REON

ROCKET ENGINE OPERATIONS — NUCLEAR

REPORT NO. 2712

TO

AEC-NASA SPACE NUCLEAR PROPULSION SYSTEM

CRYOGENIC TENSILE PROPERTIES OF SELECTED MATERIALS

NERVA PROGRAM

CONTRACT SNP-1 1 JANUARY 1964

AEROJET
GENERAL TIRE
GENERAL

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AEROJET-GENERAL CORPORATION

A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

ABSTRACT

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Fifteen different metals and three Teflon-based plastics were tensile tested at room temperature, and at cryogenic temperatures ranging as low as -423°F. Both standard and notched-type specimens were used for the metals, the latter having stress concentration factors (K_t) from 5 to 18. Test results are compared with information from other sources when available.

Metals tested were: titanium alloys 5Al-2.5 Sn-ELI, 6Al-4V-ELI; stainless steel types 321, 347-c, and AM350; iron base alloys A-286 and 18% Ni moraging steel; nickel alloys Hastelloy C, Inconel X-750, and Inconel 713-c; aluminum alloys A356-T6, 2219-T81, 5456-0, 6061-T6, 7079-T6.

Plastics tested were Teflon-TFE, Armalon and Rulon A.

W. D. Stinnett
NERVA Technical Systems, Manager
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I. INTRODUCTION

The information presented in this report was compiled from tests performed both at the Aerojet-General Corporation plants in Sacramento, and at the Von Karman Research Center at Azusa. It represents the results of some screening tests conducted during a materials irradiation program determination of cryogenic properties of materials; and includes verification tests on the properties of some of the materials in the as-fabricated condition. The following classes of materials were involved:

Titanium Alloys ;
Stainless Steel and Iron Base Alloys ;
Nickel-Base Alloys ;
Aluminum Alloys ;
Organic Materials. 1/2

A total of 15 metals and three Teflon-base materials were tested.

SECTION II

MATERIALS

II. MATERIALS

A. TITANIUM ALLOYS

Two types of titanium alloys were tested: A-110-AT-ELI (5Al-2.5Sn) and C120-AV-ELI (6Al-4V).

1. A-110-AT-ELI (5Al-2.5 Sn)

Several conditions of this material were tested.

a. Hot rolled and annealed plates (0.25 in.)

b. Forged plate (0.5 in.)

c. Extruded cylinders

d. Forged and rolled rings

e. Die-forged closures.

Material for items c, d, and e were taken from parts used in the fabrication of the titanium pressure vessel S/N 001TPV.

2. C 120 AV ELI (6Al-4V)

Specimens for this alloy were taken from forged plate of 0.555 inch thickness.

B. STAINLESS STEEL AND IRON BASE ALLOYS

Five alloys were tested in this series:

321 stainless steel

347-c stainless steel casting

AM-350 (SCT-850)

A-286 Iron Base Alloy

18% Ni (250) maraging steel

1. 321 Stainless Steel

This alloy was procured as 0.25 inch thick plate in the fully annealed condition.

2. 347-c Stainless Steel - Sand Casting

This alloy was sand cast in test bars (having dimensions of approximately 0.25 x 2.0 x 16.0 in.) and in conformance to AMS 5363-B, Class I. All specimens were completely X-rayed prior to machining. The castings were annealed at 1950°F for 30 minutes.

3. AM-350 (SCT) Stainless Steel

This alloy was procured in the hot-rolled, annealed and pickled condition in accordance with AMS 5548 condition H. After rough machining, the specimens were heat treated to the SCT-850 temper and then final machined. The heat treatment was as follows:

Solution treatment:

1710°F ±25°, 30 minutes, water quenched.

Refrigerated:

-100°F ±10°, 3 hours.

Aged:

850°F, three hours, air cooled.

4. A-286 Iron Base Alloy

This alloy was procured in the hot-rolled, annealed and pickled condition to specification AMS 5525. It was heat treated as follows:

Solution treated:

1800°F, 1 1/2 hours, air cooled.

Aged:

1350°F, 16 hours, air cooled.

5. 18% Nickel (250) Maraging Steel

Two forms of this alloy were tested: 0.090 inch thick sheet and 3/8 inch dia. high-strength bolts. Materials were supplied both in standard and in peened conditions.

Two melting conditions were represented in sheet material.

a. air melted

b. air melted, vacuum remelted.

The sheet specimens were aged at 900°F for 3 hours after fabrication. The bolts were received in the hardened condition.

C. NICKEL-BASE ALLOYS

The alloys tested in this series were Hastelloy C, Inconel X-750, and Inconel 713-c.

1. Hastelloy C

This material was procured as 0.25 in. plate in the solution heat treated condition conforming to AMS 5530C.

2. Inconel X-750

This material was procured as 0.25 in. sheets cold-rolled, annealed and pickled. The material was precipitation hardened by heating at 1300°F ±25° for 20 hours and air cooled.

3. Inconel 713-c

This material was procured as vacuum investment cast in blanks approximately 0.25 x 2.0 x 10 inches. All test bars were X-rayed for soundness of material prior to machining. Specimens were cast, four per mold; pouring temperature was 2550°F.

D. ALUMINUM ALLOYS

Five aluminum alloys were included in the series. These were A356-T6, 2219-T81, 5456-0, 6061-T6, and 7079-T6. The material was prepared in the following manner:

1. A356-T6

This material was cast in test bars having dimensions of approximately 0.25 x 2.0 x 15.0 in., and was x-rayed for soundness prior to further work. The material was heat treated to the T-6 condition as follows:

a. Solution Treatment: 1000°F, 10 hours, water-quenched

b. Aged: 16 hours at room temperature

c. Precipitation Hardened: 310°F, 4 hours

2. 2219-T81

This alloy was procured in the form of heat treated, 0.25-in.-thick plate material.

3. 5456-0

This alloy was procured in plates of 0.25 inches thickness; in the H321 temper. The annealed "0" condition of the specimens was obtained by heating them at 650°F for 30 minutes and air cooling to room temperature.

4. 6061-T6

Two forms of this alloy were tested. One consisting of 0.25 inch plate, the other of a rolled ring forging from the aluminum pressure vessel (heat number 4034 P/N 281498-1-A0). Heat treatment after forging consisted of:

a. Solution Treatment: 975°, one hour, water quenched.

b. Precipitation Hardened: 350°, 7.5 hours, air cooled.

5. 7079-T6

This alloy was tested in three different forms: sheet, plate, and round bars. All specimens were supplied by ACFI, Albuquerque Division, and included both welded and non-welded specimens. The weldments were made by ACFI utilizing C-809 weld wire. Tensile specimens conforming to those detailed in Section III-B, were made for the sheet and plate material, and R-1 type specimens were made for the round bars. For the notched welded specimens, the notches were provided in the center of the weld joint.

In addition to the base metals, tests were conducted on: as welded, welded and fully heat treated, and aged-after-welding specimens. The specimens fully heat treated after welding represented good quality weldments. Specimens in the as-welded and welded-aged conditions were below minimum weld quality, but were tested to give some idea of strength value associated with rejectable quality material.

E. TEFLON-BASE MATERIALS

1. Teflon, TFE

The processing details of this material constitute proprietary information of the manufacturer. However, in general, processing follows this procedure: a predetermined quantity (based on end-product dimensions) of Du Pont No. 5 powder, 300 micron size (which is typical for general purposes), is spread on smooth platens and compressed under 2000 to 5000 psi for 5 to 10 sec at room temperature. After sintering at 700°F (i.e., above the 621°F transition to amorphous gell), it is cooled to room temperature. When necessary, material is stress relieved at about 500°F.

2. Armalon (A Laminate of Glass Cloth Impregnated with Teflon, TFE; a Patented Product of E. I. duPont)

This material was manufactured from a No. 112 glass fabric, which was repeatedly dipped in Teflon T-30 suspensoid (an aqueous dispersion containing 59 to 61% solids) until the desired thickness was attained. The Teflon impregnated glass cloth was fused at 750°F and a pressure of 100 psi. The laminate was transferred to a cold press, and a pressure of 100 psi applied until cool. The 0.125-in. sheet used in this test program was built up from a series of 0.005-in. laminates which had at least two pressure-temperature operations similar to the above. As in the case of Teflon, this information is of a general nature, the specific processing details being proprietary.

3. Rulon A (Fiberglass-Filled Teflon, TFE; a Patented Product of the Dixon Corporation)

This material is a filled Teflon of proprietary composition, and was developed for bearing-type applications. The manufacturer's information indicates a considerable improvement over Teflon in resistance to wear, creep, and cold-flow. It is also said to have one-half the thermal expansion of Teflon.

SECTION III

EXPERIMENTAL EQUIPMENT AND SPECIMEN TYPES

III. EXPERIMENTAL EQUIPMENT AND SPECIMEN TYPES

A. EQUIPMENT

All tensile tests were performed on 60,000-lb capacity Baldwin-type hydraulic-operated tensile machines.

For the tests at -100° and -320°F a special liquid container was fabricated. The container consisted of two stainless steel beakers of different sizes, which were nested and welded together at the top, forming a double-walled vessel, open at one end. A hole was bored in the bottom of this chamber and the lower specimen-gripping fixture was inserted and welded in place. The chamber between the inner and outer walls was then evacuated and sealed off to provide thermal insulation. With a standard R1 (.505-in. dia) specimen in position, the fluid level in the container could be easily maintained three inches above the top of the specimen. The container held approximately one gallon of cryogenic fluid, which was added manually as required. The -100°F temperature was achieved by using dry ice and alcohol; the -320°F by using liquid nitrogen. Strain measurements were taken by means of a standard high-temperature-type extensometer (equipped with extension rods) mounted on the tensile specimen. The extension rods extended upward to a position above the cryogenic fluid, where they attached to a differential transformer, from which strain signals were transmitted to the stress-strain chart on the tensile machine.

Tests at -423°F were conducted in the cryogenic test cell, at the Von Karman Center (AGC), and utilized a 20,000 lb capacity cryostat. Figure 1 shows the cryostat in position for a tensile test, connected to a 125-liter dewar containing liquid hydrogen. Liquid hydrogen enters the cryostat through the flexible vacuum-jacketed tube connected to the lid. Gaseous hydrogen exhausts through the other tube shown. The electrical lead in Figure 1 is the extensometer connection. Figure 2 gives a side view of the cryostat, showing additional details of the exhaust system.

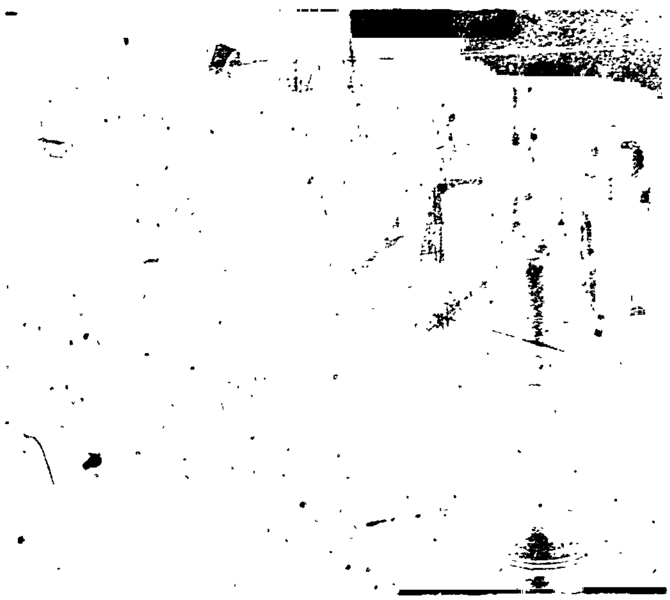


Figure 1

Liquid Hydrogen Cryostat
and Supply Dewar

Figure 2

Closeup of Liquid Hydrogen
Cryostat

The additional electrical lead is attached to the liquid-level indicators, which consist of carbon resistors mounted in a rake. Strain measurements were taken by means of a standard room temperature Baldwin averaging extensometer (Model PS3M) as modified for cryogenic use. The modification consisted of replacing the rubber-jacketed lead-in wires with Teflon-coated wires, and replacing all the carbon-steel parts with ones made of 300-series stainless steel. During one of the test series strain-type measurements were taken by crosshead movement using a deflectometer, since the extensometer was undergoing factory repairs. The deflectometer output was fed into the long-strain recorder through the normal extensometer connection. These strain indications were not accurate due to overall system deformations; and curves derived from them are labeled "estimated strain."

B. SPECIMENS

The majority of materials were tested using modified NASA type flat specimens as shown in Figures 3 and 4, or using the R-3 type round specimens, as specified in Method 211.1 of Federal Test Method Standard No. 151a. Figure 3 shows the unnotched metal specimen. Figure 4 shows the notched metal specimen, having a stress-concentration factor, K_t, of 6.3. R-3 type specimens shown in Figure 5 (test section of 0.25 in. dia x 1 in. long) were used extensively because the loads required to break a specimen at -423°F would in many cases have exceeded the capacity of the liquid-hydrogen cryostat. This size also enabled the fabrication of a greater number of specimens from limited quantities of material. Non-standard specimens were necessary in the cases of some of the 7079 aluminum alloy specimens and 18% Nickel steel bolts, because of the materials available. For example, some of the 7079 specimens consisted entirely of weld-deposited metal.

Figure 6 shows the REON type of specimen used for testing the plastic-materials. Figure 7 shows the notched and unnotched Type R-1 specimens.

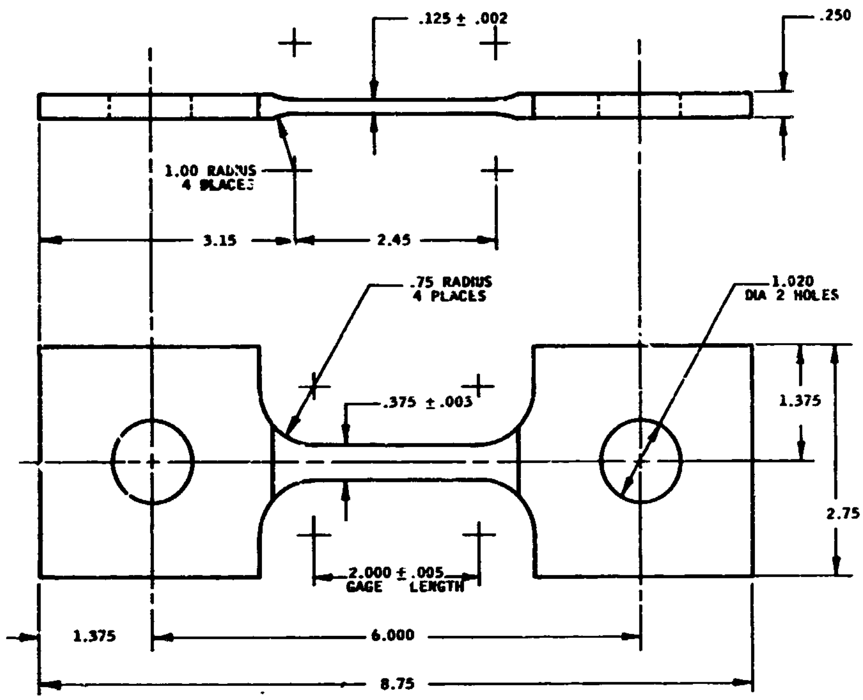


Figure 3

Unnotched Specimens,
Sheet Material

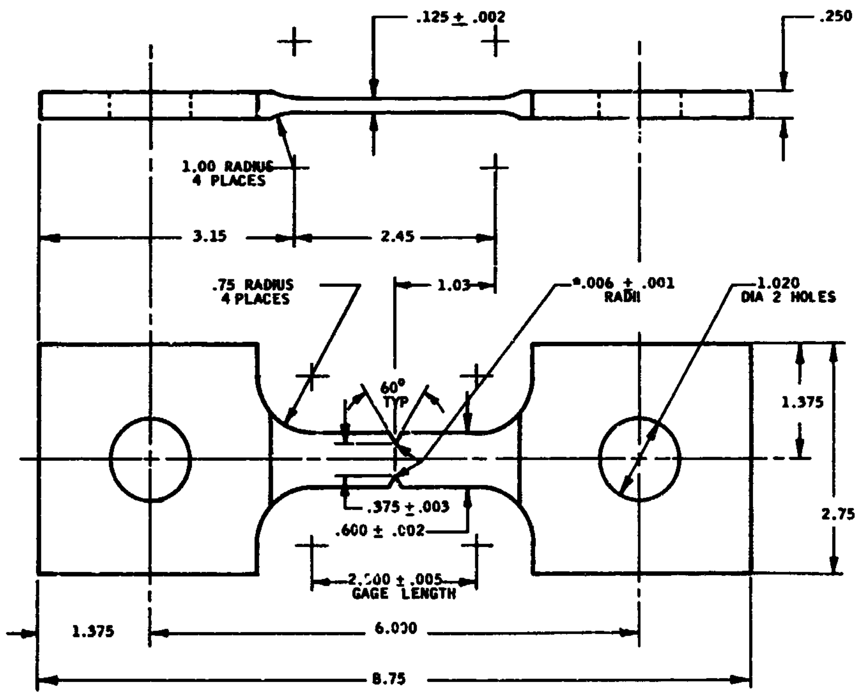
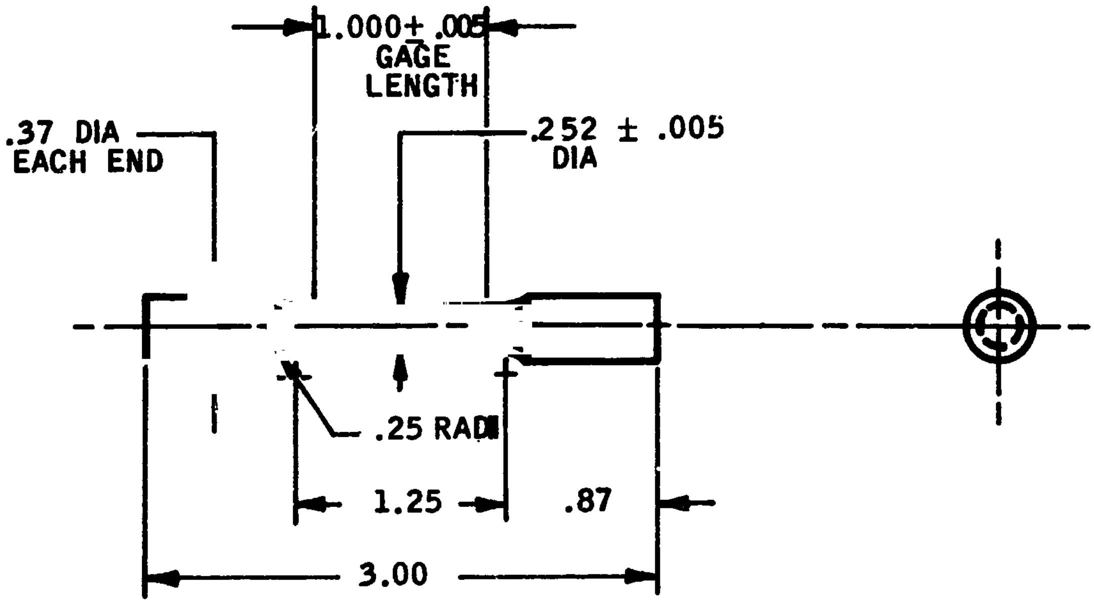


Figure 4

Notched Specimen, Sheet Material



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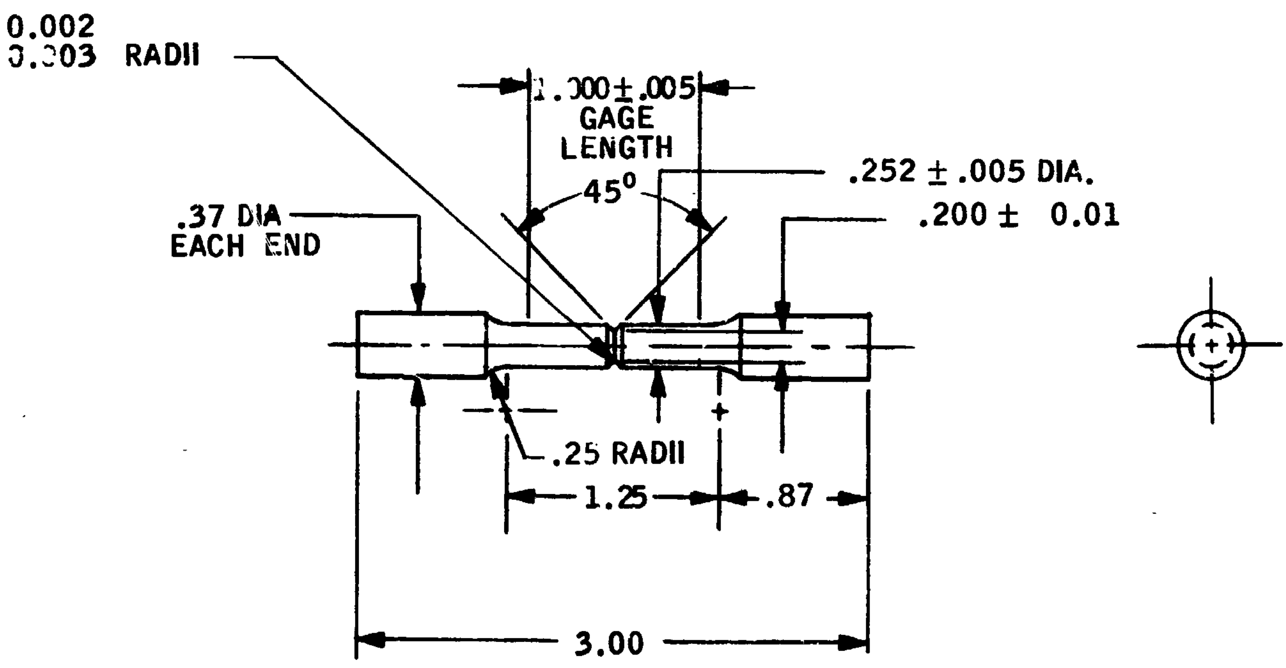


NOTCHED

Figure 5

Round Specimen Type R3
Unnotched and Notched

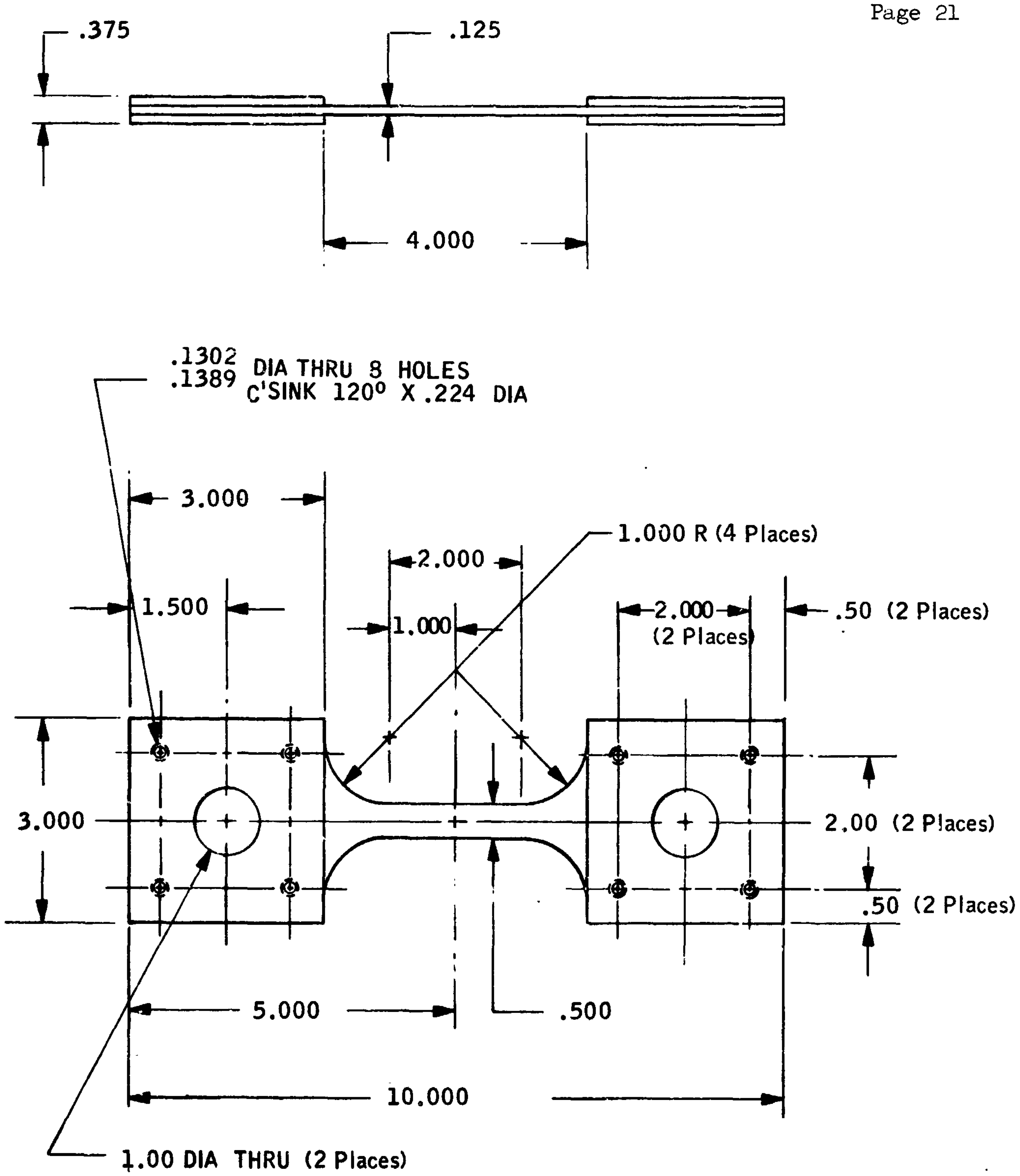
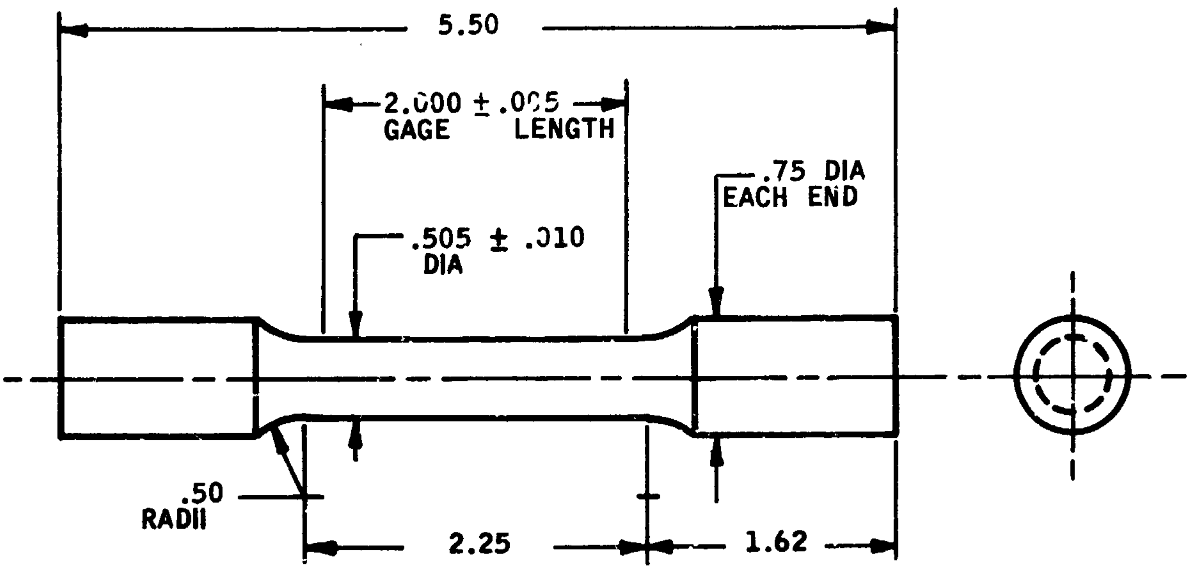
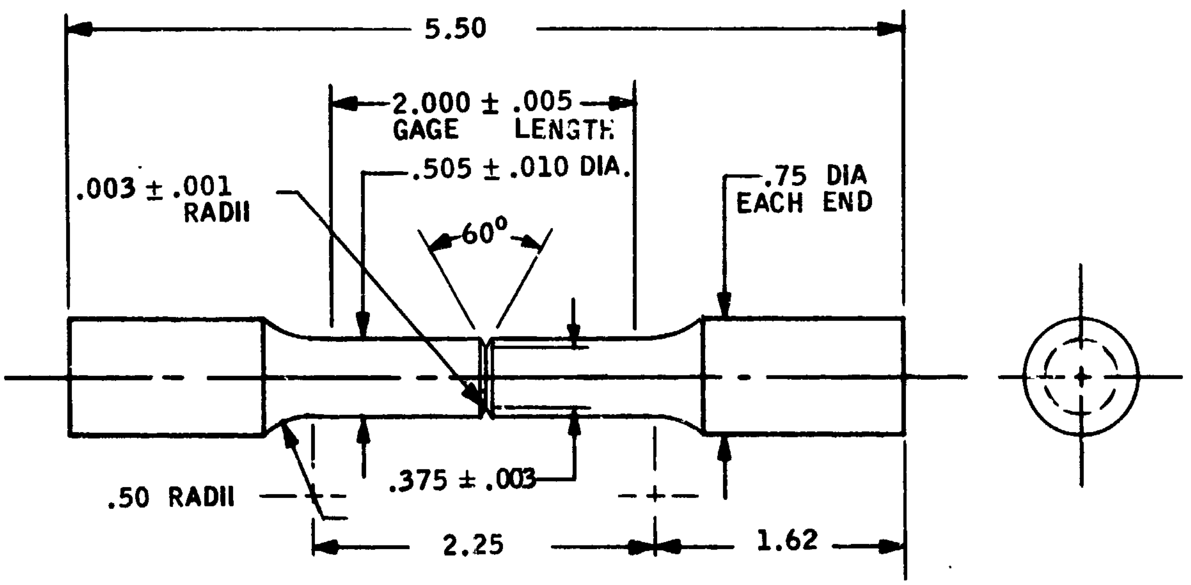


Figure 6

Non Metallic Specimen



UNNOTCHED



NOTCHED

Figure 7

Round Specimen Type R-1,
Unnotched and Notched

SECTION IV

TEST PROCEDURES

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IV. TEST PROCEDURES

All tensile tests were conducted in accordance with Method 211.1 of Federal Test Method Standard No. 151a, which is essentially identical with ASTM Specification E8-61T. Load as a function of deformation was autographically recorded. Strain-rate used for these tests was 0.005 inch-per-inch-per-minute. In the majority of tests an extensometer was used for strain measurements. However, in one series of tests at -423°F, during which the extensometer was inoperative, the speed of testing was controlled according to rates of stressing. The stress rates were selected, on the basis of best available information, as those which would be approximately equivalent to the strain rate of 0.005 inch-per-inch-per-minute. The stressing rates for the several materials were as follows:

Material	Stressing Rate to Proportional Limit, psi/minute	Stressing Rate, Proportional Limit to Failure, psi/minute
Titanium Alloys	82,000	2,000
Stainless Steels and Iron-Base Alloys	145,000	2,000
Nickel-base Alloys	155,000	2,400
Aluminum Alloys	53,000	700

During the latter series of tests approximate strain measurements were taken by means of a deflectometer, which plotted crosshead movement. Stress-strain diagrams were then developed based on actual load values, elongation in 2" (measured after failure), and load-deflection curves traced by the tensile-machine recorder. The procedure used was as follows:

A. Actual load values were used to determine the stress levels.

B. The elongation in two inches after fracture was assumed to be the total plastic deformation under the load.

C. The elongation in 2" was then assumed to be equal to the distance along the abscissa between the origin and the intersection of a line, drawn through the point of fracture and parallel to the recorder trace below the proportional limit. This became the basis for constructing the stress-strain curves. Curves drawn in this manner had their abscissae labelled "estimated strain."

SECTION V

TEST RESULTS AND DISCUSSION

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V. TEST RESULTS AND DISCUSSION

The results of all tests are presented in tabular and graphic form on the following pages. For each material, the first pages present chemical analyses and average tensile properties. Following this information there are complete test data for each specimen.

A. TITANIUM ALLOYS

Sample analysis of chemical composition of all heats of titanium materials reported, compared with the specification requirements, is shown in Table 1. Average tensile properties for each heat and test temperatures are shown in Table 2.

Table 1

Chemical Analysis of Titanium Alloys

Alloy Designation		Heat No. [illegible]	Al	Sn	Fe	C	Mn	V	Others	H_2	O_2	N_2
A-110-AT-ELI (5Al-2.5 Sn)	Specification Limit	Min	4.70	2.0	-	-	-	-	-	-	-	-
		Max	5.60	3.0	0.15	0.08	-	-	-	0.0125	0.12	0.05
	Sample Analysis	D-3272 Plate	5.19	2.30	0.13	0.022	0.006	-		0.0055	0.0312	0.0045
	Sample Analysis	D-3272 Forging	5.05	2.40	0.08	0.012	-	-		0.0048	0.064	0.024
	Sample Analysis	D-3273 Extruded Cylinders	5.12	2.57	0.04	0.04	0.01			0.0058	0.065	0.010
	Sample Analysis	D-3346 Forged Extruded	5.02	2.49	0.07	0.06	-			0.0062	0.066	0.009
	Sample Analysis	V-2096 Forged Plate	5.30	2.50	0.10	0.025	-			0.009	0.080	0.027
C-120 AV, ELI (6Al-4V)	Specification Limit	Min	5.50	-	-	-	-	3.50		-	-	-
		Max	6.50	-	0.10	0.08	-	4.50		0.015	0.13	0.05
	Sample Analysis	D-3067 Forged Plates	6.10		0.07	0.05		4.00		0.0033	0.09	0.017

Table 2

Average Tensile Properties of
Titanium Alloys 5Al-2.5 Sn ELI
and GAR-AV-ELI

Material	Temp. °F	Specimen Direction	Ultimate Strength psi	Notch Ultimate Strength, psi	Yield Strength (0.2%)psi	Elongation in 1 in. %	Reduction in Area, %	Notched to Unnotched Ratios N-Ult/Un-Ult	Notched to Unnotched Ratios N-Ult/Un-Y.S.	Number of Tests
A110-AT, ELI (5Al-2.5 Sn)										
1/4" Plate, HRA	RT	(t)	122,500	142,800(K_t= 18.0)	114,400	15.5**	40.0	1.17	1.25	1U, 4N
	-423		219,100	171,000(K_t= 18.0)	205,000*	17.1**	17.8	.78	.84	2U, 4N
1/2" Plate, forged (Heat V-2096)	RT	(t)	124,300	169,400(K_t= 7)	115,600	17.0**	38.2	1.36	1.47	3@
	-320		192,900	231,200(K_t= 7)	182,500	14.0**	24.7	1.20	1.27	3@
	-423		214,300	226,000(K_t= 5.8)	203,500	9.8	16.0	1.06	1.11	3@
1/2" Plate, forged (Heat V-2096)	RT	(l)	126,500	181,200(K_t= 7)	121,000	19.3**	47.3	1.43	1.50	3@
	-320		198,800	248,000(K_t= 7)	192,000	14.5**	33.2	1.25	1.29	3@
	-423		221,300	235,000(K_t= 5.7)	218,000	7.5	24.0	1.06	1.08	3U, 2N
Forged Adapter Ring No. 220 (Heat D-3272)	RT	(c)	122,900	167,900(K_t= 7-9)	113,000	14.0	33.6	1.37	1.48	4@
	-100		143,100	188,800(K_t= 8-9)	130,700	11.0	28.1	1.32	1.44	4@
	-320		182,700	234,200(K_t= 8-9)	163,500	14.0	24.3	1.28	1.43	5@
	-423		197,400	234,400(K_t= 7-10)	178,800	10.0	21.8	1.19	1.31	5@
Forged Closure No. 217 (Heat D3346)	RT	(c)	118,300	157,600(K_t= 9)	107,800	15.0	39.3	1.33	1.46	4@
	-100		140,600	183,300(K_t= 9)	130,700	14.0	34.5	1.30	1.40	4@
	-320		182,700	233,700(K_t= 8)	153,500	19.5	34.2	1.28	1.52	4U, 5N
-	423		214,000	235,400(K_t= 7-10)	184,400	19.5	21.6	1.10	1.28	
Extruded Cylinder No. 465 (Heat D3346)	RT	(c)	117,300	159,900 (K_t= 6-7)	108,100	16.4	47.5	1.36	1.48	5@
	-100		136,600	187,100(K_t= 6-7)	125,000	14.0	35.1	1.37	1.50	5@
	-320		181,800	233,600(K_t= 6-8)	166,700	11.6	35.6	1.28	1.40	5@
	-423		207,200	236,200(K_t= 6-8)	190,800	13.5	19.2	1.14	1.24	5@
Extruded Cylinder No. 218 (Heat D 3273)	RT	(c)	124,100	235,400(K_t= 7-10)	114,200	15.0	43.7	1.90	2.06	5@
	-100		142,200	195,300(K_t= 7-8)	131,400	13.0	37.5	1.37	1.49	5@
	-320		185,000	240,200(K_t= 8)	171,800	21.0	35.6	1.30	1.40	5@
	-423		205,800	238,900(K_t= 7-10)	192,200	13.6	29.0	1.16	1.24	5@
Extruded Cylinder No. 219 (Heat D3273)	RT	(c)	122,200	16[illegible],800(K_t= 7-9)	111,400	14.0	40.3	1.35	1.48	5@
	-100		141,400	188,100(K_t= 6-10)	130,200	12.0	35.8	1.33	1.45	5U, 4N
	-320		183,400	238,600(K_t= 7-9)	173,700	17.0	35.6	1.30	1.38	5@
	-423		208,200	237,800(K_t= 7-10)	190,800	13.3	21.8	1.14	1.25	5@
Extruded Cylinder No. 219 (Heat D3273)	RT	(l)	119,900	165,100(K_t= 8-9)	107,500	15.0	43.6	1.38	1.54	5@
	-100		139,300	186,700(K_t= 8-9)	123,800	12.0	34.8	1.34	1.[illegible]1	5@
	-320		187,500	239,500(K_t= 7-9)	167,000	1[illegible].0	36.5	1.28	1.43	5@
	-423		211,200	253,300(K_t= 8-10)	198,600	15.6	22.6	1.20	1.28	5@
6Al-4V, ELI										
1/2" Plate, forged (Heat D3067)	RT	(l)	140,600	198,300(K_t= 6-7)	133,000	14.0	39.8	1.41	1.49	3@
	-100		167,900	226,100(K_t= 5-6)	163,100	13.0	30.8	1.35	1.39	3@
	-320		227,000	276,100(K_t= 4-6)	214,400	10.7	31.3	1.22	1.29	3@
	-423		239,000	264,000(K_t= 6)	228,000	11.0	24.2	1.10	1.16	3@
1/2" Plate forged (Heat D3067)	RT	(t)	138,800	188,900(K_t= 7-8)	132,700	14.7	43.7	1.36	1.42	3@
	-100		162,600	214,800(K_t= 7)	156,900	13.3	35.3	1.32	1.37	3@
	-320		216,900	259,000(K_t= 6-8)	207,100	11.0	30.2	1.19	1.25	3@
	-423		239,000	224,000(K_t= 6-8)	231,000	6.0	22.3	.94	.97	3@

*Based on strain estimated from crosshead travel of tensile machine.
**Elongation in 2"-(t) transverse, (l) longitudinal, (c) circumferential.

1. Alloy A110-AT-ELI (5Al-2.5Sn, Extra Low Interstitial)

In general, the tensile properties were much the same, regardless of manufacturing process. There were a few exceptions in which some specimens increased their strength more rapidly than others as the temperature decreased. This effect, and some of the other variations in properties, can undoubtedly be attributed to the processing method. Flat tensile specimens as shown in Figures 3 and 4 were tested for the hot rolled and forged plates. R-3 type specimens (Figure 5) were tested for the rest of the materials including forged plates tested at -423°F. Rolling direction of flat specimens was in transverse direction to the specimen axis. Specimens for the forged plates were tested both longitudinally and transversely to the rolling direction. All R-3 type specimens were taken in the circumferential direction with exception of one heat (D7219) from the extruded cylinder where both circumferential and longitudinal specimens were tested.

Several interesting comparisons were made possible by the variety of metal working processes used in manufacturing the materials from which specimens were taken. These data are shown in Tables 2 and 3, and Figures 8 through 33. A significant characteristic of all specimens was ductility at cryogenic temperatures. This accompanied a notch toughness indicated by a notched-unnotched ratio greater than 1.0 for the ultimate strength in the presence of notches having a stress-concentration factor, K_t, of 6 to 10. The sharp notch ratio (K_t = 18.0) for transverse specimens of hot rolled plate at -423°F was 0.78. This value closely approximates that of 0.81 reported for transverse specimens of 6061-T6 aluminum alloy by Hanson (NASA), Reference 4. It is of interest to note that the notch-unnotched ultimate strength for longitudinal specimens of hot-rolled plate, taken from the same heat, was 0.88 (Reference 10), which exceeds the value in Reference 4 shown for longitudinal specimens of 6061-T6 (i.e., 0.75).

