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ONSET OF CREEP STRESS MEASUREMENT OF METALLIC MATERIALS

INTERIM REPORT

15 APRIL 1964

NASA CONTRACT NASw-739

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1. INTRODUCTION

Creep deformation versus time records portraying the deformation behavior of metals subjected to constant loads at elevated temperatures show that as increasingly greater loads are applied, an accompanying increase in creep rate takes place. Conversely, when smaller and smaller loads are applied, the creep rates diminish and approach zero at some appreciable load level. In the observations reported herein, those stresses which are present when creep rates are in the neighborhood of the zero value are scrutinized in order to ascertain those stresses at which the creep rates of some metals evidence a zero creep rate condition at various temperatures. For discussion convenience, the threshold stresses just below which creep is not present, and just above which creep is present, at various temperatures is called the onset of creep stress.

2. APPROACH

In the approach taken in this series of observations it is first assumed that creep rates would associate with the amount of plastic strain introduced into metals as a result of loading them for creep testing. Thus to establish a base of departure, stress strain diagrams are developed from load-deformation diagrams resulting from tension tests. These stress-strain curves are drawn with particular attention to those stresses which associate with plastic strains in the 0.05 to 0.5 percent range as observed from load deformation diagrams.

Initial fifty-hour creep tests are made with materials which are loaded at stresses sufficient to produce the initial plastic strains indicated by tension tests. In applying these loads steps to assure their being applied at strain-rates equivalent to those used in tension testing are taken. The results of these initial creep tests are used to determine the range of stresses in which the onset of creep stress is expected to appear in more precise testing.

In those tests in which the onset of creep stresses are finally measured, special procedures embodied in a specially constructed creep test machine are used to control creep test temperatures and the resolution of the creep strain measurements. In the onset of creep stress region the creep strains are quite small, and for their measurement the combination of very sensitive strain sensing devices and extended times which allow cumulative creep to become appreciable are used in ascertaining creep rates.

3. MATERIALS

The eight materials listed below are in test:

1. Ti-8Al-1Mo-1V, Duplex annealed
2. Ti-6Al-4V, Mill annealed
3. Ti-5Al-2 1/2 Sn, Mill annealed
4. AM-350, Condition H
5. AM-355 CRT
6. PH 15-7 Mo, Condition A
7. PH 14-8 Mo, Condition A
8. 18% Nickel Maraging Steel

The materials listed are in the form of 0.050 x 36 x 96-inch sheet. All materials were procured on a commercial basis to obtain production run rather than sample lot representations. Each material was supplied in the scale free condition customary in the supply of commercial product. Any straightening or flattening represented by the sheets was that normal to commercial production. Except for the PH 15-7 Mo and Ph 14-8 Mo steels which were identified as 2D finish, and the AM-355 with its cold rolled finish, all materials were supplied with an annealed, de-scaled and flattened finish.

The chemical compositions of the materials are shown in Table 1. The mechanical properties of the materials in the various conditions reported by sources are listed in Table 2.

4. MATERIALS CONDITIONING

The material conditioning steps required by the various materials are accomplished in the General Dynamics/Convair Materials and Processes Laboratory by laboratory personnel. All furnaces used were surveyed for temperature uniformity in the empty condition prior to use. Furnaces operating at less than 1000°F were within plus or minus 5°F, and those operating in the 1000 to 1850°F range were within plus or minus 15°F. In view of the short time that any material is at temperatures over 1000°F, air atmospheres are used. In all cases the heat treat scale observed is light and mostly distinguished only by discoloration. In order to avoid difficulties from variations in scale removal processes, pickling or etching is not used to improve the appearance of the heat treated materials. Conditioning at sub-zero temperatures, where required, is carried out in isopropyl alcohol-dry ice baths maintained at -100 to -105°F. All tempering and aging treatments at temperatures under 1000°F are carried out in air atmospheres, and pickling or etching for temper discoloration removal is not used to avoid introduction of surface variations peculiar to various surface conditioning processes. Air quenching or cooling is used throughout the conditioning treatments. In all cases the materials are suspended from rods and separated to provide free access of room air to them.

Heat Treatments

Ti-8Al-1Mo-1V. Some early tension and preliminary creep tests were made with material (TMCA Heat V-1555) which was supplied in the single annealed (1450°F, 8 hours, furnace cool) condition. Prior to the use this material was duplex annealed by treating it at 1450°F, 10 minutes and air cooling. The duplex annealed material (TMCA Heat D4539) chiefly used for onset of creep stress testing was obtained from the mill in this condition.

Ti-6Al-4V. This material is tested in the as received, mill annealed condition.

Ti-5Al-2 1/2 Sn. This material is tested in the as received, mill annealed condition.

AM-350. The two sheets of this material were received in Condition H, which represents solution treatment at 1900 to 1975°F and air cooling. Conditioning subsequent to receipt consists of re-solutionizing at 1710°F for 10 minutes and air cooling, hardening by sub-zero cooling at -100°F for 3 hours, and tempering at 850°F for 3 hours and air cooling.

AM-355. This material was received in the CRT condition and is tested in the as received condition.

PH 15-7 Mo. All tests with this material are made with Condition RH-1100 material processed at Convair. This processing involves austenite conditioning (1750°F, 15 minutes, air cooling) the mill annealed, Condition A, as received material. One hour after the austenite conditioned material is cooled to room temperature, it is hardened at -100°F for 8 hours, and then aged at 1100°F for 1 hour and air cooled.

PH 14-8 Mo. The Condition A, as received, mill annealed PH 14-8 Mo used for tests is processed to the RH-1050 condition at Convair. The conditioning used includes austenite treatment at 1700°F, for 1 hour and air cooling; hardening by chilling at -100°F for 8 hours within one hour after the austenite treated material cooled to room temperature; and aging at 1050°F for 1 hour and air cooling.

18% Nickel Maraging Steel. The as received, mill annealed 18 percent nickel maraging steel is conditioned for test by aging at 950°F for 3 hours and air cooling. This aging treatment follows producer recommendation for obtaining 230,000 psi minimum yield strength material.

5. TEST PROCEDURE

Tension Tests

All tension tests are made in a 60,000 pound capacity Tinius Olsen Electromatic universal testing machine. This machine is provided with a Tinius Olsen electronic strain rate controller which can automatically control the strain rate within predetermined limits (ordinarily 0.003 to 0.007 inch per minute). Automatic strain rate control, however, is not used in making these tests. Instead the unit is used as a strain pacer and by manually adjusting drive speeds with the infinitely variable Thymotrol speed control, these tests are made at a strain rate of 0.0045 to 0.0055 inch per inch per minute. Calibrations with Morehouse proving rings show the weighing accuracy of the machine better than plus or minus one-half of one percent.

All elevated temperature tension tests are heated in a 10-inch wide by 18-inch high by 24-inch deep, electrically heated, forced convection, box-type, testing machine furnace. The temperature control for this unit is effected by a thermocouple attached to the test specimen. This thermocouple actuates a strip-chart potentiometer-controller of 1/3 of 1 percent full scale accuracy which has its on-off mercury switches adjusted for plus or minus 2°F operation. These switches regulate the on-off power supply for the furnace heaters. The furnace itself is held to plus or minus 5°F temperature variation when surveyed in the empty condition. The iron-constantan thermocouples used with this unit are point checked against Bureau of Standards secondary standard thermocouples in a Leeds and Northrup deep well furnace. Leeds and Northrup K-2 potentiometers are used throughout calibrations.

Strain pick up in tension testing utilizes modified Baldwin clamp-on reach rod assemblies which actuate Tinius Olsen Type S1, ASTM Type B, differential transformer extensometers. These extensometers have an accuracy of one part in ten thousand and are calibrated with a Tinius Olsen extensometer calibrating, super-micrometer device.

In the performance of tests, a tare load is applied to assure take up of slack in gripping devices and proper seating of spherical grip mounts. Then the extensometer is attached and the test is carried out at the desired strain rate throughout the desired range of strain, whereupon the extensometer is removed and fracture is accomplished with a cross-head travel rate of 0.05-inch per minute.

Tension test specimen configuration is shown in Figure 1.

Creep Tests

Arcweld Model J and XJ 12,000-pound capacity creep test machines are used in preliminary creep testing. The calibration of these machines with Morehouse proving rings shows their accuracy to be one-half of one percent or better. The heat required for testing is supplied by Arcweld cylindrical vertical tube, electrically heated furnaces. Temperature surveys with normal furnace arrangements show them capable of maintaining temperatures within plus or minus 5°F. When these arrangements are augmented with additional external insulation and plugs inserted in the top and bottom openings, temperature variations of plus or minus 2°F are attainable. Temperature regulation during creep test is accomplished by a chromel-alumel thermocouple attached to the center of specimen gage lengths. This termocouple actuates a 1/3 of 1 percent full scale accuracy potentiometer controller which governs the on-off input of furnace power. In addition to the control thermocouple, recording thermocouples are attached at each end of the gage length of the specimens. The recording thermocouples serve chiefly to advise need for improved external insulation and plugging to optimize furnace temperature distribution.

The strain pick-up from creep specimens is done with Arcweld Model A-210 creep extensometers. These units consist of clamp-on reach rod devices which mechanically transfer strain indications to an externally positioned differential transformer extensometer. The extensometer output is amplified and modulated to provide input to a multi-point 1/3 of 1 percent full scale, strip-chart recorder which maintains a continuous record of the creep strains.

Loads are applied to the creep test machines by dead weights. In normal operation dead weight loading is accomplished by a weight elevator which supports the dead weights as they are applied, and permits a slow lowering of the weights for applying their force to the specimens. In this series of tests the application of weights by means of the elevator was unsatisfactory. In order to overcome the disadvantage of the elevator loading method, the dead weights are counterbalanced, and after the elevator has retracted the counter weights are slowly removed. The counter weight consists of a hopper bottomed bucket fitted with an adjustable opening at the hopper. In use this container is filled with small lead shot, and these are slowly metered out to provide a slow rate of load application. Ordinarily load application times range four to seven minutes.

Figure 1 shows the specimen configuration used for these tests.

Onset of Creep Stress Tests

Onset of creep stress test procedure is described in General Dynamics/Convair Report GD/C-64-(in preparation.).

6. TEST RESULTS

Tension test results with the eight materials listed above are given in Tables 2 to 10. Table 10 lists the 0.01 percent plastic strain stresses which were obtained when initial creep tests showed a general tendency for creep to assert its presence when stresses equivalent to those required to produce 0.05 percent plastic strain in tension tests were used. Figures 2 to 9 chart Table 1 to 9 data averages. Figures 10 to 16 show the modulii of elasticity used for stress strain diagram preparation.

Tables 12 to 36 summarize preliminary creep test results for Ti-8Al-1Mo-1V, Ti-6Al-4V, Ti-5Al-2 1/2 Sn, AM-350, and PH 15-7 Mo materials. Figures 10 to 34 chart the Table 11 to 35 data and indicate the trends observed in these tests.

7. DISCUSSION OF RESULTS

Tension Tests

Ti-8Al-1Mo-1V Duplex Annealed. The data shown in Table 3 and Figure 2 display stress-strain behavior in keeping with anticipations through the 450 to 600°F range. In this temperature range the stresses required to produce given amounts of strain decreased as temperatures increased without significantly altering the afine relationships of the stress strain curves. At 650°F, however, the stress-strain behavior changed somewhat and an increased tendency for the material to strain-harden early in the straining process was observed. This change in behavior occurred before the yield strength offset occurred and suggested that the proportional limit of the material was changed as a result of microstructural alterations in the material. Beyond the yield strength offset, the stress-strain behavior of the material at 600 and 650°F was practically identical. In keeping with the hypothesis that onset of creep stresses associate with the proportional limits of materials, it was expected that the onset of creep stress for this material at 650°F would slightly exceed that found at 600°F, but still be less than that appearing at 550°F.

Ti-6Al-4V Annealed. Table 4 and Figure 3 data show Ti-6Al-4V stress-strain behavior in keeping with expectations throughout the 450 to 650°F temperature range. The peculiarity of the 500, 550 and 600°F curves to "sag" at strains at and above yield strength strains is asserted in the data, but is of small magnitude, and apparently indicates data scatter rather than any significant physical event.

Ti 5Al-2 1/2 Sn Annealed. The data shown in Table 5 and Figure 3 display stress-strain behavior features of Ti-5Al-2 1/2 Sn not in keeping with normal expectations. The tendency of this alloy to display stress-strain behavior akin to that exhibited by mild steel, especially at 450, 500 and 550°F is shown in the curves. This behavior is not surprising since it has been observed before on occasion by the writer in the inspection of titanium alloys at room temperature. The incidence of this behavior at 450°F and its disappearance at 600°F is of possible interest in the behavior of structural elements, but other than causing some possible distortion of proportional limit-temperature relationships would not seem to exert much effect on conditions associated with the onset of creep. The tendency for this alloy to strain harden rapidly at 650°F, like Ti-8Al-1Mo-1V, also is shown by the curves.

AM-350 SCT. The surprisingly large scatter found with this alloy undoubtedly is reflected in the data shown in Table 6 and Figure 5. In verifying the outcome of heat treatments applied to this alloy, the scatter in the room temperature tension tests were disturbing enough to warrant re-calibration checking of the equipment used for heat treatment. Repeated heat treatments did not diminish the scatter in the several tests which all represented material from a single sheet. The stress-strain curves shown in Figure 5 resemble those characteristic of non-heat treatable austenitic stainless steels, and although the yield strengths are high, the proportional limits suggested are low. The tendency for this alloy to exhibit increased strain-hardening behavior also is shown in Figure 5. Consultation with the material supplier did not aid in clarifying the situation described.

AM-355 CRT. Table 7 and Figure 6 display stress-strain data for AM-355 CRT. In general these curves resemble those shown for AM-350 SRT. Although this material exhibits much less scatter in properties, especially in the region of and above the yield strength, some variation, especially at 600°F, in the strain hardening behavior of the alloy was observed. The tendency for elevated temperatures to cause severe elongation drop-offs is shown by the data. This suggests desirability of fracture toughness and impact testing at the temperatures noted to confirm the material's reliability.

PH 15-7 Mo Condition RH 1100. Stress-strain data for PH 15-7 Mo Condition RH 1100 are shown in Table 8 and Figure 7. Figure 7 curves generally display characteristics expected in aged or tempered martensitic alloys. The confusion of the Figure 7 curves is attributed both to data scatter, and insensitivity of the stress-strain behavior of the material to temperature variation in the range under observation. The tendency for elevated temperatures to cause appreciable elongation drop-offs is shown by the data and suggests the possible desirability of fracture toughness and impact testing at the temperatures noted to confirm the material's reliability.

PH 14-8 Mo Condition RH 1050. Table 9 and Figure 7 exhibit stress-strain data for PH 14-8 Mo, Condition RH 1050. These data show the generally parallel stress-strain behavior of this alloy with that of PH 15-7 Mo, Condition RH 1100. The tendency for elevated temperatures to curtail the elongation of PH 14-8 Mo, Condition RH-1050 is not evident as it was with PH 15-7 Mo, Condition RH 1100. The already low elongation of the alloy was not affected in significant amount by heating. The low elongations at elevated temperature suggest, however, a desirability for fracture toughness and impact testing at the higher temperatures to assure the metal's dependability.

18% Nickel Maraging Steel. Stress-strain data for 18% Nickel Maraging Steel are given in Table 10 and Figure 9. The stress-strain characteristics of this material closely resemble those of a tempered martensitic steel. In view of the highly alloyed composition of the 18% nickel maraging steel the uniformity of the data in the region of and above the yield strength offset is surprising. The low elongations exhibited by the material at room and elevated temperatures is noteworthy. Although existing data indicates that the toughness of this alloy is quite good at room temperature, elevated temperature fracture toughness and impact tests appear necessary to establish the dependability of the material.

General Comment. The elastic modulus data used in preparing the stress strain curves of Figures 2 to 9 are shown in Figures 10 to 16. Elastic modulii are not shown for PH 14-8 Mo steel. These data are not available from the material producer, and PH 15-7 Mo modulii are used for stress-strain curve preparation.

Creep Tests

Introductory Comment. The creep tests discussed here are performed in conventional creep testing equipment with tension type specimens provided with 2-inch gage length sections. These tests are carried out in accordance with ASTM and ARTC practices in vogue. The strain measuring equipment used is equivalent to ASTM Type B extensometers. The strains are measured continuously throughout a 50-hour test period, but for data recording purposes only selected points representative of the progress of primary and secondary creep are transferred to working charts. The secondary creep data given below represent the slope of a faired straight-line secondary creep curve which extends from the point of initiation of secondary creep to the 50-hour point. For convenience in calculating creep rates, the secondary creep curve is projected to the zero-time axis and curve slopes are taken over the full 50-hour period.

Throughout the creep testing discussed below, the appearance or non-appearance of creep was not orderly. In some cases creep would appear in one of a pair of duplicate tests and not in the mate. In other cases creep would disappear at one stress, to appear again at a lower stress. This was taken to indicate that the variations present in the materials themselves are great and although variations in testing practice probably did influence test outcomes to a degree, it is believed in view of precautions observed in testing that material "scatter" exerts the predominant effect upon the data.

The somewhat erratic occurrence of significant data requires performance of tests in greater numbers than originally expected. These occurrences also show that caution must be exercised in determining the stress at which creep disappearance occurs at various temperatures in various materials. In general this means that enough tests should be made to provide a sufficient number of data points to establish stress versus creep rate curves, and to assure that the lower stresses at which creep disappearances are observed are in fact those at which creep disappearance is present.

Ti-8Al-1Mo-1V Duplex Annealed. Stress versus creep rate data for Ti-8Al-1Mo-1V are listed in Tables 12 to 16 and plotted in Figures 17 to 21. In the charts only those points at which creep occurred are plotted. Notations, however, indicate those stresses at which non-occurence of creep was observed. Figure 17 shows the results of creep tests run at 450°F. Of six tests run, three resulted in data points which were insufficient to define a trend, although the decrease in creep with decrease in stress appeared orderly. Figure 18 illustrates a case at 500°F where the disappearance of creep took place at one stress, only to appear at a lower stress. Figure 19 representative of conditions at 550°F indicates a somewhat orderly decrease of creep rate as stresses decreases along with the tendency for the data to scatter in characteristic fashion. Figures 20 and 21 represent conditions found at 600 and 650°F which are typical of the behavior of the material.

The tests with Ti-8Al-Mo-1V were made at stresses equivalent to those required to produce plastic strains from 0.05 to 0.25 percent in tension tests. These tests show the tendency for the alloy to evidence creep susceptibility in the presence of appreciable plastic strain resulting from load application. In the single instance where a stress lower than that required to produce 0.01 percent plastic strain in tension tests was used, creep was evidenced. This vaguely hinted that plastic strain in this amount could be associated with creep activity.

Ti-6Al-4V Annealed. Stress versus creep rate data for Ti-6Al-4V are listed in Tables 17 to 21 and charted in Figures 22 to 26 largely reiterate the conditions found in tests with Ti-8Al-1Mo-1V. In the case of the Ti-6Al-4V tests run at 500°F the appearance of creep arrest at a stress between those required to produce 0.01 and 0.05 percent plastic strain in tension tests was counter to the general observation that creep occurs in the presence of appreciable plastic strains.

Ti-5Al-2 1/2 Sn Annealed. Tables 22 to 26 list stress versus creep data, and Figures 27 to 31 chart this data for Ti-5Al-2 1/2 Sn. Because the experiences related above strongly suggested that creep initiates in the presence of stresses required to produce strains of 0.01 percent or less in tension tests, and because of the peculiarities of the Ti 5Al-2 1/2 Sn stress strain curves (Figure 4), the stresses used for searching out the creep arrest stress for Ti 5Al-2 1/2 Sn and subsequently discussed materials were found by ratioing the yield strength of the material under test. Usually the search started at 80 percent of the yield strength and proceeded by bracketing in 5 and then 2 1/2 percent increments. In the case of Ti 5Al-2 1/2 Sn this approach to an extent simplified the estimation of the creep arrest stress region. The method however was not productive of a greater number of data points for curve plotting since the material continued to creep or not creep at given stresses according to specimen idiosyncrasies. In general these tests shows that creep arrest could be expected at stresses slightly under the stress required to produce 0.01 percent strain in tension tests.

AM-350 SCT. The stress versus creep rate data in reduced form at writing are shown in Tables 27 to 31 and Figures 32 to 36. Although these data are sketchy, they contain the suggestion that creep arrest can be expected at some stress less than that required to produce 0.01 percent plastic strain in tension tests.

PH 15-7 Mo Condition RH-1100. The stress versus creep rate data in reduced form at writing are shown in Tables 32 to 36 and Figures 37 to 41. These data also are sketchy and they contain the same suggestions that the AM-350 SCT data contain.

In running creep tests with PH 15-7 Mo, Condition RH 1100 at 120 ksi stress and 450°F a condition of negative creep was found at the end of 50-hour tests. Consultation with the material supplier indicated that this was an uncommon occurrence which could be attributed to austenite transformation induced by the high testing stress and fostered by the materials conditioning at 1100°F.

8. CONTINUATION OF EFFORT

Prior work at this facility indicates that the initial loading to which a structure is subjected at elevated temperature results in a profound effect upon its deformation history. Chief among these is the work hardening effect of the initial loading which establishes a pseudo-elastic limit according to the maximum stress applied. In other words the greater the initial stress, the greater will be the pseudo-elastic range within which the material will work upon subsequent reloadings which do not exceed the initial maximum stress. It is of interest to note that under these conditions the greater part of the plastic deformation from load application will take place in the initial loading of the structure. It is also known that the establishment of a pseudo-elastic limit does not arrest creep activity and its attendant capacity for producing additional time dependent plastic deformation. It is not known how the magnitude of the pseudo-elastic limit affects creep rates.

In the present work the determination of those stresses at various temperatures wherein creep thresholds occur are of primary interest, and are the search objective. In performing this work it is recognized that stress-strain diagrams detail considerable of the structural behavior of materials and that in relating such things as creep behavior to stress-strain diagrams convenient engineering estimations may be provided.

Accordingly in further study of the creep and stress-strain information at hand and becoming available re-study of stress-strain data in the 0.01 to 0.05 percent plastic strain range will be made to attempt better portrayal of stress-versus plastic strain conditions. With better data of this kind at hand and information from creep tests which are informative of stresses required to induce creep activity, it appears possible to relate the two in terms of plastic strains and thus shed light on maximum stresses desired in creep resistant structures.

TABLE 1. C

Material	C	Mn	P	S	Si	Cr
Ti-8Al-1Mo-1V	0.026					
Ti-8Al-1Mo-1V	0.022					
Ti-6Al-4V	0.023					
Ti-5Al-2 1/2 Sn	0.025					
AM-350	0.096	0.75	0.015	0.010	0.27	16.64
AM-355	0.12	0.77	0.021	0.009	0.34	15.35
PH 15-7 Mo	0.075	0.56	0.016	0.013	0.35	14.98
PH 14-8 Mo	0.037	0.36	0.004	0.002	0.34	14.71
18% Ni M.A.S.*	0.017	0.04	0.003	0.008	0.05	

*18% Nickel Maraging Steel. Ti - 0.52%, Zr - 0.005%, Ca - 0.01%

HEMICAL ANALYSES OF MATERIALS

Ni	Mo	V	Sn	Al	Fe	N_2	H_2	O_2	Cu	Co
	1.10	1.04		7.77	0.09	0.011	0.015	0.085		
	1.1	1.0		7.6	0.08	0.012	0.014			
		4.1		5.9	0.12	0.016	0.006			
			2.3	5.2	0.33	0.015	0.006			
4.30	2.79					0.096				
4.62	2.73					0.095				
7.98	2.16			1.06						
8.12	2.25			1.21						
17.21	4.87			0.18					0.13	7.97

TABLE 2. MECHANICAL PROPERTIES OF MATERIALS

Material	Heat No.	Condition	Mechanical Properties		
			Yield Strength KSI	Ultimate Strength KSI	Elongation %
Ti-8Al-1Mo-1V	V-1555 (a)	Single Annealed	148.5	153.4	11.5
		Duplex Annealed	138.5	149.2	10.0
	D-4539 (a)	Duplex Annealed	134.5	149.9	14.0
Ti-6Al-4V	D-4321 (a)	Mill Annealed	134.0	139.0	13.0
Ti-5Al-2 1/2 Sn	D-2242 (a)	Mill Annealed	127.5	132.1	16.3
AM-350	55431 (b)	Annealed	49.1	132.2	46.0
		SCT	172.6	204.7	16.0
		D.A.	151.6	178.3	13.0
AM-355	55467 (b)	CRT	231.0	236.0	15.0
PH 15-7 Mo	890681 (c)	Annealed	54.5	133.3	25.0
		TH	195.0	201.5	8.0
		RH	218.5	236.5	6.0
PH 14-8 Mo	33570 (c)	Annealed	54.5	133.3	25.0
		SRH-950	208.2	229.0	5.0
		SRH-1050	199.5	205.0	6.0
18% Ni M.A.S.	X15400 (d)	As Shipped	124.4	164.2	5.0
		950° F. - 3 hr. age	231.3	249.5	2.5

(a) Titanium Metals Corporation of America
(b) Allegheny Ludlum Steel Corporation
(c) Armco Steel Corporation
(d) United States Steel Corporation

TABLE 3. MECHANICAL PROPERTIES OF Ti-8Al-1Mo-1V* AT 450 to 650°F

Temp °F		Offset-Percent									Ultimate Strength KSI	Elongation % in 2"
		0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50		
		Stress-KSI										
450		85.6	89.5	92.2	93.6	94.3	94.9	95.3	95.5	95.7	95.9	113.0	12.0
		87.3	90.7	92.7	93.8	94.6	95.2	95.6	95.9	96.3	96.5	112.0	11.0
		82.0	88.4	91.8	92.6	93.3	93.8	94.1	94.5	95.0	95.2	111.1	11.5
	Ave.	84.9	89.6	92.2	93.3	94.1	94.6	95.0	95.3	95.7	96.2	112.0	11.5
500		79.6	85.9	88.9	90.7	91.7	92.1	92.4	92.8	93.1	93.1	109.5	11.0
		83.1	86.8	89.4	90.6	91.8	92.2	92.5	92.7	93.0	93.0	110.0	10.5
		83.9	87.8	90.3	91.6	92.2	92.4	92.6	93.2	93.4	93.4	109.5	11.5
	Ave.	82.2	86.8	89.5	91.0	91.9	92.2	92.5	92.9	93.2	93.2	109.7	11.0
550		83.6	84.3	86.2	87.9	88.9	89.3	89.7	89.8	90.4	90.6	108.4	11.0
		76.9	81.4	84.6	86.3	87.6	88.2	88.4	89.0	89.3	89.5	106.7	12.0
		82.0	86.0	87.3	88.1	88.6	89.0	89.4	89.8	90.2	90.5	106.7	11.0
	Ave.	80.8	83.9	86.0	87.4	88.3	88.8	89.1	89.2	90.0	90.2	107.3	11.3
600		76.9	81.3	84.2	85.9	86.5	87.1	87.2	87.6	88.0	88.4	104.2	11.0
		69.8	76.4	79.3	82.1	84.0	85.4	86.1	86.8	87.0	87.3	104.7	12.0
		75.9	79.7	82.4	84.4	85.4	85.9	86.3	86.7	87.3	87.7	103.9	11.0
	Ave.	74.2	79.2	82.0	84.1	85.3	86.1	86.6	87.7	87.5	87.8	104.3	11.3
650		76.0	80.7	82.8	84.5	85.1	86.0	86.5	86.8	87.4	88.0	102.9	11.0
		76.0	79.8	81.9	83.6	84.4	85.5	85.9	86.3	86.9	87.6	102.4	11.0
		76.6	81.1	83.4	84.7	85.3	86.2	86.4	86.8	87.4	87.8	102.4	11.0
	Ave.	76.2	80.6	82.7	84.3	84.9	85.9	86.3	86.8	87.2	87.8	102.6	11.0

*Heat No. 0.050" x 36" x 96" Sheet; Double Annealed.

