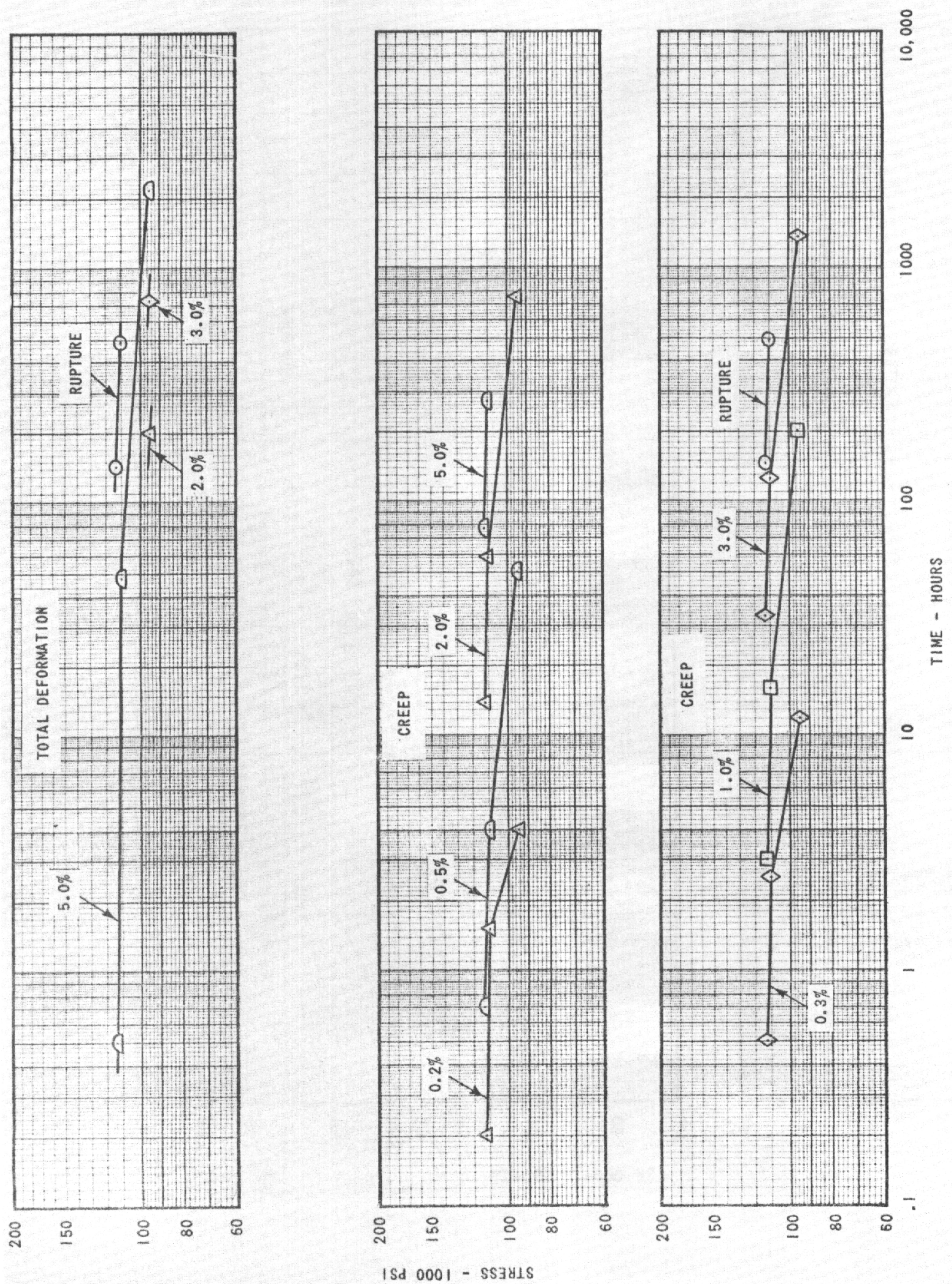


Figure 18 TENSILE CREEP-RUPTURE CHARACTERISTICS OF HEAT-TREATED 6AL-4V TITANIUM ALLOY SHEET AT 700° F

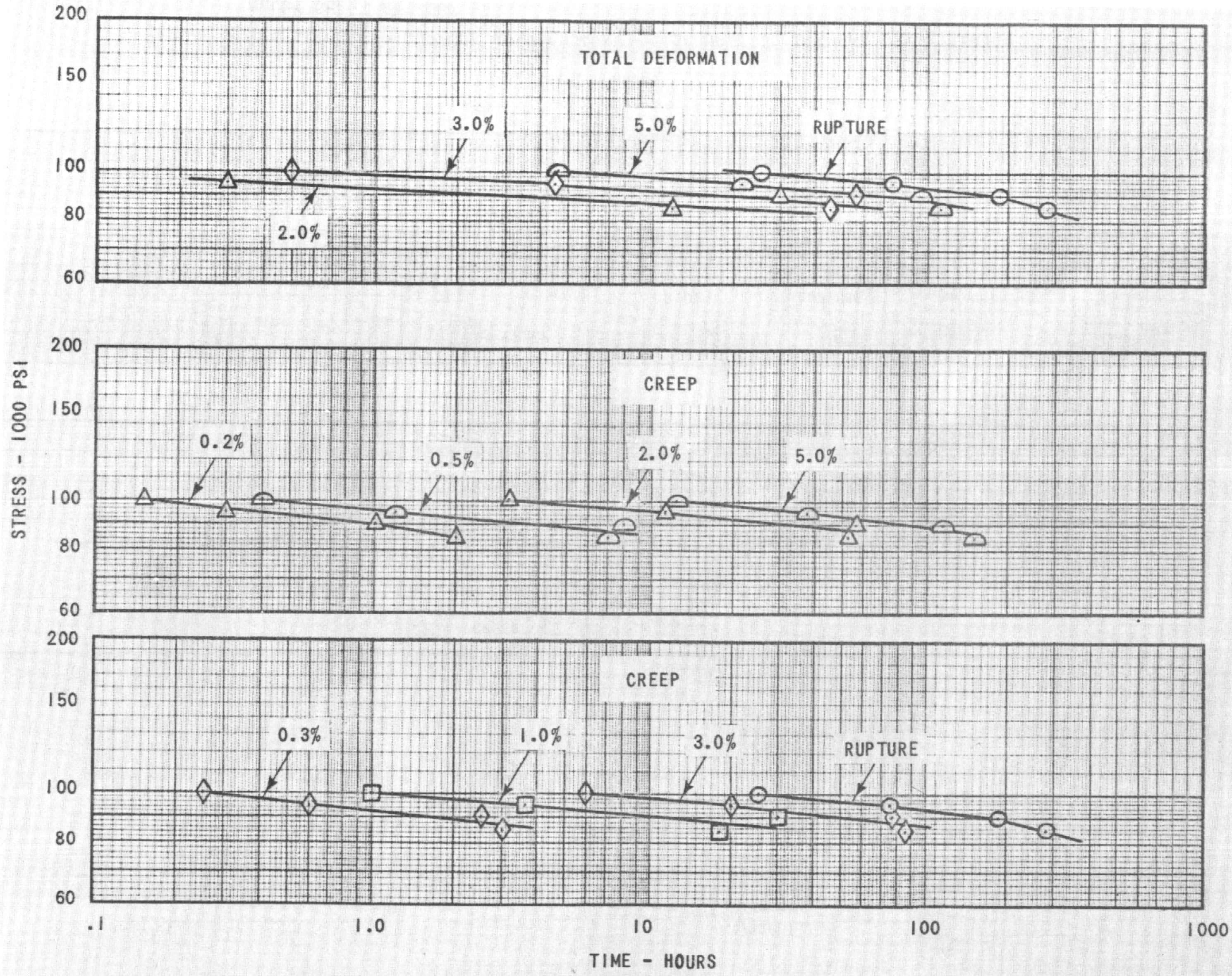


Figure 19 TENSILE CREEP-RUPTURE CHARACTERISTICS OF HEAT-TREATED 6AL-4V TITANIUM ALLOY SHEET AT 800°F

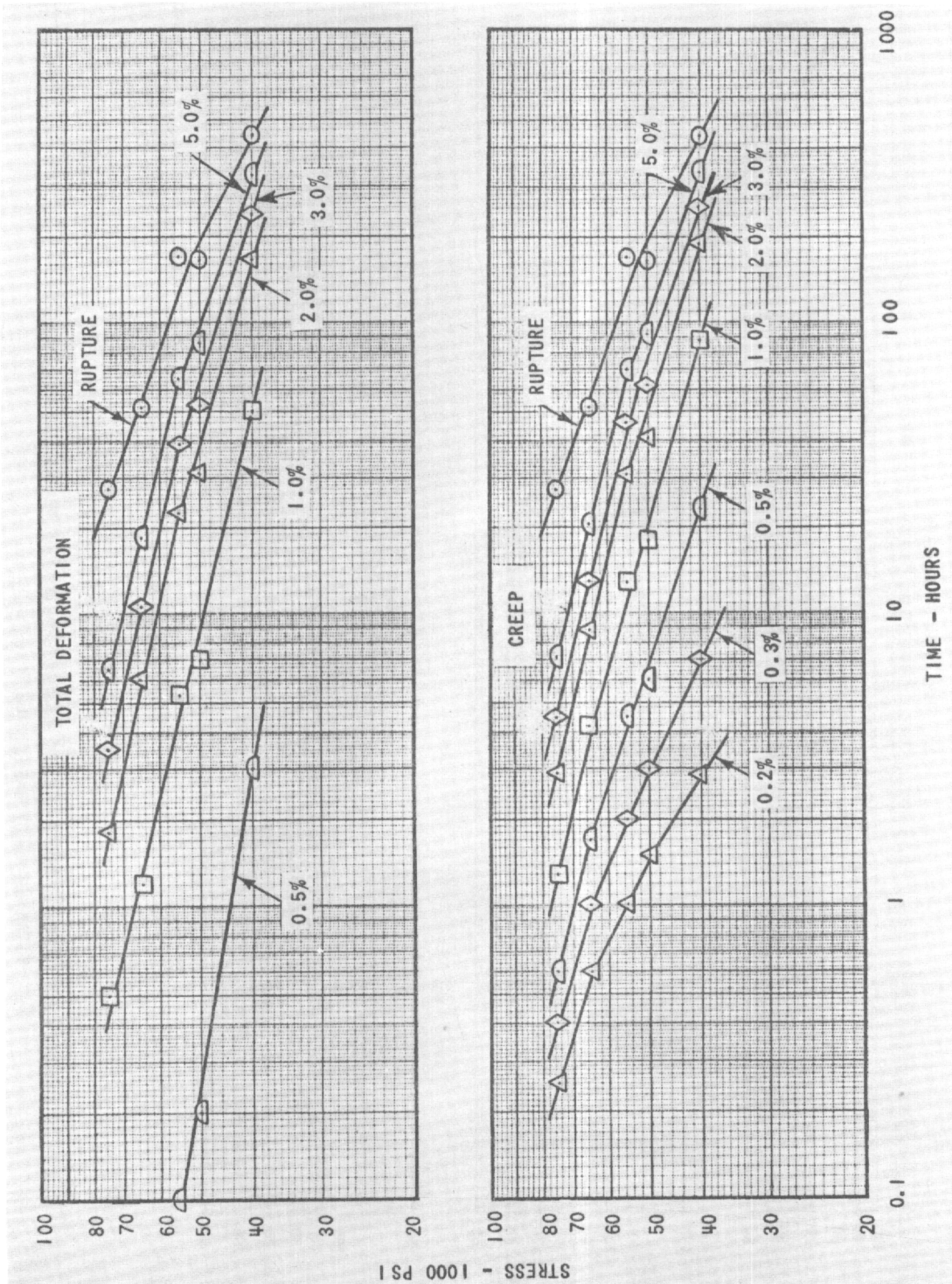


Figure 20 TENSILE CREEP-RUPTURE CHARACTERISTICS OF HEAT-TREATED 6AL-4V TITANIUM ALLOY SHEET AT 900°F

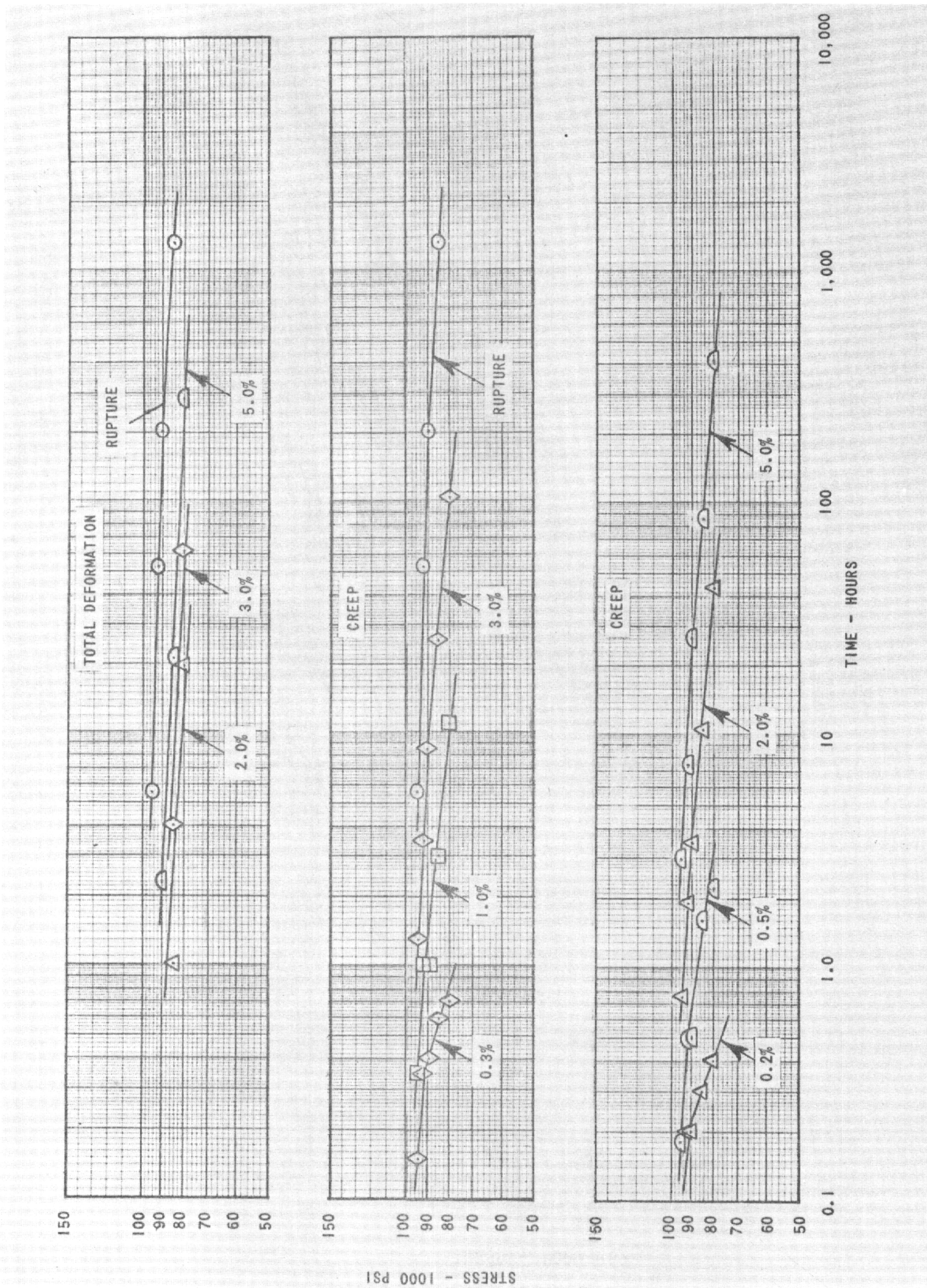


Figure 21 TENSILE CREEP-RUPTURE CHARACTERISTICS OF VACUUM ANNEALED 6AL-4V TITANIUM ALLOY BAR AT 700°F