Table 3

Tensile Properties of Titanium Alloys A-110-AT-ELI for Plates, Forgings and Extrusions at Room Temperatures -100°F, -320°F and -423°F

Material	Heat No.	Temp °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%), psi	Elongation in 1", %	Reduction in Area, %
Plate (0.125" spec. from 0.25 stock)	D-3272	RT	Unnotched (transverse)	122,500	114,400	15.5**	40.0
		-423	Unnotched (transverse)	218,300	208,000*	2.3**	11.0
				219,800	202,000*	3.0**	8.5
Forging No. 220 (R-3 type specimens taken circumferentially)	D-3272	RT	Unnotched	121,200	110,300	15.0	35.4
				121,800	111,600	15.0	32.2
				123,000	113,200	14.0	33.9
				125,500	116,800	13.0	32.9
			Notched (K_t= 7-9)	166,700			
				167,300			
				168,200			
				169,400			
		-100	Unnotched	140,900	127,500	10.0	26.7
				142,000	130,000	11.0	29.0
				143,800	131,300	12.0	28.1
				145,500	134,000	10.0	28.4
			Notched (K_t= 8-9)	186,800			
				187,400			
				189,300			
				191,700			
		-320	Unnotched	181,500	163,800	10.0	27.8
				181,600	160,500	14.0	24.4
				182,800	163,300	15.0	24.4
			Notched (K_t= 8-9)	229,400			
				229,400			
				236,200			
				237,200			
				238,800			
		-423	Unnotched	191,000	178,000	12.0	22.0
				195,000	177,000	12.0	20.0
				195,000	177,000	11.0	23.0
				200,000	177,000	9.0	23.0
				206,000	185,000	6.0	21.0
			Notched (K_t= 7-10)	226 2			
				233 0			
				233 8			
				236 2			
				242 8			

*Based on strain estimated from crosshead travel tensile machine.

**Elongation in 2".

Table 3 (cont.)

Material	Heat No.	Temp °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%), psi	Elongation in 1", %	Reduction in Area, %
Forging No. 217 (R-3 type specimens taken circumferentially)	D-3346	RT	Unnotched	116,900	106,900	16.0	40.3
				118,000	107,100	15.0	41.4
				118,900	108,300	15.0	37.0
				119,300	109,000	15.0	37.7
			Notched (K_t= 9)	153,700			
				155,900			
				159,400			
				161,500			
		-100	Unnotched	138,800	-	11.0	35.5
				138,800	-	13.0	34.3
				141,300	131,300	15.0	36.0
				143,400	130,000	15.0	32.2
			Notched (K_t= 9)	176,700			
				182,500			
				185,900			
				187,900			
		-320	Unnotched	178,900	158,600	20.0	34.4
				180,900	148,400	16.0	-
				185,700	-	14.0	31.2
				185,800	-	16.0	37.2
			Notched (K_t= 8)	228,100			
				233,000			
				234,500			
				236,200			
				236,600			
		-423	Unnotched	207,000	190,000	-	24.0
				211,000	187,000	18.0	24.0
				214,000	182,000	-	16.0
				218,000	183,000	-	16 0
				220,000	180,000	21.0	27.0
			Notched (K_t= 7-10)	221,000			
				236,100			
				239,000			
				239,800			
				240,900			
Forged Plate (R-3 type specimens from 0.5" plate)	V-2096	-423	Unnotched (long)	218,000	214,000	9.0	19.0
				223,000	217,000	6.0	20.0
				223,000	223,000	-	33.0
			Notched (long) K_t= 5-7	228,000			
				242,000			
		-423	Unnotched (trans)	212 0	205,000	8.0	17.0
				215 0	-	12.0	17.0
				216 0	202,000	9.0	14.0
			Notched (trans) K_t= 5-7	215 0			
				230 0			
				234 0			

Table 3 (cont.)

Material	Heat No.	Temp °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%), psi	Elongation in 1", %	Reduction in Area, %
Extruded Cylinder No. 218 (R-3 type specimens taken circumferentially	D-3273	RT	Unnotched	117,700	107,600	15.0	42.9
				124,200	114,200	15.0	44.9
				124,400	114,600	15.0	44.0
				126,000	116,600	14.0	44.3
				128,400	117,900	13.0	42.3
		RT	Notched (K_t = 7-9)	160,600			
				164,300			
				165,600			
				173,000			
				174,800			
		-100	Unnotched	139,600	127,200	12.0	38.8
				142,600	133,700	13.0	39.6
				143,400	131,100	12.0	36.6
				143,600	-	14.0	38.1
				143,900	133,600	13.0	34.4
			Notched (K_t = 7-8)	192,400			
				193,700			
				196,800			
				196,800			
				196,900			
		-320	Unnotched	181,600	167,900	20.0	38.0
				182,100	167,200	21.0	36.4
				184,800	174,900	20.0	38.9
				185,700	172,200	21.0	33.0
				188,500	177,000	22.0	31.9
			Notched (K_t = 8)	236,000			
				238,200			
				240,500			
				241,900			
				244,400			
		-423	Unnotched	196,000	192,000	12.0	33.0
				201,000	183,000	16.0	28.0
				206,000	194,000	16.0	30.0
				206,000	196,000	9.0	28.0
				210,000	196,000	15.0	26.0
			Notched (K_t = 7-10)	235,000			
				236,100			
				237,500			
				240,000			
				246,200			

Table 3 (cont.)

Material	Heat No.	Temp °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%), psi	Elongation in 1", %	Reduction in Area, %
Extruded	D-3273	RT	Unnotched	119,800	110,100	13.0	44.4
Cylinder No.				121,700	110,700	13.0	40.0
219				122,100	111,700	16.0	39.4
(R-3 type				123,600	112,500	14.0	35.1
specimens				124,000	112,200	15.0	35.1
taken		RT	Notched	158,800			
circumfer-			(K_t= 7-9)	159,000			
entially				164,200			
				168,800			
				173,600			
		-100	Unnotched	139,600	128,800	12.0	38.8
				141,100	130,500	13.0	37.7
				141,200	127,200	13.0	34.4
				141,900	130,300	13.0	34.5
				143,000	134,400	11.0	33.4
			Notched	183,500			
			(K_t= 6-10)	186,100			
				187,400			
				195,500			
		-320	Unnotched	180,500	-	[illegible].0	36.4
				183,200	-	22.0	35.1
				184,100	174,700	17.0	36.6
				184,400	-	15.0	38.3
				184,800	172,600	15.0	31.8
			Notched	234,600			
			(K_t= 7-9)	235,000			
				237,000			
				239,700			
				246,900			
		-423	Unnotched	196,000	189,000	13.0	32.0
				209,000	189,000	-	15.0
				210,000	192,000	11.0	30.0
				212,000	193,000	16.0	21.0
				214,000	191,000	-	11.0
			Notched	221,800			
			(K_t= 7-10)	235,700			
				241,800			
				243,900			
				245,900			

Table 3 (cont.)

Material	Heat No.	Temp °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%), psi	Elongation in 1", %	Reduction in Area, %
Extruded Cylinder No. 219 (R-3 type specimens taken longitudinally	D-3273	RT	Unnotched	118,500	104,500	15.0	43.8
				120,100	108,800	16.0	44.8
				120,200	107,900	14.0	42.8
				120,200	108,200	16.0	43.1
				120,400	108,100	14.0	44.4
			Notched (K_t = 8-9)	162,800			
				164,800			
				165,100			
				166,000			
				166,700			
		-100	Unnotched	137,400	124,200	11.0	32.7
				138,400	123,300	13.0	37.6
				138,700	120,600	15.0	38.3
				140,200	127,300	11.0	27.5
				141,700	123,600	10.0	38.0
			Notched (K_t = 8-9)	184,100			
				185,200			
				185,600			
				186,200			
				191,900			
		-320	Unnotched	186,700	164,600	16.0	37.2
				186,800	163,900	16.0	30.7
				187,000	167,700	14.0	37.8
				188,000	171,900	16.0	38.3
				188,100	-	15.0	38.4
			Notched (K_t = 7-9)	236,800			
				238,200			
				238,600			
				241,200			
				242,800			
		-423	Unnotched	204,000	198,000	14.0	24.0
				210,000	199,000	14.0	30.0
				214,000	198,000	15.0	20.0
				214,000	198,000	16.0	17.0
				214,000	200,000	19.0	22.0
			Notched (K_t = 8-10)	245,900			
				252,100			
				253,000			
				256,000			
				259,900			

Table 3 (cont.)

Material	Heat No.	Temp °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%), psi	Elongation in 1", %	Reduction in Area, %
Extruded Cylinder No. 465 (R-3 type specimens taken circumferentially)	D-3346	RT		114,800	105,000	17.0	47.1
				115,200	105,000	18.0	47.5
				117,600	107,500	16.0	44.0
				119,200	111,100	15.0	48.1
				119,800	111,700	16.0	50.7
			Notched (K_t= 6-7)	150,600			
				154,700			
				156,100			
				161,500			
				166,600			
		-100	Unnotched	135,100	122,500	15.0	36.9
				135,100	124,200	16.0	33.9
				135,700	124,200	15.0	36.1
				137,400	121,200	11.0	31.3
				139,600	133,000	13.0	37.1
			Notched (K_t= 6-7)	184,600			
				184,600			
				187,800			
				188,600			
				190,000			
		-320	Unnotched	181,000	167,700	10.0	36.6
				181,500	164,300	14.0	35.5
				181,600	158,400	14.0	29.0
				182,100	170,000	15.0	37.6
				183,000	173,400	15.0	39.2
			Notched (K_t= 6-8)	230,300			
				232,700			
				233,600			
				233,900			
				237,300			
		-423	Unnotched	205,000	186,000	14.0	24.0
				205,000	194,000	13.0	13.0
				208,000	191,000	-	17.0
				208,000	194,000	14.0	17.0
				210,000	189,000	13.0	25.0
			Notched (K_t= 6-8)	233,000			
				233,000			
				235,000			
				236,000			
				244,000			

Table 3 (cont.)

Material	Heat No.	Temp °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%), psi	Elongation in 2", %	Reduction in Area, %
1/2" Forged Plate	V-2096	RT	Unnotched (l) standard	127,600	123,300	19.0	48.3
				127,400	222,300	21.0	46.4
				124,500	117,500	18.0	47.1
			Notched (l) standard (K_t = 7)	189,200			
				186,800			
				167,600			
		-320	Unnotched (l) standard	200,000	191,800	16.0	32.4
				198,400	193,500	13.5	29.6
				198,400	190,800	14.0	37.5
			Notched (l) standard (K_t = 7)	256,800			
				245,500			
				241,700			
		-423	Unnotched (l) R-3	223,000	217,000	6.0*	20.0
				223,000	223,000	-	33.0
				218,000	214,000	9.0*	19.0
			Notched (l) R-3 (K_t = 5-7)	242,000			
				228,000			
1/2" Forged Plate	V-2096	RT	Unnotched (t) standard	126,700	117,900	18.0	39.6
				123,200	114,500	17.0	34.5
				122,900	114,400	16.0	40.6
			Notched (t) standard (K_t = 7)	173,500			
				170,000			
				164,800			
		-320	Unnotched (t) standard	193,100	182,800	11.0	17.6**
				192,900	181,400	16.0	35.1
				192,800	183,200	14.0	21.5**
			Notched (t) standard (K_t = 7)	241,000			
				237,200			
				215,300			
		-423	Unnotched R-3	216,000	202,000	9.0*	14.0
				215,000	-	12.0*	17.0
				212,000	205,000	8.0*	17.0
			Notched (t) R-3 (K_t = 5-7)	234,000			
				230,000			
				215,000			

*Based on strain estimated from crosshead travel of tensile machine.

**Broke at punch mark delineating gage length.

(l) longitudinal.

(t) transverse.

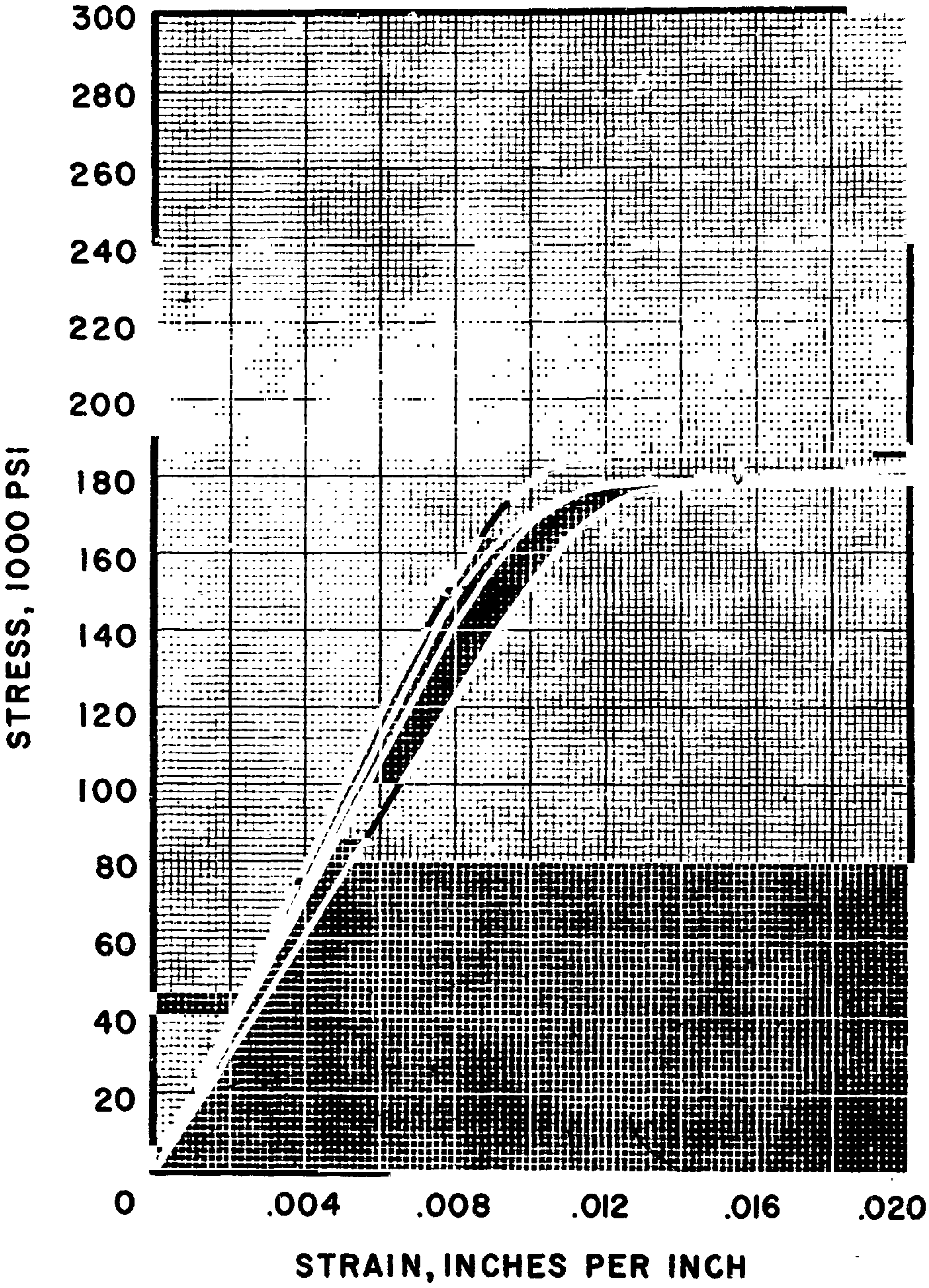


Figure 8

Titanium Alloy A-110-AT-ELI Forging (Heat D3272 Ring No. 220), Stress-Strain Diagram at -423°F

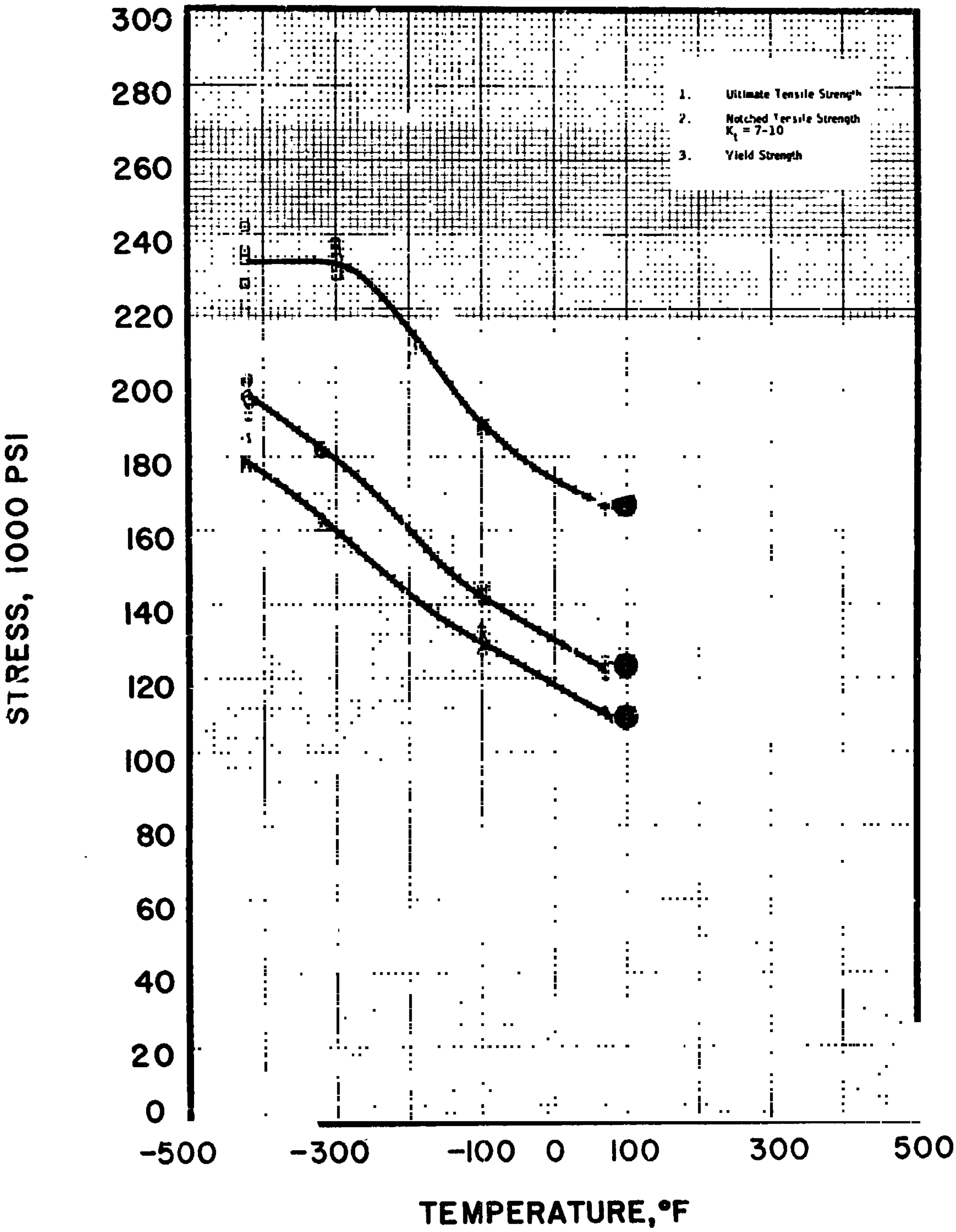
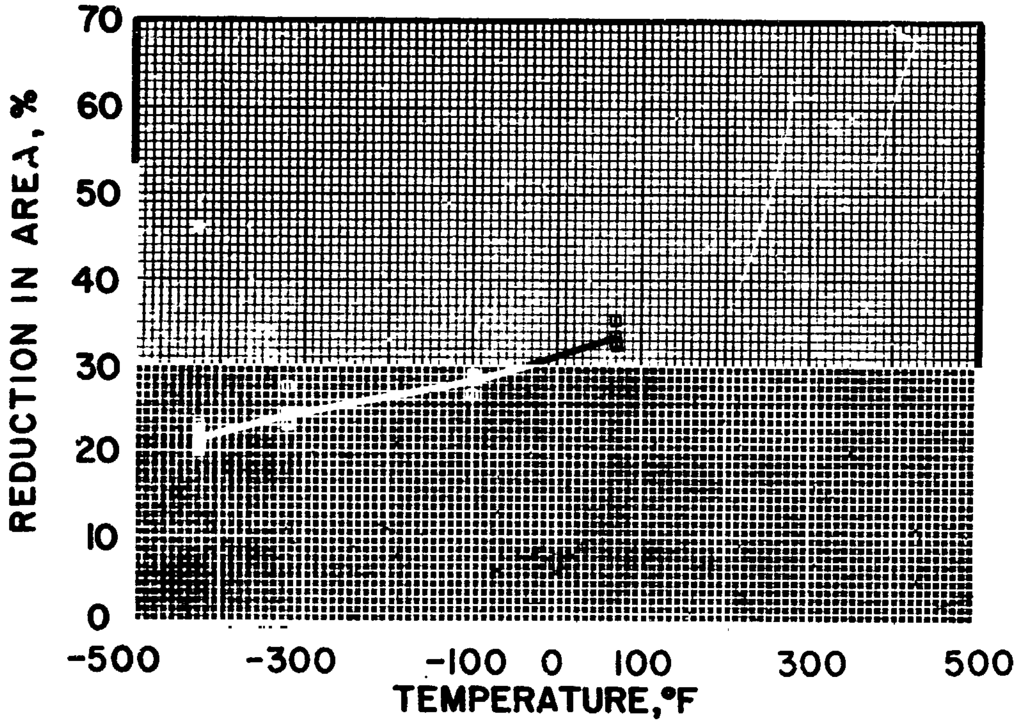


Figure 9

Titanium Alloy A-110-AT-ELI Forging (Heat D3272 Ring No. 220)
Tensile Ultimate, Yield, and Notched Strength as a Function of Temperature



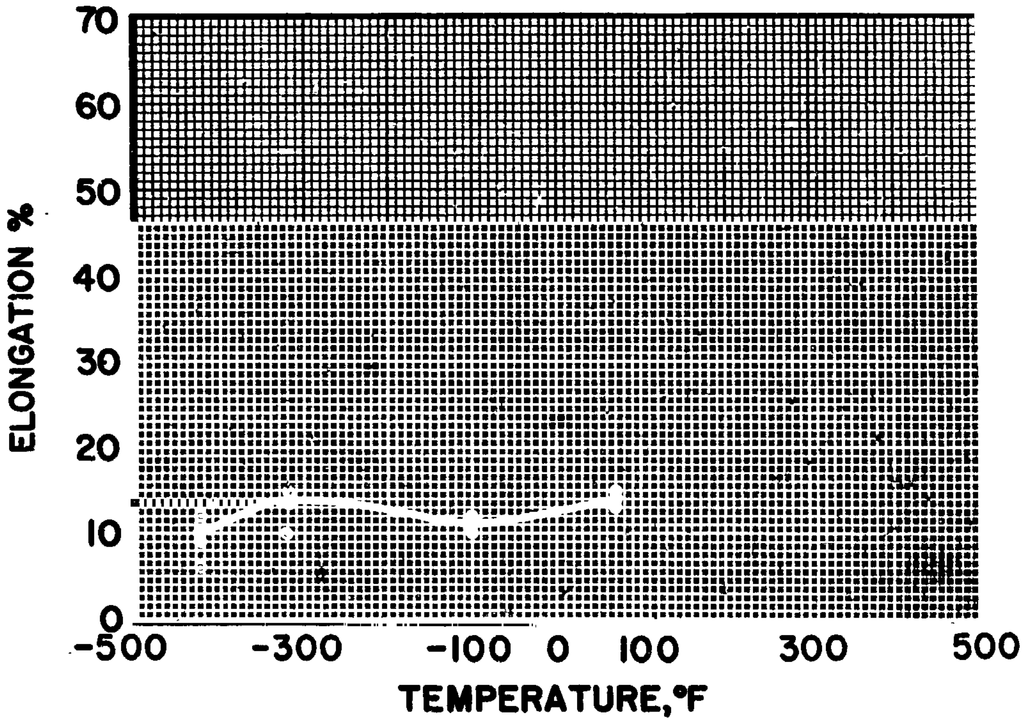


Figure 10

Titanium Alloy A-110-AT-ELI Forging (Heat D3272 Ring 220), Elongation and Area Reduction as a Function of Temperature

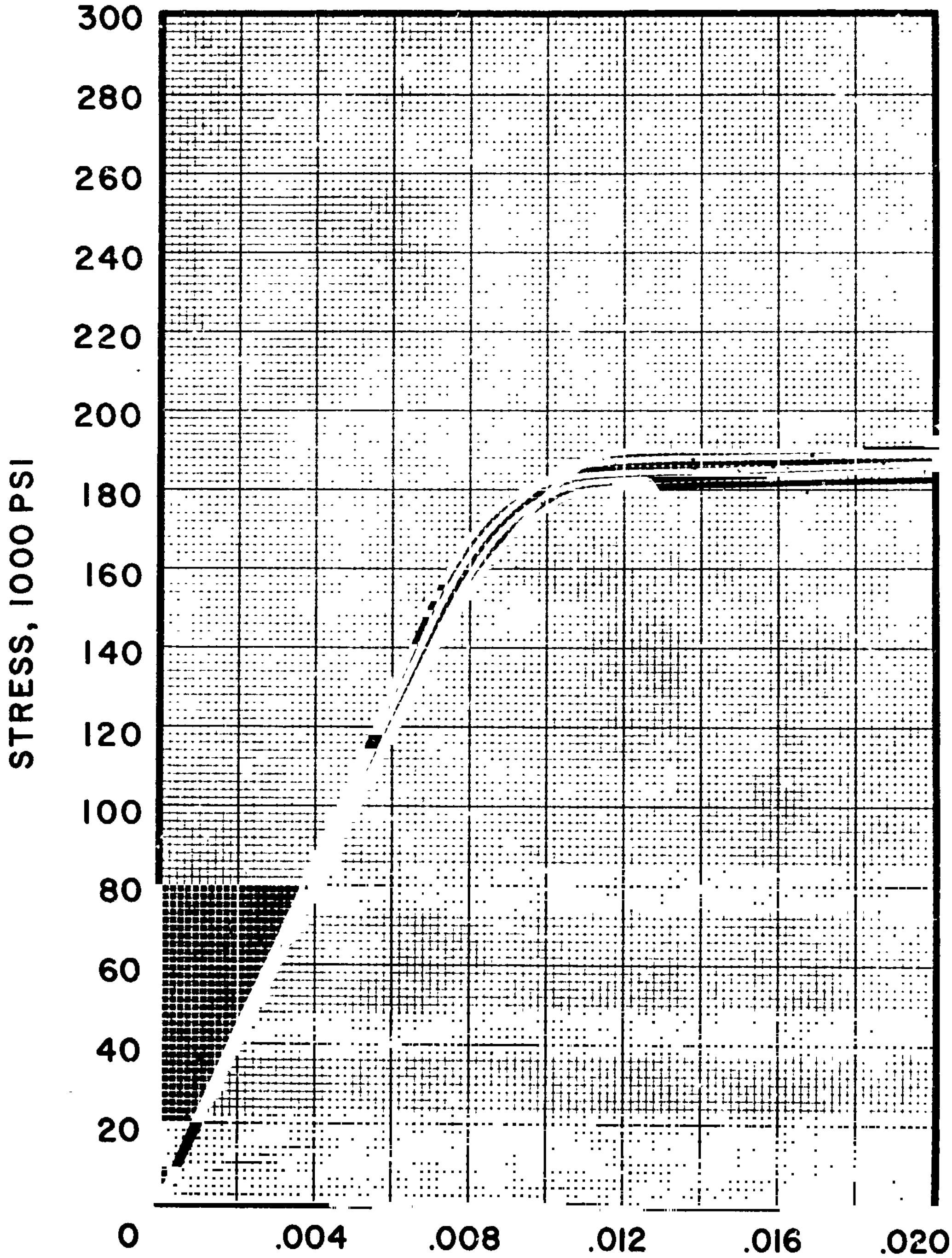


Figure 11

Titanium Alloy A-110-AT-ELI Forging (Heat 3346 Ring No. 217)
Circumferential Direction, Stress-Strain Diagram at -423°F

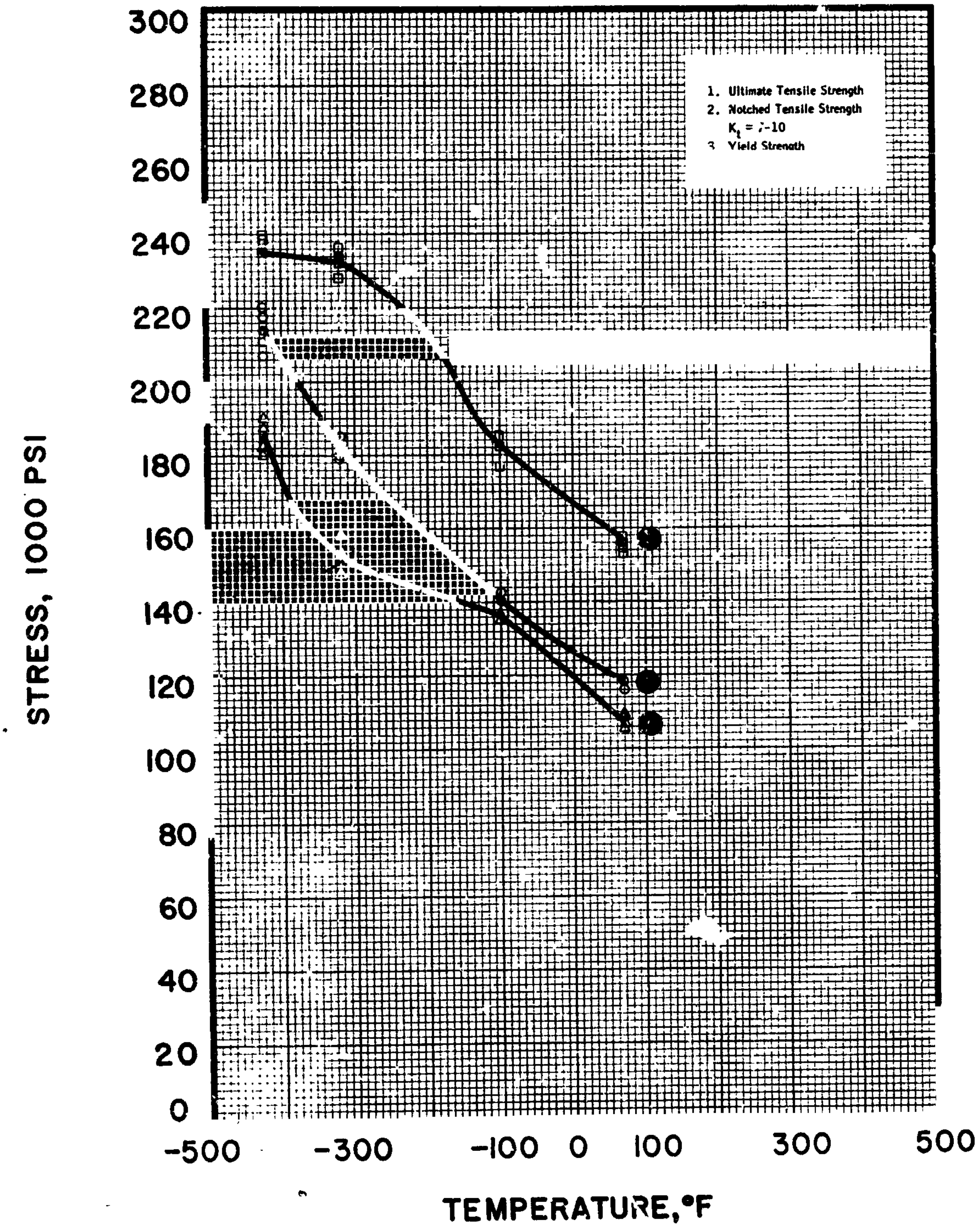
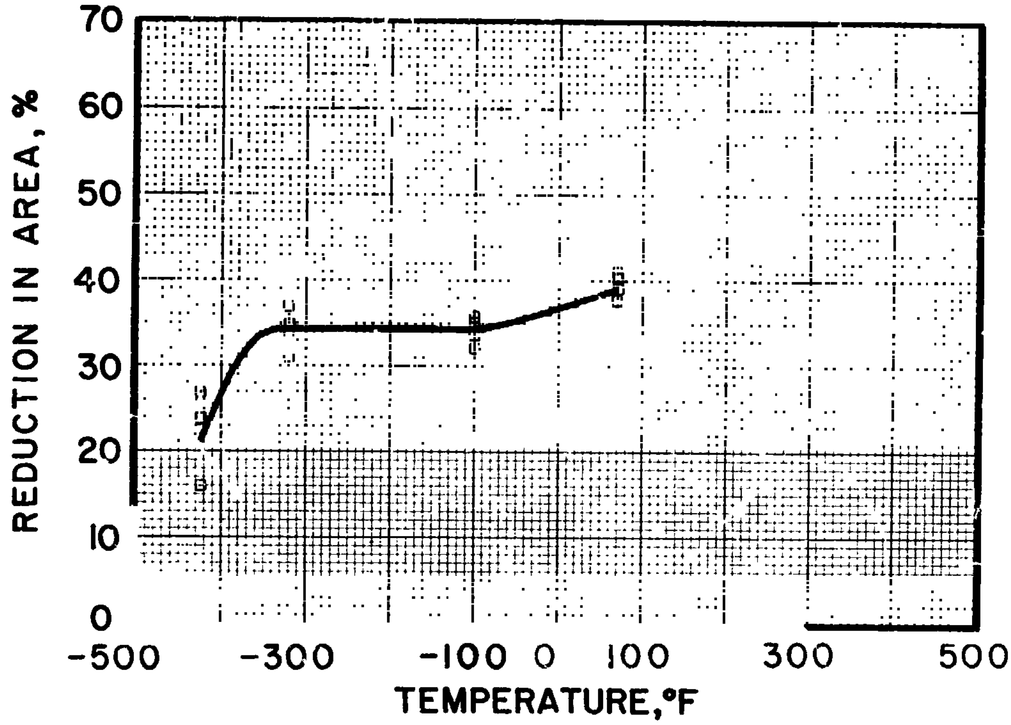


Figure 12

Titanium Alloy A-110-AT-ELI Forging (Heat 3346 Ring No. 217)
and Circumferential Direction, Tensile Ultimate, Yield
and Notched Strength as a Function of Temperature



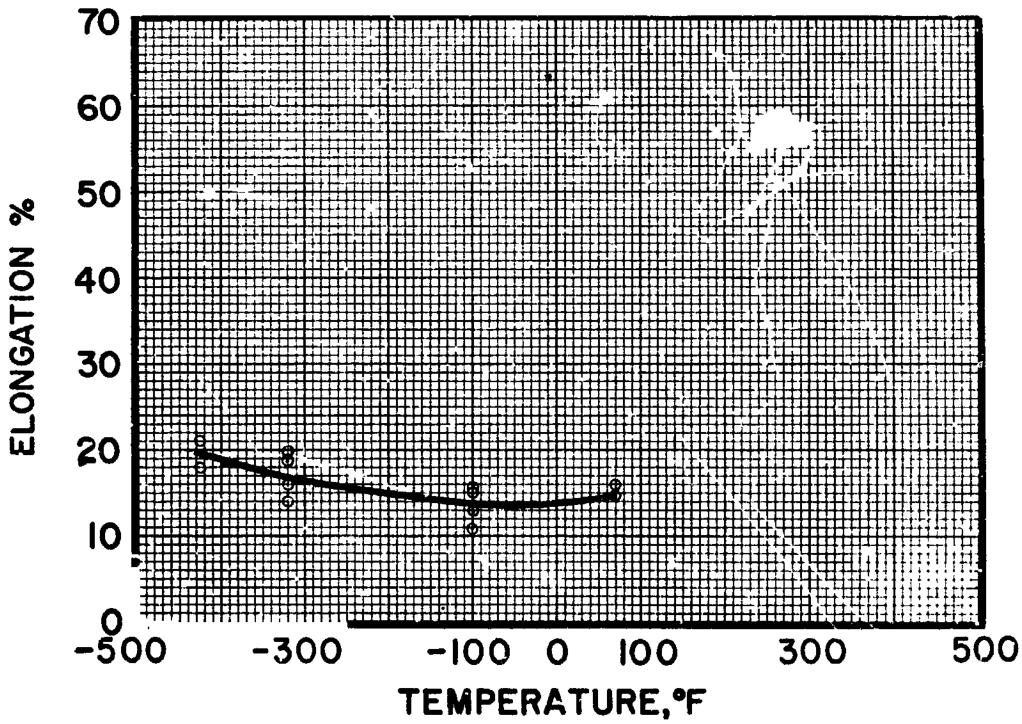


Figure 13

Titanium Alloy A-110-AT-ELI Forging (Heat 3346 Ring No. 217)
Circumferential Direction, Elongation and Area Reduction as a Function
of Temperature

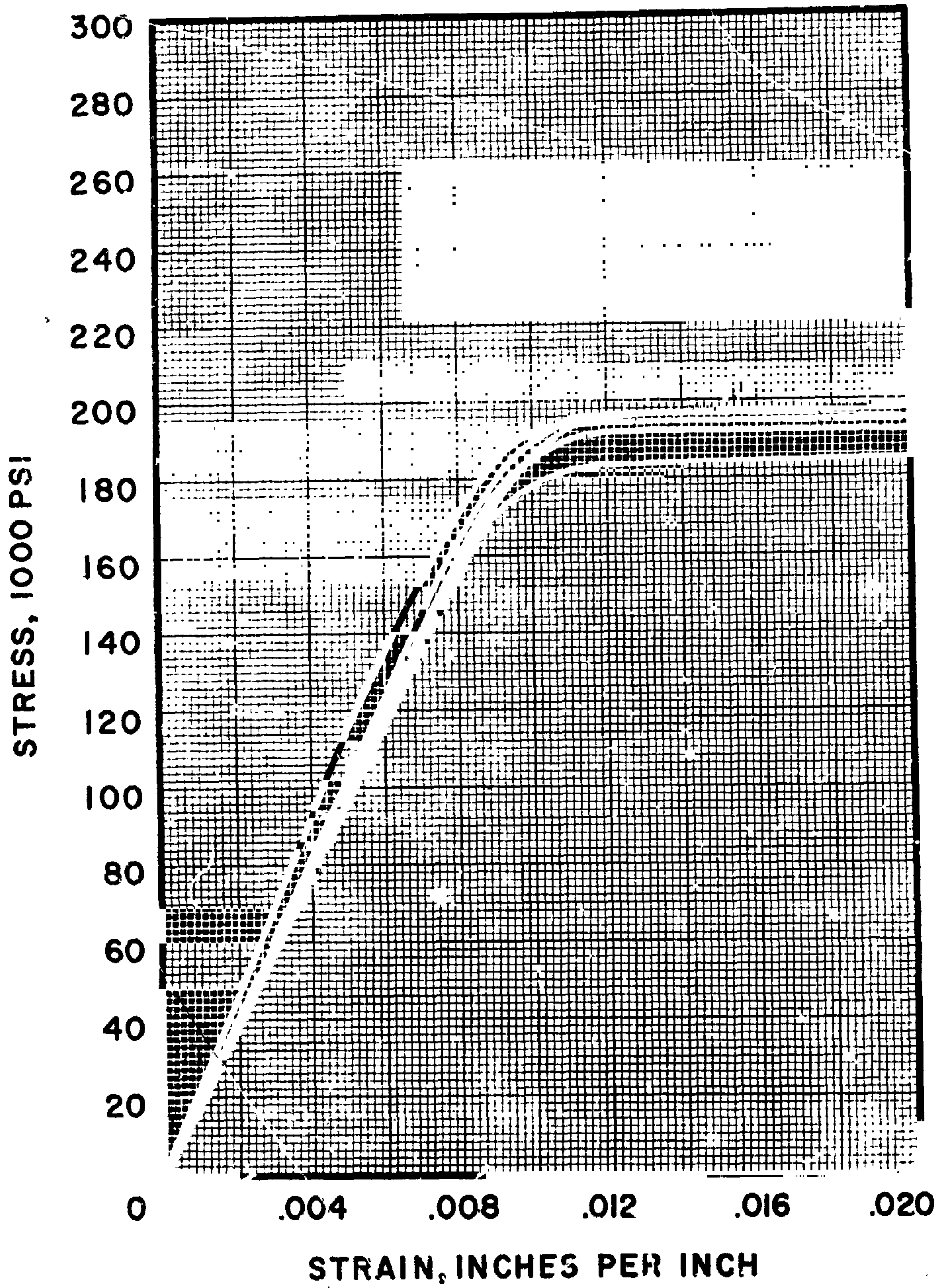


Figure 14

Titanium Alloy A-110-AT-ELI Extrusion (Heat 3273 Ring No. 218)
Circumferential Direction, Stress-Strain Diagram, at -423°F