TABLE 4. MECHANICAL PROPERTIES OF Ti-6Al-4V AT 450 TO 650° F

Temp °F		Offset-Percent 0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	Ultimate Strength KSI	Elongation % in 2"
		Stress-KSI											
450		100.2	100.3	99.7	99.6	100.1	99.7	99.9	100.0	100.2	104.3	121.7	11.0
		95.2	99.5	100.7	101.5	101.3	101.2	101.6	101.7	101.7	101.7	117.9	11.0
		104.5	106.9	107.3	106.4	105.8	105.6	106.0	106.0	106.0	106.2	120.4	10.0
	Ave.	100.0	102.2	102.6	102.5	102.4	102.2	102.5	102.6	102.6	104.1	120.0	10.7
500		95.2	96.5	96.6	96.5	96.6	96.9	97.2	97.4	97.8	98.0	111.7	9.5
		93.5	95.0	95.0	95.0	95.2	95.5	95.8	96.0	96.2	96.2	109.3	10.0
		94.0	94.8	94.5	94.9	95.1	95.2	95.5	95.7	96.1	96.5	112.2	9.5
	Ave.	94.2	95.4	95.4	95.5	95.6	95.9	96.2	96.4	96.7	96.9	111.1	9.7
550		86.6	89.5	90.7	91.4	91.6	92.0	92.4	92.8	93.1	93.5	107.8	8.5
		91.6	92.6	92.7	92.8	93.5	93.8	94.3	94.6	94.9	95.3	110.3	9.5
		88.0	91.4	92.3	92.7	92.8	93.1	93.5	94.1	94.3	94.7	111.6	8.8
	Ave.	88.7	91.2	91.9	92.3	92.6	93.0	93.4	93.8	94.1	94.5	109.9	8.9
600		88.7	90.3	90.4	91.5	91.5	91.7	91.8	92.5	93.1	93.5	105.7	8.3
		89.8	90.4	90.7	91.0	91.5	92.1	92.7	93.1	93.6	93.9	105.9	8.8
		83.5	87.9	89.9	89.9	90.6	91.0	91.6	92.0	92.6	93.4	106.5	9.0
	Ave.	87.3	89.5	90.3	90.8	91.2	91.6	92.0	92.5	[illegible]	93.6	106.0	[illegible]
650		73.8	82.3	[illegible]	86.8	88.0	88.5	88.9	89.3	[illegible]	90.2	103.1	8.5
		80.5	86.6	89.4	90.6	90.8	91.7	92.3	92.8	[illegible]	93.4	105.0	9.0
		88.0	88.1	88.6	89.0	89.1	89.7	90.2	90.8	[illegible]	91.4	103.5	[illegible]
	Ave.	80.8	85.7	87.7	88.8	89.3	90.0	90.5	91.0	91.3	91.7	103.9	8.5

TABLE 5. MECHANICAL PROPERTIES OF Ti-5Al-2 1/2 Sn AT 450 TO 650° F

Temp °F		Offset-Percent										Ultimate Strength KSI	Elongation % in 2"
		.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50		
		Stress-KSI											
450		88.3	84.6	84.0	83.0	81.8	80.8	80.1	79.3	79.3	79.3	95.3	19.0
		81.5	80.6	79.6	78.5	77.2	75.6	75.0	75.5	75.5	75.6	94.8	21.0
		84.0	82.9	81.6	80.1	79.2	78.9	79.1	79.2	79.2	79.3	93.9	18.0
	Ave.	82.9	82.7	81.7	81.4	79.4	78.4	78.1	78.0	78.0	78.1	94.7	19.3
500		78.8	78.8	78.3	78.0	77.7	77.2	76.7	76.0	75.3	75.9	94.0	18.0
		80.8	80.4	79.5	78.9	77.9	77.5	77.1	76.9	76.8	76.8	93.2	18.0
		78.5	78.5	78.4	78.2	78.0	77.8	77.5	77.3	76.6	76.4	95.2	17.5
	Ave.	79.4	79.2	78.7	78.4	77.9	77.5	77.1	76.7	76.2	76.4	94.1	17.8
550		74.8	74.9	74.4	74.1	73.8	73.6	73.5	73.4	73.4	73.4	91.0	19.0
		74.7	75.7	75.8	75.8	75.4	75.0	74.7	74.4	74.3	74.1	94.2	19.5
		69.8	70.4	70.4	69.9	69.3	69.1	68.9	68.7	68.5	68.5	89.0	20.0
	Ave.	73.1	73.7	73.5	73.3	72.8	72.6	72.4	72.2	72.1	72.0	91.4	19.5
600		70.0	70.2	69.8	69.3	68.8	68.3	67.9	67.8	67.7	67.4	86.4	18.0
		70.1	70.1	69.7	69.5	69.3	69.1	69.1	69.1	69.1	69.0	87.7	17.5
		65.2	67.7	68.2	68.6	68.6	68.3	68.1	67.8	67.7	67.6	84.9	20.0
	Ave.	68.4	69.3	69.2	69.1	68.6	68.6	68.4	68.2	68.2	68.0	86.3	18.5
650		67.3	68.2	68.6	68.6	68.4	68.4	68.3	68.3	68.3	68.4	86.2	16.5
		68.4	69.7	69.7	69.5	69.0	68.9	68.9	68.9	69.1	69.2	86.9	16.5
		71.6	72.2	71.8	71.3	70.9	70.9	70.9	70.9	70.9	71.1	88.0	16.5
	Ave.	69.1	70.0	70.0	69.8	69.4	69.4	69.4	69.4	69.4	69.6	87.0	16.5

TABLE 6. MECHANICAL PROPERTIES OF AM-350 SCT AT 450 TO 650° F

Temp °F	Offset-Percent										Ultimate Strength KSI	Elongation % in 2"
	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50		
	Stress-KSI											
R.T.	133.1	146.5	154.9	161.6	165.7	168.4	171.2	172.5	173.3	176.7	206.5	18.0
	118.4	140.2	149.1	154.4	159.3	163.1	165.6	168.0	169.5	171.3	200.4	18.0
	146.7	154.2	158.8	162.8	166.0	168.4	170.5	172.5	174.2	176.0	208.1	18.5
	Ave. 132.7	147.0	154.3	159.6	162.6	166.6	169.1	171.0	172.3	174.6	205.0	18.2
450	94.8	108.0	117.3	124.5	128.3	132.1	135.3	137.9	140.2	149.6	169.7	9.5
	94.3	111.4	124.0	131.6	137.7	143.0	147.3	150.9	154.0	156.8	184.7	8.0
	101.2	118.9	131.3	138.5	145.1	149.9	153.6	156.1	159.2	161.7	186.1	7.0
	103.6	115.5	122.7	128.9	134.1	138.1	142.1	144.9	147.4	149.8	177.6	8.0
	111.5	120.2	128.1	133.7	138.0	142.0	145.4	148.2	150.5	152.7	178.5	7.0
	Ave. 101.1	114.8	124.7	131.4	136.6	141.1	144.7	147.5	150.2	154.1	179.3	7.9
500	97.0	109.2	116.0	122.9	127.0	130.3	133.5	136.4	138.8	140.3	165.4	9.5
	107.5	116.2	124.1	129.0	132.6	136.0	138.7	141.4	143.8	145.3	173.9	8.5
	98.2	109.6	118.8	124.0	127.8	132.4	135.2	137.4	139.8	141.4	171.2	9.0
	102.3	118.1	124.9	130.0	134.3	138.3	142.5	145.6	148.8	151.0	179.7	7.5
	119.3	125.6	130.6	134.3	137.9	141.0	144.2	146.4	148.3	150.3	172.8	10.0
	Ave. 104.9	115.7	122.9	128.0	131.9	135.6	138.8	141.4	143.9	149.6	172.2	8.9
550	87.9	99.8	106.0	113.5	118.5	122.7	126.4	129.7	132.4	134.9	166.3	9.0
	66.3	97.8	111.6	123.4	129.4	137.1	142.8	147.2	151.1	157.0	196.5	6.5
	103.3	115.1	122.6	129.9	135.8	139.9	144.0	147.3	150.1	152.8	182.3	7.0
	87.1	101.0	111.3	117.7	123.2	127.2	131.3	134.5	137.5	140.0	171.4	10.0
	94.1	110.3	119.0	124.8	130.7	135.6	139.0	142.6	142.6	148.3	173.6	7.5
	Ave. 87.7	104.8	114.1	121.9	127.5	132.3	136.7	140.3	142.7	146.6	178.1	8.0
600	94.5	102.9	110.6	117.0	121.6	125.7	128.8	132.4	134.6	136.7	172.3	8.0
	78.0	96.0	108.1	115.6	121.6	127.3	129.9	137.6	137.6	140.4	174.3	7.0
	92.8	105.9	114.6	120.1	124.8	128.9	131.4	138.1	137.1	139.1	169.9	10.0
	90.6	101.6	108.8	115.4	119.8	124.8	128.3	131.3	134.1	136.7	169.5	10.5
	106.3	118.1	125.2	132.4	136.7	141.4	145.0	147.9	151.1	153.8	187.0	7.5
	Ave. 92.4	104.9	113.4	120.1	124.9	129.6	132.5	137.4	138.9	141.3	174.6	8.6

TABLE 6. MECHANICAL PROPERTIES OF AM-350 SCT AT 450 TO 650° F (Cont.)

Temp °F	Offset-Percent										Ultimate Strength KSI	Elongation % in 2"
	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50		
	Stress-KSI											
650	95.0	101.8	110.2	117.6	122.0	125.6	128.5	131.8	134.1	136.1	164.1	11.0
	89.2	110.8	118.9	125.4	130.6	135.9	139.3	142.4	145.4	147.3	177.9	7.0
	103.2	114.2	123.6	129.5	135.4	140.8	144.9	148.6	153.7	156.7	190.2	5.5
	103.4	113.6	122.1	129.0	134.3	138.7	142.4	145.2	147.7	150.1	181.3	7.0
	111.9	118.6	125.0	129.8	133.1	135.9	138.9	141.1	143.8	146.0	173.6	8.0
	Ave. 100.5	111.8	119.9	126.2	131.1	135.4	138.8	141.8	144.9	147.2	171.4	7.7

TABLE 7. MECHANICAL PROPERTIES OF AM-355 CRT AT 450 TO 650° F

Temp °F	Offset-Percent										Ultimate Strength KSI	Elongation % in 2"
	0.05		0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50		
	Stress-KSI												
R. T.		169.0	187.9	208.1	216.9	223.0	226.6	229.0	229.4	227.4	227.4	244.4	20.0
		221.9	227.7	231.6	233.5	233.7	234.1	234.5	234.9	234.9	234.9	246.7	16.5
		148.6	198.8	212.9	222.5	227.7	234.5	235.7	236.1	233.3	232.1	243.8	17.5
	Ave.	179.8	204.8	217.5	224.3	228.1	231.7	233.1	233.5	231.9	231.8	245.0	18.0
450		147.4	167.3	181.3	191.2	198.2	202.4	206.2	208.8	210.4	212.0	222.7	3.5
		151.0	167.3	179.6	189.8	195.9	210.0	203.3	205.3	207.8	209.4	218.8	3.5
		156.4	177.0	189.3	195.5	200.0	203.7	205.8	207.8	209.1	210.7	218.5	3.5
	Ave.	148.3	170.5	183.4	192.2	198.0	205.4	205.1	207.3	209.1	210.7	220.0	3.5
500		121.5	145.7	160.9	170.0	180.2	186.2	191.3	195.1	197.6	199.6	213.0	3.5
		146.2	163.3	174.9	185.3	192.0	197.2	202.0	204.0	206.8	208.8	221.9	4.0
		140.7	158.9	173.2	181.7	188.6	193.9	197.6	201.2	203.3	204.9	204.9	3.5
	Ave.	136.1	156.0	169.7	179.0	186.9	192.4	197.0	200.1	202.6	204.4	213.3	3.7
550		128.5	150.2	164.0	171.9	181.8	187.7	191.7	194.5	196.8	198.8	218.2	4.5
		139.4	161.4	173.3	183.3	191.2	196.4	200.4	202.4	204.8	206.8	228.3	3.5
		132.4	149.0	160.8	170.6	178.4	184.3	189.4	192.9	195.3	197.3	212.9	4.0
	Ave.	133.4	153.5	166.0	175.3	183.8	189.5	193.8	196.6	199.0	201.0	219.8	4.0
600		118.6	140.2	154.9	165.7	170.6	175.3	178.4	180.4	181.6	183.1	193.7	4.0
		156.0	172.0	181.0	186.8	192.0	195.2	198.0	200.0	201.0	202.0	213.6	4.0
		152.2	165.7	175.5	181.6	186.9	189.0	191.8	194.3	196.3	197.1	207.4	4.0
	Ave.	142.2	159.3	170.5	178.0	183.2	186.5	189.7	191.9	193.0	194.1	204.9	4.0
650		117.2	142.6	158.2	169.5	175.8	181.6	185.5	189.5	192.2	194.1	210.6	4.5
		139.5	157.0	169.6	181.2	186.8	189.9	192.2	194.8	196.7	197.7	209.7	5.0
		112.1	138.9	155.8	165.9	172.6	178.6	182.5	185.5	187.5	189.5	202.8	5.0
	Ave.	122.9	146.2	161.2	172.2	178.4	183.4	186.7	189.9	192.1	193.8	207.7	4.8

TABLE 8. MECHANICAL PROPERTIES OF PH 15-7 Mo* AT 450 TO 650° F

Temp °F	Offset-Percent										Ultimate Strength KSI	Elongation % in 2"
		0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50		
		Stress-KSI											
R. T.		159.0	161.4	163.2	164.4	165.4	166.0	166.6	167.0	167.0	167.6	178.8	11.5
		151.7	156.0	159.0	160.6	162.2	163.4	164.2	164.8	164.8	165.5	177.4	10.0
		156.7	159.2	158.8	161.8	163.1	163.7	164.1	164.7	164.7	165.3	175.7	9.0
	Ave.	155.8	158.9	160.3	162.3	163.6	164.4	165.0	165.5	165.5	166.1	177.3	10.2
450		109.9	129.8	137.7	141.6	143.8	145.1	146.3	147.3	148.4	148.6	155.8	6.5
		130.4	137.7	140.8	142.6	144.1	144.9	145.7	146.5	147.1	147.3	154.9	7.0
		119.6	132.6	139.1	141.5	143.3	144.7	145.7	146.6	147.6	148.0	154.7	6.5
	Ave.	120.0	133.4	139.2	141.9	143.7	144.9	145.9	146.8	147.7	148.0	155.1	6.7
500		106.0	124.5	134.6	140.5	142.4	144.4	145.6	146.5	147.5	148.1	155.1	5.5
		99.3	124.1	132.5	137.1	140.2	141.8	143.4	144.3	145.3	146.1	153.2	5.5
		100.4	120.9	128.8	133.3	136.4	138.0	139.7	144.1	142.1	143.2	151.4	6.0
	Ave.	101.9	123.2	132.0	137.0	139.7	141.4	142.9	144.0	145.0	145.8	153.2	5.7
550		127.1	134.5	136.5	138.6	139.8	140.6	141.4	142.3	143.1	143.5	149.7	6.0
		120.8	129.2	133.5	135.7	137.3	138.8	139.6	140.6	141.4	142.0	149.8	7.5
		130.2	138.2	141.7	143.9	145.6	146.6	147.4	148.5	148.7	149.5	154.2	5.0
	Ave.	126.0	137.9	137.2	139.4	140.9	142.0	142.8	143.8	144.4	145.0	151.2	6.2
600		115.8	131.3	136.5	138.7	140.7	141.5	142.5	143.3	143.9	144.7	150.5	5.0
		128.4	135.0	138.9	140.8	142.2	143.3	144.1	144.9	145.3	145.7	152.3	5.5
		126.5	134.6	138.2	140.4	142.2	143.0	144.0	144.8	145.4	146.1	150.7	5.0
	Ave.	123.6	133.6	137.9	140.0	141.7	142.6	143.5	144.3	144.9	145.5	151.2	5.2
650		128.3	134.0	136.4	138.4	140.2	141.4	142.5	143.1	143.7	144.5	149.7	4.5
		120.0	129.4	135.0	138.5	140.5	142.2	143.4	144.6	145.2	146.1	151.8	4.5
		129.2	133.7	136.3	138.1	139.3	140.9	141.7	142.1	143.1	143.3	148.8	5.0
		122.6	131.5	135.4	137.6	139.5	141.1	142.1	143.1	143.8	144.2	151.7	5.5
	Ave.	125.0	132.2	135.8	138.2	139.9	141.4	142.4	143.2	144.0	144.5	150.5	4.9

*Heat No. 890681; 0.050" x 36" x 96" Sheet, 2D Finish, Condition RH 1100.

TABLE 9. MECHANICAL PROPERTIES OF PH 14-8 Mo* AT 450 TO 650° F

Temp °F		Offset-Percent										Ultimate Strength KSI	Elongation % in 2"
		0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50		
		Stress-KSI											
450		148.3	156.1	160.2	162.2	164.3	165.6	166.4	167.0	167.6	168.2	171.7	5.0
		131.1	143.0	150.6	154.0	156.5	157.9	159.0	160.6	161.0	161.6	167.6	5.5
		161.4	164.9	166.6	167.6	168.3	169.3	169.7	169.9	170.1	170.3	173.9	5.0
	Ave.	146.9	154.7	159.1	161.3	163.0	164.3	165.0	165.8	166.2	166.7	171.1	5.2
500		122.4	136.4	144.9	148.8	151.5	153.2	154.6	155.4	156.3	157.1	162.1	5.0
		135.3	145.6	149.3	152.8	154.9	156.8	157.8	159.0	159.6	160.3	165.2	5.0
		146.9	153.1	156.4	158.9	160.3	161.8	162.8	163.4	164.1	164.5	167.1	4.5
	Ave.	134.9	145.0	150.2	153.5	155.6	157.3	158.4	159.3	160.0	160.6	164.8	4.8
550		151.6	157.2	160.1	162.4	163.6	164.4	165.3	165.9	166.3	166.7	169.6	5.0
		150.3	155.9	158.2	159.8	160.7	161.9	162.3	162.7	163.4	164.0	166.5	5.0
		143.4	153.2	157.1	159.8	161.7	162.9	164.2	164.8	165.8	166.3	169.8	5.0
		148.5	155.8	160.0	162.5	164.6	165.6	166.7	167.3	168.3	169.0	173.3	4.5
	Ave.	148.5	155.5	158.9	161.1	162.7	163.7	164.6	165.2	166.0	166.5	169.8	4.9
600		144.3	150.4	153.7	155.8	157.4	158.7	159.7	160.5	161.1	161.5	164.8	4.5
		138.3	145.9	151.1	152.5	154.6	155.4	157.0	157.7	158.7	159.3	166.1	4.5
		142.9	149.6	153.2	155.4	157.1	159.0	159.6	160.8	161.3	161.7	166.3	4.5
	Ave.	141.8	148.4	152.7	154.6	156.3	157.7	158.8	159.7	160.3	160.8	165.7	4.5
650		136.1	143.6	147.5	150.4	152.2	153.7	155.1	155.9	157.0	157.4	163.8	5.0
		125.4	137.7	143.7	147.2	149.7	151.1	152.3	153.1	154.2	155.2	162.2	5.0
		131.1	139.0	143.5	146.0	147.9	149.8	151.4	152.0	153.3	153.9	160.3	5.0
	Ave.	130.8	140.1	144.9	147.9	149.9	151.5	152.9	153.7	154.8	155.5	158.8	5.0

*Heat No. 33750; 0.050" x 36" x 96" Sheet, 2D Finish, Condition RH-1050

TABLE 10. MECHANICAL PROPERTIES OF 18

Temp °F	Offset-Pe				
	0.05	0.10	0.15	0.20	0.25
	Stress-I				
R.T.	182.6	211.3	224.0	228.2	231.6
	207.6	221.3	227.8	232.4	235.0
	215.5	227.7	233.8	237.4	239.9
	Ave. 201.9	220.1	228.5	232.7	235.7
450	192.0	204.3	210.3	214.4	216.0
	193.6	204.2	209.8	212.8	215.2
	182.3	197.7	204.7	209.0	210.0
	Ave. 189.3	202.1	208.3	212.0	213.7
500	185.3	198.6	204.1	206.9	208.8
	177.1	194.6	204.2	209.5	213.3
	166.4	184.4	195.1	203.3	208.2
	Ave. 176.3	192.5	201.1	206.6	210.1
550	180.3	191.8	198.4	202.5	204.9
	153.7	180.3	190.2	196.3	200.4
	182.5	193.4	199.8	203.9	205.9
	Ave. 172.1	188.5	196.1	200.9	203.8
600	186.3	196.1	200.7	204.3	206.2
	168.3	188.8	196.3	201.2	204.1
	174.0	188.0	194.3	199.1	202.4
	Ave. 176.2	191.0	197.1	201.7	204.2
650	173.4	183.5	189.3	193.4	195.5
	168.2	177.9	183.7	188.4	190.8
	171.3	185.2	190.8	194.3	198.4
	Ave. 170.9	182.2	187.9	192.0	194.9

PERCENT NICKEL MARAGING STEEL AT 450 TO 650° F

rcent					Ultimate Strength KSI	Elongation % in 2"
0.30	0.35	0.40	0.45	0.50		
KSI						
235.4	236.9	237.3	238.4	239.2	240.7	3.0
237.1	238.7	243.3	244.5	245.4	247.6	3.0
241.9	242.3	243.3	243.9	245.1	245.9	2.5
238.2	239.3	241.3	242.6	243.2	244.8	2.9
218.0	218.6	220.3	220.9	221.9	226.0	2.5
217.8	219.0	220.8	221.2	221.6	226.4	3.0
212.9	212.6	214.6	215.8	218.5	224.1	3.0
216.0	216.8	218.6	219.3	220.7	225.5	2.8
211.8	212.9	214.3	214.9	215.9	220.2	3.0
215.4	217.5	218.7	219.3	220.8	226.4	3.0
211.1	213.1	214.8	216.2	217.2	223.9	3.0
212.8	214.5	215.9	216.8	218.0	223.5	3.0
207.8	208.6	210.3	210.9	211.5	219.3	3.0
202.9	204.9	206.6	207.8	209.4	218.6	2.5
207.8	209.4	211.1	211.7	212.5	219.7	2.5
206.2	207.7	209.3	210.1	211.2	219.2	2.7
208.4	209.8	211.4	212.4	212.6	219.9	2.5
207.0	208.7	211.3	212.3	213.6	221.4	2.5
204.9	206.6	207.9	208.6	209.9	220.2	3.0
206.7	208.4	210.2	210.5	212.0	220.5	2.7
198.7	200.0	201.2	202.5	203.1	215.1	2.5
192.8	194.2	196.1	196.8	198.1	210.0	2.0
201.7	203.4	204.0	204.6	205.6	214.9	2.5
197.8	199.2	200.4	201.3	202.3	213.3	2.3

TABLE 11. AVERAGE STRESSES REQUIRED FOR 0.01 PERCENT TENSILE STRAIN

Material	Temperature - °F				
	450	500	550	600	650
	Stress-KSI				
Ti-8Al-1Mo-1V D.A.	75.5	74.1	71.8	62.9	67.9
Ti 6Al-4V Ann	85.6	84.1	68.9	70.5	66.8
Ti 5Al-2 1/2 Sn Ann	80.8	74.0	64.9	66.0	64.2
AM-350-SCT	89.2	92.1	74.2	77.3	92.6
AM-355-CRT	122.5	102.3	96.3	115.2	83.1
PH 15-7 Mo-RH 1100	101.5	77.7	101.4	106.0	107.0
PH 14-8 Mo-RH 1050	131.7	117.9	134.6	129.9	118.7
18% Ni Marage Steel	155.8	138.5	128.6	134.0	137.4

TABLE 12. SUMMARY OF CREEP TEST RESULTS
Ti-8Al-1Mo-1V
450°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	92.3	0.0000086
2	92.3	0.0000070
3	85.0	0.0000028
4	85.0	Nil
5	71.5	Nil
6	71.5	Nil

TABLE 13. SUMMARY OF CREEP TEST RESULTS
Ti-8Al-1Mo-1V
500°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	91.9	0.000020
2	91.9	0.000023
3	91.1	0.000004
4	91.1	0.000004
5	82.2	0.000004
6	82.2	0.000004
7	71.6	0.000006
8	71.6	0.000008