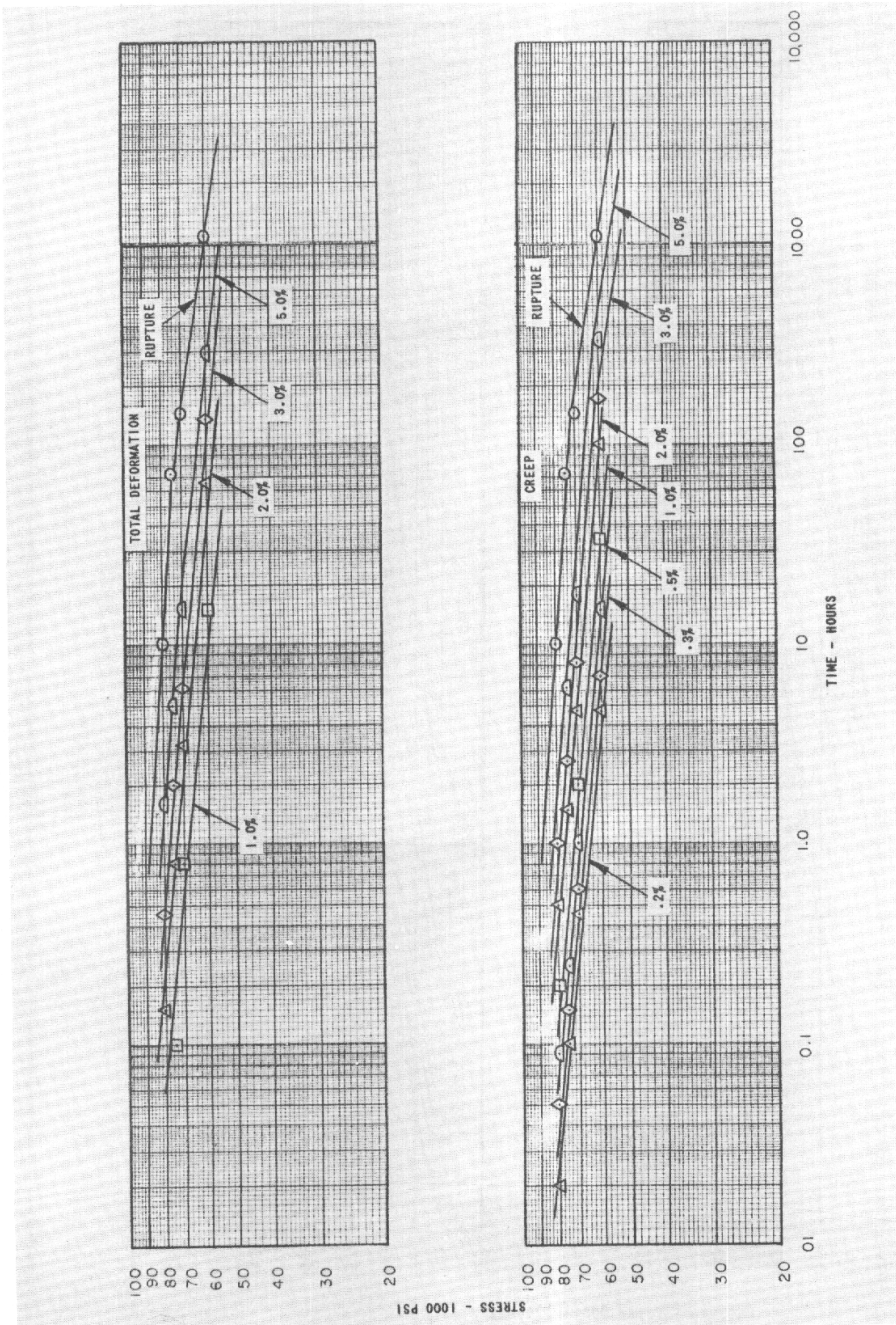


Figure 22 TENSILE CREEP-RUPTURE CHARACTERISTICS OF VACUUM ANNEALED 6AL-4V TITANIUM ALLOY BAR AT 800°F

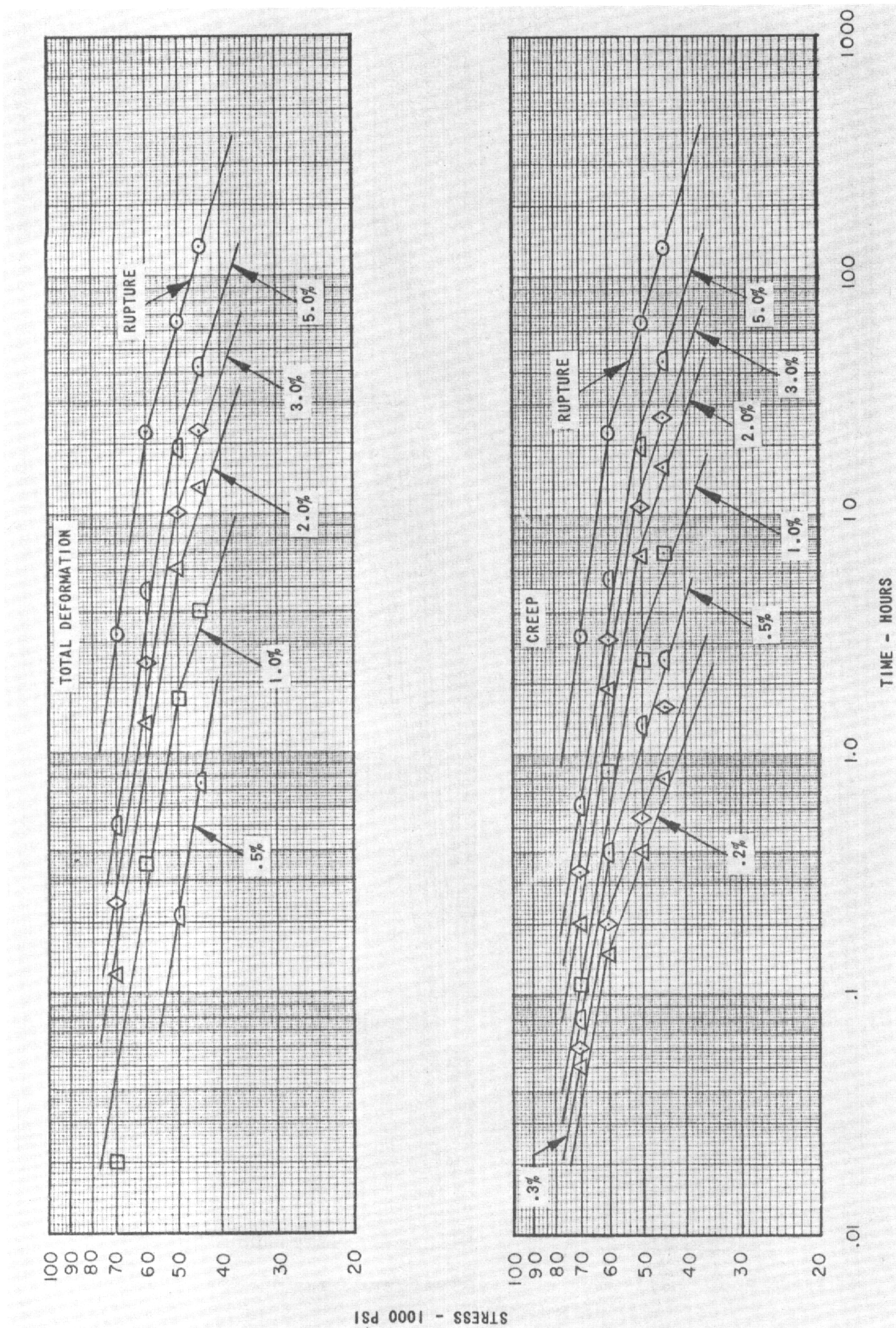


Figure 23 TENSILE CREEP-RUPTURE CHARACTERISTICS OF VACUUM ANNEALED 6AL-4V TITANIUM ALLOY BAR AT 900°F

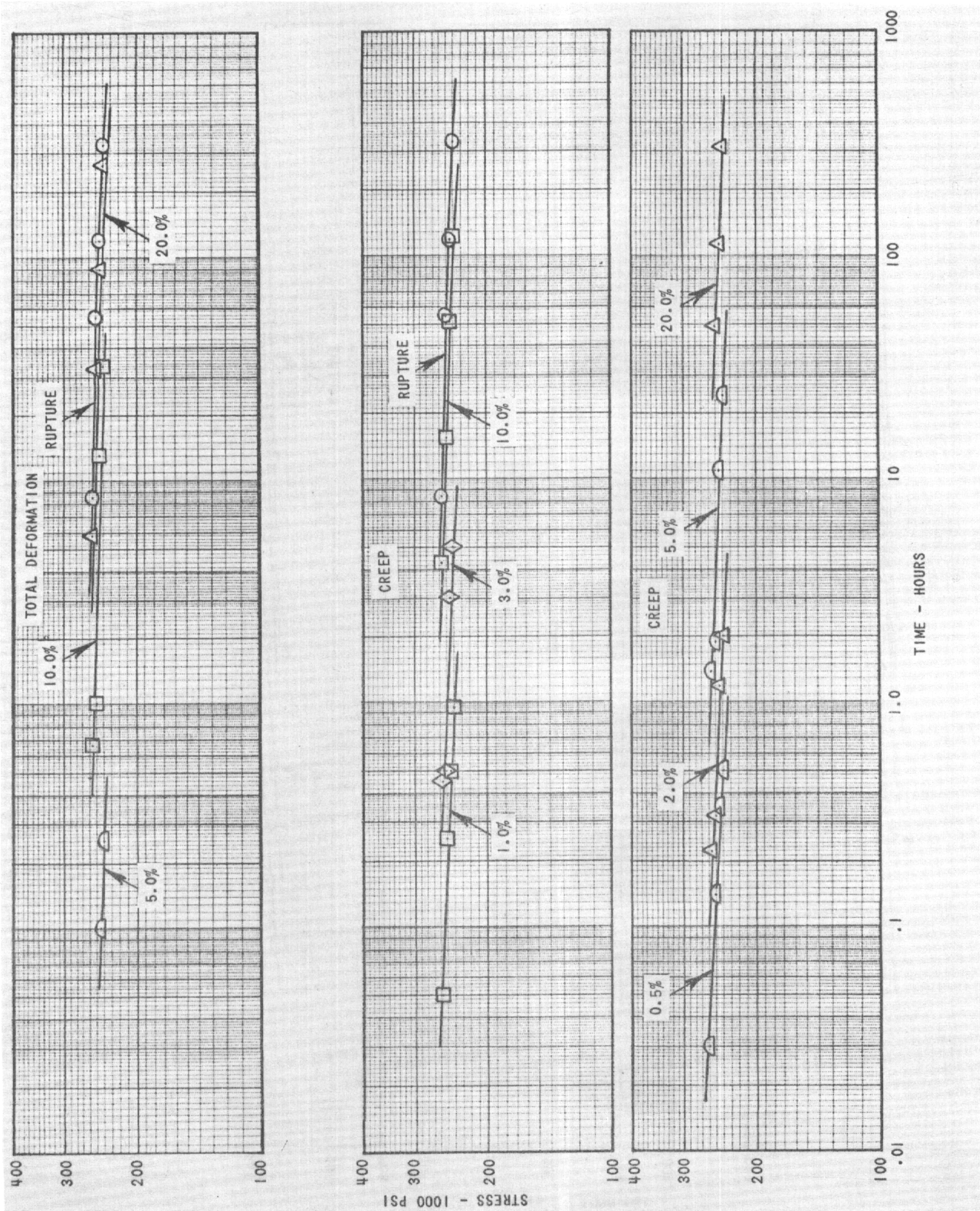


Figure 24 BEARING CREEP-RUPTURE CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL SHEET AT 700°F FOR BEARING HOLE DIAMETER OF 3/16 INCH AND EDGE DISTANCE OF 1.5 D. ALLOY TESTED IN TH 1050 CONDITION

