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SELECTION OF OPTIMUM MATERIALS FOR USE IN LIQUID-HYDROGEN-FUELED AEROSPACE VEHICLES

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General Dynamics|Astronautics, San Diego, California
J. L. Christian and J. R. Kerr, Authors)

NOTICES

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FOREWORD

This report was prepared by General Dynamics/Astronautics, A Division of General Dynamics Corporation (GD/A), under Contract AF 33(657)-9445, project No. 651-G.

The work was administered under the direction of the Air Force Materials Laboratory, with Messrs. Marvin Knight and C. L. Harmsworth acting as project engineers.

The program at GD/A was performed under the direction of Mr. F. J. Dore, Director of Advanced Systems, and Mr. J. F. Brady, Manager of Spaceplane Project, with Messrs. J. L. Christian and J. E. Chafey acting as GD/A project engineers. Project advisers included Messrs. A. Hurlich, O. Oldendorph, and A. Eulberg.

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ABSTRACT

The primary objectives of this program were to select optimum materials for structural applications in cryogenic-fueled, recoverable, aerospace vehicles, and to determine the effect of various environmental exposures upon the mechanical properties of these materials. The program was conducted in two phases.

Phase I consisted of the selection of an optimum material for application in each of four service areas in aerospace vehicles. These areas included external structure, insulated structure, liquid-oxygen tank, and liquid-hydrogen tank. Selection of materials was based upon data obtained from a number of metal producers, and from a test program in which tensile and notched tensile tests were conducted over the temperature range from -423°F to 800°F on ten of the most promising alloys. Materials were selected on the basis of mechanical and physical properties, availability, and fabricability. Materials selected were Hastelloy X for the external structure, titanium-13V-11-Cr-3Al for the insulated structure, 301 stainless steel for the liquid-oxygen tanks, and titanium-5Al-2.5Sn ELI for the liquid-hydrogen tanks. Phase I test data are presented and the results of the test program and literature survey are discussed.

The objective of Phase II was to determine the effects of a number of different environmental exposures on the mechanical properties of those materials selected in Phase I of the program. The exposures included long-time thermal exposures at several elevated temperatures in air, oxygen and/or hydrogen gas, and thermal cyclic exposures from cryogenic to elevated temperatures. Mechanical property data included tensile, notched tensile and fusion-weld tensile properties, static and axial fatigue properties of large welded joints, and crack-propagation properties. These data, and the results of metallographic studies, were analyzed to determine the effect of specimen exposures upon mechanical properties, and to evaluate the suitability of the materials for their selected applications. Conclusions and recommendations are reported.

This technical documentary report has been reviewed and is approved.

D. A. SHINN
Chief, Materials Information Branch
Materials Applications Division
AF Materials Laboratory

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ELI	=	extra low interstitials
EFH	=	extra full hard
FH	=	full hard
K_t	=	stress concentration factor
psi	=	pounds per square inch
ksi	=	1000 pounds per square inch
D	=	oxide thickness, inches
ln	=	natural logarithm
R	=	gas constant
t	=	time
σ_G	=	gross stress, psi
P	=	load, pounds
A	=	area, square inches
σ_N	=	net stress, psi
W	=	specimen width, inches
K_C	=	fracture toughness at critical crack length, $\left(\frac{\text{lb}}{\text{in.}^2}\sqrt{\text{in.}}\right)$
G_C	=	strain energy release rate at critical crack length, $\left(\frac{\text{in.-lb}}{\text{in.}^2}\right)$
E	=	elastic modules, psi
TS	=	tensile strength, (lb/in.^{2})
F_{ty}	=	0.2 percent yield strength, (lb/in.^{2})
F_{tu}	=	tensile strength, (lb/in.^{2})
El	=	elongation, percent
CR	=	cold rolled

1 INTRODUCTION[1]

The primary objective of this program was to determine the effect of various environmental exposures on the mechanical properties of several engineering alloys which may be employed for structural applications in cryogenic-fueled, recoverable, aerospace vehicles. This program, conducted in two phases, was limited to the evaluation of materials for four major structural areas of the vehicle i.e., 1) external structure, 2) insulated, non-tank structure, 3) liquid-oxygen tank, and 4) liquid-hydrogen tank.

Phase I was a screening study consisting of an evaluation of candidate materials for each of the four enumerated service areas. This study included a literature review, a review of pertinent data generated previously on related programs conducted at GD/A, and a limited test program to determine the mechanical properties of several promising materials at the anticipated service temperatures. The purpose of this study was to select one material for each of the four service areas to be evaluated in Phase II of the program. Candidate materials were chosen for inclusion in the screening phase on the basis of strength-to-density, adequate toughness at service temperatures, compatibility with fuels, resistance to oxidation, creep and fatigue properties, formability, weldability, reasonable cost, and availability in foil gauges. Emphasis was placed on the evaluation of very thin-sheet, or foil-gauge, (0.003- to 0.013-inch thickness) materials. The results of the literature survey and screening tests were analyzed. Four materials were selected for Phase II testing.

The Phase II study consisted of determining the effects of various environmental exposures on the mechanical properties of four engineering materials. Actual service exposures are dependent upon the flight profile. For the purpose of this program however, the following exposure conditions were evaluated for the four major structural areas of interest:

Hot Structure - oxidizing atmospheres, temperature range 75° to 2200°F.

Insulated, Non-Tank Structure - oxidizing atmospheres, temperature range 75° to 800°F.

Liquid Oxygen Tank - oxidizing atmospheres, temperature range -320° to 800°F.

Liquid Hydrogen Tank - liquid and gaseous hydrogen and oxidizing atmospheres, temperature range -423° to 800°F.

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[1] Manuscript released by the authors (July 1963) for publication as an ASD Technical Documentary Report.

The mechanical properties, determined after exposure to the above conditions, included tensile, notched tensile and fusion-weld tensile, crack-propagation, and axial-fatigue properties at the minimum anticipated service temperatures. In addition, a number of metallographic examinations were made to determine the effects of exposures on the microstructure. The results of Phase II testing were analyzed to determine the acceptability and limitations of the selected materials for their anticipated service applications.

The need for studies of this type is emphasized by the fact that a high degree of structural reliability is required of materials repeatedly subjected to severe environmental conditions and that very little literature exists on this topic (References 1 through 7).

2 PHASE I - SCREENING STUDY

2.1 <u>TEST PROGRAM.</u> Although the major portion of the screening study consisted of a literature survey of applicable data, it was found that the lack of mechanical-property data on foil-gauge materials did not permit an accurate assessment of the candidate materials. Therefore, a test program was conducted in which seven hundred tensile and notched tensile tests were performed at temperatures ranging from -423° to 800°F on ten candidate engineering alloys. The purpose of this program was to provide sufficient data to make the best selection of materials for each of the four structural areas for Phase II evaluations.

Information provided by the test program included strength-to-density ratios, tensile ductility, and toughness, as determined by notched/unnotched tensile strength ratios, each as a function of temperature. Additional mechanical-property and physical-property data, and information on fabricability, cost, and availability were obtained from a literature survey and from inquiries to the metal producers.

2.2 <u>MATERIALS AND TEST SPECIMENS.</u> The materials screen tested in the Phase I program included the following, as enumerated for each of the service areas:

External structure
- Hastelloy X
- Haynes 25
- Hastelloy R-235
- René 41
- Inconel 718

Insulated non-tank structure
- Titanium-8Al-1Mo-1V
- Titanium-13V-11Cr-3Al

Liquid-oxygen tank
- 301 EFH stainless steel

Liquid-hydrogen tank
- Titanium-5Al-2.5SnELI alloy
- 310 FH stainless steel

Each of the candidate materials was proposed for evaluation based on one or more of the following desirable properties: high strength-to-density ratio, adequate toughness for structural applications at cryogenic temperatures, good fabricability, good corrosion resistance, compatibility, low cost, and ready availability (References 8 through 19). The history and nominal chemical analysis of each of the materials tested in Phase I are given in Table 1. Typical microstructures are shown in Figures 2 through 11.

The test specimens used in this portion of the program included standard flat (sheet) tensile specimens and edge-notched tensile specimens. The stress concentration factor (K_t) of the notched specimens is 6.3, as determined by the equation

$$K_t = \sqrt{a/r}$$

where

a = one half of the width between the notches

r = the radius of the notch

The stress concentration factor is 7.2 as determined by Peterson's equation (Reference 20), and 7.5 as determined by Neuber's concept (Reference 21). A more detailed description of the test specimens is given in Reference 22. Drawings of the tensile and notched tensile specimens are shown in Figure 1.

Particular care was exercised in the handling, machining, measurement, etc. of test specimens during fabrication and testing in order to assure reliable and consistent test results. Each specimen was individually examined under magnification and measured. Only those specimens conforming to machining prints and free of surface and edge defects were used in the test program.

2.3 APPARATUS AND PROCEDURE. The apparatus used in conducting the smooth and notched tensile tests consisted of three universal testing machines, with maximum load capabilities of 10,000, 30,000, and 50,000 pounds. Each machine is equipped with automatic, continuous stress-strain recorders and strain pacers. The moderately elevated temperature (600° and 800° F) tests were performed with the specimens located within vertical resistance-wound furnaces mounted on the test machines (see Figures 12 and 13). The extensometers, located below the furnace, are activated by vertical extension arms, the upper ends of which are clamped to the specimen inside of the furnace. The tests were conducted at sub-zero temperatures and performed with the specimens immersed in an appropriate cryogenic liquid in cryostats. The cryostats are fitted with tension rods permitting them to be positioned between the columns on the testing machines (see Figure 14). A cryo-extensometer assembly (Figure 15) permits a continuous recording of the stress-strain curves. A thorough description of the liquid-hydrogen cryostats, cryo-extensometers, and accessory equipment (as well as the safety features, rapidity of testing, and sequence of operations) may be found in References 22 and 23.

Tensile tests were conducted at 75° F (room temperature), at -100° F by immersion in a bath of dry ice and alcohol, at -320° F by immersion in liquid nitrogen, at -423° F by immersion in liquid hydrogen, and at 600° and 800° F by holding in electrically heated furnaces. Unnotched tensile tests were performed at a strain rate of 0.001 in./in./min until 0.2-percent offset yield strength, followed by 0.15-in./min loading rate until specimen failure occurred. Notched tensile tests were performed at a loading rate of 0.01-in./min until failure. Elongation measurements were made over two-inch gauge lengths made by very light scribe marks on a surface dye.

2.4 <u>RESULTS AND DISCUSSION.</u> The results will be presented and discussed individually for each of the four service areas in order to provide maximum clarification and interpretation of the experimental results. Several correlations between the data for the materials of one service area and another are noted, and graphs showing properties of all the alloys on a strength-to-density basis are presented.

2.4.1 <u>Materials for External Structure.</u> A number of commercially available nickel- and cobalt-base alloys have been developed. These alloys possess relatively high strengths at elevated temperatures, good oxidation and corrosion resistance, and are ductile, formable, and weldable. The alloys evaluated for service in the external structure were Hastelloy X, Hastelloy R-235, René 41, and Inconel 718 nickel-base alloys and Haynes 25 cobalt-base alloy.

Inconel 718 is a recently commercialized age-hardenable nickel-base alloy that has good strength, creep resistance, and ductility properties at temperatures up to approximately 1300°F, and is formable and weldable. Hastelloy R-235 and René 41 are also nickel-base, precipitation-hardenable alloys which have useful engineering properties to approximately 1600°F. In the temperature range of 1600°F to approximately 1900°F, Hastelloy X and Haynes 25, in the solution-treated condition, possess good combinations of mechanical properties and oxidation resistance.

Other alloys initially included for consideration were the nickel-base alloys Udimet 500 and Udimet 700, but both were eliminated after it was determined that they are neither available nor procurable within a reasonable time, in thin sheet or foil form.

In addition to information obtained from literature and from the metal producers, a limited test program was conducted on five of the more promising nickel- and cobalt-base alloys. The history and nominal chemical composition of these alloys are given in Table 1. The results of tensile and notched tensile tests from -423°F to 800°F are given in Figures 16 through 23. The yield strength and tensile strength-to-density ratios, as a function of temperature, are given in Figures 28 and 29.

Because a number of present aerospace vehicle design concepts may require that portions of the hot structure be subjected to very low temperatures, knowledge of the mechanical properties of these alloys is desirable over the entire spectrum of temperatures. Although considerable data exist on many of these alloys at both cryogenic and elevated temperatures (Reference 8 through 11), it was found that most of the data were on thicker sheet and in heavily cold rolled or aged tempers. The screening tests were performed on materials in the form (thin sheet) and temper (annealed or slightly cold rolled) required for a majority of the Aerospace vehicle external structural areas.

An analysis of the screening test data indicates that the Haynes 25 alloy exhibited unusually low elongation values at all testing temperatures (see Figure 16). However, the notched tensile strengths and notched/unnotched tensile strength ratios remained high at all temperatures down to -423°F, indicating a high order of resistance to brittle fracture. Other significant features are the generally lower tensile strengths and higher yield strengths at all testing temperatures from room temperature to 800°F, as compared to normal values given in the literature for the Haynes 25 alloy.

The Haynes R-41 (René 41), Hastelloy R-235, Hastelloy X, and Inconel 718 alloys are all characterized by the retention of high ductilities, as evidenced by elongation values and relatively constant notched/unnotched tensile-strength ratios over the entire temperature range from -423°F to 800°F (see Figures 16 through 23). While the notched/unnotched ratios are below unity for all these alloys (generally taken as a sign of reduced toughness and resistance to crack propagation), the fact that the notched tensile specimens exhibited considerable deformation prior to fracture, that the notched tensile strength increased continuously with decreasing temperatures (see Figures 20 and 21), and that the notched/unnotched strength ratios did not decrease with decreasing test temperatures (see Figures 22 and 23) indicates that the overall resistance of these alloys to brittle fracture remains as good down to liquid hydrogen temperature as it is at room temperature. It is therefore believed that all of the superalloys tested can be used reliably for applications involving service at extreme sub-zero temperatures.

The strengths of the annealed and slightly cold-worked superalloys, except that of the Haynes 25 alloy, are within the normal ranges expected for these materials.

The selection of materials for the external structural components allows for multiple choices, depending upon the operating temperature of specific components or areas of the vehicle. In actual design, of course, it is anticipated that materials will be selected which have optimum properties permitting the design of minimum weight structures for the particular regimes of stress, temperature, and other environments to be encountered in service. Hence, no one metal or alloy will satisfy the manifold requirements for the external structural area.

A large number of alloys are available for use in the temperature range of 1000°F to 1300°F. Many of them are precipitation-hardenable, nickel-base alloys in the heat-treated condition, such as René 41, Hastelloy R-235, or Inconel 718 (the Udimet 500 and 700 alloys are not included since neither is available in thin sheet or foil stock nor is expected to be for some time). The strengths of all these alloys, with the exception of the Udimets, fall off rapidly in the temperature range of 1300°F to 1600°F.

For applications involving low loads, Hastelloy X, Inconel X, and Haynes 25 should be considered for use since they are available in a large variety of shapes and sizes and they are readily formed and welded. Much information is available on their properties, and manufacturing experience is readily available. Hastelloy X and Haynes 25 are especially attractive since they are used in the solution-treated condition, and weld efficiencies will therefore approach 100 percent. Inconel X will develop lower weld efficiencies since this alloy derives most of its strength through an aging treatment.

René 41, Hastelloy R-235, and Haynes 25 possess sufficient strength and stability above 1300°F to approximately 1600°F to be useful at moderate and low loads. Above 1600°F, the selection of material becomes more difficult. Most of the alloys decrease in strength very rapidly and are rather unstable, and many of them are prone to rapid oxidation. The alloy having the best resistance to oxidation at temperatures in the range of 1600°F to 2200°F is Hastelloy X, but this alloy is quite low in short-time creep strength over this temperature range. At 1800°F, one percent total creep deformation (non-recoverable elongation) will occur in ten hours at a stress level of 6000 psi, whereas the tensile strength is 22,000 psi and the 0.2-percent yield strength is 15,000 psi. At 2000°F, the tensile strength is 13,000 psi and the 0.2-percent yield strength is 8000 psi. The one percent creep-deformation strength is not accurately ascertained at 2000°F, but is likely to be less than 4000 psi.

Some of the hot structural area design concepts envision the use of thin sheet and foil materials as cover sheeting over composite thermal protection systems where the loads on the cover plate will be extremely low, and a high order of oxidation resistance is required. For this reason, Hastelloy X, in spite of its low strength and poor creep resistance at elevated temperatures, is of considerable interest and was selected for the Phase II evaluation program.

2.4.2 Materials for Insulated Structure. Two sheet alloys are considered for application as structural materials within the insulated portions of an Aerospace vehicle. These portions are not subjected to cryogenic temperatures from contact with the liquid fuels, or to highly elevated temperatures resulting from aerodynamic heating. Both materials considered are titanium alloys: the 13V-11Cr-3Al-Ti all beta alloy in the annealed condition, and the 8Al-1Mo-1V-Ti non-heat treatable alpha alloy. Both of these alloys exhibit excellent formability and weldability, good strength, fracture resistance, and ductility properties at temperatures up to 800°F to 1000°F, and good resistance to deformation under load at temperatures up to 600°F to 800°F. The strength-to-weight ratios of both of these alloys are equivalent to those of alloy steels heat-treated to 250,000 and 260,000 psi.

Both of these titanium alloys have been extensively investigated and developed under the Department of Defense Titanium Sheet Rolling Program, and sheet production methods have been established. While the 13V-11Cr-3Al-Ti alloy has been successfully produced in foil gauges, it has recently been found that the 8Al-1Mo-1V-Ti sheet cannot be furnished in thicknesses below approximately 0.020 inch.

Smooth and notched tensile strengths were determined on these alloys over the temperature range from 75°F to 800°F and are reported in Figures 24 and 25.

The ductilities and notched/unnotched strength ratios of the two titanium alloys, 8Al-1Mo-1V and 13V-11Cr-3Al-titanium, considered for the insulated non-tank structural areas, are high over the entire range of temperatures from room to 800°F. The 8Al-1Mo-1V alloy is approximately 15,000 to 20,000 psi stronger than the 13V-11Cr-3Al alloy at room temperature, but their strengths are almost equal at 600°F to 800°F.

Plots of tensile strength/density and yield strength/density ratios versus test temperature of all the alloys are shown in Figures 28 and 29. These curves are based on longitudinal tensile properties. The alloy showing the highest ratio of strength-to-density over the range of room temperature to 800°F is the 8Al-1Mo-1V-titanium alloy, and this superiority would undoubtedly prevail down to extreme sub-zero temperatures. However, this alloy was considered unsuitable for use as a cryogenic fuel tankage material for liquid oxygen because of the incompatibility of thin-skinned titanium structures with liquid and gaseous oxygen (References 24 through 26) and for liquid hydrogen tankage because of the reduced toughness and poor resistance to crack propagation at -423°F. Previous GD/A tests, conducted on 0.096-inch-thick sheet, showed that the 8Al-1Mo-1V-titanium alloy has considerably reduced ductility and a notched tensile strength considerably lower than its yield strength at -423°F (Reference 13). Previous tests on the 13V-11Cr-3Al-titanium alloy have shown that this alloy is also not acceptable for structural applications at cryogenic temperatures (Reference 12). However, since some designs indicate that insulated structural areas will not likely be subjected to sub-zero temperatures, these titanium alloys, as well as a number of high strength alloy steels, nickel steels, and precipitation-hardening stainless steels, could be used.

For structural applications, from room temperature to approximately 1000°F, alloy steels are probably best on a basis of density-compensated strength and elastic-modulus considerations. However, when buckling and bending are important design criteria, titanium alloys generally supersede the steels. A major problem with the low- and medium-alloy steels, and with precipitation-hardenable stainless steels such as PH 15-7Mo or AM 355, is that they require heat treatment to develop high strengths. While this treatment is feasible in small sizes and thicker sections, it becomes a very difficult, if not impracticable, procedure in large sections and assemblies fabricated from thin sheet and foil stock. While the new 20 and 25 percent nickel steels may be hardened by more simple heat treatments involving substantially lower temperatures, the problem attendant upon aging large complex structures of very thin sections make it desirable to eliminate the need for heat treatment.

Based on the above discussion, the selection of titanium alloys which require no heat treatment, are weldable, formable, and possess good combinations of ductility and resistance to crack propagation, appears justified for the insulated non-tank structural area. Of the two alloys considered for these applications, the 8Al-1Mo-1V titanium alloy is somewhat stronger at room temperature, but this advantage disappears at 600°F. The minimum thickness in which this alloy can currently be procured is 0.020-inch and the producing industry holds out little promise of supplying this alloy in foil gauges up to 0.010-inch before a year or more. On this basis, the 13V-11Cr-3Al-titanium alloy was selected for the more intensive Phase II evaluation tests.

2.4.3 Materials for Liquid-Oxygen Tank. It was possible to select the material for liquid-oxygen tankage application on the basis of extensive prior experience developed at GD/A in the course of development and production of the Atlas missile. Extra hard, cold-rolled, 301 stainless steel sheet, procured to GD/A Specification 0-71004, has been used for the fuel and liquid-oxygen tanks of the Atlas, and extensive experience has been gained in the production of large structures using this material in sheet thicknesses in the range of 0.010-inch to approximately 0.030-inch. Various tempers of this alloy have been deep-drawn, stretch-formed, and welded into components, such as 10- and 12-foot-diameter propellant tanks, bulkheads, ducting, and other complex shapes. Much mechanical property data, including strength properties of base metal and weld joints and fatigue resistance of complex welded joints, are already available on this material over the temperature range of -423°F to room temperature (References 14 through 17, and 27 through 29).

Several tests were performed on the EFH cold-rolled 301 stainless steel in 0.010-inch-thick sheet from -423°F to 800°F (see Figures 26 through 29). The test data show that this material suffers a loss of short-time tensile strength in the range of 40 to 50 ksi at 600°F to 800°F as compared to the room temperature values. This alloy, in common with all metals, undergoes an increase in tensile strength at cryogenic temperatures.

2.4.4 Materials for Liquid-Hydrogen Tank. Two materials were considered as candidates for application in the liquid-hydrogen tanks: cold-rolled 310 stainless steel and the titanium-5Al-2.5Sn alloy. The 301 stainless steel is not recommended for use at -423°F because both the base metal and weld joints can manifest brittle behavior at liquid-hydrogen temperature (References 15 and 16, 27 through 29). The 17Cr-7Ni (Type 301) stainless steel is normally completely austenitic when cooled from an elevated temperature. However, when the alloy is cold-worked at room or moderately elevated temperatures, some decomposition to martensite occurs. The amount formed increases with increasing cold work. In the extra-hard, cold-rolled condition (approximately 60-percent cold reduced), the alloy consists of approximately 60- to 70-percent martensite, with the remainder being austenite. The resulting low-carbon martensite retains excellent ductility and resistance to brittle fracture at temperatures down to at least -320°F. But, depending upon carbon content, amount of cold reduction, processing variables, etc., it may exhibit a significant degree of embrittlement at -423°F. The considerable heat-to-heat variation in the mechanical properties of 301 steel at -423°F makes this alloy unreliable for liquid-hydrogen tankage.

The 25Cr-20Ni (Type 310) stainless steel is, on the other hand, a completely stable austenitic alloy and will not undergo any transformation to martensite, even when severely cold rolled at room temperature and strained to fracture at -423°F (Reference 18). This alloy cannot, however, be cold-rolled to as high a strength as Type 301, since hardening of the latter alloy is achieved through two mechanisms: cold-working of austenite, and transformation to martensite. Type 301 extra hard, cold-rolled stainless steel sheet, procured to GD/A Specification 0-71004, has a minimum yield strength of 160,000 psi and a minimum tensile strength of 200,000 psi at room temperature. Type 310, when cold-rolled 75 percent (as compared to 60 percent for Type 301, to meet the requirements of GD/A Specification 0-71017) has a minimum yield strength of 140,000 psi and a minimum tensile strength of 180,000 psi.

Type 310 cold-rolled stainless steel sheet has been extensively tested at sub-zero temperature down to -423°F and the strength, resistance to fracture, and fatigue resistance of base metal and weld joints have been thoroughly evaluated in sheet material ranging from 0.010-inch to 0.025-inch thickness (References 15, 18, 27, and 29). This material is now being thoroughly evaluated at GD/A for use in the Centaur high-energy, upper stage vehicle, which employs liquid-hydrogen and liquid-oxygen propellants.

The second alloy being considered for liquid-hydrogen tankage is the 5Al-2.5Sn-titanium alloy in the ELI (Extra Low Impurity) grade developed cooperatively by the Titanium Metals Corporation of America and GD/A. Work at GD/A showed that when the interstitial impurity elements (particularly oxygen and iron) are kept low, the alloy retains a very high level of ductility and resistance to brittle fracture in both base metal and weld joints at temperatures down to -423°F (Reference 19). Based on this work, GD/A Specification 0-71010 was developed to cover the procurement of low impurity titanium-5Al-2.5Sn alloy sheet for use in cryogenic temperature applications. Several heats of this material, ranging in thickness from 0.012 to 0.025-inch have been evaluated at GD/A over the temperature range from room temperature down to -423°F, and have been found to possess excellent combinations of strength, ductility, brittle fracture resistance, and fatigue resistance in both base-metal and weld-joint configurations (References 19 and 22).

Titanium and titanium alloys exhibit a particularly significant increase in both yield and tensile strengths with decreasing temperature and are approximately twice as strong at -423°F than at room temperature. By comparison, aluminum alloys and austenitic steels generally undergo only 25 to 50 percent increases in yield strength and 40 to 60 percent increases in tensile strength over the same temperature range. Thus, while the strength/density ratio of the titanium-5Al-2.5Sn alloy is only slightly higher than that of extra-hard, cold-rolled 301 stainless steel at room temperature, the titanium alloy has a 50 percent higher strength/density ratio at -423°F. Consequently, for structures that experience maximum stresses at cryogenic temperatures, the use of low-temperature design allowables permits significant weight savings in the case of titanium alloys.

Unfortunately, the high chemical reactivity of thin-skinned titanium and titanium alloys with both gaseous and liquid oxygen precludes its use for oxygen tanking. Extensive tests, conducted both at GD/A (References 24 and 26) and the Marshall Space Flight Center of NASA, involving the puncturing of pressurized, thin diaphragms of titanium, fracturing of welded joints by static tensile and cyclic loads, simulated micrometeoroid penetration tests, and the detonation of explosive charges in the vicinity of thin titanium sheet in the presence of liquid and gaseous oxygen, have demonstrated the marked tendency of titanium to undergo violent deflagration and combustion in the oxygen environment.