TABLE 14. SUMMARY OF CREEP TEST RESULTS
Ti-8Al-1Mo-1V
550°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	87.5	0.000009
2	87.5	0.000007
3	86.0	0.000012
4	86.0	0.000025
5	83.9	0.000025
6	83.9	0.000012
7	80.8	0.000003
8	80.8	Nil

TABLE 15. SUMMARY OF CREEP TEST RESULTS
Ti-8Al-1Mo-1V
600°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	86.1	0.000026
2	86.1	0.000018
3	84.1	Nil
4	84.1	0.000007
5	79.2	0.000004
6	79.2	Nil
7	74.2	Nil
8	74.2	Nil

TABLE 16. SUMMARY OF CREEP TEST RESULTS
Ti-8Al-1Mo-1V
650°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	84.2	0.000040
2	84.2	0.000096
3	83.3	0.000072
4	83.3	0.000076
5	80.5	0.000064
6	80.5	0.000044
7	76.2	Nil
8	76.2	Nil

TABLE 17. SUMMARY OF CREEP TEST RESULTS
Ti-6Al-4V
450°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	100.0	0.000009
2	100.0	0.000012
3	97.2	0.000001
4	97.2	Nil
5	94.8	Nil
6	94.8	Nil
7	94.5	0.000002
8	94.5	
9	93.3	0.000012
10	93.3	0.000006

TABLE 18. SUMMARY OF CREEP TEST RESULTS
Ti-6Al-4V
500°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	95.5	0.000008
2	95.5	Nil
3	94.2	0.000092
4	94.2	0.000008
5	90.6	Nil
6	90.6	Nil
7	88.4	Nil
8	88.4	Nil
9	88.4	Nil
10	88.4	Nil

TABLE 19. SUMMARY OF CREEP TEST RESULTS
Ti-6Al-4V
550°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	92.3	0.000018
2	92.3	Nil
3	88.7	0.000006
4	88.7	Nil
5	85.4	0.000006
6	85.4	0.000001
7	82.9	0.000002
8	82.9	0.000009
9	80.6	Nil
10	80.6	0.000013

TABLE 20. SUMMARY OF CREEP TEST RESULTS
Ti-6Al-4V
600°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	90.8	0.000066
2	90.8	0.000016
3	87.3	0.000023
4	87.3	0.000024
5	84.0	Nil
6	84.0	0.000032
7	81.8	Nil
8	81.8	Nil
9	79.5	0.000013
10	79.5	0.000012

TABLE 21. SUMMARY OF CREEP TEST RESULTS
Ti-6Al-4V
650°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	88.8	0.000040
2	88.8	0.000030
3	80.8	0.000022
4	80.8	Nil
5	76.3	0.000009
6	76.3	Nil
7	73.9	0.000023
8	73.9	Nil
9	69.4	0.000019
10	69.4	Nil

TABLE 22. SUMMARY OF CREEP TEST RESULTS
Ti-5Al-2 1/2 SN
450°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	82.9	0.000018
2	82.9	--
3	78.0	0.000010
4	78.0	0.000010
5	73.2	0.000072
6	73.2	0.000016
7	69.2	Nil
8	69.2	0.000012
9	67.0	Nil
10	67.0	Nil

TABLE 23. SUMMARY OF CREEP TEST RESULTS
Ti-5Al-2 1/2 SN
500°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	78.5	0.000020
2	78.5	0.000025
3	77.3	0.000002
4	77.3	0.000010
5	70.6	0.000004
6	70.6	Nil
7	68.5	0.000010
8	68.5	Nil
9	66.5	Nil
10	66.5	Nil

TABLE 24. SUMMARY OF CREEP TEST RESULTS
Ti-5Al-2 1/2 SN
550°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	73.1	0.000015
2	73.1	0.000015
3	72.0	0.000011
4	72.0	0.000005
5	65.9	Nil
6	65.9	Nil

TABLE 25. SUMMARY OF CREEP TEST RESULTS
Ti-5Al-2 1/2 SN
600°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	68.4	0.000015
2	68.4	0.000015
3	66.3	0.000002
4	66.3	0.000004
5	64.0	Nil
6	64.0	Nil

TABLE 26. SUMMARY OF CREEP TEST RESULTS
Ti-5Al-2 1/2 SN
650°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	69.1	0.000008
2	69.1	Nil
3	66.3	0.000009
4	66.3	0.000012
5	64.6	Nil
6	64.6	0.000026
7	62.9	Nil
8	62.9	Nil

TABLE 27. SUMMARY OF CREEP TEST RESULTS
AM-350 SCT
450°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	98.6	Nil
2	98.6	Nil
3	92.3	0.000002
4	92.3	Nil
5	88.0	Nil
6	88.0	Nil

TABLE 28. SUMMARY OF CREEP TEST RESULTS
AM-350 SCT
500°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	96.1	Nil
2	96.1	0.000006
3		
4		
5		
6		

TABLE 29. SUMMARY OF CREEP TEST RESULTS
AM-350 SCT
550°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	91.4	Nil
2	91.4	Nil
3	85.3	0.00002
4	85.3	Nil
5		
6		

TABLE 30. SUMMARY OF CREEP TEST RESULTS
AM-350 SCT
600°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	96.3	Nil
2	96.3	Nil
3	93.0	0.000027
4	93.0	Nil
5	90.2	Nil
6	90.2	Nil

TABLE 31. SUMMARY OF CREEP TEST RESULTS
AM-350 SCT
650°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	94.5	0.000006
2	94.5	
3	88.2	0.000012
4	88.2	0.000011
5	81.5	Nil
6	81.5	Nil

TABLE 32. SUMMARY OF CREEP TEST RESULTS
PH 15-7 MO, CONDITION RH-1100
450°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	120.0	-0.000008
2	120.0	-0.000044
3	99.3	0.000022
4	99.3	Nil
5		
6		

TABLE 33. SUMMARY OF CREEP TEST RESULTS
PH 15-7 MO, CONDITION RH 1100
500°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	101.9	0.000010
2	101.9	0.000018
3	95.8	0.000002
4	95.8	0.000002
5	89.1	Nil
6	89.1	Nil

TABLE 34. SUMMARY OF CREEP TEST RESULTS
PH 15-7 MO, CONDITION RH-1100
550°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	126.0	Nil
2	126.0	0.000001
3	122.0	Nil
4	122.0	0.000006
5	115.2	Nil
6	115.2	Nil

TABLE 35. SUMMARY OF CREEP TEST RESULTS
PH 15-7 MO, CONDITION RH-1100
600°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	123.6	0.000080
2	123.6	0.000024
3	119.2	0.000006
4	119.2	0.000037
5	112.0	0.000012
6	112.0	Nil

TABLE 36. SUMMARY OF CREEP TEST RESULTS
PH 15-7 MO, CONDITION RH-1100
650°F

Specimen No.	Stress KSI	Secondary Creep Rate In/In/Hr
1	125.0	0.000068
2	125.0	0.000006
3	117.7	0.000006
4	117.7	0.000043
5		
6		

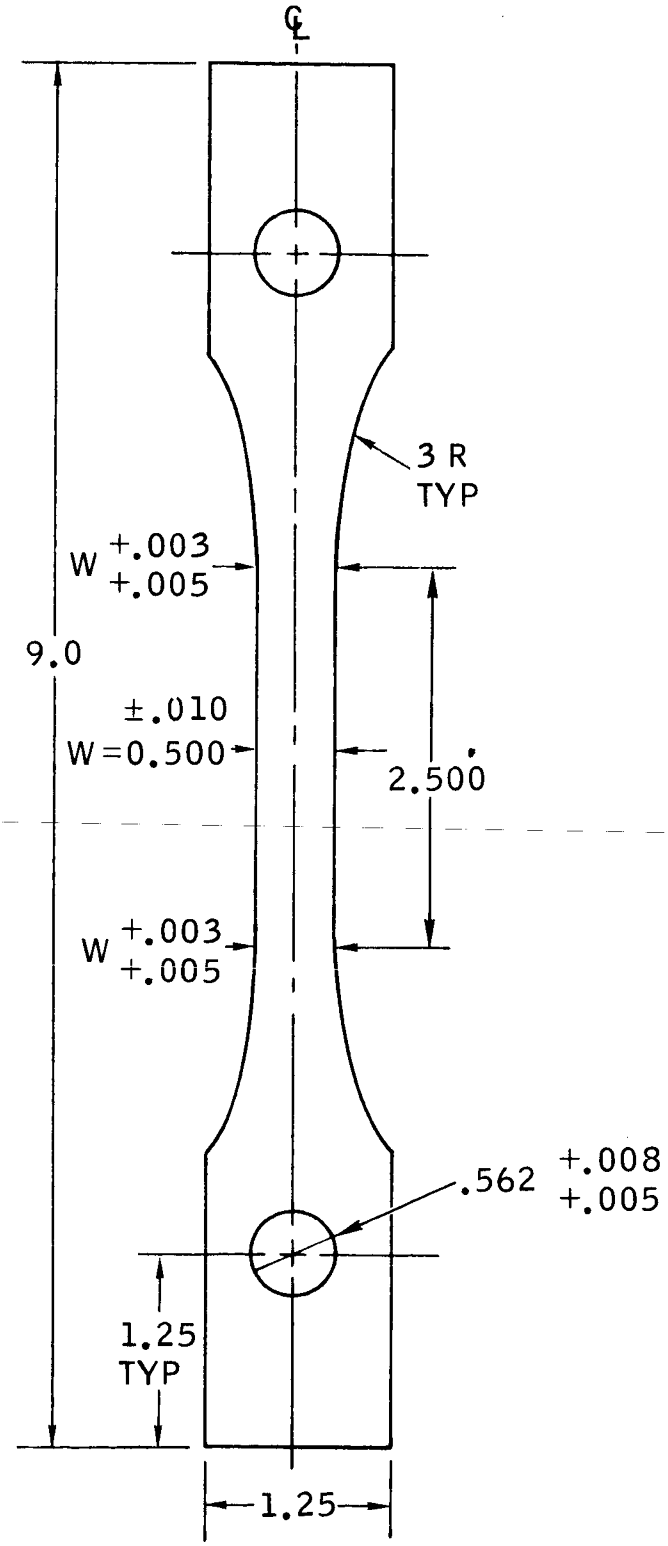


Figure 1. Tension Test Specimen

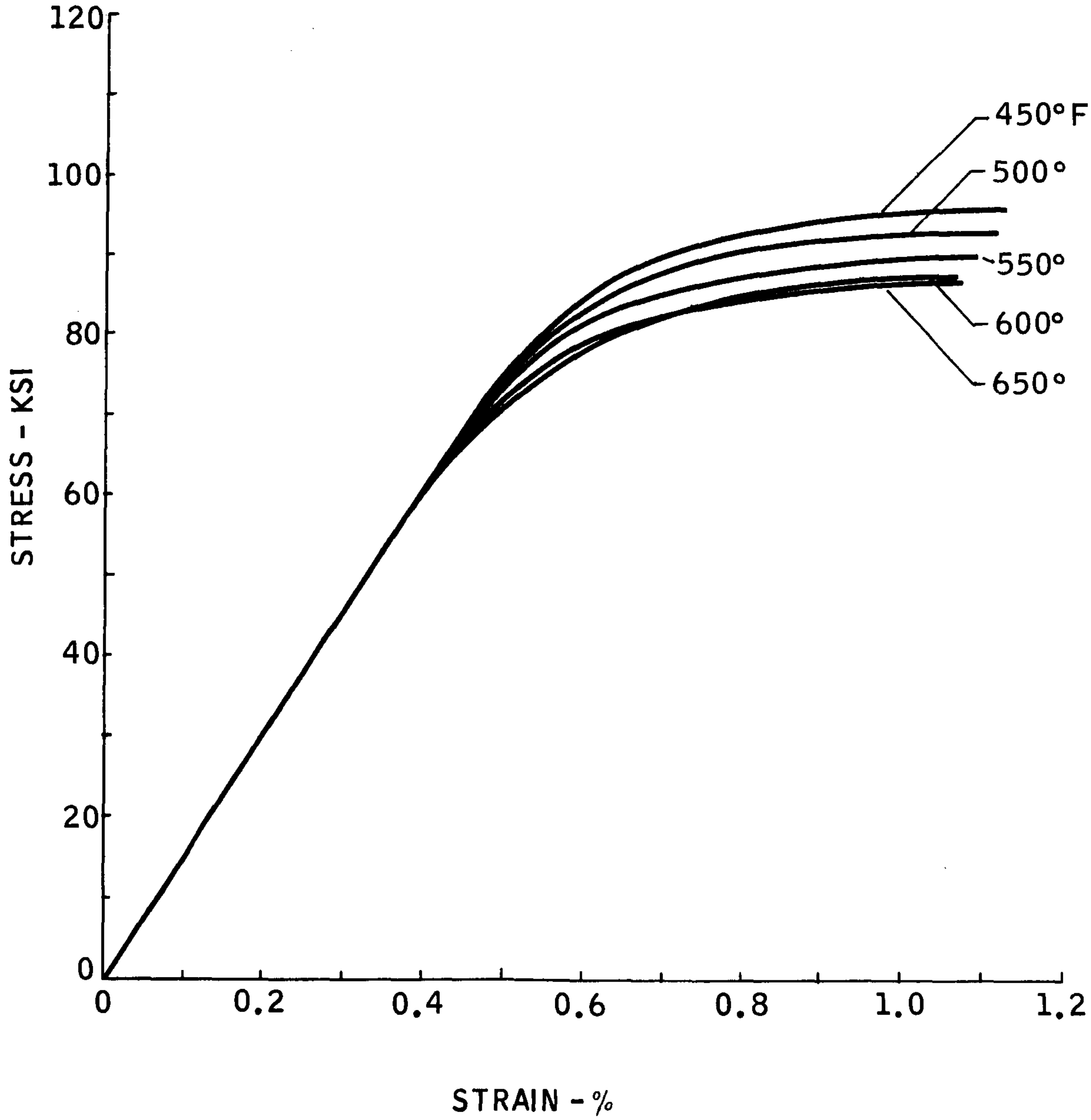


Figure 2. Elevated Temperature Stress
Strain Diagrams for 0.050" Thick Ti-8Al-1Mo-1V Duplex Annealed Sheet.
Titanium Metals Corporation of American Heat V-1555

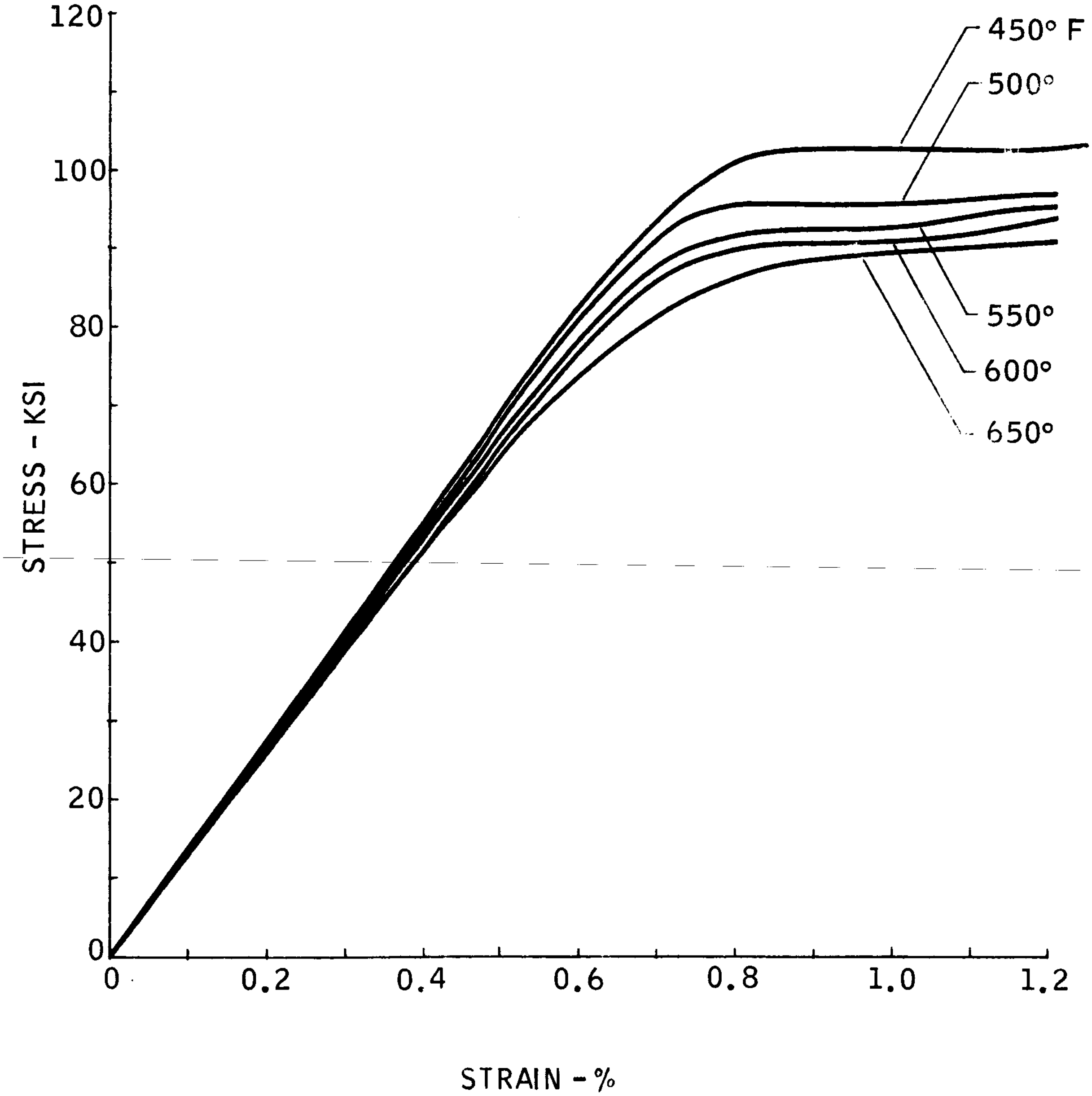


Figure 3. Elevated Temperature Stress
Strain Diagrams For 0.050" Thick Ti-6Al-4V Annealed Sheet,
Titanium Metals Corporation of American Heat D-4231

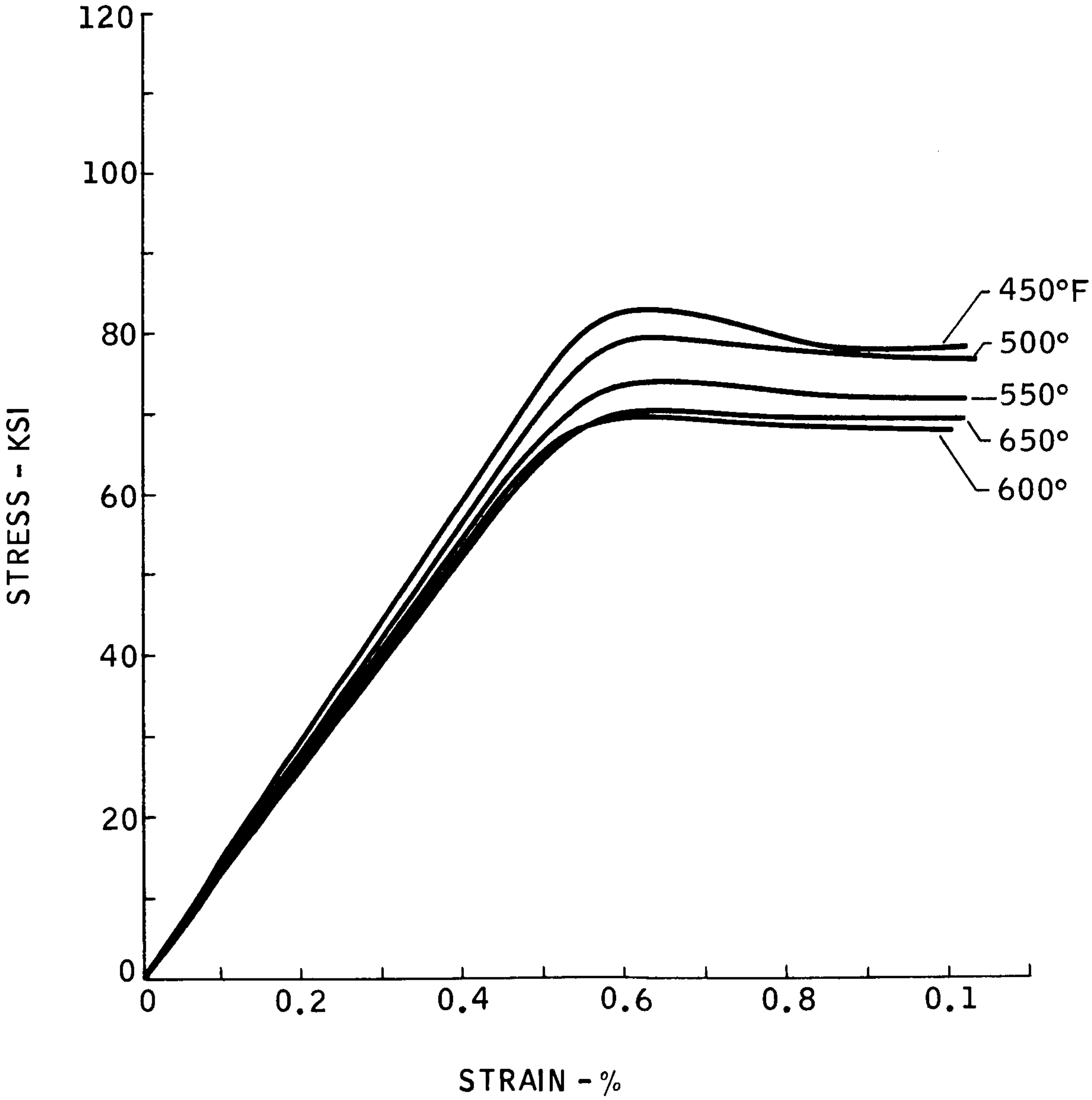


Figure 4. Elevated Temperature Stress
- Strain Diagrams for 0.050" Thick Ti-5Al-2 1/2Sn Annealed Sheet.
Titanium Metals Corporation of American Heat D-2242

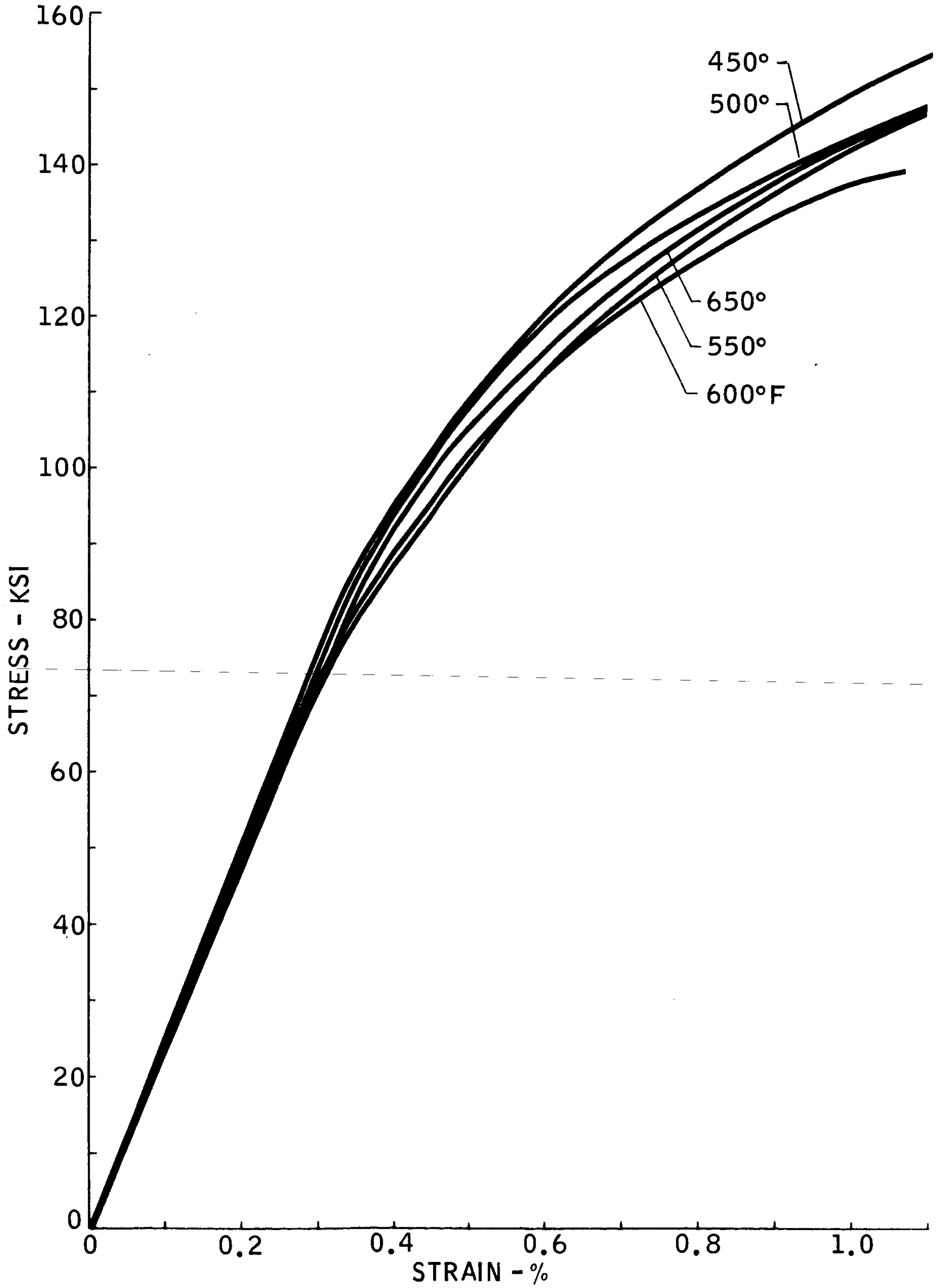


Figure 5. Elevated Temperature Stress - Strain Diagrams for 0.050" Thick AM-350 SCT Sheet. Allegheny Ludlum Steel Corporation Heat 55431