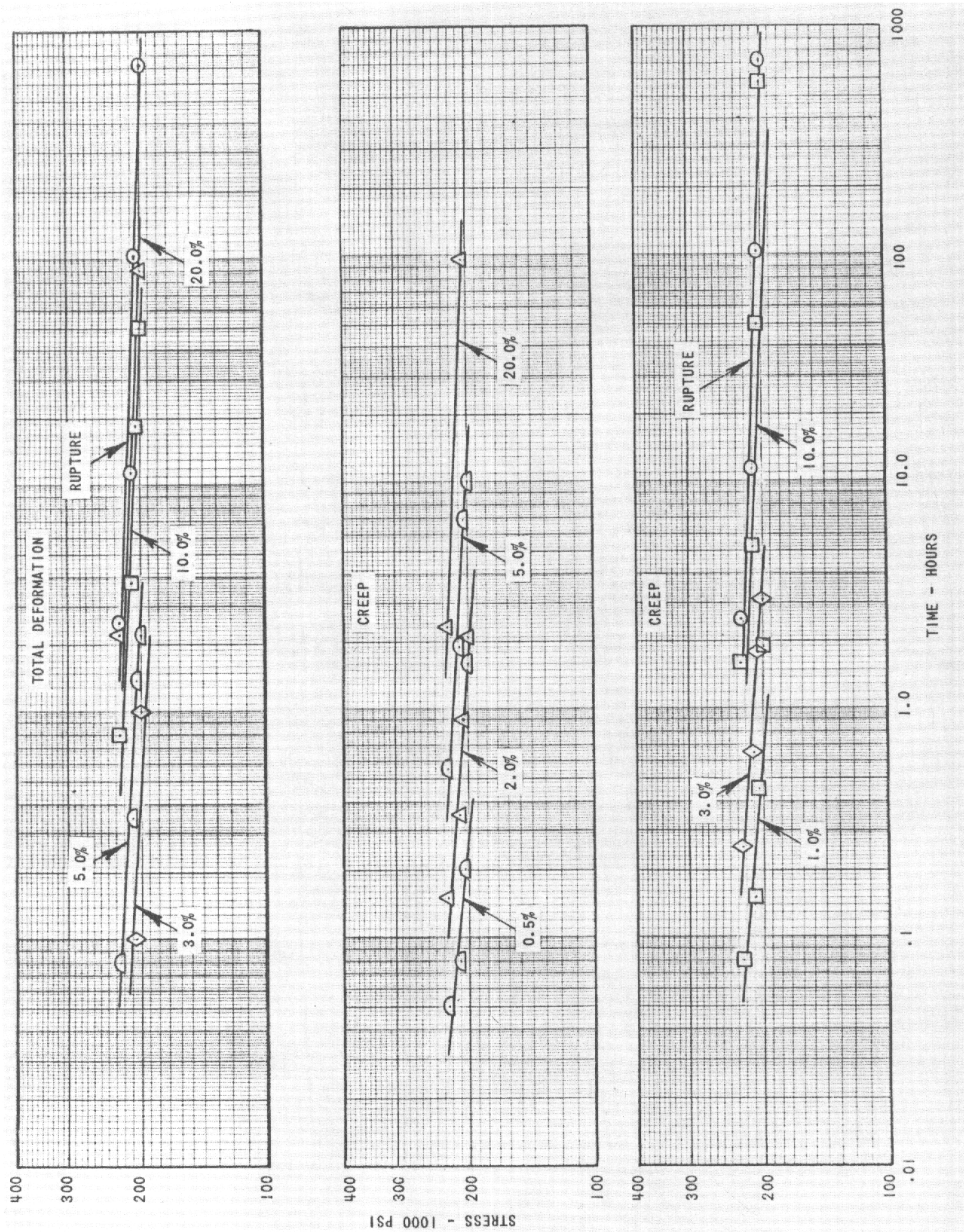


Figure 25 BEARING CREEP-RUPTURE CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL SHEET AT 800°F FOR BEARING HOLE DIAMETER OF 3/16 INCH AND EDGE DISTANCE OF 1.5 D. ALLOY TESTED IN TH 1050 CONDITION

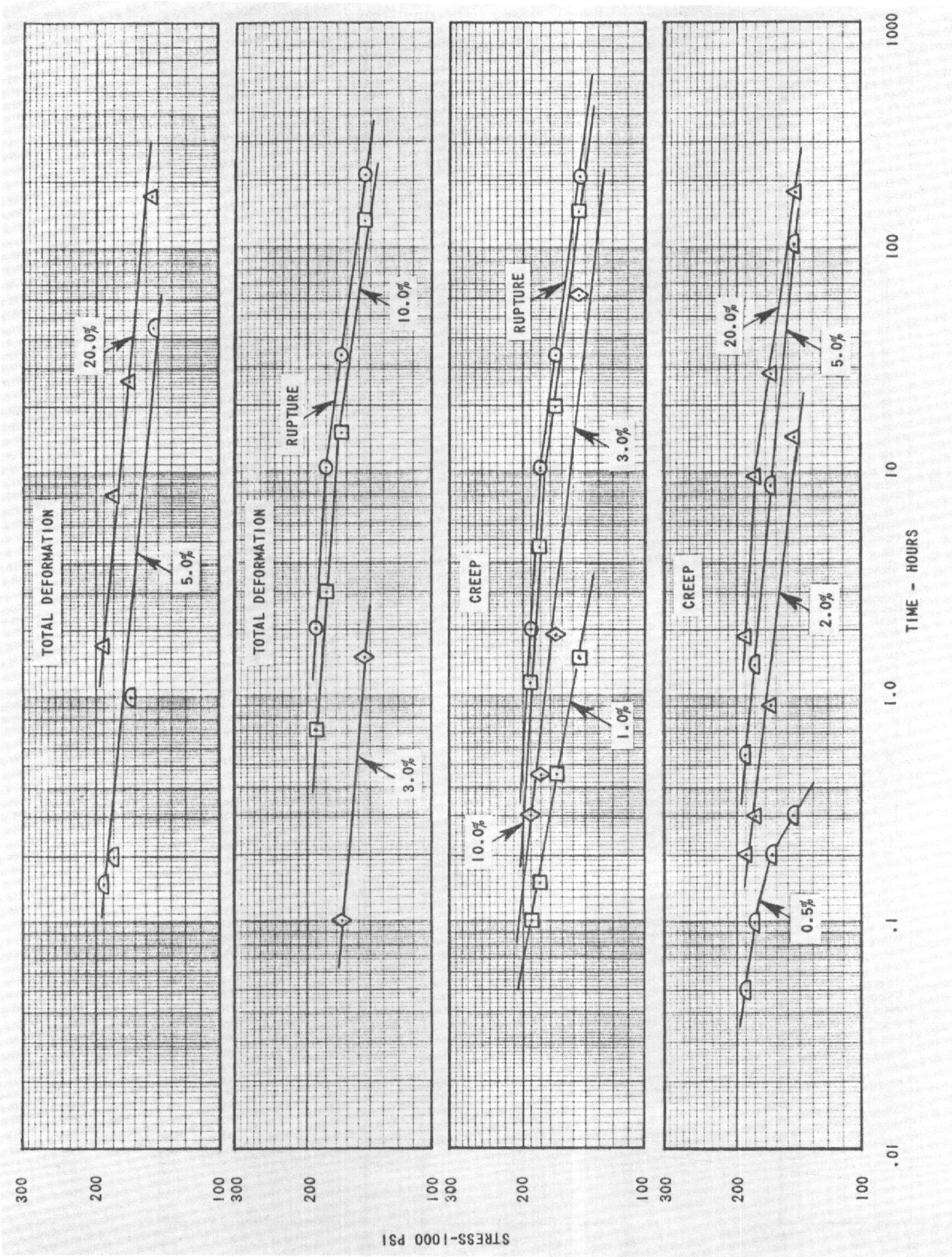


Figure 26 BEARING CREEP-RUPTURE CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL SHEET AT 900°F FOR BEARING HOLE DIAMETER OF 3/16 INCH AND EDGE DISTANCE OF 1.5 D. ALLOY TESTED IN TH 1050 CONDITION.

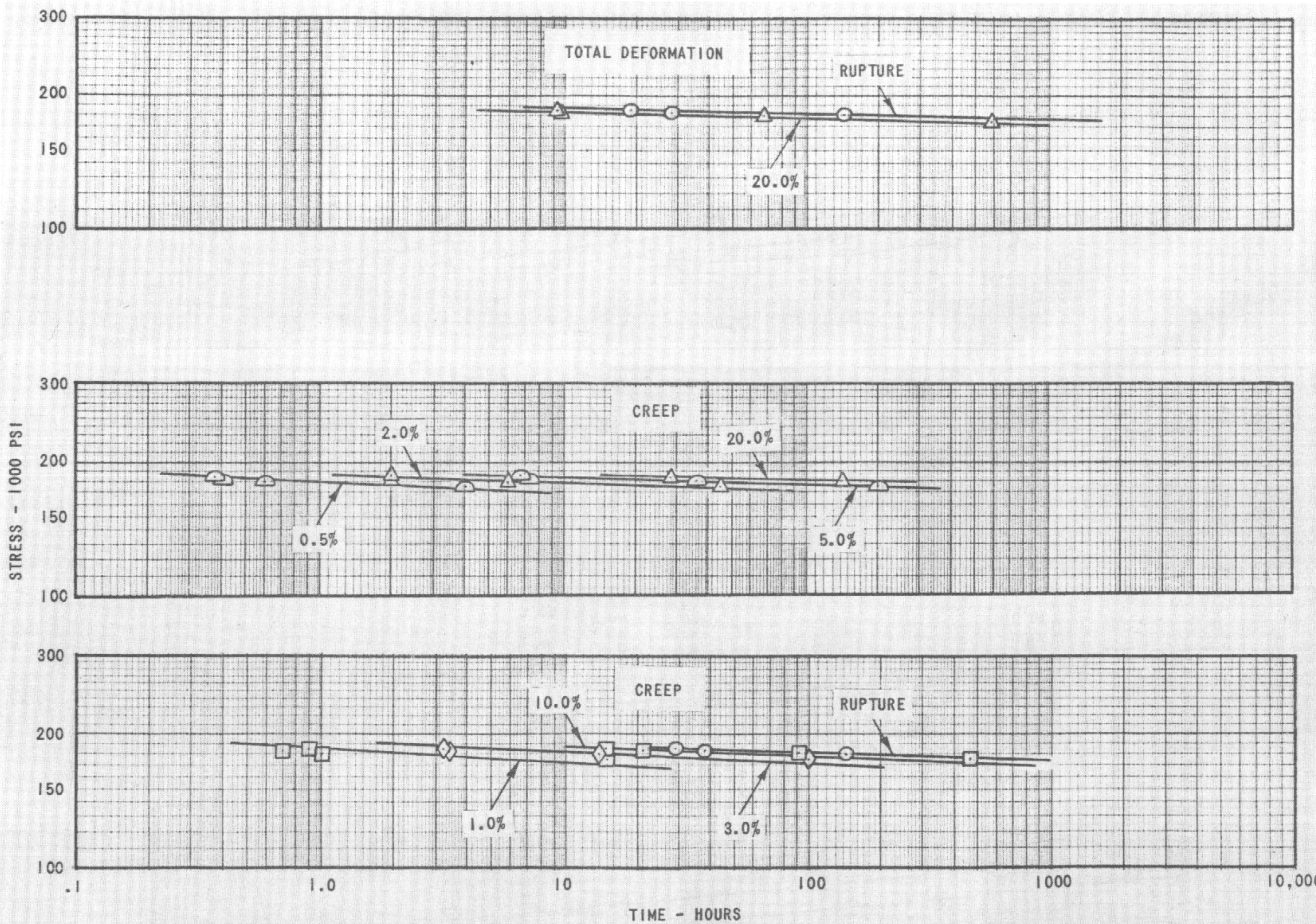


Figure 27 BEARING CREEP-RUPTURE CHARACTERISTICS OF HEAT-TREATED 6AL-4V TITANIUM ALLOY SHEET AT 700°F FOR BEARING HOLE DIAMETER OF 3/16 INCH AND EDGE DISTANCE OF 1.5 D