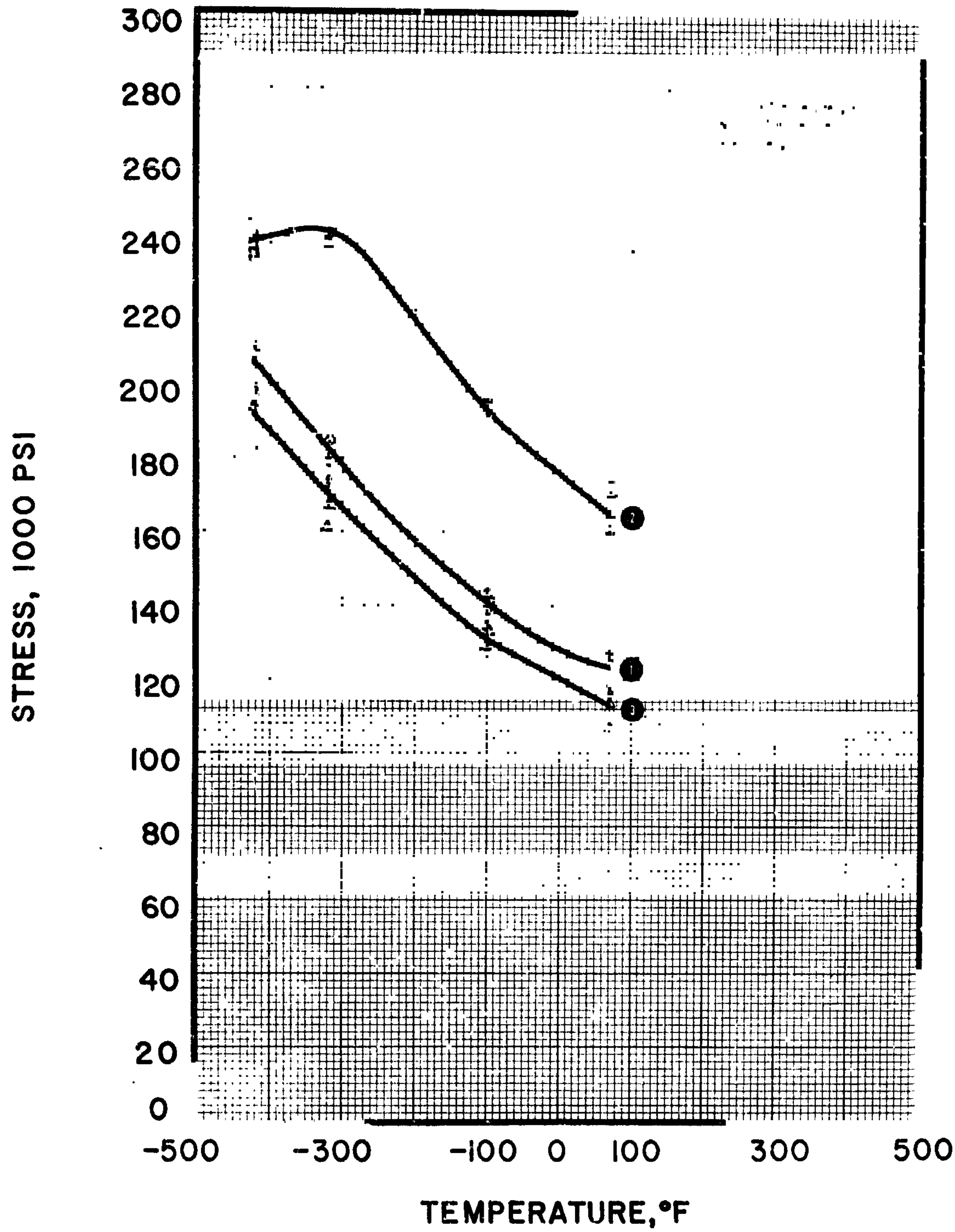
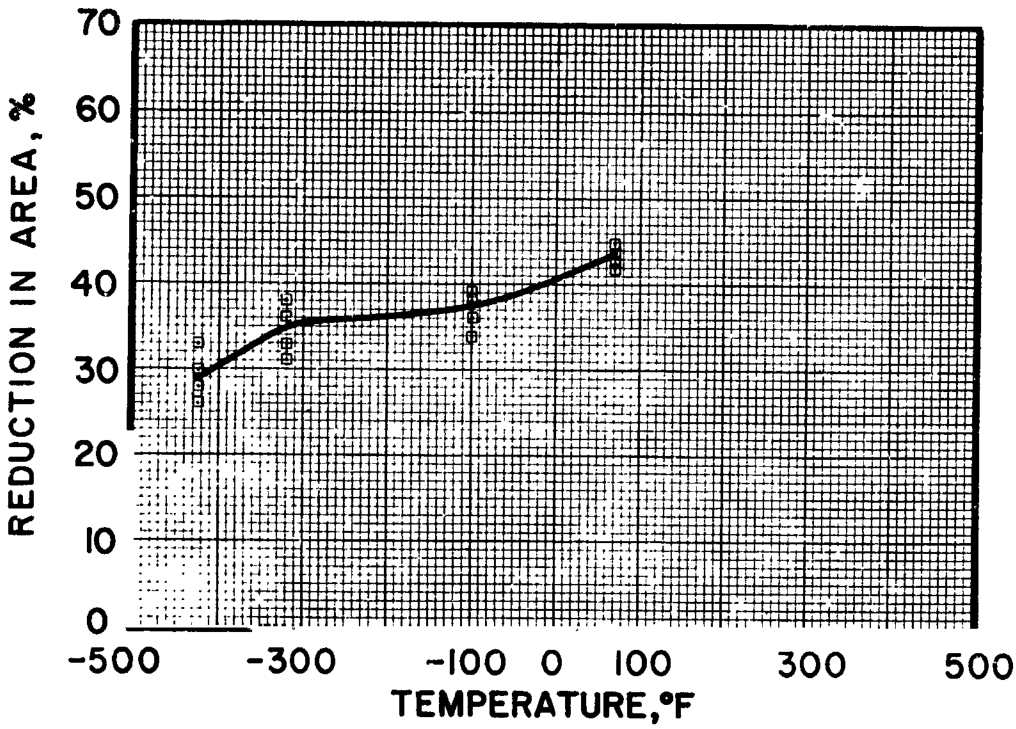


Figure 15

Titanium Alloy A-110-AT-ELI Extrusion (Heat 3273 Ring No. 218)
Circumferential Direction, Tensile Ultimate, Yield and
Notched Strength as a Function of Temperature



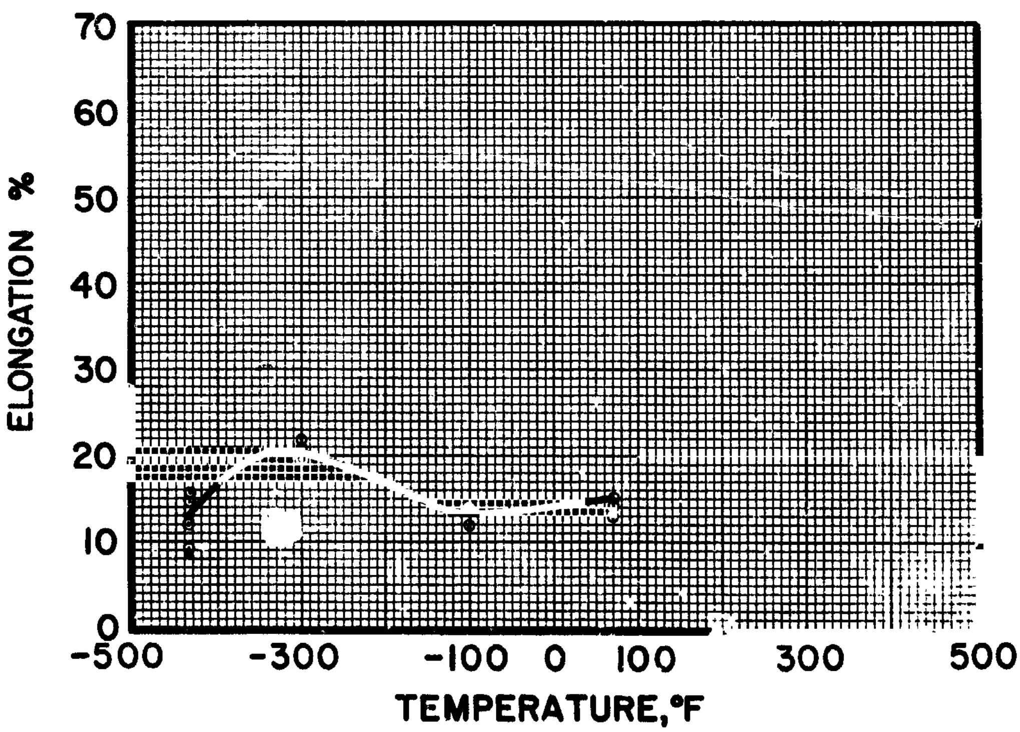


Figure 16

Titanium Alloy A-110-AT-ELI Extrusion (Heat 3273 Ring No. 218)
Circumferential Direction, Elongation and Area Reduction
as a Function of Temperature

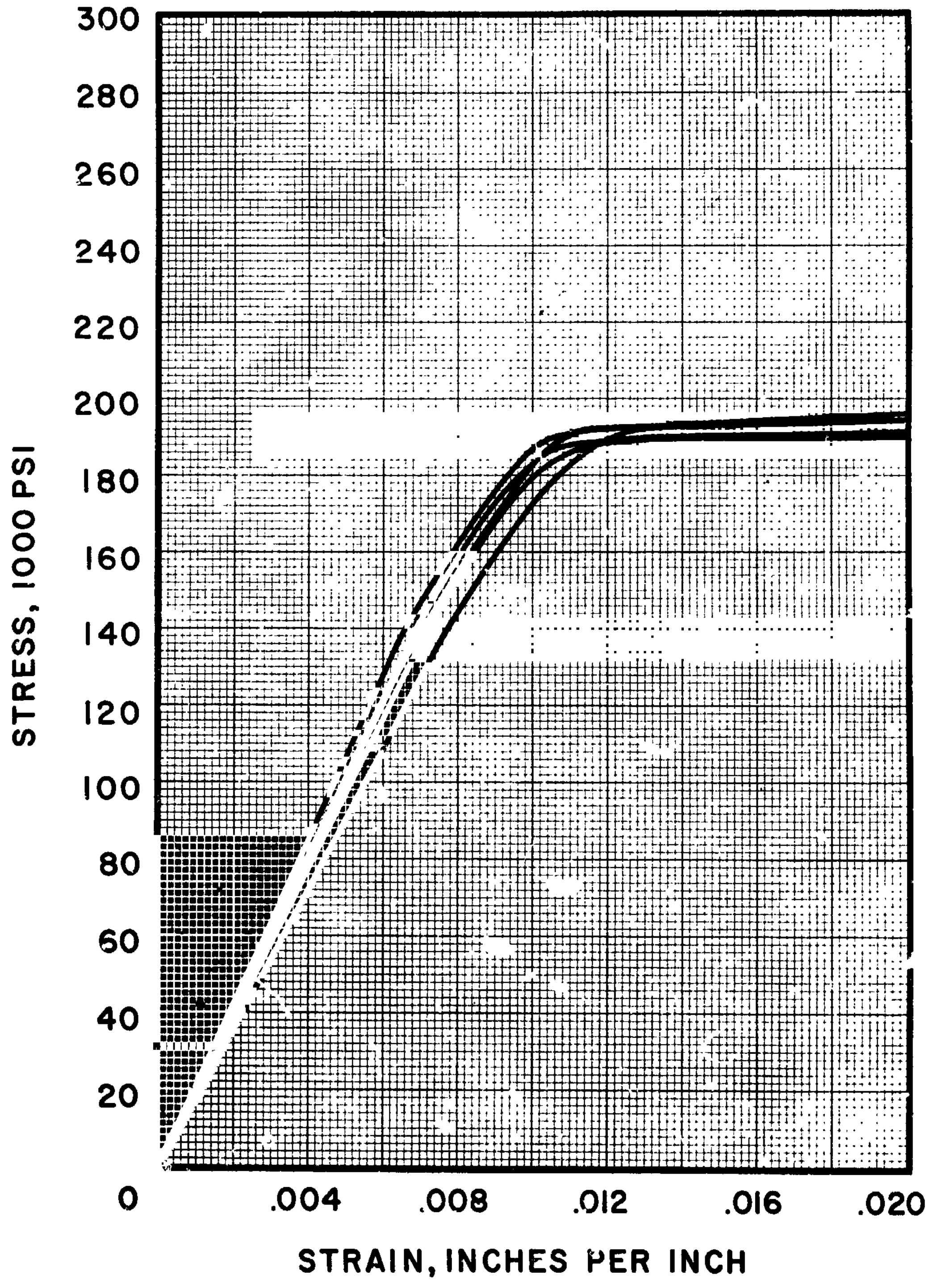


Figure 17

Titanium Alloy A-110-AT-ELI Extrusion (Heat 3273 Ring No. 219)
Circumferential Direction, Stress-Strain Diagram at 423°F

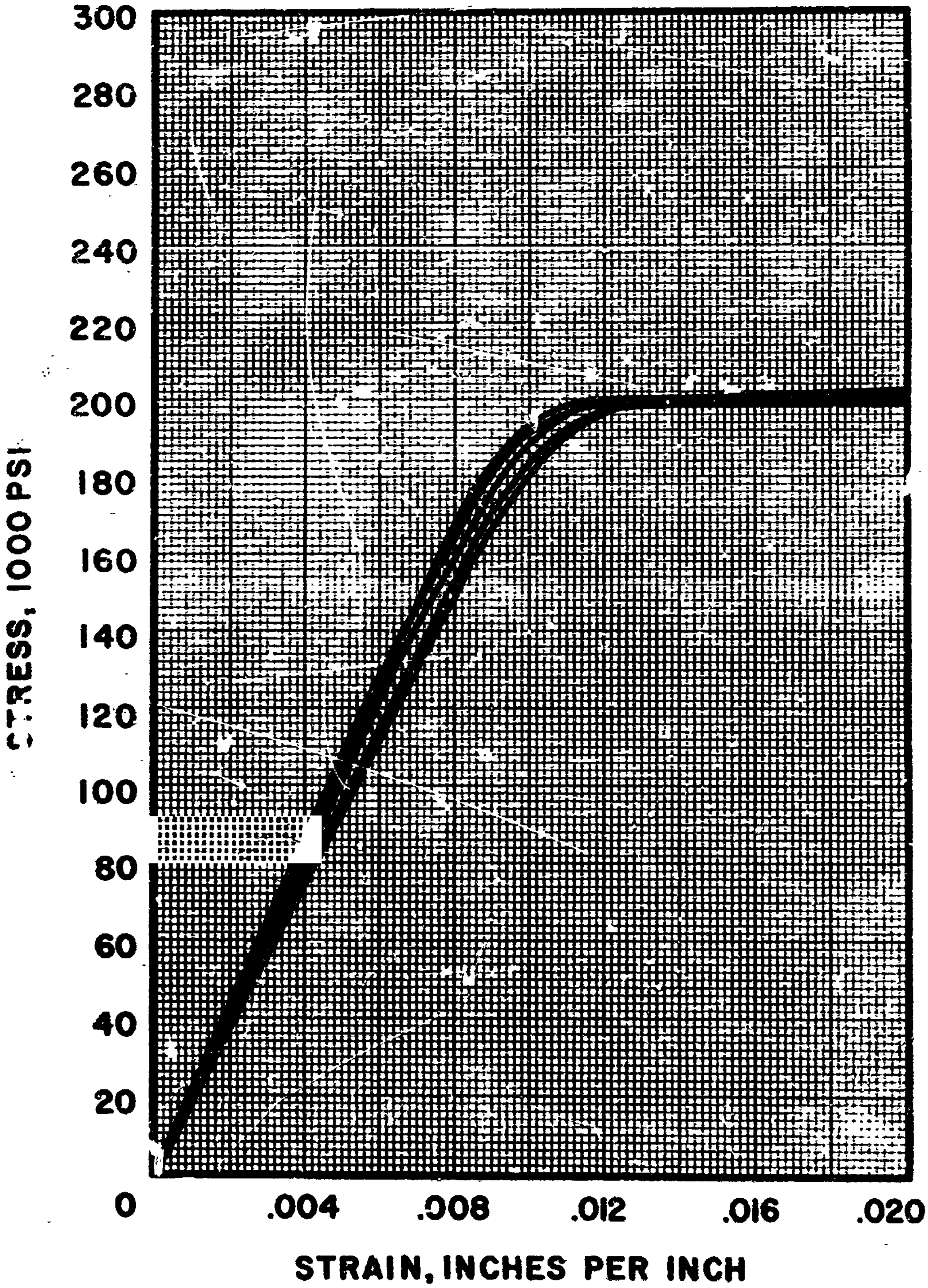


Figure 18

Titanium Alloy A-110-AT-ELI Extrusion (Heat 3273 Ring 219)
Longitudinal Direction, Stress-Strain Diagram at 423°F

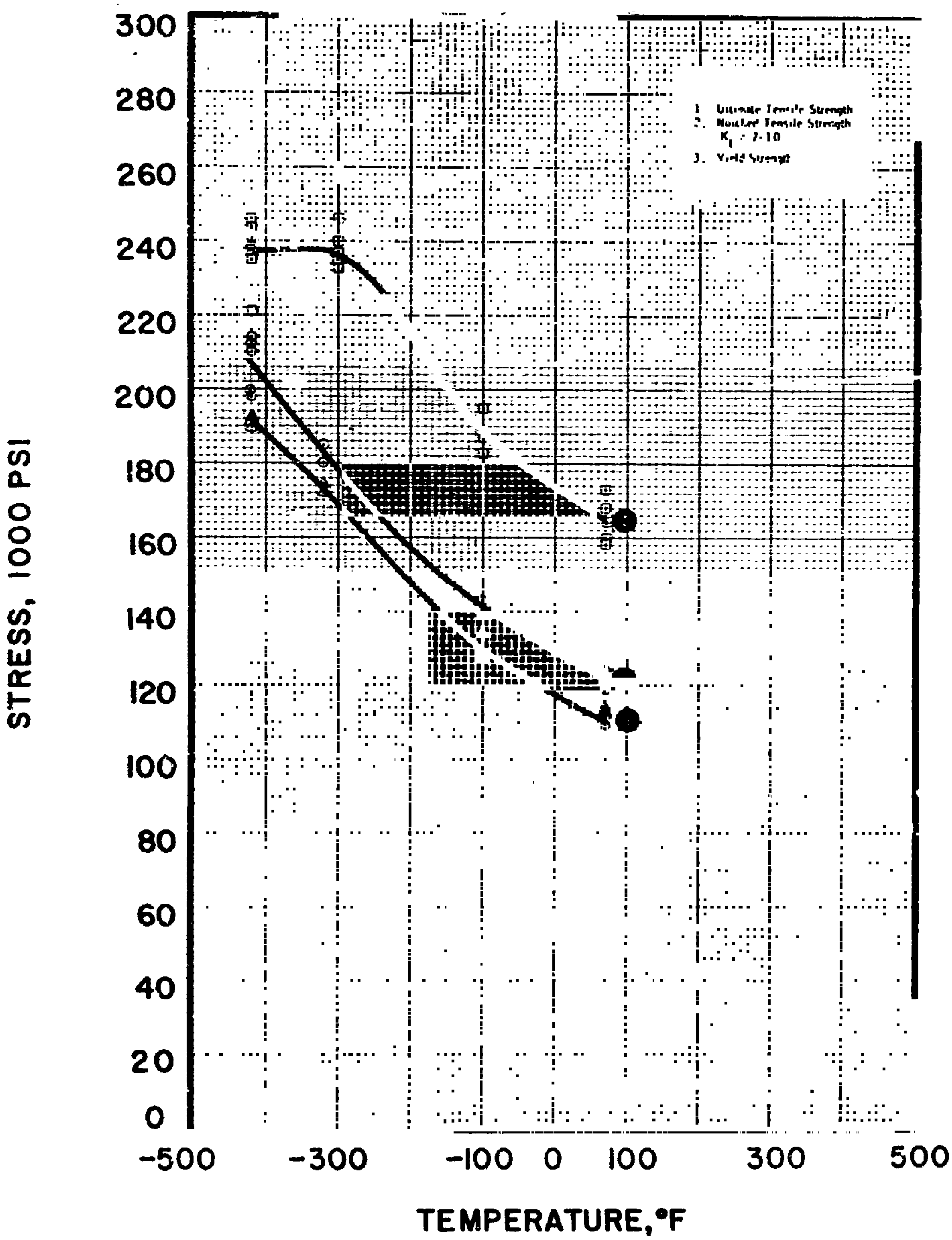
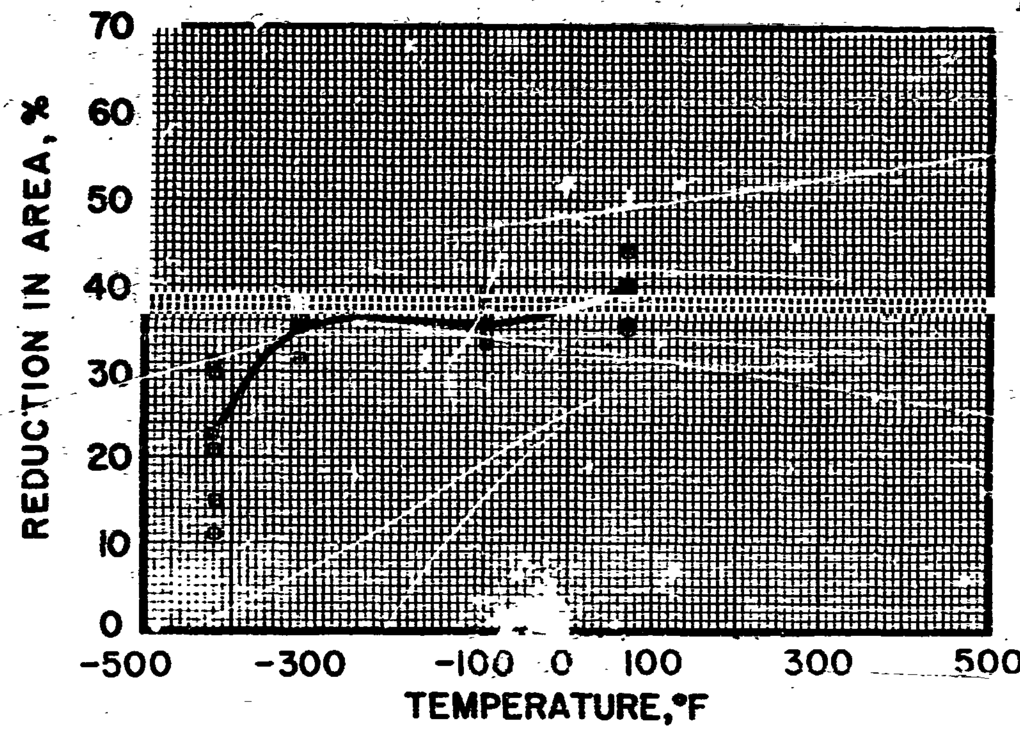


Figure 19

Titanium Alloy A-110-AT-ELI Extrusion (Heat 3273 No. 219) Circumferential, Tensile Ultimate, Yield and Notched Strength as a Function of Temperature



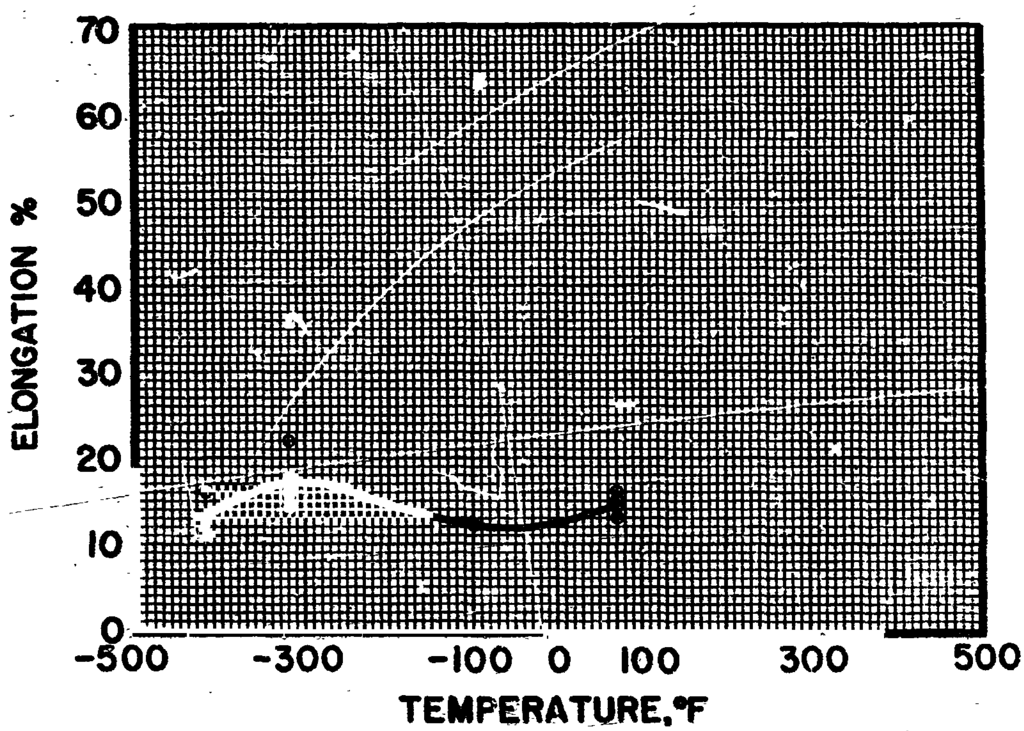


Figure 20

Titanium Alloy A-110-AT-ELI Extrusion (Heat 3273 Ring No. 219) Circumferential, Elongation and Area Reduction as a Function of Temperature

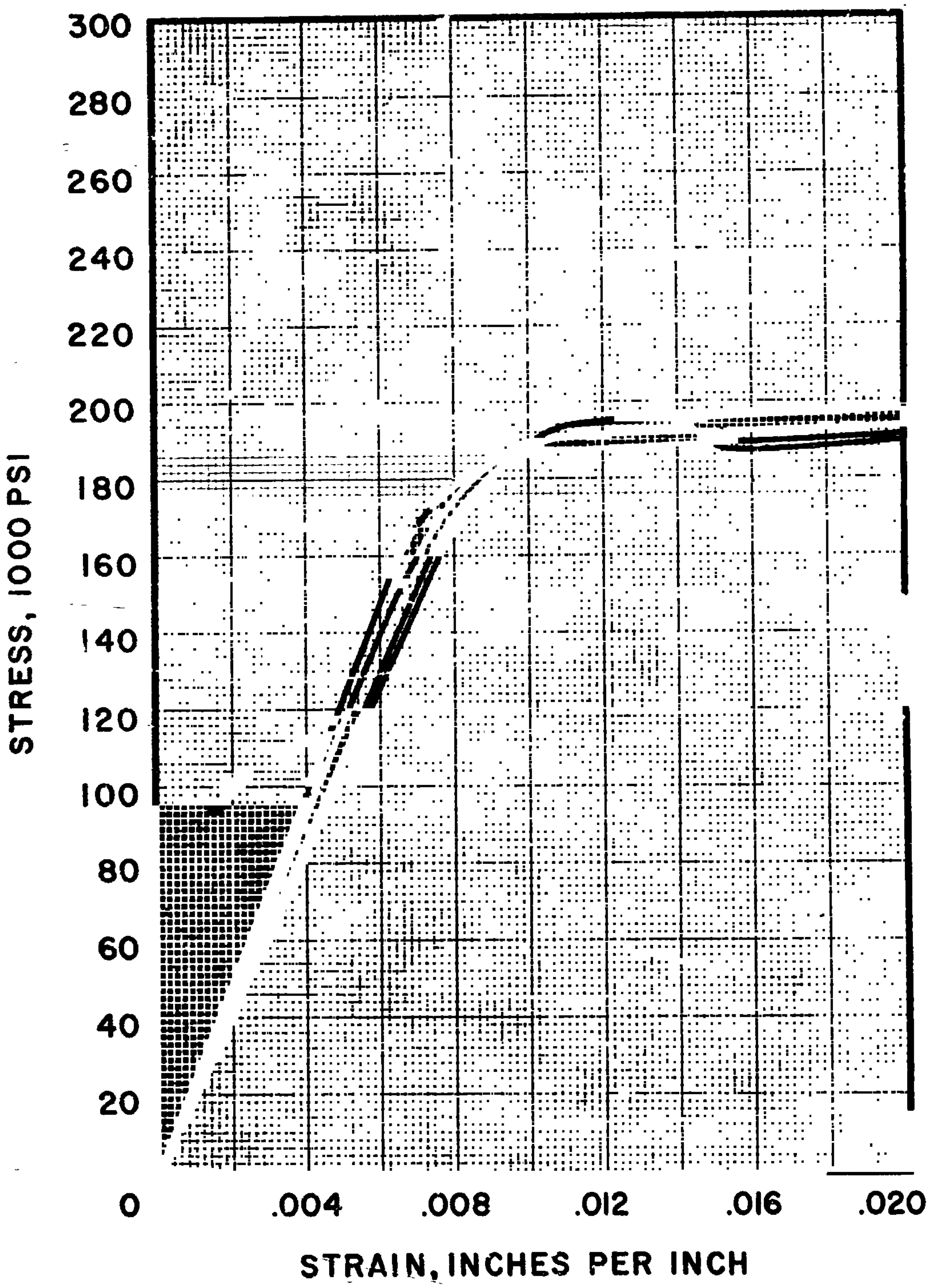


Figure 21

Titanium Alloy A-110-AT-ELI Extrusion (Heat 3346 Ring No. 465) Circumferential Direction, Stress-Strain Diagram at 423°F

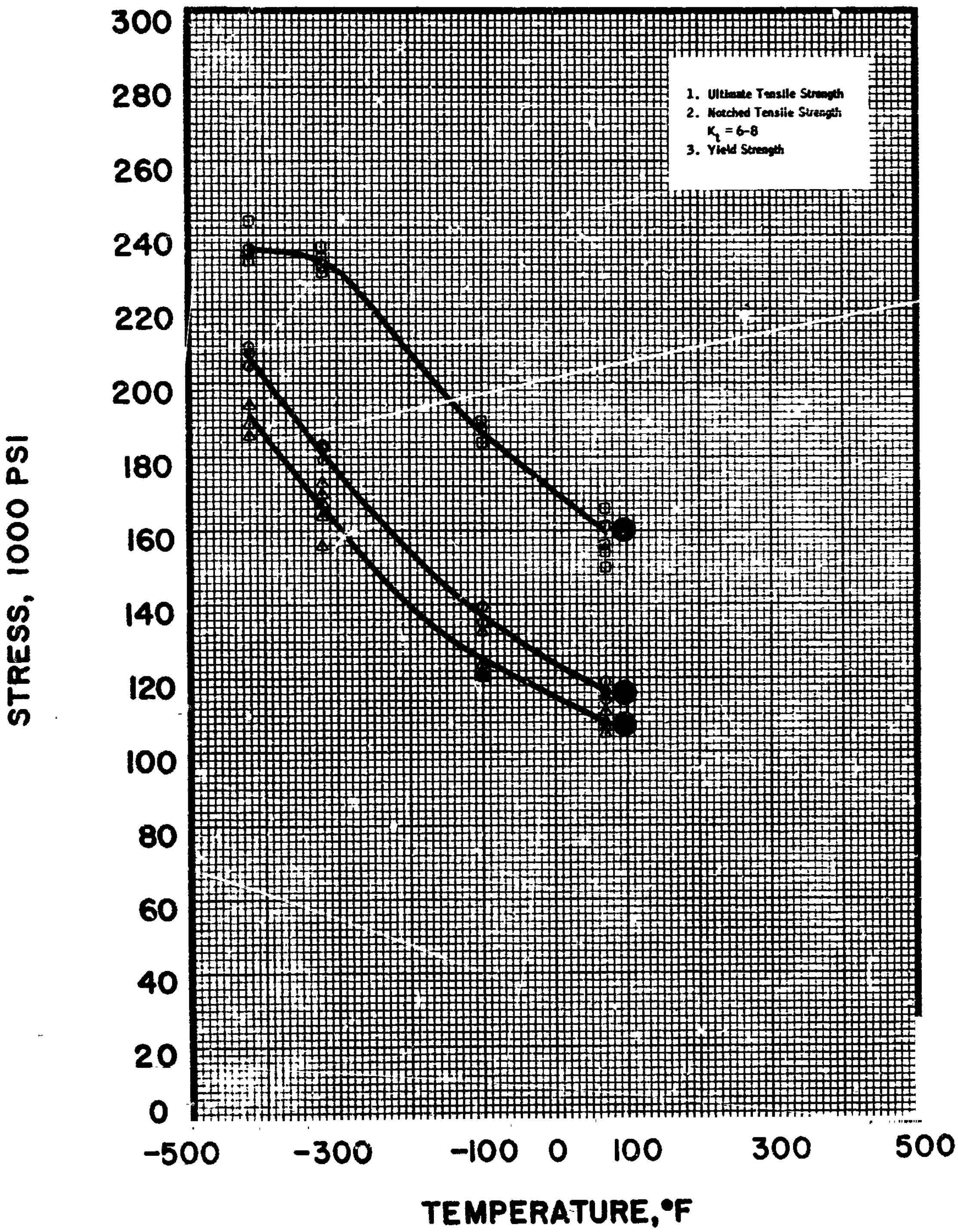
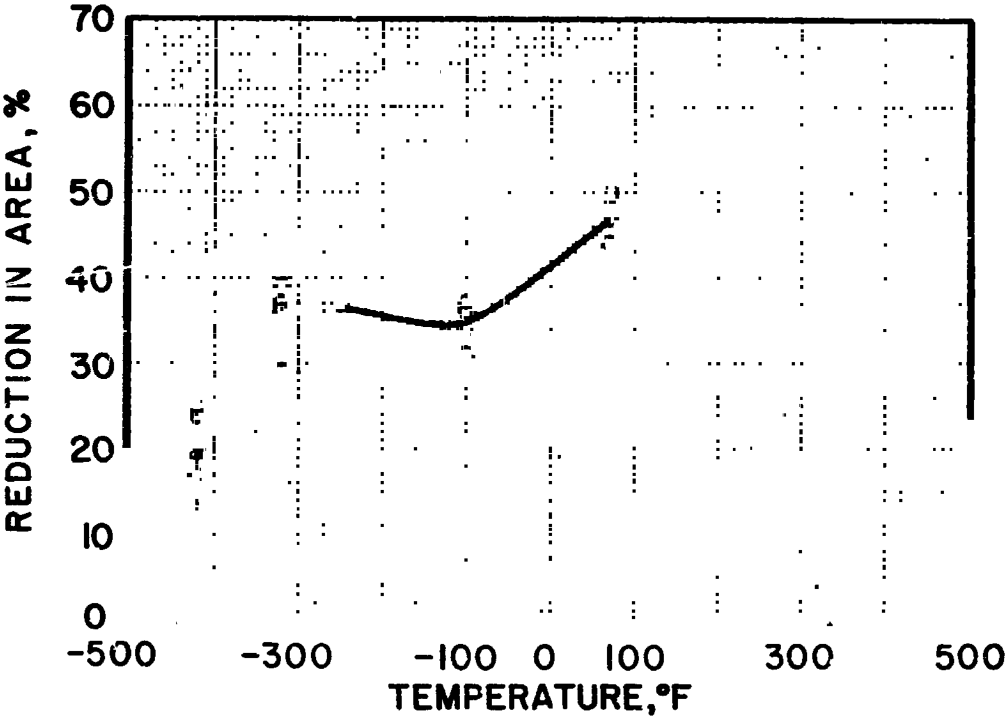


Figure 22

Titanium Alloy A-110-AT-ELI Extrusion (Heat 3346, Ring No. 465)
Circumferential Direction, Tensile Ultimate, Yield and
Notched Strength as a Function of Temperature



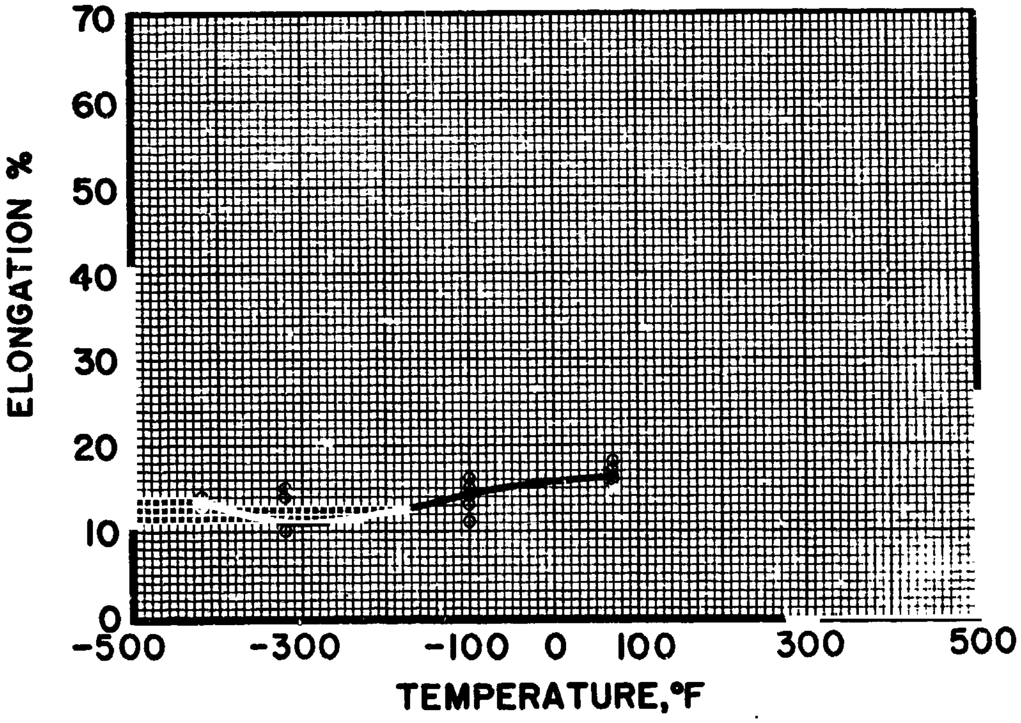


Figure 23

Titanium Alloy A-110-AT-ELI Extrusion (Heat 3346 Ring No. 465) Circumferential Direction, Elongation and Area Reduction as a Function of Temperature

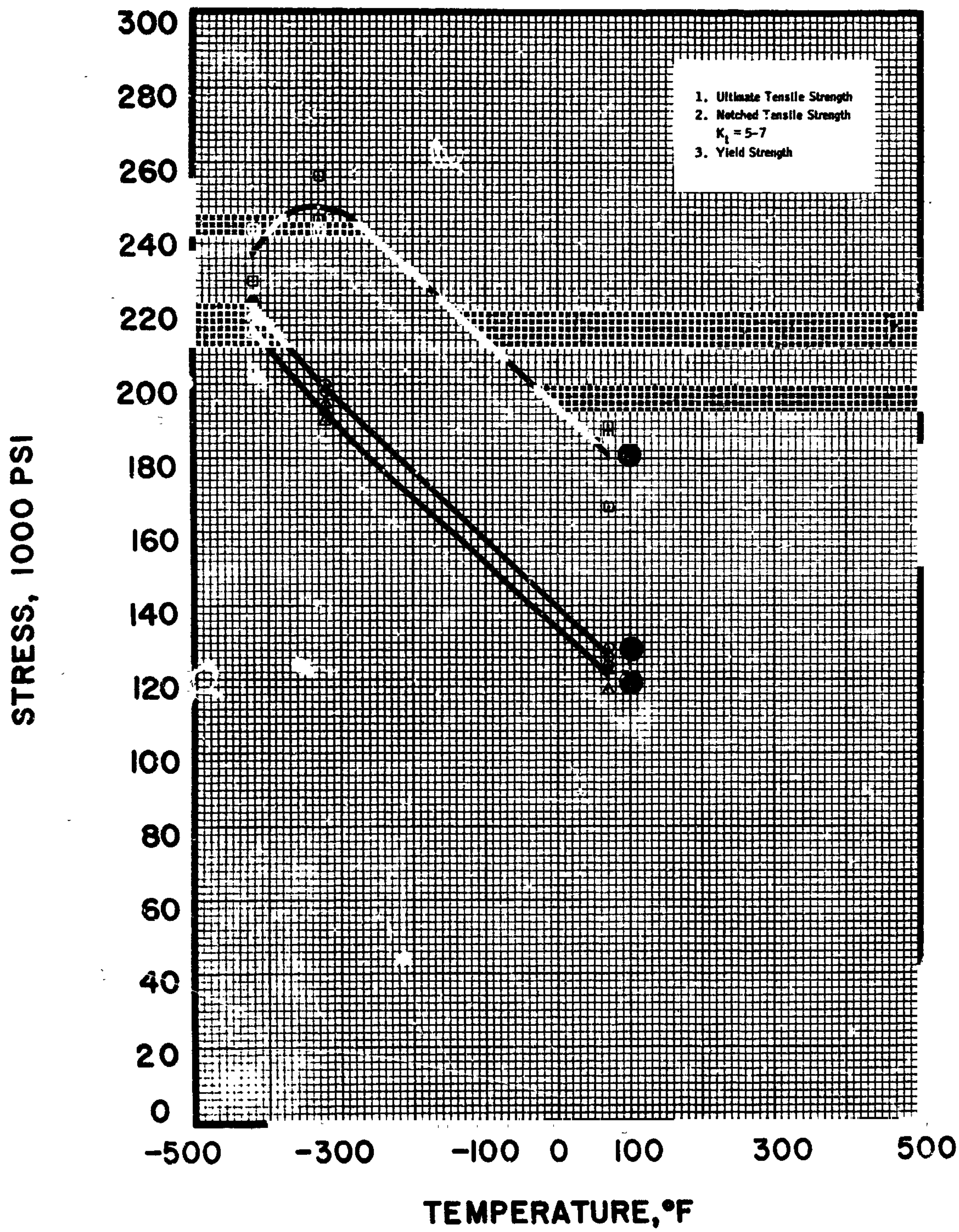


Figure 24

Titanium Alloy A-110-AT-ELI Forged Plate (Heat V-2096), Longitudinal Direction

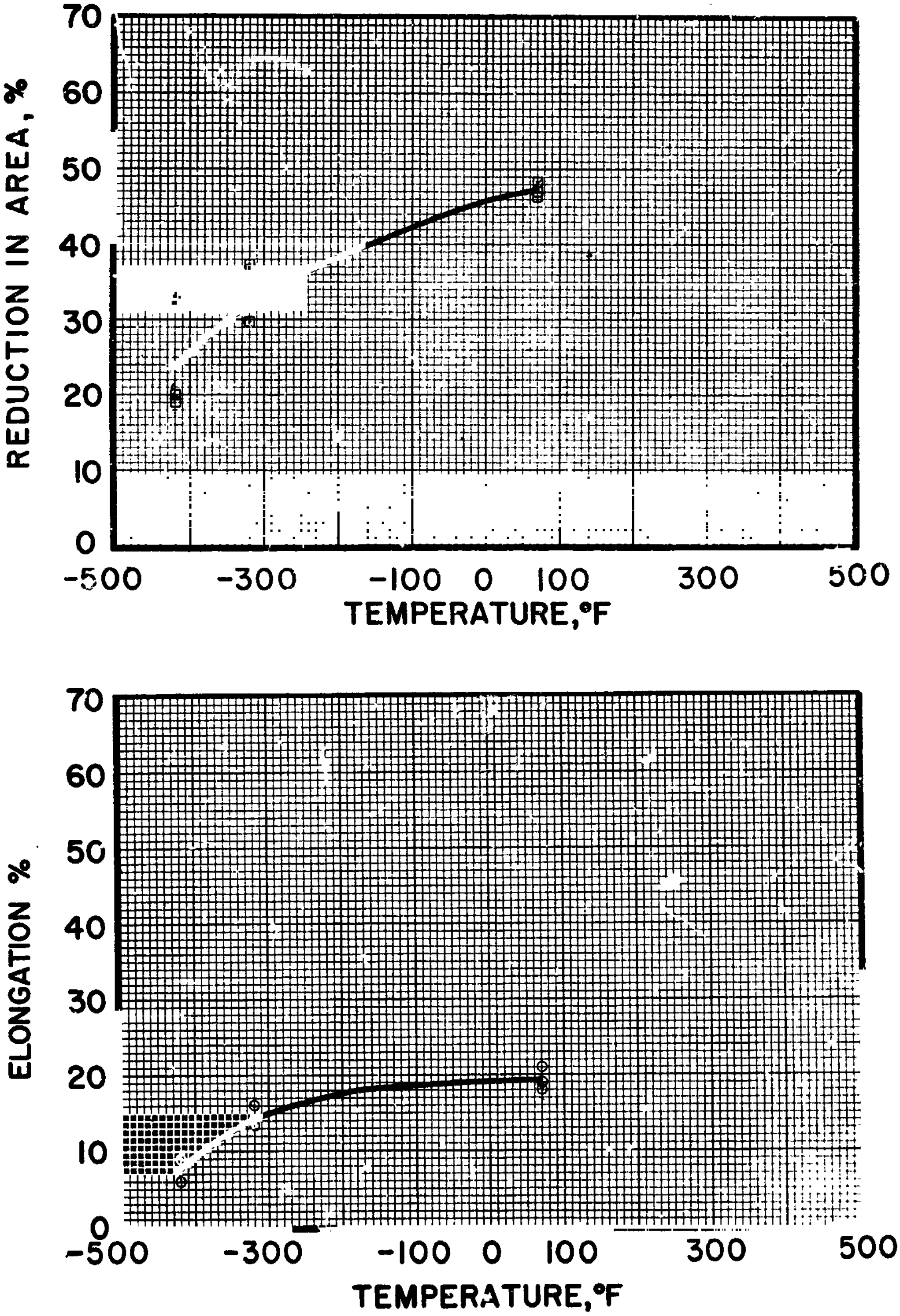


Figure 25

Titanium Alloy A-110-AT-ELI Forged Plate (Heat V-2096)
Longitudinal Direction, Elongation and Area Reduction
as a Function of Temperature