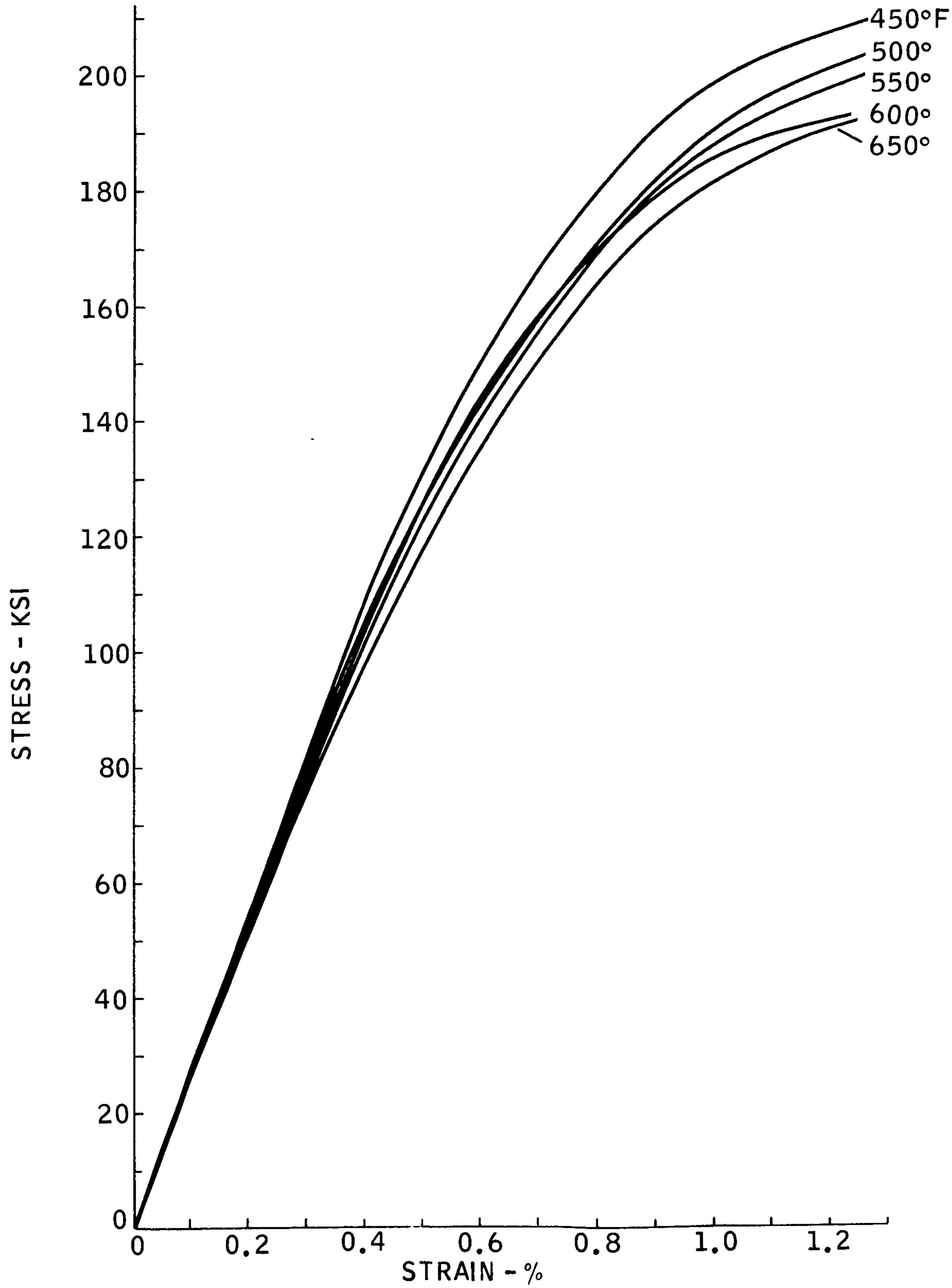


Figure 6. Elevated Temperature Stress - Strain Diagrams for 0.050" Thick AM-355 CRT Sheet. Allegheny Ludlum Steel Corporation Heat 55467

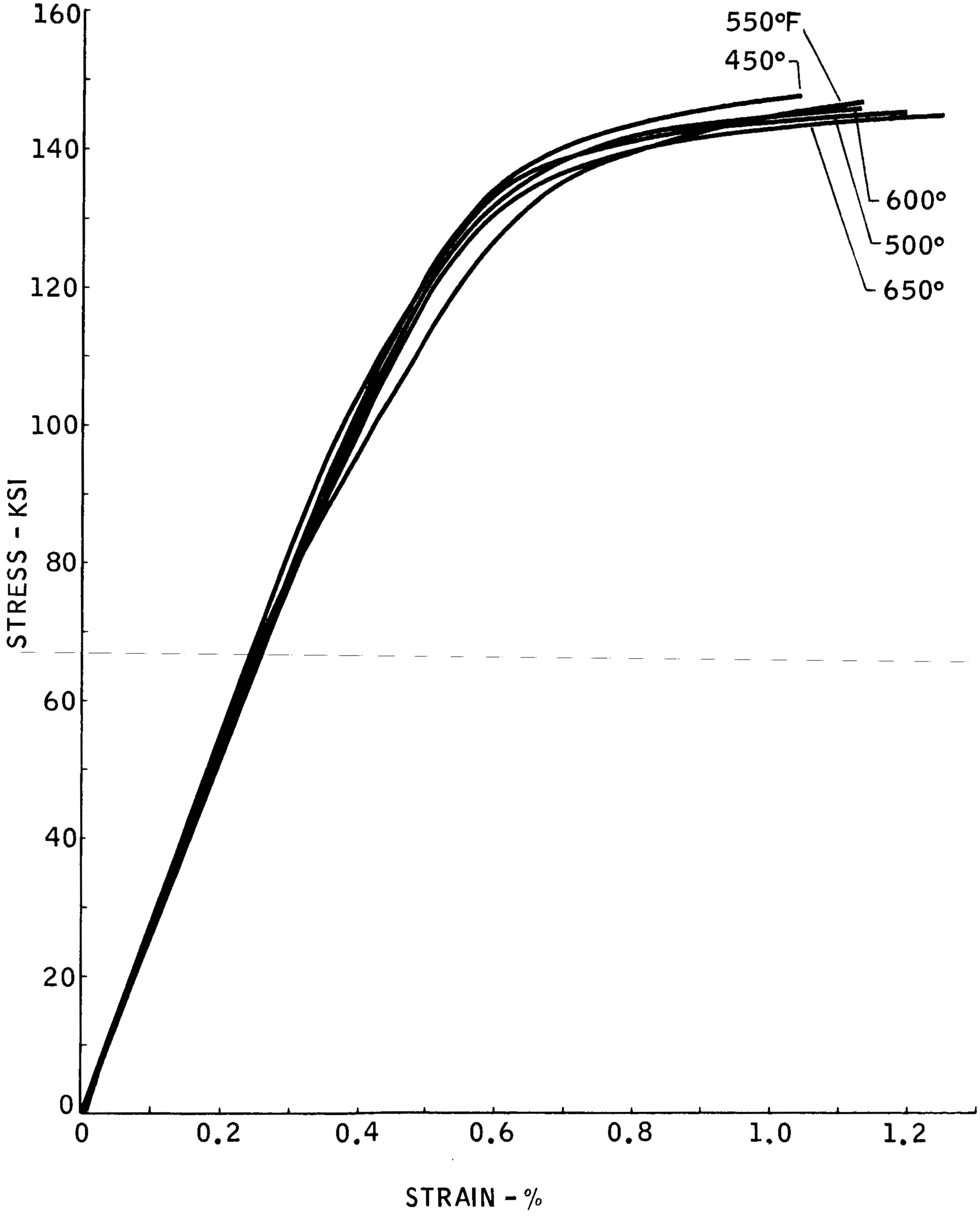


Figure 7. Elevated Temperature Stress - Strain Diagrams for 0.050" Thick Ph 15-7Mo Condition RH-1100 Sheet. Armco Steel Corporation Heat 890681

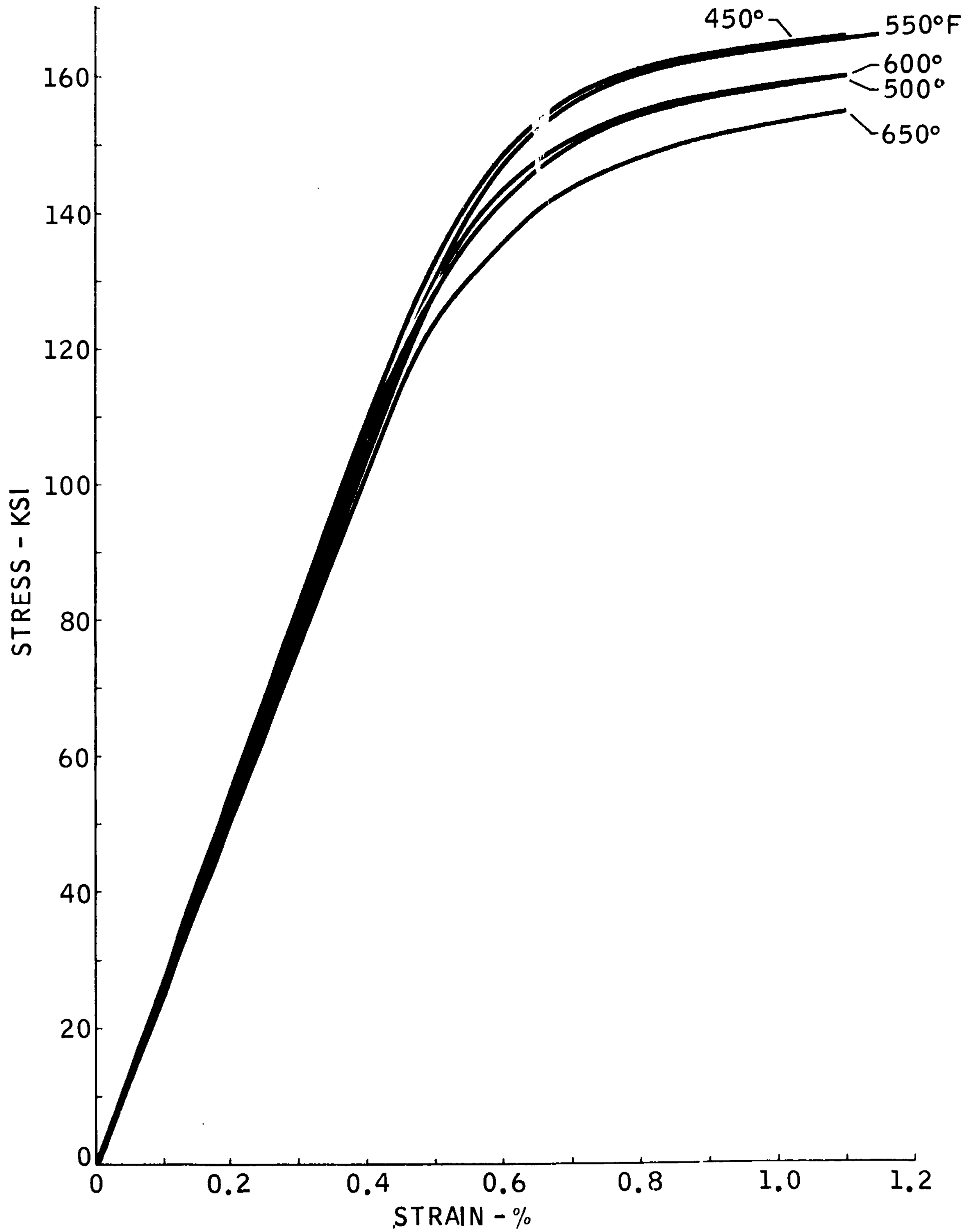


Figure 8. Elevated Temperature Stress - Strain Diagrams for 0.050" Thick PH 14-8Mo Condition RH-1050 Sheet. Armco Steel Corporation Heat 33750

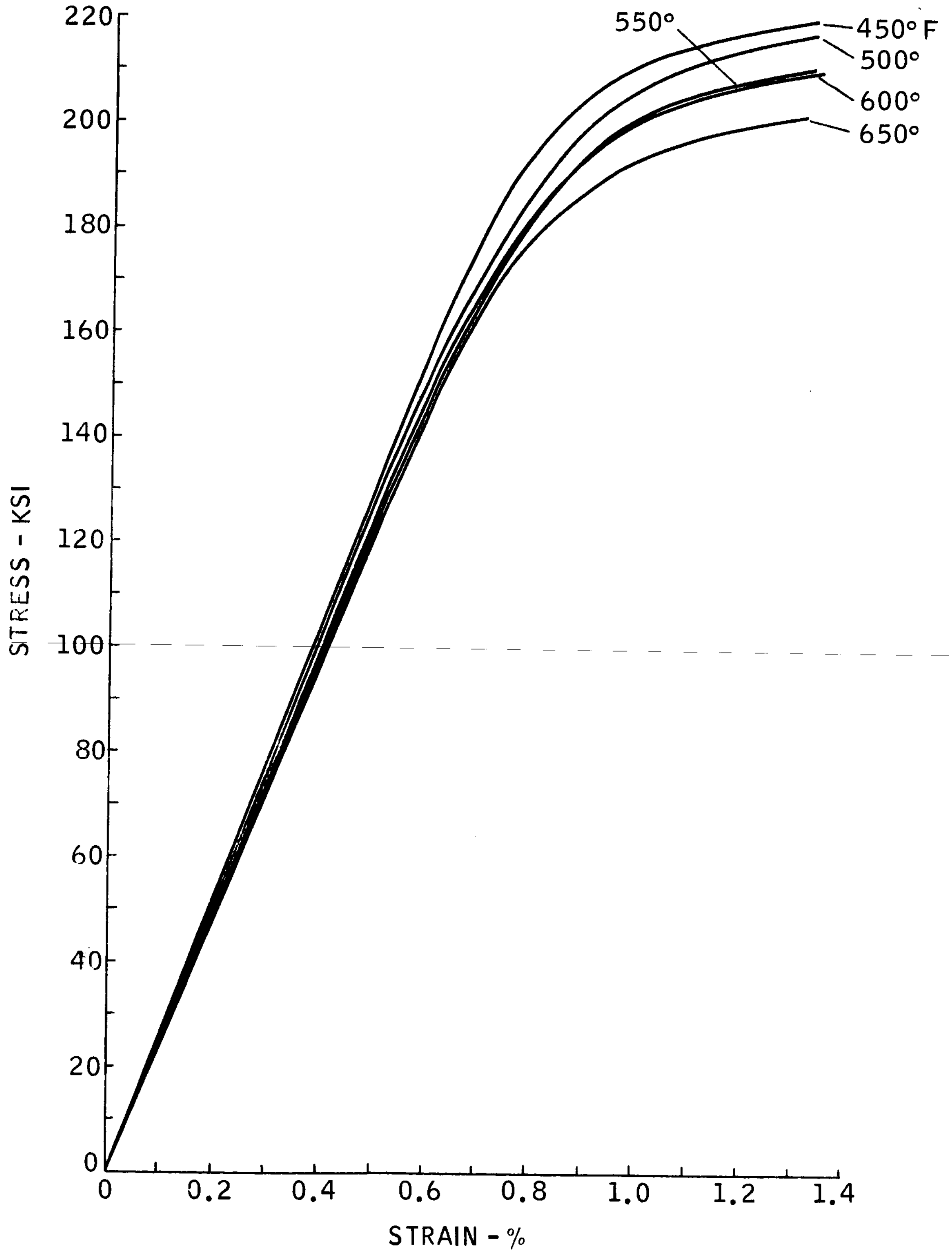
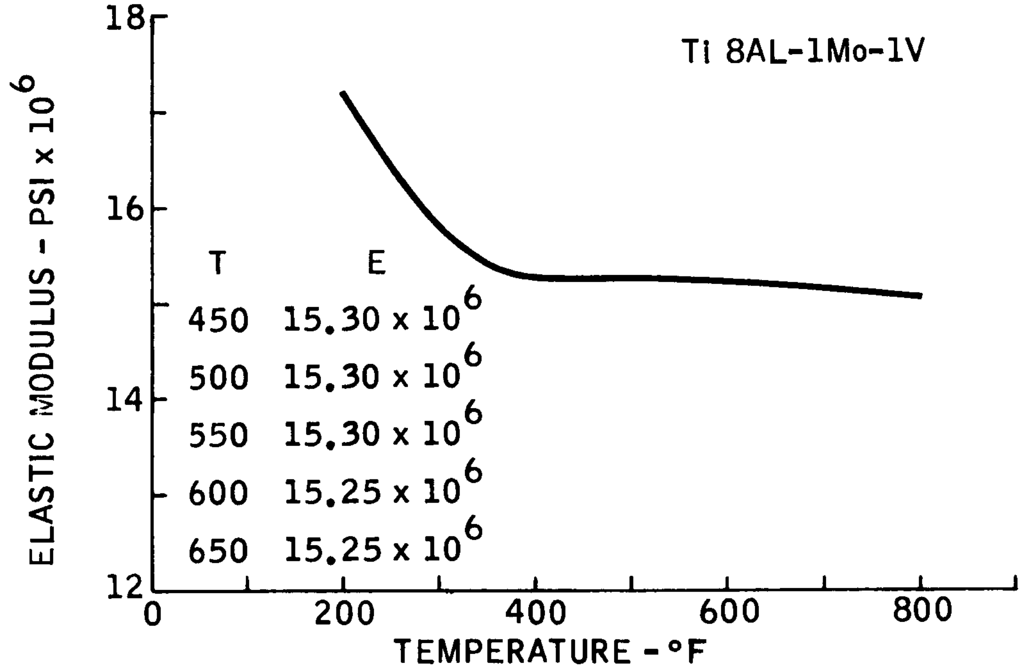
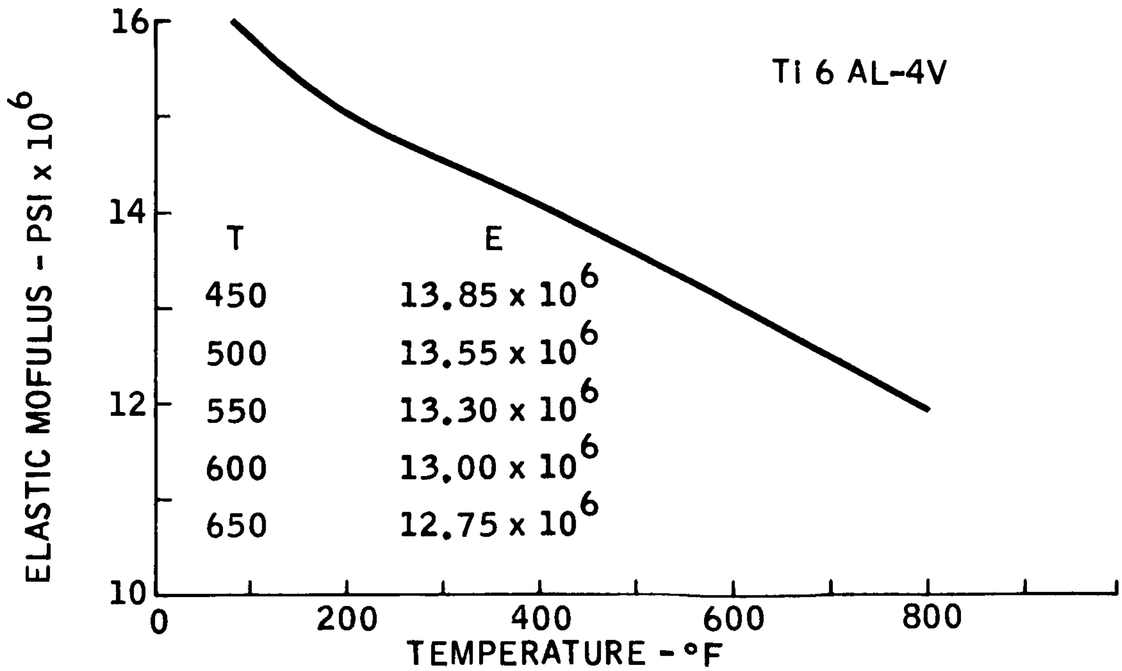


Figure 9. Elevated Temperature Stress - Strain Diagrams for 0.050" Thick 18% Nickel Maraging Steel Sheet. United States Steel Corporation Heat x 15400



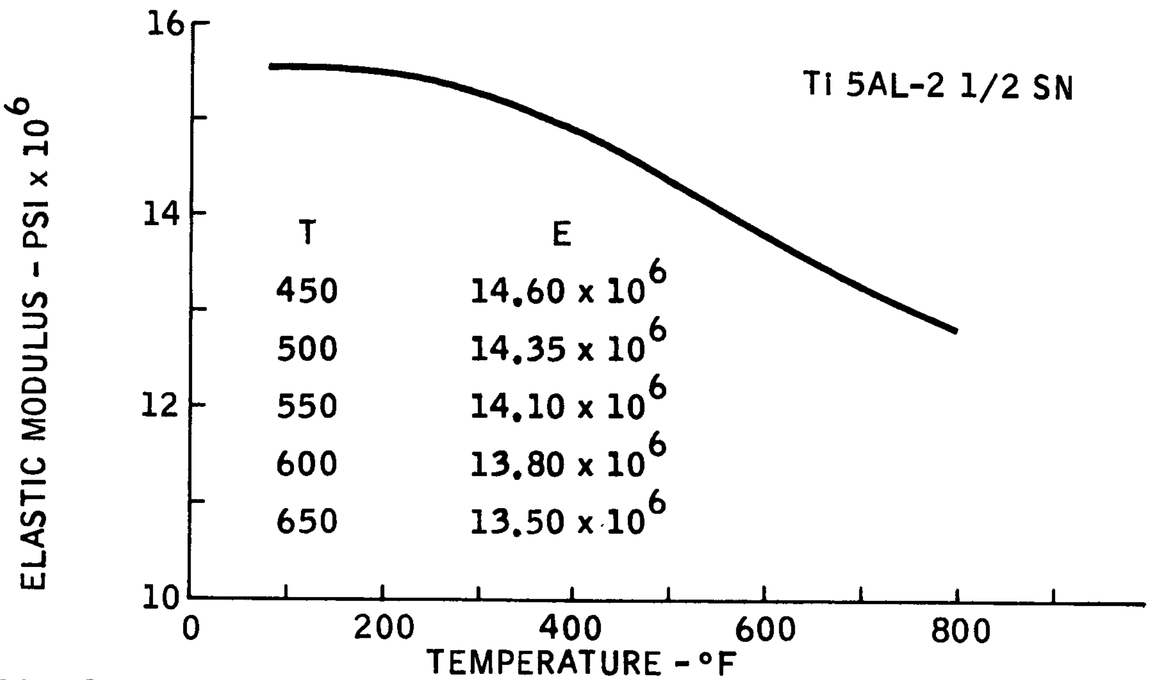
SOURCE: SUMMARY REPORT NOos-59-6227-c.