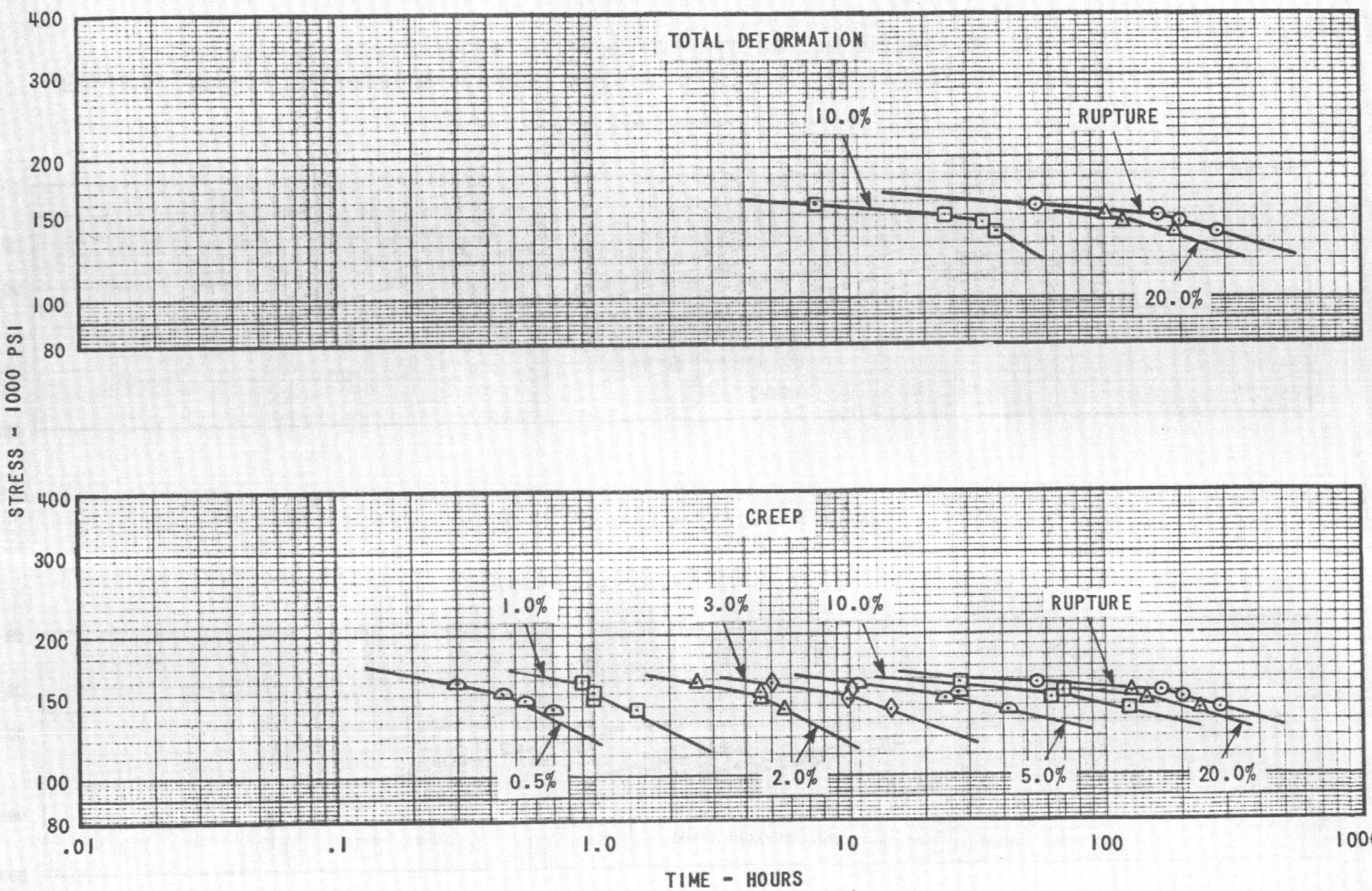


Figure 28 BEARING CREEP-RUPTURE CHARACTERISTICS OF HEAT-TREATED 6AL-4V TITANIUM ALLOY SHEET AT 800°F FOR BEARING HOLE DIAMETER OF 3/16 INCH AND EDGE DISTANCE OF 1.5 D.

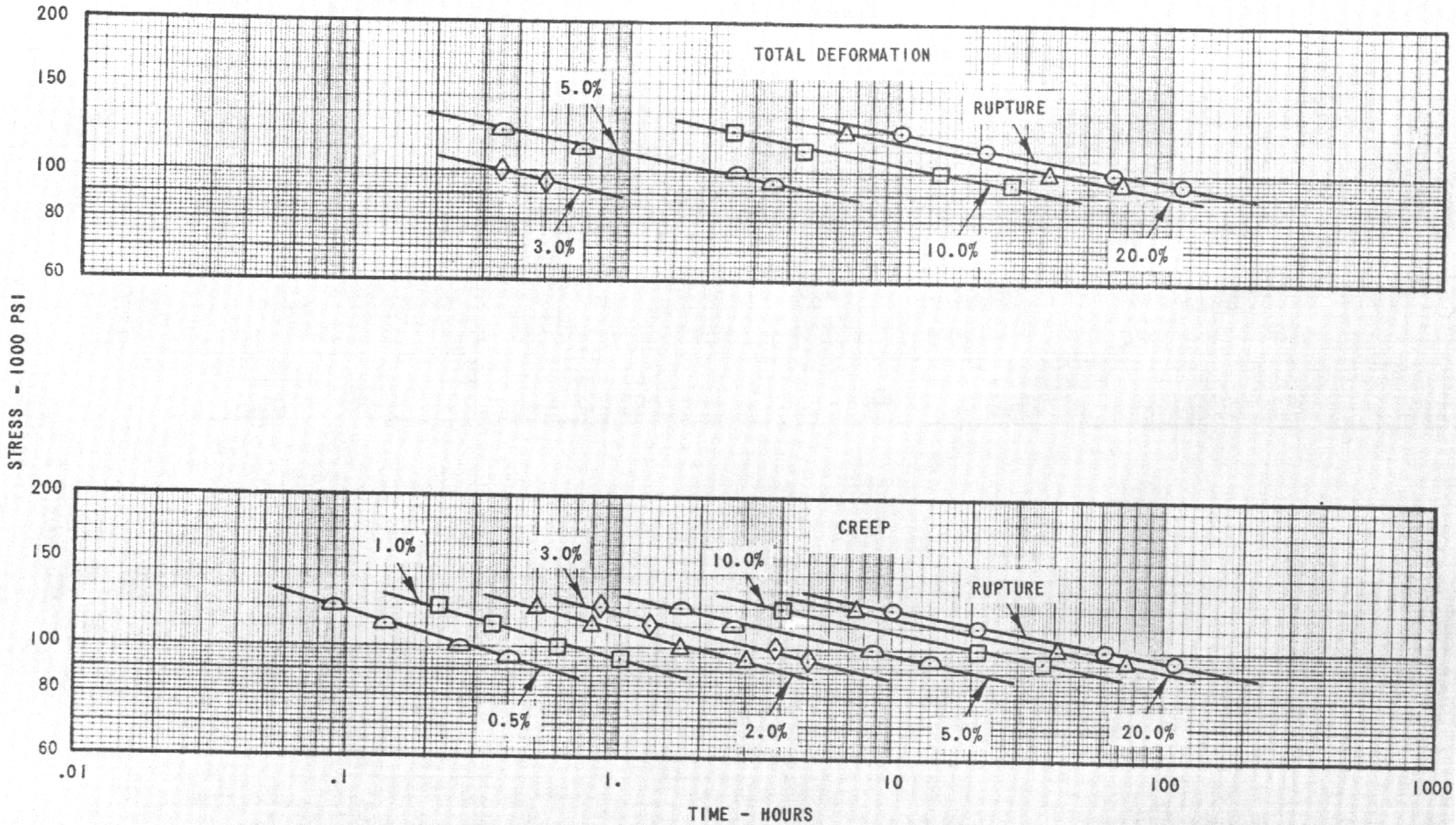


Figure 29 BEARING CREEP-RUPTURE CHARACTERISTICS OF HEAT-TREATED 6AL-4V TITANIUM ALLOY SHEET AT 900°F FOR BEARING HOLE DIAMETER OF 3/16 INCH AND EDGE DISTANCE OF 1.5 D

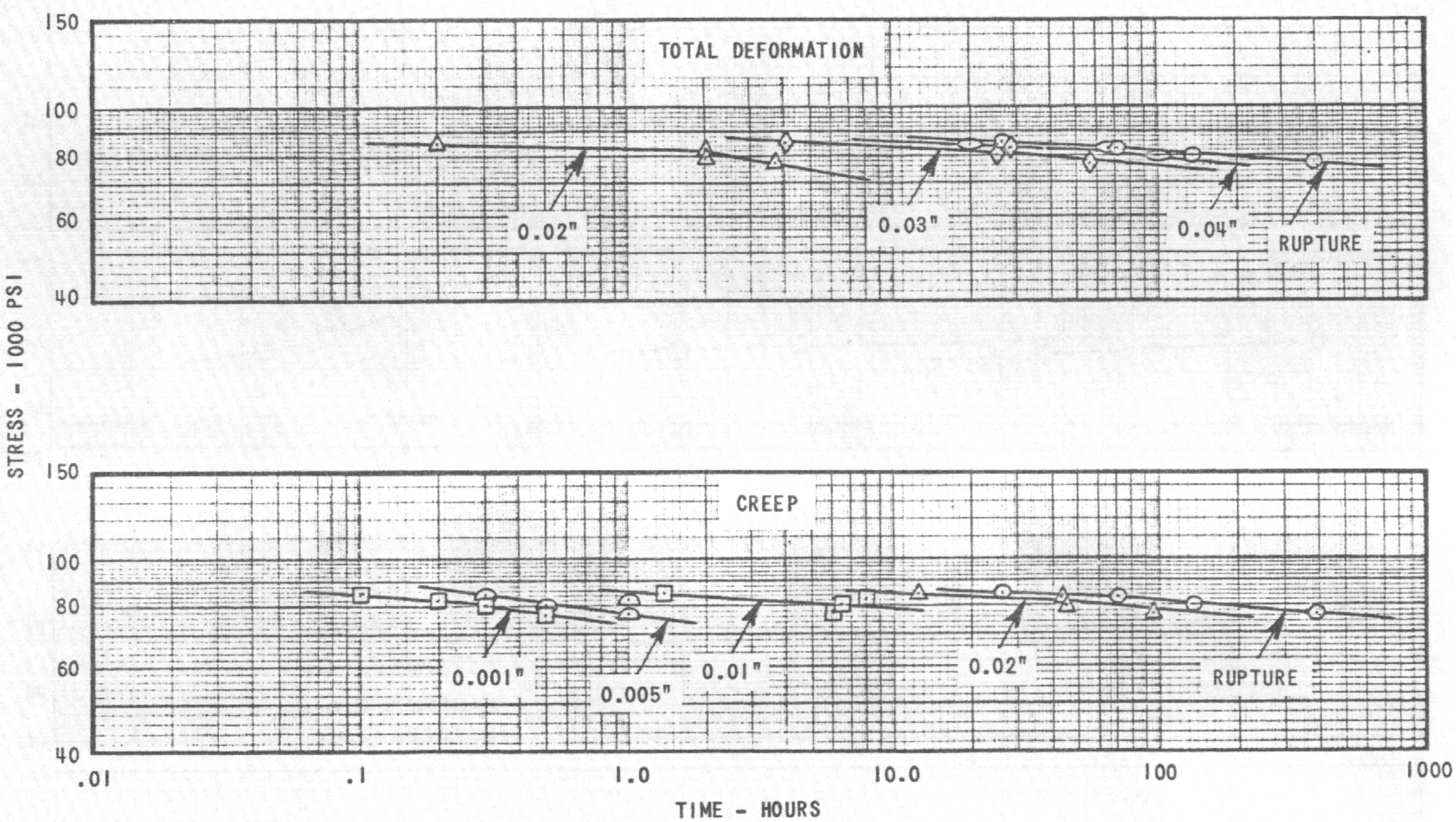


Figure 30 SHEAR CREEP-RUPTURE CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL BAR IN TH 1050 CONDITION AT 800°F