Data obtained from the screening tests on the titanium-5Al-2.5Sn alloy and 310 stainless steel are given in Figures 26 through 29. The titanium-5Al-2.5Sn alloy possesses higher yield and tensile strength-to-density ratios than 310 stainless steel at room and cryogenic temperatures, but not at the 600°F to 800°F temperature range because of the significantly greater decrease in strength at elevated temperatures for the titanium alloy than for the 310 stainless steel. The screening test data indicated that both of the candidate materials remain tough over the temperature range from -423°F to 800°F.

The material selected for the liquid-hydrogen tankage application is the 5Al-2.5Sn-titanium alloy (ELI grade) for the following reasons:

a. Higher tensile strength-to-weight ratio, as compared to 310 stainless steel over the entire range of temperatures from -423°F to 300°F, and higher yield strength-to-weight ratios up to 500°F.

b. Ability to develop 100-percent weld-joint strength efficiency with simple fusion butt welds, whereas the cold-rolled stainless steel requires doubler sheet reinforcement because of the weakening effect of the annealed fusion weld.

c. Extremely high fatigue resistance of fusion butt welds in the titanium alloy at extreme sub-zero temperatures.

3 PHASE II - EFFECTS OF THERMAL EXPOSURES

3.1 TEST PROGRAM. The purpose of the Phase II test program was to determine the effects of various environmental exposures on the mechanical properties of those engineering materials selected in the first phase of the investigation for each of the four previously mentioned service areas. The test program consisted of:

a. The determination of those mechanical properties of interest for the selected materials in the as-received condition in order to determine base-line properties.

b. Exposure of additional specimens to various environmental exposures, followed by measurement of the desired mechanical properties of the exposed specimens.

c. An analysis of the test results to determine the effects of the exposures.

Mechanical properties were determined with a minimum of five replicate test specimens per condition. Because the exposure and test conditions were different for each of the materials for the four service areas, they will be discussed individually.

The tests performed on the as-received Hastelloy X (the material selected for the external hot structure) consisted of determining the tensile, notched tensile, and fusion-weld tensile properties at 75°F on 0.005- and 0.010-inch-thick sheet material. Environmental exposures consisted of:

a. One hundred hour thermal exposures at 1600°, 1800°, 2000°, and 2200°F in air on unstressed 0.005- and 0.010-inch-thick tensile specimens.

b. Thermal cyclic exposures from 75° to 1600°, 1800°, 2000°, and 2200°F in air for 100 cycles at ten minutes exposure time per cycle on 0.005- and 0.010-inch-thick tensile, notched tensile, and weld tensile specimens.

c. Oxidation exposures at reduced partial pressures of oxygen which consisted of one hundred hour thermal exposures at 1600°, 1800°, 2000°, and 2200°F at each of two partial pressures (0.1 and 1.0 psig) of oxygen in a helium atmosphere on 0.005- and 0.010-inch-thick notched tensile specimens.

d. Spalling exposures which consisted of cyclic thermal exposures from 75° to 1800°F in each of two partial pressures (0.1 and 1.0 psig) of oxygen in a helium atmosphere for one hundred cycles at thirty minutes exposure time per cycle on 0.005- and 0.010-inch-thick notched tensile specimens.

After the various exposures, the tensile, notched tensile, and fusion-weld tensile specimens were tested at 75°F. Visual and metallographic (X-ray and electron microscopic, when necessary) examinations were conducted on the fractured test specimens. The results were then analyzed to determine the effects of the various exposures on the mechanical properties of interest.

Tensile, notched tensile, fusion-weld tensile, and axial-fatigue tests were conducted at 75°F on the as-received titanium-13V-11Cr-3Al alloy in 0.005- and 0.010-inch-thick sheet. Environmental exposures consisted of:

a. One hundred hour thermal exposures in air at 400°, 600°, and 800°F on 0.005- and 0.010-inch-thick tensile specimens and 0.010-inch-thick fusion-welded axial-fatigue specimens.

b. Thermal cyclic exposures from 75° to 400°, 600°, and 800°F in air for one hundred cycles at ten minutes exposure time per cycle on 0.005- and 0.010-inch-thick-tensile, notched tensile, and fusion-weld tensile specimens.

c. Oxidation exposures at reduced partial pressures of oxygen (0.1 and 1.0 psig) in a helium atmosphere for one hundred hours at 400°, 600°, and 800°F on 0.005- and 0.010-inch-thick notched tensile specimens.

All exposed specimens were subsequently tested at 75°F, and the fractured specimens were examined visually and by metallographic means. The results were analyzed to determine the effects of the exposure conditions on the mechanical properties of the titanium-13V-11Cr-3Al alloy.

Type 301 stainless steel, selected for liquid-oxygen tank applications, was evaluated in three thicknesses (0.003, 0.006, and 0.010-inch) in the extra full-hard, cold-rolled temper. Tests on the as-received material included tensile, notched tensile, fusion-weld tensile, axial fatigue of complex welded joints, and crack-propagation tests conducted at 75° and -320°F. Environmental exposures consisted of:

a. One hundred hour thermal exposures at 400°, 600°, and 800°F in air on tensile specimens of all three thicknesses and on 0.010-inch-thick axial-fatigue and crack-propagation specimens.

b. Thermal cyclic exposures from -320° to 400°, 600°, and 800°F in liquid nitrogen at the low temperature and in air at the elevated temperatures for one hundred cycles at ten minutes exposure time per cycle on tensile, notched tensile, and fusion-weld tensile specimens of all three gauges and on 0.010-inch-thick crack-propagation specimens.

c. Oxidation exposures at 0.1- and 1.0-psig partial pressures of oxygen in a helium atmosphere for one hundred hours at 400°, 600°, and 800°F on notched tensile specimens of all three gauges. Exposed specimens were subsequently tested for mechanical properties at -320°F, and the fractured specimens were examined. The results were analyzed to determine the effects of the various exposures on the properties of EFH 301 stainless steel.

The material selected for the liquid-hydrogen tanks (titanium-5Al-2.5Sn ELI) was evaluated in the annealed temper in 0.006- and 0.013-inch-thick sheet. Mechanical properties on the as-received material were determined at 75° and -423°F and included tensile, notched tensile, fusion-weld tensile, and axial-fatigue and crack-propagation tests. Environmental exposures consisted of:

a. One hundred hour thermal exposures at 400°, 600°, and 800°F in air on 0.006- and 0.013-inch-thick tensile specimens and 0.013-inch-thick axial-fatigue and crack-propagation specimens.

b. Thermal cyclic exposures from -423° to 400°, 600°, and 800°F in liquid hydrogen at the low temperature and in air at elevated temperatures for one hundred cycles at ten minutes exposure time per cycle on tensile, notched tensile, and fusion-weld tensile specimens of 0.006- and 0.013-inch thickness and 0.013-inch-thick crack-propagation specimens.

c. Oxidation exposures in 0.1- and 1.0-psig partial pressures of oxygen in helium atmosphere for one hundred hours at 400°, 600°, and 800°F on 0.006- and 0.013-inch-thick notched tensile specimens and 0.013-inch-thick crack-propagation specimens.

d. Hydrogen diffusion exposures on 0.013-inch-thick notched tensile and crack-propagation specimens. The hydrogen exposures were performed on both stressed (an applied mechanical load of about fifteen percent of the material's tensile strength at temperature) and unstressed specimens. Exposures were made for one-half hour, five hours, and fifty hours at 400°, 600°, and 800°F, in three pressures (0.1 and 1.0 psig and 15.0 psia) of hydrogen gas.

Tests on the exposed specimens were performed at -423°F. Fractured specimens were then examined visually and by metallographic means. The test data were analyzed to determine the effects of various exposures on the mechanical properties of the titanium-5Al-2.5Sn ELI alloy.

A total of nearly 1500 specimen tests and 350 metallographic examinations were performed in Phase II.

3.2 MATERIALS AND TEST SPECIMENS. The materials selected for the Phase II test program included Hastelloy X nickel-base alloy, cold-rolled EFH 301 stainless steel, Ti-13V-11Cr-3Al and Ti-5Al-2.5Sn ELI titanium-base alloys. The history and chemical analyses of these materials is given in Table 2.

The Hastelloy X was evaluated in two thicknesses, 0.005 and 0.010 inch. Both gauges were ordered in the annealed temper. However, the test data indicate that an appreciable amount of cold work remained in the 0.005-inch-thick Hastelloy X. The titanium-13V-11Cr-3Al alloy was also evaluated in the annealed temper in 0.005- and 0.010-inch-thick sheet. 301 stainless steel was evaluated in the extra-full-hard cold-rolled temper in the 0.003-, 0.006-, and 0.010-inch gauges. Except for the elongation on the 0.006-inch-thick material, each of three heats of 301 stainless steel met the requirements of GD/A specification 0-71004 (160 ksi minimum 0.2-percent yield strength, 180 ksi minimum tensile strength, and 2.0-percent minimum elongation). Each of the above materials were purchased in the desired gauges. In the case of the titanium-5Al-2.5Sn ELI alloy, however, the minimum gauge which could be commercially produced was 0.013-inch-thick. Since data on thinner gauge material was most desirable, specimen blanks (1-1/2 inches wide by 9 inches long) were sheared from the 0.013-inch-thick material and rolled to 0.006-inch thickness on a six-inch wide, two-high, laboratory rolling mill at GD/A Advance Materials Research Laboratory. Intermediate anneals were not required and edge cracking did not occur until after 55- to 60-percent reduction. The required 120 specimen blanks were rolled and annealed in vacuum at 1500°F for one hour. Tensile properties of the 0.006- and 0.013-inch-thick annealed material agree with what would be expected for the extra low impurity, annealed titanium-5Al-2.5Sn alloy.

The test specimens used in this phase of the program consisted of tensile, notched tensile, fusion-weld tensile, axial-fatigue and crack-propagation specimens. The tensile and notched tensile specimens were the same design as those used in Phase I, were described in that section, and shown in Figure 1. The weld-tensile specimens contained a butt fusion weld perpendicular to the axis of the test specimens which were machined to the same dimensions as the smooth tensile specimens (Figure 1). Weld schedules used in the fabrication of the weld tensile specimens and axial-fatigue specimens are given in Table 3. The fatigue specimens are 38 inches long with test sections approximately 4 inches wide and 16 inches long. The test sections contain either a butt fusion weld (for the titanium alloys) or a butt fusion weld plus a doubler sheet attached by spot welds (for 301 stainless steel). Drawings of the axial-fatigue specimens are given in Figures 30 and 31. The reason for the doubler plate on the 301 stainless steel is to provide a higher joint efficiency, which is about 50 to 70 percent without the doubler and 90 to 100 percent with the doubler. A doubler is not required for either of the two titanium alloys in the annealed temper since the plain butt weld possesses nearly 100 percent joint efficiency. The joints used in this study are typical of those which may be used in the Aerospace vehicle. In addition, information is available on the static and fatigue properties of these types of joints (References 22, 27, and 30). The crack-propagation specimens are four-inch wide sheet specimens containing a 1-1/4-inch-long central crack electrically discharge machined by an Elektro-Jet machine (see Figure 32). Much crack-propagation data have been obtained as a function of temperature with this particular type of specimen (Reference 30).

Particular care was exercised in the handling, machining, measurement, etc. of test specimens during fabrication, environmental exposures, and testing in order to assure reliable and consistent test results. Each specimen was individually examined under magnification and measured. Only those specimens conforming to machining prints and free of surface and edge defects were used in the test program.

3.3 <u>APPARATUS AND PROCEDURE.</u> The general procedure followed in the Phase II test program consisted of the following steps.

a. Procure desired test materials.

b. Make specimen layout on sheet materials.

c. Perform fusion welds.

d. Shear specimen blanks.

e. Identify specimen.

f. Machine specimens.

g. Inspect and measure specimens.

h. Weld on doublers as required.

i. Perform specimen exposures.

j. Perform specimen tests.

k. Make visual and metallographic examinations, and analyze results.

With the exceptions of the 0.006-inch-thick titanium-5Al-2.5Sn ELI material, each of the test materials was commercially procured. The 0.006-inch-thick titanium-5Al-2.5Sn ELI material was rolled from the 0.013-inch-thick stock and annealed at GD/A on a six-inch wide, two high, laboratory rolling mill and a vacuum retort furnace.

Fusion welds were performed on straight-line inert-arc fusion welding equipment. Weld schedules are shown in Table 3. Specimen blanks were sheared on factory and/or laboratory shears. Standard milling machines, punch presses, and an electrical discharge machine (Elektro-Jet) were used for machining test specimens. Specimens were inspected and measured with micrometers and an optical comparator.

Specimens received thermal, cyclic, oxidation, spalling, and gaseous-hydrogen (with and without applied load) exposures as follows. Thermal exposures were made for one hundred continuous hours (in air) at 400°, 600°, and 800°F for the 301 stainless steel and the two titanium alloys, and at 1600°, 1800°, 2000°, and 2200°F for the Hastelloy X. The 400°, 600°, and 800°F exposures were performed in a resistance heated (Glo-bar) furnace (shown in the background, Figures 33 through 35). The higher temperature exposures were performed in a Glo-bar, box furnace (Figure 36). Specimens were positioned on metallic or ceramic holders during the exposures. Cyclic exposures were made from -423° to 400°, 600°, and 800°F for the titanium-5Al-2.5Sn ELI; -320° to 400°, 600°, and 800°F for 301 stainless steel; 75° to 400°, 600°, and 800°F for the titanium-13V-11Cr-3Al alloy; and 75° to 1600°, 1800°, 2000°, and 2200°F for the Hastelloy X material. The specimens were subjected to one hundred cycles, at ten minutes per cycle (in air) at room and elevated temperatures and immersed in the proper cryogen at low temperatures. The cryogens were liquid hydrogen (-423°F) and liquid nitrogen (-320°F) contained in cryostats. Resistance-heated furnaces were used for the elevated temperature exposures. Metallic hangers were used to hold the specimens during the cyclic exposures.

Oxidation exposures were performed at reduced partial pressures (0.1 and 1.0 psig) of oxygen in an inert atmosphere. These exposures were made for one hundred hours. The two titanium alloys and the 301 stainless steel were exposed at 400°, 600°, and 800°F in the retort (12-inch diameter by 18-inch length) shown in Figures 33 through 35. The Hastelloy X was exposed at 1600°, 1800°, 2000°, and 2200°F in a quartz tube mounted in a resistance-wired furnace (Figure 37). This furnace was also used for the spalling tests performed at the same temperatures (30 minutes at temperature for 100 cycles) on the Hastelloy X material.

Hydrogen gas exposures were performed on the titanium-5Al-2.5Sn ELI alloy at various pressures (15 psia of hydrogen gas and 0.1 and 1.0 psig of hydrogen gas in a helium gas atmosphere) and temperatures (400°, 600°, and 800°F) for one-half, five, and fifty hours. Specimens were exposed both with and without an applied load at 600°F. Apparatus used consisted of the gas retort (Figures 33 through 35) and a load applicator (Figures 38 and 39).

After exposure, the specimens were tested in tension, fatigue, or crack-propagation apparatus. The tensile testing apparatus is described in paragraph 2.3. Fatigue testing was conducted at six cycles per minute on the hydraulically actuated test beds (see Figures 40 and 41) described in Reference 22. Crack-propagation testing was conducted in a windowed cryostat located on a universal testing machine (Figure 42). The apparatus and procedure are described in References 22 and 30. Standard metallographic laboratory equipment was used to examine the broken specimens.

3.4 RESULTS AND DISCUSSION. The experimental results will be discussed individually for each of the four materials tested in Phase II in order to present maximum clarification and interpretation.

3.4.1 Hastelloy X. The test results for Hastelloy X are presented in Tables 4 and 5 and Figures 43 through 47. Tensile properties of the 0.005-inch-gauge material are given in Table 4, while those for the 0.010-inch-gauge material are given in Table 5. These tables contain tensile data from specimens for all exposure conditions as well as those tested in the as-received condition. Note that the data indicate that the 0.005-inch-gauge material is not fully annealed (some degree of cold work remains), since the yield and tensile strengths are higher and elongation lower than what would be expected for fully annealed Hastelloy X (see Reference 8, and compare with properties of 0.010-inch-gauge material in Table 5). The notched/unnotched tensile-strength ratios are quite low for both the 0.005- and 0.010-inch-gauge as-received materials; however, this appears to be typical for many of the nickel-base alloys (Reference 10). As would be expected for annealed material, the fusion welds of the 0.010-inch-gauge material are 100 percent joint efficient (in fact, four of the five specimens failed in the base metal).

Figure 43 shows the effects of 100-hour thermal exposures (in air) on the room temperature tensile properties of both the 0.005- and 0.010-inch-gauge materials. Exposures were carried out at 1600°, 1800°, 2000°, and 2200°F. Oxidation of the 0.005-inch specimens at 2000° and 2200°F, and of the 0.010-inch specimens at 2200°F was so severe (see Figure 47A) that tensile testing was not possible. The 2200°F exposures were repeated, however, using small 0.010-inch-gauge specimens which were removed at frequent intervals for visual observation. While no tensile information was obtained, the tests did indicate that 0.010-inch-gauge material could withstand exposure (in air) up to 48 hours before experiencing excessive deterioration as a result of oxidation (see Figure 47B).

Results from specimens that could be tested revealed that large reductions were observed in the yield strengths for both gauges of material. At the higher temperatures, this decrease was between 30 and 40 percent of the as-received values. The tensile strengths were also reduced but to a lesser extent. Tensile elongation dropped by one-third or more for the 0.010-inch-gauge material at all temperatures and by more than one-half for the 0.005-inch-gauge material exposed at 1800°F.

The combination of oxidation with a relatively small specimen thickness is attributed to being a major factor for the drastic reduction in mechanical properties during the 100-hour thermal exposure in air. Oxidation of Hastelloy X occurs by the formation of a tight, spall-resistant oxide scale which, once formed, inhibits further damage from the oxidizing atmosphere. In large sections, the presence of the oxide scale subtracts little from the overall strength; for sheet and foil-gauge material, however, the oxide layer can make up a substantial percentage of the cross-sectional area. It is believed that this effect contributes to the decrease in tensile properties.

By means of metallographic examination of the 100-hour thermal exposure specimens and the smaller exposure samples (those shown in Figure 47B), the data plotted in Figures 47C and D were obtained. Figure 47C is a plot of ln D versus 1/T for 100-hour exposures, where D is oxide thickness and T represents the temperature.

This curve has a slope equal to about 23,000/R, where R is the gas constant. In Figure 47D, ln D is plotted against ln t for a temperature of 2200°F. Here, t represents time. The slope is close to 1/2. Using the information available from these curves, the following equation was obtained to describe the increase in oxide thickness, D, during oxidation in air:

$$D \propto t^{\frac{1}{2}} \exp-\left(\frac{2300}{RT}\right) \qquad (1)$$

Oxide growth is initially rapid and decreases with increasing time. Evidence of excessive oxidation is plainly shown in photomicrographs A, B, C, and D of Figure 48.

The results of thermal cyclic exposures in air are illustrated in Figure 44 for the 0.005-inch-gauge material and in Figure 45 for the 0.010-inch-gauge material. The time at each temperature for each cycle was five minutes. One hundred cycles were performed: therefore, the specimens were held at elevated temperatures for a minimum of 500 minutes or 8-1/3 hours total time. As would be expected, the effect on the mechanical properties was much less severe than that which occurred during the 100-hour continuous exposures.

For the 0.010-inch-thick material, the yield and tensile strengths did not decrease appreciably except for the 75° to 2200°F exposure. In like manner, the elongation dropped sharply for the 75° to 2200°F exposure. The unusually large decrease in elongation of those specimens exposed to the 75° to 1600°F cycles is not clearly understood, but is believed to be a real effect.

The yield and tensile strengths of the 0.005-inch-gauge Hastelloy X behaved similarly to the heavier gauge material, except that the fall-off in strength took place at a lower temperature. Both the 75° to 2000°F and the 75° to 2200°F exposures resulted in a considerable decrease in strength properties. The elongation, on the other hand, did not suffer and actually showed an increase for all exposures except the 75° to 2200°F cyclic exposure.

As compared to the base metal tensile properties, the notched tensile and weld tensile properties were not severely affected (i.e., the notched/unnotched tensile-strength ratios and weld-joint efficiencies remained nearly the same as for the as-received material). This was true for both gauges of material.

The explanation for the decrease in tensile properties during cyclic thermal exposure is again that of oxidation taking place on thin-gauge materials. A comparison of the amount of oxidation that occurred during continuous exposure and the cyclic exposure can be seen in Figure 48A, B, E, and F. The less severe attack during the latter exposure is readily apparent.

Another series of thermal exposures performed on the Hastelloy X involved 100-hour oxidation tests at 1600°, 1800°, 2000°, and 2200°F in two different partial pressures of oxygen. The tests were carried out under unit atmospheres of helium gas containing 0.1 psig and 1.0 psig oxygen. Both the 0.005- and 0.010-inch-gauge materials were studied. Only notched tensile strengths were measured, and these are plotted in Figure 46. For the 0.010-inch-gauge material, very little difference was observed between the results for 0.1-psig and 1.0-psig oxygen exposures. This is further shown by the similarity in microstructures as presented in Figure 48G and H. The effect of the oxidation on the room temperature notched tensile strength was a slight decrease as the exposure temperature was increased. Contrary to what would be expected, the results for the 0.005-inch-gauge material show the 0.1-psig oxygen exposure to be more harmful than that of the 1.0-psig oxygen atmosphere. The only explanation that can be offered is the possibility that a less pure grade of helium was used for the 0.1-psig oxygen exposures. The presence of small traces of water vapor, for example, could have influenced the test results. With the exception of the slight increase for the 1600°F tests, the notch tensile strengths of the 0.005-inch specimens were found to decrease more rapidly with temperature than those of the 0.010-inch material. This is in line with the results of the air exposure tests discussed earlier and may be interpreted in the same manner.

Specimens previously exposed in partial pressures of oxygen were also examined metallographically to study the temperature dependence on oxide growth. The results are plotted in Figure 47C for the 1.0-psig oxygen exposures. No data could be obtained for the 0.1-psig oxygen tests. Oxidation appears to obey the same temperature dependence in 1.0-psig oxygen as in air. The rate, however, is less.

The last group of thermal exposures are the spalling tests. Two sets of notched tensile specimens were cycled 100 times between room temperature and 1800°F in helium atmospheres containing 0.1- and 1.0-psig oxygen. The time at 1800°F was 30 minutes per cycle, giving a total exposure time of 50 hours. The effect of the two different oxygen pressures was negligible (see Tables 4 and 5). For the 0.010-inch-gauge material, the notched tensile strength exhibited a slight decrease from the as-received value. This decrease was about the same as that observed after the cyclic exposures in air, but not as great as that obtained after the 100-hour continuous exposure in partial pressures of oxygen. This type of behavior would be expected. The value for the notched tensile strength of the 0.005-inch-gauge material after the spalling tests fell between that of the cyclic exposures in air and the 100-hour continuous exposure in reduced pressures of oxygen. In agreement with the results for the cyclic exposure tests in air, the notched tensile strength of the 0.005-inch-gauge material after the spalling test was greater than the as-received value. The results for both the 0.005- and 0.010-inch-gauge materials agree well with those of the tests discussed earlier.

The test data indicate that thin-gauge Hastelloy X is acceptable for structural use to at least 1800°F, although considerably lower stress allowables are required for material that will be subjected to elevated temperatures for extended periods of time. In particular, this is true for 0.005-inch-gauge material above 1600°F and 0.010-inch-gauge material above 1800°F. For design purposes, the thermal cyclic exposures do not appear to be as restrictive as does the 100-hour thermal exposure. Here again, however, a degradation of properties is to be expected for 0.005-inch-gauge material above 1800°F and for 0.010-inch-gauge material above 2000°F. Notch sensitivity and joint efficiency of welds are not affected as a result of thermal cyclic exposure. It is recommended that thin-gauge Hastelloy X material be subjected to typical flight-profile exposures, which would include thermal exposures, thermal cycling, applied loads, and subjection to various gas pressures to supplement the present data in determining design allowables and usable life of the material.

3.4.2 Titanium-13V-11Cr-3Al. The test results for the Ti-13V-11Cr-3Al alloy are presented in Tables 6, 7, and 8 and Figures 49 through 55. Tensile properties of both the as-received and exposed material are given in Table 6 (0.005-inch-gauge material) and Table 7 (0.010-inch-gauge material). Fatigue properties are given in Table 8 (0.010-inch-gauge material only). As may be seen from the as-received properties, the 0.005-inch-gauge material apparently had some degree of cold work remaining since yield and tensile strengths were greater and elongation lower than typical for fully annealed material (Reference 31). Figures 54A and 55A are photomicrographs of specimens tested in the as-received condition. Evidence of cold work in the 0.005-inch material is clearly visible. As would be expected (Reference 12), the annealed Ti-13V-11Cr-3Al alloy possesses good notched tensile and fusion-weld tensile properties.

The results of the 100-hour thermal exposures in air are shown in Figure 49. Room temperature tensile data of 0.005- and 0.010-inch-gauge material which had been exposed at 400°, 600°, and 800°F are plotted for comparison with the as-received properties. The yield and tensile strengths increased with exposure temperature, particularly at 800°F where the increase was somewhat greater than 50 percent of the as-received properties. The elongations exhibited only slight changes except at 800°F, where they decreased to very low values. For the 100-hour thermal exposures, specimen thickness appeared to have no effect on the resultant room temperature properties (i.e. between 0.005- and 0.010-inch material).

Two factors (aging and oxygen absorption) are thought to be responsible for the large increase in room temperature yield and tensile strengths after 100-hour exposure at 800°F. When in the solution-annealed condition, Ti-13V-11Cr-3Al alloy retains the high-temperature beta phase at room temperature. Upon reheating to temperatures over 600°F, the equilibrium alpha phase then precipitates from the beta phase. Although the reaction is sluggish below 1100°F, 100 hours at 800°F is sufficiently long to obtain substantial precipitation. The presence of alpha in the untransformed beta matrix causes hardening, large increases in strength, and a reduction in ductility. That aging has indeed occurred is shown in Figures 54D and 55D, which are photomicrographs typical of an aged structure. These figures can be compared with Figures 54B and 55B, which show no evidence of precipitation for exposures at 600°F.