Figure 10. Ti-8Al-1Mo-1V Elastic Modulii



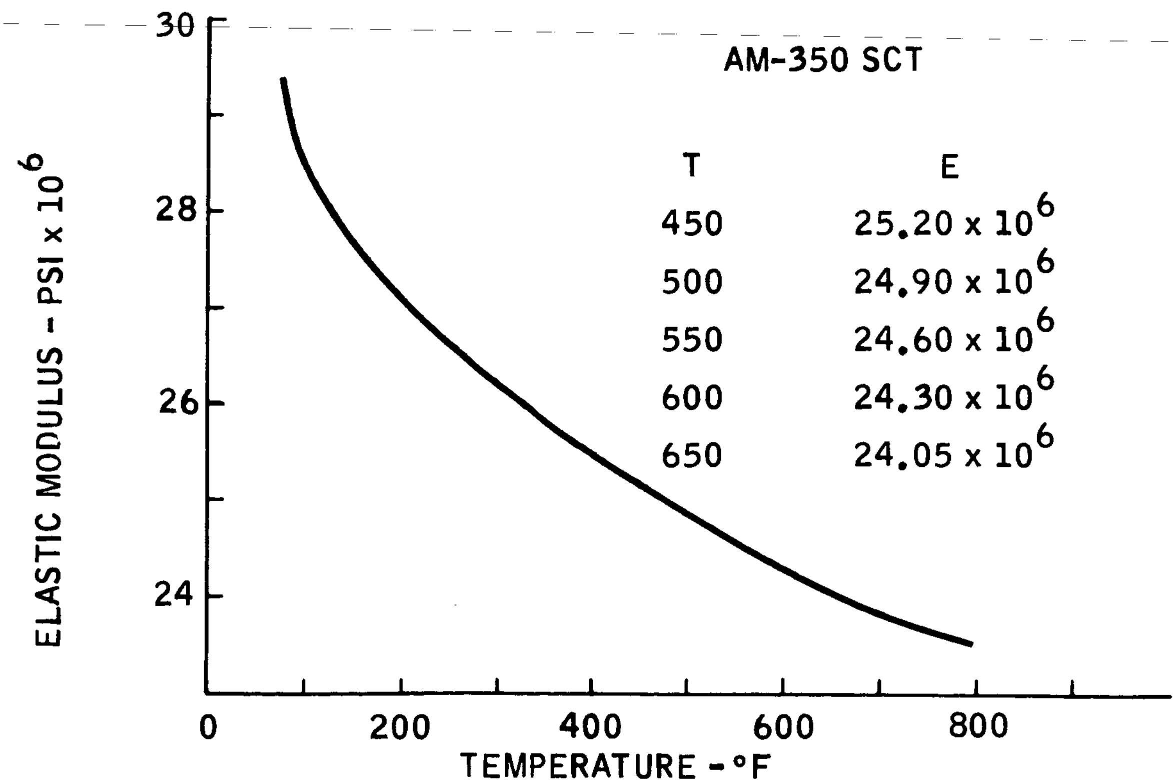
SOURCE: MIL-HDBK-5, AUGUST, 1962

Figure 11. Ti-6Al-4V Elastic Modulii



SOURCE: MIL-HDBK-5, AUGUST, 1962

Figure 12. Ti-5Al-2 1/2 Sn Elastic Modulii



SOURCE: MIL-HDBK-5, AUGUST, 1962

Figure 13. AM-350 Elastic Modulii

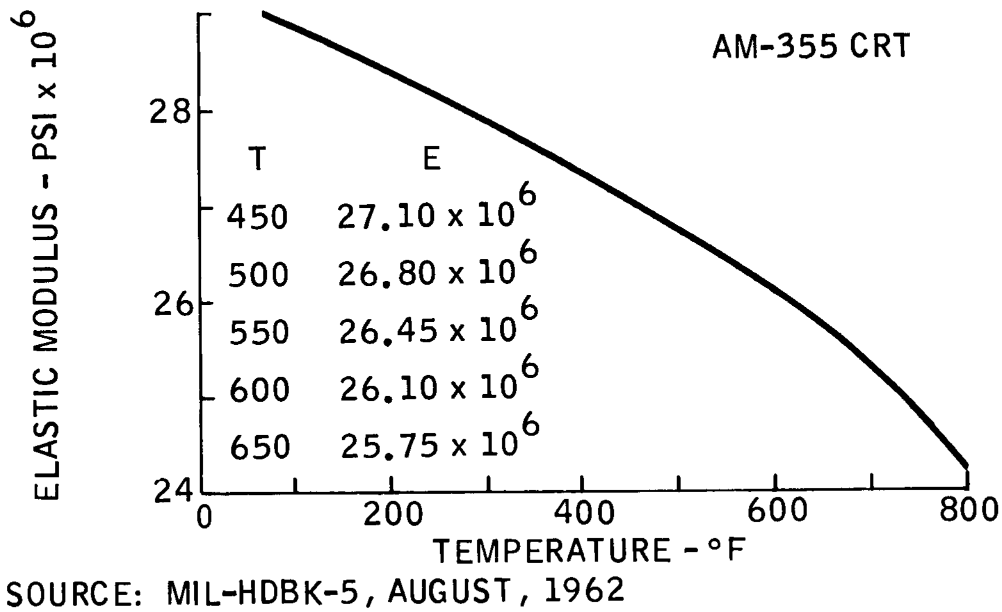


Figure 14. AM-355 Elastic Modulii

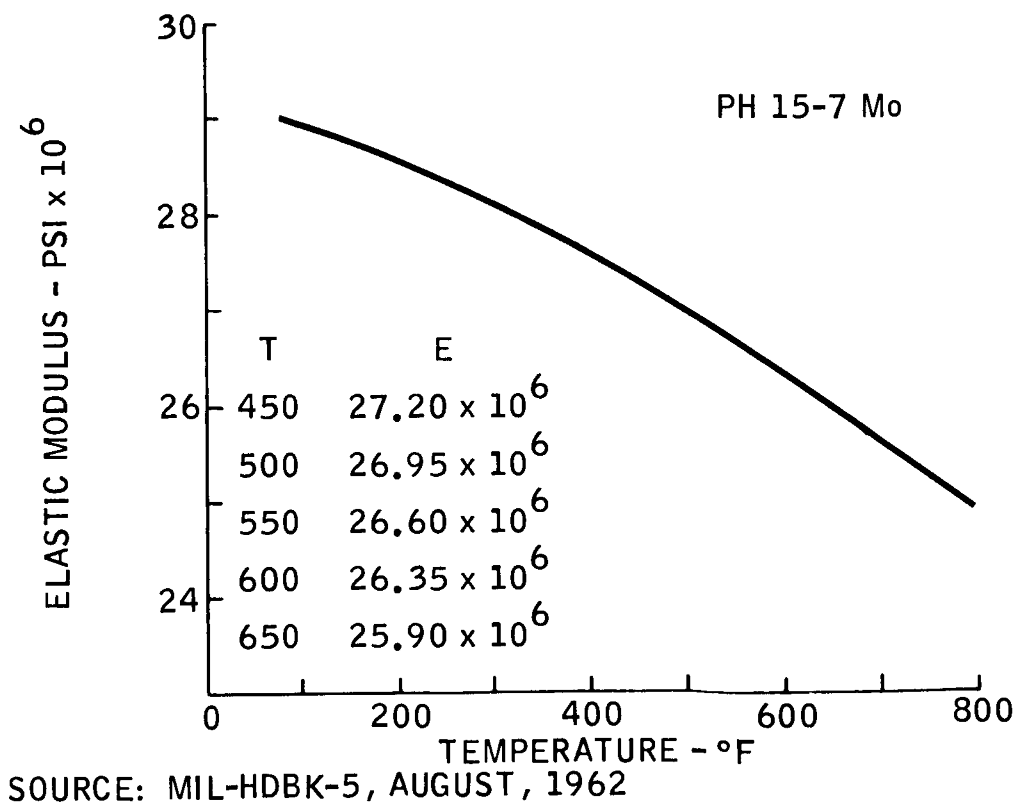
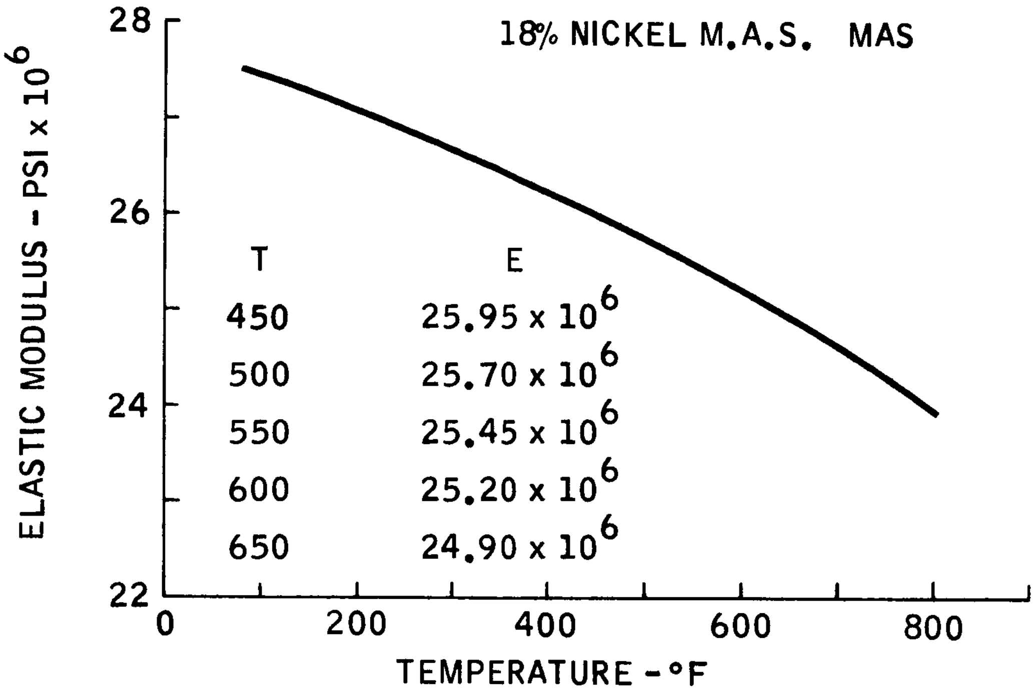


Figure 15. PH 15-7 Mo Elastic Modulii



SOURCE: ALLEGHENY LUDLUM STEEL CORPORATION, "ALMAR STEELS"

Figure 16. 18% Nickel Maraging Steel Elastic Modulii

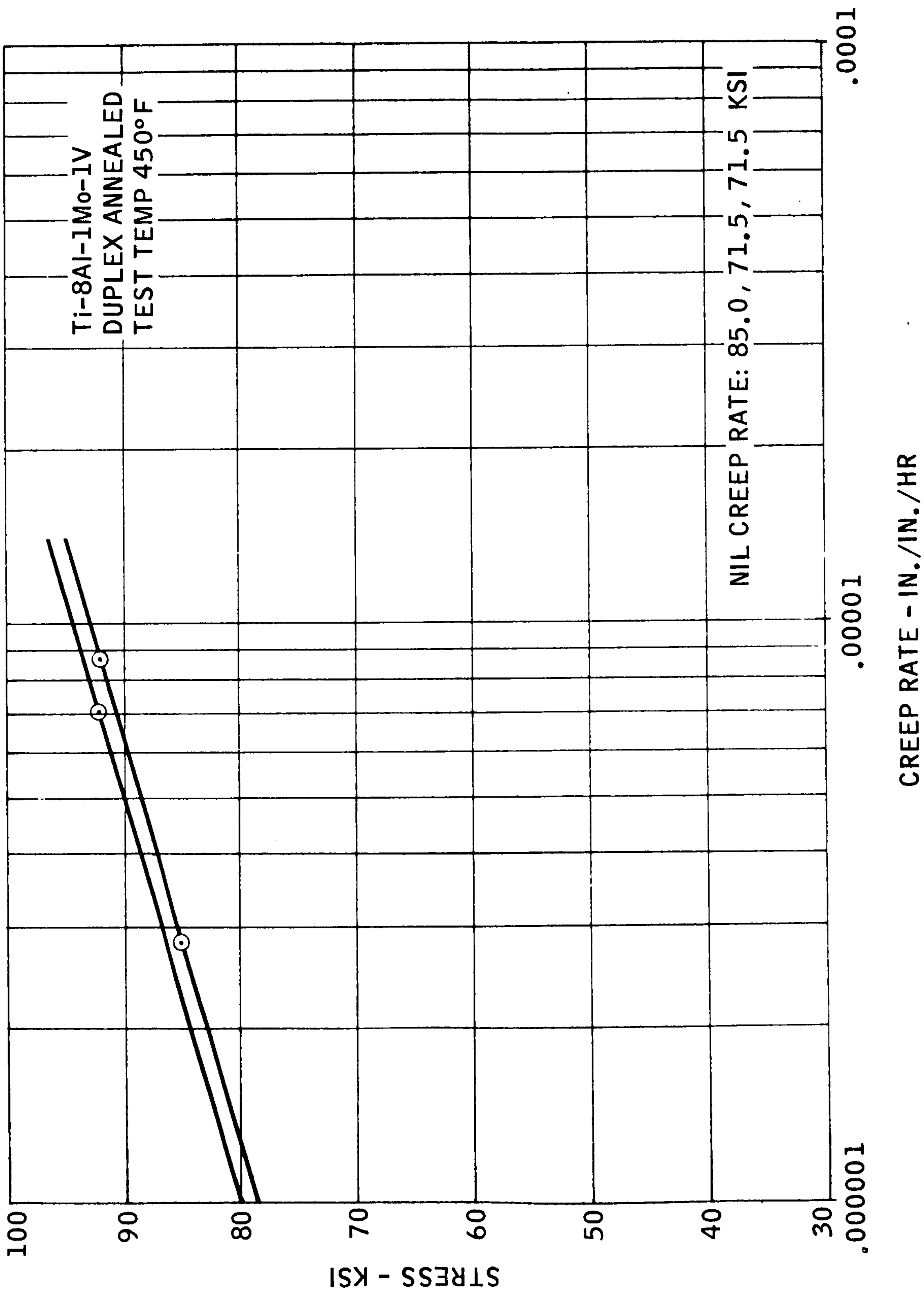


Figure 17. Stress Versus Creep Rate, Ti-8Al-1Mo-1V, 450° F

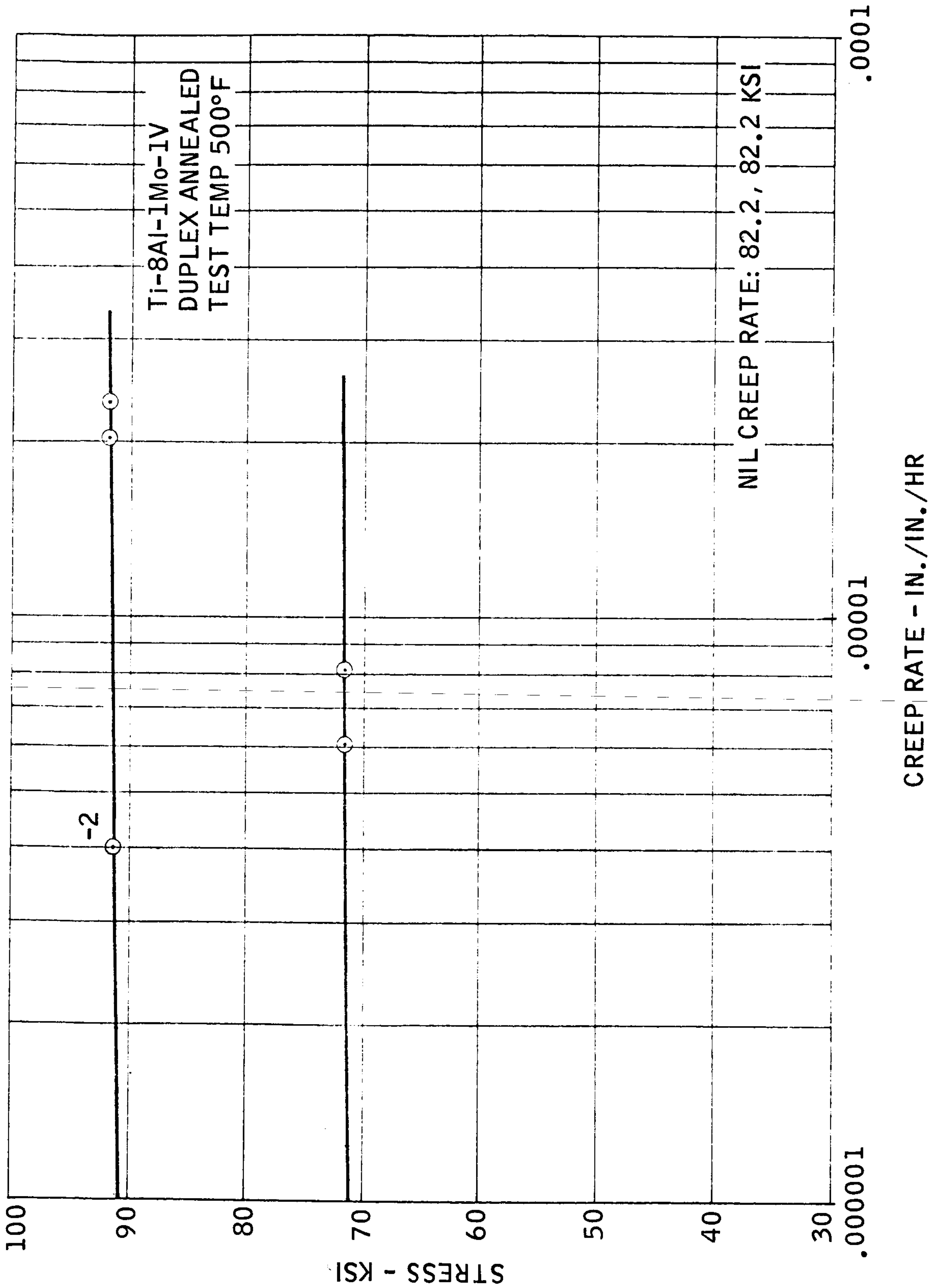


Figure 18. Stress Versus Creep Rate, Ti-8Al-1Mo-1V, 500° F.