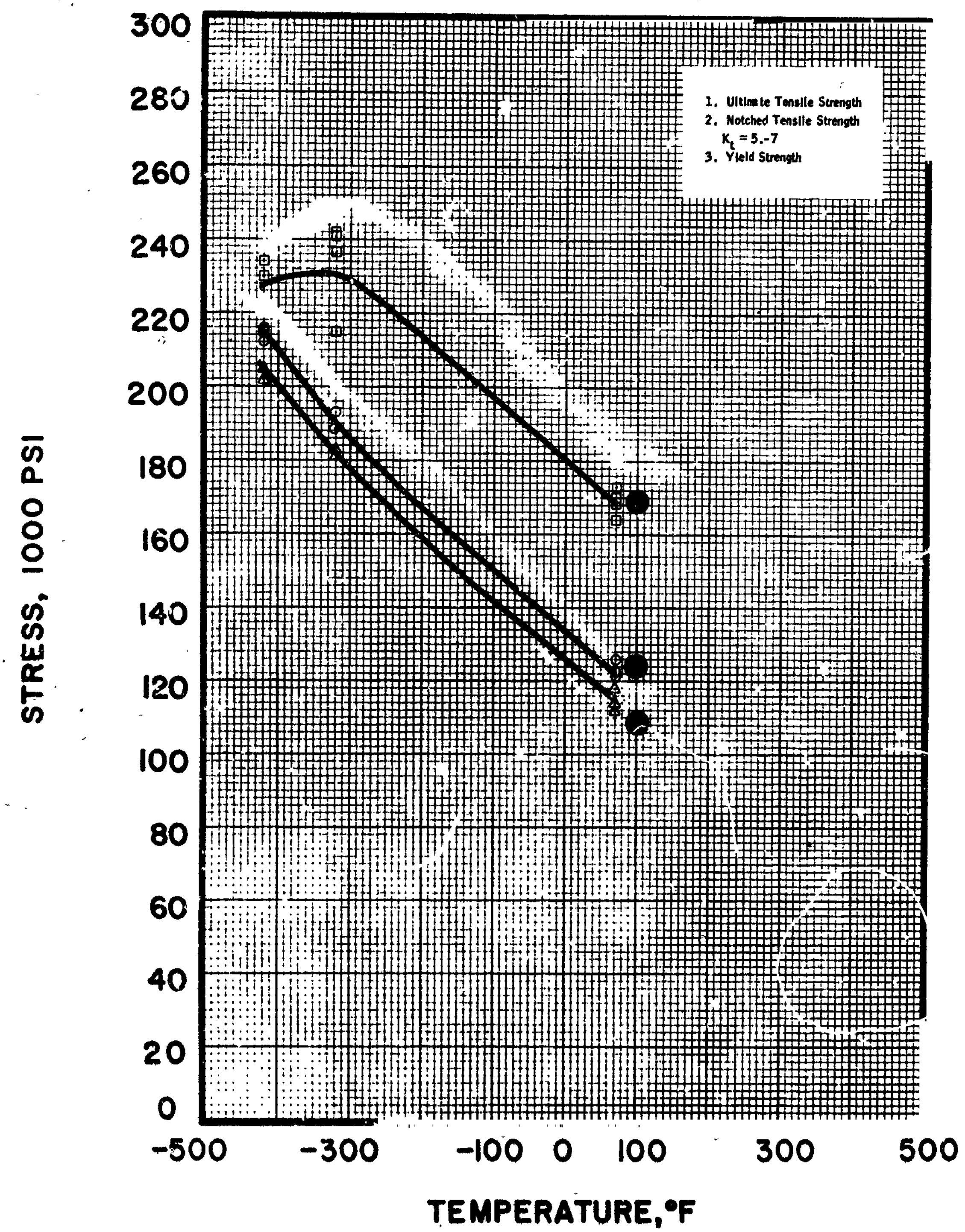
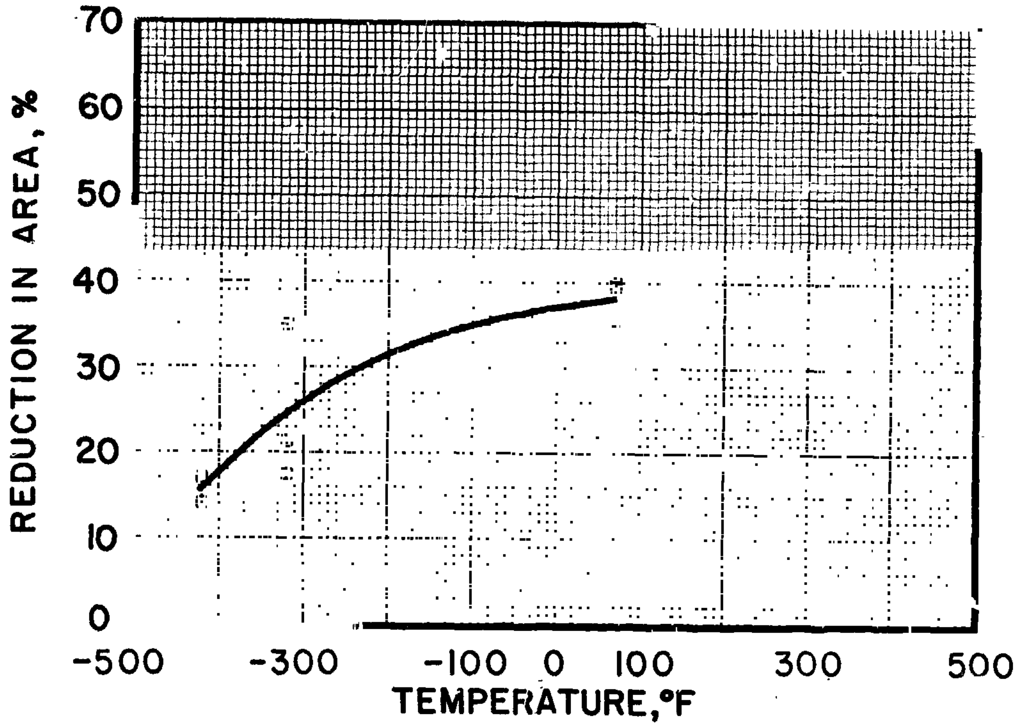


Figure 26

Titani.m Alloy A-110-AT-ELI Forged Plate (Heat V-2096) Transverse Direction, Tensile Ultimate, Yield, Notched Strength as a Function of Temperature



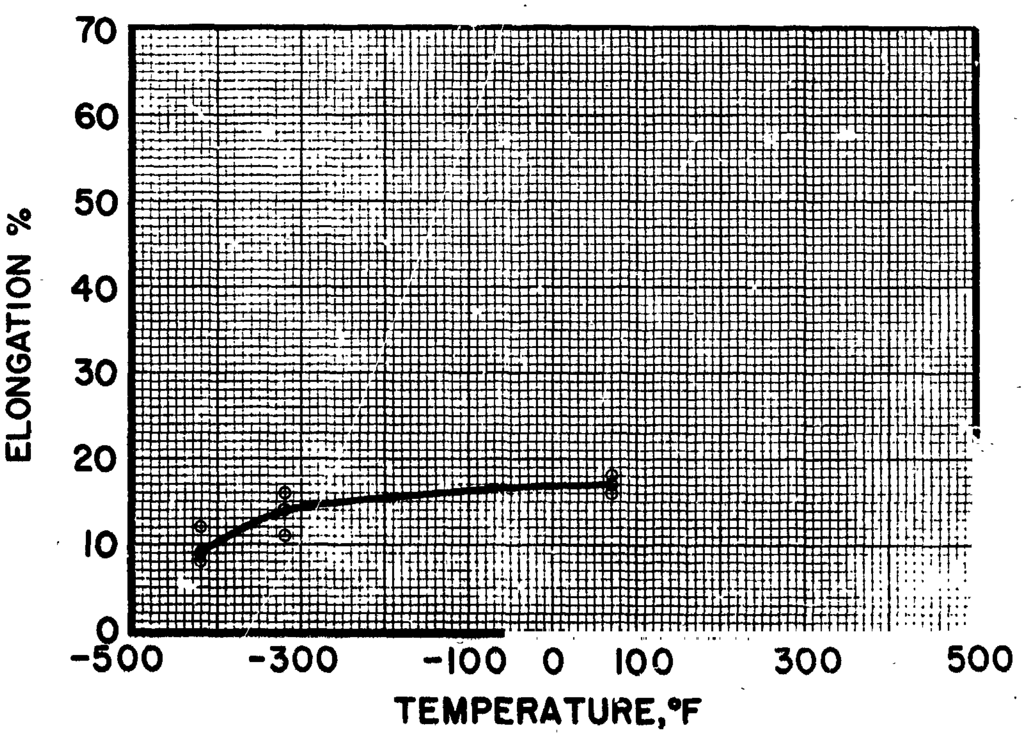


Figure 27

Titanium Alloy A-110-AT-ELI Forged Plate (Heat V-2096)
Transverse Direction, Elongation and Area Reduction
as a Function of Temperature

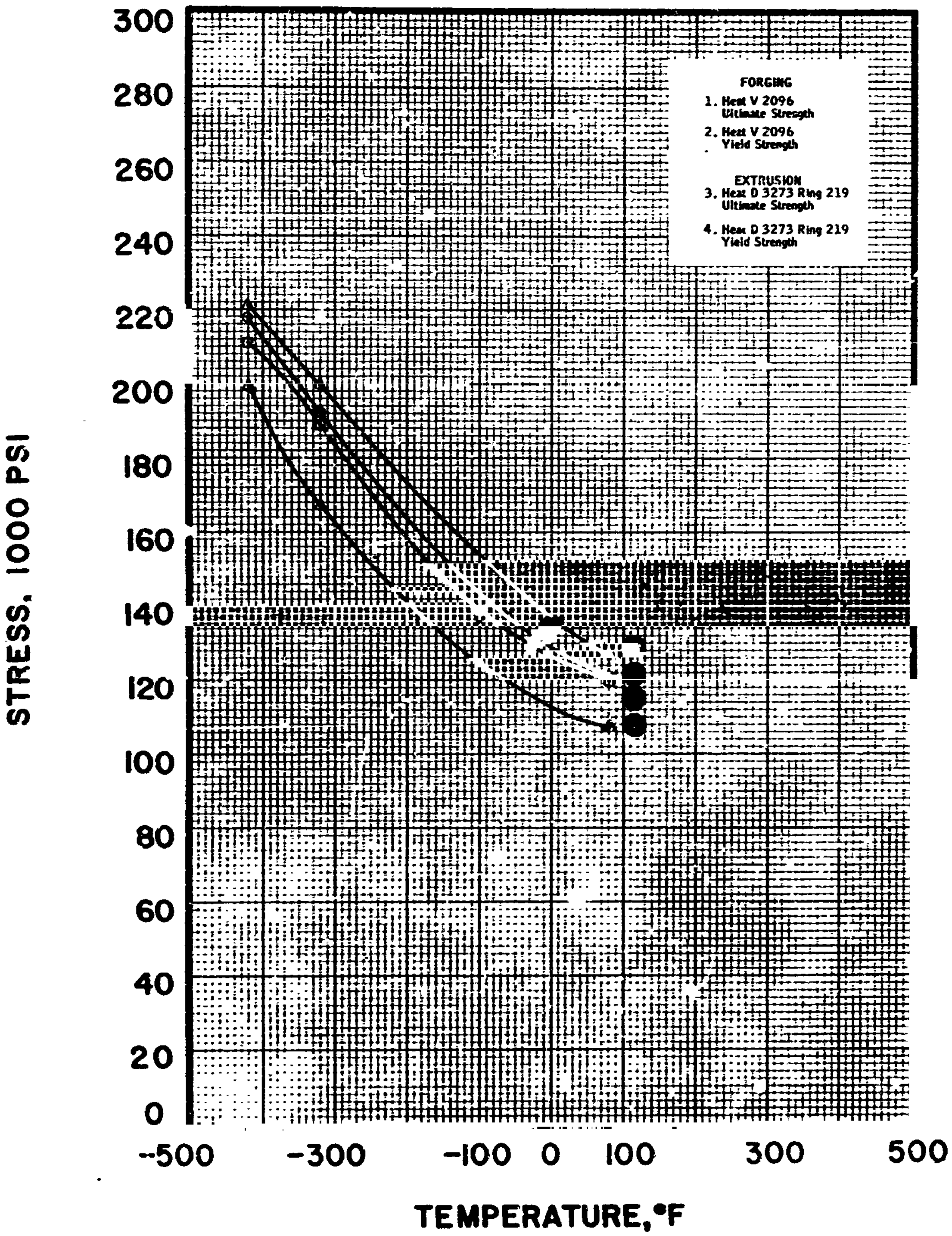
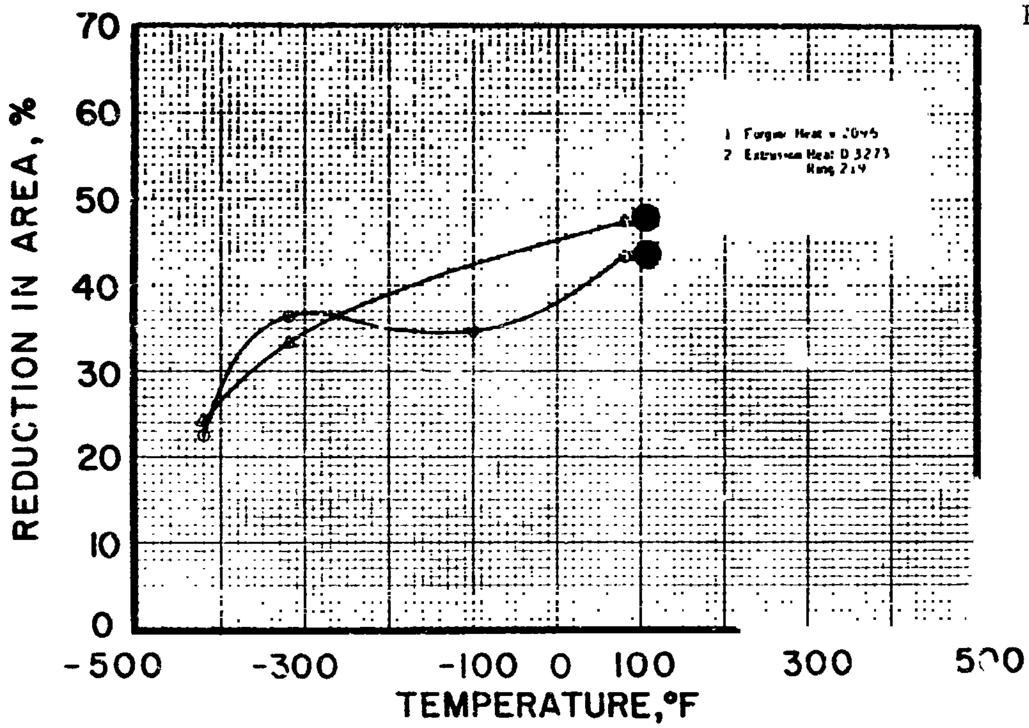


Figure 28

Titanium Alloy A-110-AT-ELI Comparison, Forgings and Extrusions Longitudinal, Tensile Ultimate and Yield Strength as a Function of Temperature



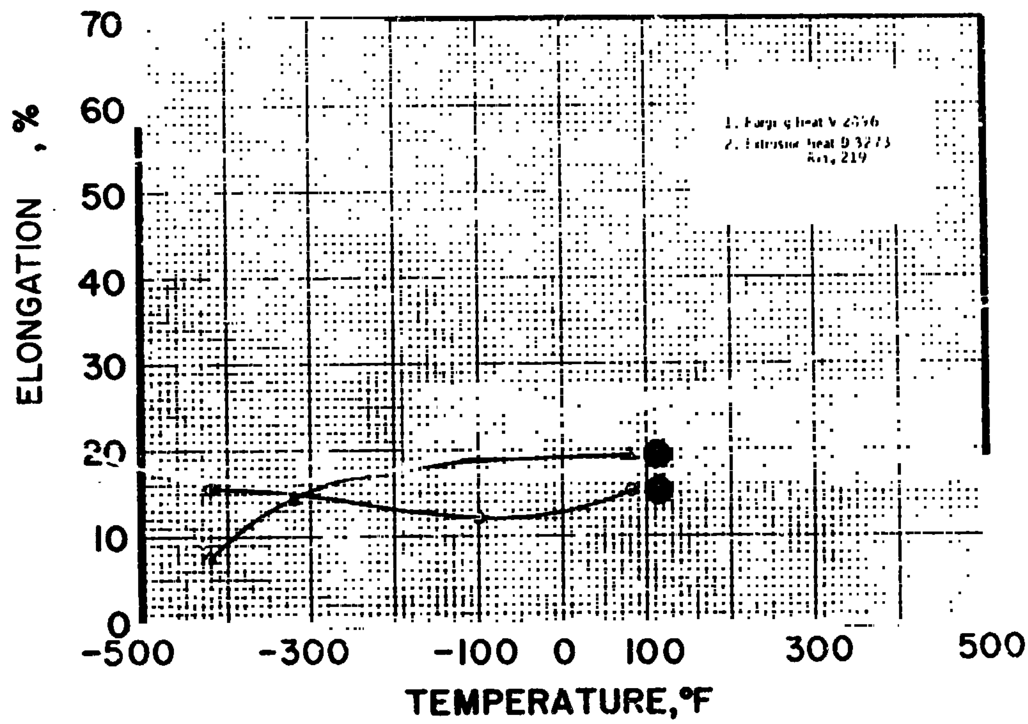


Figure 29

Titanium Alloy A-110-AT-ELI Comparison, Forgings and Extrusions
Elongation and Area Reduction as a Function of Temperature

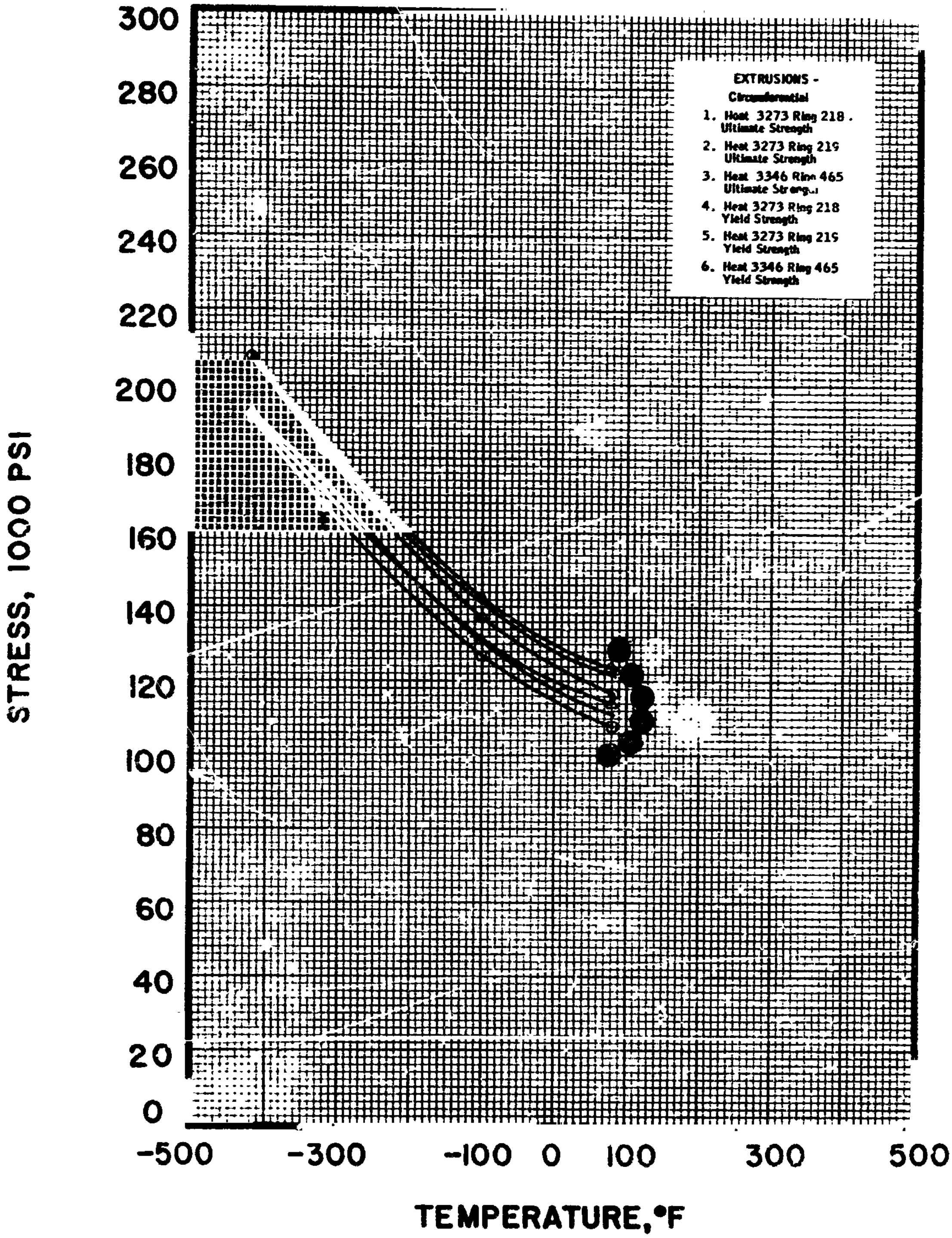


Figure 30

Titanium Alloy A-110-AT-ELI Comparison, Extruded Cylinders Circumferential, Ultimate and Yield Strength as a Function of Temperature

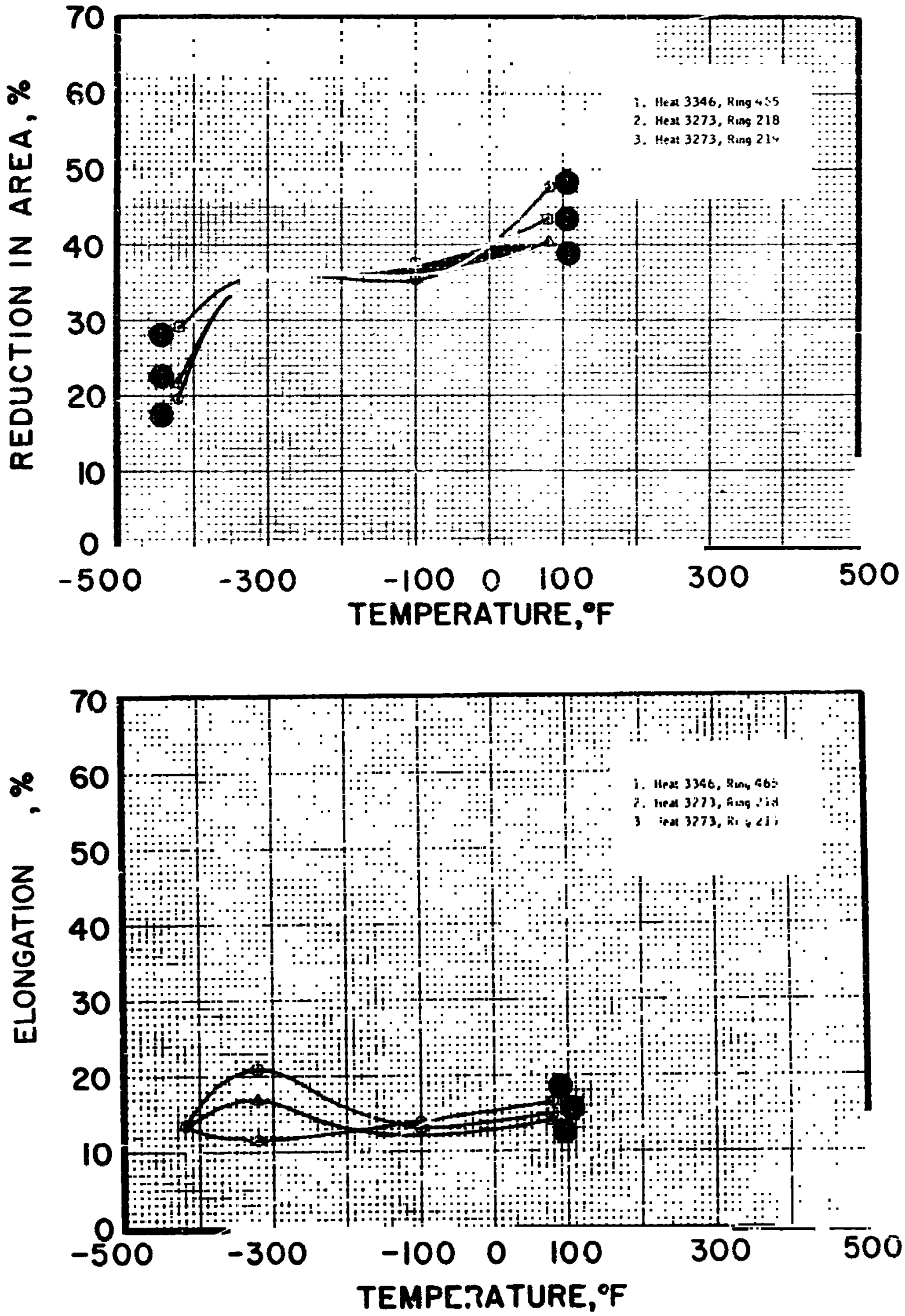


Figure 31

Titanium Alloy A-110-AT-ELI Comparison, Extruded Cylinders, Circumferential, Elongation and Area Reduction as a Function of Temperature

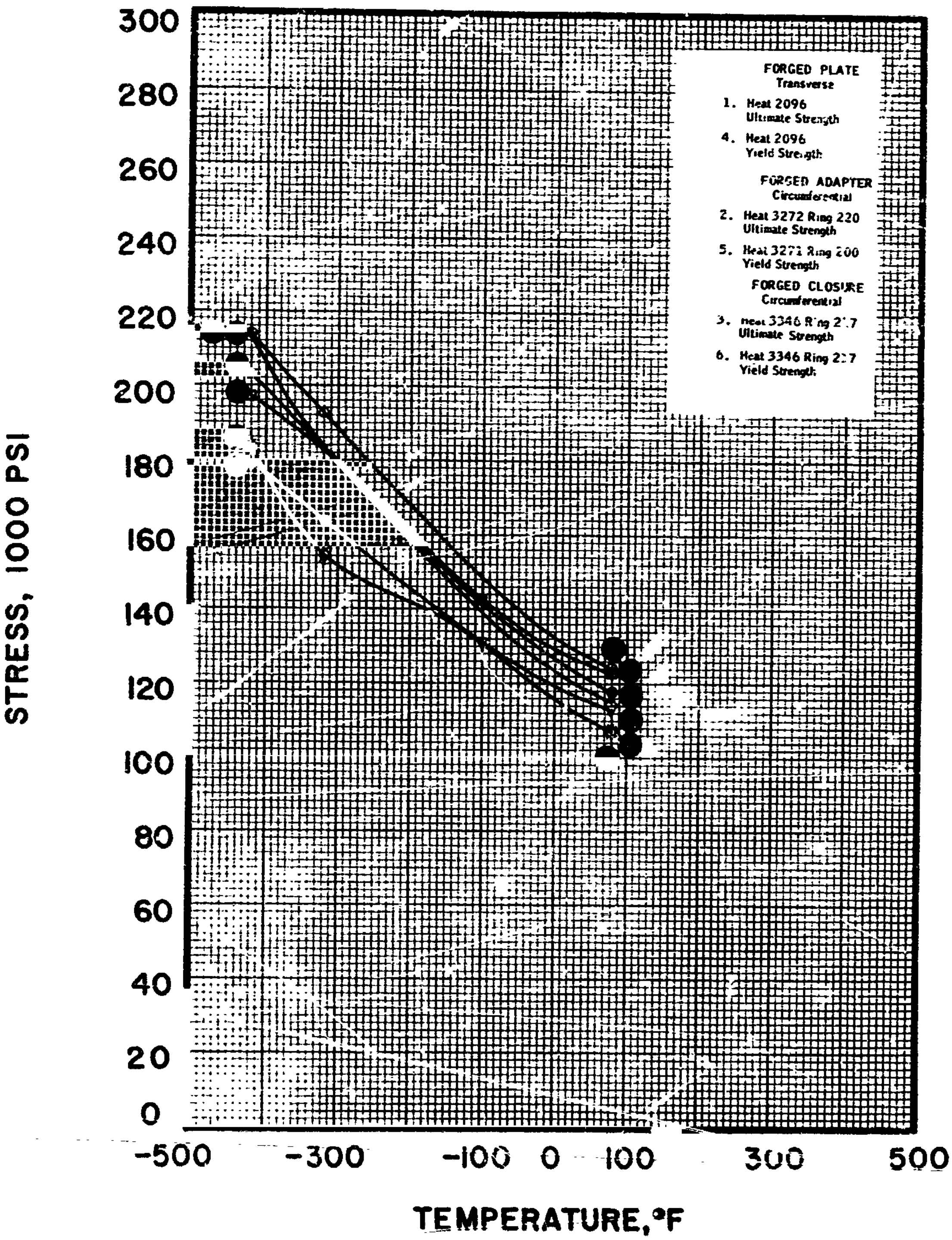
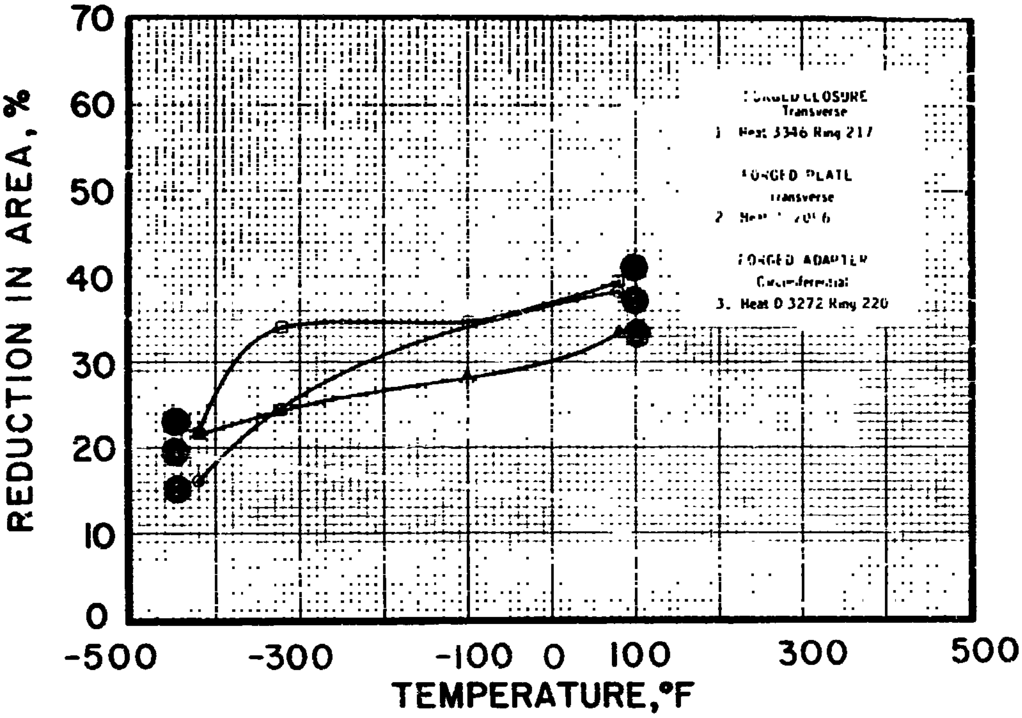


Figure 32

Titanium Alloy A-110-AT-ELI Comparison Forgings, Transverse and Circumferential Ultimate and Yield, Strength as a Function of Temperature



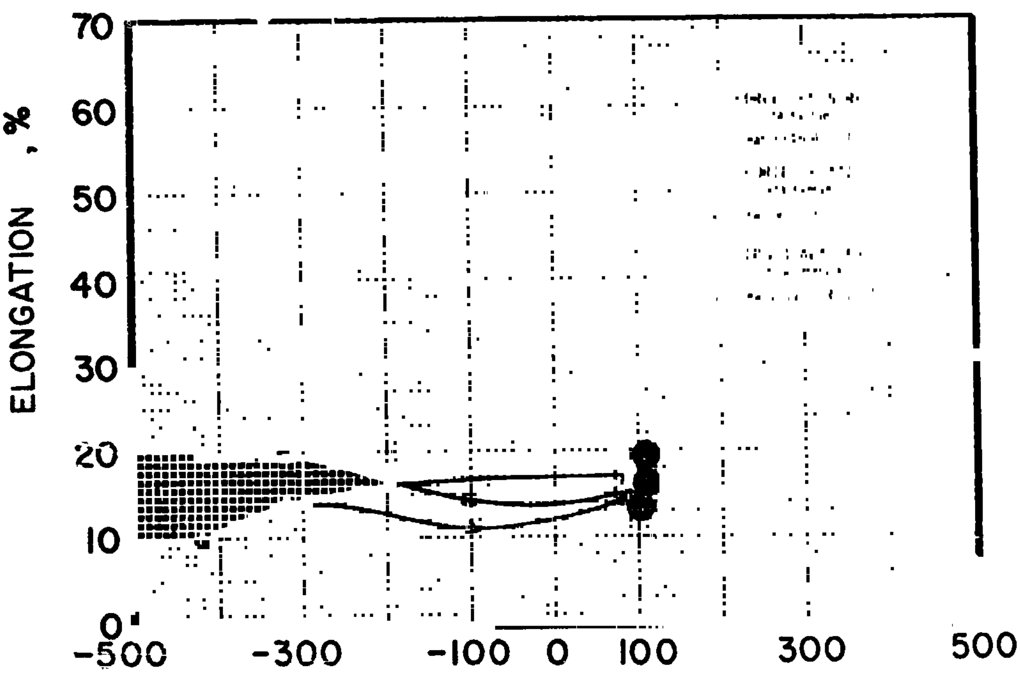


Figure 33

Titanium Alloy A-110-AT-ELI Comparison Forgings, Transverse and Circumferential, Elongation and Area Reduction as a Function of Temperature

a. Plate Materials

A comparison of hot-rolled plate with forged plate at -423°F shows that strength and ductility of transverse type specimens are approximately equal (ultimate strength 219,100 psi to 214,300, yield strength 205,000 to 203,500 psi; 17.8% to 16% area reduction). The equivalence of ductility is based on a comparison of area reductions rather than the elongations since the former is always considered the better parameter for measuring this property. This comparison is not the ideal one since the specimen sizes and configurations were not the same, one type being standard flat, and the other a subsize round.

Comparison of hot-rolled plate (transverse specimens) with extruded cylinders (circumferential specimens), all manufactured from the same heat, (D3273) shows that room temperature tensile (122,500 and 124,100 psi) yield, (114,400 and 114,200 psi) elongation, 15.5% and 15% and area reduction (40% and 43.7%) are practically identical in spite of the differences in specimen size and configuration. The longitudinal specimens from extruded stock indicate a slightly lower room temperature yield strength (107,500 psi) than the rolled plate. However, at -423°F both ultimate and yield strengths of the hot-rolled plate are noticeably higher (by about 8-10,000 psi) than those for extruded material, (both longitudinal and circumferential) except in the case of the yield strength of longitudinal specimens where the values of extruded and hot-rolled materials are almost equal. Ductility parameters at -423°F, when evaluated together, indicate that plate and extrusions are practically equal.

b. Forgings

Comparison of circumferential-type specimens from a ring forging and a closure forging showed general similarity, with a few interesting differences. The ring forging exhibited less ductility at all temperatures. At room temperature its tensile, yield and notch-ultimate strengths were higher than those of the closure forging. At -100°F, the ring forging had slightly higher tensile and notch ultimate strengths, but yield strengths were equal. At -320°F the tensile and notch ultimate strengths were equal, but the yield strength of the ring forging was higher. At -423°F the ring forging had lower tensile strength, and yield strength, but the notch-ultimate strengths were equal. The interesting feature is the crossover range, at -320°F and below, where the tensile and yield strengths of the closure forging increased to higher values than those of the ring forging.

Test results obtained from the closure forging, (heat D3346) compare very closely with the results obtained on the extruded cylinder No. 465 made from the same heat, the only differences being slightly higher yield strengths for the extrusion at -320° and -423°F and higher tensile strength at -423°F for the forging.

c. Extruded Cylinders

The tensile properties from all three extruded cylinders in the circumferential direction were very similar.

Two cylinders, extruded from material of heat D3273, exhibited test results which were nearly identical. The notch ultimate strengths shown for room temperature and -100°F represent variations in K_t, which would account for the different values.

Both longitudinal and circumferential type specimens taken from cylinder 219, heat D3273, had properties which were nearly equal. Yield strengths, however, were generally higher for circumferential specimens, and the -423°F notch ultimate strength for longitudinal specimens at the same K_t was higher by 13,000 psi.

2. Alloy 6Al-4V-ELI

This alloy represents an increase in both tensile and yield strengths over A110-AT, ELI with no evident difference in ductility over the entire range of room to cryogenic temperatures. The notch toughness, however, measured by notched/unnotched ratios ($K_t = 6.3$) is not quite as high as for the A110 alloy, although values are about 1.0 at temperatures down to -320°F. At -423°F the notched/unnotched ultimate ratio is 0.94 and, that of notched ultimate/unnotched yield is 0.97. Note that these are not "sharp notch" values, obtained by use of a high stress-concentration factor ($K_t = 18$) which is required as the next step in evaluating this material. The data are presented in Tables 3 and 4 and Figures 34 through 37, and include both longitudinal and transverse properties of notched and unnotched specimens. The tensile properties of 6Al-4V, ELI, both longitudinally and transversely at room temperature (ultimate strength 140,600 and 138,800 psi; yield strength 133,000 and 132,700 psi) and at cryogenic temperatures (ultimate strength 239,000 and 239,000; yield strength 228,000 and 231,000 psi at -423°F) are nearly equal.