The large increase in strength for the 800°F thermal exposures is not belived to be entirely the result of age hardening, however. One reason is that the elongation values are lower than would be expected for a properly aged material. Stronger evidence is found from the results of the notched tensile tests conducted on specimens after 100-hour thermal exposures in reduced partial pressures of oxygen. The results for 0.1 psig and 1.0 psig of oxygen in helium atmospheres are presented in Figure 52. These data show that 100-hour exposures up to 600°F have little effect on the notched properties and, consequently, the notched/unnotched ratios (using the unnotched values of Figure 49). At 800°F, however, the notched tensile strength falls off drastically with the notched/unnotched ratio dropping to 0.4 to 0.5 for the 0.005-inch material and 0.6 to 0.7 for the 0.010-inch material. Previous work in this laboratory (Reference 12) has shown that Ti-13V-11Cr-3Al in a solution-annealed and aged condition can be expected to have a notched/unnotched ratio well above that found in the present series of tests. Hence, the notched specimens are believed to have been embrittled as a result of oxygen pickup. This same effect, absorption of oxygen, is also believed to have been responsible (in addition to aging) for the large increases in tensile and yield strengths and the decrease in elongation found after the 100-hour exposures at 800°F in air.

The effects of thermal cycling from 75° to 400°, 600°, and 800°F (in air) on the mechanical properties of Ti-13V-11Cr-3Al are shown in Figure 50 (0.005-inch-gauge material) and Figure 51 (0.010-inch-gauge material). Exposures were performed in the same manner as for the Hastelloy X material. Unstressed material was repeatedly cycled from room temperature to an elevated temperature with five minutes hold-time at temperature for 100 cycles in air. As anticipated, the effects of thermal cycling on tensile properties were much less severe than those found for the 100-hour thermal exposures. Little change was noted in the yield and tensile strengths or in elongation values, except for the 75° to 800°F exposures. For these exposures the tensile and yield strengths increased about 20 percent for the 0.005-inch material and somewhat less for the 0.010-inch material, and the elongation values decreased. The total time at 800°F (8-1/3 hours) is believed to have been insufficient for very much precipitation to have taken place. This can be seen by comparing the microstructure after the 100-cycle, 800°F thermal exposure (Figure 55C) with the aged structure (Figure 55D). The increase in strengths at 800°F appears to be primarily the result of oxygen pickup. In addition to the appearance of the microstructure, two other factors point toward oxygen absorption. First, the 0.005-inch material shows a larger increase in strength. Oxygen absorption, but not precipitation hardening, would be expected to be influenced by specimen thickness. Second, the decrease in notched/unnotched ratios with increasing temperature for the 0.005-inch material is more indicative of oxygen embrittlement than an effect of age hardening.

Fusion-weld tensile properties of the 0.010-inch-gauge material were affected in a manner similar to that found for the base-metal properties, except for slight decreases in the joint efficiencies for the 75° to 600° and 800°F exposures. The 0.005-inch-gauge material retained good welded joint efficiencies for all temperature cycling exposures, with the exception of that from 75° to 800°F. Here, the joint efficiency dropped to 80 percent. The large grain size of the weld-metal zone may have been responsible (compare Figure 54C with 54B).

The final series of thermal exposures was performed on 0.010-inch-thick fusion-welded Ti-13V-11Cr-3Al axial fatigue specimens at 400°, 600°, and 800°F for 100 hours in air. After exposure the room temperature static-strength and axial-fatigue properties were measured. The fatigue measurements were carried out at stress levels equal to 90 percent of the static tensile strength. The results are presented in Figure 53 and Table 8.

The static tensile strength of welded joints of Ti-13V-11Cr-3Al alloy was greatly lowered as a result of 100-hour thermal exposures in air. This was in contrast to the increase found in unwelded specimens exposed for 100 hours in air and the very slight change in properties observed for welded specimens which had been thermally cycled 100 times in air. All thermally exposed specimens failed in the welded joints during static testing.

The axial-fatigue results are shown in the lower curve of Figure 53. The as-received material and that exposed at 400°F possessed a fatigue life of about 700 cycles at stress levels of 90 percent of the tensile strength. Because of the scatter in the static tensile strength values for the 600° and 800°F exposures, no reliable data were obtained from the axial-fatigue tests. With the exception of one test, all fatigue failures occurred in the welded joint. Based on the static tensile tests, the fusion welds of the Ti-13V-11Cr-3Al alloy undergo drastic reductions in strength after 100-hour thermal exposures in air. Fatigue life at 90 percent of the static tensile strength is acceptable after exposures at 400°F, but is questionable after exposures at higher temperatures.

The Phase II test results on the Ti-13V-11Cr-3Al alloy indicate that the operating temperature for this alloy should be limited to something less than 800°F. For continuous exposure at 800°F in either air or in reduced partial pressures of oxygen, embrittlement occurs as shown by a substantial reduction in tensile elongation and notched/unnotched tensile strength ratios. No serious reductions in these properties were observed after 400° or 600°F exposures. Thermal cyclic exposures in air had little effect on mechanical properties, except for the 75° to 800°F cycles. Embrittlement occurred, but was much less severe than that found for the 100-hour exposures at 800°F. Weld-tensile strength was not severely affected by thermal cycling, but decreased considerably after 100-hour exposures in air at 600° and 800°F. Additional testing of welded joints, including fatigue measurements, would be beneficial. Also of interest would be a series of exposure tests at 800°F on specimens in the solution-annealed and aged condition.

3.4.3 Type 301 Stainless Steel. Based on the data obtained from previous evaluations (References 15 through 17) and from Phase I testing, cold-rolled Type 301 stainless steel was selected for the liquid-oxygen-tankage material. The effects of various thermal exposures were determined on three gauges: 0.003-, 0.006-, and 0.010-inch-thick material. The test results are given in Tables 9 through 13 and Figures 56 through 65. The as-received properties were determined at 75° and -320°F. All other mechanical-property tests were performed at -320°F after subjection to the various environmental exposures, since this temperature is representative (actually -297°F) of the minimum (and generally most critical) operating temperature.

As may be seen from Tables 9 through 11, there is a considerable spread in the tensile properties of the three gauges of material in the as-received condition. The as-received tensile properties of the 0.010-inch-thick material are more typical of the EFH (Extra Full Hard), cold-rolled Type 301 stainless steel than are the other two gauges (References 15, 16, 22, and 30). The parent-metal yield and tensile strengths are slightly less and elongation greater for the 0.003-inch-thick material than is typical. This is probably due to a lesser degree of cold work in the 0.003-inch gauge than for the 0.010-inch-thick material. Also, the notched/unnotched tensile strength ratio is less than normal for the 0.003-inch-thick material, particularly at -320°F. The reason for this is suspected to be gauge effect. It has been known for some time that each material possesses an optimum toughness at some thickness and that above or below this thickness the toughness decreases (for an example, see Reference 30, page 70). An additional atypical behavior of the 0.003-inch-thick material is the weld elongation at -320°F, which is much less than for typical fusion-weld. This may be caused by a gauge effect or by a mismatching of the edges (or some similar problem) during welding of the extremely thin-gauge material.

The parent-metal tensile and yield strengths of the 0.006-inch-thick 301 stainless steel are considerably higher than normal for the EFH condition, and the elongation at 75°F is much less than typical. These properties are attributed to a larger amount of cold-working than is normal. This also explains the atypical lower joint efficiency at 75°F. The notched/unnotched tensile strength ratios (at 75° and -320°F) of the as-received 0.006-inch-thick material are less than normal, and are probably the result of the greater amount of cold-working or a gauge effect, or both.

Table 12 gives the axial-fatigue (or repeated loading) properties of complex welded joints of the as-received 0.010-inch-thick material. Properties presented are for the longitudinal direction (parallel to the direction of rolling) on fusion-welded joints which are strengthened by doubler plates of 0.010-inch-thick material attached over the fusion weld by several rows of resistance spot welds (see Figure 30). The static properties are typical of EFH 301 stainless steel; however, the number of cycles to failure are less than previously obtained, i.e., about 150 to 200 cycles at a stress level of 228 ksi (References 16 and 22). Again, this may be caused by a gauge effect since the majority of fatigue data on Type 301 stainless steel has been obtained on 0.020- to 0.032-inch-thick material. A possible additional explanation is that the stress concentration at the spot welds, the area of failure for this type of joint, is greater since the nugget diameters are smaller for the 0.010-inch-thick material than for thicker gauges.

The crack-propagation properties of the as-received 0.010-inch-thick Type 301 stainless steel at -320°F are given in Table 13. Values given include specimen width, thickness, and initial notch length, critical load and critical notch length (the load and crack length at onset of rapid fracture), and the gross-stress, net-stress, fracture-toughness and strain-energy release rate. These data were calculated from the following equations:

$$\sigma_G = P/A \tag{2}$$

$$\sigma_N = P/t\,(W-2a) \tag{3}$$

$$K_C = \sigma_G \sqrt{W \tan \frac{\pi a_f}{W}} \tag{4}$$

$$G_C = K_C^2/E \tag{5}$$

where

σ_G = gross stress (ksi)

P = critical load (lb)

A = area (in.^{2})

σ_N = net stress (ksi)

t = thickness (in.)

W = width (in.)

a = 1/2 of the initial notch length (in.)

K_C = fracture toughness (ksi$\sqrt{\text{in.}}$)

G_C = strain energy release rate (in. lb/in.^{2})

E = elastic modulus (ksi)

a_f = 1/2 of the critical notch length (in.)

A thorough description of the crack propagation specimens, testing procedure, and calculations may be found in Reference 30. Table 13 shows the gross- and net-stress, fracture-toughness and strain-energy release rate are significantly less for the transverse direction (perpendicular to the direction of rolling) than for the longitudinal direction. This is typical of cold-rolled EFH 301 stainless steel; however the K_C and G_C values for both directions are about 50 percent lower than is typical of heavier gauge (0.025-inch-thick) 301 stainless steel (Reference 30). Again, this may be attributed to a gauge effect.

Tensile, fatigue and crack-propagation specimens were exposed to various temperatures (400°, 600°, and 800°F) for 100 hours in an air atmosphere and subsequently tested at -320°F, in order to determine the effect of long-time thermal exposures. In general, the strength, ductility (as measured by elongation) and toughness (as determined by fatigue and crack-propagation testing) improved after the 400° and 600°F exposures, but were impaired by the 800°F exposure. The explanation for this is not clear (i.e. an increase in F_{ty}, F_{tu} and elongation as a result of 400° and 600°F exposure). It is believed to be a complex system with a number of different and simultaneous effects. The following possible explanations are offered. The increase in ductility and improved fatigue life may be caused by stress relieving and/or tempering; whereas the increase in yield, ultimate and weld tensile strengths may be the result of aging and possibly slight oxidation. The impairment of properties as a result of the 800°F exposure may be a combined result of tempering, precipitation and agglomeration of precipitates (overaging), and oxygen embrittlement. Although it is not clearly understood why, the effects are believed to be real, and, in fact, some of them have been noted previously (Reference 17). Microstructures are shown in Figures 64 and 65. These offer the following information. The microstructures are fairly typical of cold-rolled Type 301 stainless steel with the possible exception of a slightly larger number and size of inclusions (stringers). There is no evidence of substantial oxidation with the exception of the 800°F exposed specimens and a few of the 600°F exposed specimens particularly at the fusion welds, which indicated some oxygen diffusion penetrating to a depth of 0.0005 to 0.001 inch from each surface. Martensite tempering is quite evident in the 800°F exposed specimens manifested by the dark appearing etched martensite and unetched austenite. It is interesting to note that thermal exposure offers a possible method of detecting grain boundaries and grain size in cold-rolled, metastable, austenitic stainless steels. Grain size and boundaries cannot normally be seen in the microstructure of heavily cold-rolled 301 stainless steel, but it is believed that grains of parent austenitic (white), austenite-martensite mixtures (gray) and martensite (dark gray) are evident in the photomicrographs of the 800°F exposed specimens.

To determine the effect of cyclic thermal exposures on the properties of 301 stainless steel, specimens were repeatedly cycled from -320°F to 400°, 600°, and 800°F for 100 cycles, being held at temperature for a minimum of five minutes per cycle or 8 1/3 hours minimum total time at both the cryogenic and elevated temperatures. In general, the yield and tensile strengths, elongation, weld tensile strength, notched tensile strength and crack propagation values increased as a result of the exposures. The same explanations as given for the thermal exposures are offered. The reason for the increase, instead of decrease, of properties for the -320°F to 800°F exposures is believed to be a result of the shorter time at temperature as compared to the 100-hour thermal exposure. There is a considerable amount of scatter in the weld tensile strength data. This is believed to have been caused by a preferential oxidation at the weld and heat affected areas as well as possible mismatch etc. during welding of the thin-gauge materials. As noted in Table 9, the 0.003 inch-thick notched tensile specimens failed during the thermal cyclic exposure after 15 to 40 cycles (see Figure 64 for typical failure). The specimens were not mechanically loaded (no applied stress) during the exposure; therefore, thermal stresses are believed to have caused the failures. Although there was probably some thermal shock on the specimens, the procedure involved an intervening warm-up, or cool-down, at room temperature (e.g. -320° to 75° to 400°, 600°, or 800° to 75° to -320°, etc.). This exposure is probably more severe than would be experienced in service; however, it is strongly recommended that severe stress concentrations be avoided, and all stress concentrations be minimized, in the design and fabrication of components from foil-gauge materials. Failures may have been caused by a gauge effect since thicker gauge specimens did not fail during exposures. Or, the failures may have been the result of the poor toughness qualities of this particular heat and coil of material. Additional testing to substantiate or negate these results is recommended.

Results of oxidation exposures in partial pressures of oxygen in a helium atmosphere indicate the following. In general, the notched tensile strength (a measure of toughness) increased after 400° and 600°F exposures, and decreased after 800°F exposures. There was, generally, little or no difference in the properties as a function of oxygen content (0.1 or 1.0 psig of O_2 in a helium atmosphere). This exposure is quite similar to the 100-hour thermal exposure in air, and the explanation of the effects of exposure on the properties is believed to be the same as for the thermal exposure. Based on the rather large decreases in notched tensile strengths after the 800°F exposure, cold-rolled, EFH Type 301 stainless steel is not recommended for structural applications at -320°F after long-time exposures at 800°F.

It appears from the test data that elevated temperature is the most effective parameter in the evaluation of the effects of various exposures on the mechanical properties of 301 stainless steel. Exposures at 400° and 600°F improved the mechanical properties whereas, long-time exposures at 800°F resulted in an impairment of the low-temperature mechanical properties. Time at temperature was also found to be influential since short-time exposures at 800°F were not found to be detrimental.

It is recommended that additional testing be conducted, particularly on the very thin (0.003-inch-thick) 301 stainless steel. Also, testing after exposures between 600° and 800°F should be conducted to more accurately define the upper temperature limit. Based upon the test results, cold-rolled, EFH Type 301 stainless steel is believed to be a satisfactory material for liquid-oxygen tank structure; however, it is recommended that sharp stress concentrations be avoided and that long-time thermal exposures be limited to less than 800°F.

3.4.4 Titanium-5Al-2.5Sn ELI. The results of the Phase II test program for titanium-5Al-2.5Sn ELI are given in Tables 14 through 17 and Figures 66 through 74. As was mentioned in the section on test materials, the 0.013-inch-thick material was commercially procured, whereas the 0.006-inch-gauge material was re-rolled from the 0.013-inch-thick stock and subsequently annealed at GD/A. The as-received tensile properties (see Table 15) of the 0.013-inch-thick material are fairly typical of the ELI grade of Ti-5Al-2.5Sn. The slightly lower yield strength, greater elongation at room temperature, and higher-than-normal notched/unnotched tensile strength ratio at -423°F is attributed to the very low interstitial and iron contents (see Table 2). The as-received fatigue and crack-propagation properties indicate excellent toughness at -423°F, as expected from the tensile and notched tensile properties. The yield and tensile strength of the 0.006-inch-gauge material (Table 14) in the as-received condition are slightly less than for the 0.013-inch-thick material. This condition is attributed to the lack of cold-rolling as a finishing operation for the 0.006-inch-thick material. The 0.006-inch-thick material possesses excellent notch toughness to -423°F.

The effects of 100-hour thermal exposures on the tensile properties of the Ti-5Al-2.5Sn ELI alloy are shown in Figure 66. In general, the exposures caused an increase in yield and tensile strength, increasing with exposure temperature, and either no change or slight reduction in elongation. The 0.006-inch-thick material was more severely affected than the thicker gauge material. The static tensile properties of large welded joints (Table 16 and Figure 71) were increased slightly as a result of the thermal exposure and, in general, the fatigue properties were decreased (the very low number of cycles-to-failure for the room-temperature fatigue tests after the 400°F exposure is believed to have been primarily caused by the higher stress level). Values of G_C and K_C were increased slightly as a result of the 100 hour thermal exposures (Table 17 and Figure 72). The effect of the thermal exposures on the mechanical properties of the Ti-5Al-2.5Sn ELI material is believed to have been primarily caused by the absorption of gases during exposure. The photomicrographs in Figure 74 show some indications of gas pickup, particularly at the higher temperatures. This condition also explains the greater effect on the thinner gauge material.

Thermal cyclic exposures resulted in increases in yield and tensile strength, slight reductions or no change in tensile elongation, increases in fusion-weld tensile strengths, and significant decreases in notched tensile strength. These effects are again believed to be primarily caused by gas absorption during exposure. Microstructures were very similar to those for the thermal exposures. The decrease in notched tensile strength is believed to be significant, but not of sufficient magnitude to prevent the use of the material for structural applications, particularly when room temperature design allowables are being used. The crack-propagation data show a decrease in toughness due to thermal cyclic exposures (from -423° to 800°F) but substantiate adequate toughness for structural applications.

The effects of 100-hour thermal exposures (in partial pressures of oxygen gas in a helium atmosphere) on the notched tensile properties of the titanium-5Al-2.5Sn ELI alloy are shown in Figure 69. The exposures resulted in rather large decreases of the notched tensile strength, particularly for the 0.013 inch thick material after 800°F exposures. The results of the crack propagation tests do not, however, indicate any severe embrittlement due to the oxidation exposures (Figure 72). Unitl additional data becomes available to more accurately define the effects of thermal exposures on this alloy in air and reduced partial pressures of oxygen gas, it is recommended that caution be exercised in the selection of safe design allowables.

The effects of elevated-temperature thermal exposures in a hydrogen or partial hydrogen gas atmosphere on the titanium-5Al-2.5Sn ELI material are shown in Figure 70. Exposures were made on unstressed specimens for one-half, five, and fifty hours at 400°, 600°, and 800°F in 15.0 psia and 1.0 and 0.1 psig of hydrogen gas. There was a pronounced decrease in the notched tensile strength as a result of the hydrogen exposures. There was, however, little effect on the crack propagation properties after exposure in various pressures of hydrogen gas at 600°F (Figure 72).

An unavoidable delay in the testing of the crack propagation specimens may be the reason for the lack of an effect due to the exposure. It was nearly two months after the crack propagation specimens were exposed before testing; whereas the notched specimens were tested shortly after exposure. Another possible explanation of the data is that the four inch wide, center-notched crack propagation specimens are less capable of detecting a decrease in toughness of the titanium-5Al-2.5Sn ELI alloy than are edge notched (K_t = 6.3) specimens. The decrease in notched toughness is believed to be caused by hydrogen absorption. Microstructurals studies substantiate this belief. Large numbers of titanium hydride platelets are visible in the microstructures, as may be seen in Figure 74.

In addition to the unstressed exposures, a number of notched tensile specimens were exposed to various hydrogen-gas pressures for various times at 600°F under an applied mechanical load. The results are given in Table 15. The load was applied by means of a load applicator (see Figures 38 and 39) simultaneously on five specimens for each exposure. Specimens were clamped by a pin-grip arrangement, and if the load was applied equally to each specimen the originally intended stress levels were 10 ksi or about 15 percent of the strength of this material (in air) at temperature. It is possible that the load was not evenly distributed, in which case the maximum load on any one specimen would be 50 ksi (or 75 percent of the material's short-time tensile strength in air at 600°F). This information is provided because a number of the specimens failed during the exposure. Examples of the failed specimens are shown in Figure 73. Because of these failures, the load was decreased to 5 ksi per specimen for two of the 50-hour exposures; however, failure still occurred during exposure (after 8 and 14 hours as compared to 2-1/2 hours maximum when loaded at 10 ksi per specimen). Those loaded specimens that did not fail during exposure possessed notched tensile properties equal to, or slightly less than, those exposed to hydrogen with no applied load. While it would seem that those exposures in atmospheres containing the highest hydrogen-gas content would result in the most detrimental effects, this was not necessarily so. A possible explanation for the lower notched tensile strength for those specimens exposed to hydrogen-helium-gas mixtures as compared to values for those specimens exposed to a pure hydrogen gas (15.0-psia) atmosphere is the presence of water impurities in the helium gas. These impurities (at elevated temperatures) may cause greater gas absorption, and thus a more pronounced effect on the notched tensile properties of the titanium alloy. It is recommended that additional tests be performed to better determine the effect of hydrogen exposures, particularly under an applied load, on the Ti-5Al-2.5Sn ELI material. Based on the present data, however, it is recommended that extreme caution be exercised in the employment of this material for cryogenic structural applications after exposure to elevated temperatures (600°F or above) in a hydrogen-containing atmosphere. This is particularly true if the material is stressed during exposure, since it appears that the creep-rupture life of notched specimens is quite poor in a hydrogen, or partial hydrogen, atmosphere.

In conclusion, thermal, cyclic, and oxidation exposures (at 400°, 600°, and 800°F) on the Ti-5Al-2.5Sn ELI alloy, in general, resulted in an increase in the yield, tensile, and weld tensile strengths and in a reduction in the notched tensile strength, fracture-toughness, and axial-fatigue life. The loss in toughness is believed to be significant and should be taken into account in establishing design allowables, but is not believed to be critical enough to justify rejection of the alloy for structural applications. Thermal exposures in hydrogen-containing-atmospheres result in decreases in notched tensile strengths and fracture toughness, particularly those exposures at 600° and 800°F. Application of an applied load during the exposure at 600°F resulted in several failures, indicating a very poor creep-rupture life. It is recommended that additional testing be performed to more accurately define the effects of hydrogen exposures on the Ti-5Al-2.5Sn ELI alloy; until then, extreme caution should be exercised in the use of this material for structural applications when exposed, or after exposure, to hydrogen gas at elevated temperatures.

4 RECOMMENDATIONS FOR FUTURE WORK

Because of the lack of sufficient literature data to satisfy the needs of design and metallurgical engineers working on cryogenic fueled, recoverable aerospace vehicles, it is recommended that additional studies be conducted in three areas of endeavor.

First, it is recommended, in order to provide data on an acceptable back-up material, that at least one additional material for each of the four service areas be evaluated.

Second, it is believed that a better definition of the effects of exposures on mechanical properties should be obtained for the following:

a. Hydrogen exposures, particularly with an applied load.

b. Presence of other materials such as other structural materials, insulations, sealing materials, coatings, paints, etc. in contact or near contact with the material being evaluated.

c. A better definition of effect of temperature, e.g. tests at 50°F intervals between 600°F and 800°F for the titanium alloys.

The third area of recommended study is to subject selected materials to actual flight-profile exposures and to determine the effects on mechanical properties and to determine the number of cyclic exposures to failure. This type of study is presently being conducted on superalloys and coated refractory metals under USAF Contract AF 33(657)-11289, but should also include materials for insulated structure and liquid-oxygen and liquid-hydrogen tanks.

5 SUMMARY AND CONCLUSIONS

The objectives of this investigation were to evaluate a large number of engineering materials for the purpose of selecting one material for each of four structural applications, and then to determine the effects of various environmental exposures on the mechanical properties of these selected materials. To achieve the first objective, a literature survey was conducted and then augmented by a screening test program which was conducted on thin-gauge sheet material of ten alloys. Approximately 700 tensile and notched tensile specimens were tested over the temperature range from -423° to 800°F in the Phase I test program. From these data and from the information obtained from the literature, the materials listed below were selected for the Phase II test program.

Hastelloy X for external hot structure.

Titanium-13V-11Cr-3Al for insulated structure.

Cold-Rolled Type 301 Stainless Steel for liquid-oxygen tanks.

Titanium-5Al-2.5Sn ELI alloy for the liquid-hydrogen tanks.

These materials were selected on the basis of favorable mechanical and physical properties, fabricability, and availability. They were then subjected to various environmental exposures to determine the effects on their mechanical properties and to determine their suitability for structural applications in those areas for which they were selected. Each of the materials were subjected to long-time (100-hour) thermal exposures in air at several elevated temperatures, thermal cyclic exposures from the minimum operating temperature to several elevated temperatures for 100 cycles, and oxidation exposures consisting of 100-hour exposures at elevated temperatures in partial pressures of oxygen gas. In addition, the titanium-5Al-2.5Sn ELI alloy was subjected to 100-hour exposures at various elevated temperatures in various pressures of hydrogen gas. A number of these latter exposures were also made with an applied mechanical load on the specimens during the exposure. To determine the effect on mechanical properties, tensile, notched tensile, fusion-weld tensile, axial-fatigue, and crack-propagation specimens were exposed and subsequently tested at the anticipated minimum operating temperature. These properties were then compared with base-line properties as determined on the test materials in the as-received condition. A total of nearly 1500 tensile, fatigue, and crack propagation tests were performed. In addition, nearly 400 metallographic analyses and X-ray, hardness, and magnetic measurements, when applicable, were made to help determine and explain the effects of the various exposures on the properties of the test materials.

Based on the experimental data obtained in this investigation and upon the information contained in this report, the following conclusions and recommendations are made:

a. Material for external hot structure:

1. Of the alloys evaluated for structural use above 1600°F, annealed Hastelloy X is believed to provide the best combination of properties. This alloy was selected primarily on the basis of availability in foil gauges, fabricability, and oxidation resistance at elevated temperatures.

2. Thermal exposures indicate that Hastelloy X is unacceptable (because of severe oxidation) for structural application involving long-time (100-hour) exposures (in air) above 1800°F for 0.005-inch-thick material and above 2000°F for 0.010-inch-thick material. Limited studies indicate that 0.010-inch-thick Hastelloy X may be acceptable for structural application after 2200°F exposures for up to about 50 hours exposure time. In addition, exposures at 1600° and 1800°F cause a decrease in the room-temperature yield and tensile strengths and would probably necessitate a lowering of design allowables for this application.

3. Thermal cyclic exposures indicate that both 0.005- and 0.010-inch-thick Hastelloy X is acceptable for structural use after 100 cycles from 75° to 1600°, 1800°, 2000°, and 2200°F in air. There is, however, a significant decrease in the residual strength properties after cyclic exposures to 2000° and 2200°F.