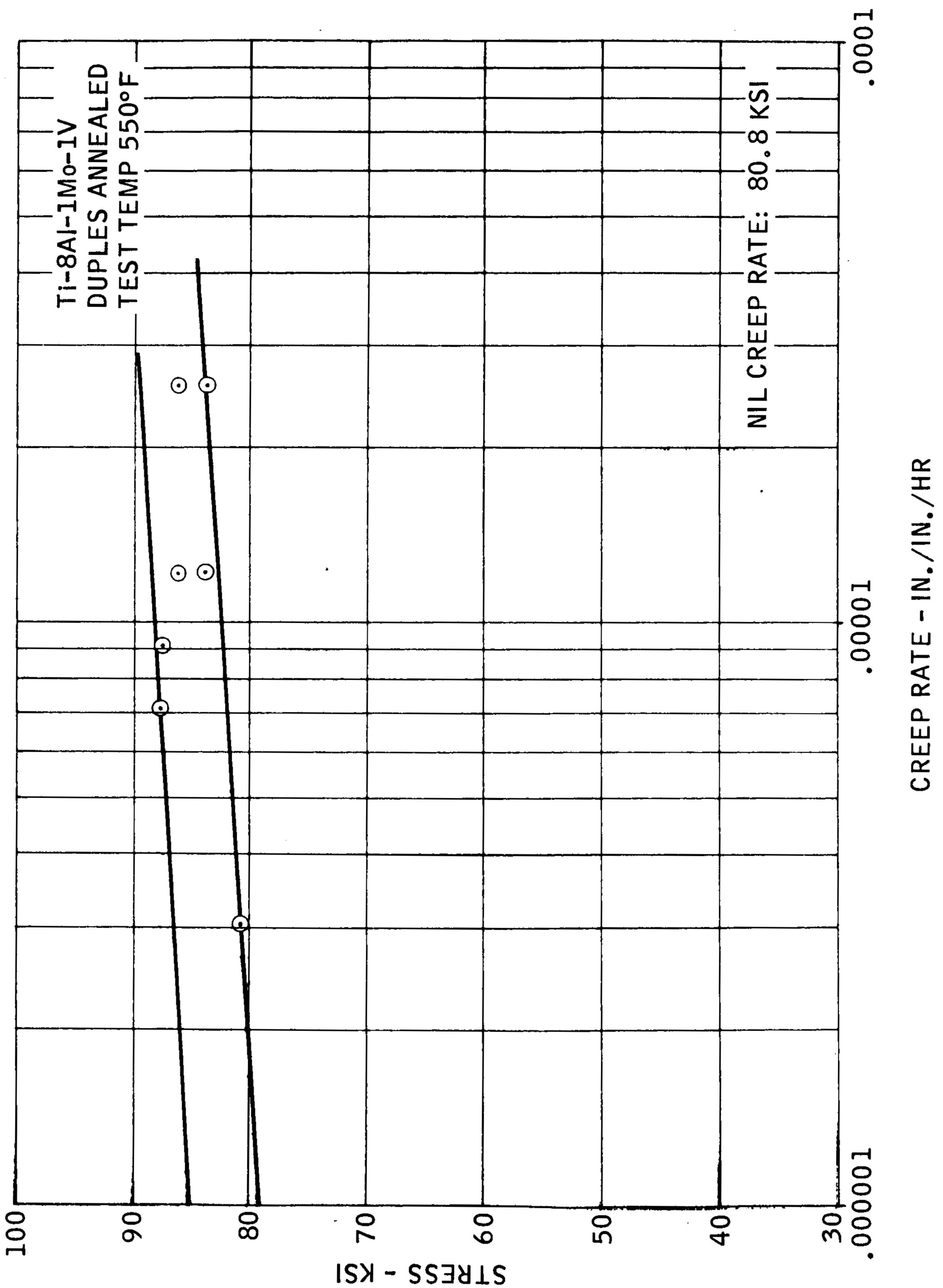


Figure 19. Stress Versus Creep Rate, Ti-8Al-1Mo-1V, 550° F

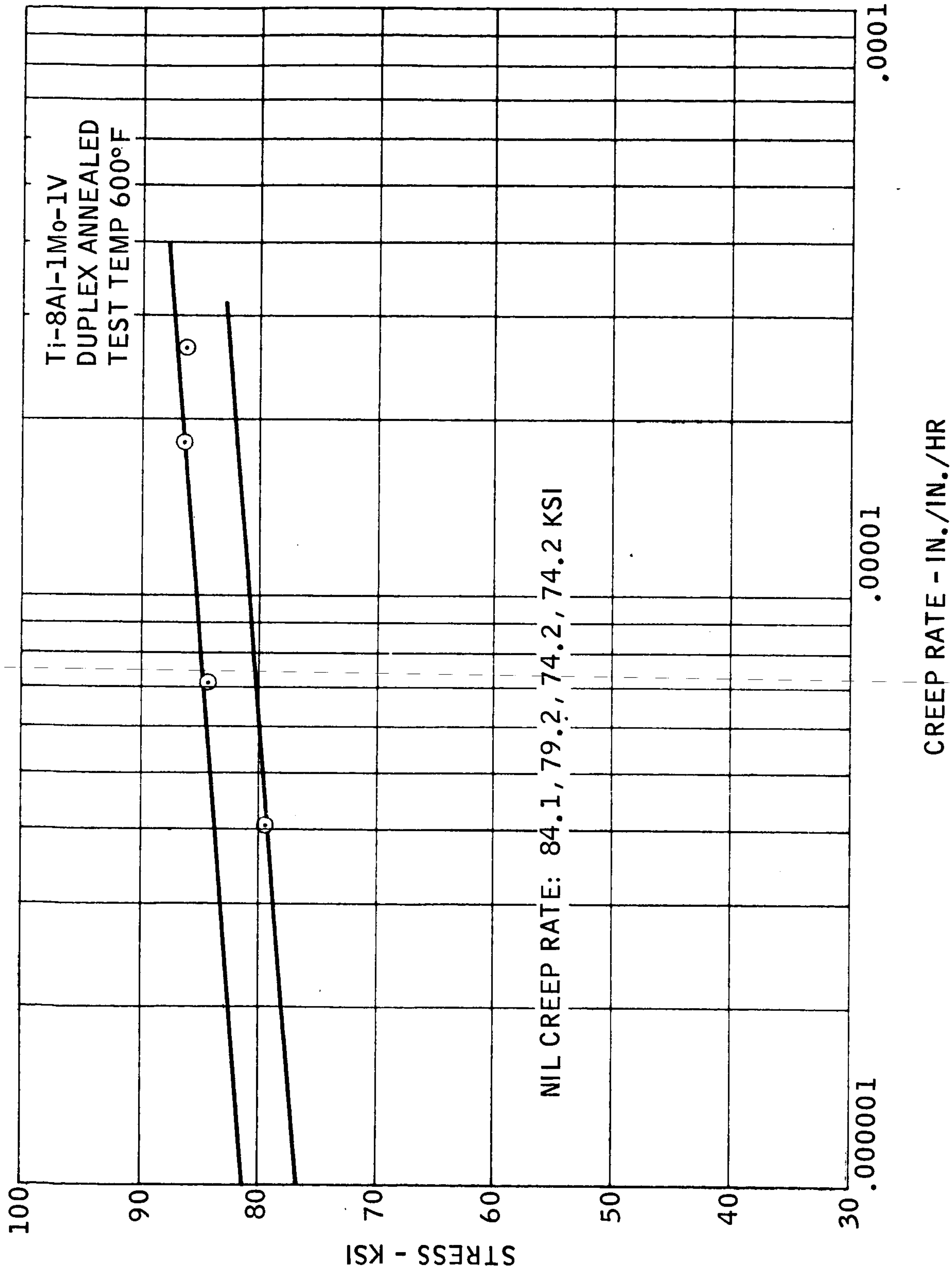


Figure 20. Stress Versus Creep Rate, Ti-8Al-1Mo-1V, 600° F

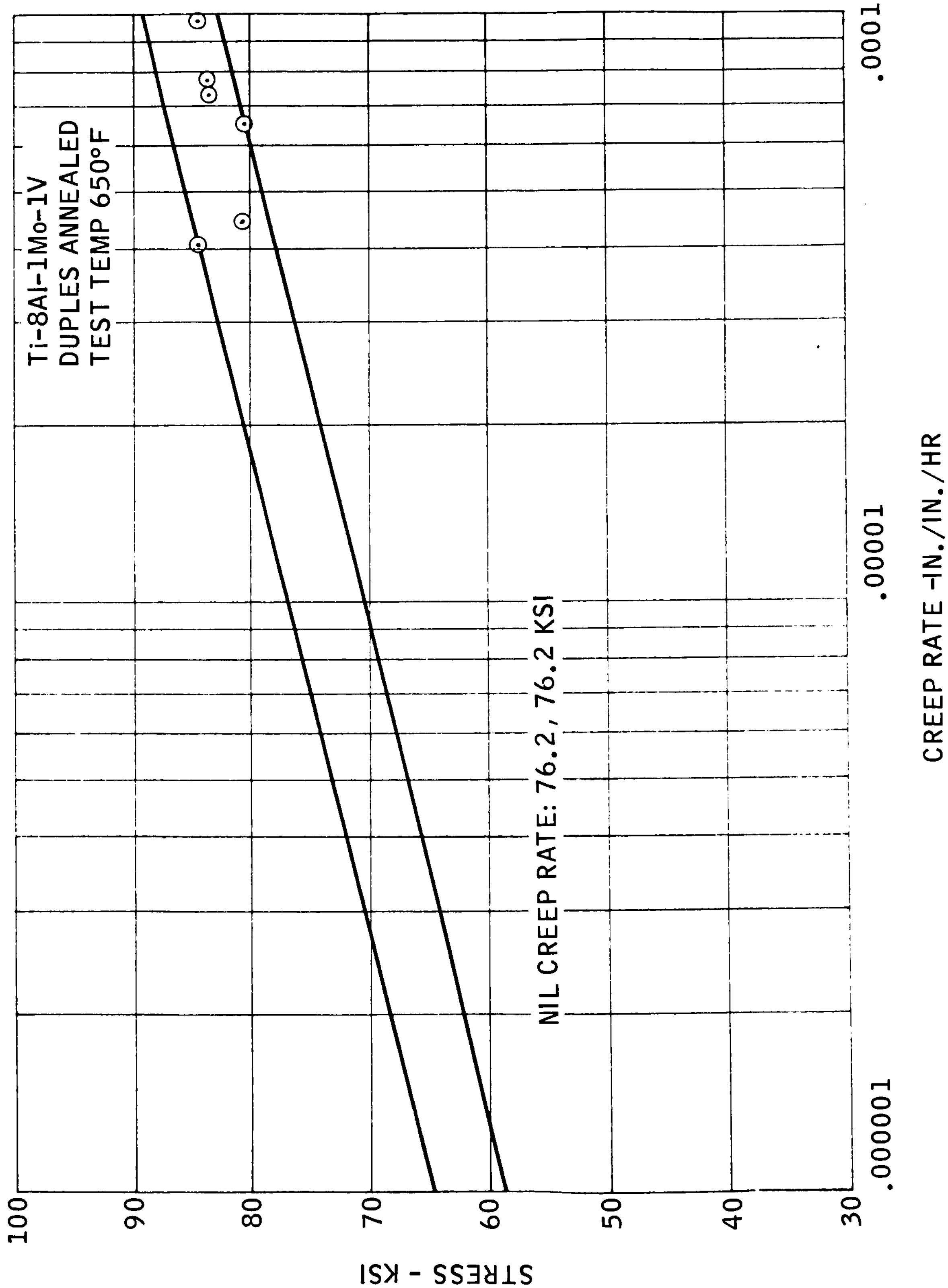


Figure 21. Stress Versus Creep Rate, Ti-8Al-1Mo-1V, 650°F

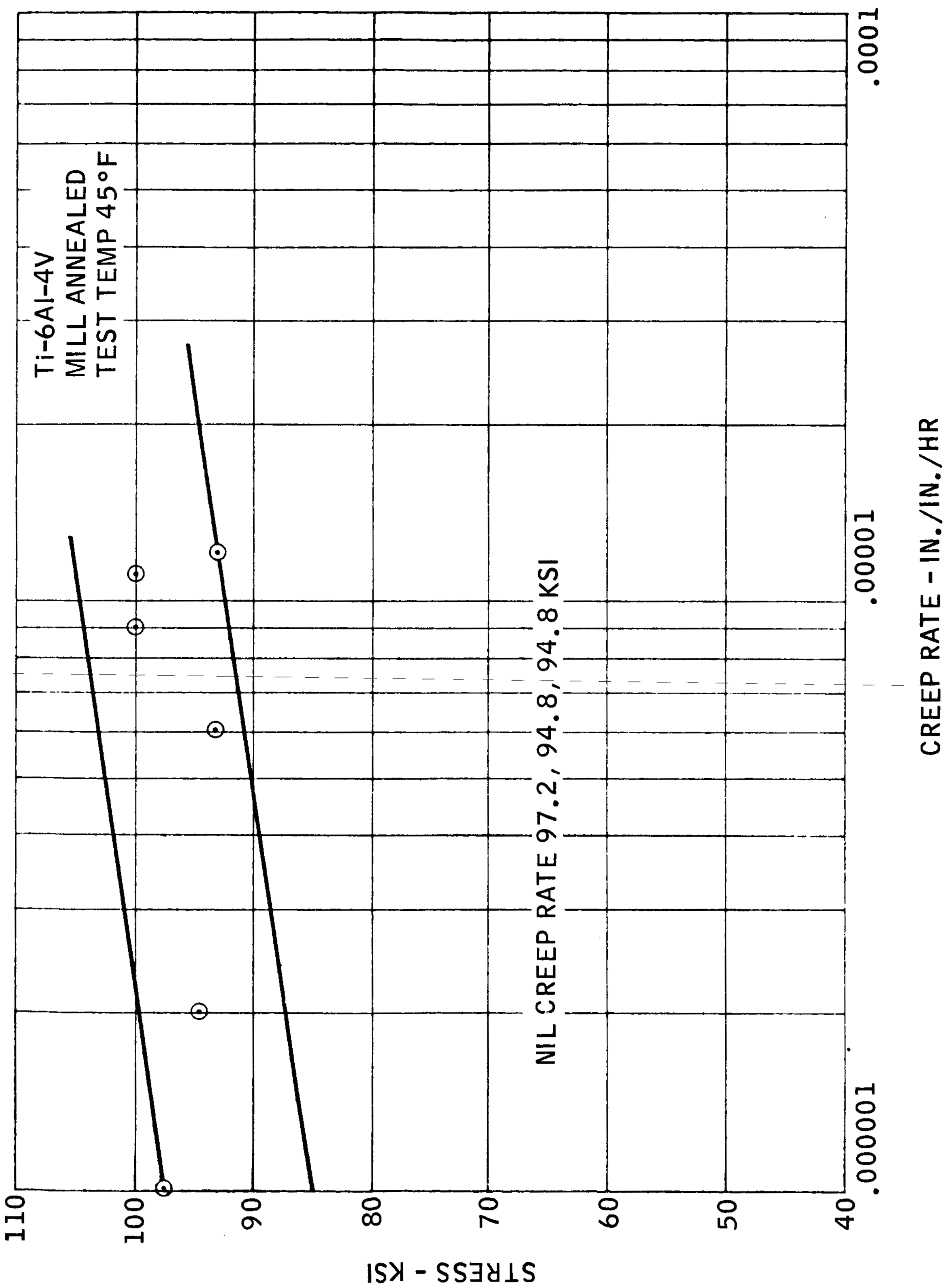


Figure 22. Stress Versus Creep Rate, Ti-6Al-4V, 450° F

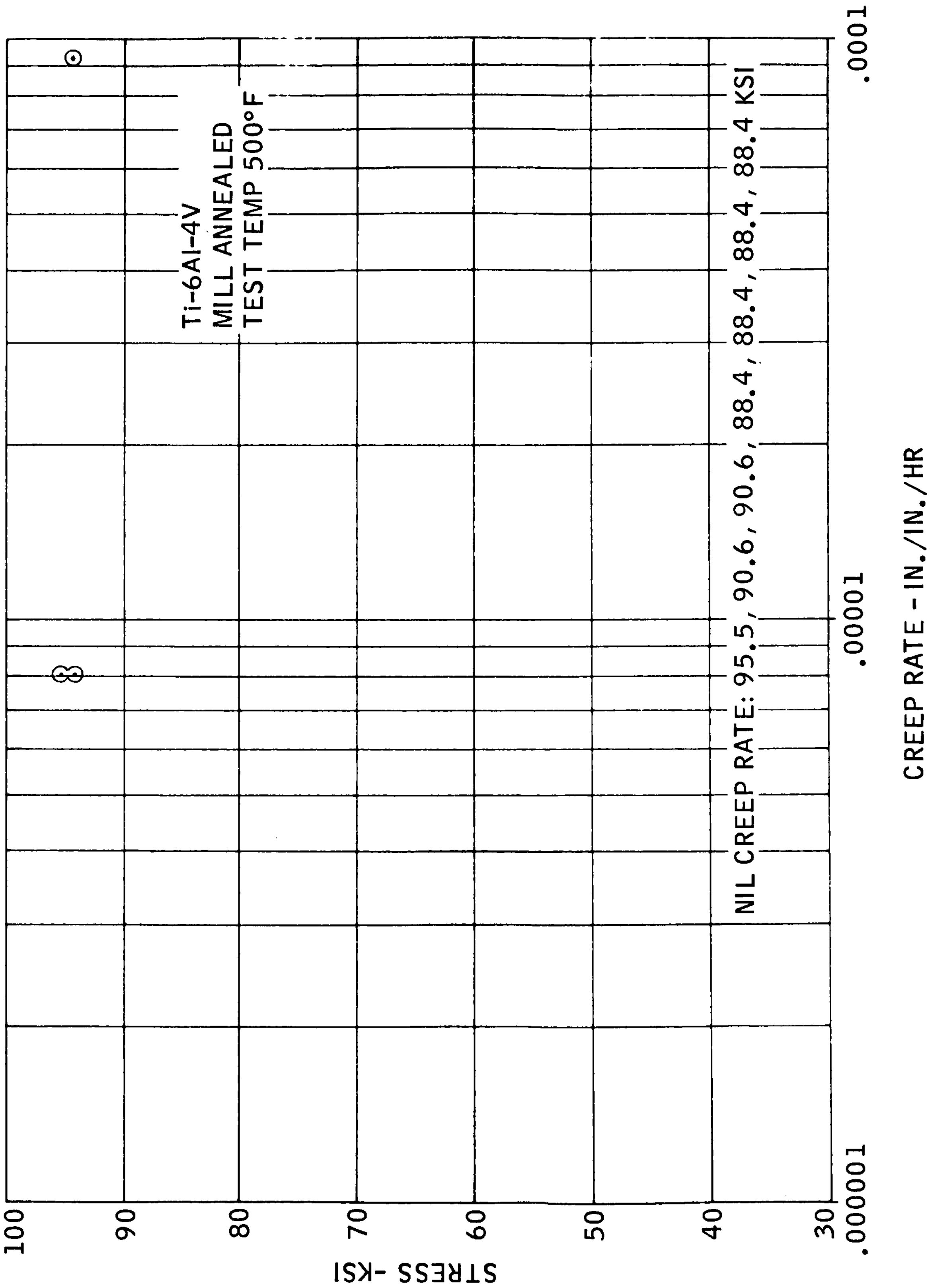


Figure 23. Stress Versus Creep Rate, Ti-6Al-4V, 500° F

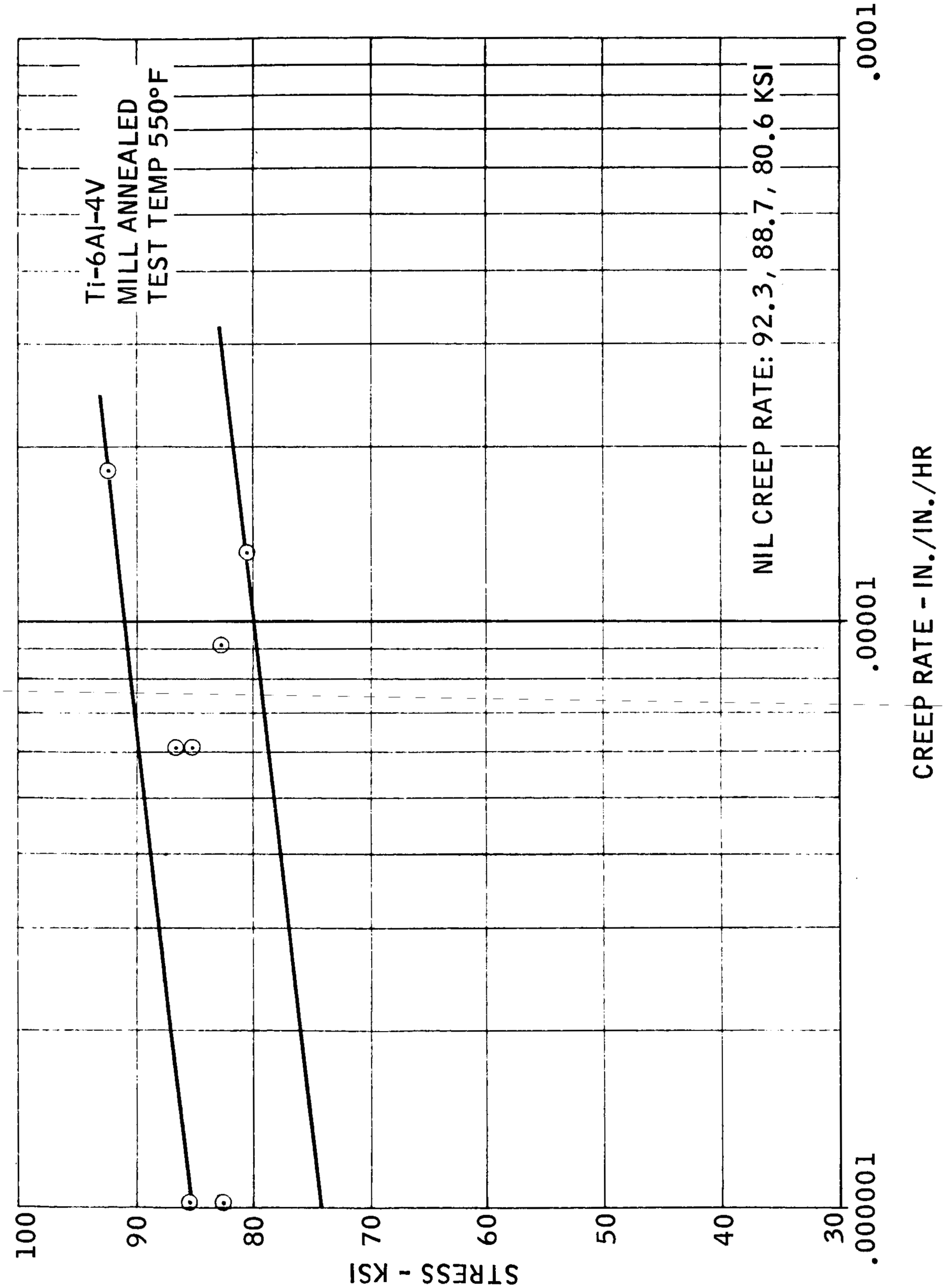


Figure 24. Stress Versus Creep Rate, Ti-6Al-4V, 550° F

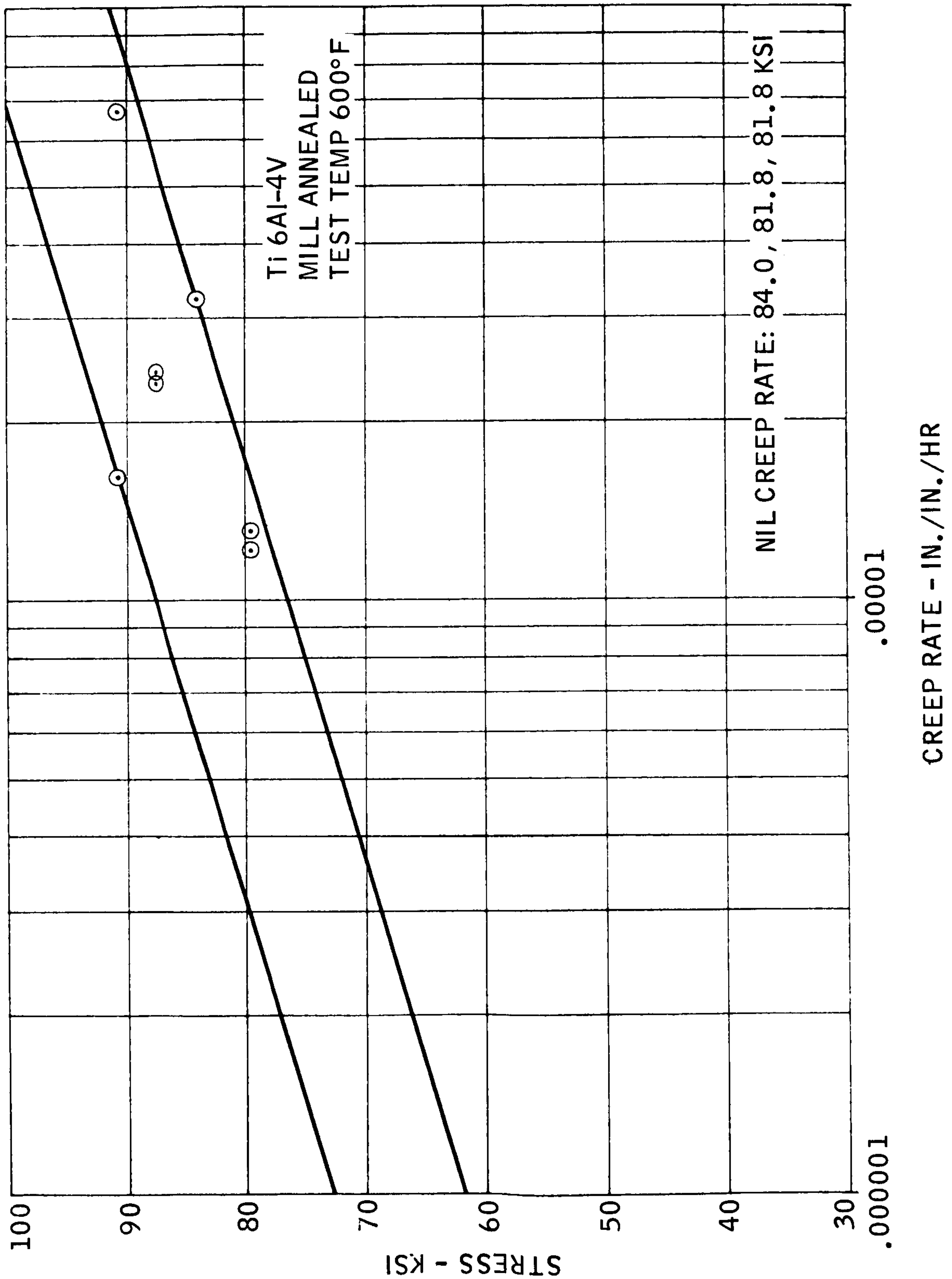


Figure 25. Stress Versus Creep Rate, Ti-6Al-4V, 600 °F

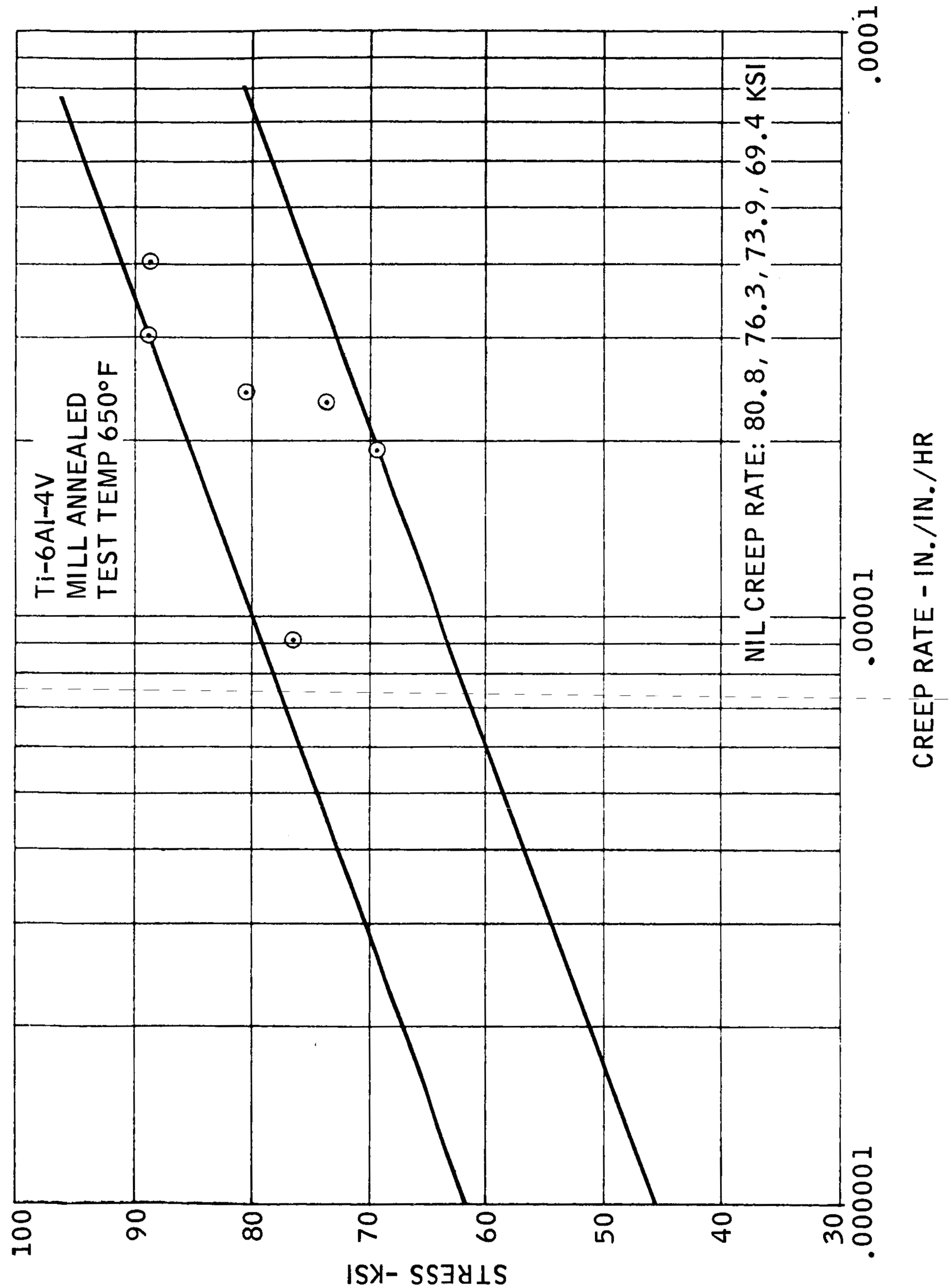


Figure 26. Stress Versus Creep Rate, Ti-6Al-4V, 650°F