Table 4

Tensile Properties of Titanium Alloy 6Al-4V-ELI Forged Plates at Room Temperature -100°F, -320°F and -423°F

Heat No.	Temp. °F	Specimen Type	Ultimate Strength, psi	Yield Strength (0.2%) psi	Elongation in 1", %	Reduction in Area, %
D 3067	RT	Unnotched	139,800	132,500	14.0	40.6
		Long.	140,500	132,800	14.0	39.1
			141,500	133,700	14.0	39.2
R-3 type		Notched	190,800			
Specimens		Long	194,200			
		(K_t=6-7)	194,900			
		Unnotched	138,200	132,100	14.0	43.8
		Transv.	138,800	133,000	15.0	44.7
			139,400	132,900	15.0	42.6
		Notched	188,300			
		Transv.	188,800			
		(K_t=7-8)	189,700			
	-100	Unnotched	165,500	160,300	13.0	33.3
		Long	165,900	162,300	13.0	28.7
			172,400	166,700	13.0	30.5
		Notched	225,200			
		Long	226,500			
		(K_t=5-6)	226,700			
		Unnotched	162,300	153,800	13.0	36.1
		Transv.	162,700	159,700	13.0	34.0
			162,900	159,100	14.0	35.9
		Notched	211,100			
		Transv.	216,400			
		(K_t=7)	217,000			
	-320	Unnotched	219,900	211,500	11.0	34.9
		Long	220,800	211,400	11.0	31.4
			230,300	220,400	10.0	27.6
		Notched	270,300			
		Long	275,100			
		(K_t=4-6)	282,800			
		Unnotched	215,600	206,200	10.0	28.7
		Transv.	217,400	207,200	11.0	30.7
			217,600	208,000	12.0	31.3
		Notched	252,500			
		Transv.	261,900			
		(K_t=6-8)	262,500			
	-423	Unnotched	230,000	230,000	11.0	23.0
		Long	241,000	225,000	12.0	24.6
			247,000	228,000	10.0	24.9
		Notched	262,000			
		Long	263,000			
		(K_t=6)	267, 00			
		Unnotched	231,000	231,000	6.0	25.7
		Transv.	236,000	-	6.0	20.1
			251,000	-	6.0	21.0
		Notched	220,000			
		Transv.	222,000			
		(K_t=6-8)	231,000			

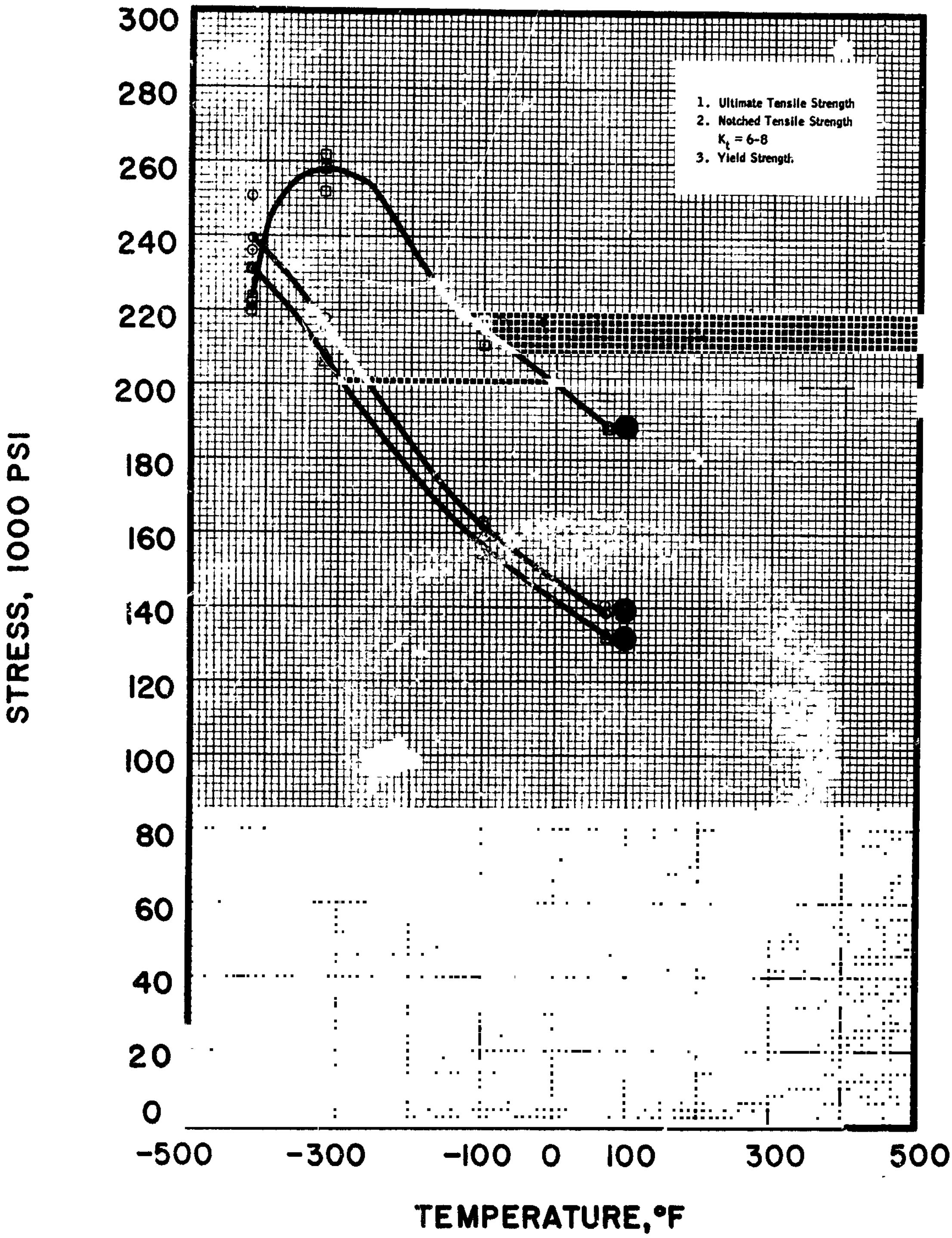
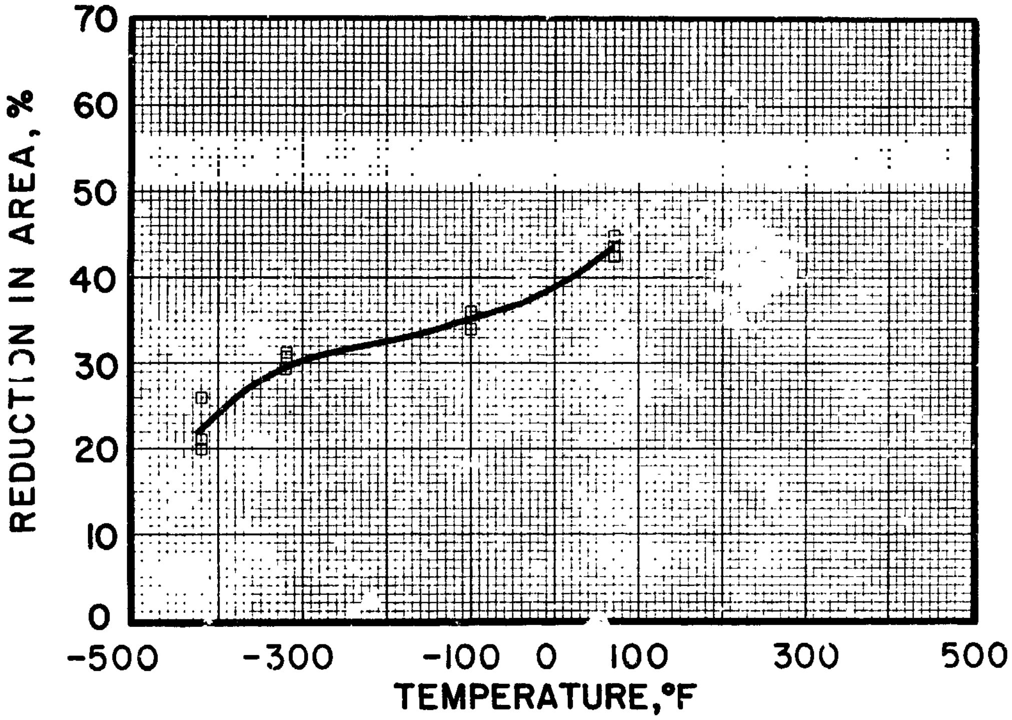


Figure 34

Titanium Alloy 6Al-4V-ELI Forged Plate (Heat D3067), Transverse Tensile Ultimate, Yield and Notched Strength as a Function of Temperature



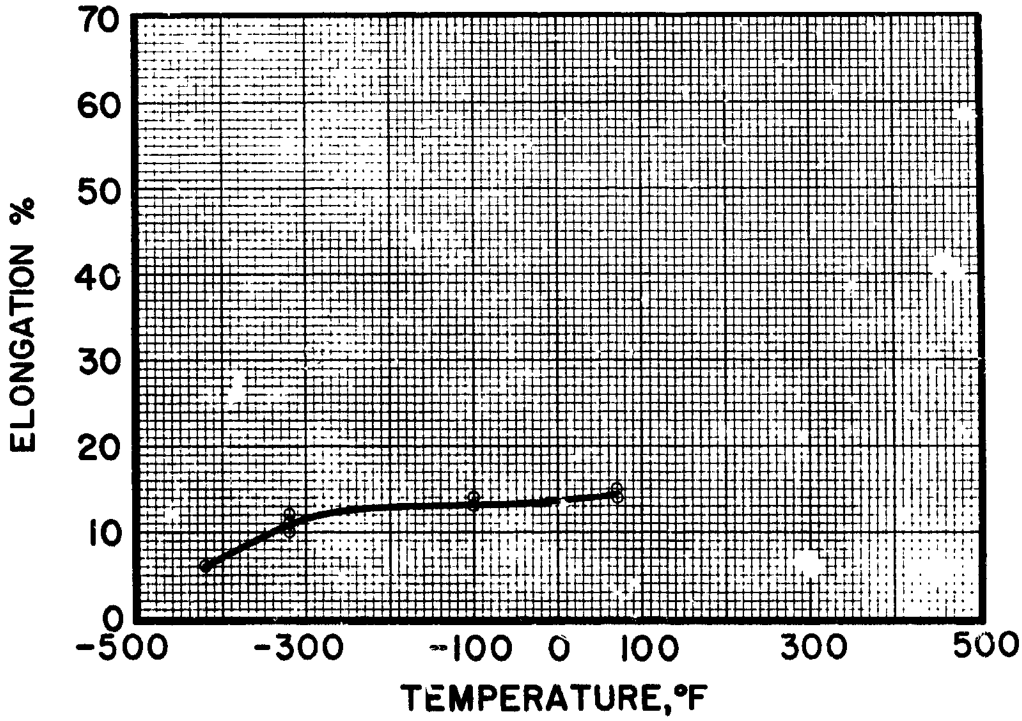


Figure 35

Titanium Alloy 6Al-4V-ELI Forged Plate (Heat D3067), Transverse Elongation and Area Reduction as a Function of Temperature

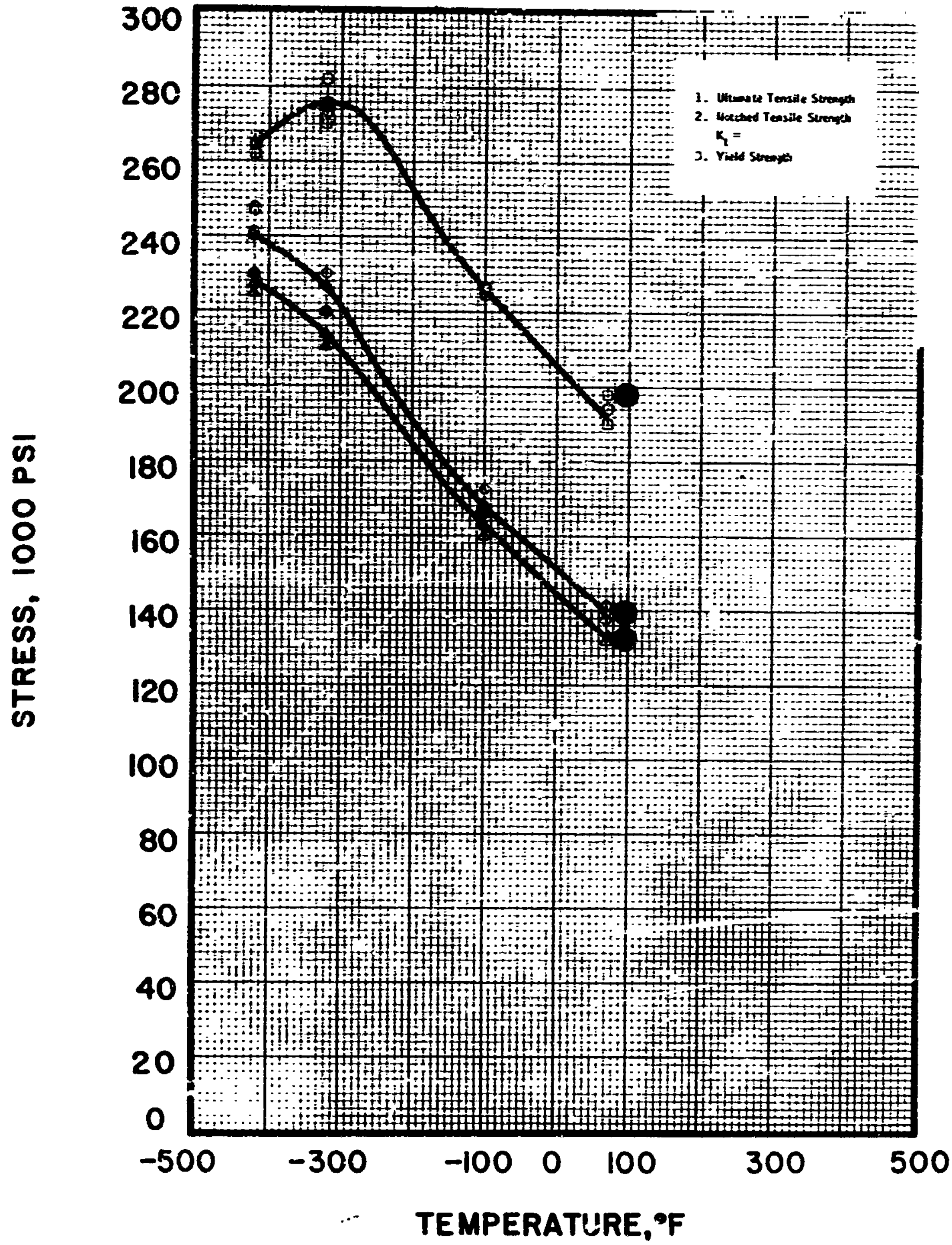


Figure 36

Titanium Alloy 6Al-4V-ELI Forged Plate (Heat D3067), Longitudinal, Ultimate Tensile, Notched and Yield Strength as a Function of Temperature

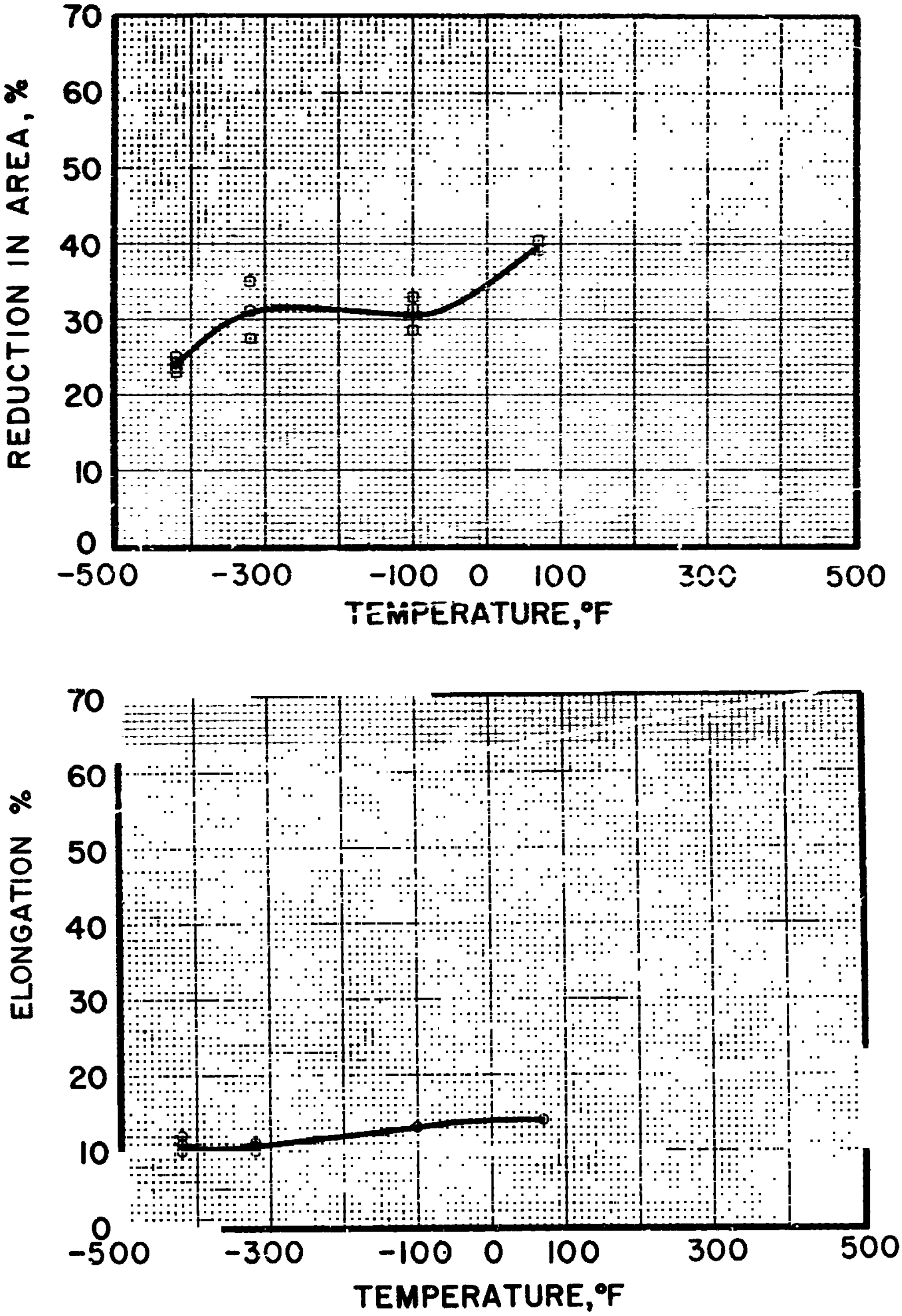


Figure 37

Titanium Alloy 6Al-4V-ELI Forged Plate (Heat D3067)
Longitudinal, Elongation and Area Reduction
as a Function of Temperature

B. STAINLESS STEELS AND IRON BASE ALLOYS

Chemical composition (as obtained by sample analysis and compared to the corresponding specification requirements) of all stainless steels and iron base alloys are shown in Table 5. Average tensile properties of these alloys are shown in Table 6.

Table 5

Chemical Analysis of Stainless Steel and Iron Base Alloys

Material Designation			C	[illegible]r	Mo	Mn	Si	S	P	Nb	Ta	Al	Ti	[illegible]	Fe	Others	Ni	H_2 ppm	O_2 ppm	N_2 ppm
-321	Specification Limit	Min.	-	1[illegible].00	-	-	0.40	-	-			-	6xC	-	Bal.		8.00			
		Max.	0.08	1[illegible]	0.50	2.00	1.00	0.03	0.04	-	-	-	0.70	0.50	Bal.		11.00			
	Sample Analysis		0.045	17.8		1.80	0.54	0.013	0.015	-	-	0.07	0.57	0.37	- Bal.		10.5	100	10	8
347-c Sand Casting	Specification Limit	Min.	-	17.00	-	-	-	-	-	10×C	-		-	-	Bal.		9.00			
		Max.	0.10	20.00	0.50	2.00	1.50	0.04	0.04	1.35	-		-	0.50	Bal		12.00			
	Sample Analysis		0.08	19.30	0.28	1.09	1.00	0.018	0.014	1.25	0.21	-	0.75	0.31	Bal.		9.35	15	690	110
AM-350	Specification Limit	Min.	0.08	16.00	2.50	0.50	-	-	-						Bal.	$0.07 N_2$	4.00			
		Max.	0.12	17.00	3.25	1.25	0.50	0.03	0.04						Bal.	$0.13 N_2$	5.00			
	Specimen Analysis		0.08	15.73	2.78	0.75	0.32	0.009	0.02						Bal.	$0.113 N_2$	4.28	6	290	1130
A-286	Specification Limit	Min.	-	13.50	1.00	1.00	0.40	-	-			-	1.90		Bal.	0.001 B	24.00			
		Max.	0.08	16.00	1.50	2.00	1.00	0.03	0.04			0.35	2.30		Bal.	0.01 B	27.00			
	Specimen Analysis		0.061	14.8	1.15	1.11	0.77	0.003	0.01			0.26	2.03		Bal.		25.65	-	5	7
18% Ni Maraging Steel (Preliminary Data)	Specification Limit (Tentative)	Min.	0.01	-	4.6	-	-	-	-			-	0.30		Bal.	7.0 Co*	17.00			
		Max.	0.03		5.1	0.10	0.10	0.01	0.01			0.10	0.50			8.0 Co	19.00			
	Specimen Analysis																			

*Others Continued: 0.003 max. B; 0.02 max. Zr; 0.05 max. Ca

Table 6

Average Tensile Properties of Stainless Steel and Iron Base Alloys

Alloy	Temp. °F	Ultimate Strength psi	Notch Ultimate Strength, psi	Yield Strength (0.2%) psi	Elongation in 2 in. %	Reduction in Area, %	Notched to Unnotched Ratios N-Ult/Un-Ult	N-Ult/Un-Y.S.	Number of Tests
Type 321	RT	81,250	84,300(K_t=6.3)	34,350	58.3	65.4	1.04	2.45	2U, 3N
	-423	216,700	106,300	57,000*	30.3	51.7	0.49	1.87	2 @
Type 347-c Cast	RT	85,600	72,300(K_t=6.3)	39,900	30.9	25.4	0.63	1.79	4U, 3N
	-423	113,500	102,300	84,000*	4.3	5.1	0.90	1.22	2 @
AM350-SCT (850°F)	RT	200,050	211,300(K_t=6.3)	161,100	9.3	33.5	1.05	1.31	2U, 4N
	-423	306,700	80,900	295,000*	1.5	0.9	0.26	0.27	2 @
A-286	RT	155,650	152,900(K_t=6.3)	106,150	19.8	33.9	0.98	1.44	2U
	-423	216,600	202,500	141,000*	24.5	32.2	0.93	1.43	
18% Ni Maraging "V-long"	-423	356,000	322,300(K_t=6.3)	347.50	2.3**	-	0.90	0.93	2U, 3N
Steel "V-transv" (0.09" sheet)		365,000	328,000	350,500	2.8**	-	0.90	0.94	2U, 3N
"A-long"	-423	356,000	323,300(K_t=6.3)	344,000	3.0**	-	0.91	0.94	1U, 3N
"A-transv"		345,000	321,000	339,000	3.5**	-	0.93	0.95	2U, 3N
3/8-in. Dia. bolting	-423	335,000	-	-	-	-	-	-	3 @
peened bolting		380,000	-	-	-	-	-	-	3 @

*Based on strain estimated from crosshead travel of tensile machine.

**Elongation in 1".

"A" Air melted.

"V" Vacuum remelt of "A".

1. Stainless Steel Type 321

The increase in tensile strength of this material from 81,250 at room temperature to 216,700 psi at -423°F (approx. 65%) is much higher than the increase in the 0.2% yield strength (approx. 16%) from 34,350 to 57,000 psi. The data are shown in Tables 6 and 7 and Figure 38. In spite of these strength increases, the ductility, i.e., elongation and area reduction, remained high at -423°F. The notched ultimate strength at -423°F was much higher than the unnotched yield strength (by a ratio of 2.56) and is indicative of satisfactory notch toughness, in spite of notched to unnotched ratio of 0.49. At this temperature, these test results are in agreement with the data reported by NBS (References 1 and 7).

Table 7

Tensile Properties of 321 Stainless Steel at Room Temperature and -423°F

Material	Temp. °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%) psi	Elongation in 2", %	Reduction in Area, %	Hardness Rockwell
Type 321 Annealed	RT	Unnotched	78,700	29,800	59.0	67.0	A-43
			83,800	38,900	57.5	63.8	A-47
	RT	Notched (K_t= 6.3)	84,000				
			84,400				
			84,600				
	-423	Unnotched	210,800	58,000*	32.5	51.3	
			222,600	56,000*	28.2	52.0	
	-423	Notched (K_t= 6.3)	101,100				
			111,500				

*Based on strain estimated from crosshead travel of tensile machine.

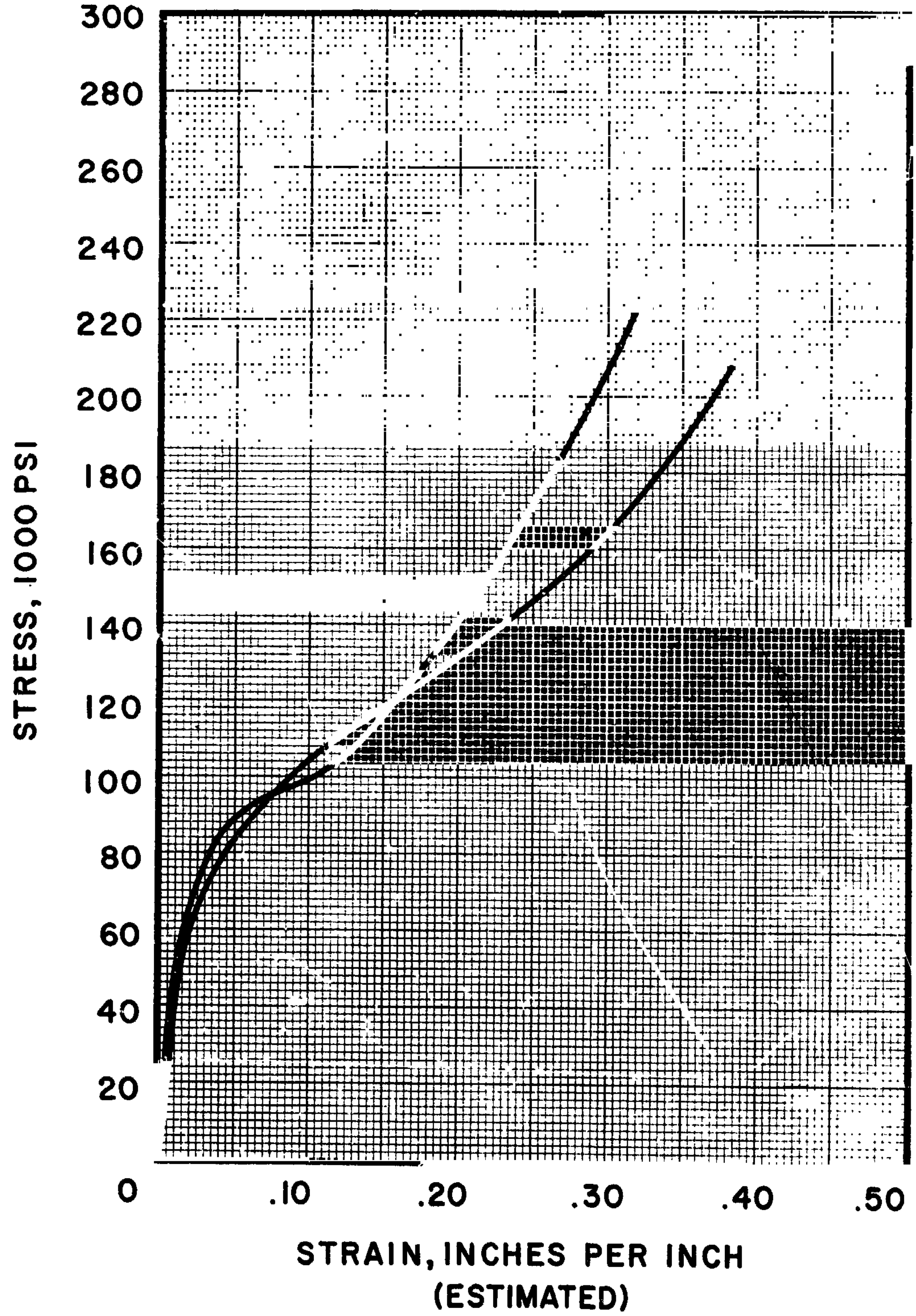


Figure 38

Stainless Steel Type 321 Sheet, Stress-Strain Diagrams (at -423°F)

2. Stainless Steel Type 347-c (Casting)

The room temperature ultimate (85,600 psi) and yield strengths (39,900 psi) were comparable to those of Type 321 wrought material, which is generally typical of 300 series stainless steels. However, the increase in tensile strength at -423°F (113,500 psi) was much less (15%), and the increase in yield strength was much greater (up to 84,000 psi approx 80%). (See Table 6 and 8 and Figure 39 for these data.) The ductility of the cast specimens reduced drastically with decrease in temperature as shown by a drop from 30.9% elongation at room temperature to 4% at -423°F. This indicates a strong tendency toward brittle behavior. It should, however, be noted that the notch-ultimate strength at -423°F was appreciably higher than the unnotched yield strength indicating that the material may still be useful at cryogenic temperatures.

The microstructure of this material normally consists of dendritic austenite (face-centered cubic) with discontinuous pools of ferrite (body-centered cubic) at interdendritic boundaries. The ferrite promotes ductility at room temperature, but becomes brittle at cryogenic temperatures. Brittle behavior at cryogenic temperatures is usually observed in the case of body-centered cubic metals, while face-centered cubic metals are normally ductile.

Table 8

Tensile Properties of 347-C Stainless Steel Sand Casting at Room Temperature and -4.,°F

Material	Temp. °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%)psi	Elongation in 2", %	Reduction in Area, %	Hardness Rockwell
+7C Sand cast)	RT	Unnotched	83,900	38,700	28.0	29.2	
			85,400	37,900	35.5	24.9	
			86,400	40,200	32.0	25.6	
			86,600	42,800	28.0	21.9	
	RT	Notched	66,000				
			73,800				
			74,300				
	-423	Unnotched	111,800	85,000*	5.0	4.1	
				83,000*	3.5	6.1	
	-423	Notched (K_t= 6.3)	98,600				
			105,900				

Based on strain estimated from crosshead travel of tensile machine.

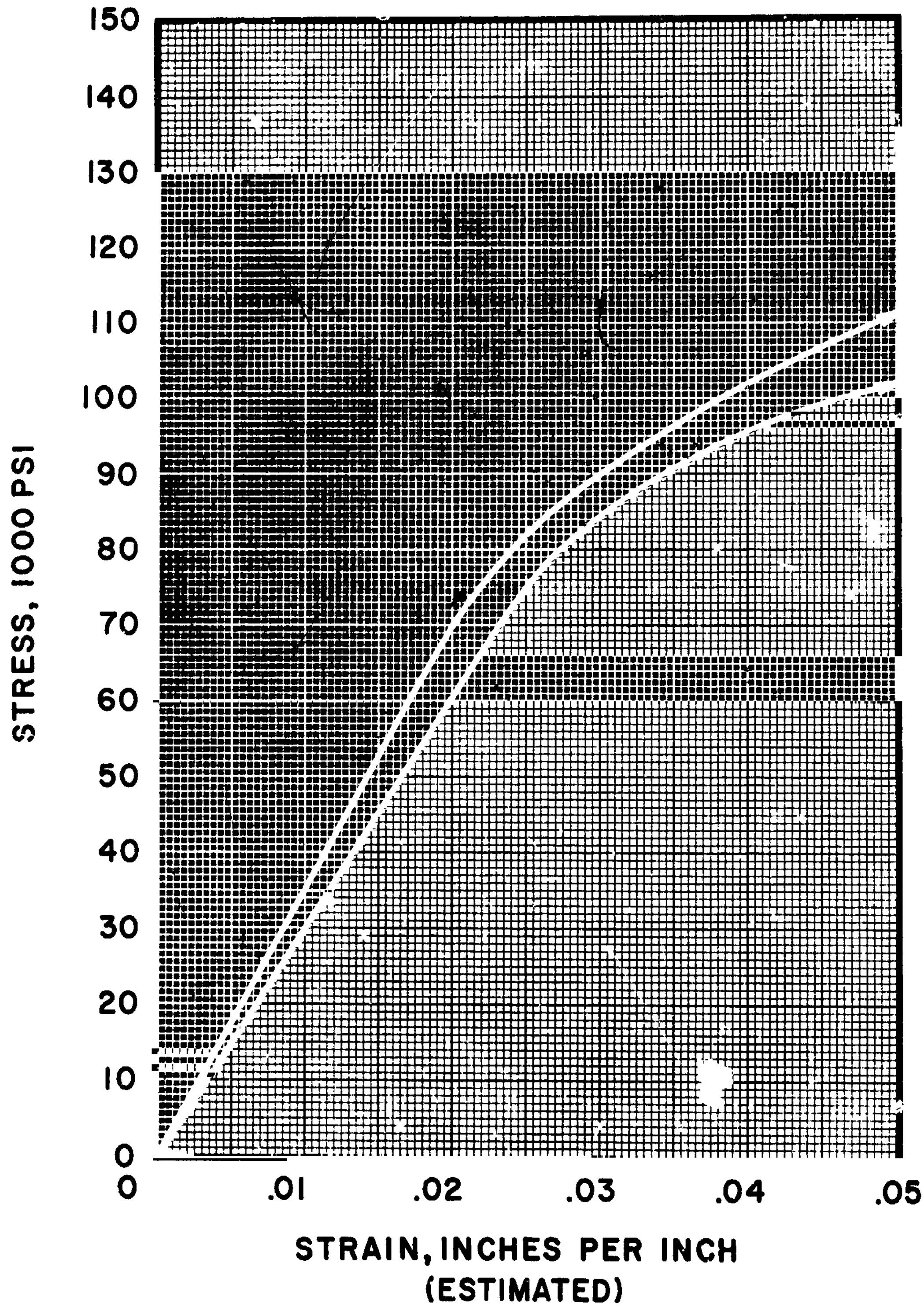


Figure 39

Stainless Steel Type 347-C Casting, Stress-Strain Diagrams (at -423°F)

3. Stainless Steel - AM350 (SCT)

This material, a martensitic stainless steel, reaches very high ultimate (306,700 psi) and yield strengths (295,000 psi) at -423°F. However, the ductility is greatly reduced and the material becomes so notch-sensitive that it is not suitable for cryogenic applications. The data is presented in Tables 6 and 9 and Figure 40.

Table 9

Tensile Properties of AM-350 SCT (850) Stainless Steel at Room Temperature -423°F

Material	Temp. °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%) psi	Elongation in 2", %	Reduction in Area, %	Hardness Rockwell
AM350 SCT (850°F)	RT	Unnotched	199,200	162,100	9.5	35.6	C-47
			200,900	160,100	9.0	31.4	C-45
	RT	Notched	209,600				
			210,600				
			211,900				
			213,100				
	-423	Unnotched	305,900	288,000*	1.0	-0	
			307,500	302,000*	2.0	0.9	
	-423	Notched (K_t= 6.3)	77,500				
			84,300				

*Based on strain estimated from crosshead travel of tensile machine.

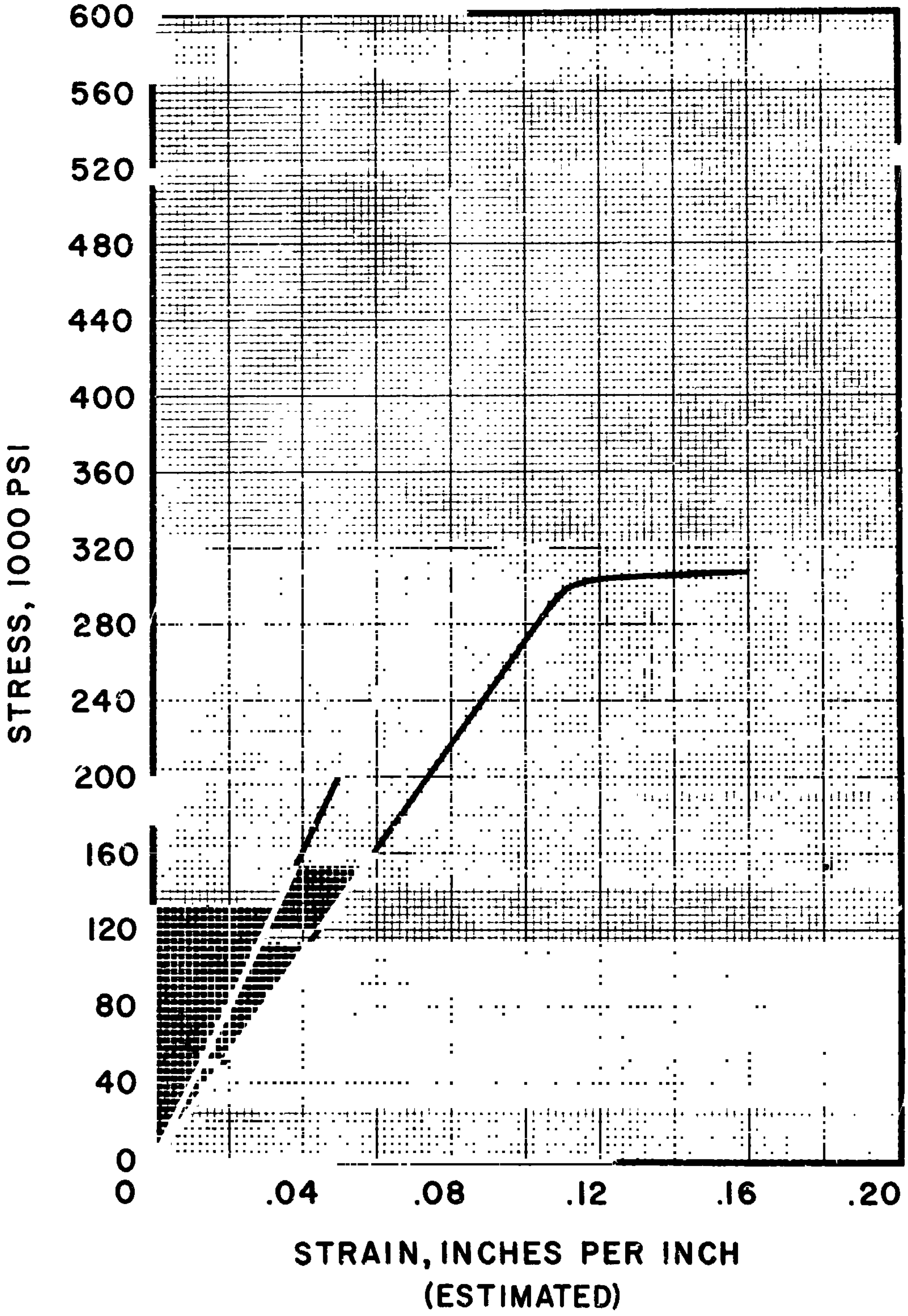


Figure 40

Steel AM-350 SCT Sheet, Stress-Strain Diagram
(at -423°F)

4. Alloy A-286, Age Hardened

This material is ideally suited to cryogenic applications. It is an austenitic type material, precipitation hardened to achieve high room-temperature strength. At -423°F the ultimate (216,600 psi) and yield strengths (141,000 psi) are appreciably increased, above room temperature values (155,650 psi and 106,150 psi respectively) while ductility remains the same as at room temperature (19.8% to 24.5% elongation and 33.9% to 32.2% area reduction). The data obtained from these tests is shown in Tables 6 and 10 and Figure 41. Note the extreme notch toughness of the materials at -423°F. The ratio of notched-ultimate to unnotched yield strength is 1.50, and the ratio of notch-ultimate to unnotched-ultimate is 0.94. Similar results have seen observed by other investigators (Reference 6).

Table 10

Tensile Properties of A-286 Stainless Steel at Room Temperature and -423°F

Material	Temp. °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%) psi	Elongation in 2", %	Reduction in Area, %	Hardness Rockwell
A-286	RT	Unnotched	155,300	107,700	20.5	35.5	C-31
			156,000	104,600	19.0	32.2	C-31
	RT	Notched	150,600				
			151,900				
			154,600				
			154,600				
	-423	Unnotched	216,000	143,000*	26.5	28.9	
			217,200	139,000*	22.5	35.4	
	-423	Notched (K_t = 6.3)	185,400				
			219,600				

*Based on strain estimated from crosshead travel of tensile machine

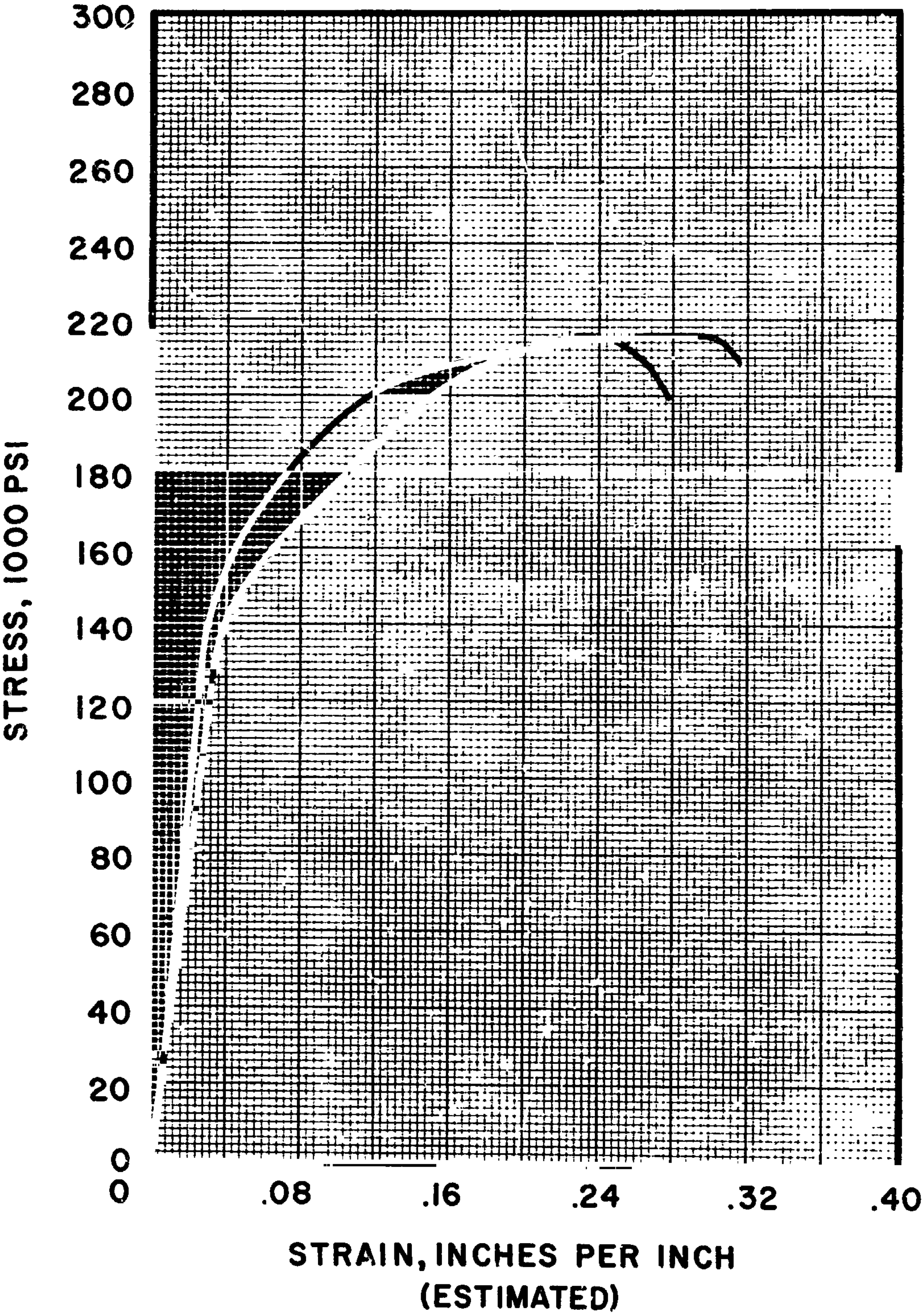


Figure 41

Steel A-286 Sheet, Stress-Strain Diagrams (at -423°F)

5. 18% - Nickel-Maraging Steel (250)

This material represents a series of alloys which have only recently come into general use. Longitudinal and transverse notched and unnotched flat specimens, one-half size, were tested. Although the elongation at -423°F is low, ranging from 2.0 to 4.0%, (see Tables 6 and 11, and Figure 42) the yield and ultimate strengths are very high (that is in the range of 350,000 to 360,000 psi) and the notch toughness appears acceptable. However, it should be noted that at -423°F the ratio of notched ultimate to unnotched yield strength is less than unity (approximately 0.95). Vacuum-melted material, tested transverse to the rolling direction, exhibited significantly higher ultimate and yield strengths than air-melted material, although these properties in the longitudinal direction were essentially equal.