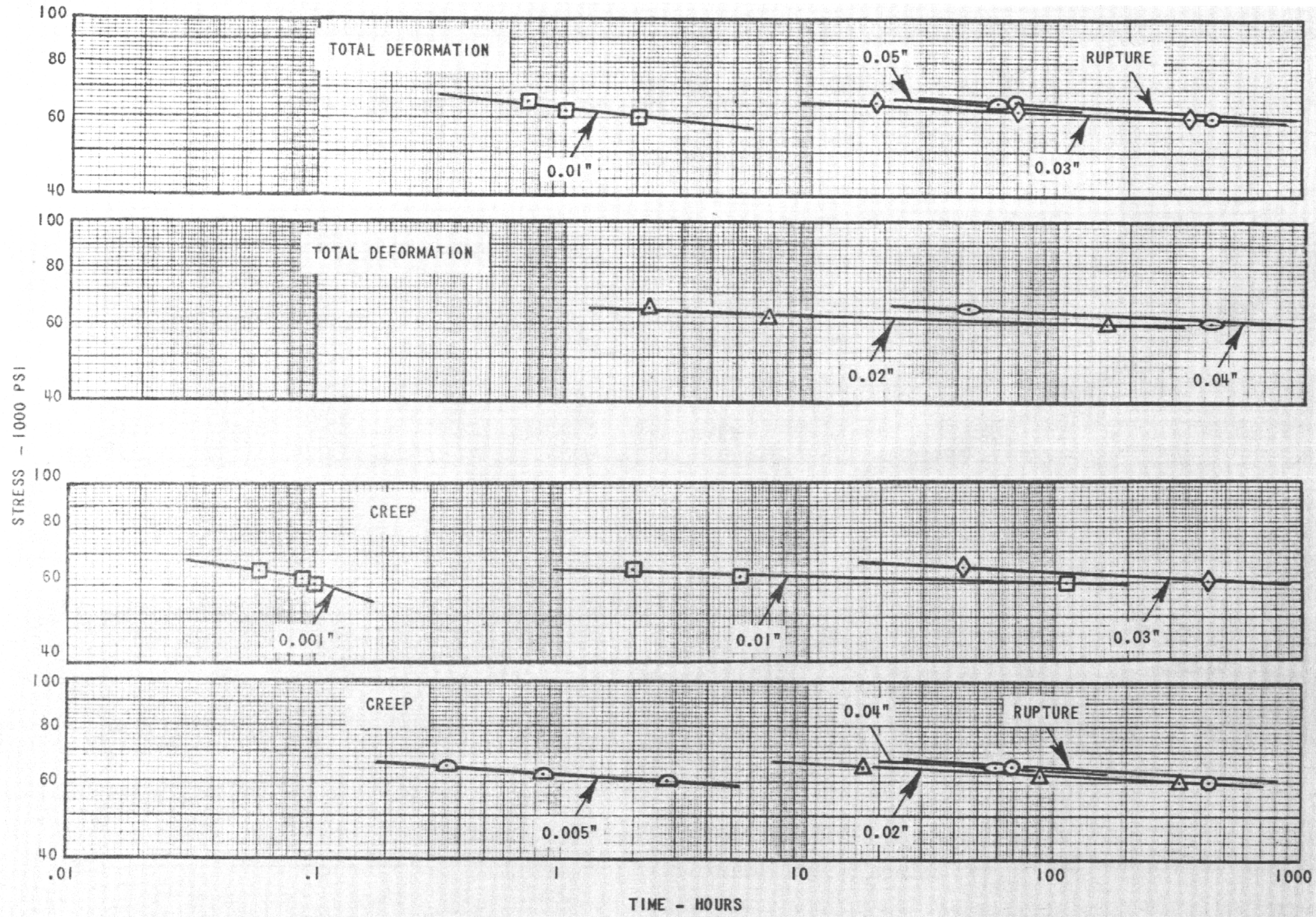


Figure 31 SHEAR CREEP-RUPTURE CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL BAR IN TH 1050 CONDITION AT 900°F