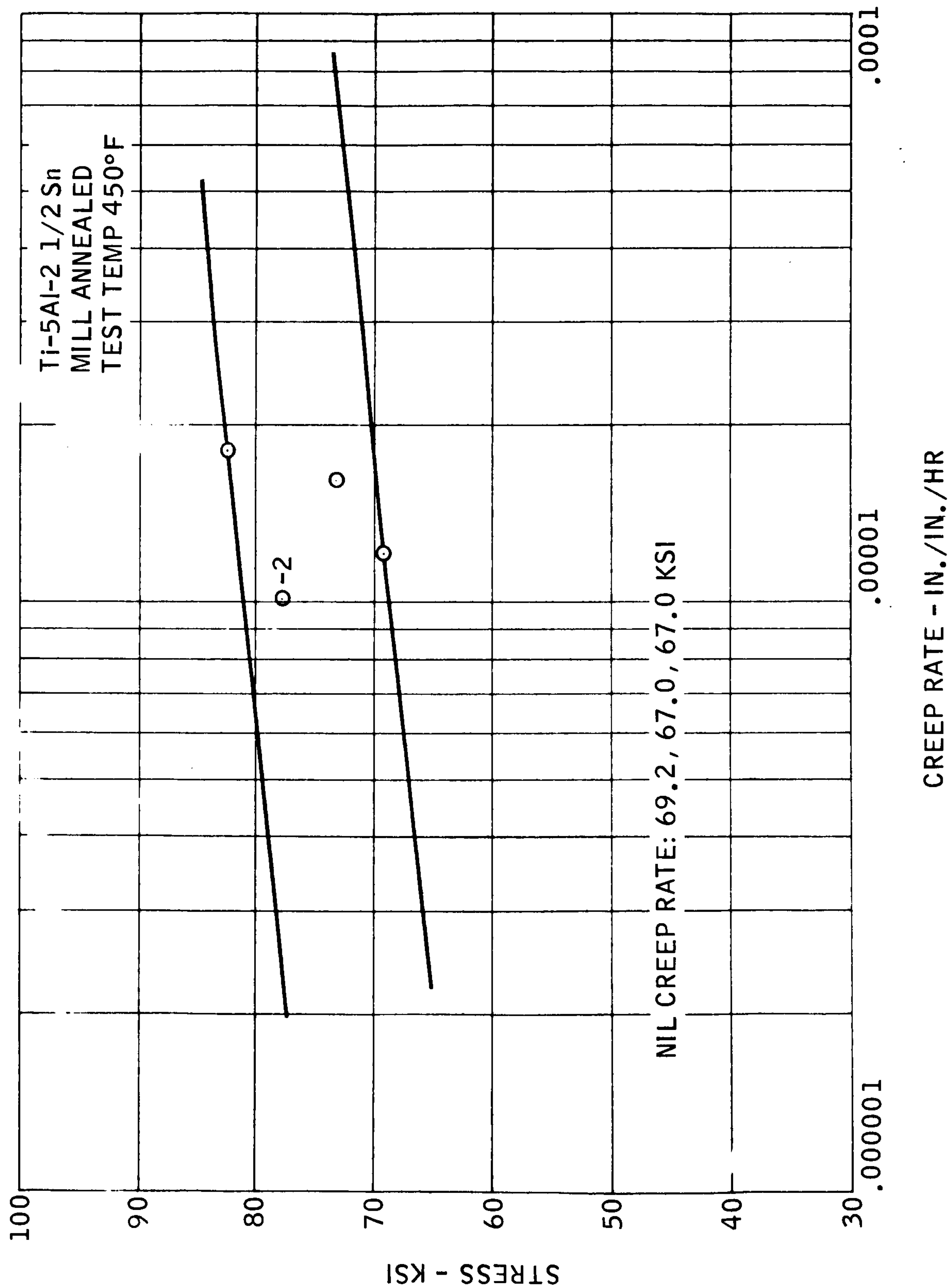


Figure 27. Stress Versus Creep Rate, Ti-5Al-2 1/2 Sn, 450°F

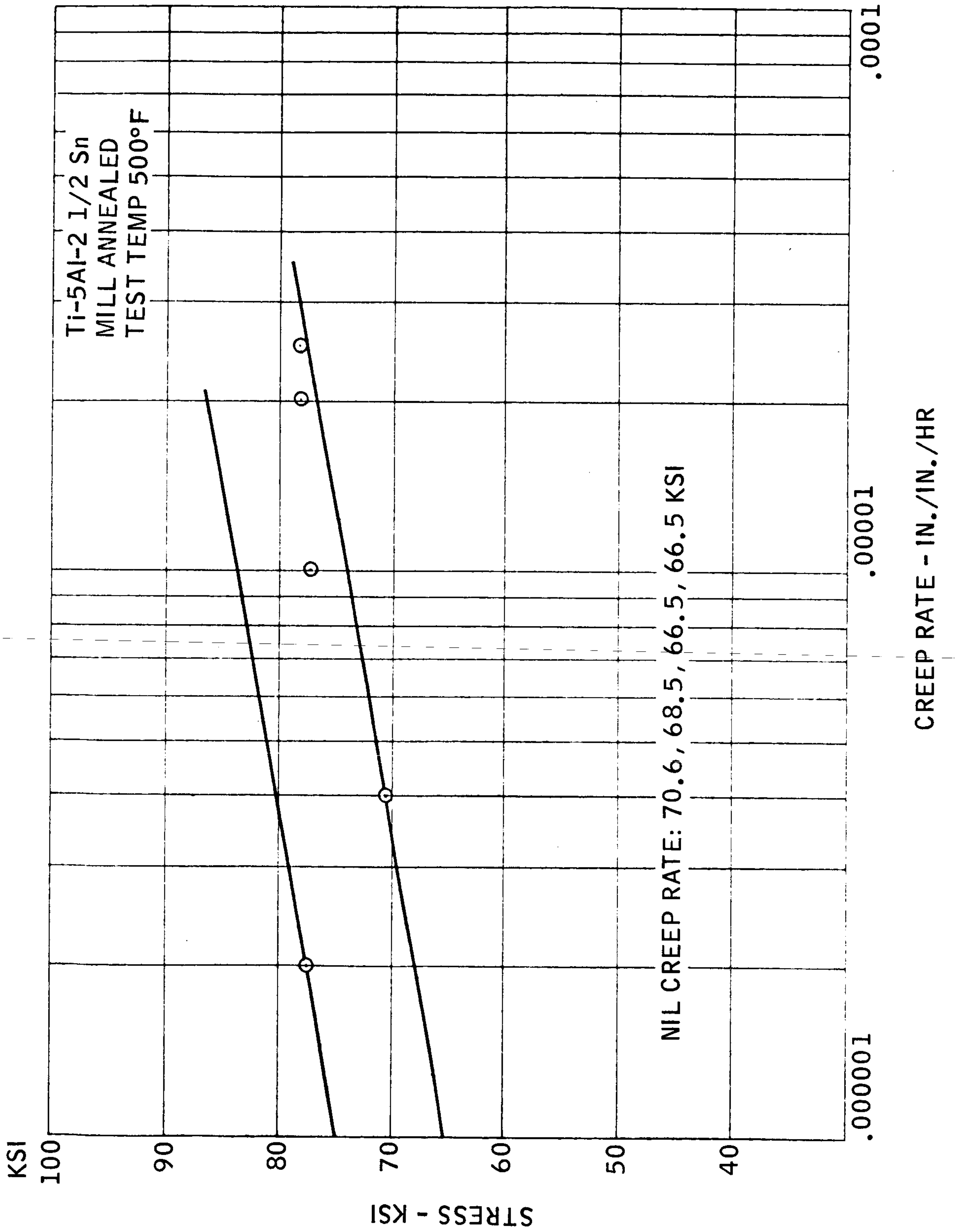


Figure 28. Stress Versus Creep Rate, Ti-5Al-2 1/2 Sn, 500° F

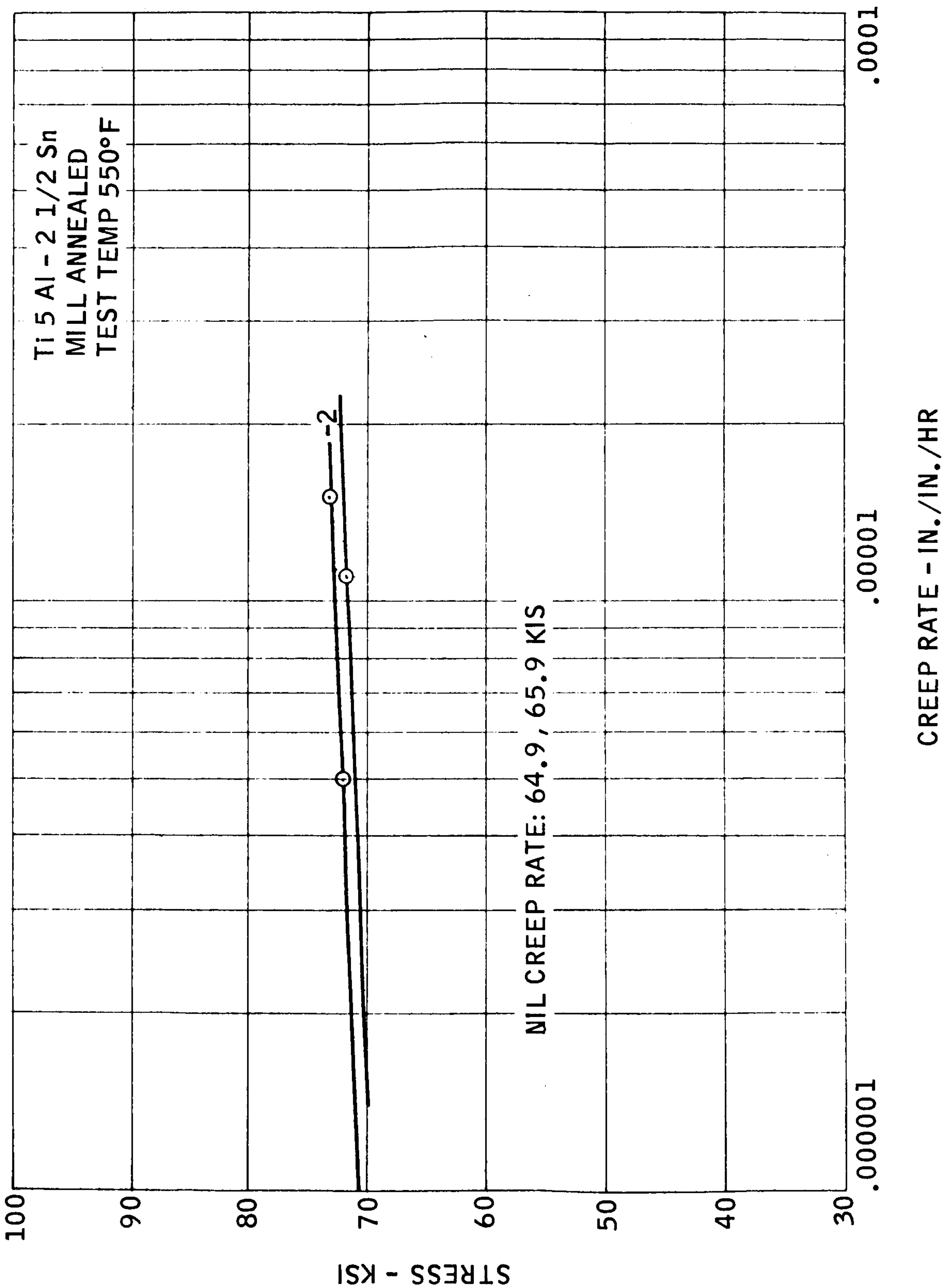


Figure 29. Stress Versus Creep Rate, Ti-5Al-2 1/2 Sn, 550° F

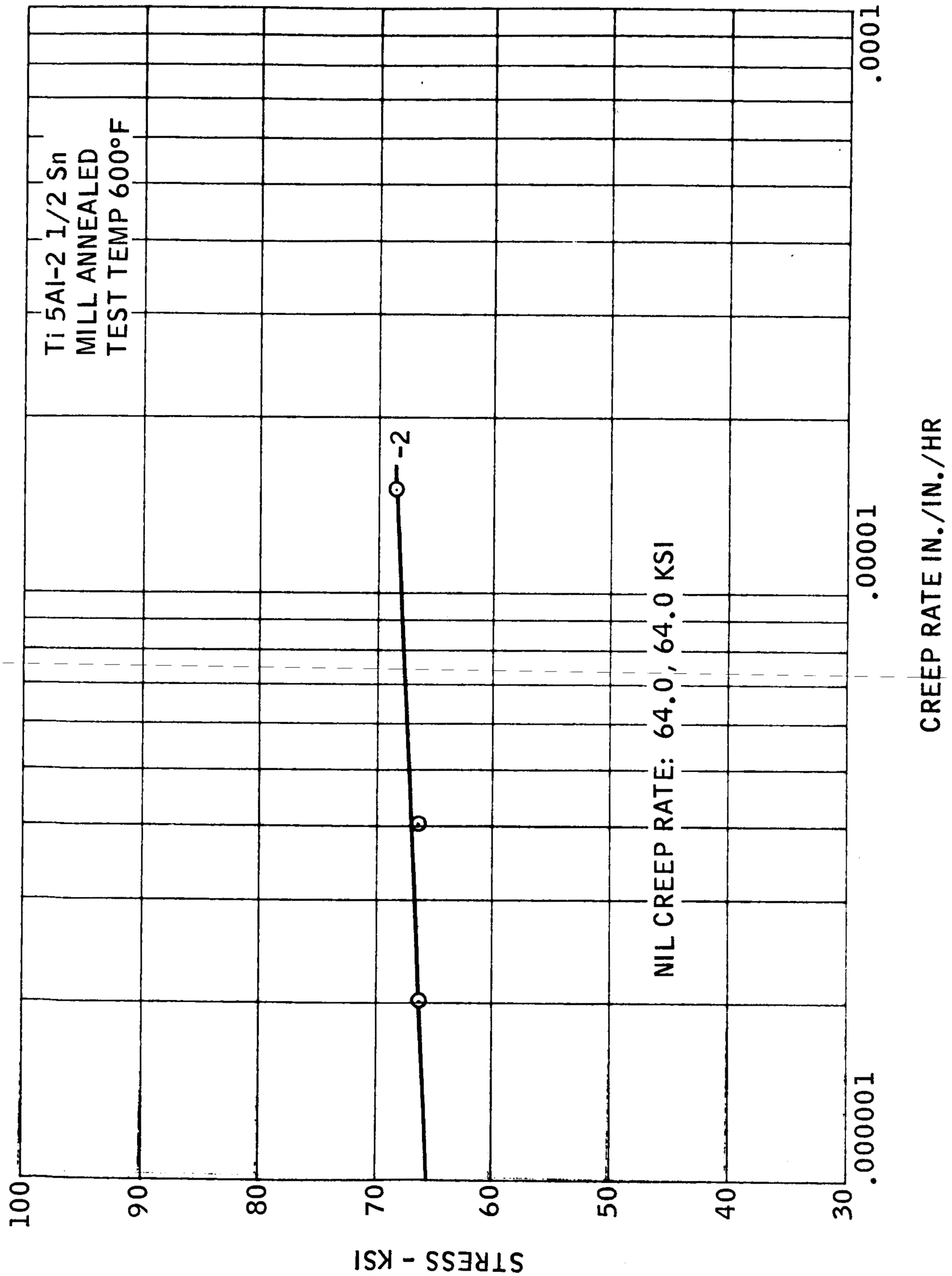


Figure 30. Stress Versus Creep Rate, Ti-5Al-2 1/2 Sn, 600°F

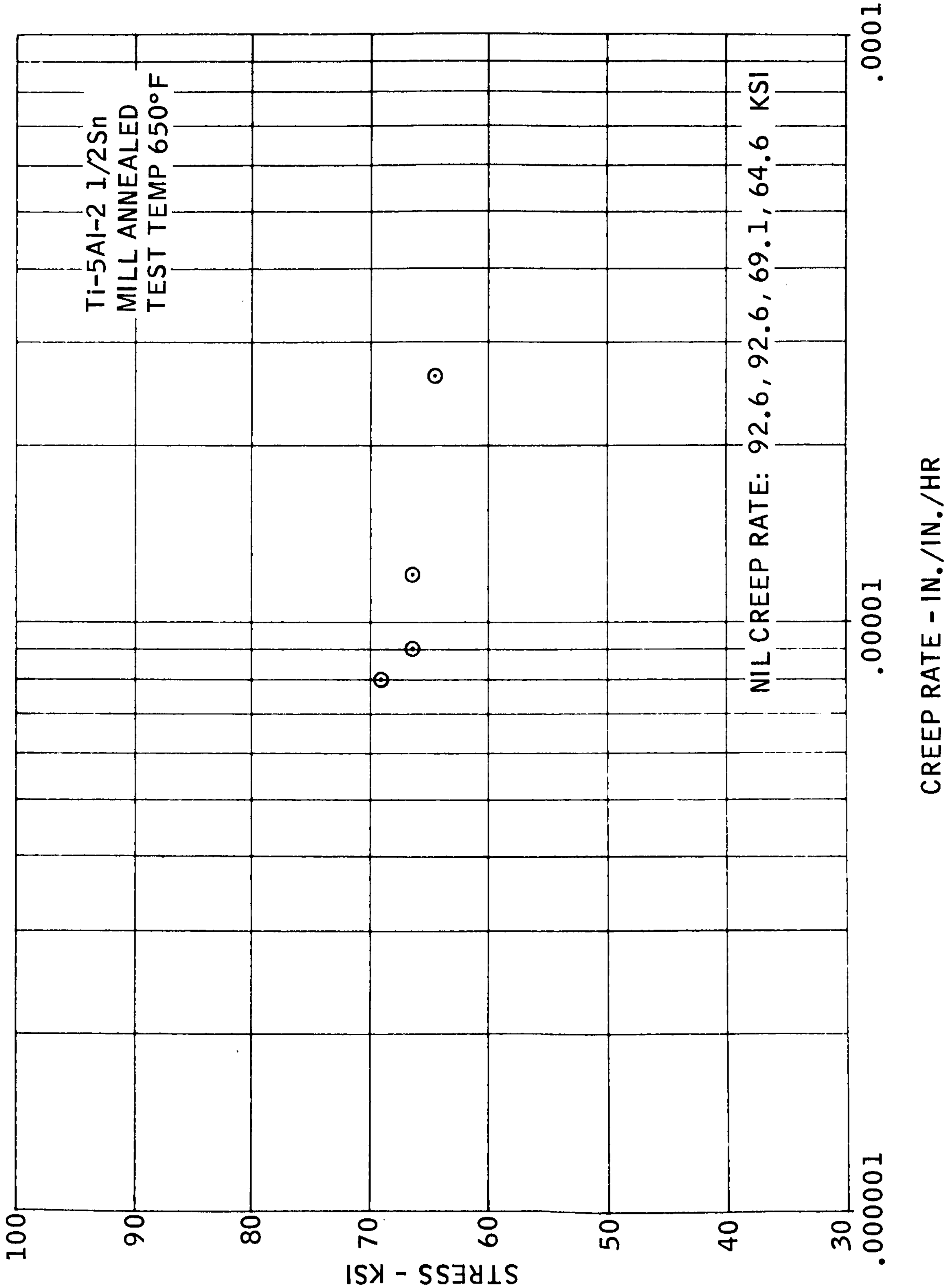


Figure 31. Stress Versus Creep Rate, Ti-5Al-2 1/2 Sn, 650° F

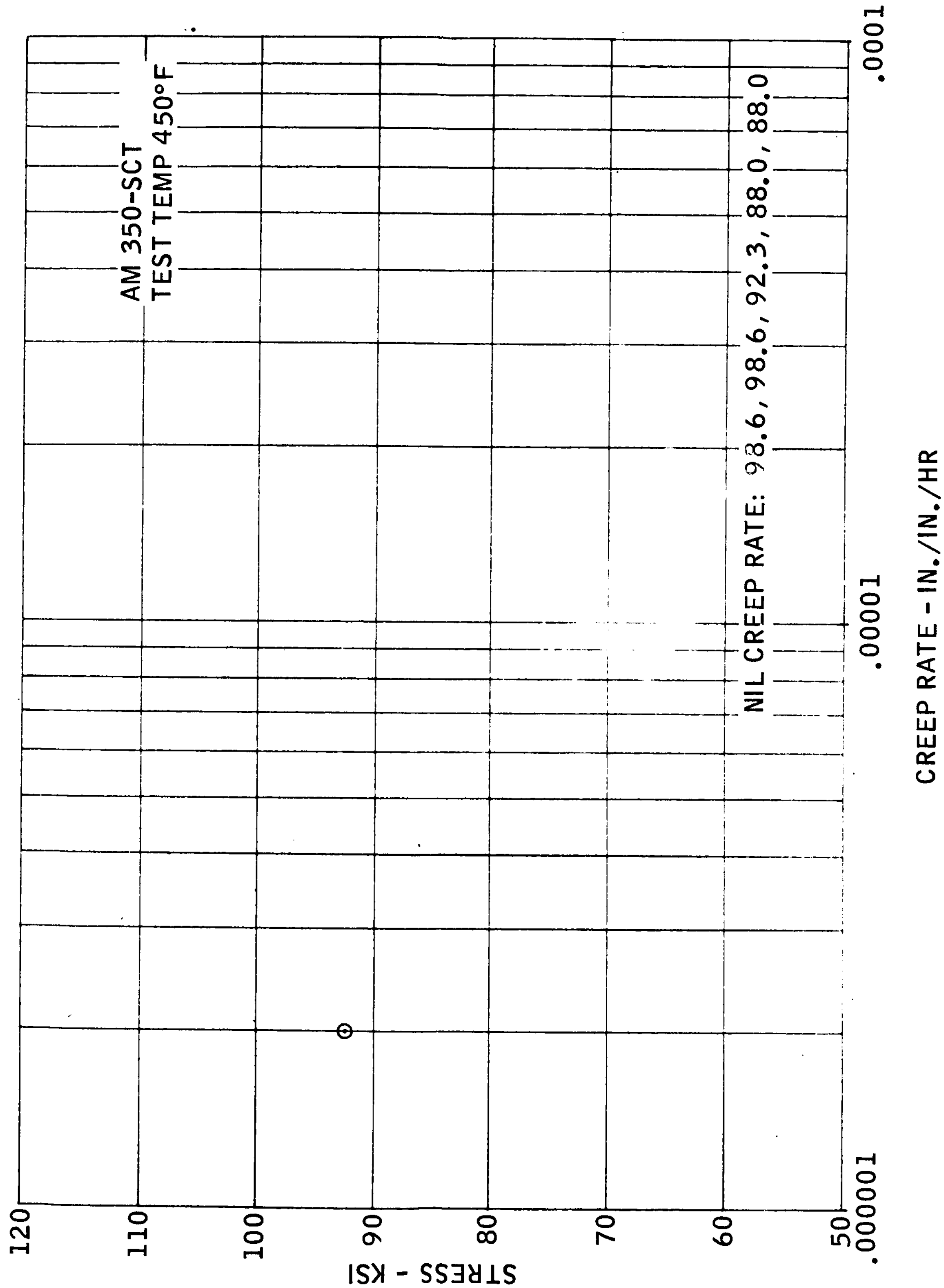


Figure 32. Stress Versus Creep Rate, AM-350 SCT, 450° F

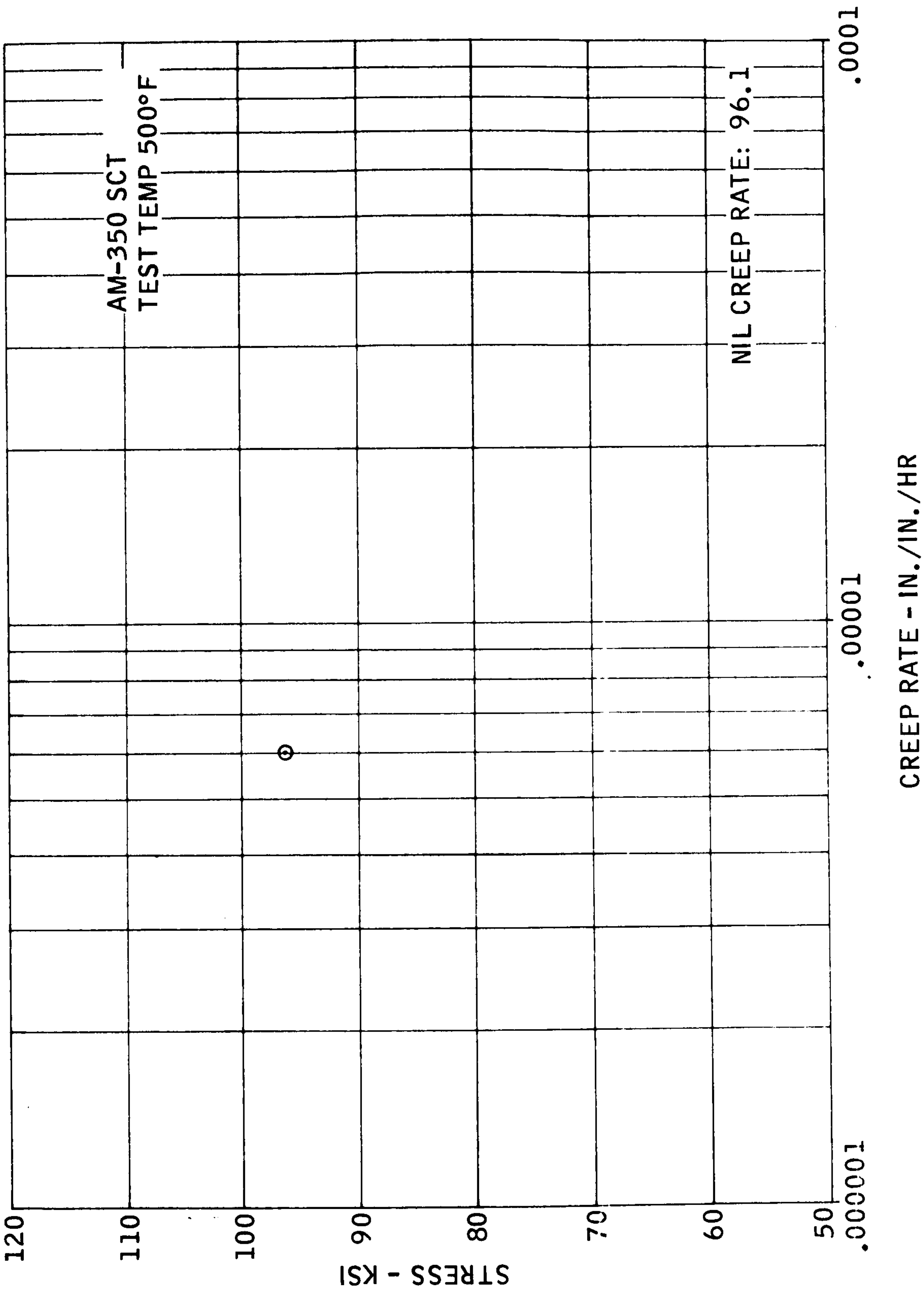


Figure 33. Stress Versus Creep Rate, AM-350 SCT, 500° F

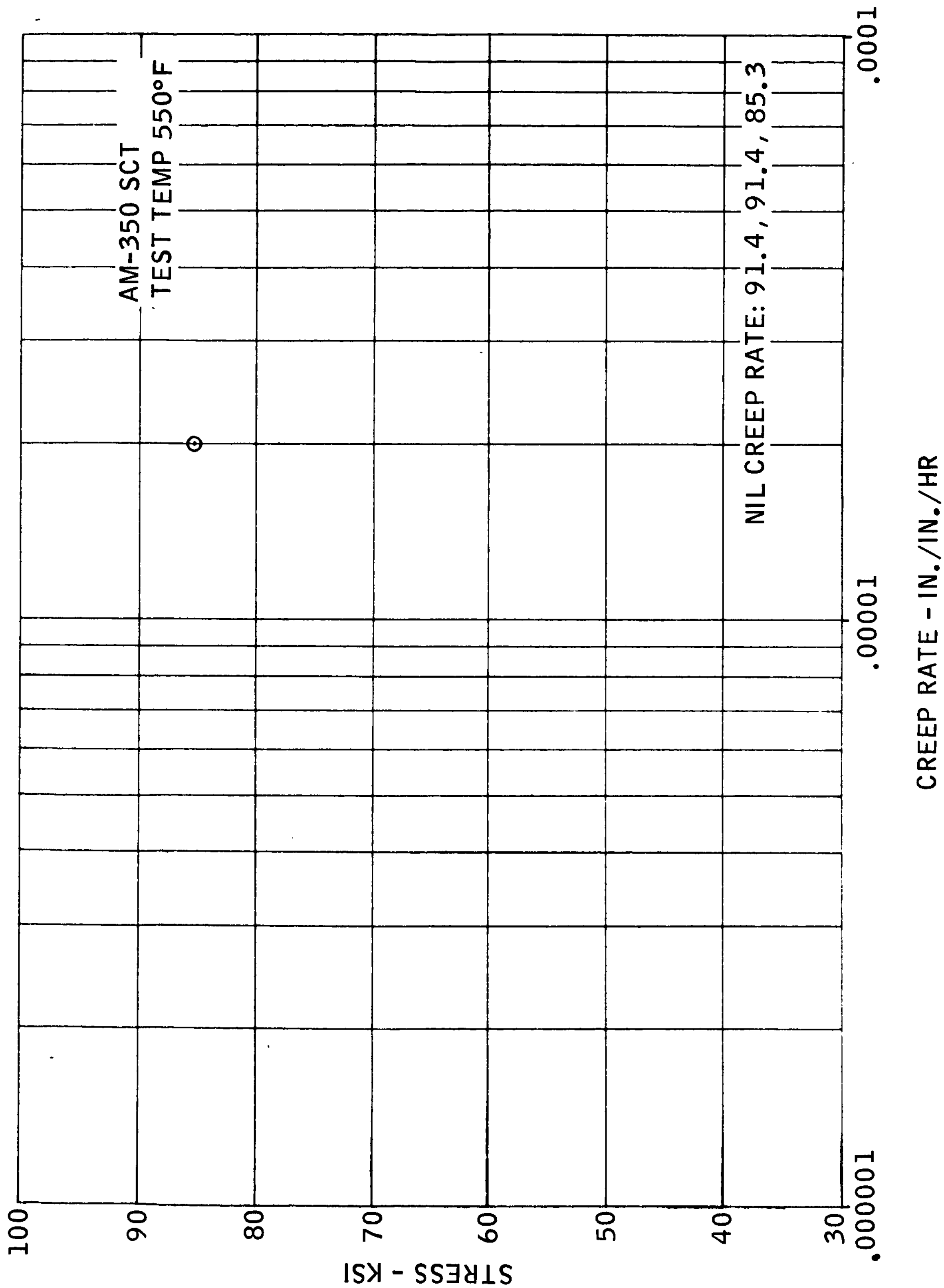