Table 11

Tensile Properties of 18% Ni (250) Maraging Steel at -423°F

Material	Series	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%), psi	Elongation in 1 in. %
Sheet (0.09 in.)	"V"	Unnotched (long)	350,000	345,000	2.0
			362,000	350,000	2.5
R-3 Size Specimens		Notched (long (K_t = 6.3)	312,000		
			325,000		
			330,000		
	"V"	Unnotched (Transv.)	362,000	347,000	3.0
			368,000	354,000	2.5
		Notched (Transv.) (K_t = 6.3)	307,000		
			328,000		
			349,000		
	"A"	Unnotched (long)	329,000		3.0
			356,000	344,000	3.0
		Notched (long) (K_t = 6.3)	294,000		
			329,000		
			347,000		
	"A"	Unnotched (Transv.)	330,000	323,000	4.0
			360,000	355,000	3.0
		Notched (Transv.) (K_t = 6.3)	303,000		
			323,000		
			337,000		
Bolts	Unpeened		302,000		
			330,000		
			373,000		
	Peened		337,000		
			394,000		
			409,000		

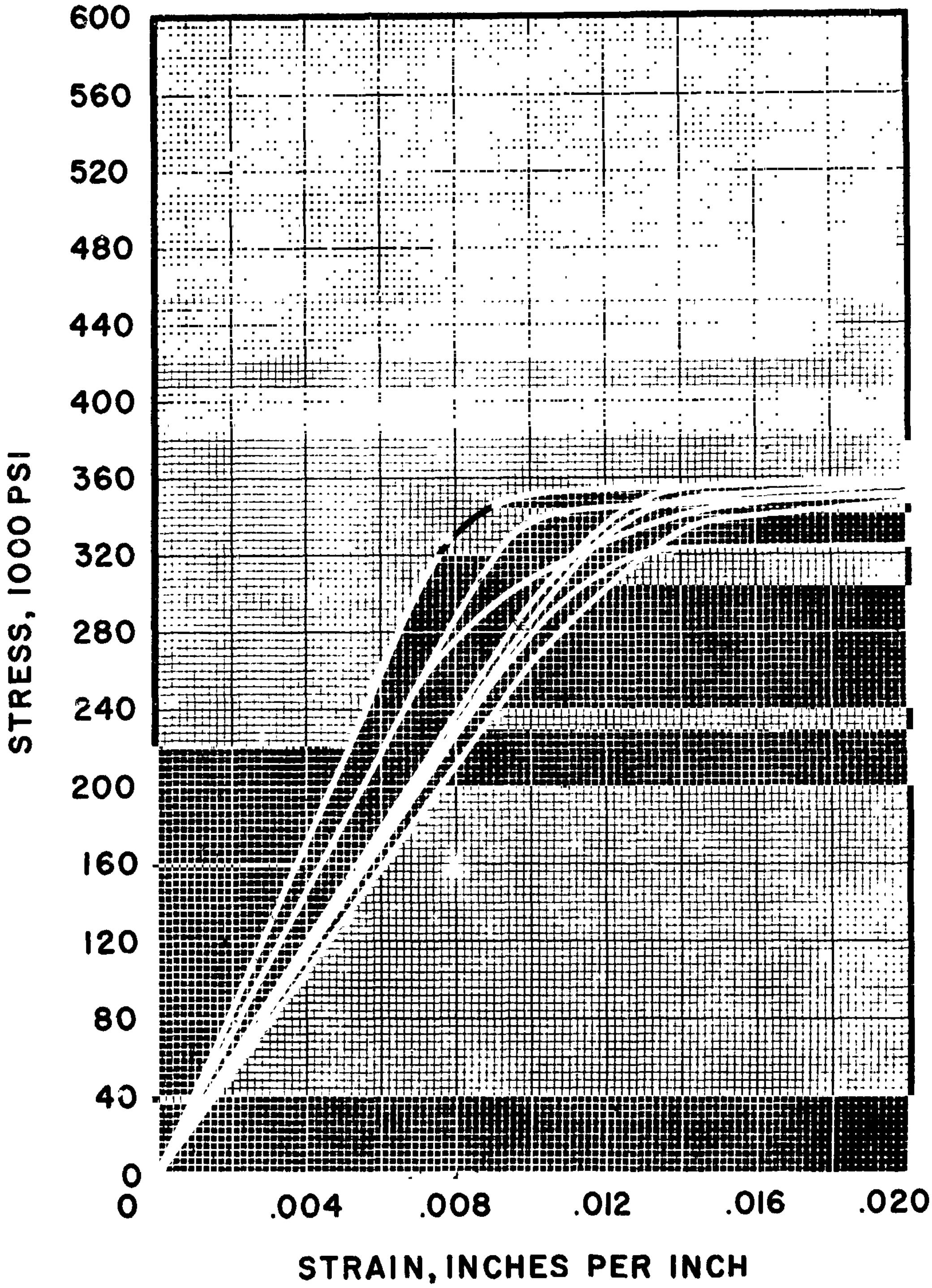


Figure 42

Maraging Steel 18% Nickel (250), Stress-Strain Diagram (·t -423°F)

C. NICKEL-BASE ALLOYS

Nickel-base alloys, although normally used for high temperature applications, are, as a class, also well-suited for cryogenic use. They have good notch toughness and retain their room temperature ductility, while increasing in both tensile and yield strengths. All three of the alloys reported here follow this pattern.

The chemical composition of these alloys obtained by sample analysis as compared with the specification requirements are shown in Table 12. Average tensile properties are shown in Table 13.

Table 12

Chemical Analysis of the Nickel Base Alloys

Material Designation			Ni	C	Cr	Fe	S	Si	Cu	Mn	Mo	Co	P	Ti	Al	Others	H_2 ppm	O_2 ppm	N_2 ppm
Hastelloy C	Specification	Min.	Bal.	-	14.50	4.00	-	-		-	15.00	-	-			3.00 W			
				0.08	16.50	7.00	0.03	1.00		1.00	17.00	2.00	0.04			4.50 W			
																C.35V			
	Specimen Analysis		Bal.	0.05	15.75	5.46	0.012	0.63		0.55	15.78	1.44	0.008			4.50E 0.26V	3	280	120
Inconel X-750	Specification Limit	Min.	70.00	-	14.00	5.00	-	-	-	-		-	-	2.25	0.40	0.70 Nb			
		Max.	-	0.08	17.00	9.00	0.01	0.50	0.50	1.00		1.00	-	2.75	1.00	1.20 Nb			
	Specimen Analysis		73.44	0.04	14.98	6.64	0.007	0.34	0.05	0.54	-	1.00	-	2.45	(.1	0.82 Nb+Ta 1.1	83	1	3
Inconel 713-c	Specification Limit	Min.	Bal.	0.08	12.00	-	-	-	-	-	3.80	-				0.005 B			
														0.50	5.50	1.80 Nb+Ta			
		Max.		0.20	14.00	2.50	0.015	0.50	0.50	0.25	5.20	1.0				0.05 Zr			
																0.015 B			
														1.00	6.50	2.80 Nb+Ta			
																0.15 Zr			
	Specimen Analysis		Bal.	0.13	12.86	0.85	0.007	0.16	0.03	0.02	4.51	0.73	0.73	6.22		2.31 Nb+Ta 0.140 Zr 0.010 B			

Table 13

Average Tensile Properties of Nickel Base Alloys

Alloy	Temp. °F	Ultimate Strength psi	Notch Ultimate Strength, psi	Yield Strength (0.2%) psi	Elongation in 2 in. %	Reduction in Area, %	Notched to Unnotched Ratios N-Ult/Un-Ult	N-Ult/Un-Y.S.	Number of Tests
Hastelloy C	RT	118,900	99,700(K_t=6.3)	59,250	46.3	57.0	.84	1.68	2U, 4N
	-423	172,150	155,550	110,000*	28.8	35.7	.90	1.41	2 @
Inconel X-750	RT	171,400	163,300(K_t=613)	109,600	26.5	42.5	.95	1.49	2 @
	-423	217,300	189,300	134,000*	24.8	32.2	.87	1.41	2U, 1N
Inconel 713-c (investment cast)	RT	104,800	116,800	99,850	2.0	5.6	1.11	1.17	2U, 4N
	-423	111,750	127,700	108,000*	1.3	4.9	1.14	1.18	2U, 4N

*Based on strain estimated from crosshead travel of tensile machine.

1. Hastelloy C

The annealed condition of this alloy, normally supplied, is suitable for cryogenic applications. The tensile (118,900 psi) and yield strengths (59,250 psi) at room temperatures are in good agreement with the vendor's data (Reference 11) and are considerably increased at liquid hydrogen temperature, with a higher percentage increase in yield strength than in ultimate strength.

This material retains comparatively high ductility (28.8% elongation and 35.7% area reduction) at -423°F despite the high percentage decrease shown in these properties.

With a stress concentration factor of $K_t = 6.3$ an actual increase in the notched-unnotched ratio (0.90) was obtained at liquid hydrogen temperature compared with this ratio (0.84) at room temperature. The tensile properties for this alloy are shown in Tables 13 and 14 and Figure 43.

Table 14

Tensile Properties of Hastelloy C at Room Temperature and -423°F

Material	Temp. °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%), psi	Elongation in 2 in. %	Reduction in Area %	Hardness Rockwell	Ref.
Hastelloy C, mill annealed	RT	Unnotched	118,200	58,700	47.0	72.8	A-60**	1
			119,600	59,800	45.5	41.1	A-60	
		Notched (K_t= 6.3)	94,600					
			97,400					
			97,500					
			109,300					
	-423	Unnotched	167,100	112,000*	28.5	35.8		
			177,200	108,000*	29.0	35.5		
		Notched (K_t= 6.3)	151,900					
			159,200					

*Based on strain estimated from crosshead travel of tensile machine.

**Equivalent to C-20.

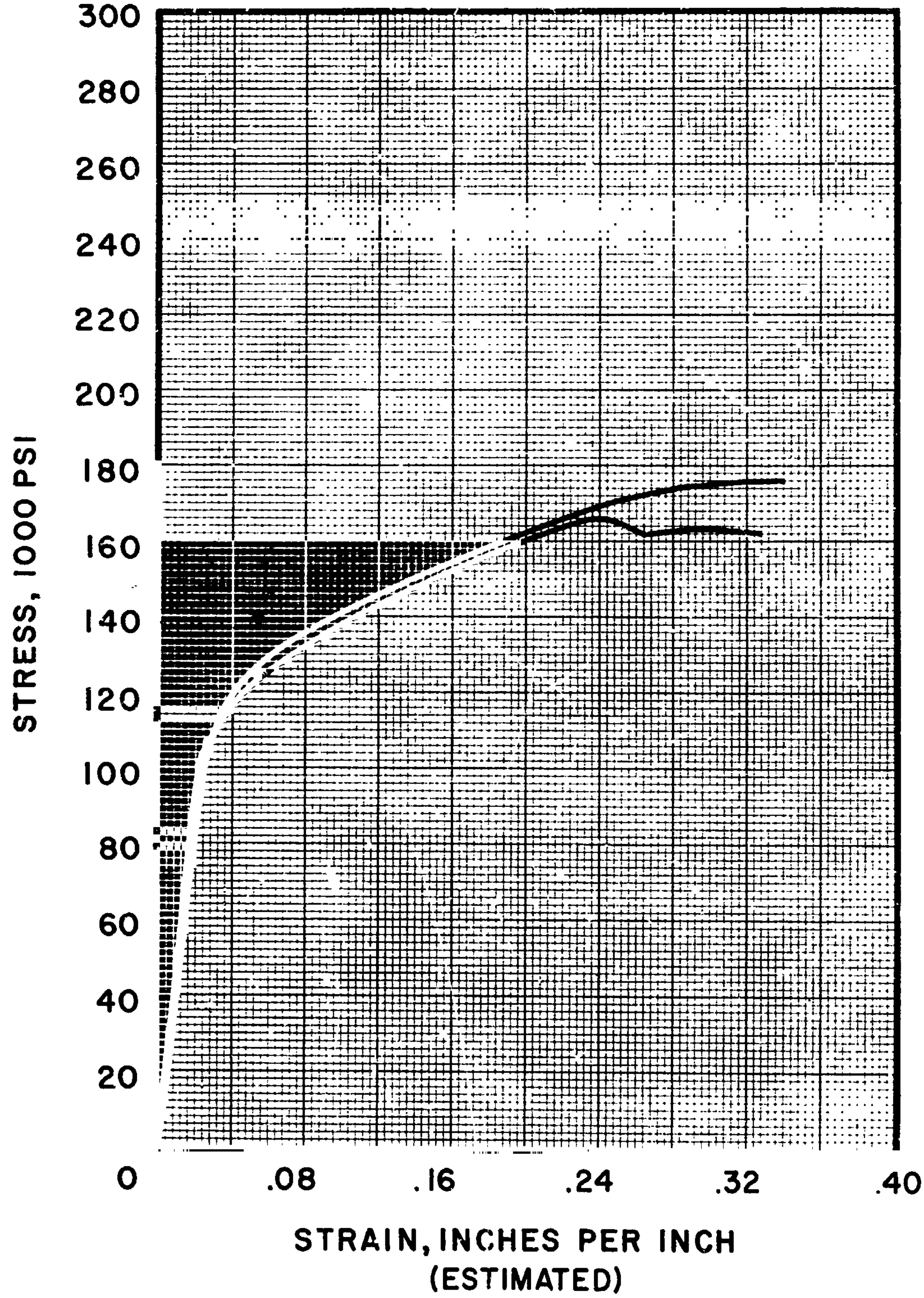


Figure 43

Hastelloy C Sheet, Stress-Strain Diagram
(at -423°F)

2. Inconel X-750

This is a precipitation hardened alloy with high tensile properties at room temperature (171,400 psi tensile, 109,600 psi yield and 26.5% elongation). The percentages of increase in tensile and yield strengths and decrease in ductility from room to liquid hydrogen temperatures are less than those for Hastelloy C. The ratio of notched ultimate to unnotched yield strength remains above unity. The data for this material are presented in Tables 13 and 15 and in Figure 44.

Table 15

Tensile Properties of Inconel X-750 at Room Temperature ~~d -423°F

Material	Temp. °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%)psi	Elongation in 2", %	Reduction in Area, %	Hardness Rockwell	
conel X-750			170,700	109,700	27.0	41.2	C-36	1
50°F, 20 hr.,			172,100	109,500	26.0	43.8	C-34	
		Notched (K_t= 6.3)	159,600					
			160,000					
			160,600					
			173,300					
	-423	Unnotched	214,900	132,000*	23.5	32.4		
			219,700	136,000*	26.0	31.9		
		Notched (K_t= 6.3)	189,300					

Based on strain estimated from crosshead travel of tensile machine.

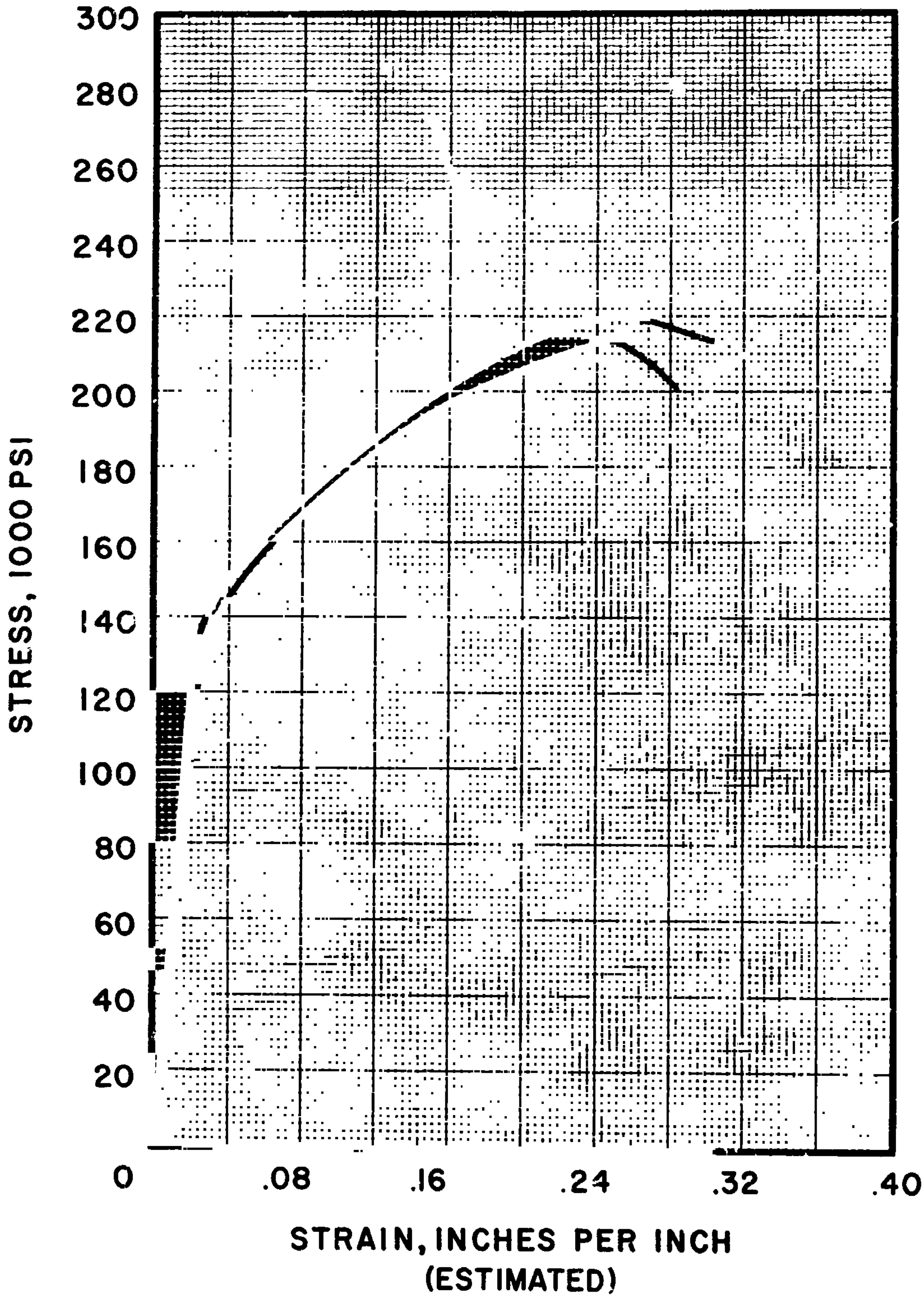


Figure 44

Inconel X-750 Sheet, Stress-Strain Diagram
(at -423°F)

3. Inconel 713-c

A very small increase in tensile and yield strength of this alloy are observed at liquid hydrogen temperature compared to the corresponding room temperature properties (from 104.800 to 111,750 for the tensile strength and from 99,850 to 108,000 psi for yield strength). Note that this alloy is notch-tough even though the ductility at $-423^{\circ}F$ is quite low (1.3% elongation). This was also noted in the case of cast 347-c stainless steel, and is evidently a characteristic of cast face-centered-cubic metals. At $-423^{\circ}F$, Inconel 713-c shows a higher yield strength and notched tensile strength than cast 347, and has about the same ultimate strength and ductility. Inconel 713-c is also noticably stronger at room temperature than cast 347 but much more brittle as shown by lower elongation and area reduction. The test results are shown in Tables 13 and 16 and Figure 45.

Table 16

Tensile Properties of Inconel 713-C (Investment Casting) at Room Temperature and -423°F

Material	Temp. °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%) psi	Elongation in 2", %	Reduction in Area, %	Hardness Rockwell	
Inconel 713 (investment cast)			104.2	98,600	2.0	6.8	C-36	1
			105.4	101,100	2.0	4.3	C-36.5	
		Notched (K_t = 6.3)	112,000					
			115,700					
			118,000					
			121,500					
	-423	Unnotched	107.7	104,000*	1.5	7.1		1
			115.8	113,000*	1.0	2.7		
		Notched (K_t = 6.3)	114,700					
			129,300					
			132,900					
			133,900					

*Based on strain estimated from crosshead travel of tensile machine.

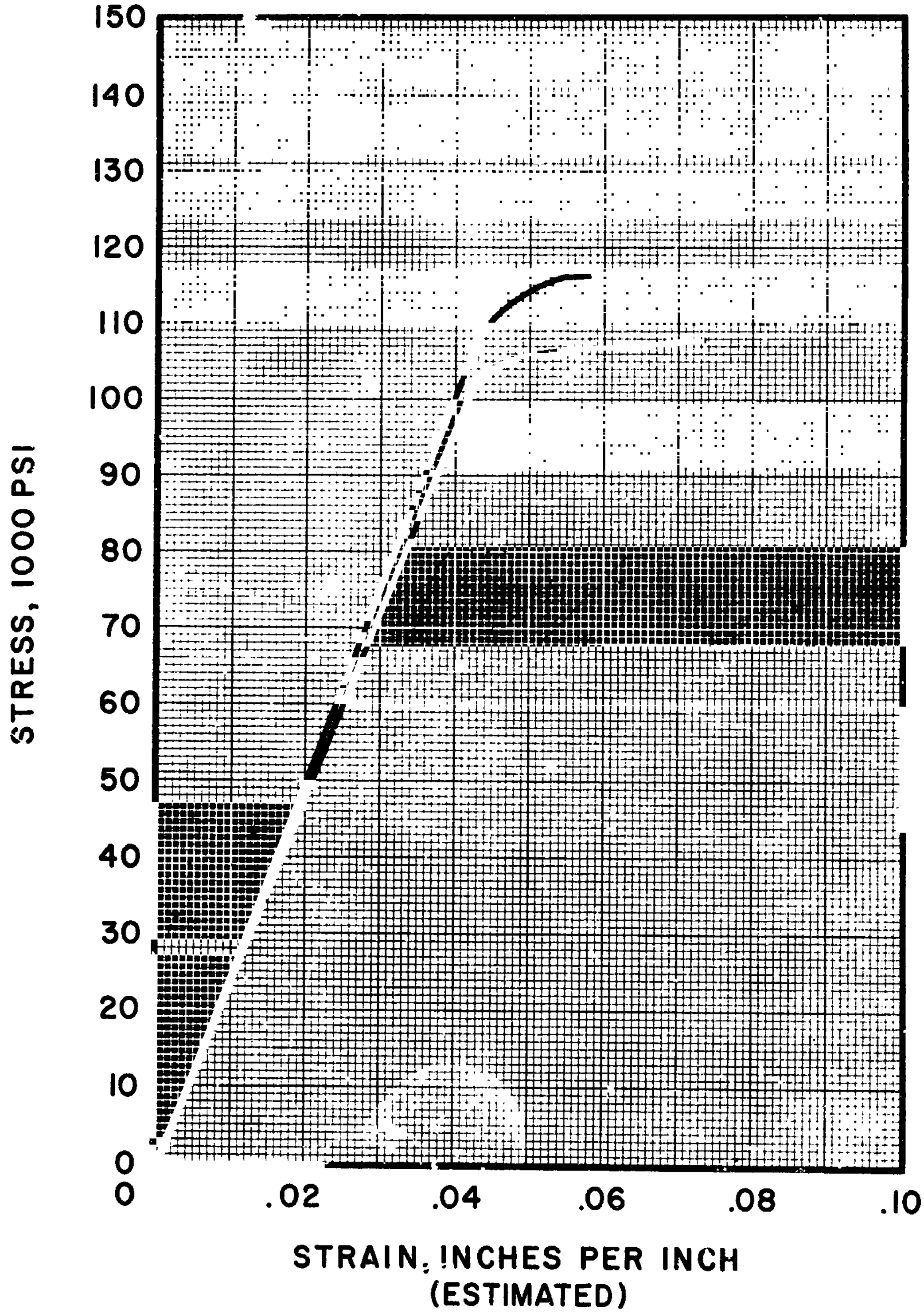


Figure 45

Inconel 713-C Casting, Stress-Strain Diagram
(at $-423^{\circ}F$)

D. ALUMINUM ALLOYS

Table 17 lists the chemical composition of all aluminum alloys as obtained by sample analysis and compared to the corresponding specification requirements.

Table 17

Chemical Analysis of Aluminum Alloys

Alloy Designation			Cu	Si	Fe	Mg	Mn	Cr	Zn	Ti	Others*	H_2 ppm	O_2 ppm	N_2 ppm
A 356-T6	Specification Limit	Min.	-	6.50	-	0.20	-	-	-	-	-			
		Max.	0.20	7.50	0.20	0.40	0.10	-	0.10	0.20	0.15			
	Sample Analysis		0.02	7.34	0.15	0.30	Nil	-	Nil	0.14		-	-	-
2219-T81	Specification Limit	Min.	5.80	-	-	-	0.20	-	-	0.02	-			
		Max.	6.80	0.20	0.30	0.02	0.40	-	0.10	0.10	0.15			
	Sample Analysis		5.5	0.08	0.20	Nil	0.25	-	-	-	0.09V	4	1	17
5456-0	Specification Limit	Min.	-	-		4.70	0.50	0.05	-	-	-			
		Max.	0.10	0.50 (Si+Fe)		5.50	1.00	0.20	0.25	0.20	0.15			
	Sample Analysis		0.08	0.06	0.20	5.29	0.70	0.11	0.04	.085	-	77	1	16
6061-T6	Specification Limit	Min.	0.15	0.40	-	0.80	-	0.15	-	-	-			
		Max.	0.40	0.80	0.70	1.20	0.15	0.35	0.25	0.15	0.15			
Sheet	Sample Analysis		0.24	0.54	0.50	0.90	0.03	0.20	0.03	0.088		30	1	7
Forging	Sample Analysis		0.34	0.61	0.28	0.85	0.05	0.16	0.12	0.06	0.02Ni			
7079-T6	Specification Limit	Min.	0.40	-	-	2.90	0.10	0.10	3.80	-	-			
		Max.	0.80	0.30	0.40	3.70	0.30	0.25	4.80	0.10	0.15			
	Sample Analysis				Not Available									

*Range shown refers to 0.05 max. for each other element and a total of 0.15% max.

1. Alloy A356-T6

The data presented are for castings made for the radiation effects test program. Properties of the nozzle castings are reported in a separate topical report (Reference 9).

The room temperature tensile properties (30,600 psi ultimate; 23,800 psi yield strength and 3.2% elongation) obtained for this alloy are below the typical properties reported by the vendor (39,700 psi ultimate 27,300 psi yield strength, and 5.5% elongation for foil-thickness material) indicating commercial quality casting. Figure 46 shows typical photomicrographs of this casting at 100X and 1000X magnifications. The coarse grain size and needle like silicide particles irregularly distributed together with pronounced inclusion content are co[illegible]butors to the low tensile properties.

The -423°F tensile properties reported (Table 18 and 19 and Figure 47) fall within the region of values which can be extrapolated from data published by NBS, Reference 1. An increase of more than 20% on the tensile strength and 26% on the yield strength from the respective room temperature data was obtained for this alloy at liquid hydrogen temperature. This increase in strength is coupled with a reduction from 3.2% to 2% elongation. The notched-unnotched ratio of ultimate strength is approximately 0.76 indicating that the material is approaching brittle behavior.

Material	Aluminum A356 T6	Lot Number	676604
Form	1/4" Cast Plate	Vendor Code	
Specification	QQA 601	AGC Code	AR
Condition	Heat treated to T6	Vendor	Aluminum Company of America

MICROSTRUCTURE (As received)

MAG: 100X
ETCHANT: Keller's

Area: General structure

Microstructure shows solid solution aluminum matrix with Al-Si eutectic, note coring. Black areas are porosity.

MAG: 1000 X
ETCHANT: Keller's

AREA: General structure

Microstructure shows solid solution aluminum matrix with Al-Si eutectic phase.

Figure 46

Aluminum Alloy A-356-T6 Microstructure

Table 18

Average Tensile Properties of Aluminum Alloys

Alloy	Temp. °F	Ultimate Strength, psi	Notch Ultimate Strength, psi	Yield Strength (0.2%), psi	Elongation in 2 in., %	Reduction in Area, %	Notched to Unnotched Ratios N-Ult/Un-Ult	Notched to Unnotched Ratios N-Ult/Un-Y.S.	Number of Tests
A-356-T6 Cast	RT	30,600	29,200(K_t=6.3)	23,800	3..	2.4	0.95	1.23	4
(0.125" Specimen)	-423	48,100	36,350(K_t=6.3)	42,000	2.0	1.8	0.76	0.87	2
2219-T81	RT	64,100	61,000(K_t=6.3)	49.800	8.5	20.5	0.95	1.22	1U, 4N
(0.125" Specimen)	-423	94,600	70,100(K_t=6.3	70,000*	13.0	25.6	0.74	1.00	2
5456-0	RT	50,900	48,100(K_t=6.3)	26,500	16.8	26.1	0.94	1.8	2U, 4N
(0.125" Specimen	-423	85,100	44,500	30,500*	24.8	25.4	0.52	1.46	2
6061-T6, Plate	RT	44,950	44,000(K_t=6.3)	41,900	11.5	33.7	0.98	1.05	2U, 4N
(0.125" Specimen)	-423	71,950	61,000	52,500*	23.8	33.7	0.86	1.16	2
forged ring	RT	44,800	63,000(K_t=8.0)	40,600	19.0	50.7	1.40	1.55	4
(R-3 Specimen)	-100	50,125	67,200	43,800	19.0	50.3	1.32	1.53	4
	-320	63,400	78,700	46,400	24,0	37.1	1.24	1.70	4
	-423	66,400	81,200	52,900	23.1	35.3	1.22	1.53	4
7079-T6 forged ring	RT	74,300	--	65,000	6.3	20.5	--	--	2
welded & re-heat	-100	74,450	--	66,100	4.5	17.5	--	--	4
treated(0.375" dia.	-300	78,370	--	73,400	1.1	4.8	--	--	4
spec.)									
1/4" base metal	-100	80,600	82,600(K_t=6)	69,300	9.5	--	1.02	1.19	1
plate	-300	90,100	82,400	77,200	6.0	--	0.91	1.07	2
	-423	97,750	79,195	--	5.0	--	0.81	--	1U, 2N
1/4" plate welded	RT	68,060	67,900(K_t=6)	59,775	3.9	--	0.99	1.13	8U, 5N
& re-heat treated	-100	72,500	67,940	63,850	4.0	--	0.94	1.06	2U, 7N
	-300	76,000	64,740	69,150	2.2	--	0.85	0.94	3U, 7N
	-423	78,460	59,300	--	2.7	--	0.76	--	3U, 9N
Rejectable quality weldments									
0.1875" sheet,	RT	49,000	48,000(K_t=6)	38,700	1.5	--	0.98	...24	1
as welded	-100	41,300	43,700	41,300	2.0	--	1.06	...06	1
	-300	49,100	44,700	48,200	3.0	--	0.91	0.93	1
	-423	52,400	36,500	--	2.0	--	0.70	--	1U, 2N
0.1875" sheet,	RT	48,400	53,000(K_t=6)	45,800	1.0	--	1.09	1.15	1
welded & aged	-100	62,800	67,800	51,200	5.0	--	0.62	0.76	1
	-300	67,300	41,500	54,700	3.0	--	0.62	0.76	1
	-423	--	34,625	--	--	--	--	--	1

*Based on strain estimated from head-travel of tensile machine.

Table 19

Tensile Properties of Cast Aluminum Alloy A-356-T6
at Room Temperatures and -423 °F

Temp. °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%), psi	Elongation in 2 in. %	Reduction in Area %
RT	Unnotched	28,300	25,300	4.5	2.4
		29,500	20,400	3.0	3.4
		31,300	-	2.5	1.2
		33,100	25,600	3.0	2.6
	Notched (K_t=6.3)	28,600	-	-	-
		28,700	-	-	-
		29,700	-	-	-
		29,700	-	-	-
-423	Unnotched	47,900	43,000*	2.5	2.22
		48,300	41,000*	1.5	1.3
-423	Notched (K_t=6.3)	36,700	-	-	-
		36,000	-	-	-

*Based on strain estimated from crosshead travel of tensile machine.

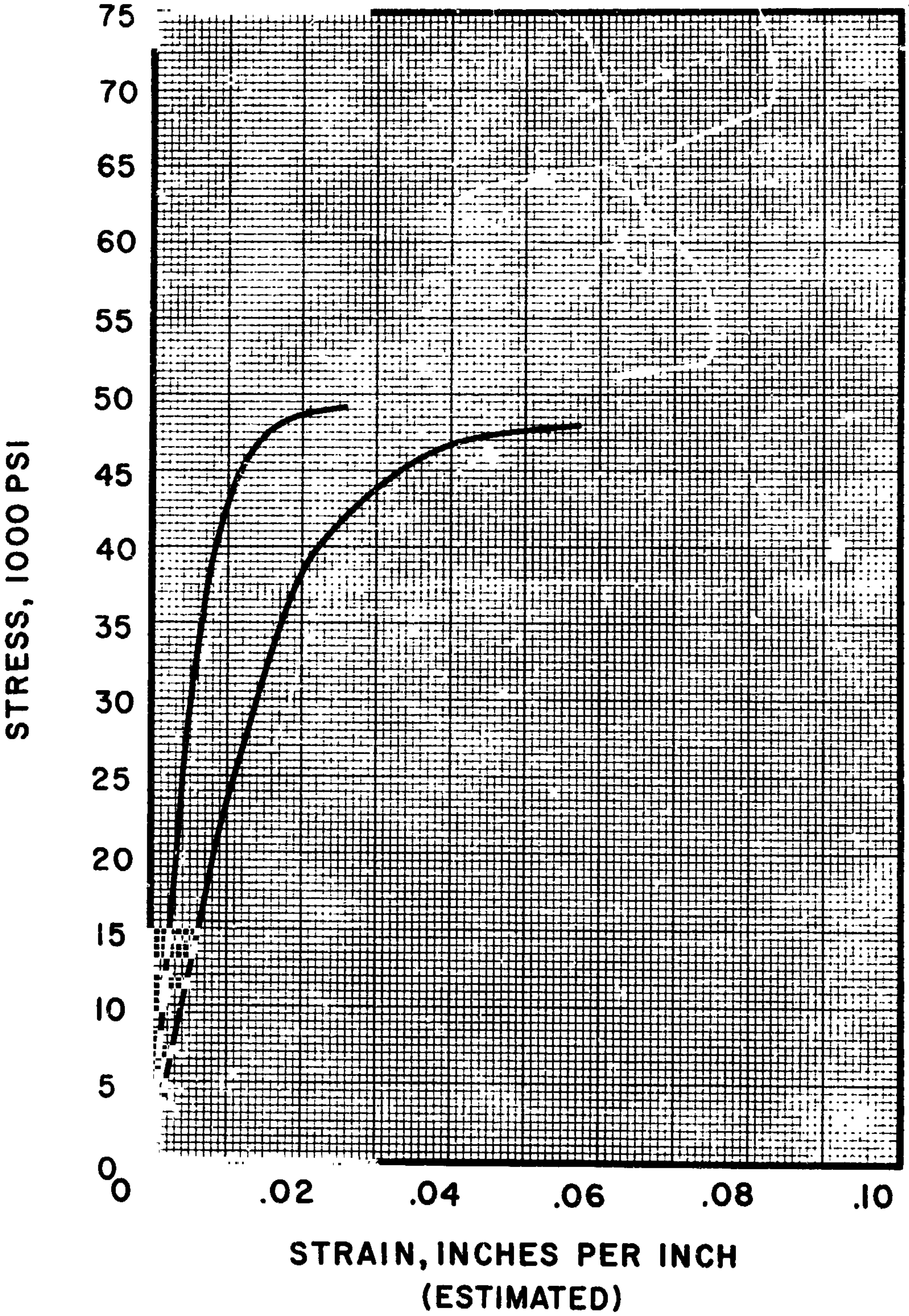


Figure 47

Aluminum Alloy A-356-T6, Stress-Strain Diagram (at -423°F)

2. Alloy 2219-T81

The tensile properties, at both room temperature (64,100 psi ultimate; 49,800 yield; 8.5 % elongation) and -423°F (94,600 psi ultimate 70,000 psi yield and 13% elongation), Tables 18 and 20 and Figure 48, coincide with information published by other investigators (Reference 3). This material, although developed for elevated temperature applications, has a combination of high strength and ductility at -423°F, which make it a useful candidate for cryogenic applications. The data show an increase in ductility as compared with room temperature data. Other investigators have also reported this trend (see References 2 and 4). The notched-unnotched ratio at -423°F is 0.74, although the notched ultimate strength is still above the unnotched yield strength. ALCOA is currently recommending the use of this material, as well as the 5000-series of aluminum alloys as substitutes or replacements for alloy 6061 in certain cryogenic applications.

Table 20

Tensile Properties of Aluminum Alloy 2219-T81
at Room Temperature and at -423°F

	Temp. °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%), psi	Elongation in 2 in. %	Reduction in Area, %
2219-T81	RT	Unnotched	64,100	49,800	8.5	20.5
	RT	Notched	57,100	-	-	-
			57,900	-	-	-
		(K_t=6.3)	59,500	-	-	-
			69,300	-	-	-
	-423	Unnotched	94,200	70,000*	12.0	25.1
			95,000	70,000*	14.0	26.2
	-423	Notched	70,500	-	-	-
		(K_t=6.3)	69,700	-	-	-

*Based on strain estimated from crosshead travel of tensile machine.

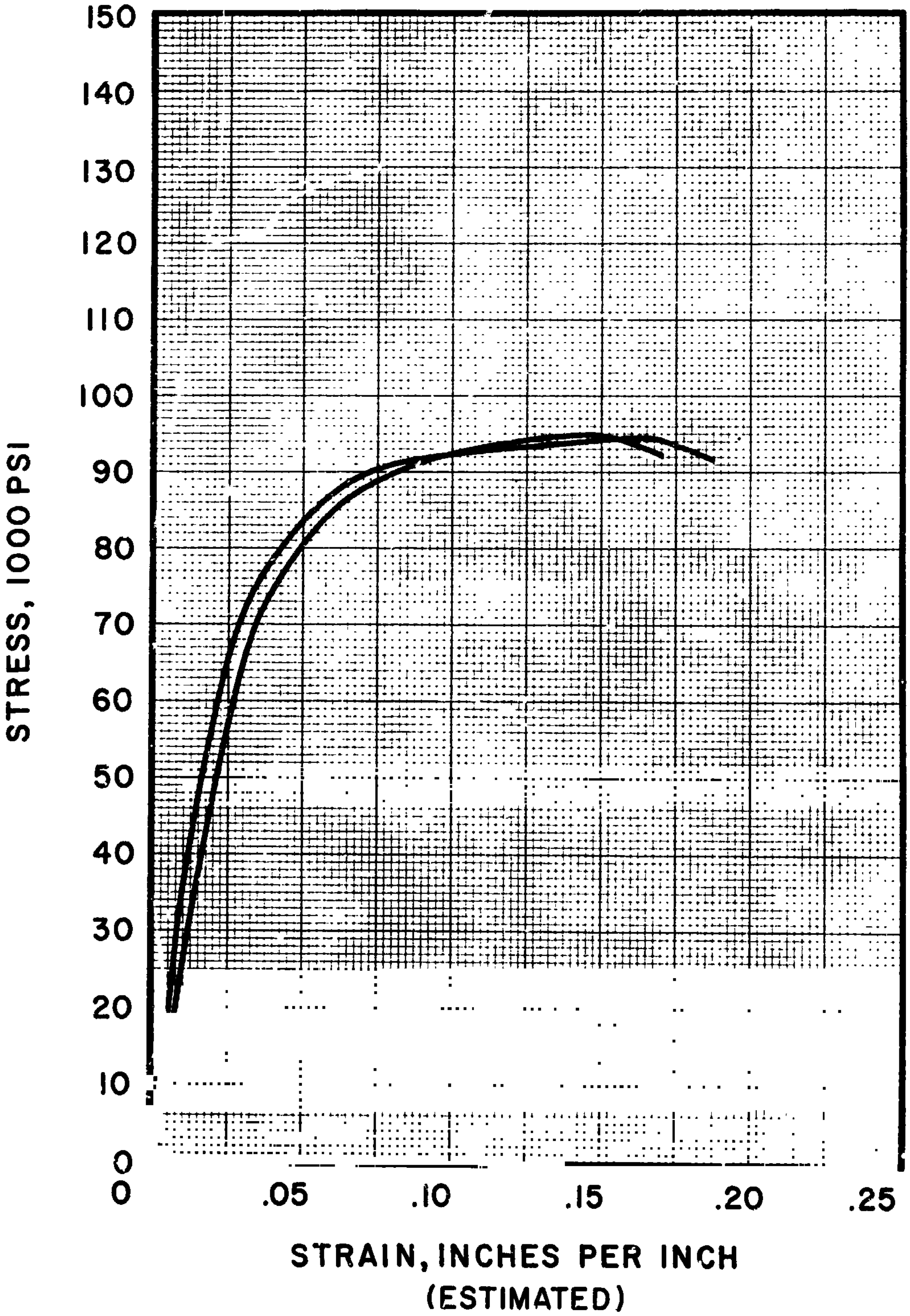


Figure 48

Aluminum Alloy 2219-T81, Stress-Strain Diagram
(at $-423^{\circ}F$)

3. Alloy 5456-0

This alloy is non heat-treatable, and was tested in the an-
iealed condition. Tensile properties (50,900 and 85,100 psi ultimate strength
;6,500 and 30,500 psi yield; 16.8% and 24.8% elongation at room temperature and
423°F respectively, shown in Tables 18 and 21 and Figure 49) are in good agree-
ent with graphic data from Battelle Memorial Institute (Reference 3) showing
ood reproducibility. The notched tensile strength was lower by 15,000 psi than
hat reported by Battelle (44,500 compared with 60,000 psi), although the stress
oncentration factor used was 6.3, while that used by Battelle was 13.5 - 15.
his variation is probably due to the fact that Battelle used 0.505" round
pecimens, while Aerojet tested 0.125" flat specimens. However, the notch ulti-
ate strength obtained from these tests is much higher than the unnotched yield
trength, indicating satisfactory notch toughness. Note the slight (10%) increase
i yield strength and substantial increase (47%) in elongation at -423° as compared
room temperature data. Consequently, this alloy is useful for cryogenic
pplications.