4. Oxidation exposures indicate that Hastelloy X is unacceptable for structural applications after 100-hour thermal exposures in reduced partial pressures of oxygen gas above 1800°F for the 0.005-inch-thick material and above 2000°F for the 0.010-inch-thick material. This is in accord with the data obtained on specimens after similar exposures in air.

5. It is recommended that thin-gauge Hastelloy X specimens be subjected to a total flight profile exposure including time, temperature, and load to determine the effects on mechanical properties, and that additional materials, such as Rene' 41 and TD nickel, be included in the test program.

b. Material for insulated structure:

1. Annealed titanium-13V-11Cr-3Al alloy was selected for insulated, internal structural use primarily because of availability in thin-gauge sheet, but also because of its desirable strength-to-density and fabrication properties.

2. Long-time (100-hour) thermal exposures show little effect on tensile properties after 400° and 600°F exposures; however, a very large increase in strength and decrease in elongation is evident after 800°F exposures. The large effect of the 800°F exposure is attributed to a combination of aging and oxidation. Based on the tensile data and information obtained from microstructural studies, it is recommended that thin-gauge Ti-13V-11Cr-3Al not be used for structural application after long-time thermal exposures at 800°F.

3. Thermal cyclic exposures from 75° to 400° and 600°F for 100 cycles show little effect on the mechanical properties of the 0.005- and 0.010-inch-thick Ti-13V-11Cr-3Al alloy. However, similar exposures at 800°F cause increase in strength and significant decreases in ductility; therefore, it is not recommended for structural use after 800°F exposures.

4. Oxidation exposures for 100 hours in reduced partial pressures of oxygen gas show little effect on notched toughness after 400° and 600°F exposures but it displays a sharp decrease in notched toughness after 800°F exposure. It is, therefore, not recommended for structural use after 800°F exposure, even in reduced partial pressures of oxygen gas.

5. Static and axial-fatigue tests of four-inch-wide fusion-welded joints show a decrease in static tensile strength after 100-hour thermal exposures at 400°, 600°, and 800°F in air, and, based on very limited data, a possible decrease in fatigue life after exposures at 600° and 800°F. These results are believed to be due to preferential gas absorption at the fusion-weld area, substantiated by metallographic analyses, and due to mismatch, porosity, etc. occurring during welding very-thin-gauge titanium. It is recommended that additional studies be conducted to better define the effect of thermal exposures on fusion-welded joints.

c. Material for liquid-oxygen tankage:

1. Cold-rolled Type 301 stainless steel was selected for the liquid-oxygen tankage material because of its favorable strength-to-density, fabricability, availability, and liquid-oxygen compatibility and because a large amount of mechanical-property and performance data are available.

2. Thermal exposures for 100 hours (in air) resulted in an increase in yield and tensile strength at -320°F after exposures at 400° and 600°F, and a decrease after exposure at 800°F. Elongations were either slightly increased or unaffected. The static tensile strength of complex welded joints at -320°F was affected similarily: an increase after

400° and 600°F exposures and a decrease after 800°F exposures. Axial-fatigue life was improved as a result of thermal exposures. Crack-propagation properties at -320°F were reduced as a result of exposures at 800°F. The reasons for these effects are not clearly understood, but are believed to be a result of a combination of factors including stress relieving, tempering, aging, and overaging. These results indicate that cold-rolled, EFH Type 301 stainless steel is acceptable for structural use after long-time thermal exposures at 400°, 600°, and possibly 800°F.

3. Thermal cyclic exposures from -320°F to 400°, 600°, and 800°F resulted, generally, in increases of the yield, tensile, fusion-weld and notched tensile strengths, and elongation. Exceptions were decreases in the weld tensile strength for some exposure conditions (believed to be due to preferential oxidation in the weld area) and failure of the 0.003-inch-thick notched tensile specimens during thermal cyclic exposures. The reason for failure of these specimens is not clearly understood; however, since specimens failed for all exposure conditions (-320°F to 400°, 600°, and 800°F) during 15 to 50 cycles, it is recommended that sharp stress concentrations be avoided in the design and fabrication of structures incorporating very thin-gauge EFH 301 stainless steel sheet material.

4. Oxidation exposures in reduced partial pressures of oxygen gas resulted in increased notched tensile strengths after 400° and 600°F exposures, but decreased notched-toughness and crack-propagation properties after 800°F exposures. The decrease in toughness after 800°F exposures is believed to be due, in part, to surface oxidation. Although the decrease in toughness is not believed to be severe enough to reject the material for structural applications after long-time exposures at 800°F, it is recommended that the material be limited to a lesser operating temperature to ensure optimium toughness.

d. Material for liquid-hydrogen tankage:

1. Annealed titanium-5Al-2.5Sn ELI was chosen for service in liquid-hydrogen tankage over other candidate materials primarily because of its impressive strength-to-density ratio, particularly at cryogenic temperatures. However, difficulty in commercial procurement of this alloy in very thin gauges may be cause for rejection of this alloy for many areas of the intended application. It is therefore recommended that the Ti-5Al-2.5Sn ELI alloy be included in the existing foil-rolling program, and that an additional material such as cold-rolled Type 310 stainless steel be investigated as a possible backup material for liquid-hydrogen tank structure.

2. Long-time (100-hour) thermal exposures at 400°, 600°, and 800°F on the Ti-5Al-2.5Sn ELI alloy resulted in increased yield and tensile strengths at -423°F with little or no effect on elongation. Static tensile strengths of four-inch-wide fusion-welded joints were slightly increased, whereas axial-fatigue life of these joints was reduced. Increased strength is believed to be due to gas absorption, which is substantiated by metallographic examination. Ductility and toughness did not seem to be severly impaired.

3. Thermal cyclic exposures for 100 cycles from -423°F to 400°, 600°, and 800°F resulted in increased yield, tensile, and weld tensile strengths of the Ti-5Al-2.5Sn ELI alloy at -423°F. Elongations were essentially unaffected. Notched tensile strengths and crack-propagation properties were decreased. The decrease in toughness is not believed to be severe enough to cause rejection of the material for structural use. However, the decrease should be considered before determining design allowables (i.e. room temperature, and not cryogenic strength allowables, are recommended to increase the safety factor).

4. Oxidation exposures for 100 hours at 400°, 600°, and 800°F in partial pressure of oxygen resulted in decreased notched tensile strengths. This decrease is attributed to oxygen absorption. As for the previous exposures, the decrease in toughness is not believed to be of sufficient severity to warrant rejection of the alloy for structural use. This is substantiated by the little or no effect shown on the crack propagation data.

5. Long-time (100-hour) thermal exposures at 400°, 600°, and 800°F in various pressures of hydrogen gas resulted in significant decreases in notched tensile strength and crack-propagation properties at -423°F. However, a more severe exposure occurred as a result of applying a mechanical load during thermal exposures at 600°F in various pressures of hydrogen gas. The application of the load caused failure in nearly half of the notched tensile specimens during exposure. The poor creep-rupture life during 600°F exposure and the decrease in toughness resulting from these exposures is believed to be due to hydrogen absorption. Microstructural studies substantiated this deficiency by showing the formation of large numbers of titanium hydride platelets. The decrease in toughness and the poor creep-rupture life caused by exposure to hydrogen gas is felt to be a serious problem. For this reason it is recommended that additional studies be performed to more accurately define the effects of hydrogen exposures on the Ti-5Al-2.5Sn ELI alloy before it is used structurally in an elevated-temperature hydrogen environment.

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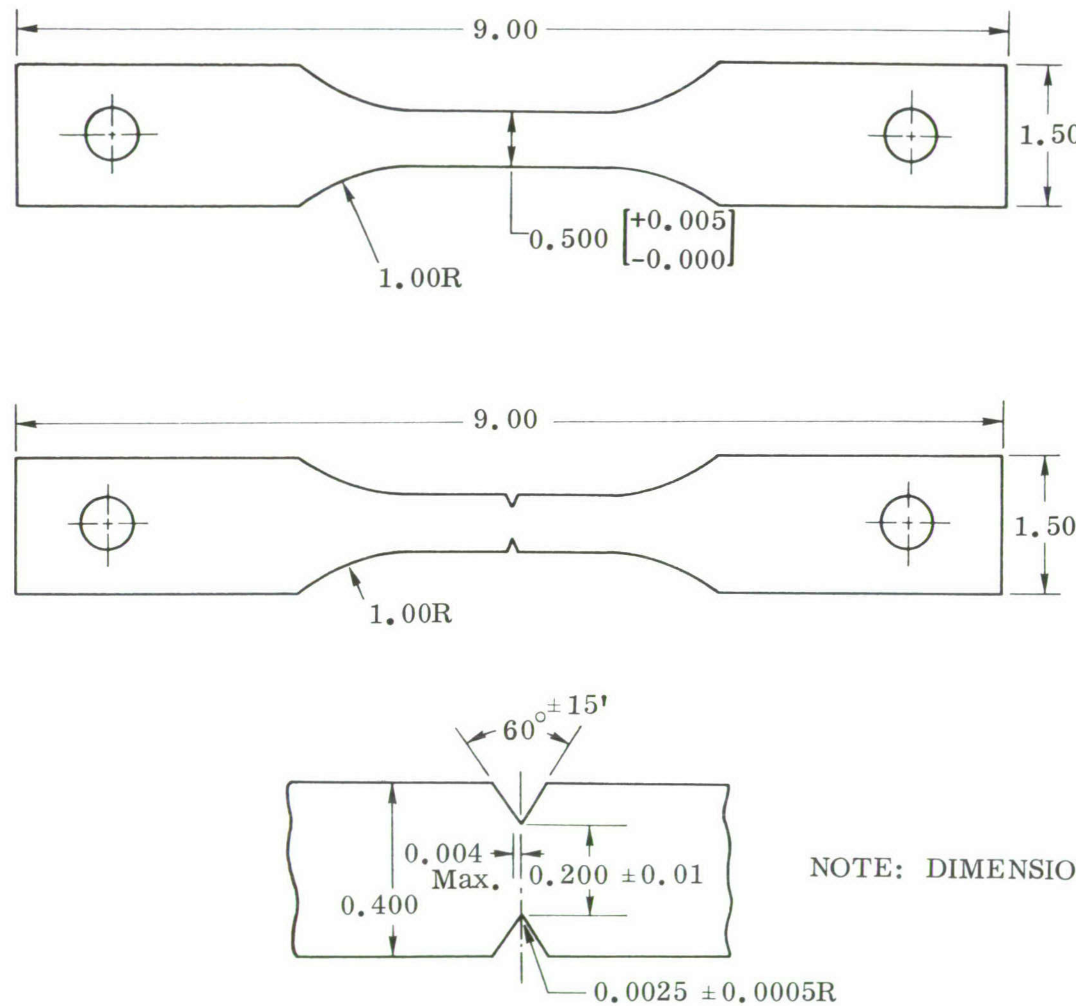
ILLUSTRATIONS



NOTE: DIMENSIONS IN INCHES

Figure 1. Standard Tensile Specimens for Smooth and Notched (K_t=6.3) Tests

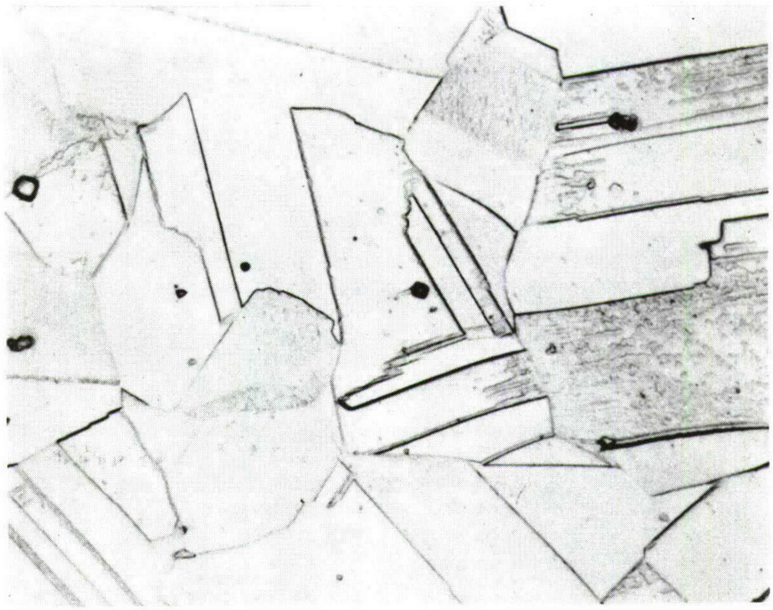


Figure 2. Photomicrograph of Haynes 25 (10% Cold Rolled)
Etchant: Hydrochloric, Chromic Acids, Electrolytic
Magnification: 500 X

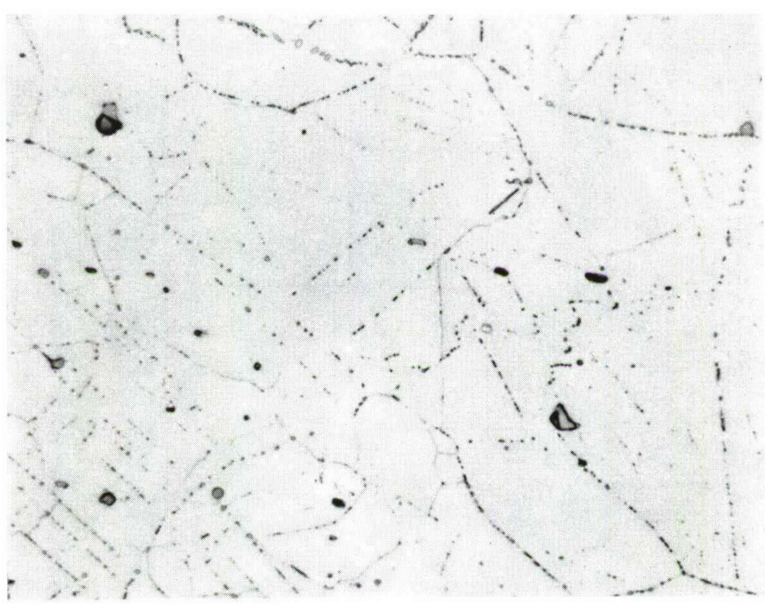


Figure 3. Photomicrograph of Haynes R-41 (Annealed)
Etchant: Marble' s Reagent
Magnification: 500 X

Figure 4. Photmicrograph of Hastelloy R-235 (10% Cold Rolled)
Etchant: Marble' s Reagent
Magnification: 500 X

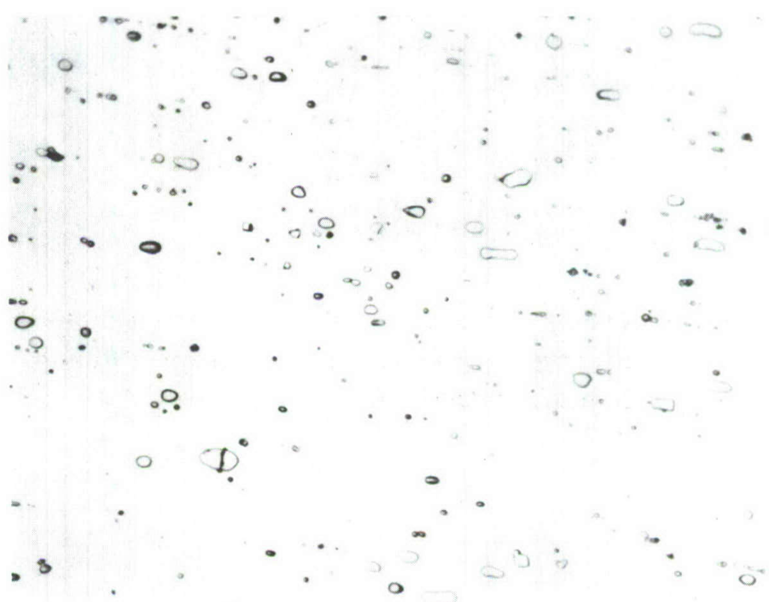


Figure 5. Photomicrograph of Hastelloy X (10% Cold Rolled)
Etchant: 10% Oxalic Acid Electrolytic
Magnification: 500 X

FOR EXTERNAL HOT STRUCTURE

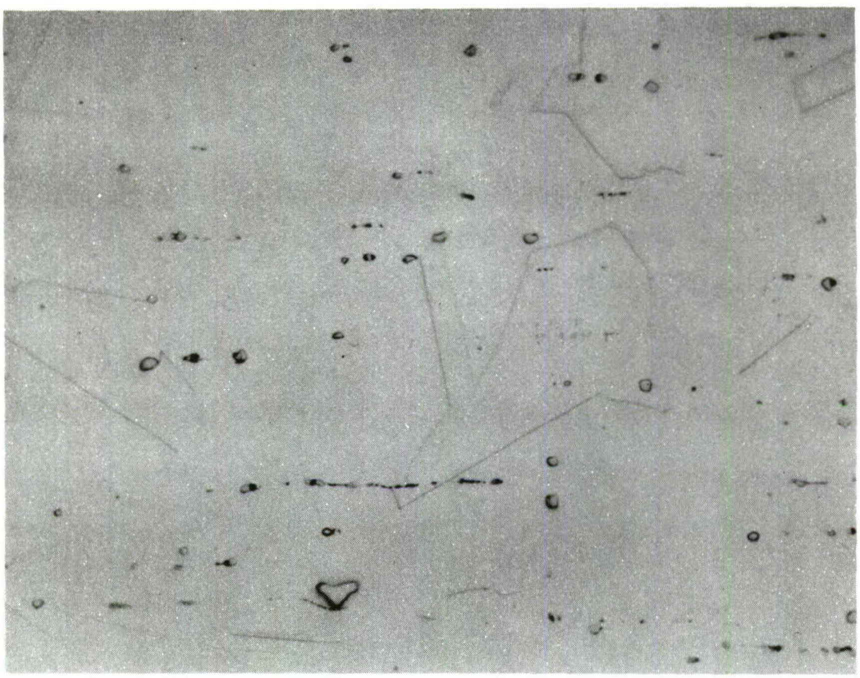


Figure 6. Photomicrograph of Inconel 718 (Annealed)
Etchant: Hydrochloric & Hydrogen Peroxide
Magnification: 500 X

Figure 7. Photomicrograph of Titanium-8Al-1Mo-1V Alloy (Annealed)
Etchant: Kroll' s
Magnification: 500 X

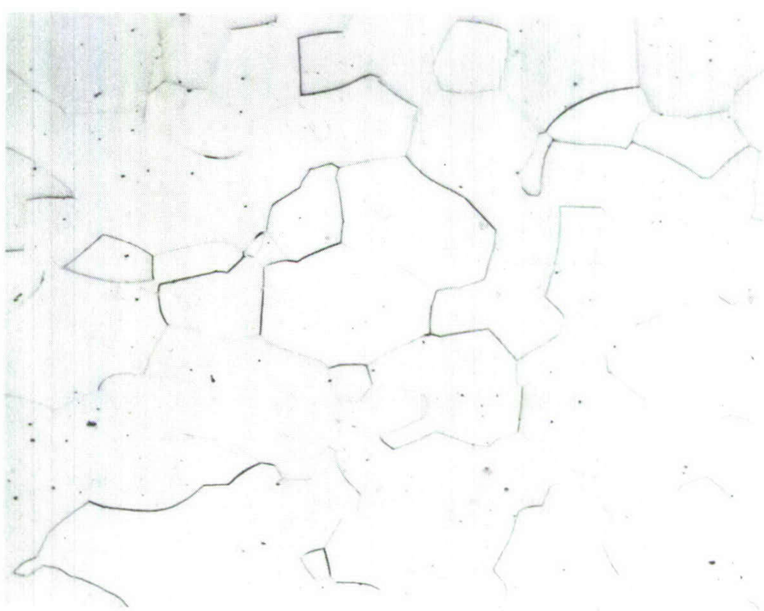


Figure 8. Photomicrograph of Titanium-13V-11Cr-3Al Alloy (Annealed)
Etchant: Modified Kroll' s
Magnification: 500 X

FOR LIQUID OXYGEN TANKAGE

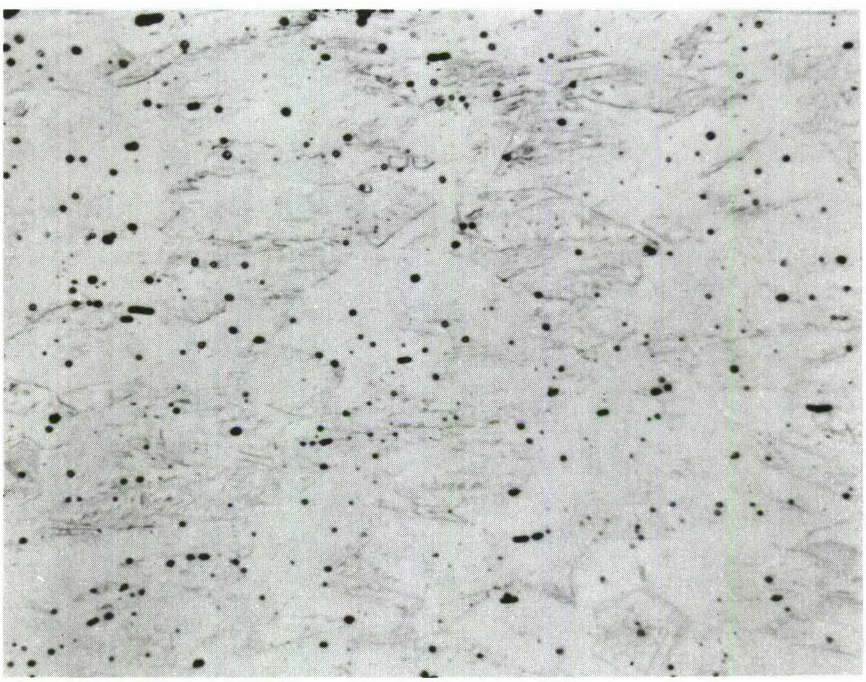


Figure 9. Photomicrograph of Type 301 Stainless Steel (Extra Full Hard)
Etchant: 10% Oxalic Acid, Electrolytic
Magnification: 500 X

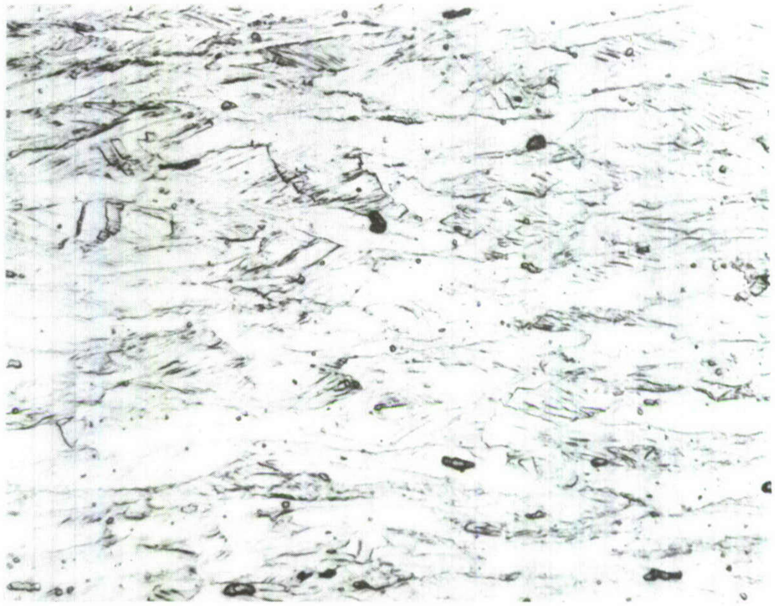


Figure 10. Photomicrograph of Type 310 Stainless Steel (Full Hard)
Etchant: Hydrochloric acid & Hydrogen Peroxide
Magnification: 500 X

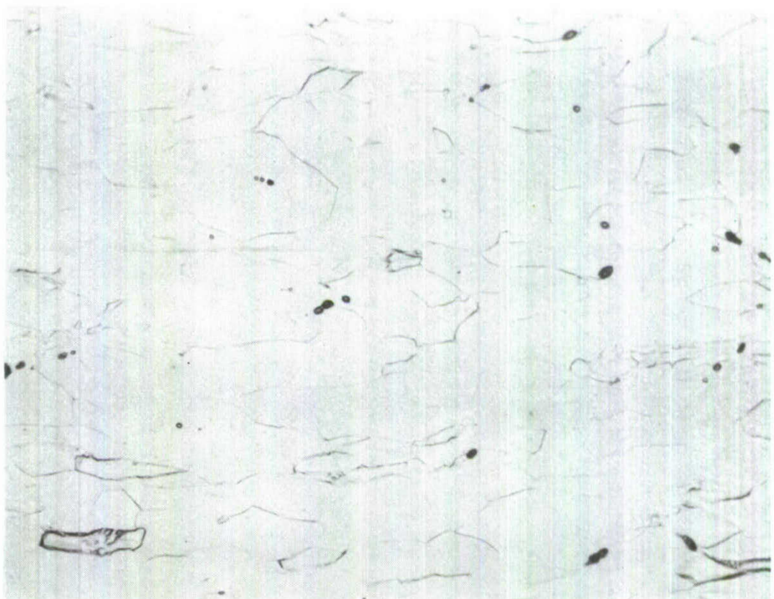


Figure 11. Photomicrograph of Titanium-5A1-2. 5Sn ELI (Annealed)
Etchant: Kroll' s
Magnification: 500 X