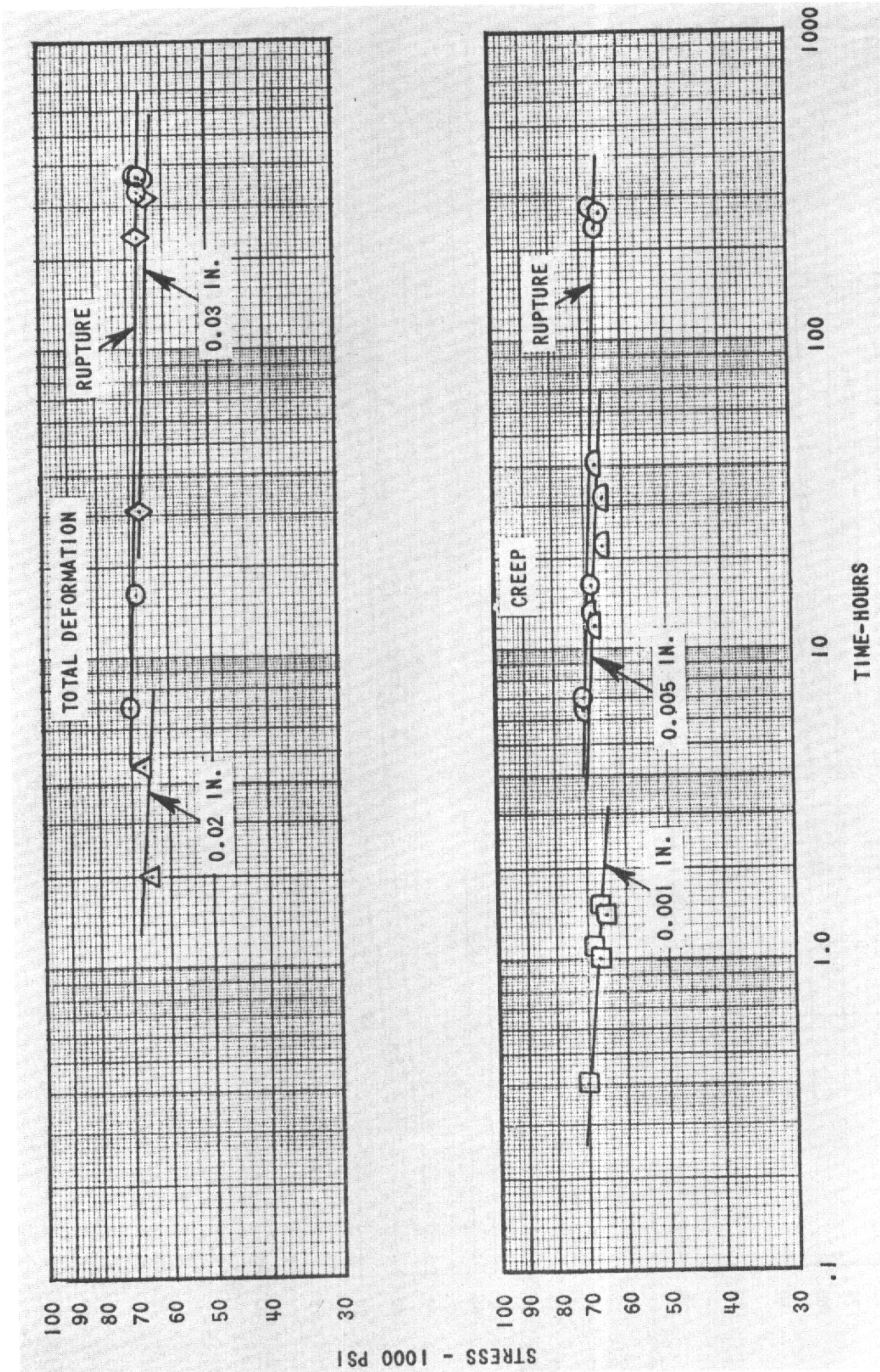


Figure 32 SHEAR PIN CREEP-RUPTURE CHARACTERISTICS OF VACUUM ANNEALED 6AL-4V TITANIUM ALLOY BAR AT 700°F

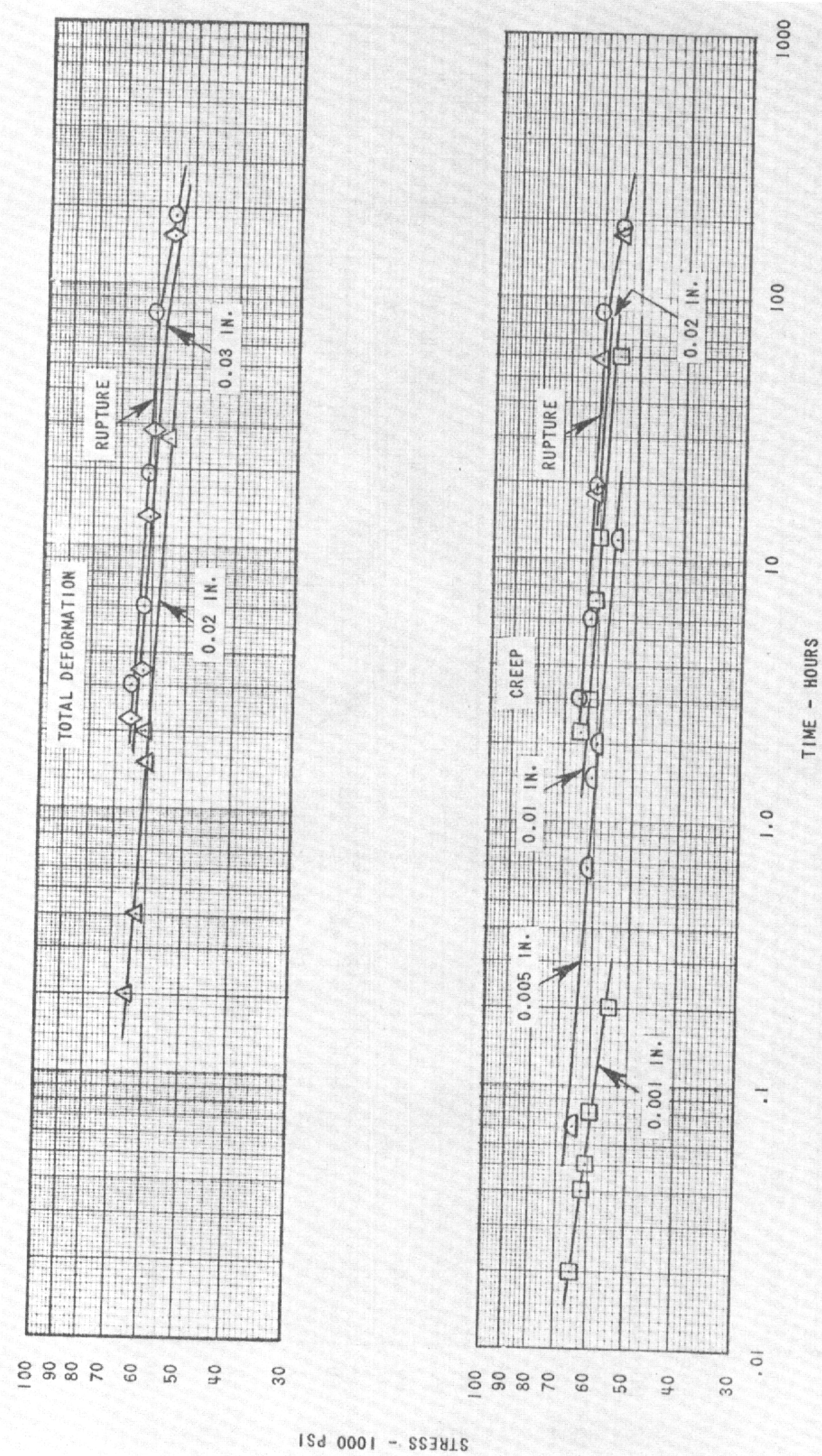


Figure 33 SHEAR-PIN CREEP-RUPTURE CHARACTERISTICS OF VACUUM ANNEALED 6AL-4V TITANIUM ALLOY BAR AT 800°F

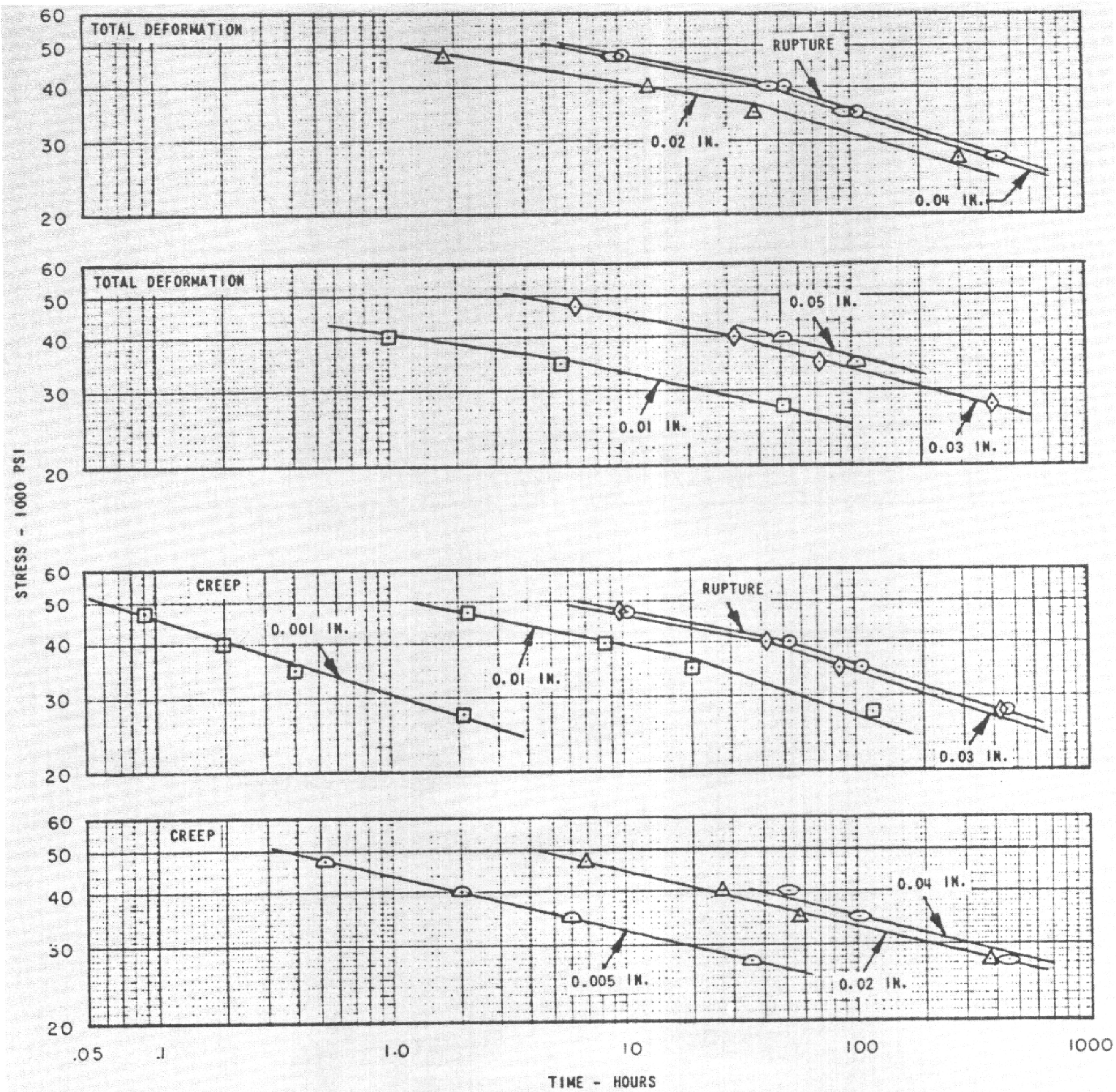


Figure 34 SHEAR-PIN CREEP-RUPTURE CHARACTERISTICS OF VACUUM ANNEALED 6AL-4V TITANIUM ALLOY BAR AT 900°F

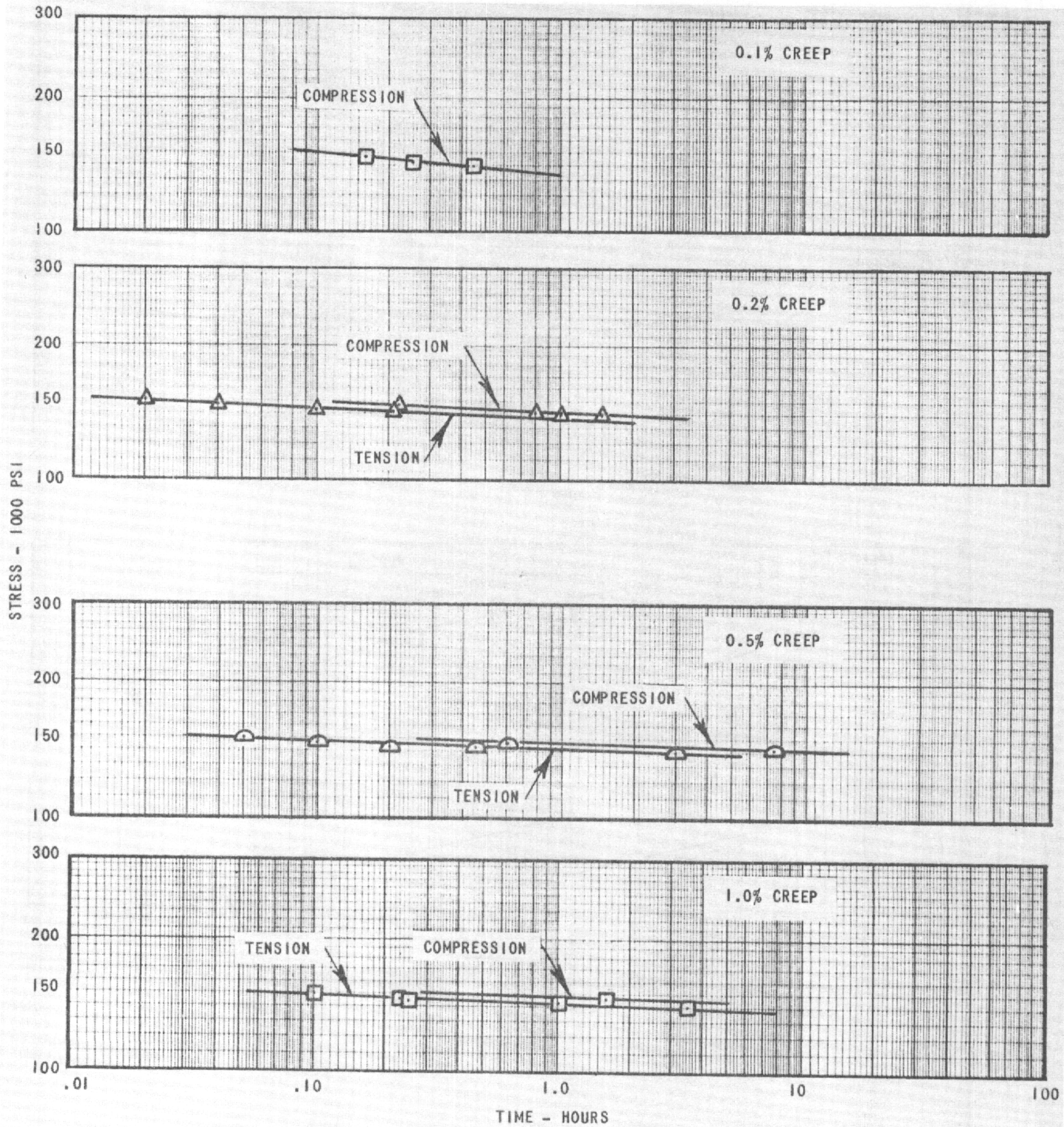


Figure 35 COMPARISON OF TENSION AND COMPRESSION CREEP CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL SHEET IN TH 1050 CONDITION AT 800°F

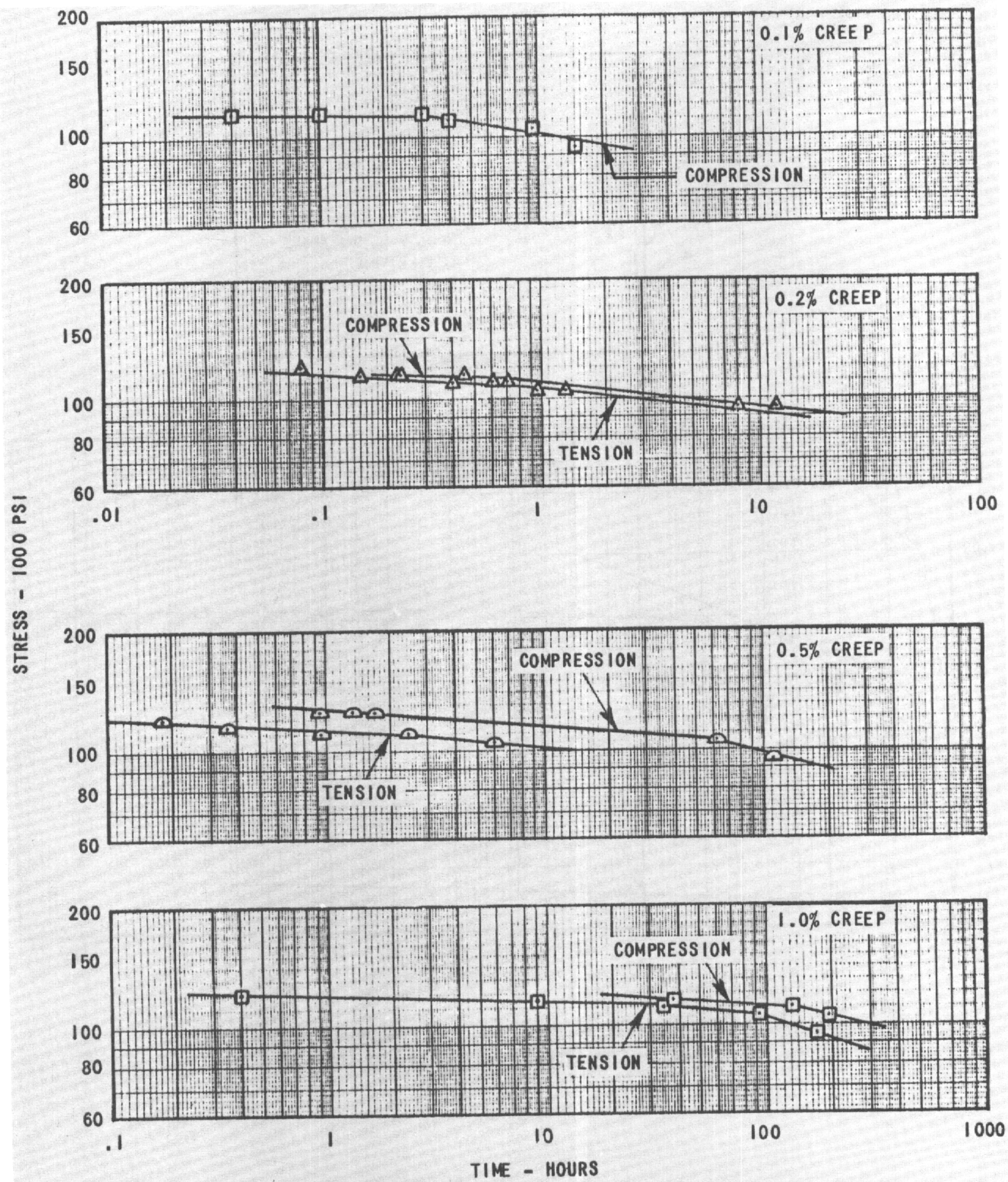


Figure 36 COMPARISON OF TENSION AND COMPRESSION CREEP CHARACTERISTICS OF PH 15-7 Mo STAINLESS STEEL SHEET IN TH 1050 CONDITION AT 900°F