Figure 34. Stress Versus Creep Rate, AM-350 SCT, 550° F

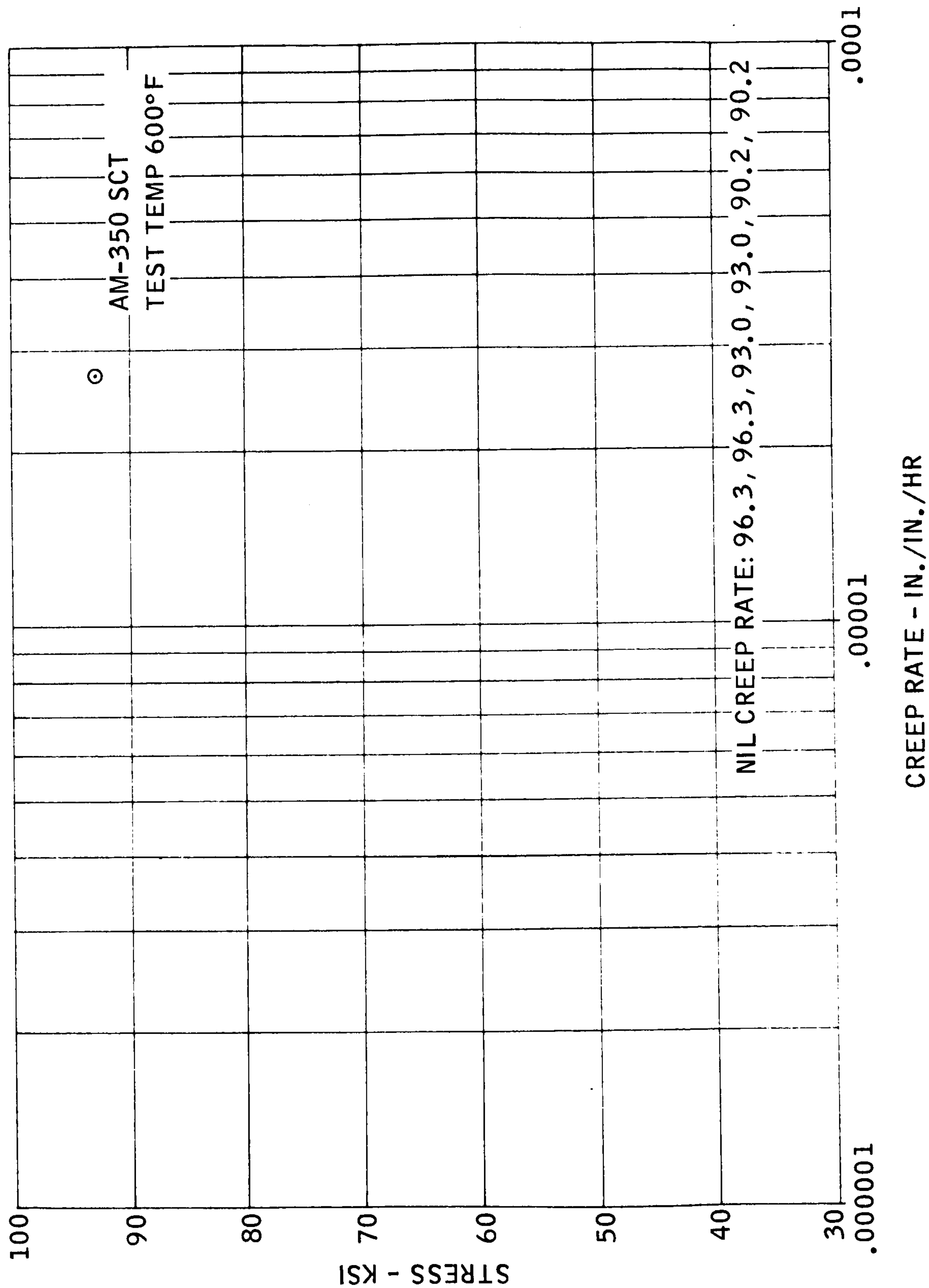


Figure 35. Stress Versus Creep Rate, AM-350 SCT, 600° F

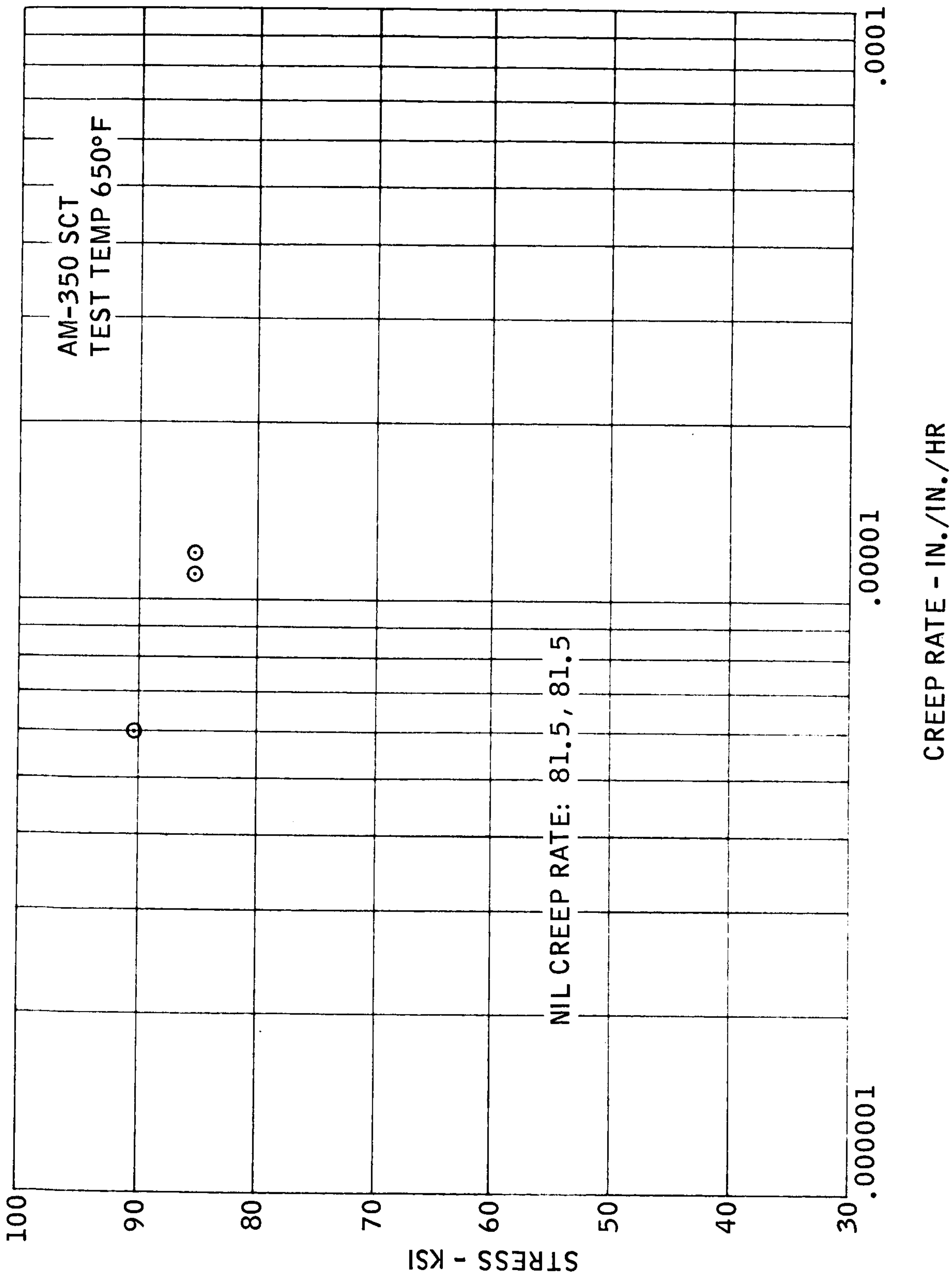


Figure 36. Stress Versus Creep Rate, AM-350 SCT, 650° F

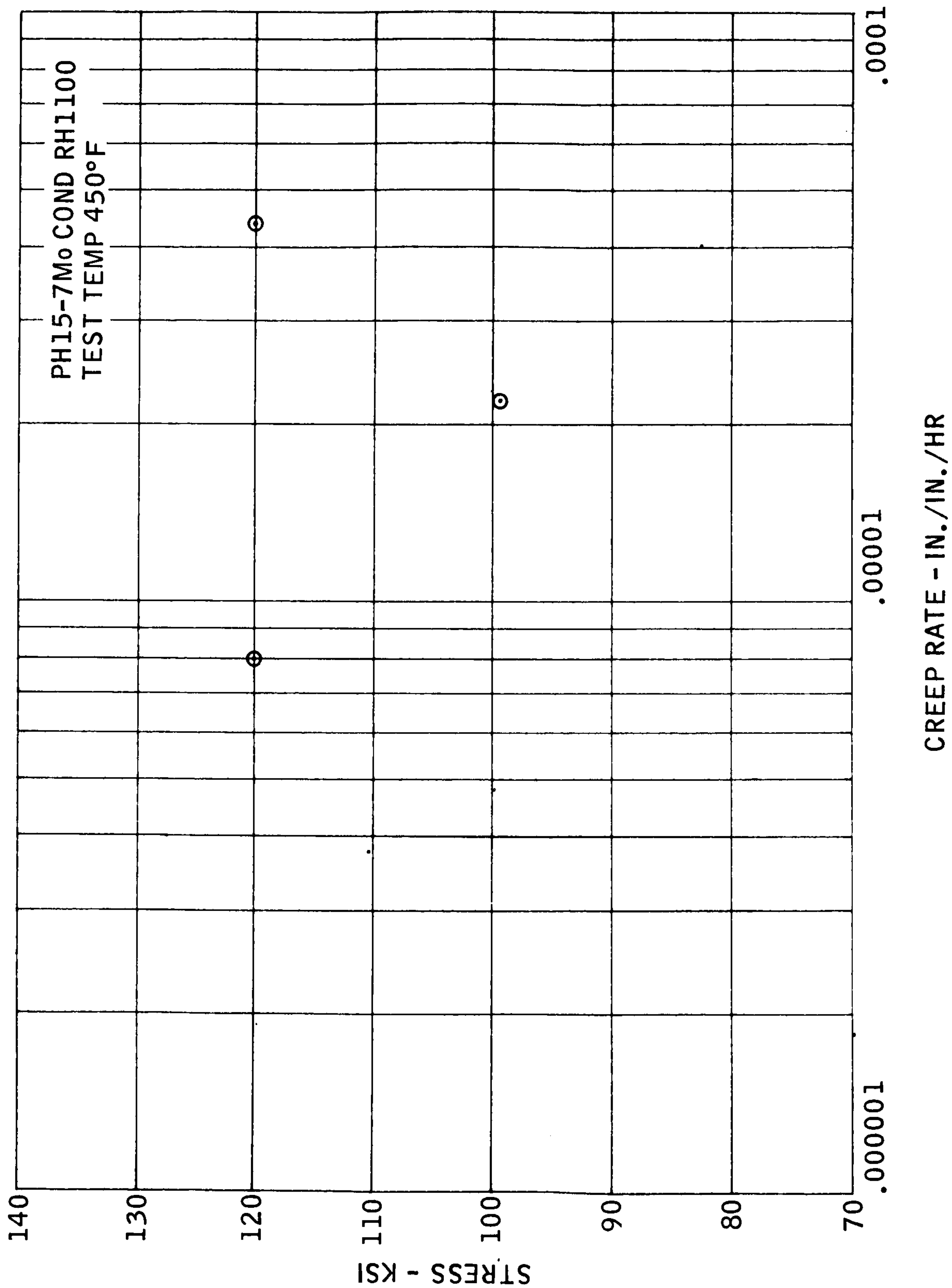


Figure 37. Stress Versus Creep Rate, PH 15-7 Mo, RH 1100, 450° F

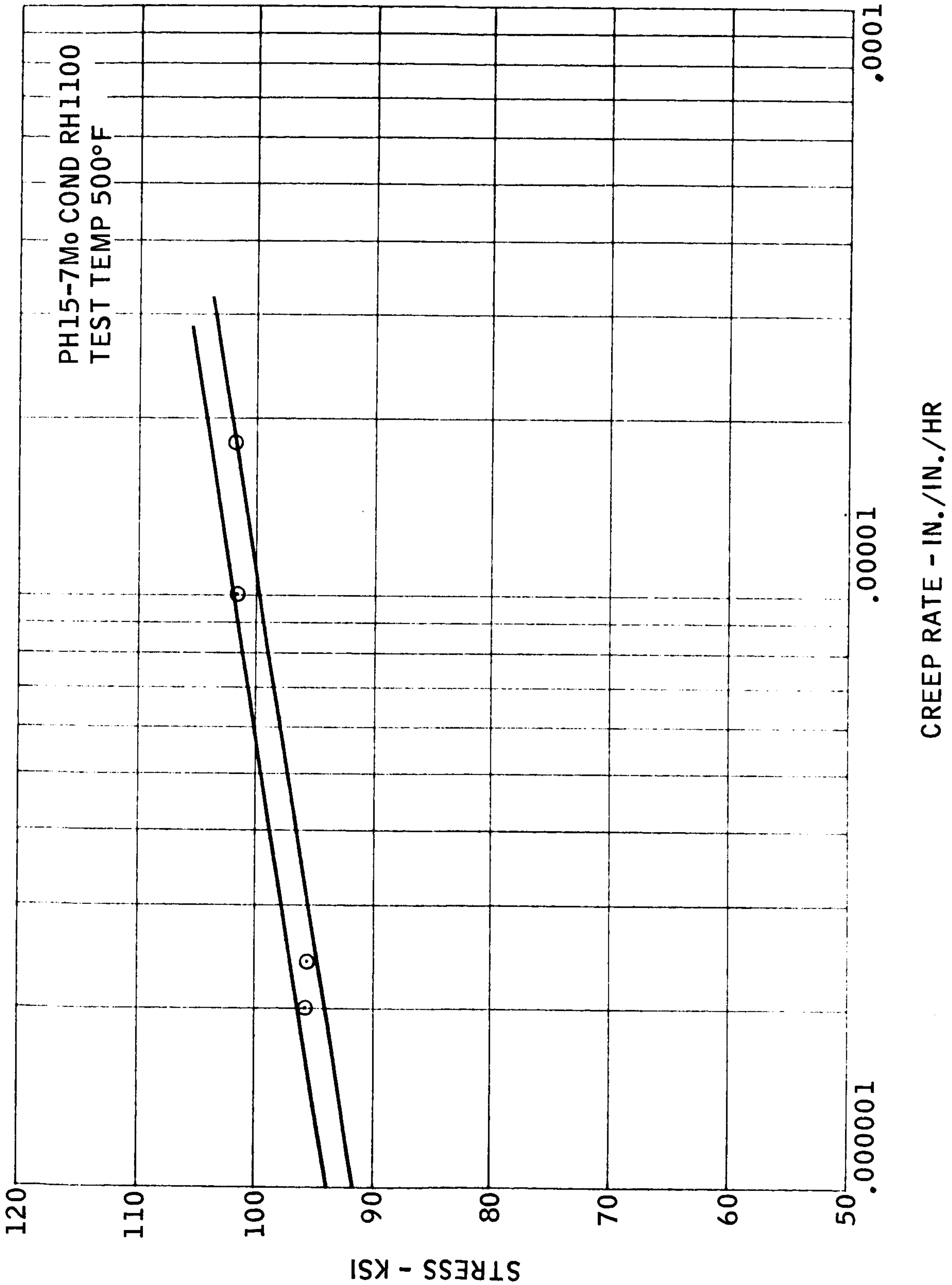


Figure 38. Stress Versus Creep Rate, PH 15-7 Mo, RH 1100, 500° F

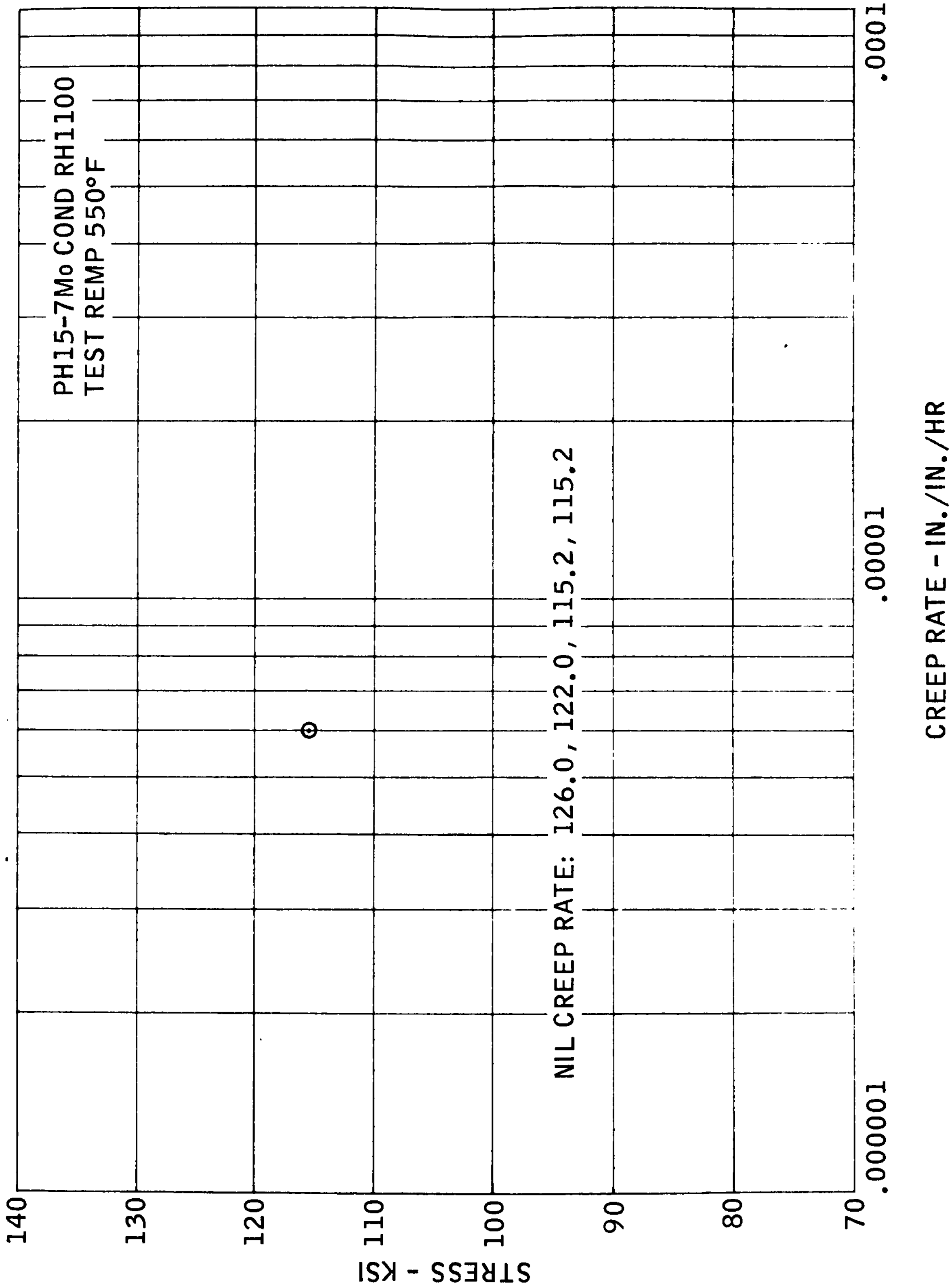


Figure 39. Stress Versus Creep Rate, PH 15-7 Mo, RH 1100, 550° F

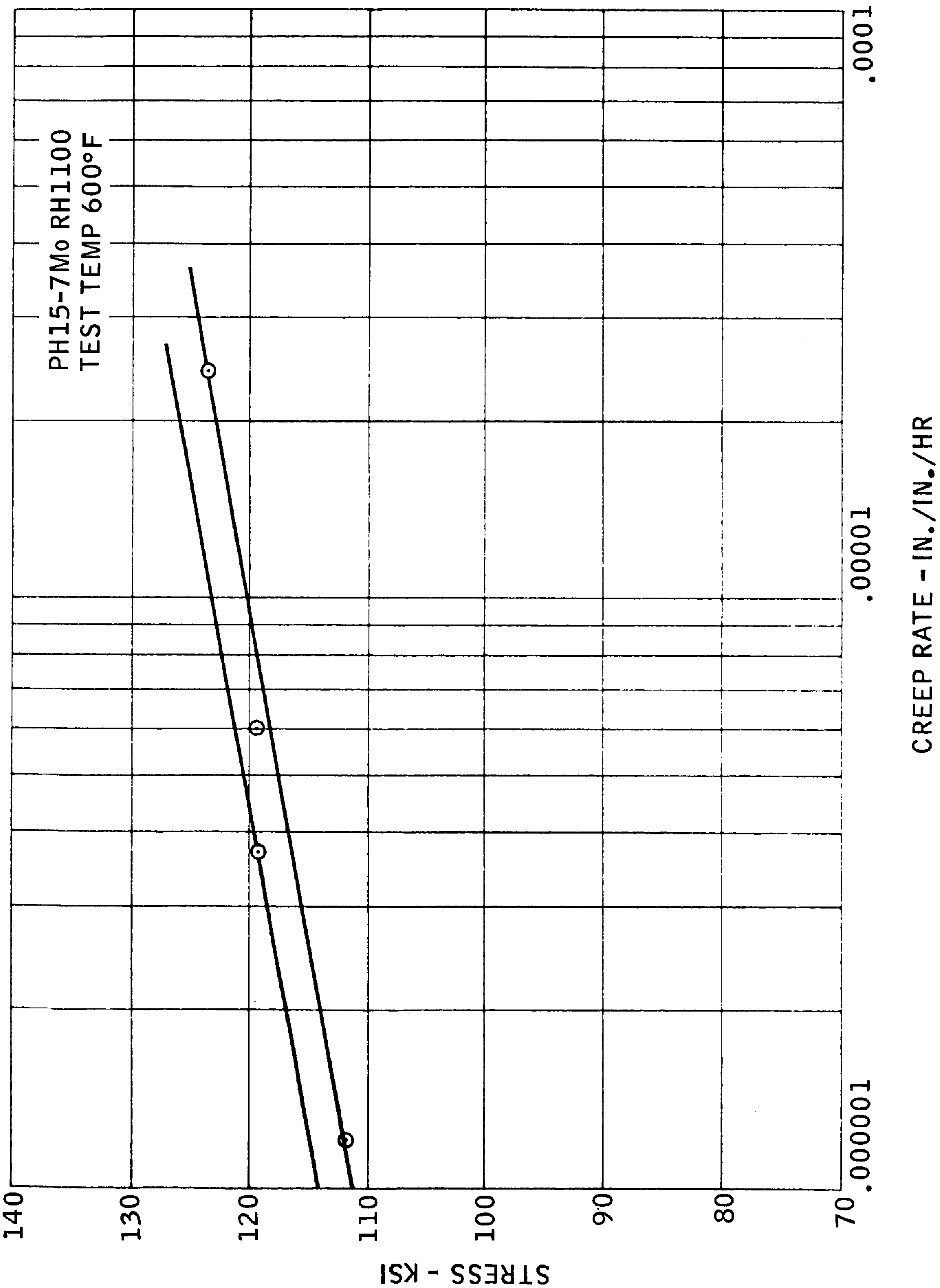


Figure 40. Stress Versus Creep Rate, PH 15-7 Mo, RH 1100, 600° F

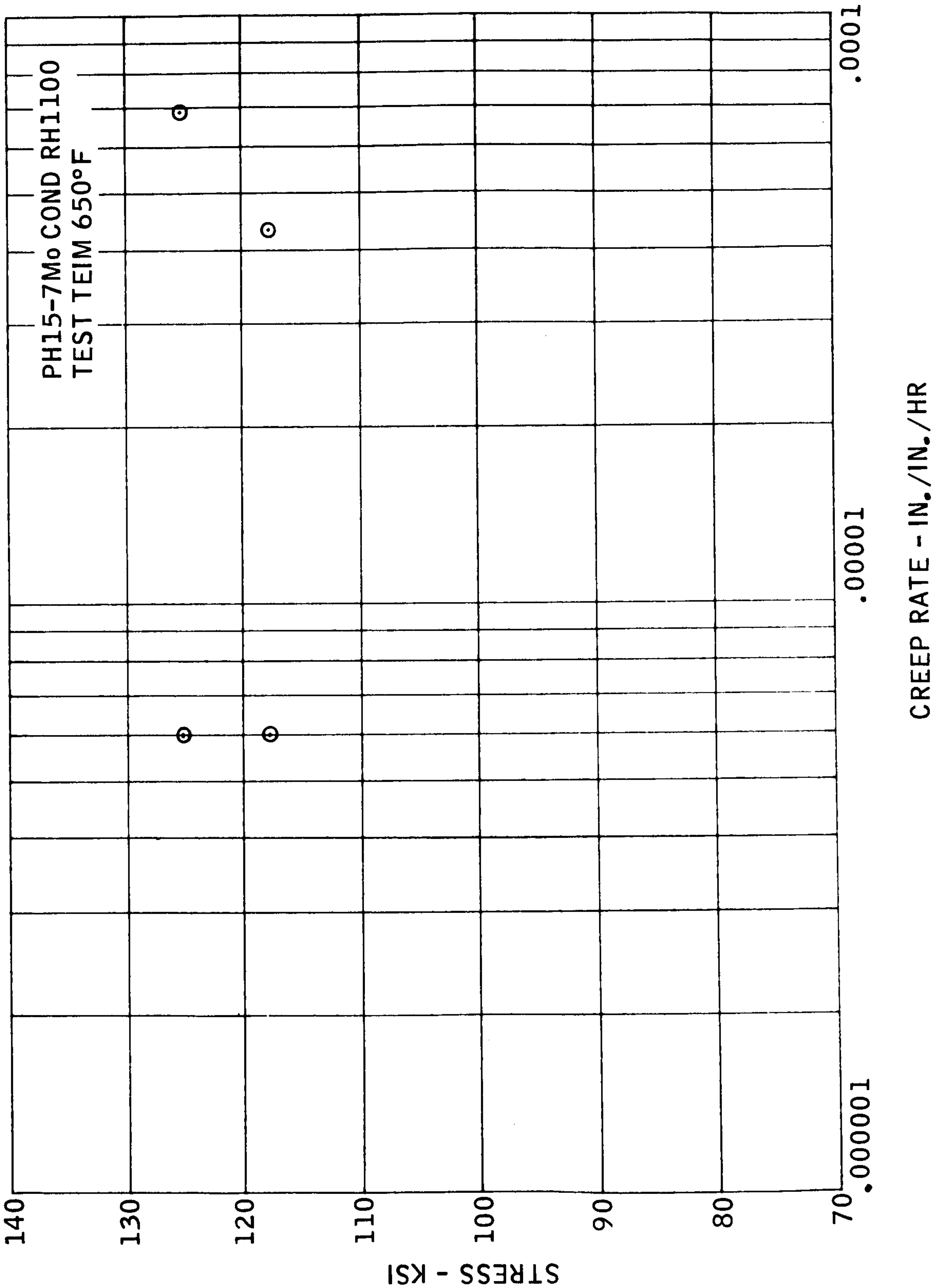


Figure 41. Stress Versus Creep Rate, PH 15-7 Mo, RH 1100, 650° F