Figure 12. Tensile Testing Apparatus Equipped for Elevated Temperature Tests

Figure 13. Resistance Furnace for Elevated
Temperature Tensile Testing

Figure 14. Liquid-Hydrogen Cryostat for Tensile Testing at -423°F

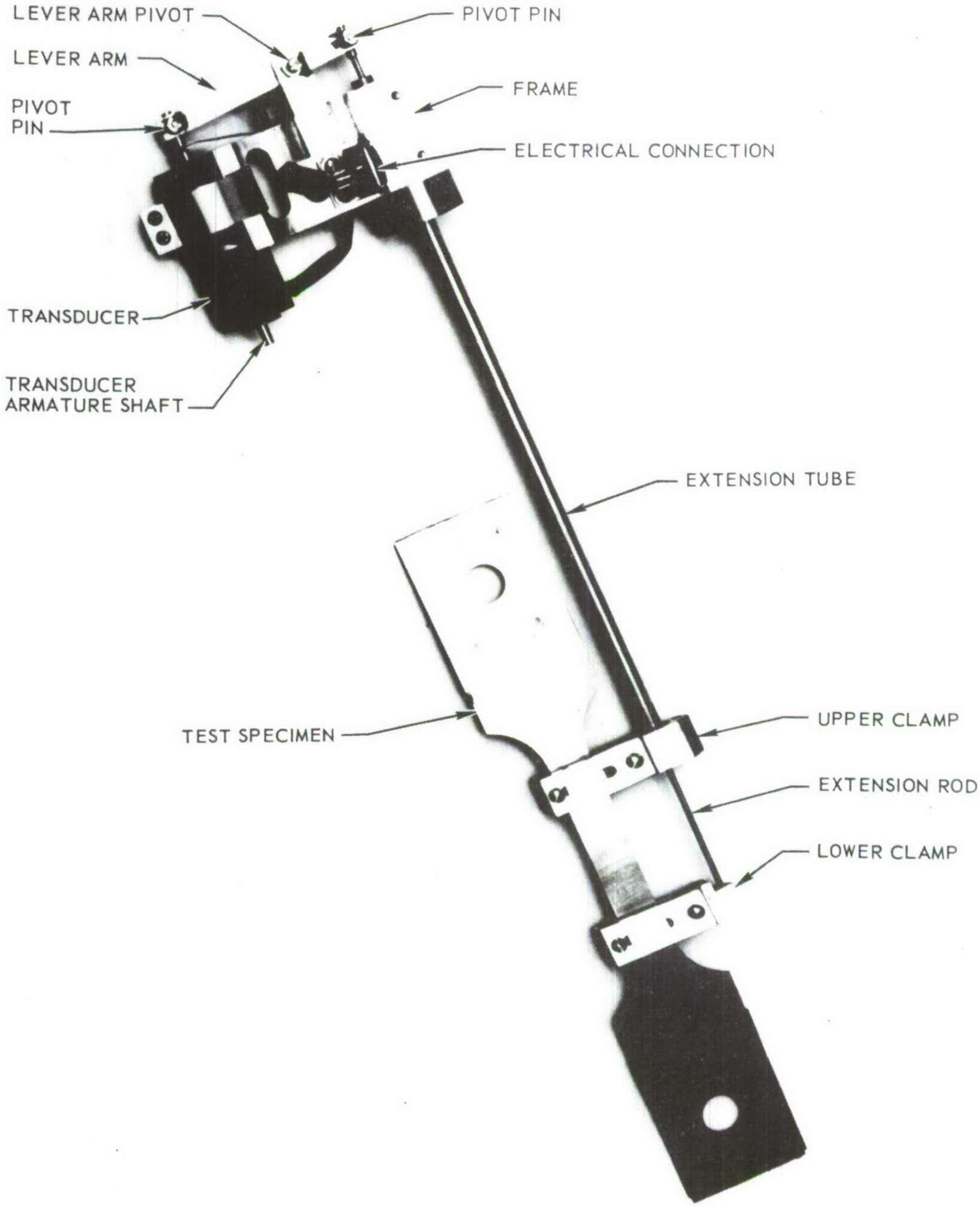


Figure 15. Cryo-Extensometer Assembly

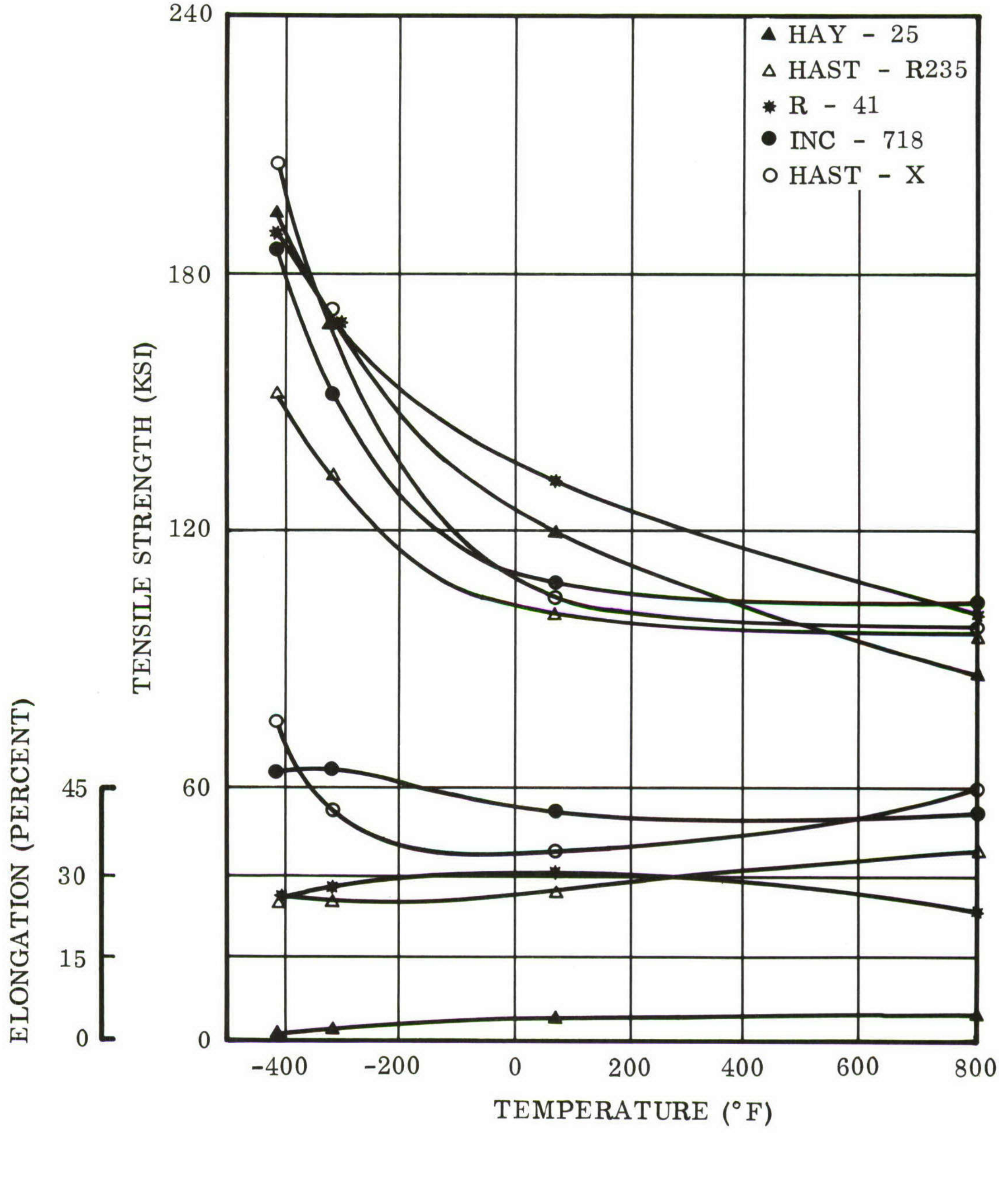


Figure 16. Tensile Strength and Elongation of Haynes 25, Haynes R-41, Hastelloy R-235, Hastelloy X, Inconel 718 at Various Test Temperatures (Longitudinal Direction)

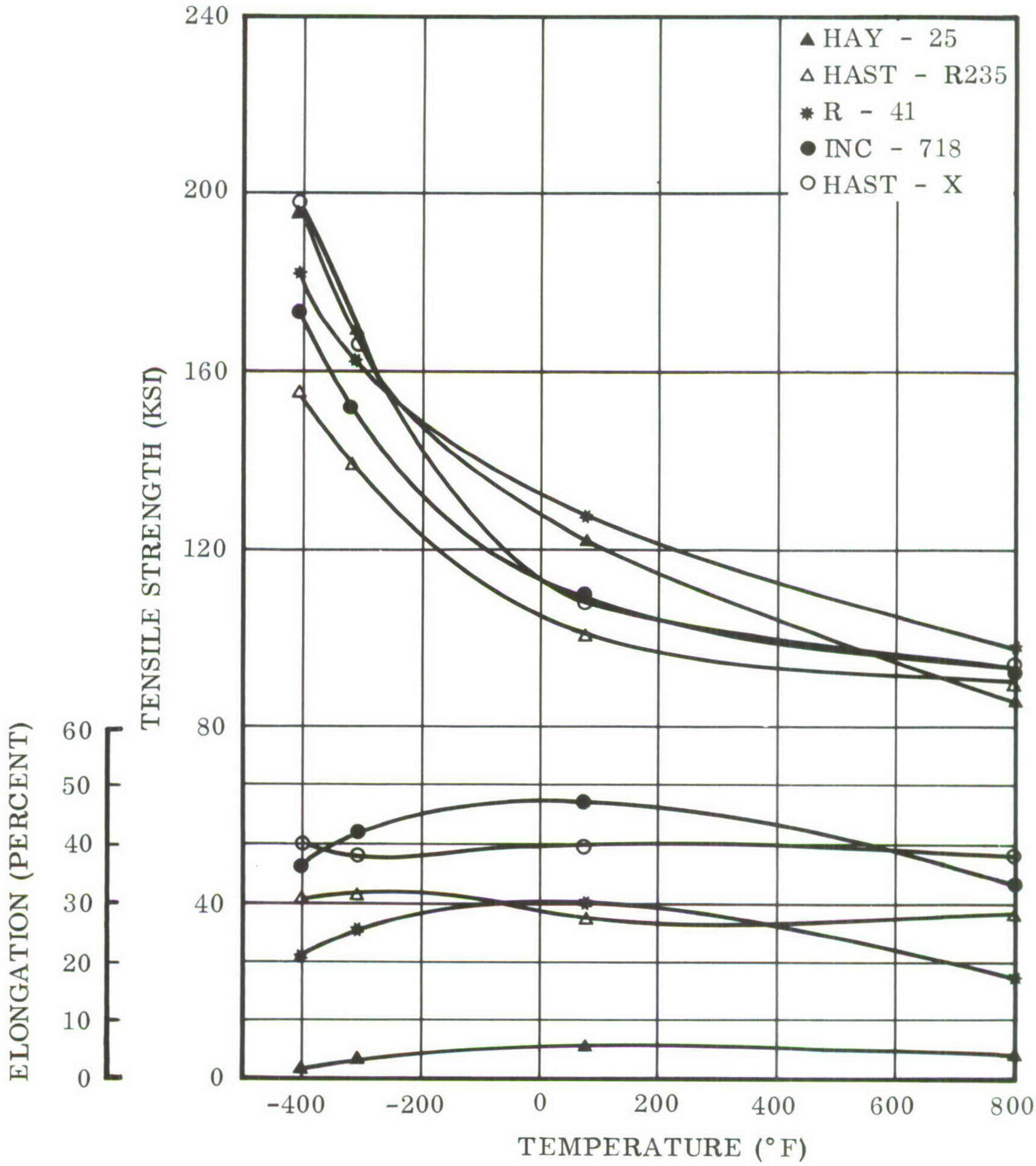


Figure 17. Tensile Strength and Elongation of Haynes 25, Haynes R-41, Hastelloy R-235, Hastelloy X, Inconel 718 at Various Test Temperatures (Transverse Direction)

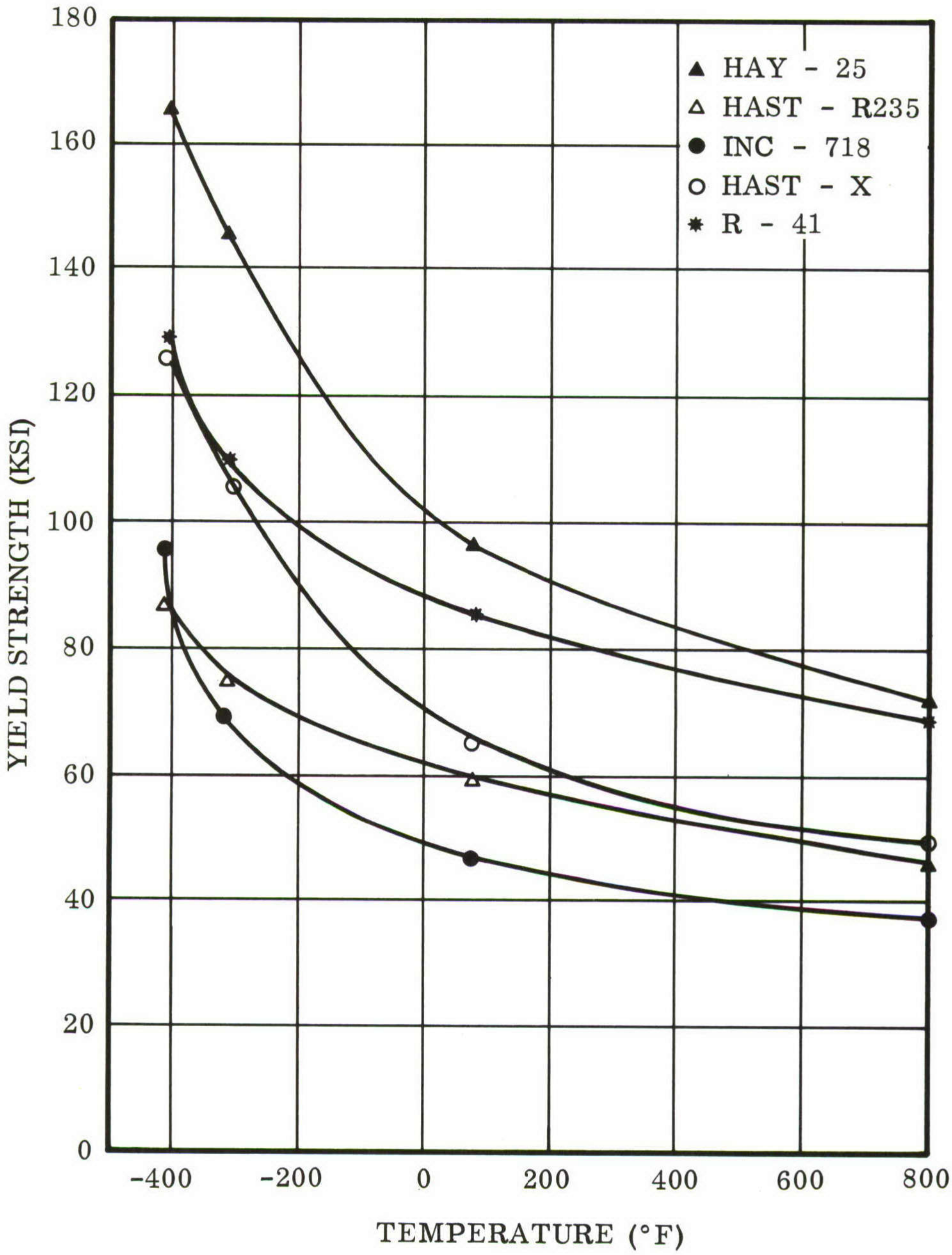


Figure 18. Yield Strength of Haynes 25, Haynes R-41, Hastelloy R-235, Hastelloy X, Inconel 718 at Various Test Temperatures (Longitudinal Direction)

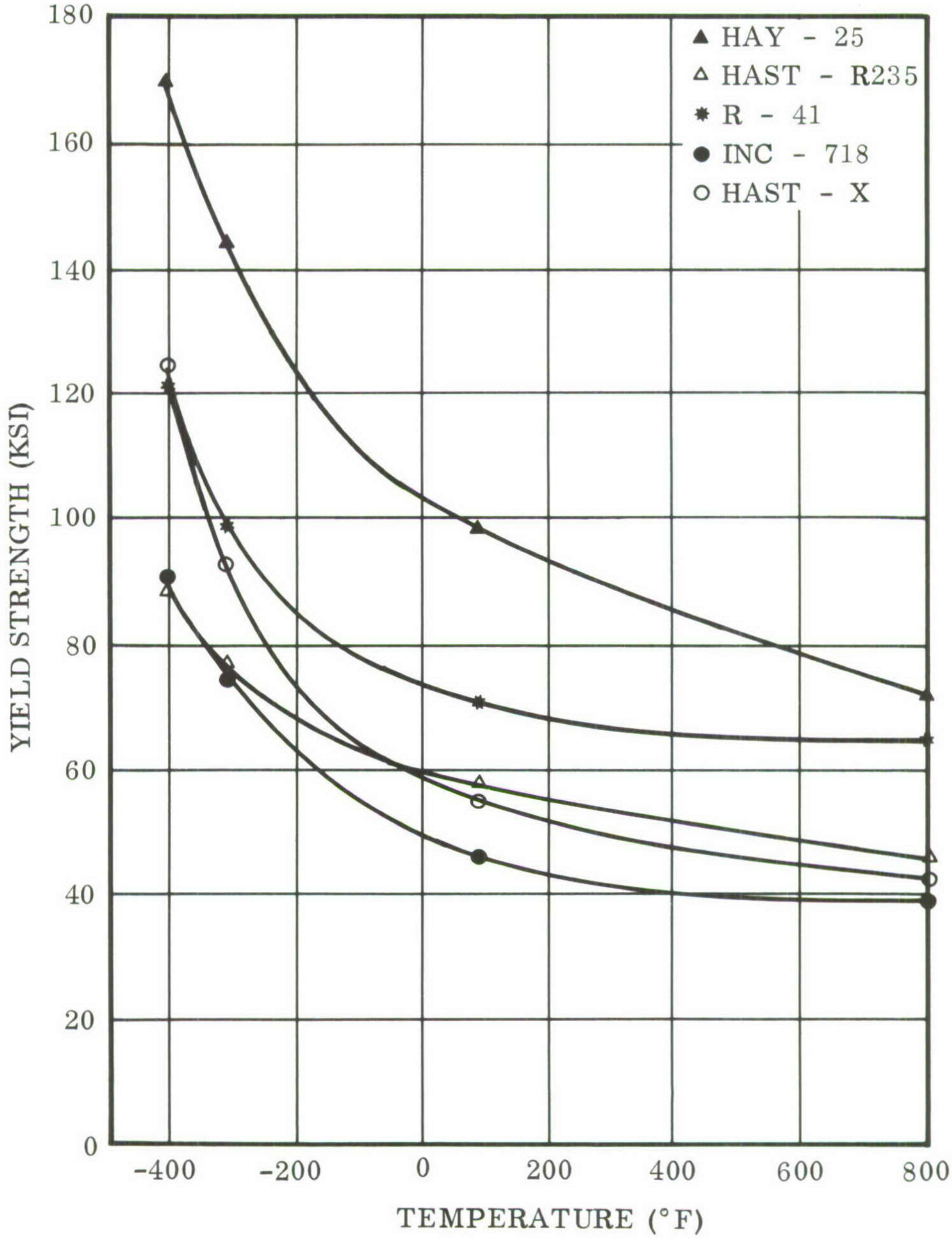


Figure 19. Yield Strength of Haynes 25, Haynes R-41, Hastelloy R-235, Hastelloy X, Inconel 718 at Various Test Temperatures (Transverse Direction)

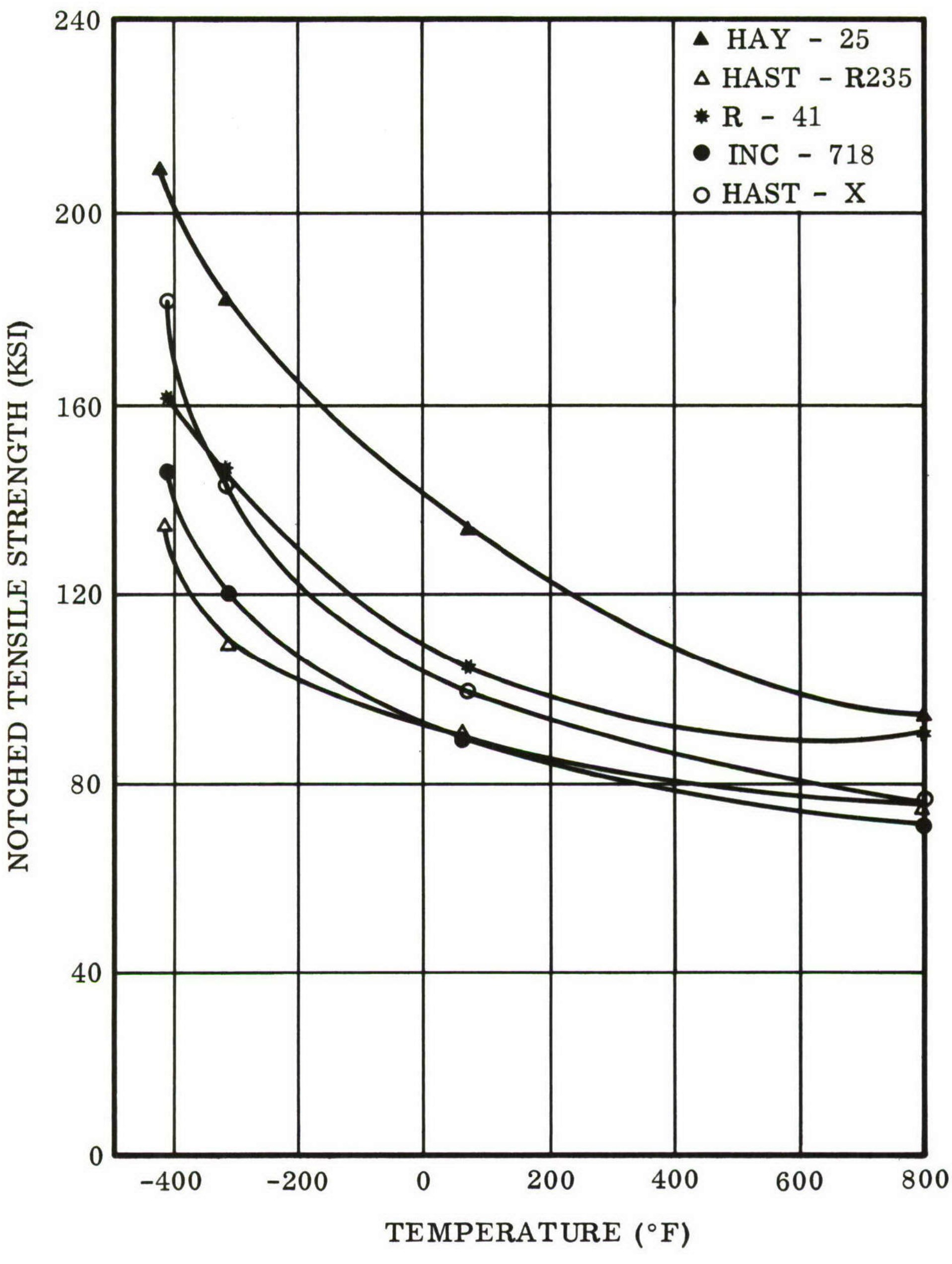


Figure 20. Notched Tensile Strength ($K_t = 6.3$) of Haynes 25, Haynes R-41, Hastelloy R-235, Hastelloy X, Inconel 718 at Various Test Temperatures (Longitudinal Direction)

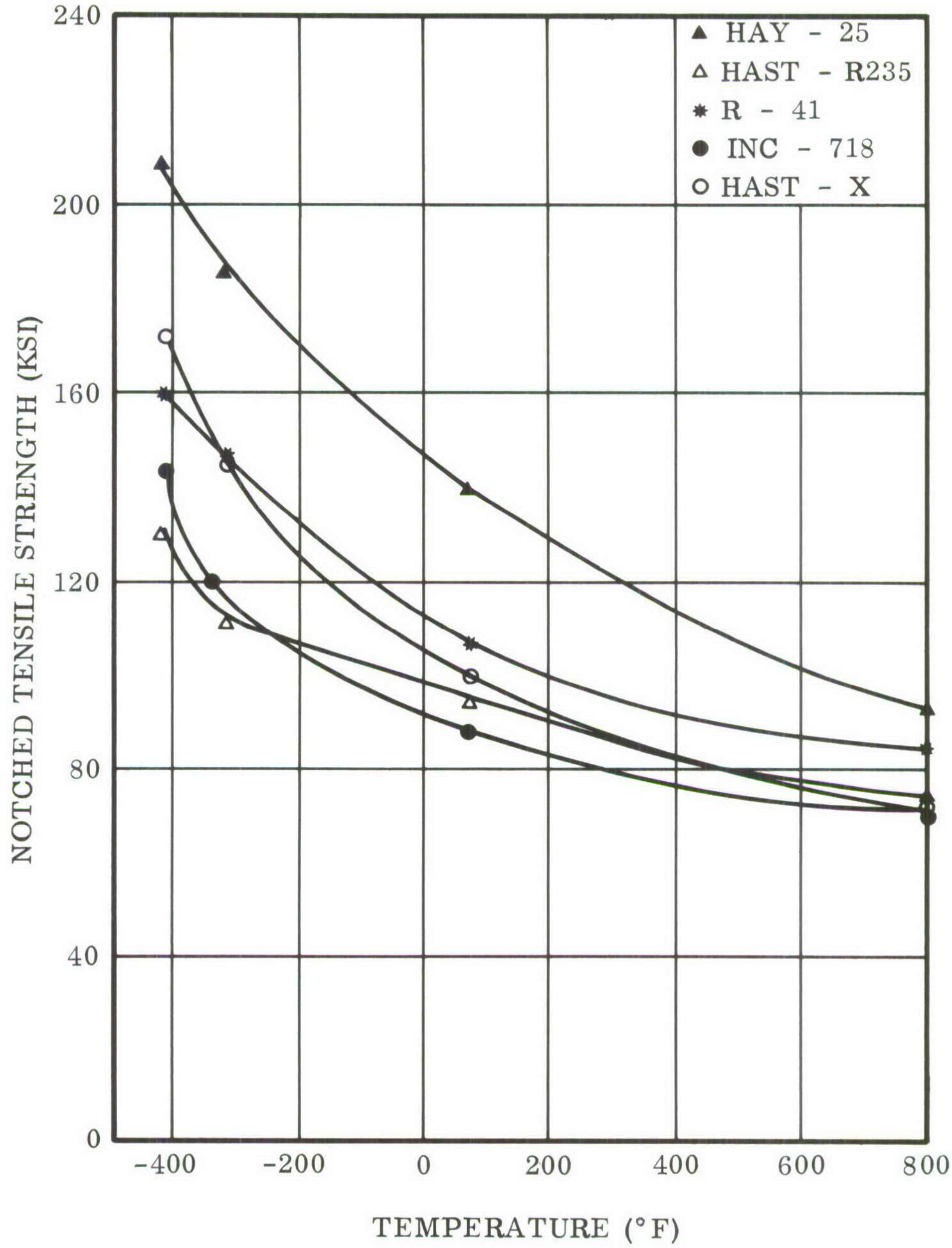


Figure 21. Notch Tensile Strength ($K_t = 6.3$) of Haynes 25, Haynes R-41, Hastelloy R-235, Hastelloy X, Inconel 718 at Various Test Temperatures (Transverse Direction)