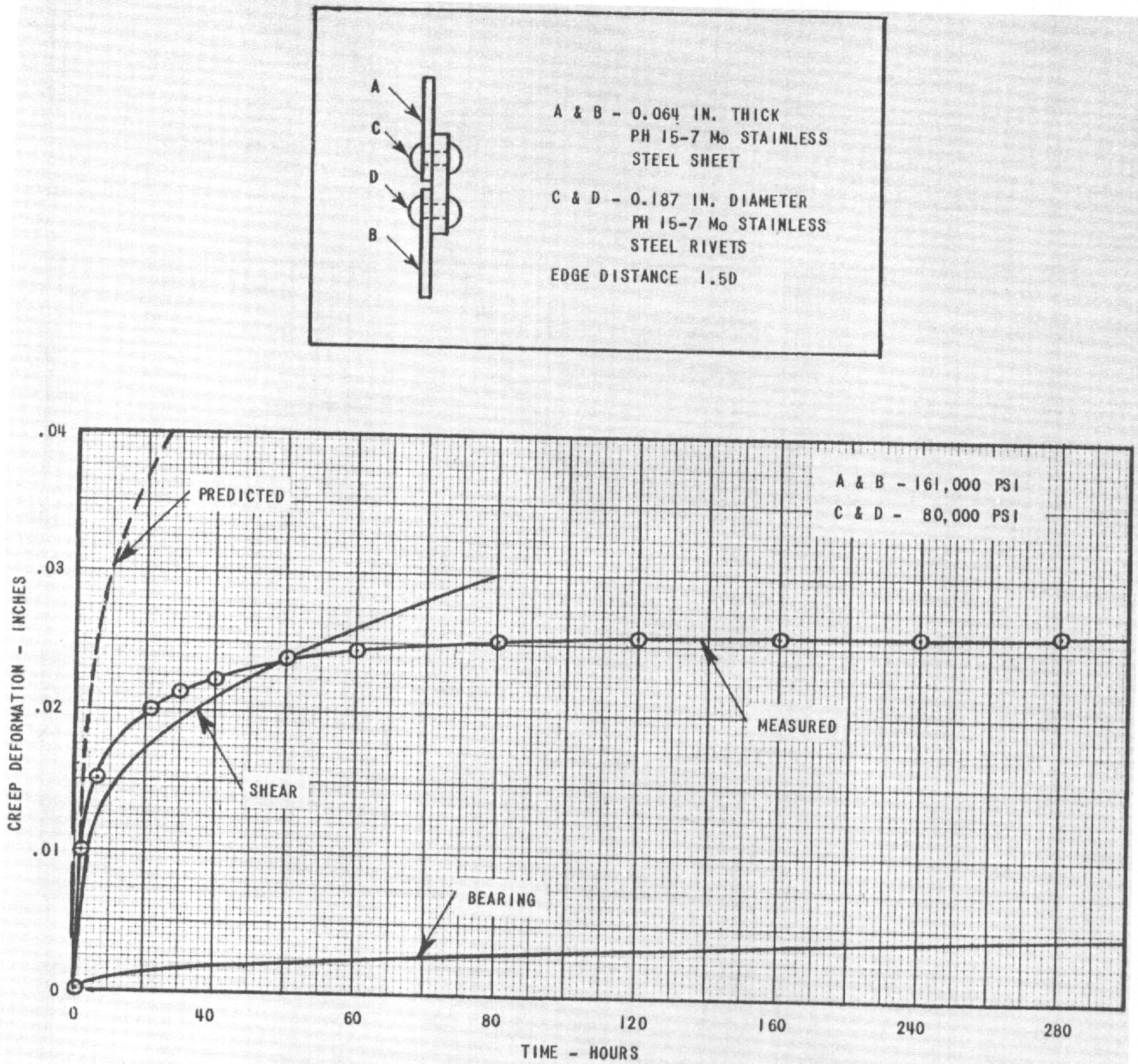


Figure 37 COMPARISON BETWEEN PREDICTED AND MEASURED CREEP BEHAVIOR OF PH 15-7 Mo STAINLESS STEEL JOINT AT 800°F

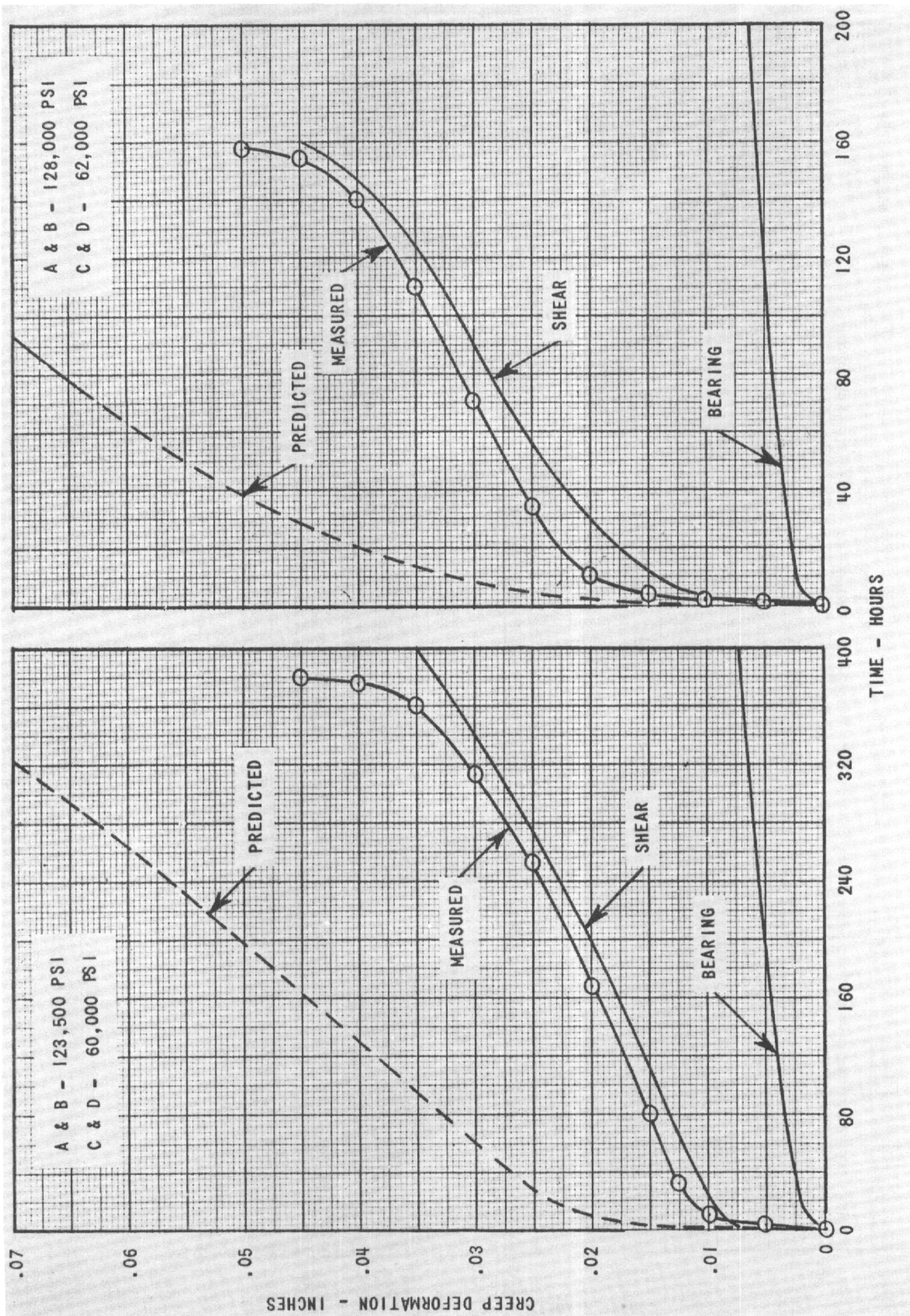


Figure 38 COMPARISON BETWEEN PREDICTED AND MEASURED CREEP BEHAVIORS OF PH 15-7 Mo STAINLESS STEEL JOINTS AT 900°F

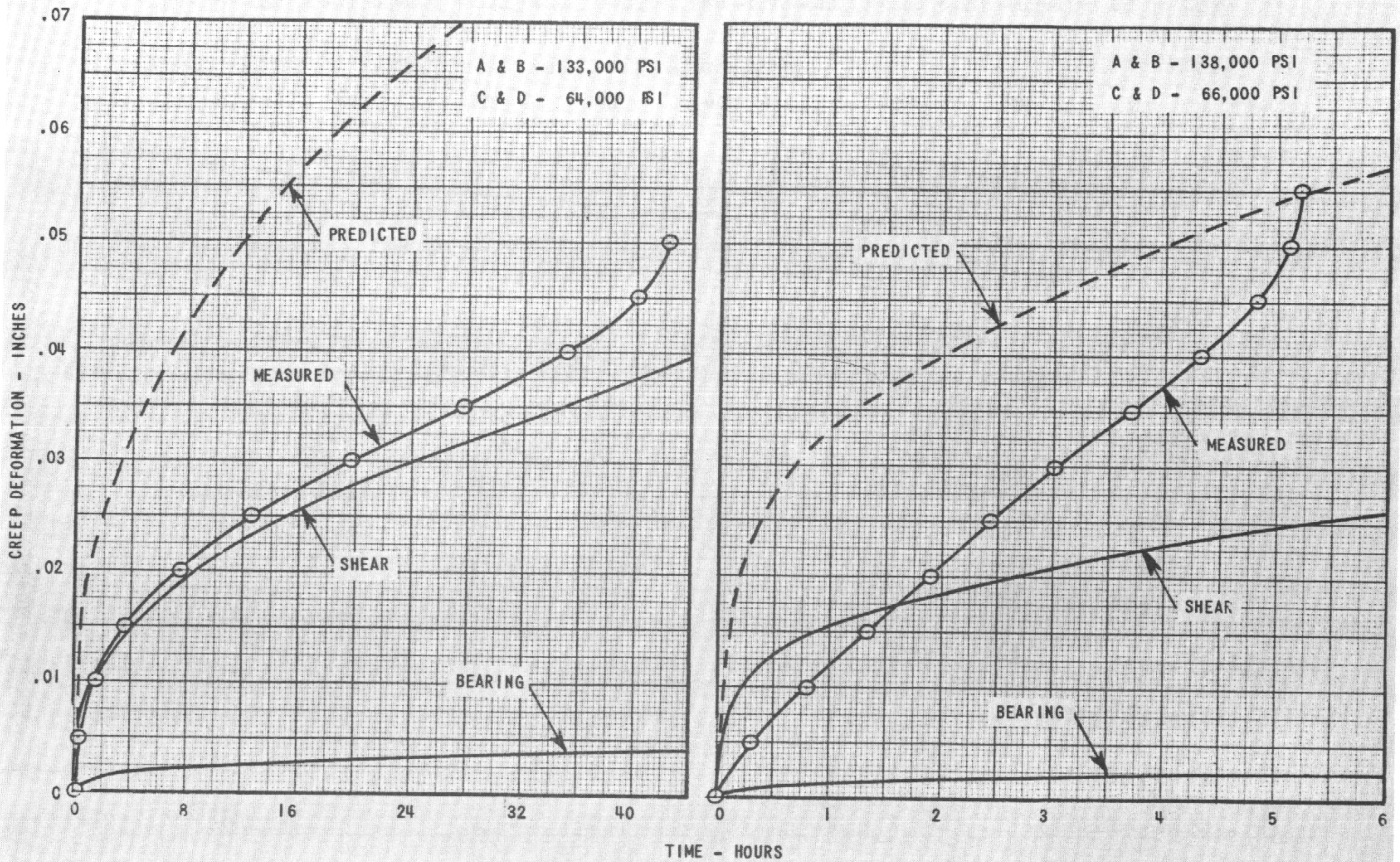


Figure 39 COMPARISON BETWEEN PREDICTED AND MEASURED CREEP BEHAVIORS OF PH 15-7 Mo STAINLESS STEEL JOINTS AT 900°F

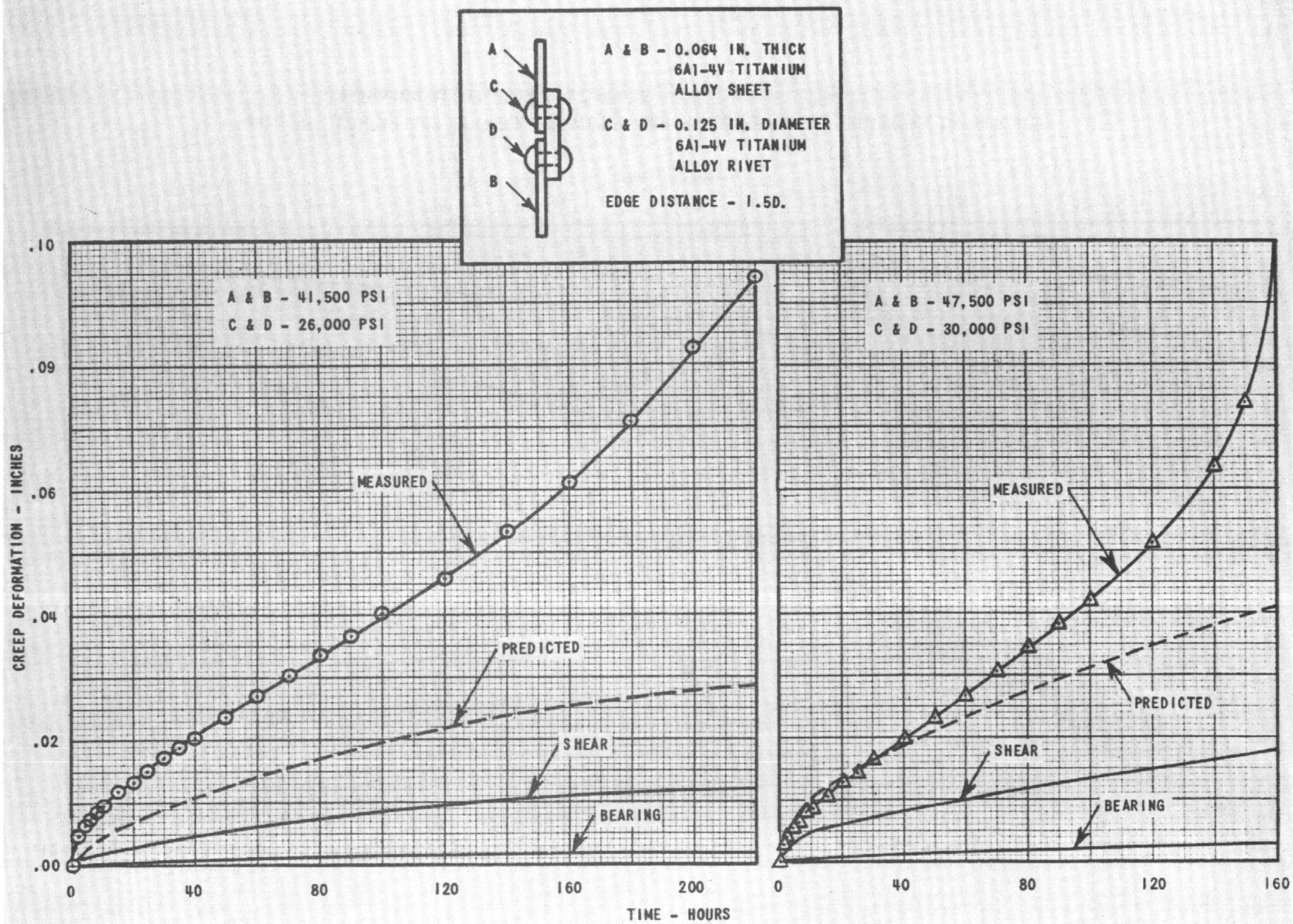