Table 21

Tensile Properties of Aluminum Alloy 5456-o at Room Temperatures and -423°F

	Temp. °F	Specimen Type	Ultimate Strength psi	Yield Strength psi	Elongation in 2 in. %	Reduction of Area, %
5456-0	RT	Unnotched	50,200	25,900*	16.0	26.2
			51,600	27,100*	17.5	26.0
	RT	Notched (K_t=6.3)	47,200	-	-	-
			48,200	-	-	-
			48,500	-	-	-
			48,500	-	-	-
	-423	Unnotched	84,600	29,500*	26.0	28.0
			85,600	31,500*	23.5	22.9
		Notched (K_3=6.3)	44,300	-	-	-
			44,300	-	-	-

*Based on strain estimated from head travel of tensile machine

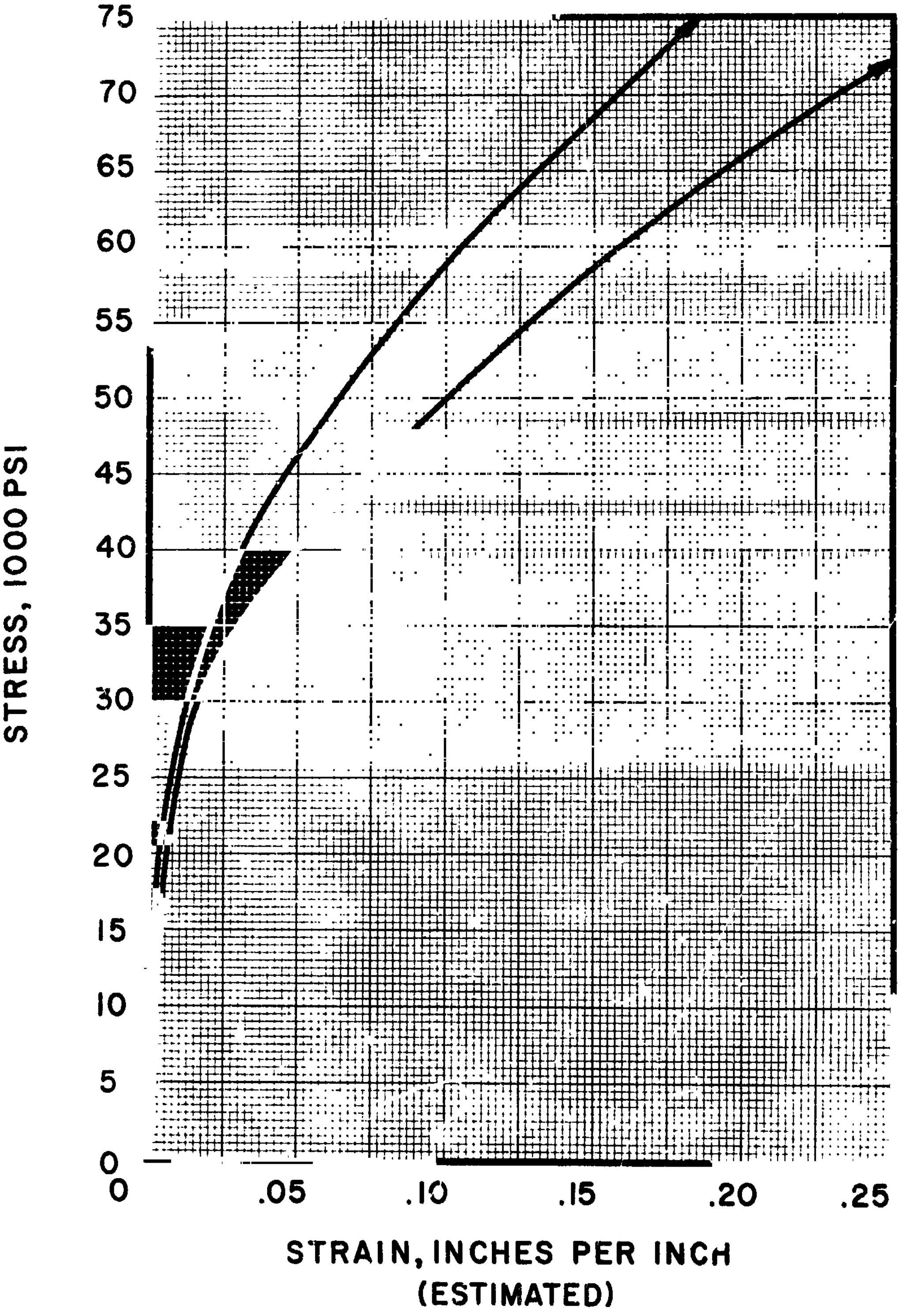


Figure 49

Aluminum Alloy 5456-0, Stress Strain Diagram
(at -423°F)

4. Alloy 6061-T6

The unnotched tensile and yield strength of both plate and forged materials: (44,950 and 44,800 psi RT ultimate; 71,950 and 66,400 psi -423°F ultimate; 41,900 and 40,600 psi RT yield; 52,500 and 52,900 psi -423°F yield) Tables 18, 22, and 23 and Figures 50, 51, 52 and 53 were in close agreement with each other at both room and cryogenic temperatures and closely correspond to the data reported by NBS (Reference 1). The yield and tensile strengths increase approximately 15% and 50%, respectively, when going from room temperature to -423°F. The reduction in area (33.7%) and elongation (11.5%) of the sheet material were appreciably lower than those of forged material (50.7% and 19% respectively) at room temperature. The notch tensile strength at -423°F was appreciably higher for the forged material, but this may have resulted, in part, from differences in the specimen size and configuration. Standard size flat specimen were used for the 1/4-inch plate and R-3 (subsize) type specimens for the forgings. As in the case of the previous aluminum alloys, high ductility and notch toughness make this alloy suitable for use under cryogenic conditions.

Table 22

Tensile Properties of Aluminum Alloy 6061-T6 Plate at Room Temperature and -423°F

	Temp. °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%), psi	Elongation in 2 in. %	Reduction in Area, %
6061-T6	RT	Unnotched	44,800	42,000*	11.0	34.8
		Unnotched	45,100	41,800*	12.0	32.4
	RT	Notched	42,300	-	-	-
			44,100	-	--	-
			44,600	-	-	-
			44,800	-	-	-
	-423	Unnotched	72,300	53,000*	25.0	33.1
		Unnotched	71,600	52,000*	22.5	34.2
		Notched	62,000	-	-	-
		Notched	60,000	-	-	-

*Based on strain estimated from head travel of tensile machine.

Table 23

Tensile Properties of Aluminum Alloy 6061-T6 Forging at Temperatures from -423°F to + 400°F

Temp. °F	Specimen Type	Ultimate Strength psi	Yield Strength (0.2%), psi	Elongation in 1 in. %	Reduction in Area, %
RT	Unnotched	41,400	38,400	19.0	64.4
		43,700	39,500	19.0	55.8
		45,400	41,100	-	34.9
		48,700	43,400	-	47.5
	Notched (K_t = 7 to 8)	62,500			
		63,100			
		63,600			
		64,000			
-100	Unnotched	46,900	44,400	17.0	62.3
		48,400	43,500	18.0	54.9
		51,700	43,000	18.0	38.0
		53,500	44,300	21.0	45.8
	Notched (K_t = 7 to 8)	65,400			
		65,900			
		67,300			
		70,100			
-320	Unnotched	61,800	46,500	-	38.1
		62,800	44,200	-	34.3
		64,300	45,900	24.0	38.2
		64,700	49,100	24.0	37.6
	Notched (K_t = 6 to 8)	77,800			
		78,000			
		78,800			
		80,000			
-423	Unnotched	63,800	-	23.0	37.1
		65,600	51,100	23.0	32.8
		68,100	54,300	-	37.8
		68,200	53,400	-	33.6
	Notched (K_t = 7)	76,700			
		78,400			
		83,600			
		87,200			
+200	Unnotched	45,900	40,800	19.0	44.7
		46,400	41,100	18.0	50.7
		46,500	41,000	19.0	50.9
		47,200	41,700	-	44.7
+400	Unnotched	38,200	35,000	21.0	52.5
		38,300	35,500	-	49.3
		38,400	34,800	24.0	68.6
		38,500	35,500	16.0	50.9

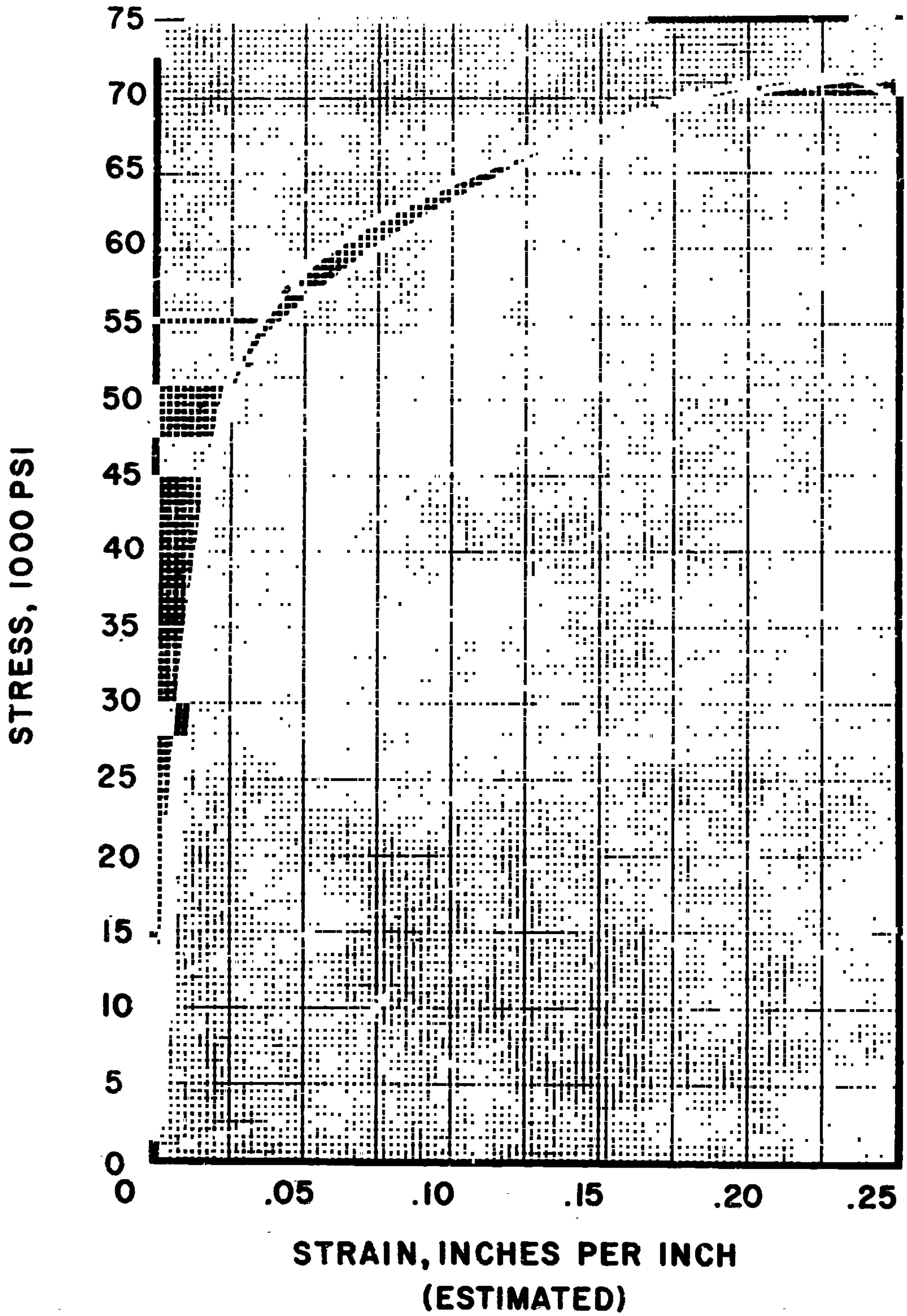


Figure 50

Aluminum Alloy 6061-T6 Sheet Material, Stress Strain Diagram (at -423°F)

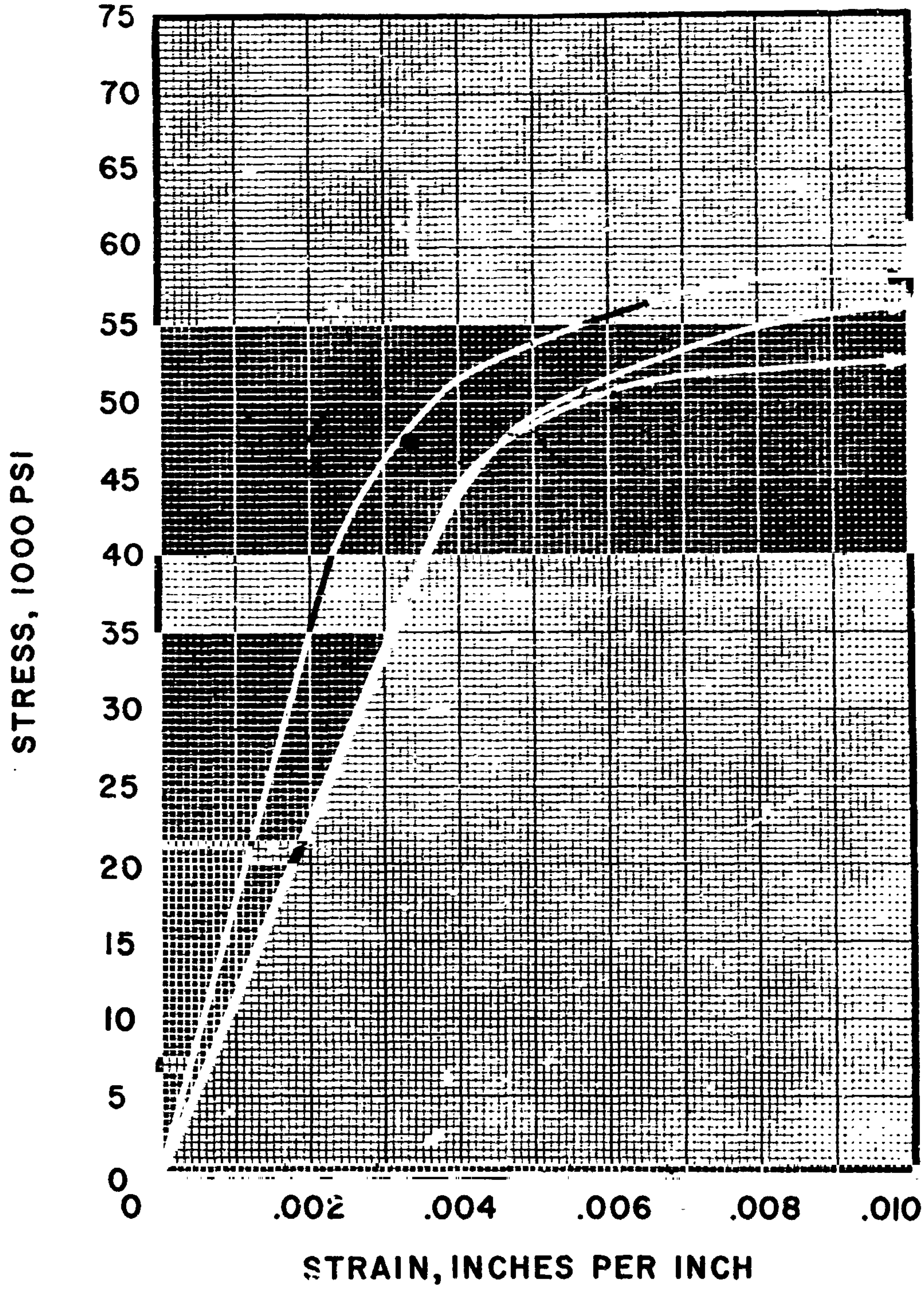


Figure 51

Aluminum Alloy 6061-T6 Forging, Stress Strain Diagram (at -423°F)

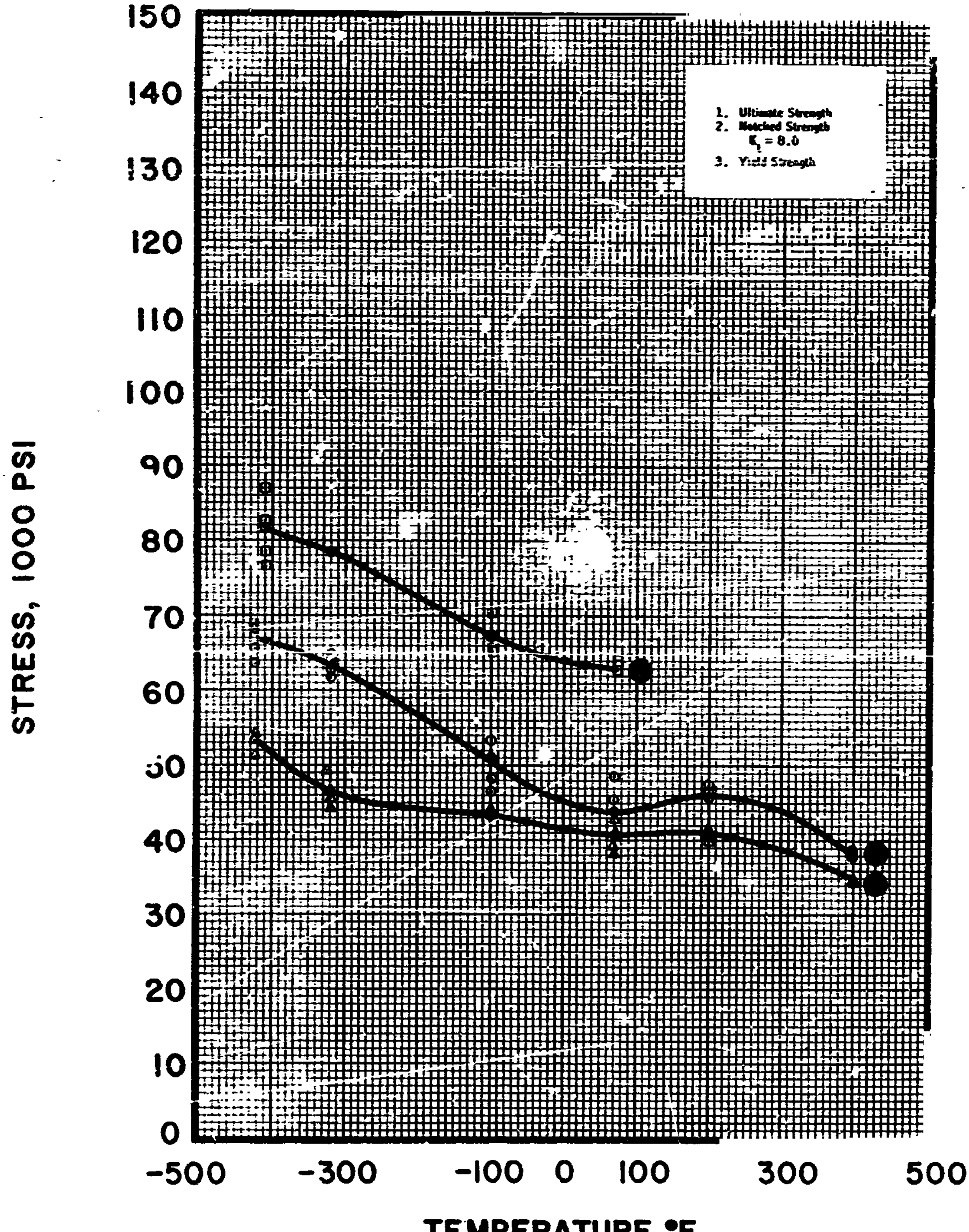


Figure 52

Aluminum Alloy 6061-T6 Forging, Tensile Ultimate, Yield and Notched Strength as a Function of Temperature

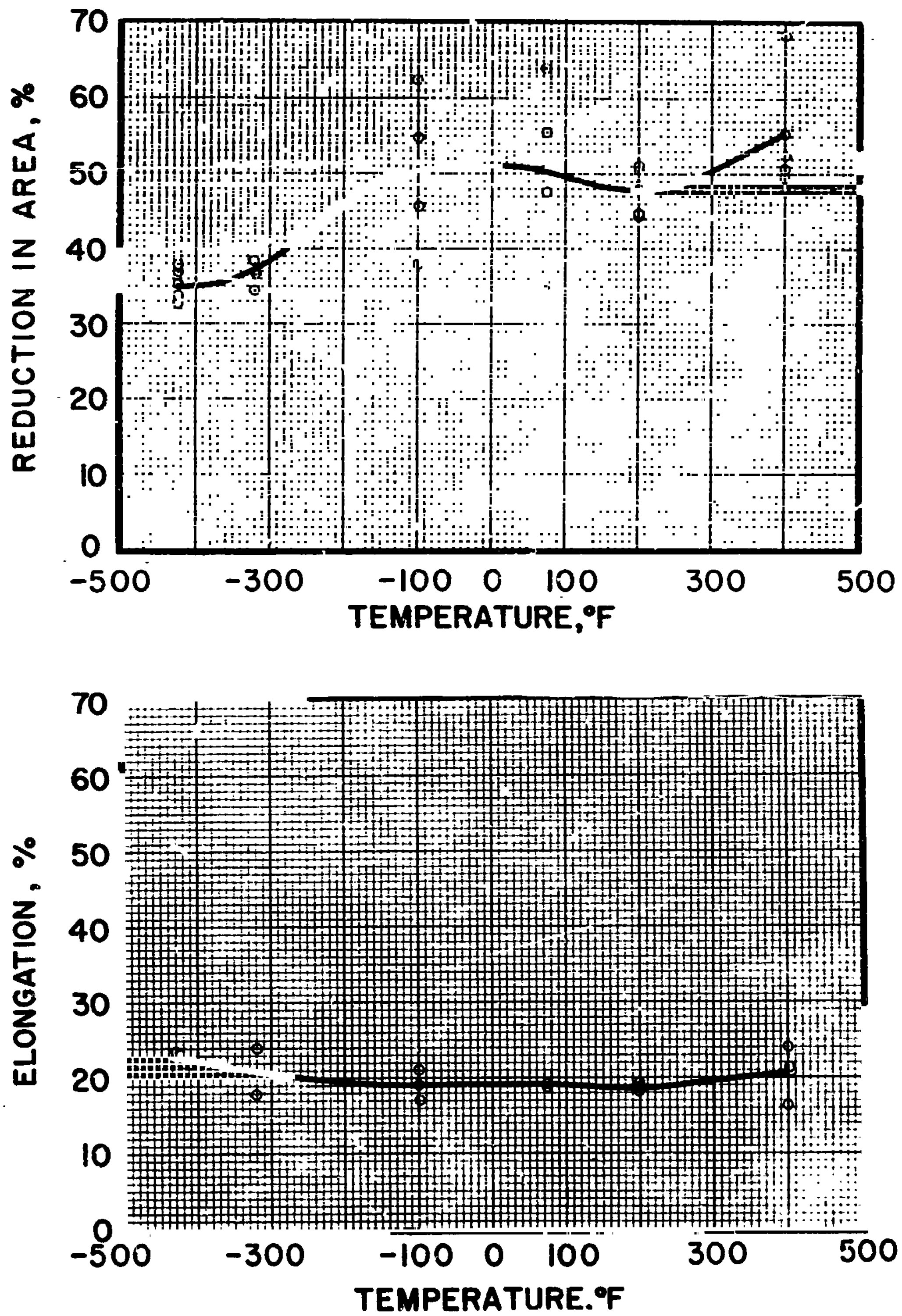


Figure 53

Aluminum Alloy 6061-T6 Forging - Elongation and Area Reduction as a Function of Temperature

5. Alloy 7079-T6

This alloy has seen rather limited use because satisfactory arc welding is difficult. However, its high strength (74,300 psi at room temperature) warrants attention, and a number of fabricators are experimenting with it. Tensile specimens conforming to Figures 3 and 4 were tested for the sheet and plate material. R-1 type specimens were tested for the round bars. In addition to the base material, specimens as-welded, welded and heat treated, and aged after welding were tested. The data from these tests are presented in Tables 18, 24 and 25 and in Figures 54 through 63. The tensile properties for base metal (97,750 psi at -423°F) were lower than those reported by Lewis Research Center for 1/8" sheet, (115,000 psi; Reference 4) and by General Dynamics for 0.080" sheet (112,000 psi), and slightly higher than for 5.0" billet material (94,400 psi; Reference 5). These comparisons indicate that the samples tested had average strength characteristics. The data for the as-welded sheet material (labelled rejectable quality weld) are included for information only. Plate material which was fully heat-treated after welding (solution heat treat, 830°F, 30 min, water quench, +5 days at RT, + 230-250°F, 48 hours) had, as expected, much higher strength and elongation at all temperatures than as-welded material, and between 80 and 92% of the values for parent metal. Welded and heat-treated specimens from forged material exhibited higher strength at all temperatures than did welded plate materials.

The base metal did not appear notch sensitive at temperatures to -300°F, but the welded specimens indicated notch sensitivity below -100°F. The very low ductility of this alloy and the indications of notch sensitivity are significant disadvantages for cryogenic applications.

Table 24

Tensile Properties of Aluminum Alloy 7079-T6 Plate. Base Material and Weldments Heat Treated after Welding at Temperatures -423°F, -300°F, -100°F and Room Temperatures

	Temp. °F	Type	Ultimate psi	Yield Strength psi	Elongation in 2 in. %	Elongation in 1 in. %
Base Metal	-100	U	80,600	69,300	9.5	8.0
		N(K_t=6)	82,600			
	-300	U	89,700	77,100	6.0	5.0
		U	90,600	77,300	6.0	8.0
		N(K_t=6)	78,500			
		N	86,400			
	-423	U	97,750		5.0	
		N(K_t=5.5)	79,460			
		N	78,950			
Welded and heat treated	RT	U	63,100	58,000	3.3	
			65,700	58,500	3.0	
			67,400	58,100	3.0	
			67,600	57,600	4.0	
			68,000	59,100	3.7	
			68,300	58,100	4.3	
			71,700	64,400	3.7	
			72,700	64,400	6.0	
		N(K_t=6.3)	63,600	-	-	
			65,800	-	-	
			66,700	-	-	
			66,800	-	-	
			76,600	-	-	
	-100	WU	75,300	68,800	4.5	8.0
			69,700	58,900	3.5	7.5
		WN(K_t=6)	69,300			
			68,100			
			70,400			
			77,000			
			69,700			
			71,600			
			69,400			
	-300	WU	80,300	68,800	3.0	5.0
			75,600		1.5	1.5
			72,300	69,500	2.0	3.0
		WN(K_t=6)	47,600			
			72,700			
			72,600			
			74,300			
			58,600			
			65,700			
			61,700			
	-423	WU	80,400		4	
			80,500		2	
			74,500		2	
		WN(K_t=5.5)	60,170			
			62,390			
			72,460			
			66,490			
			44,940			
			68,320			
			56,200			
			42,330			
			60,710			

U = unnotched
N = notched
WU = welded unnotched
WN = Welded notched

Table 25

Tensile Properties of Weldments of 7079-T6 Aluminum Alloy, as Welded and Welded-Aged Conditions at -100°F, -300°F and -423°F

	Temp.	Type	Ultimate psi	Yield Strength psi	Elongation In 2 in. %	Elongation in 1 in. %
As welded	RT	WU	39,000	38,700	1.5	-
		WN (K_t=6)	38,000	-	-	-
	-100	WU	41,300	41,300	2.0	7.0
		WN (K_t=6)	43,700			
	-300	WU	49,100	48,200	3.0	4.0
		WN (K_t=6)	44,700			
	-423	WU	52,400		2.0	
		WN (K_t=6)	32,150			
		WN (K_t=6)	40,880			
Aged (only) after welding	RT	WU	48,400	45,800	1.0	-
		WN (K_t=6)	53,000	-	-	-
	-100	WU	62,800	51,200	5.0	10.0
		WN (K_t=6)	67,800			
	-300	WU	67,300	54,700	3.0	5.0
		WN (K_t=6)	41,500			
	-423	WN (K_t=6)	32,830			
		(K_t=6)	36,420			

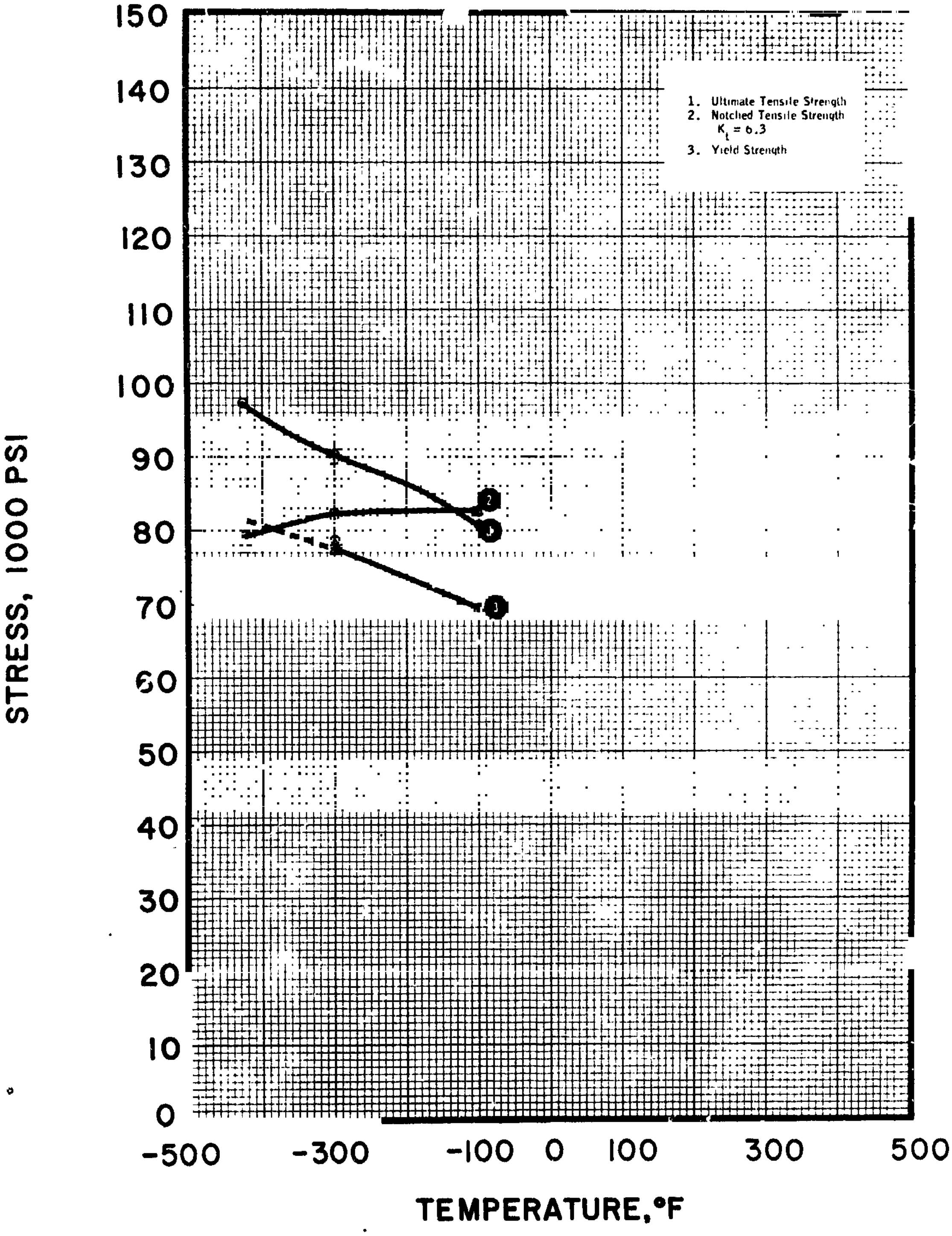


Figure 54

Tensile Ultimate, Yield and Notched Strength as a Function of Temperature

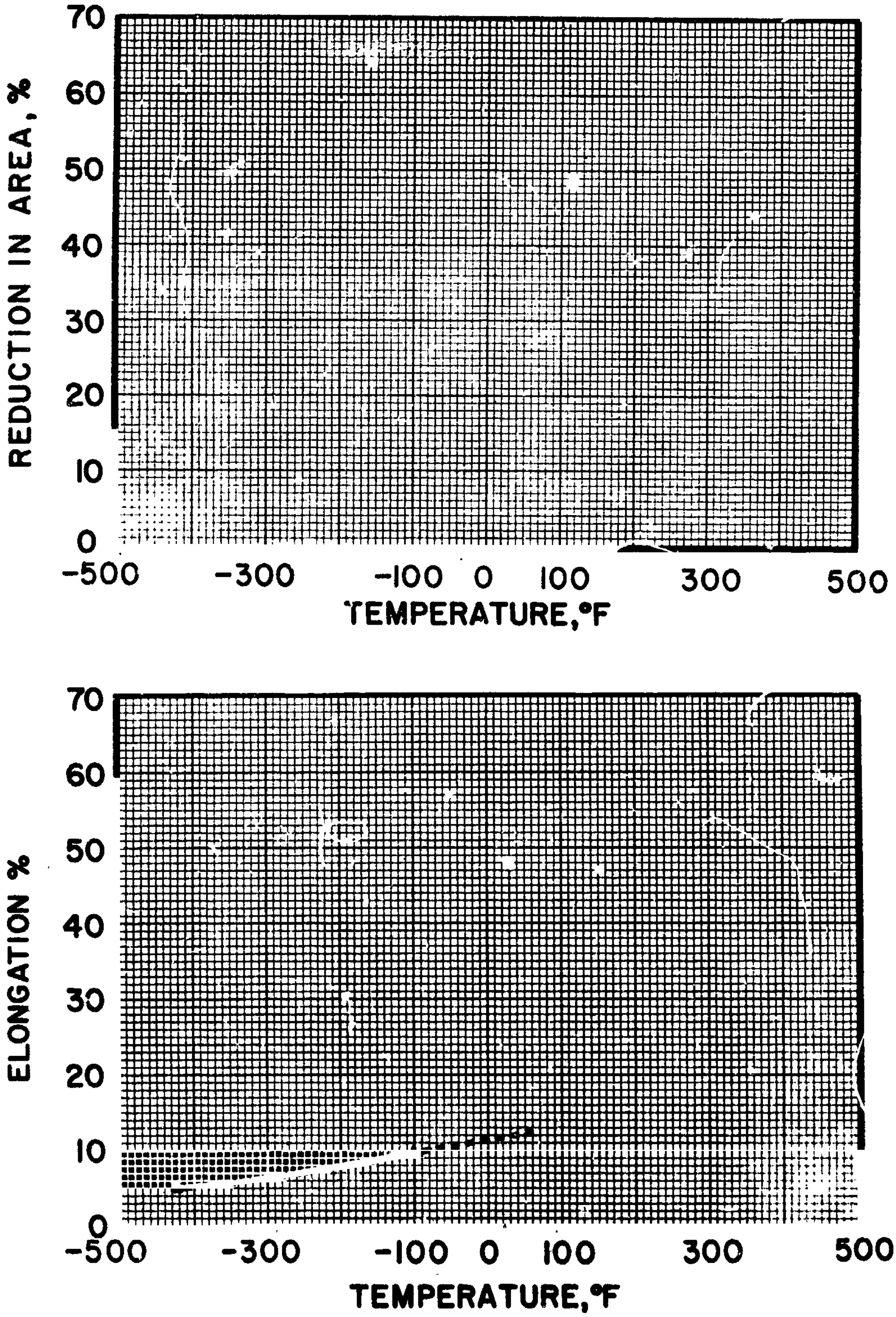


Figure 55

Aluminum Alloy 7079-T6 Plate Material,
Elongation as a Function of Temperature

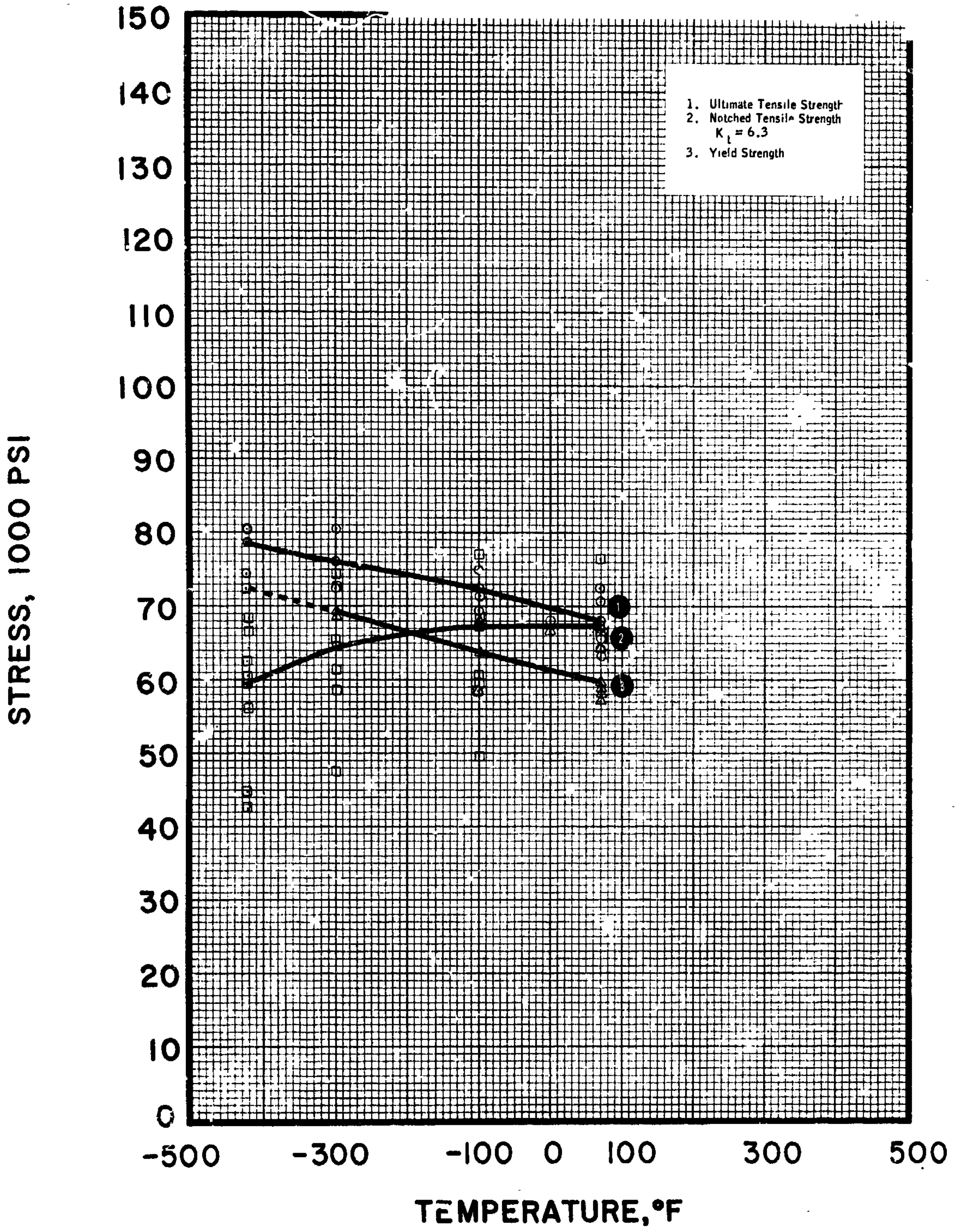
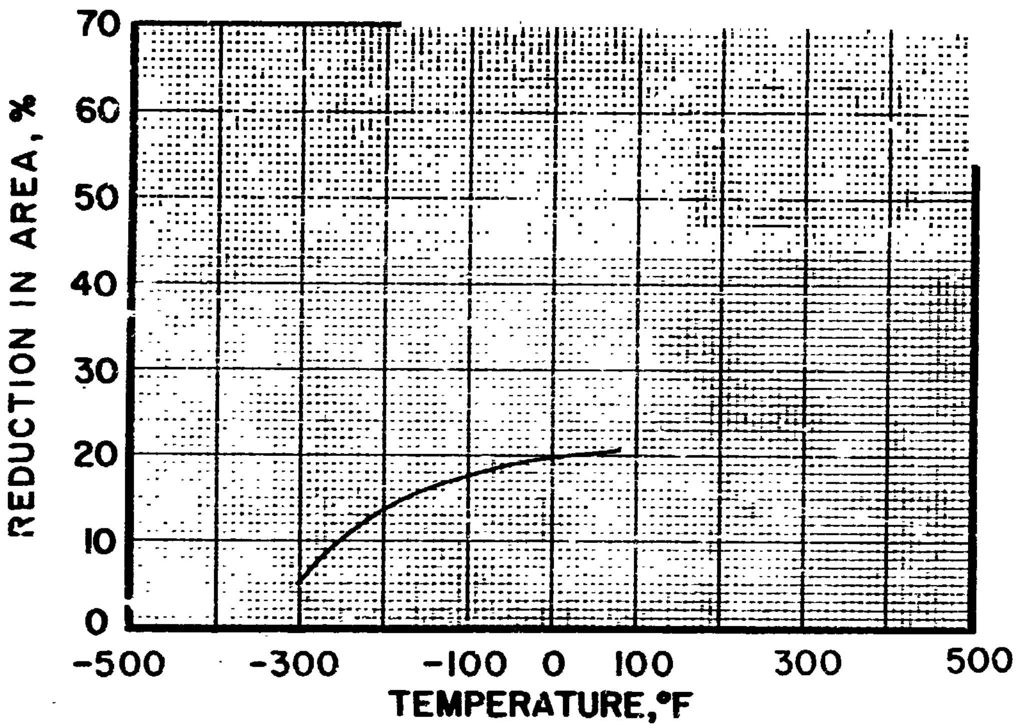