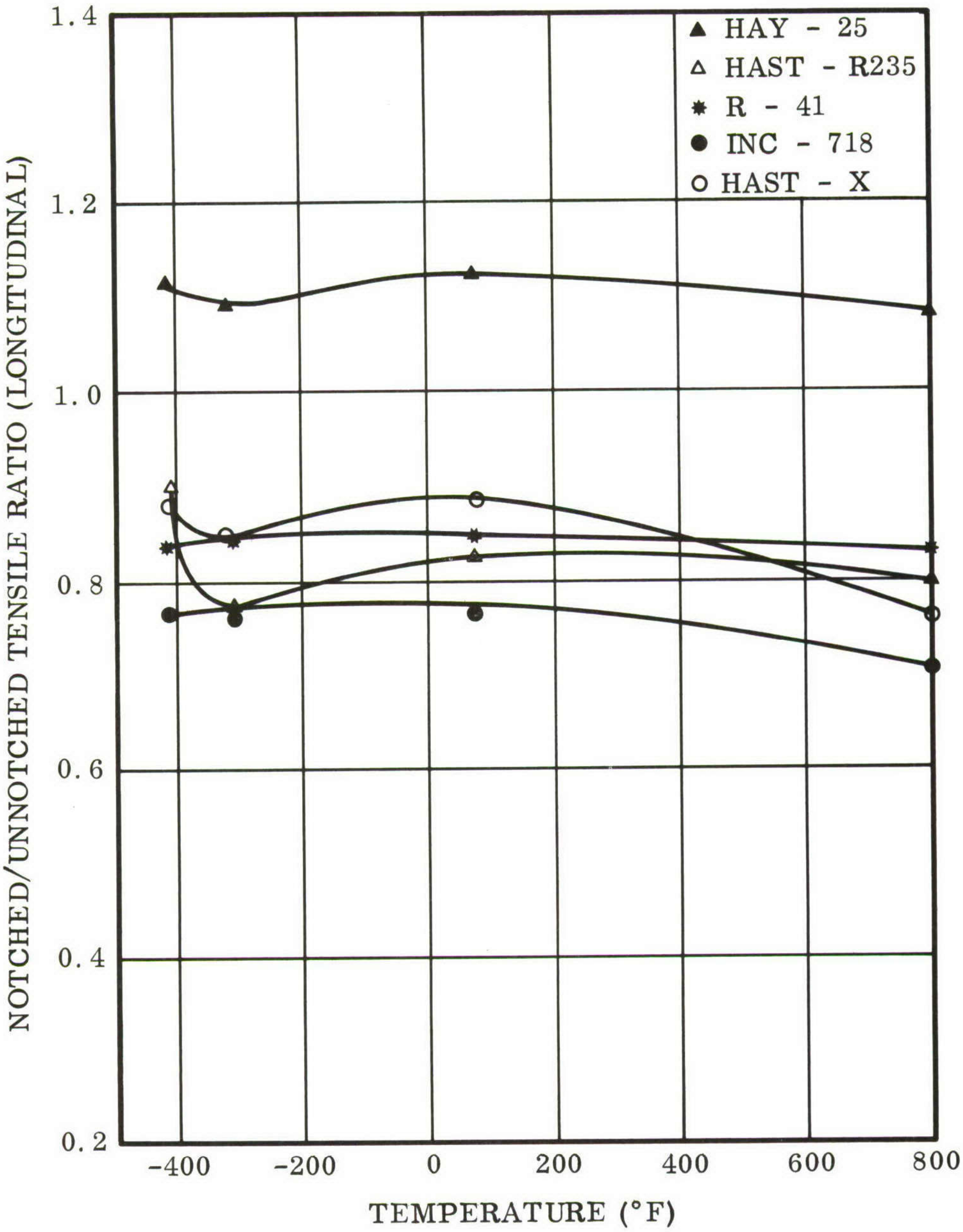


Figure 22. Notch/Unnotched Tensile Ratio of Haynes 25, Haynes R-41, Hastelloy R-235, Hastelloy X, Inconel 718 at Various Test Temperatures (Longitudinal Direction)

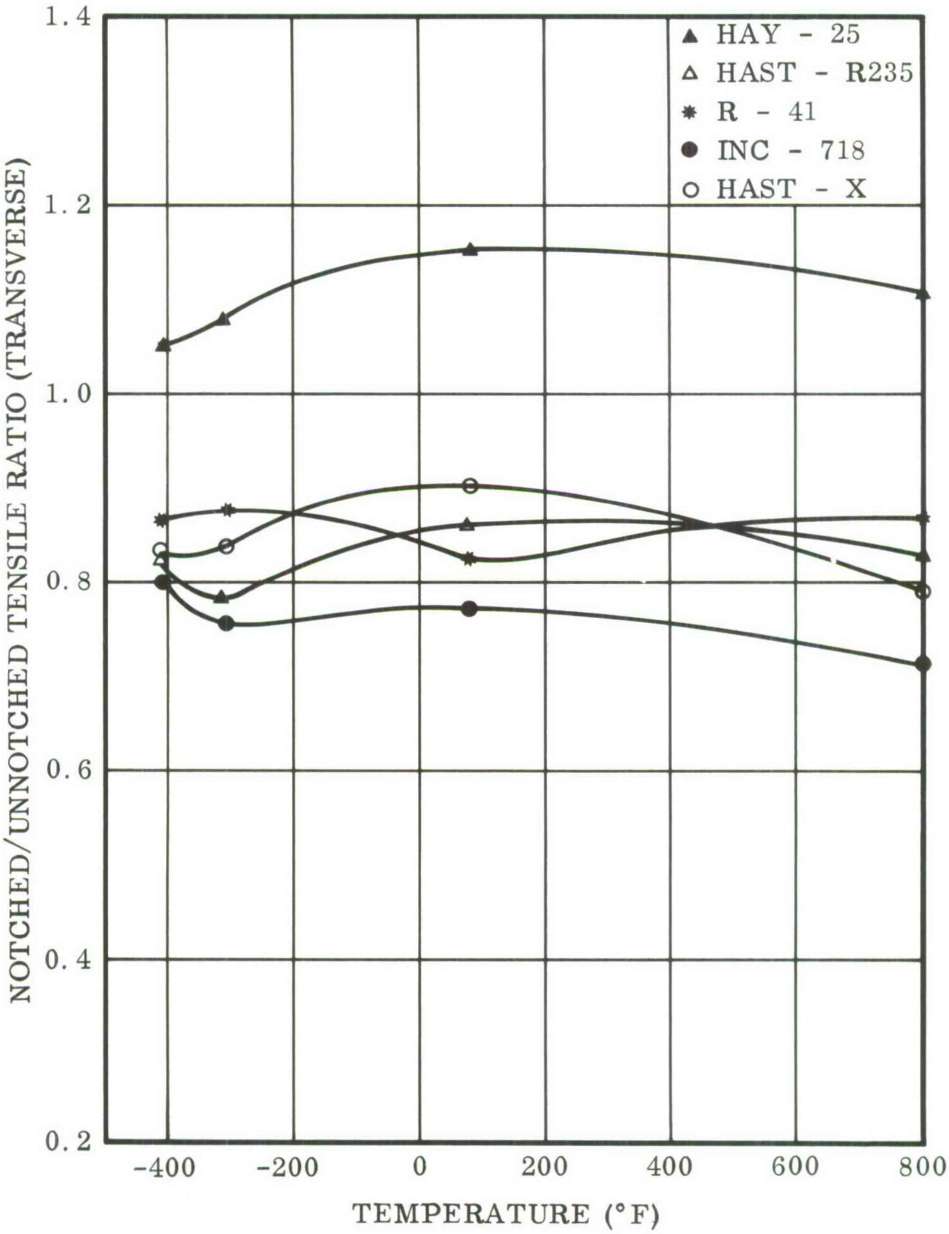


Figure 23. Notch/Unnotched Tensile Ratio of Haynes 25, Haynes R-41, Hastelloy R-235, Hastelloy X, Inconel 718 at Various Test Temperatures (Transverse Direction)

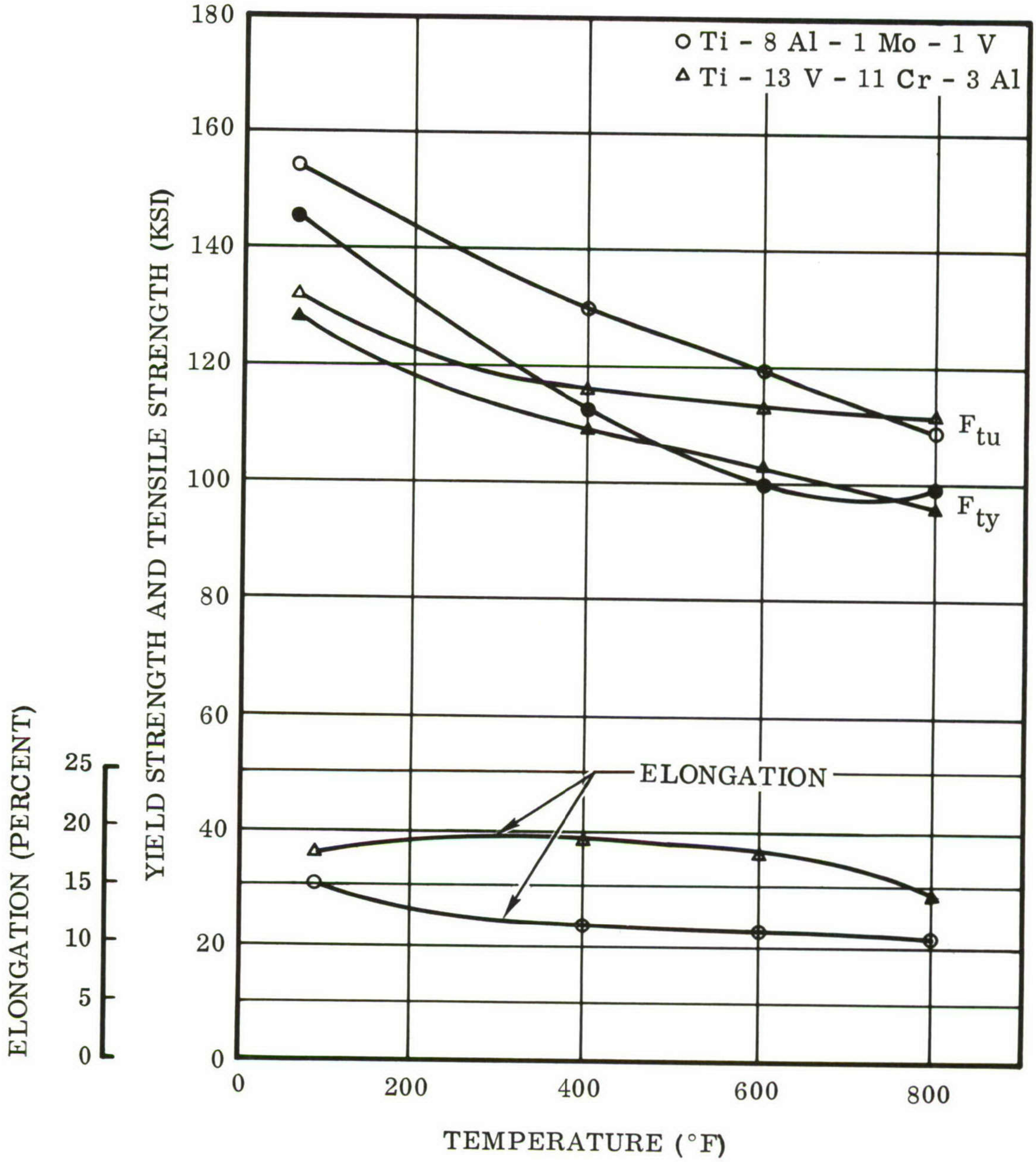


Figure 24. Mechanical Properties of Titanium-8Al-1Mo-1V Alloy and Titanium-13V-11Cr-3Al Alloy at Various Test Temperatures (Longitudinal Direction)

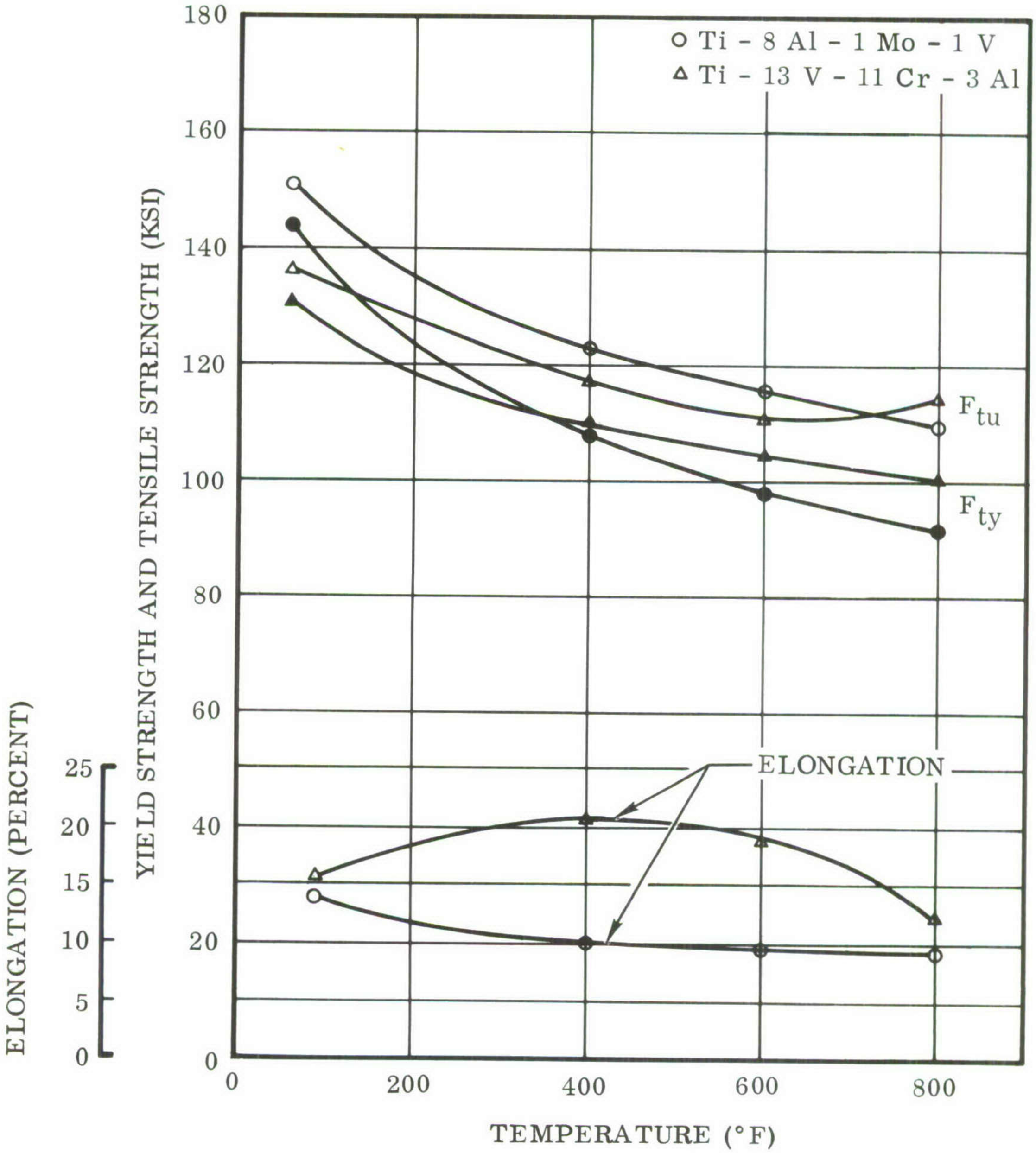


Figure 25. Mechanical Properties of Titanium-8Al-1Mo-1V Alloy and Titanium-13V-11Cr-3Al Alloy at Various Test Temperatures (Transverse Direction)

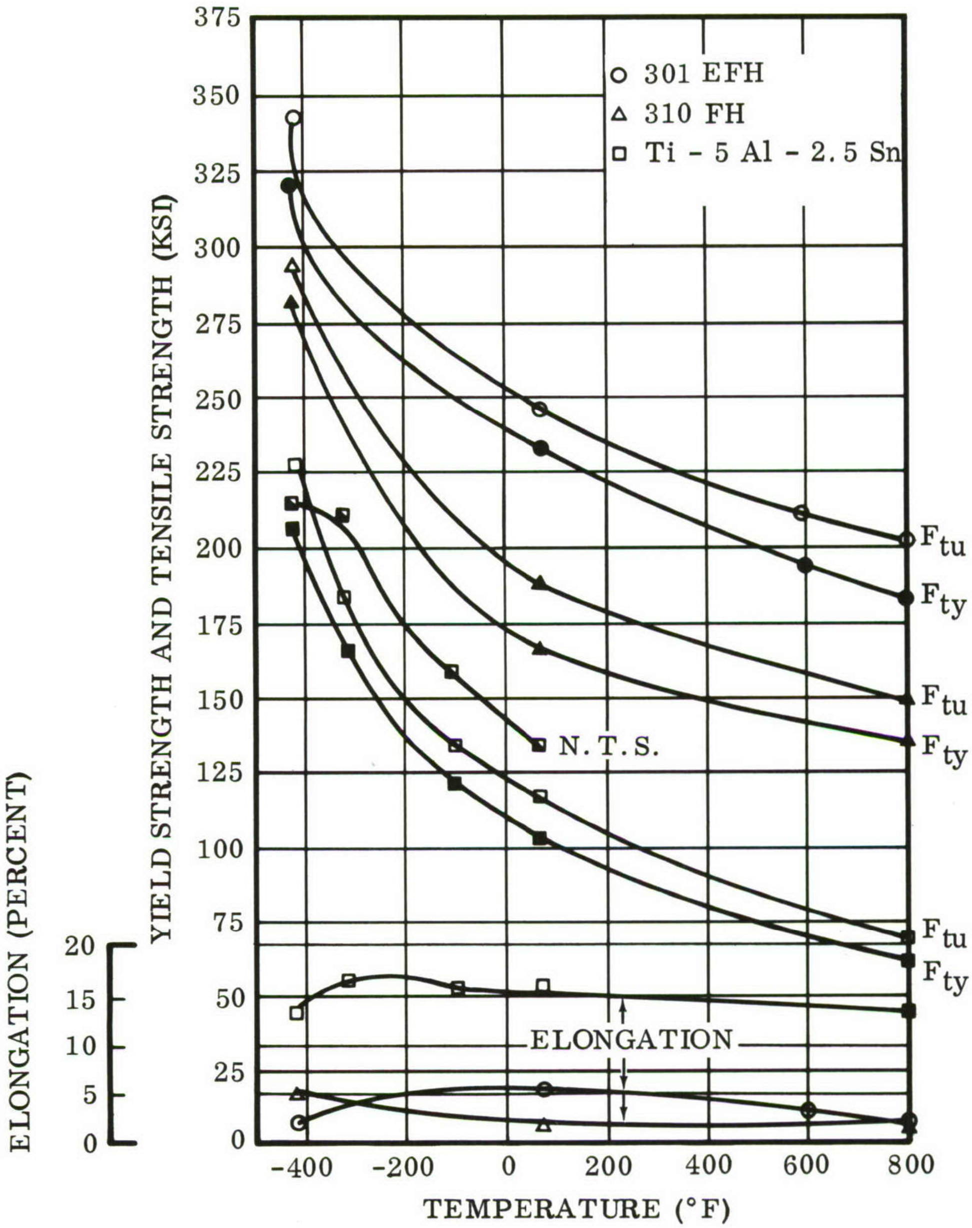


Figure 26. Mechanical Properties of Type 301 and 310 Stainless Steel and Titanium-5Al-2.5 Sn Alloy at Various Test Temperatures (Longitudinal Direction)

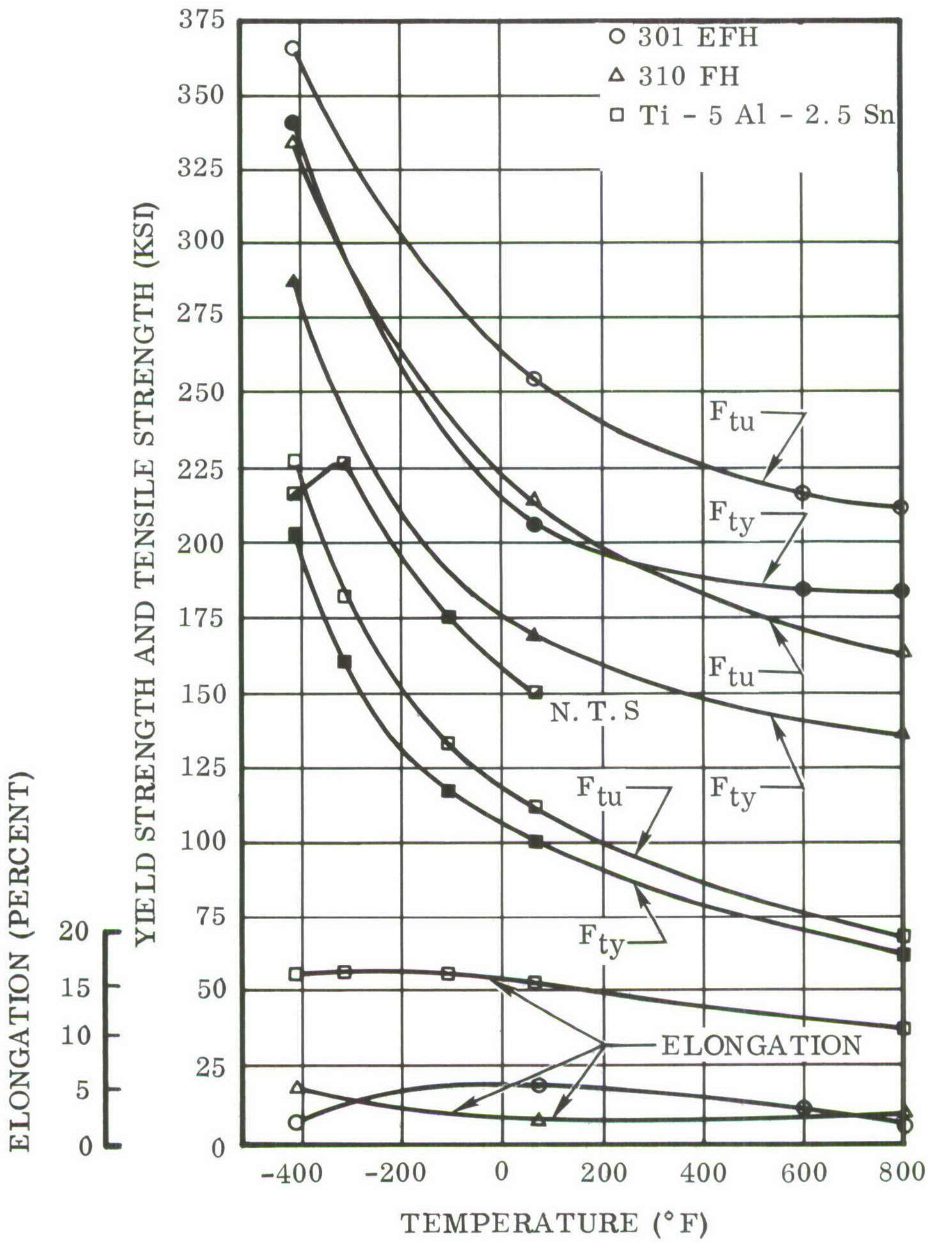


Figure 27. Mechanical Properties of Type 301 and 310 Stainless Steel and Titanium-5Al-2.5Sn Alloy at Various Test Temperatures (Transverse Direction)

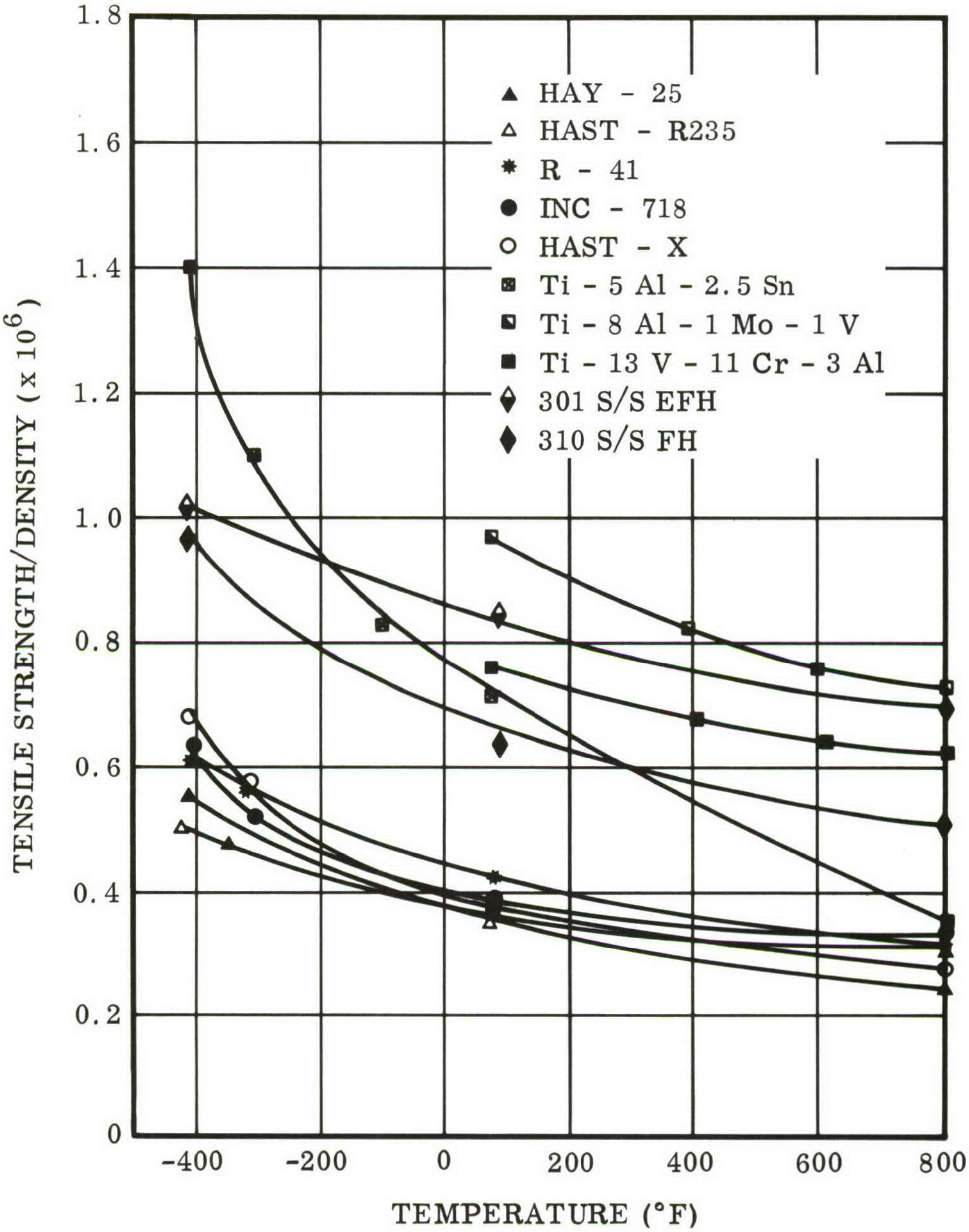


Figure 28. Tensile Strength - Density of Screening Test Alloys at Various Test Temperatures