Figure 40 COMPARISON BETWEEN PREDICTED AND MEASURED CREEP BEHAVIORS OF 6Al-4V TITANIUM ALLOY JOINTS AT 900°F

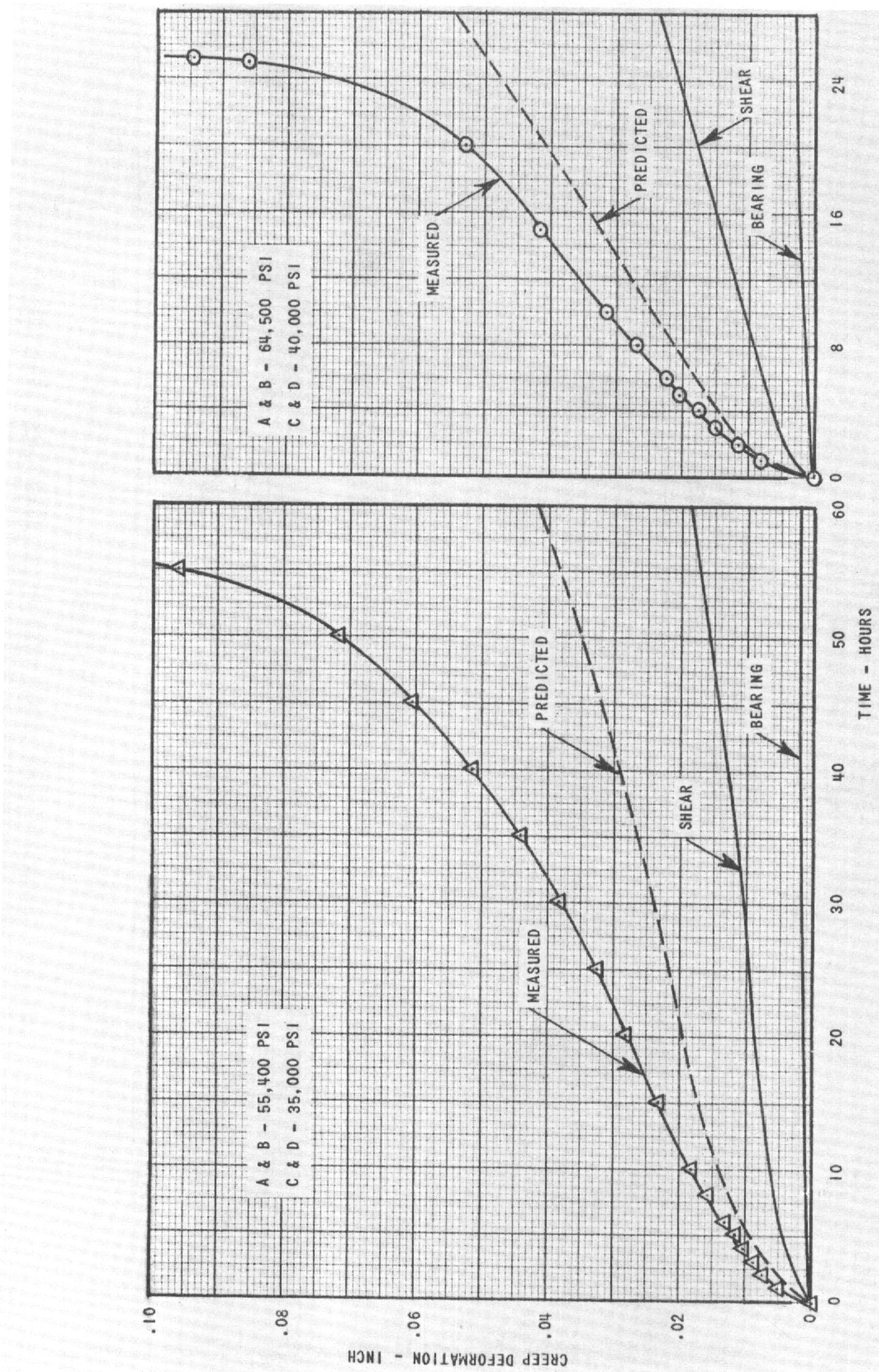


Figure 41 COMPARISON BETWEEN PREDICTED AND MEASURED CREEP BEHAVIORS OF 6Al-4V TITANIUM ALLOY JOINTS AT 900°F

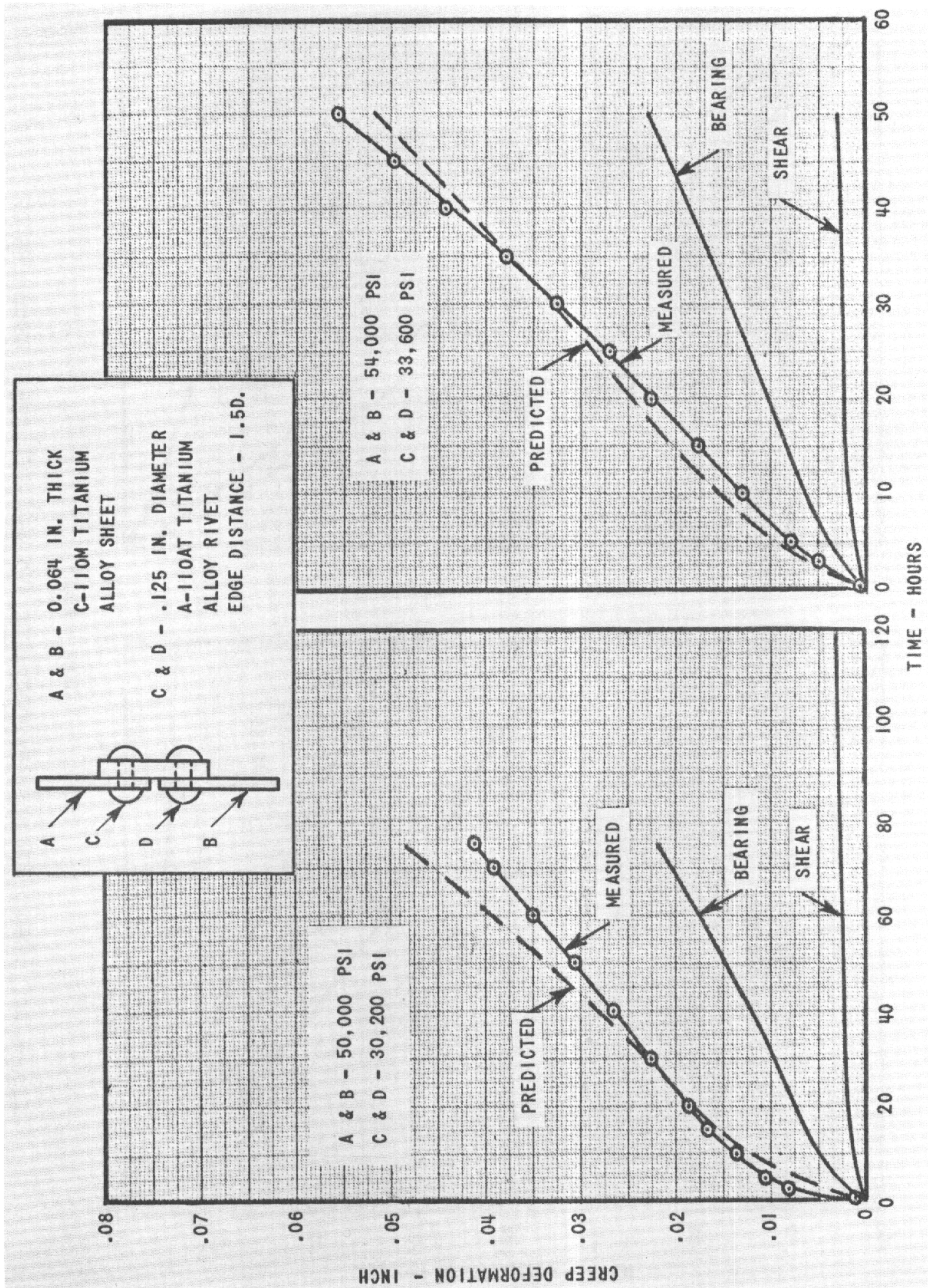


Figure 42 COMPARISON BETWEEN PREDICTED AND MEASURED CREEP BEHAVIORS OF TITANIUM ALLOY JOINTS AT 800°F

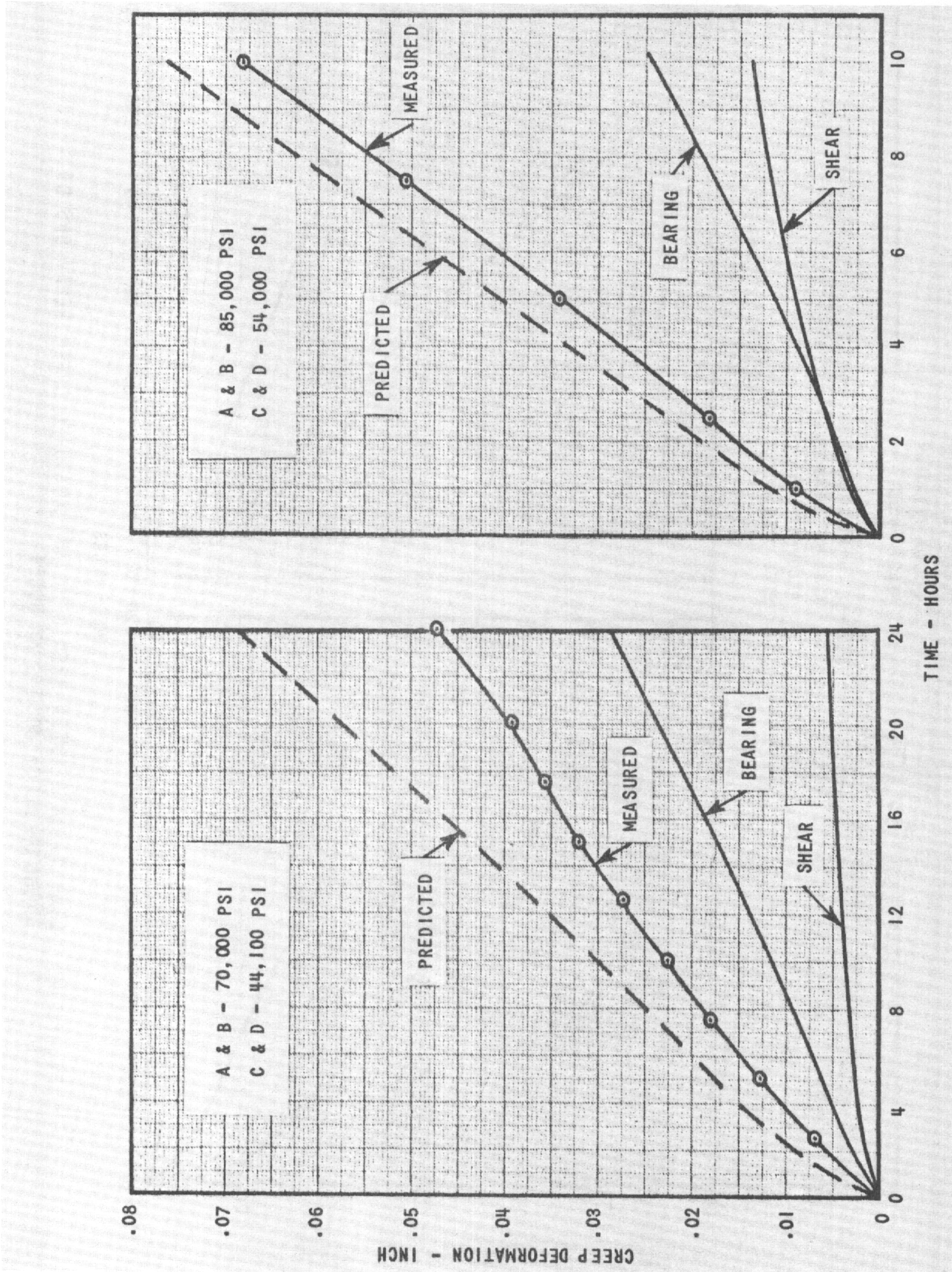


Figure 43 COMPARISON BETWEEN PREDICTED AND MEASURED CREEP BEHAVIORS OF TITANIUM ALLOY JOINTS AT 800°F