Figure 56

Aluminum Alloy 7079-T6 Plate (Heat Treated After Welding); Tensile Ultimate, Yield and Notched Strength as a Function of Temperature



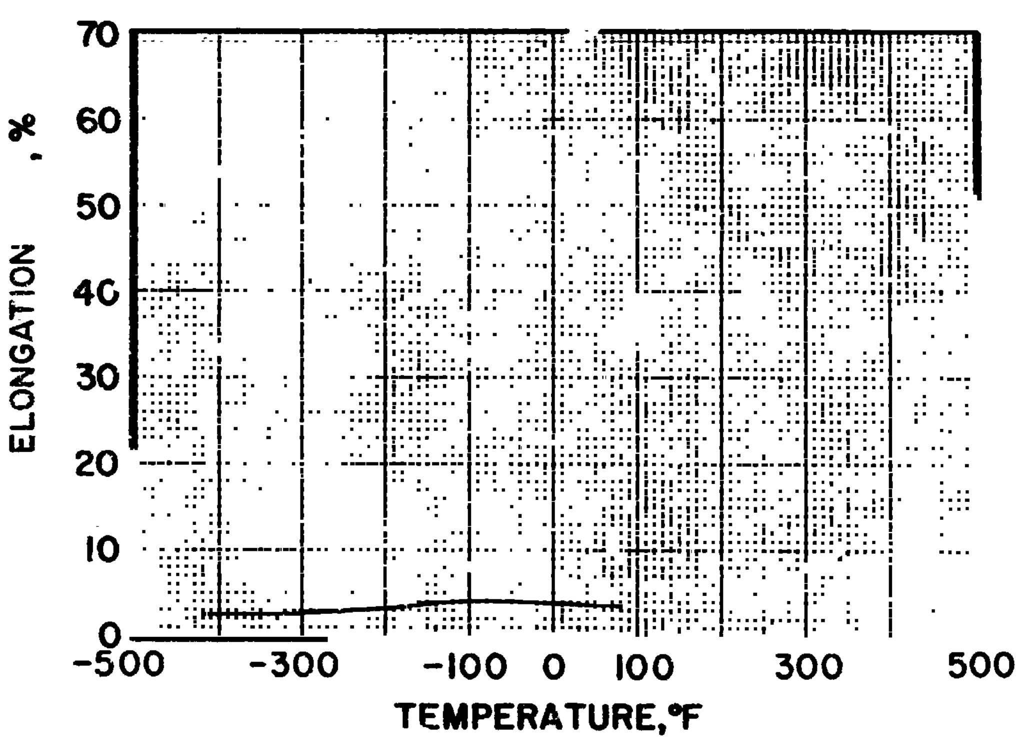


Figure 57

Aluminum Alloy 7079-T6 Plate (Heat Treated After Welding), Elongation and Area Reduction as a Function of Temperature

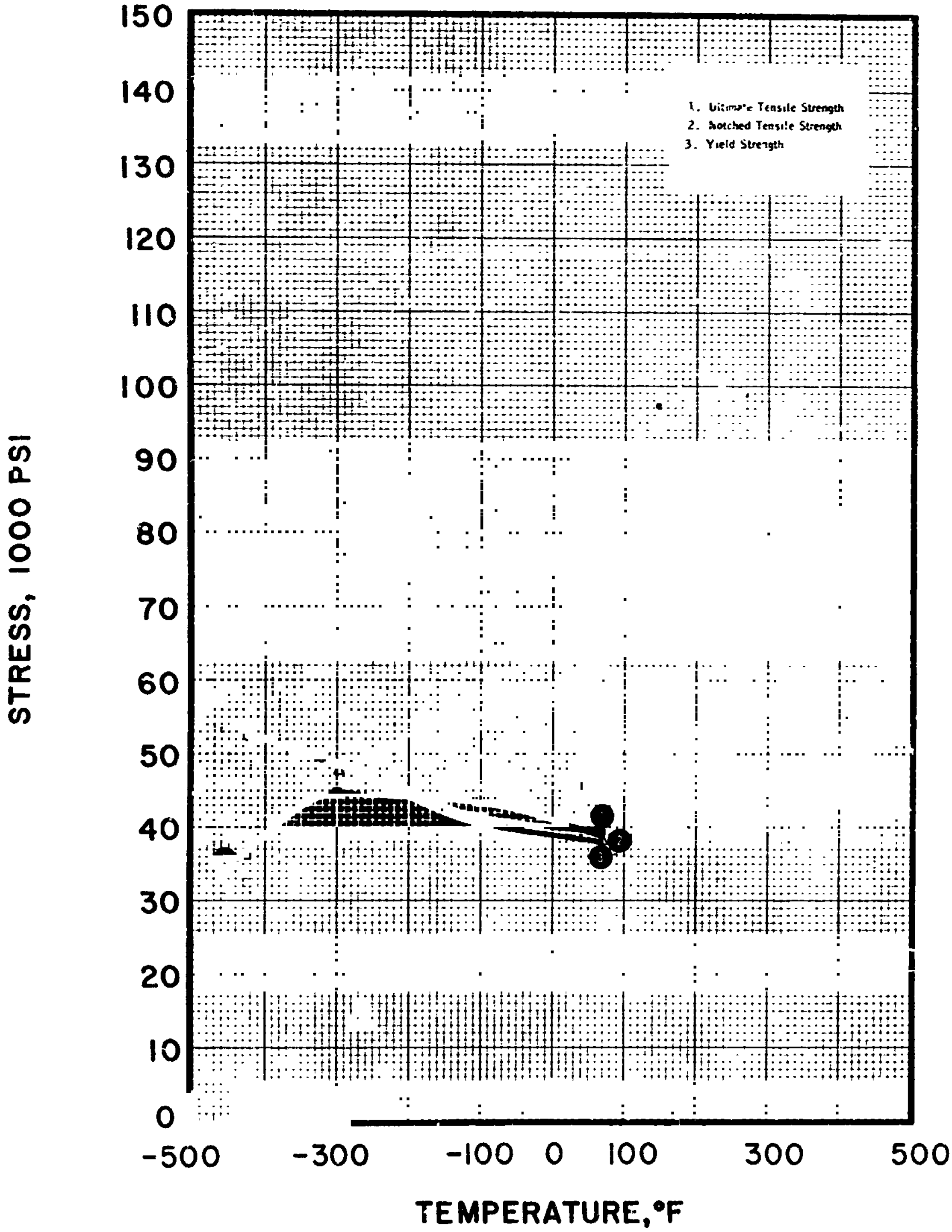


Figure 58

Aluminum Alloy 7079-T6 Sheet as Welded,
Tensile Ultimate, Yield and Notched Strength as a Function of Temperature

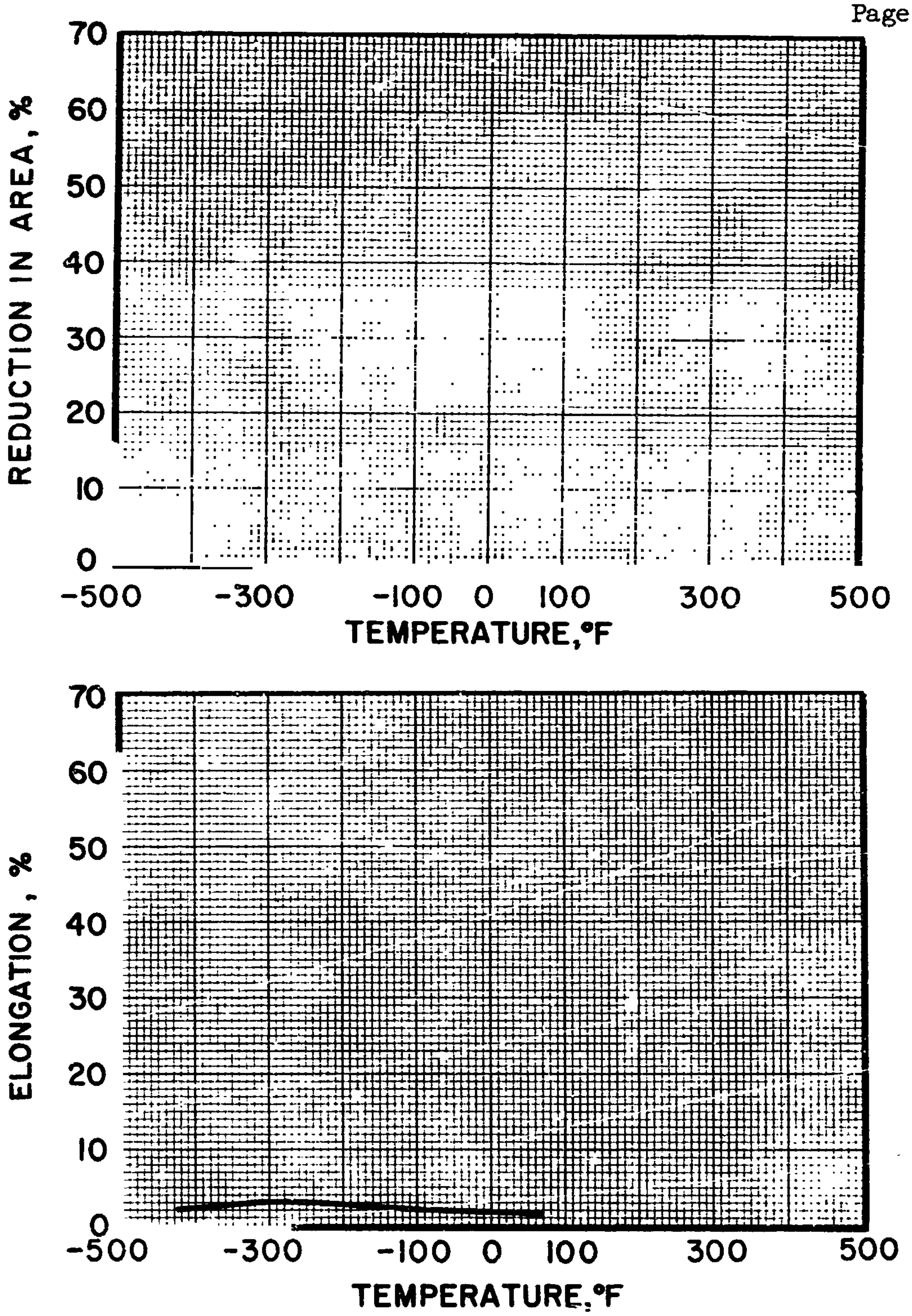


Figure 59

Aluminum Alloy 7079-T6 Sheet as Welded, Elongation as a Function of Temperature

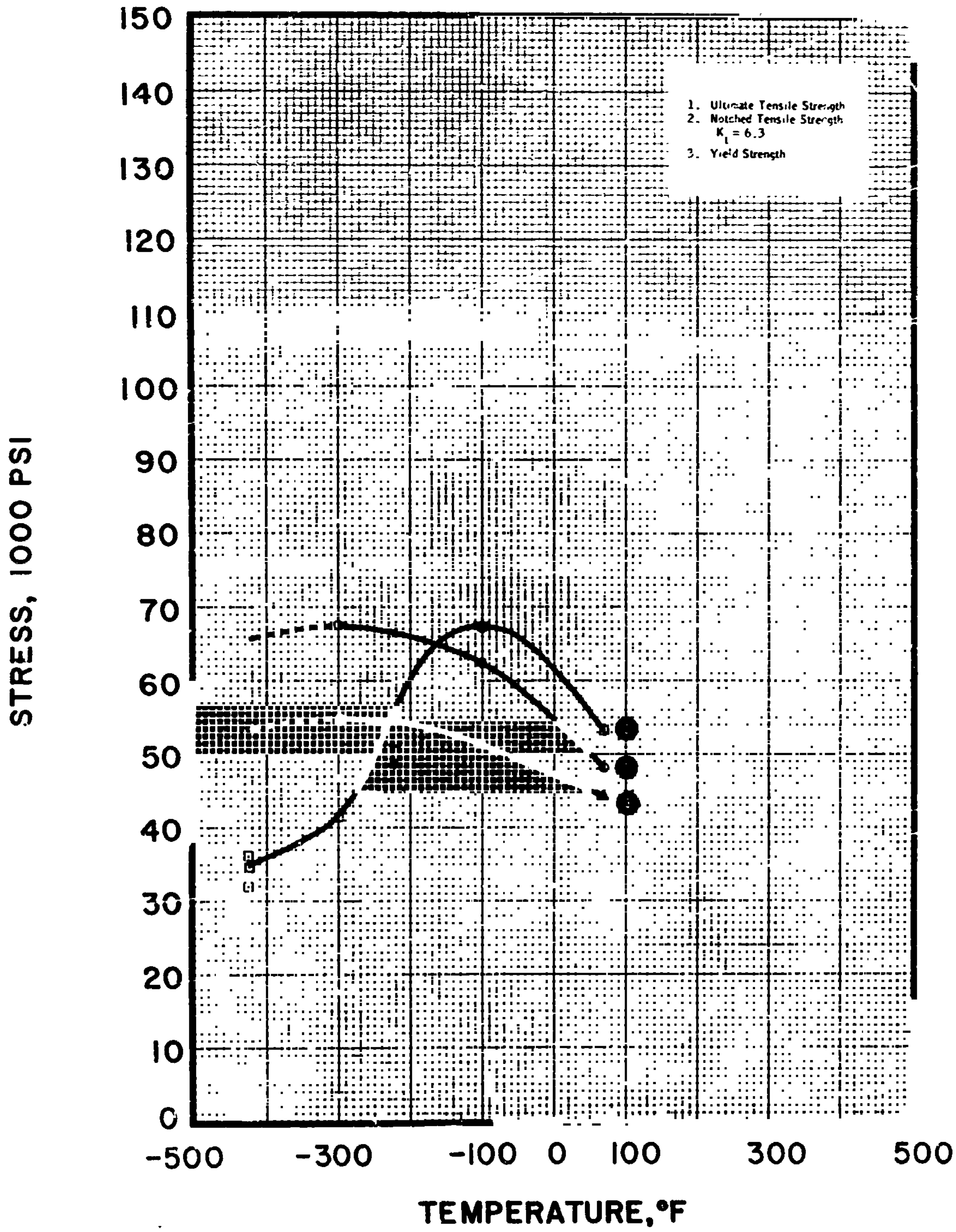
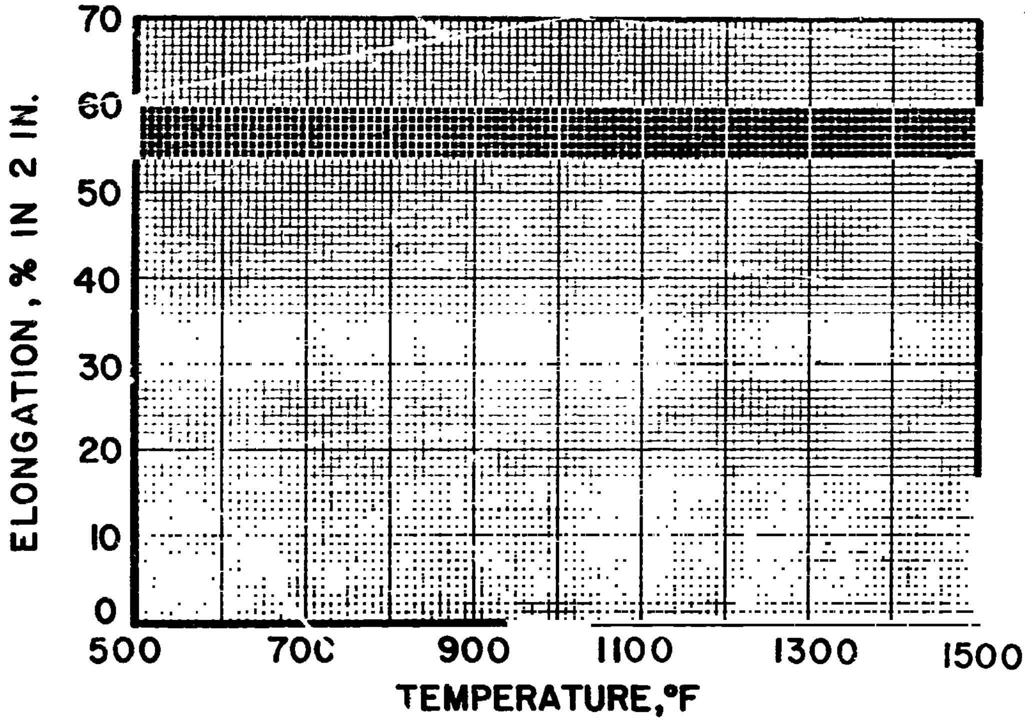


Figure 60

Aluminum Alloy 7079-T6 Sheet Plate, Welded and Aged Condition, Ultimate, Notched and Yield Strength as a Function of Temperature



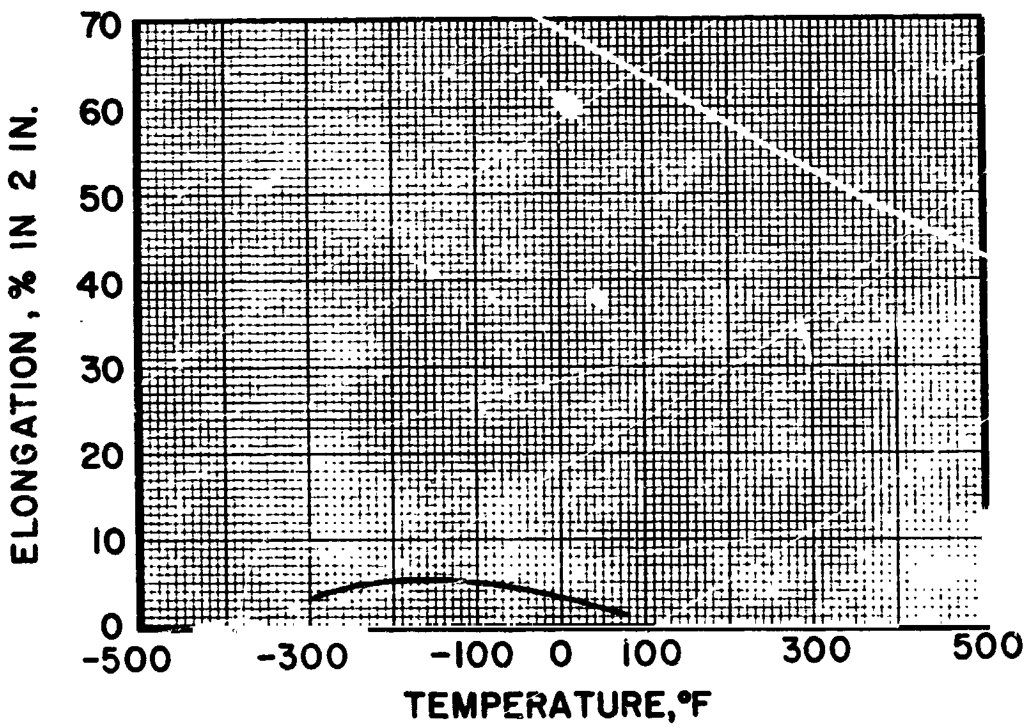


Figure 61

Aluminum Alloy 7079-T6 Sheet, Welded and Aged Condition, Elongation as a Function of Temperature

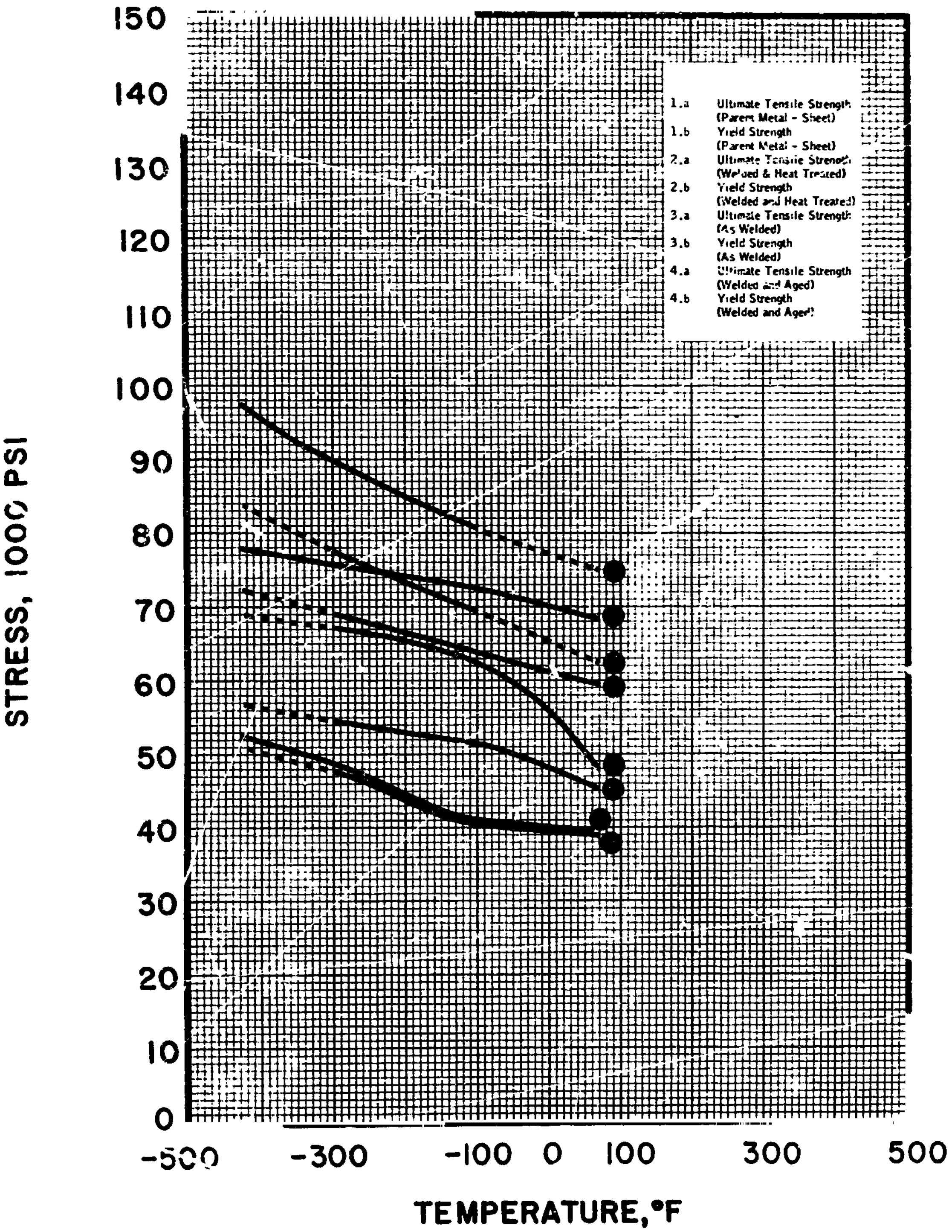
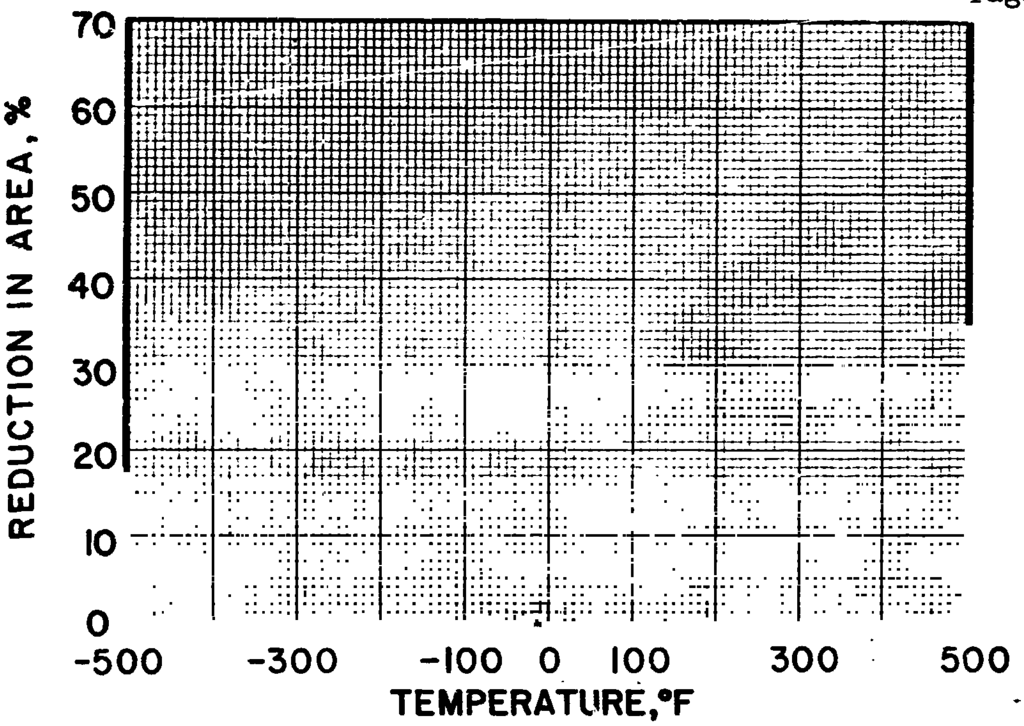


Figure 62

Aluminum Alloy 7079-T6, Comparison of Tensile Properties as a Function of Temperature (parent metal) Welded and Heat Treated, As Welded, and Welded-Aged Conditions)



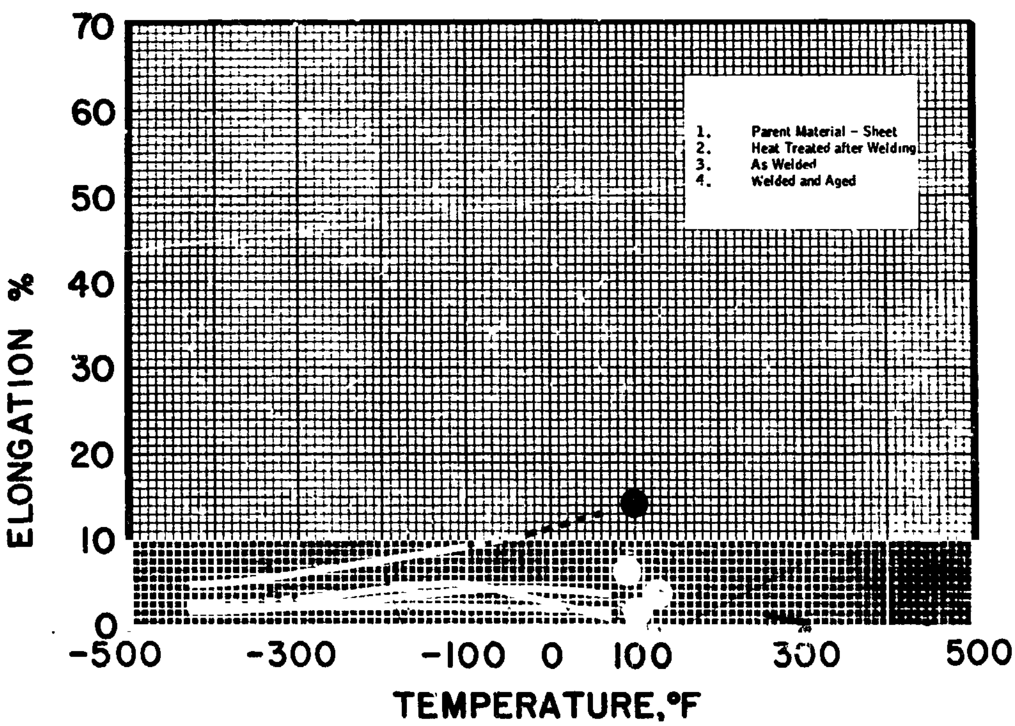


Figure 63

Aluminum Alloy 7079-T6. Comparison of Elongation and Area Reduction as a Function of Temperature (parent metal), Heat Treated After Welding, As Welded, and Welded-Aged Conditions)

E. TEFLON-BASE MATERIALS

The tensile strength of the Teflon (TFE) at -423°F is much lower than that of similar material tested by REON for evaluation of radiation effects, as reported in Reference 8; which had an average ultimate strength of 19,978 psi. However, the low values reported herein coincide with information published by NBS, Reference 1, for TFE having 72% crystallinity. The high values noted above would coincide with 52% crystallinity. Thus, the cryogenic tensile properties depend on the crystallinity of the material.

The cryogenic properties of Armalon are equivalent to those reported in Reference 8, while properties of Rulon-A are slightly higher. Room temperature ultimate strengths of both Armalon and Rulon-A coincide with values published by the manfacturers. The data are presented in Tables 26 and 27 and Figures 64, 65, and 66.

Table 26

Average Tensile Properties of Teflon-Base Materials

Material	Temp.	Ultimate Tensile Strength psi	(0.2%) psi	Elongation in 2 in. %
Teflon	RT	7433	7350	6.35
	-423°F			
Armalon	RT	8940	-	-
	-423°F	24200	-	12.05
Rulon A	RT	2480	-	-
	-423°F	9466	3800	6.6

Table 27

Tensile Properties of Teflon-Base Material at Room Temperature and -423°F

Material	Temp. °F	Ultimate Strength psi	Yield Strength (0.2%), psi	Elongation* in 2 in., (approx.) %
Teflon	-423	5,600	-	5.5
		8,200	8,100	7.2
		8,500	6,600	-
Armalon	R. T.	6,300	-	-
		6,300	-	-
		8,600	-	-
		10,900	-	-
		12,600	-	-
	-423	23,100		13.6
		25,300		10.5
Rulon A	R. T.	1,900	-	-
		2,400	-	-
		2,700	-	-
		2,700	-	-
		2,700	-	-
	-423	6,100	3,800	6.1
		10,800		6.8
		11,500		6.9

*Based on total crosshead movement divided by 2.00 in. gage length.

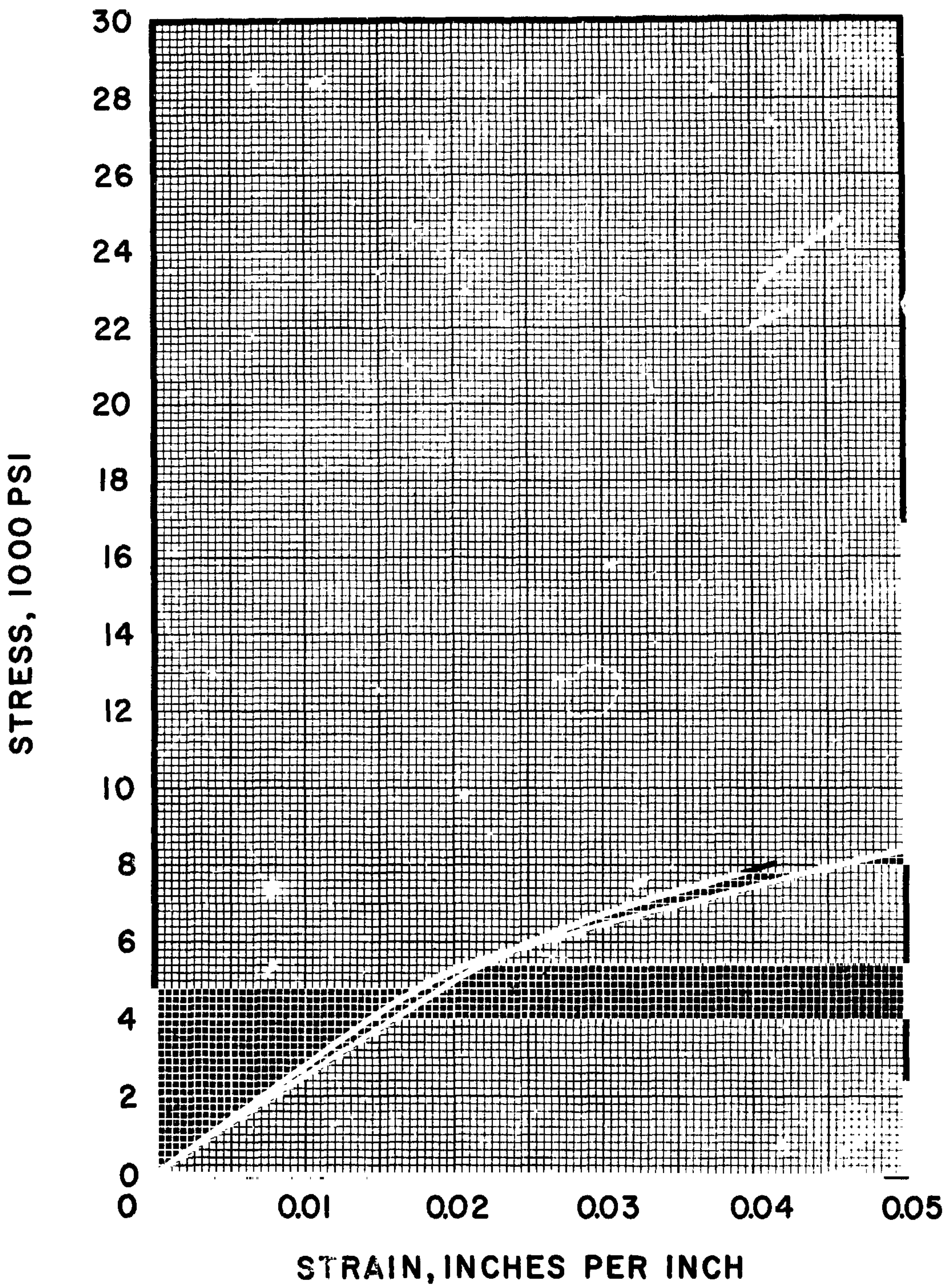


Figure 64

Teflon (TFE), Stress-Strain Diagram

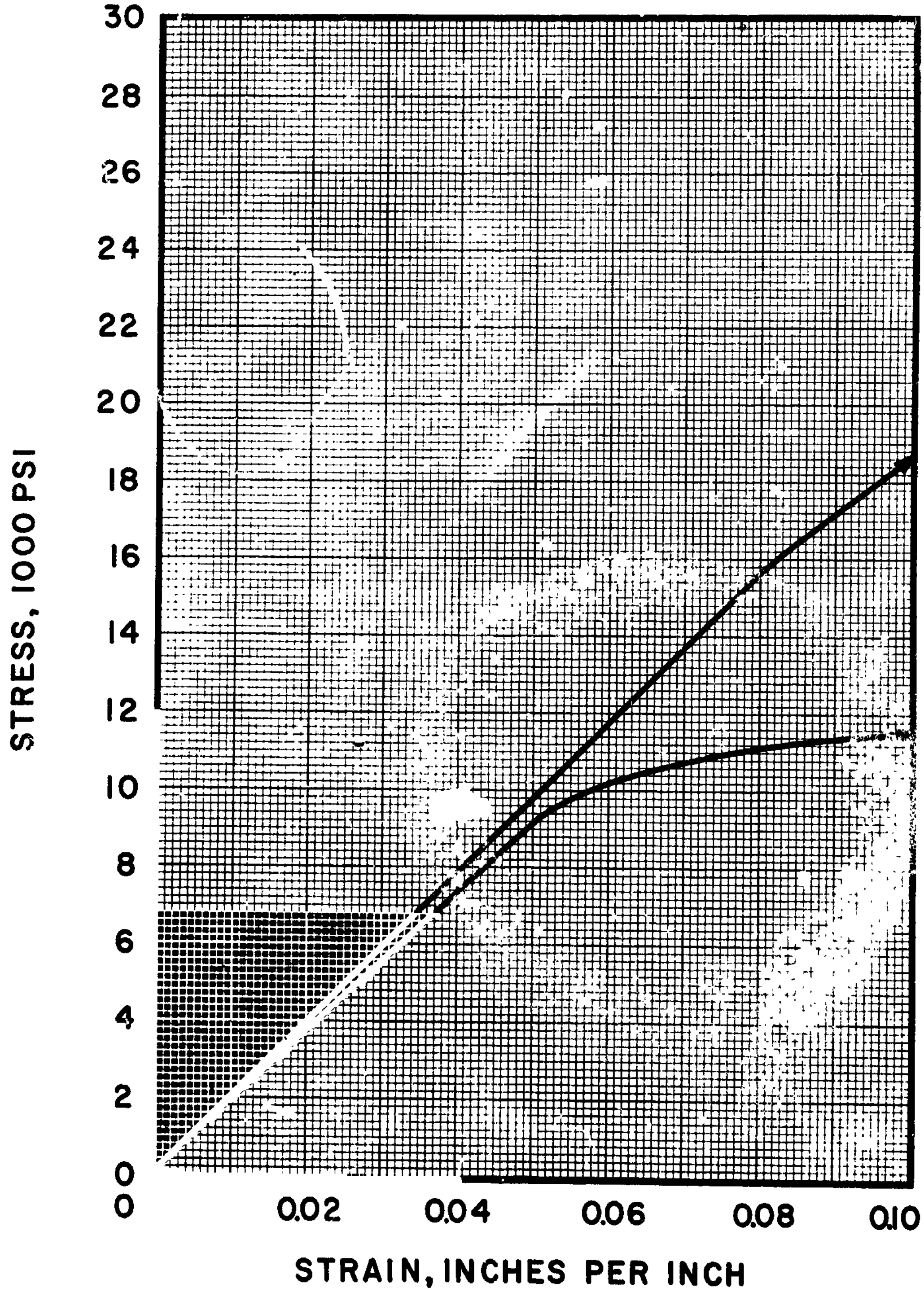


Figure 65

Armalon, Stress-Strain Diagram
(at -423°F)

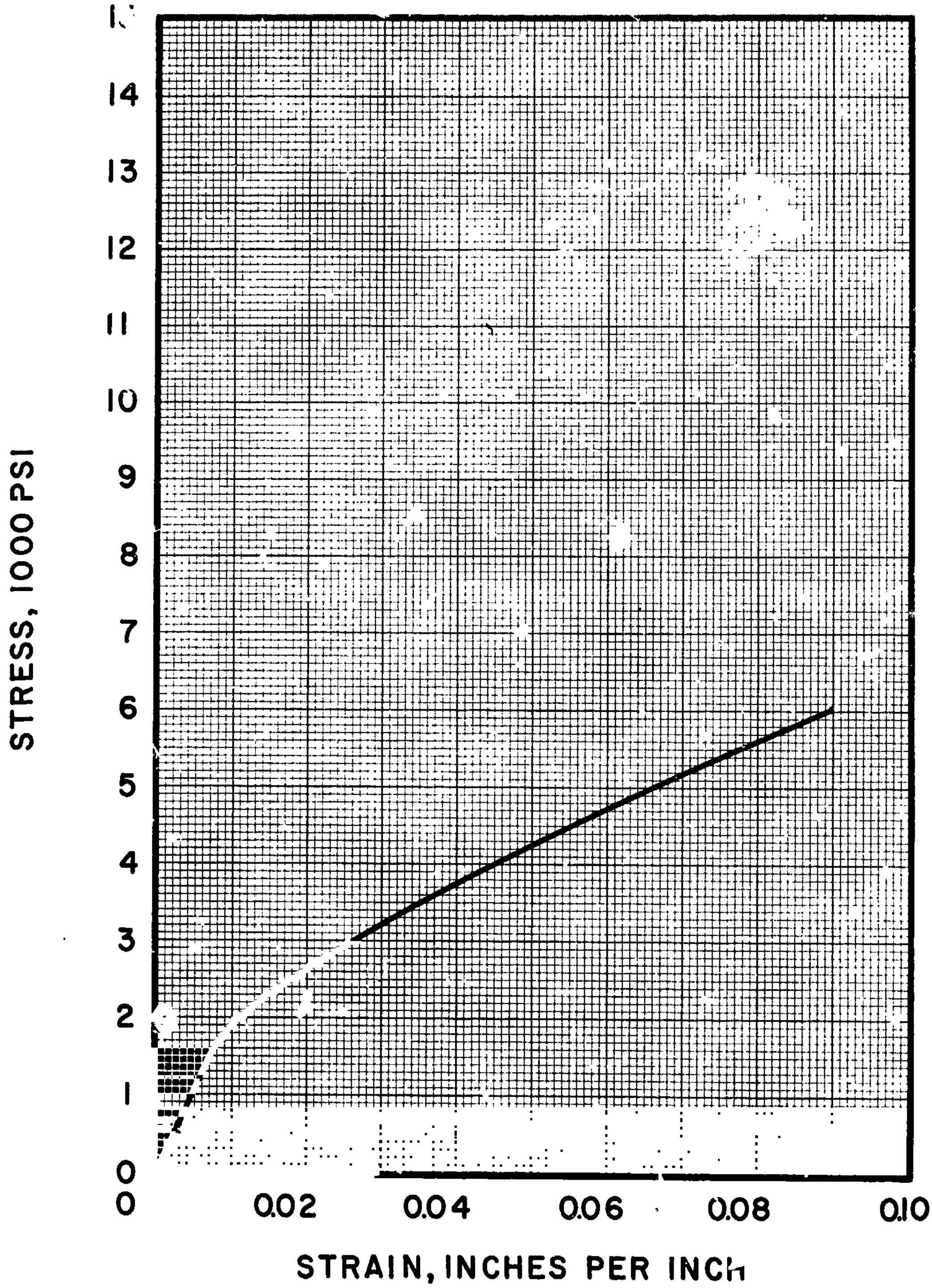


Figure 66

Rulon A, Stress-Strain Diagram (at -423°F)

SECTION VI

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VI. REFERENCES

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