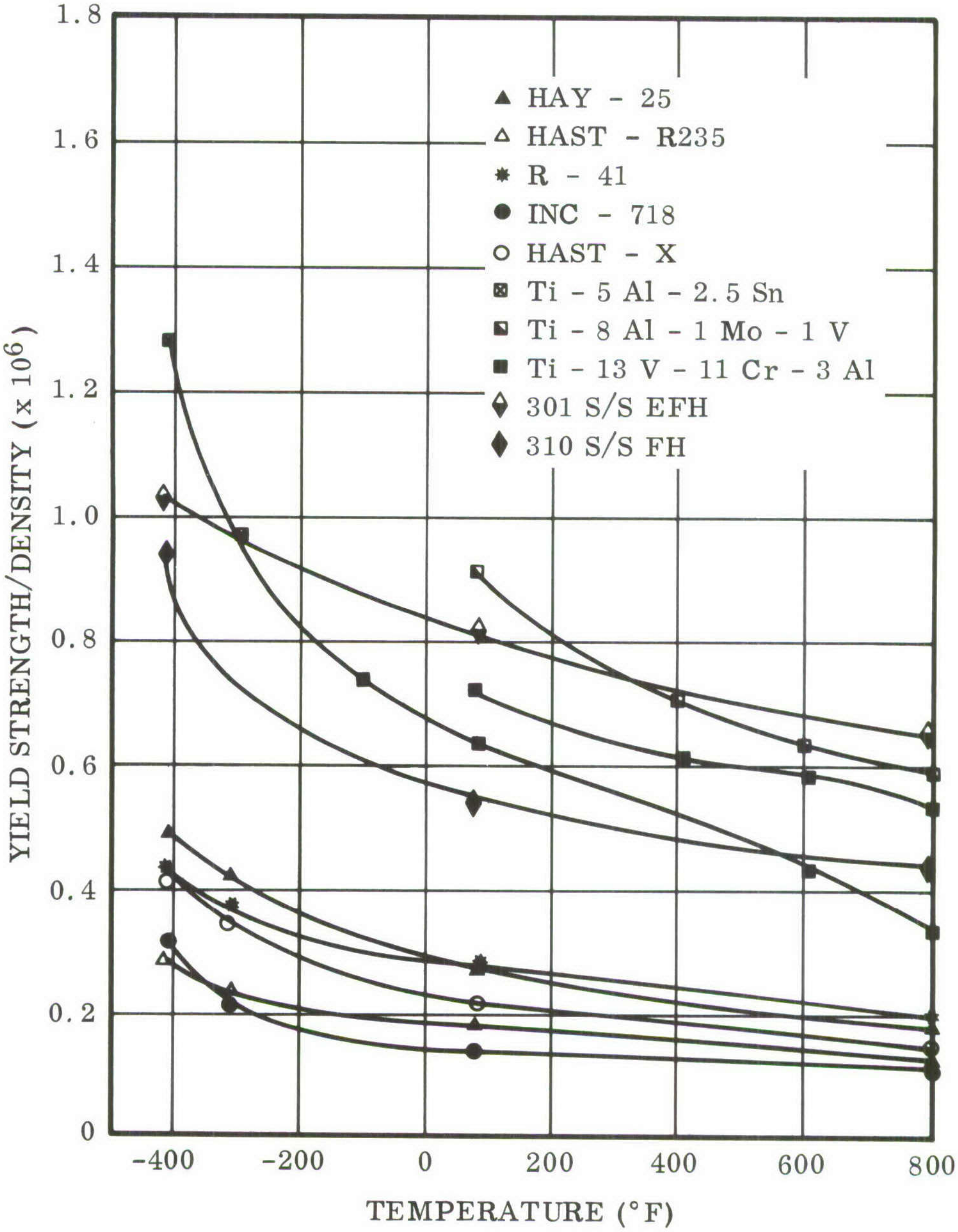
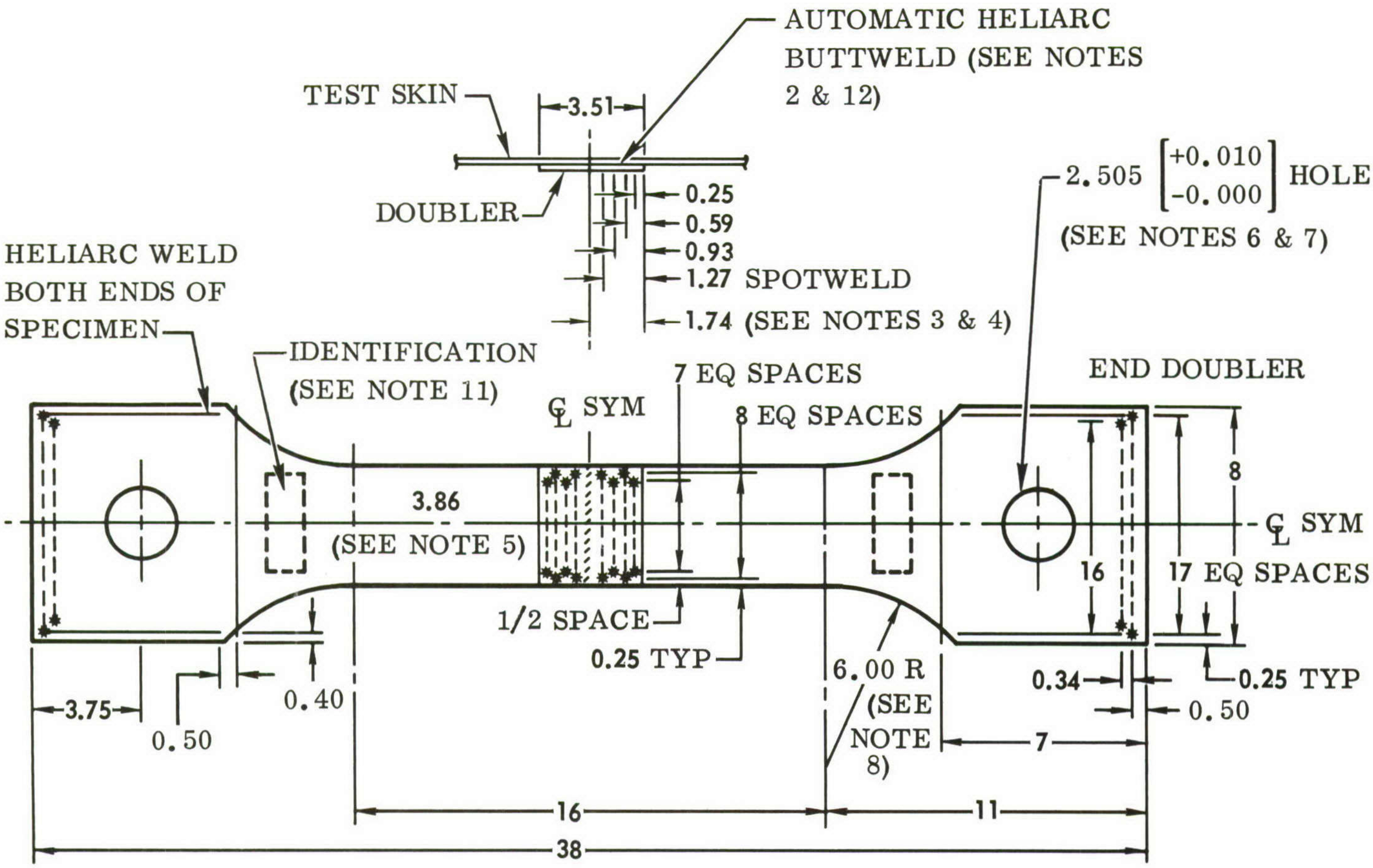


Figure 29. Yield Strength - Density of Screening Test Alloys at Various Test Temperatures

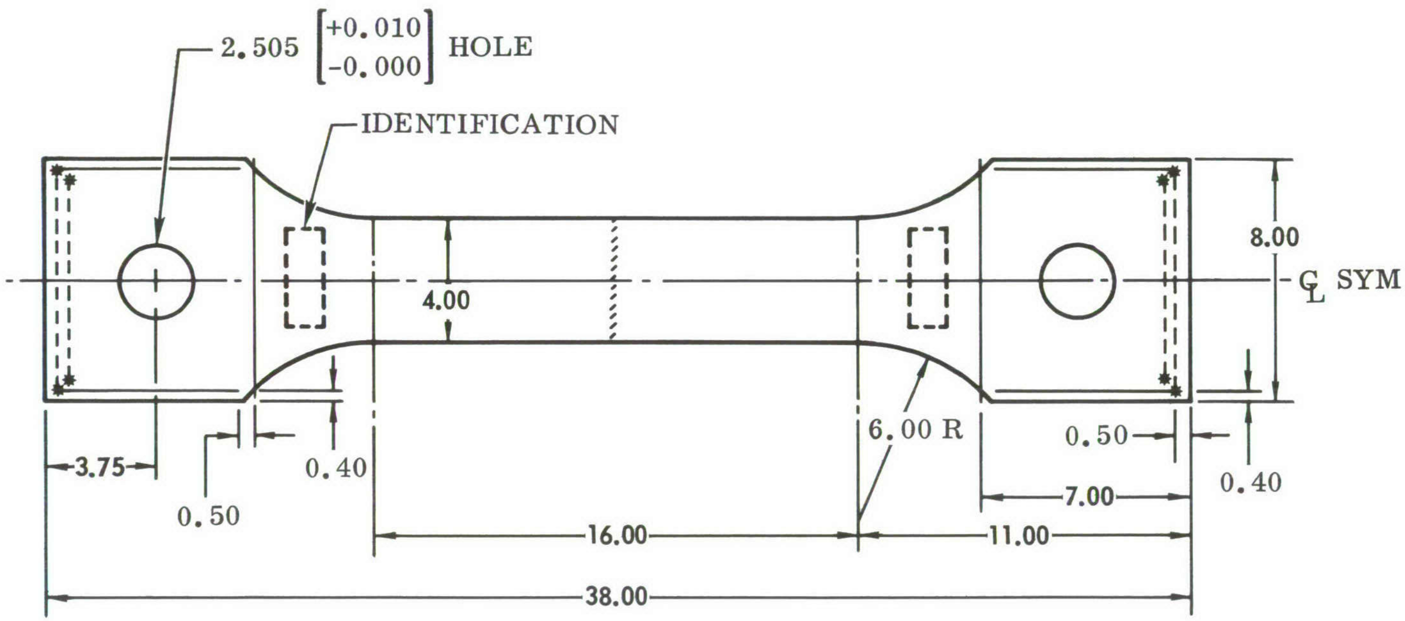


NOTE: Dimensions in Inches

NOTES

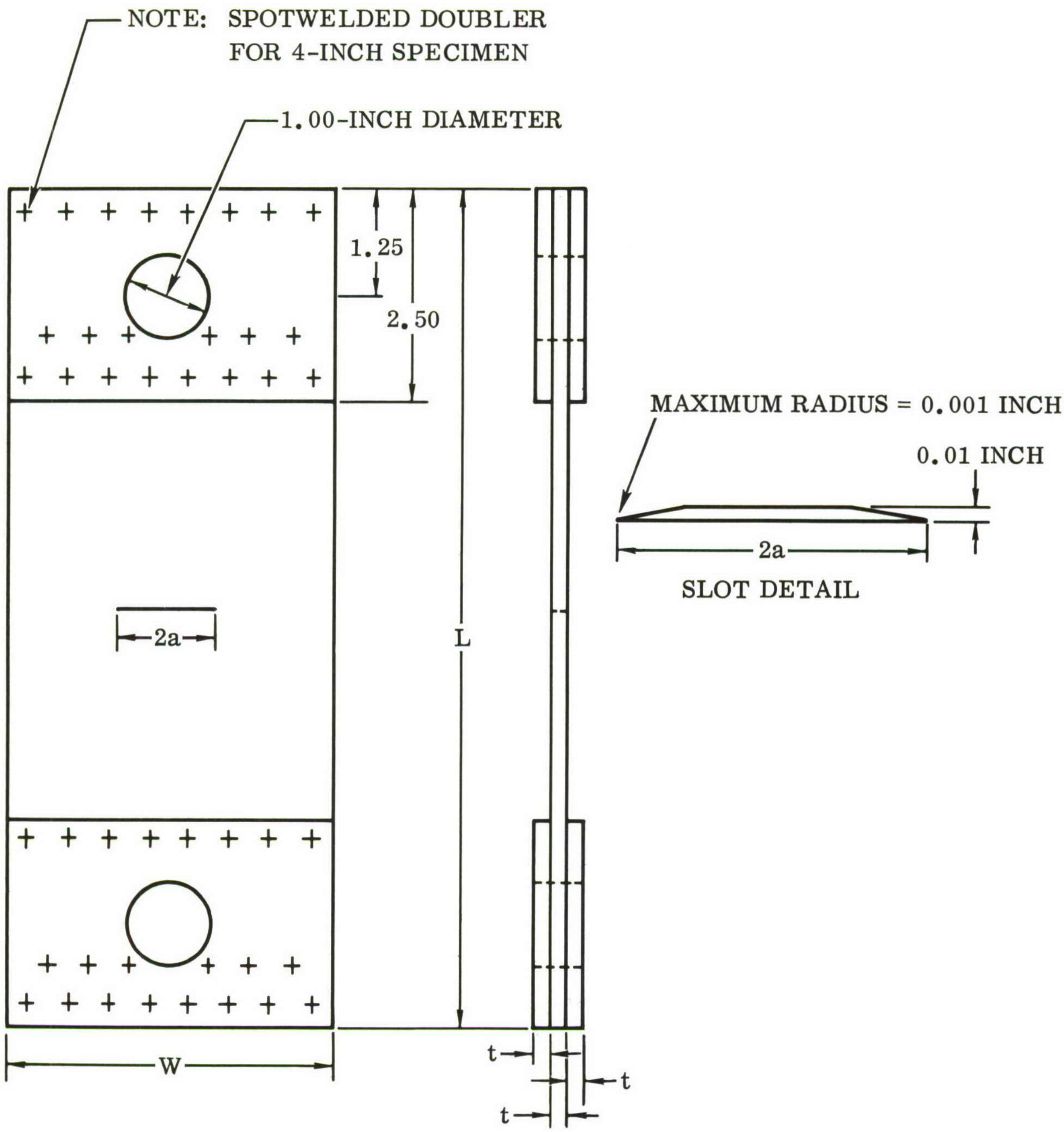
1. Metal stamping of parts not permitted.
2. Buttweld test skins prior to machining.
3. Spotwelds per spec MIL-W-6858A.
4. Tolerance on location of spotwelds to be ±0.06.
5. Test section width minimum at center. Total taper to be 0.010 from one end to center.
6. Edges of skin must be sharp and free from burrs.
7. Holes to be centered with test section ±0.015.
8. In radius no notches or undercuts permitted.
9. Material spec to be called out with specimen request.
10. Edges of test skin to be machined to 125√ finish.
11. Each specimen to have gage, coil, heat, spec and specimen number.
12. Heliarc buttwelds per spec 0-75005.

Figure 30. Axial Fatigue Specimen for 301 Stainless Steel



NOTE: Dimensions in Inches

Figure 31. Axial Fatigue Specimen for Titanium Alloys



W	L	2a
4	10	1.25

NOTE: Dimensions in Inches

Figure 32. Center-Notch Specimen

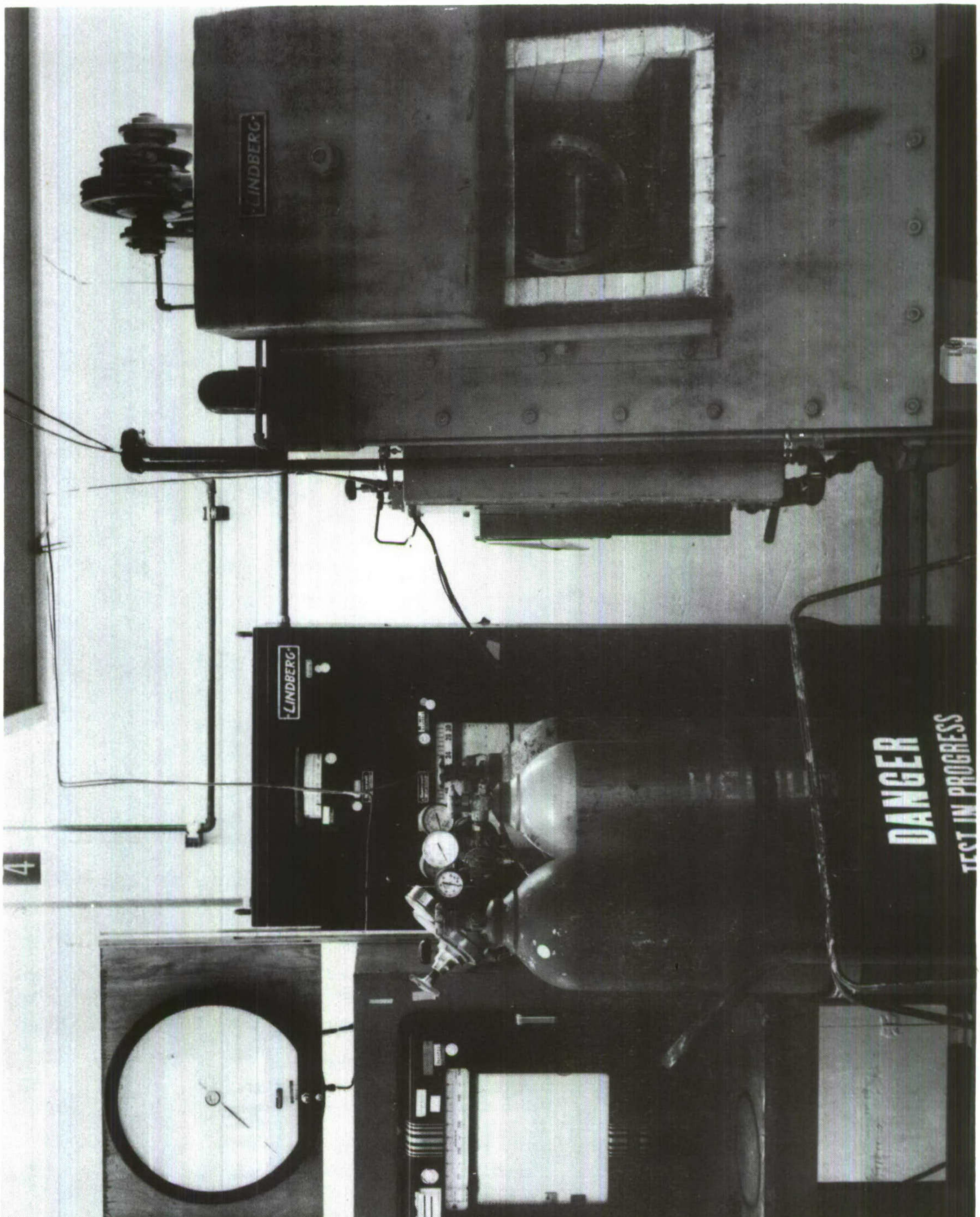


Figure 33. General View of Gaseous Exposure Test Apparatus

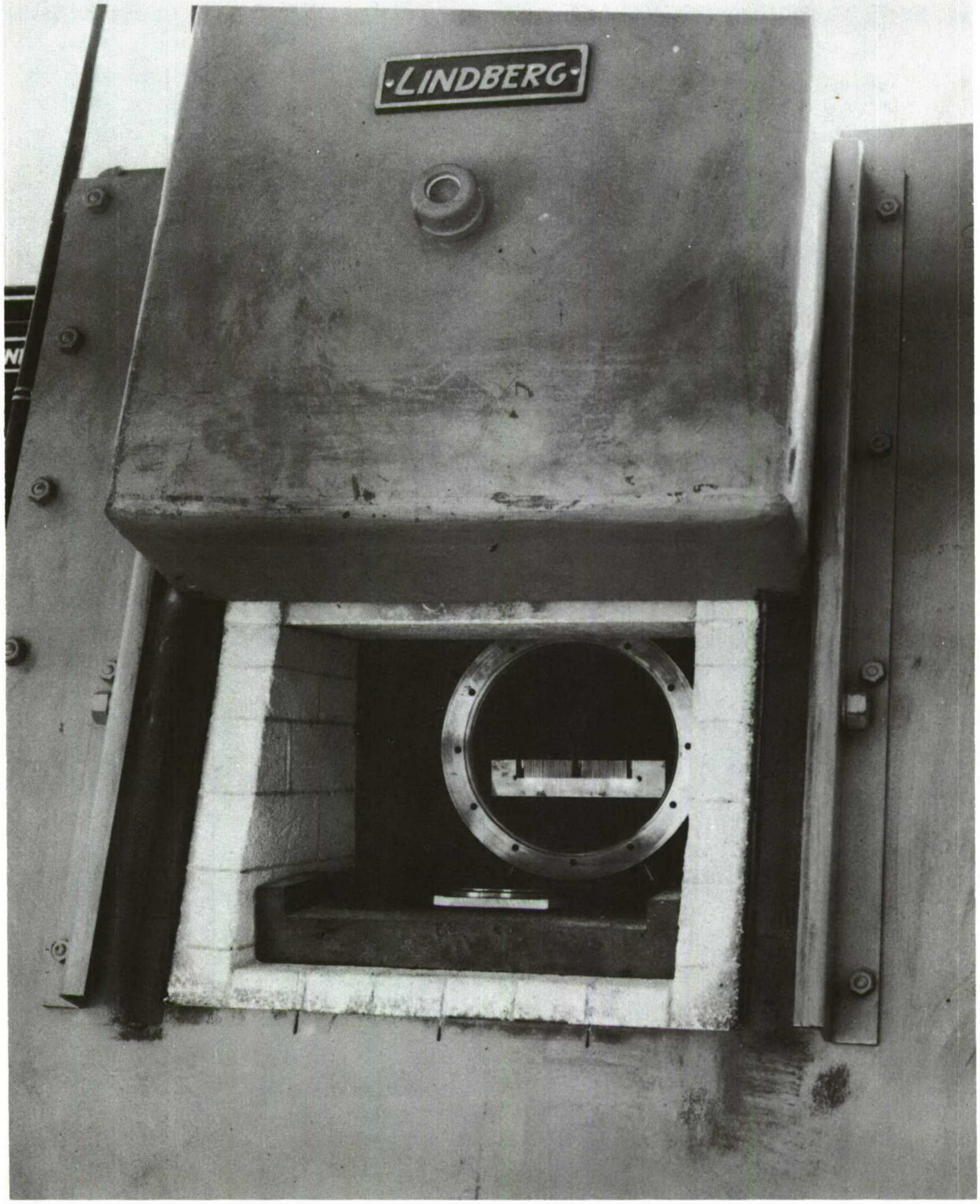


Figure 34. Close-Up View of Gaseous Exposure Test Retort Containing Specimen Fixture

Figure 35. Retort

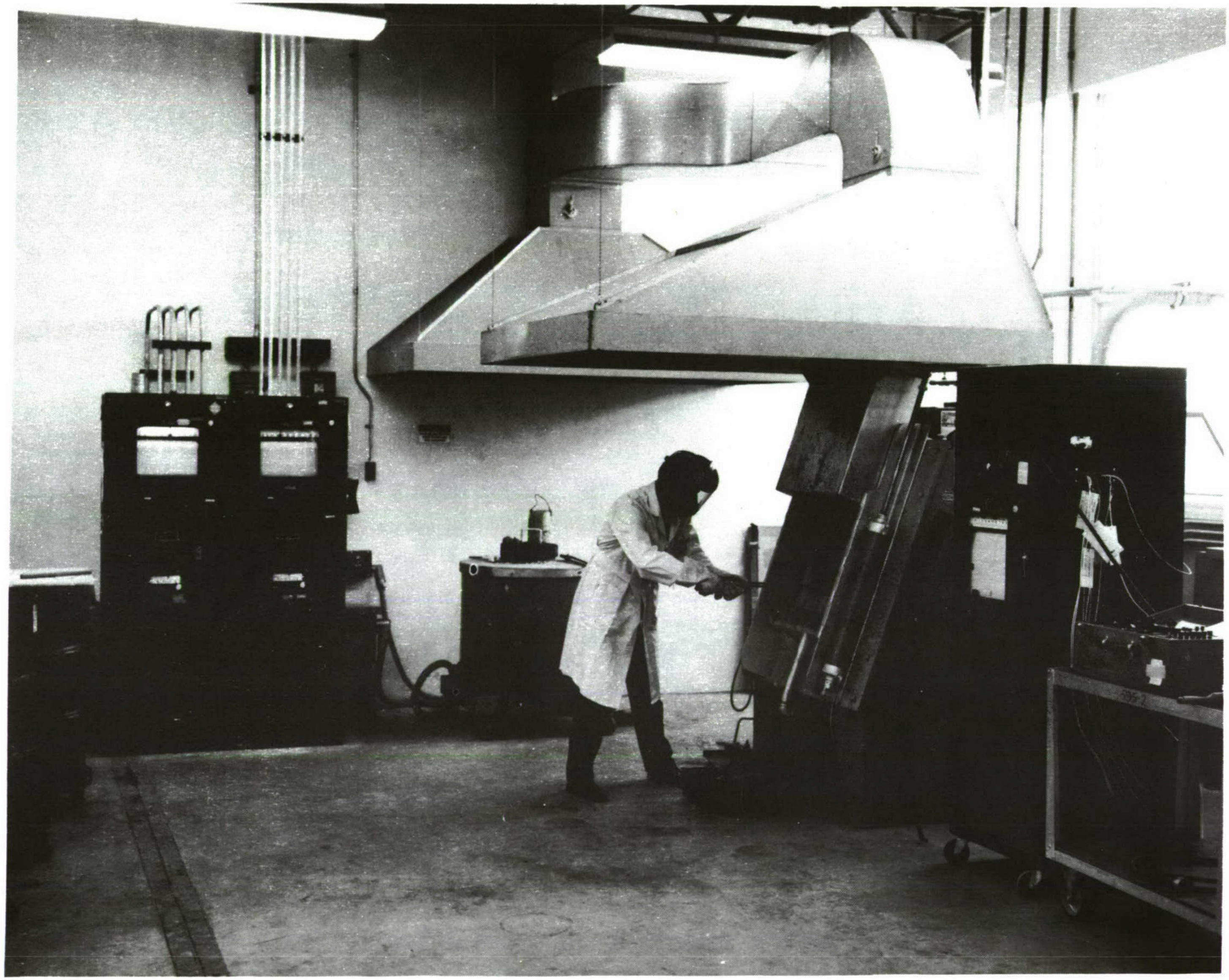


Figure 36. Glo-Bar Box Furnace

Figure 37. Apparatus for Oxidation Exposures (1600 to 2200°F)

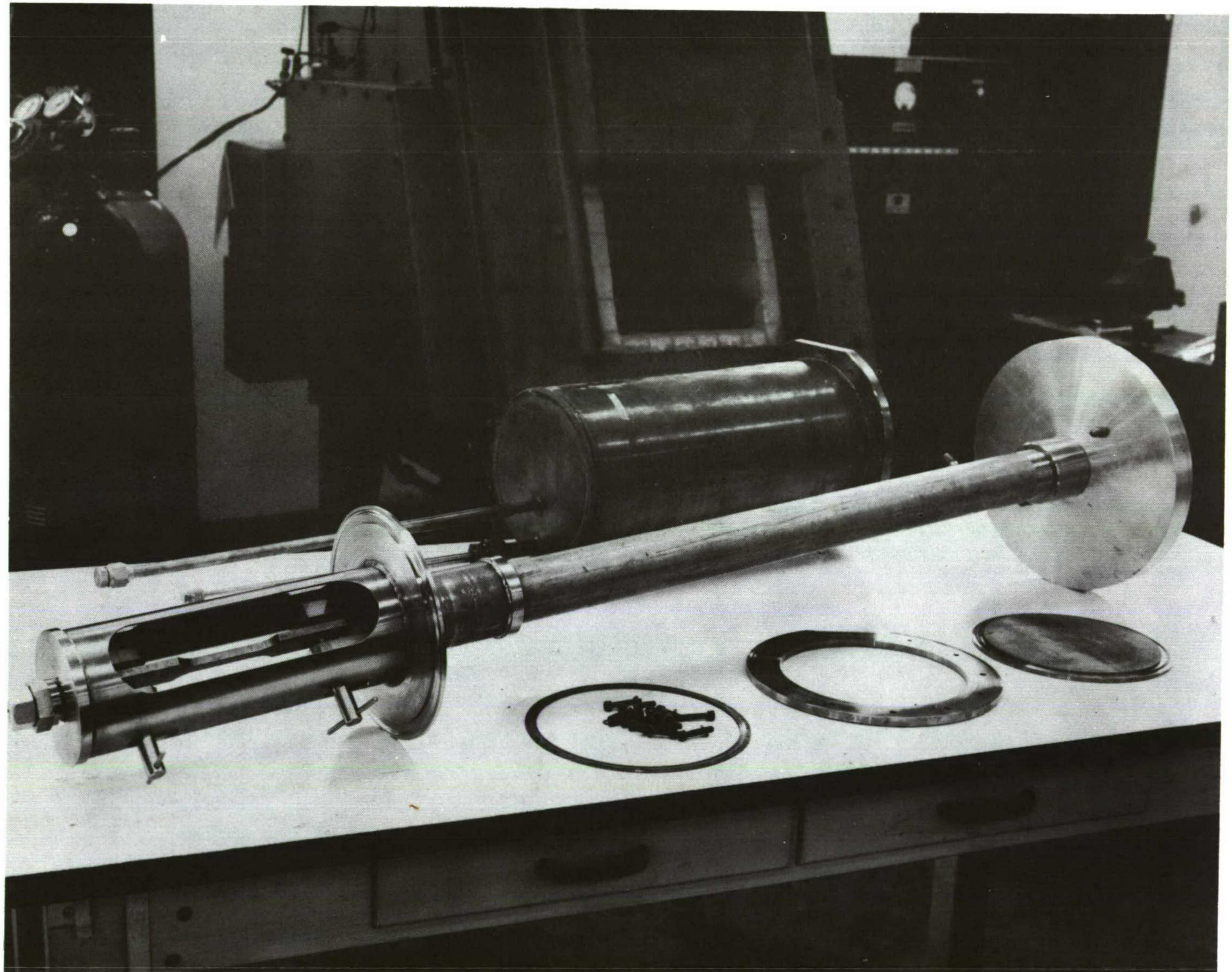


Figure 38. Load Applicator

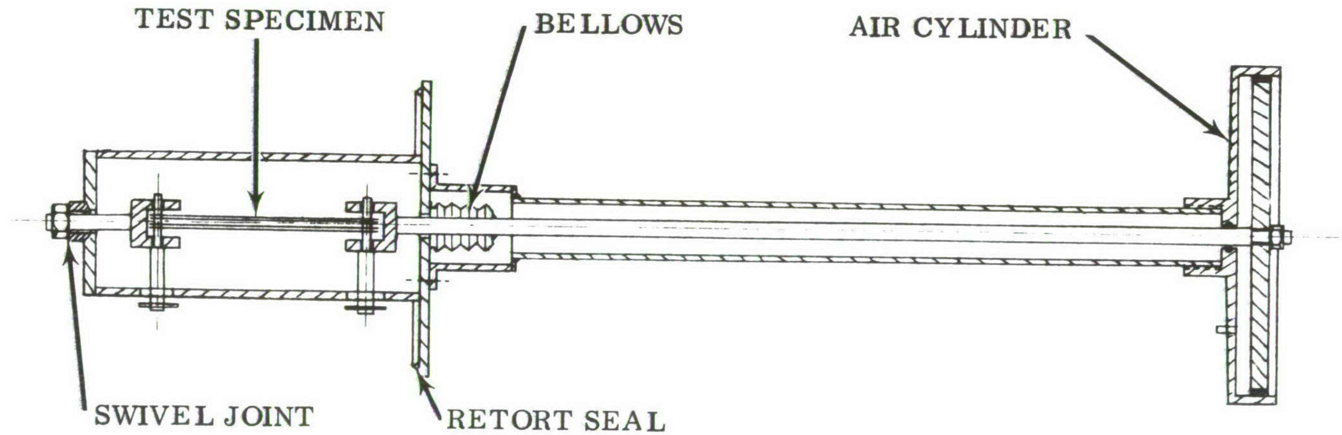


Figure 39. Schematic View of Pneumatic Load Applicator

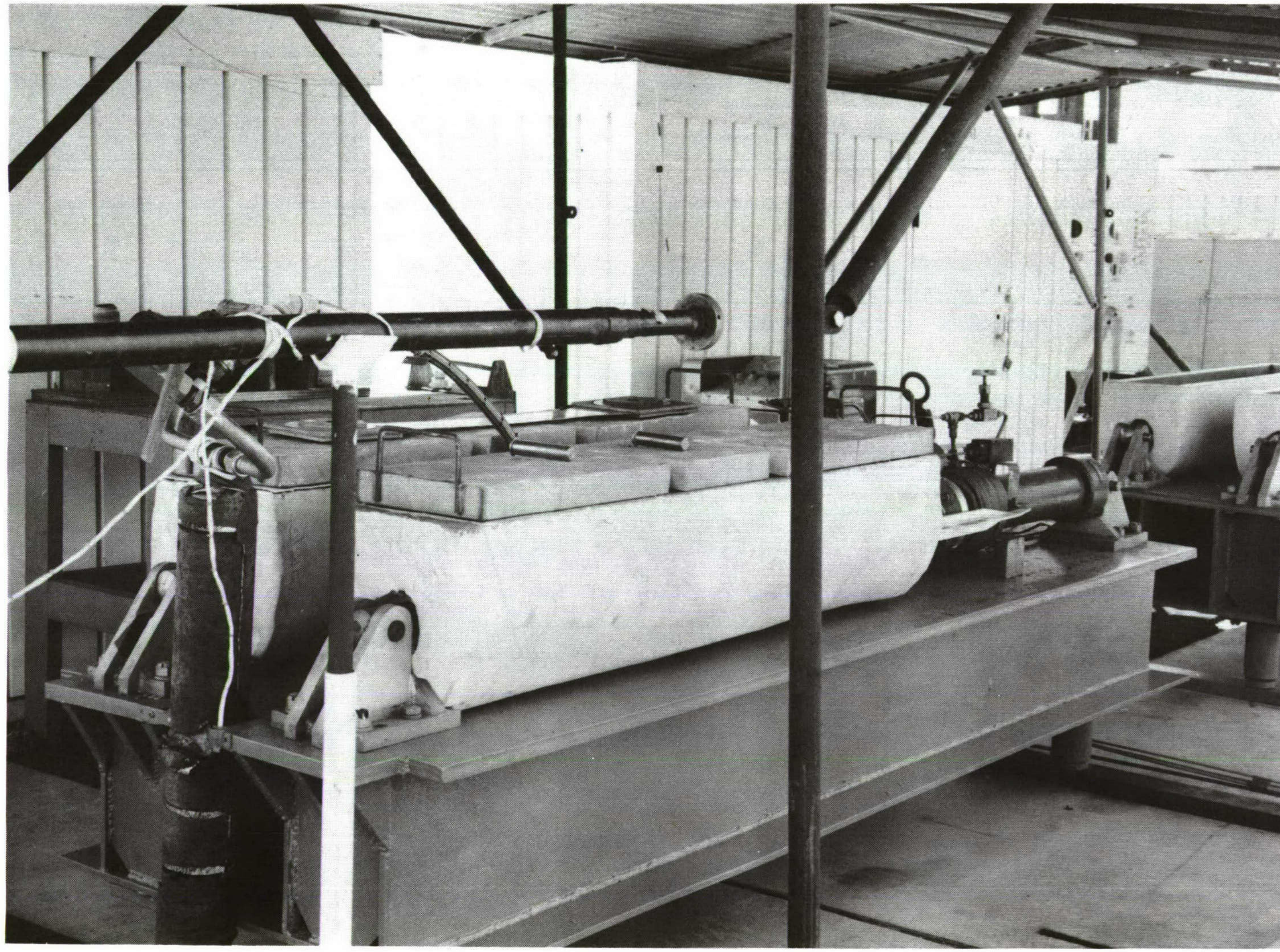


Figure 40. Fatigue Test Chambers for Room Temperature and Liquid-Nitrogen Testing

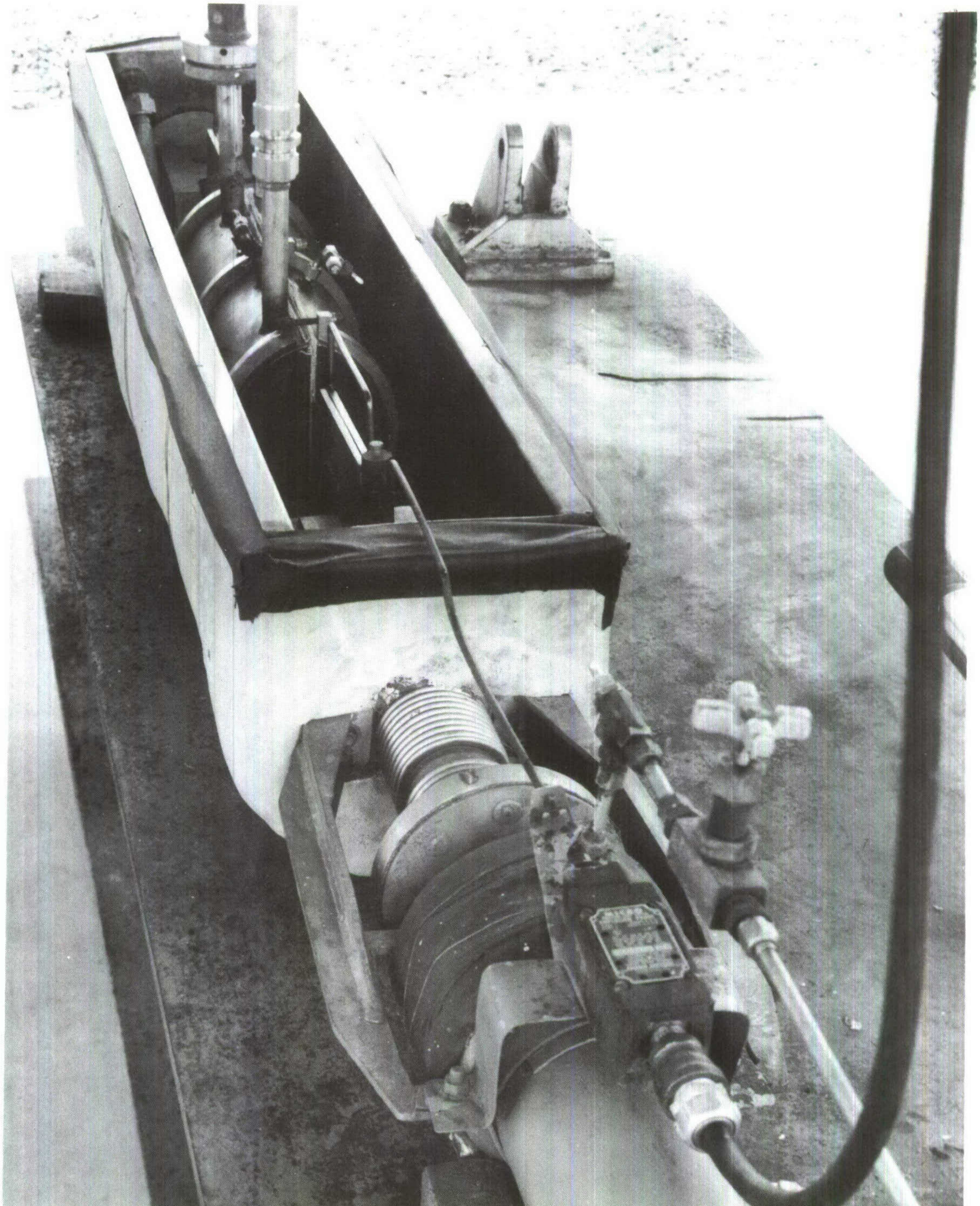


Figure 41. Fatigue Test Bed with Liquid-Hydrogen Test Chamber

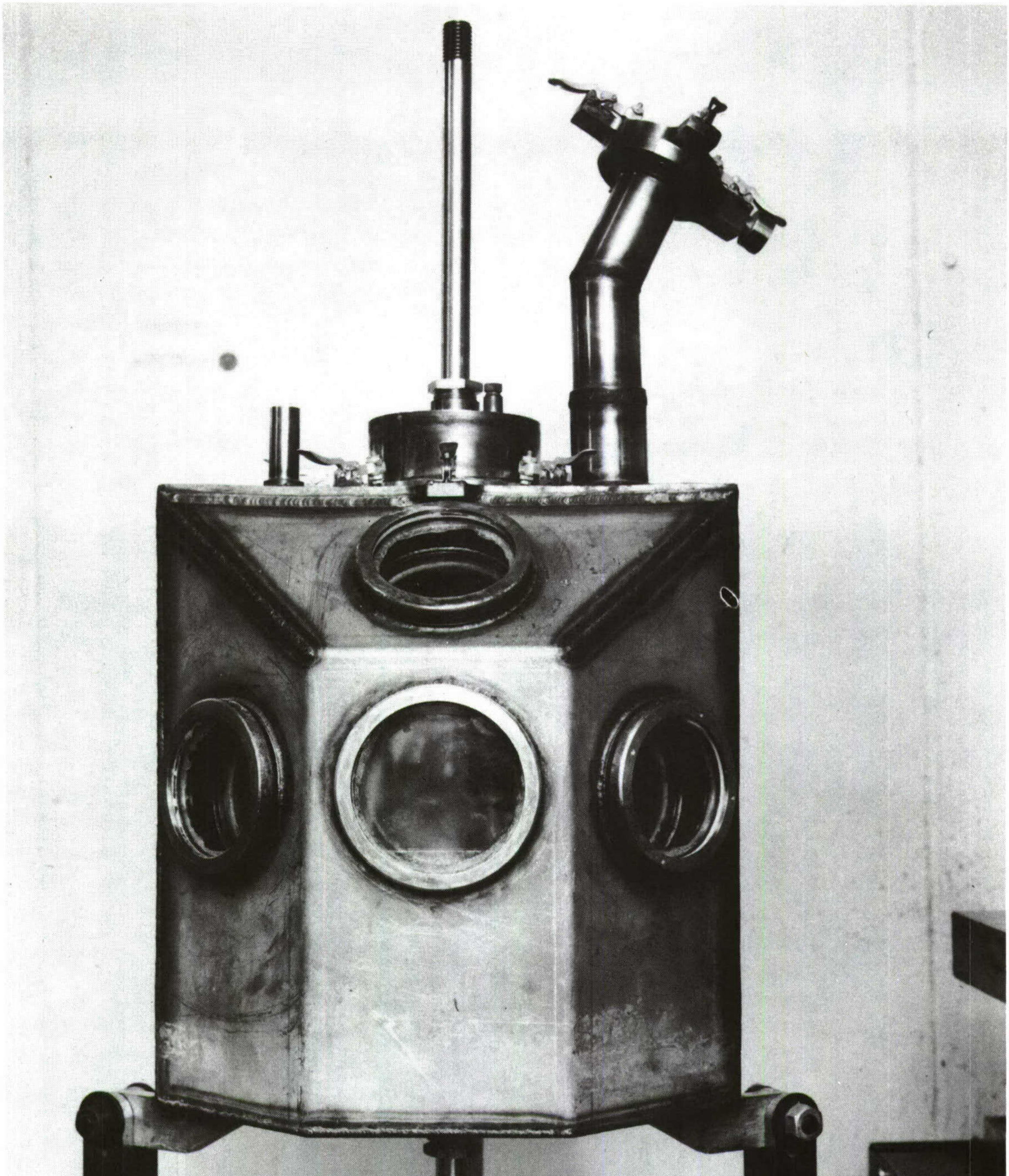


Figure 42. Liquid-Hydrogen Cryostat for Crack Propagation Testing

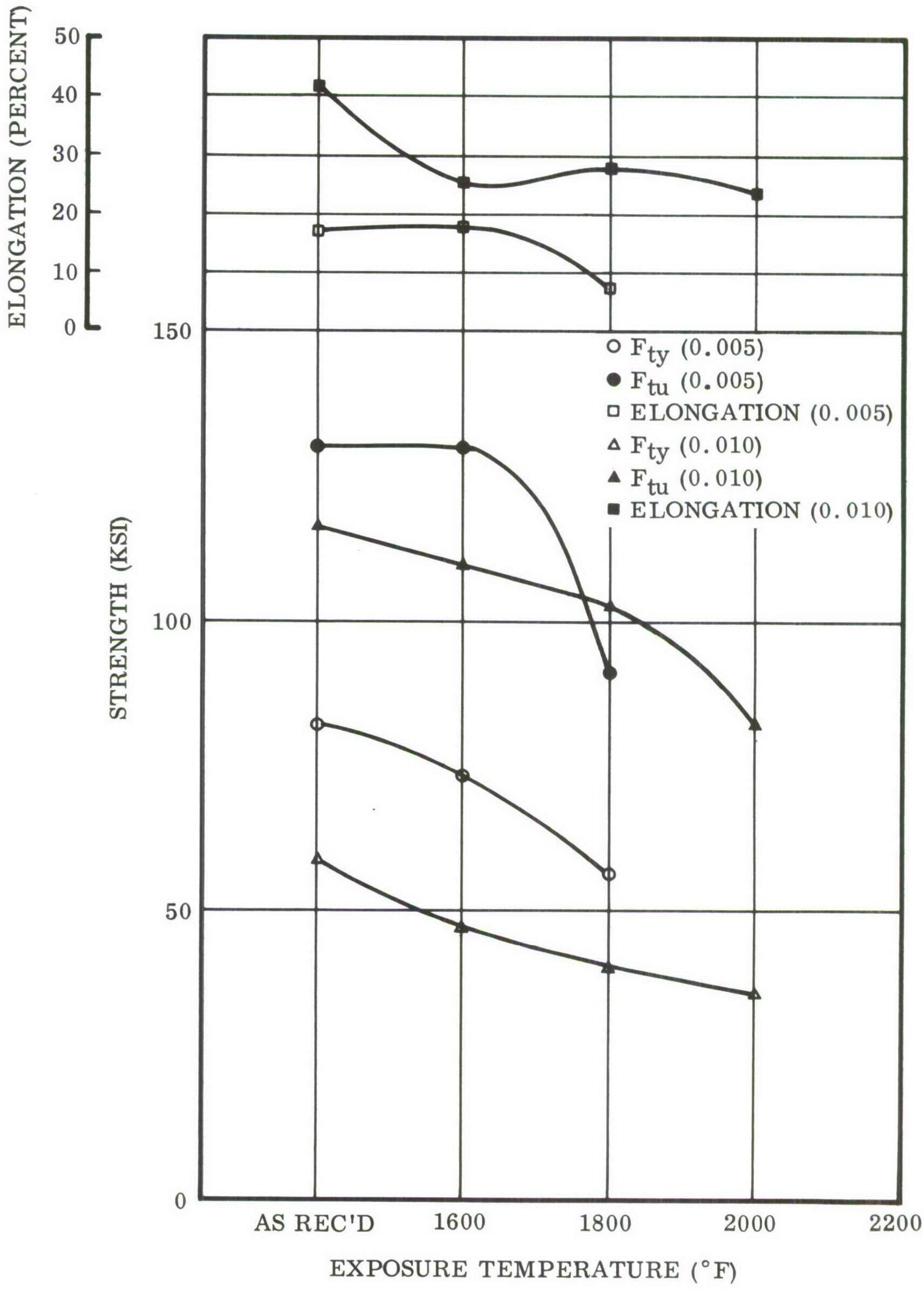


Figure 43. Mechanical Properties of Hastelloy X (at 75°F) after Thermal Exposures for 100 Hours in Air

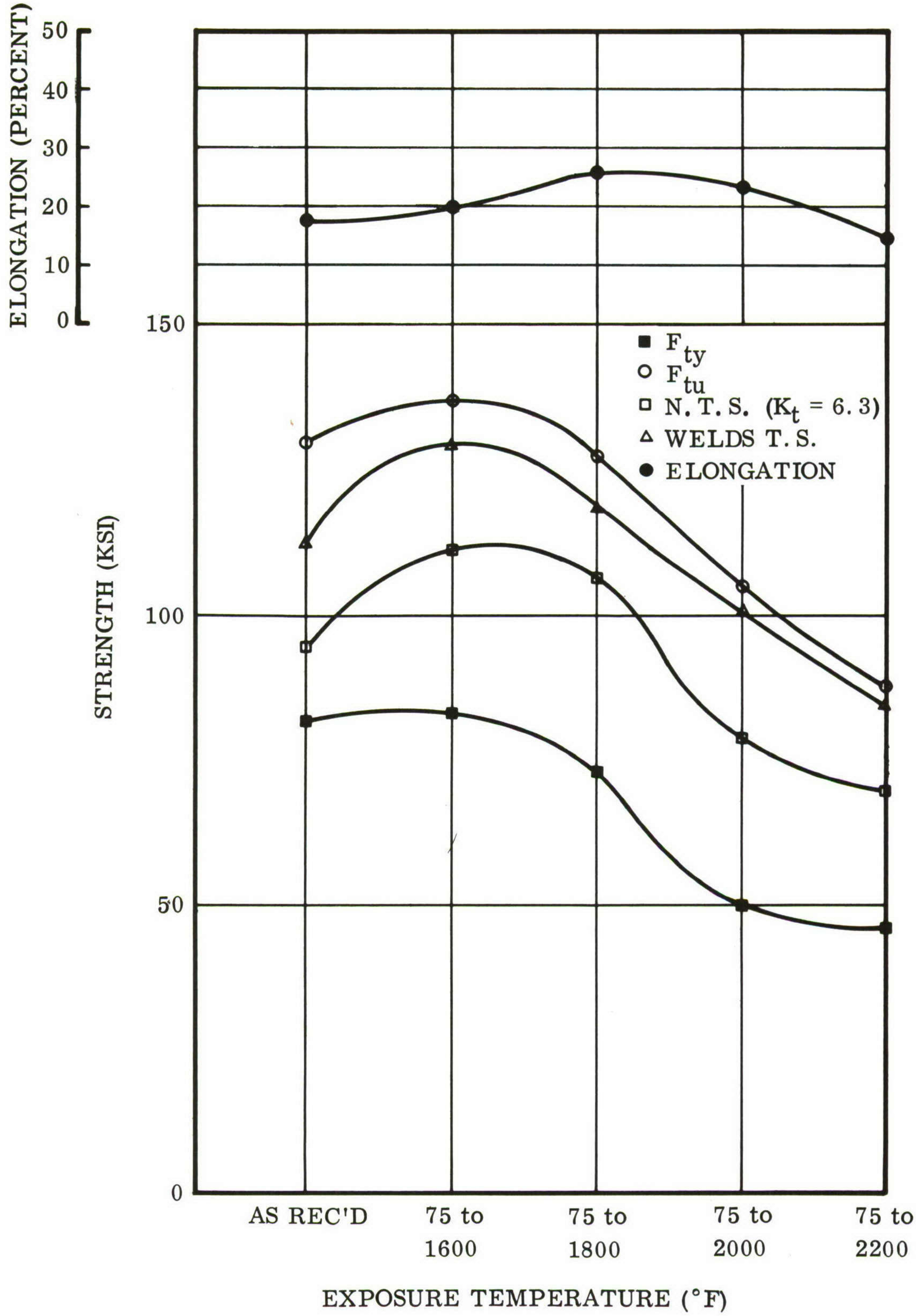


Figure 44. Mechanical Properties of Hastelloy X (at 75°F) after Thermal-Cyclic Exposures for 100 Cycles in Air (0.005 In. Thickness)

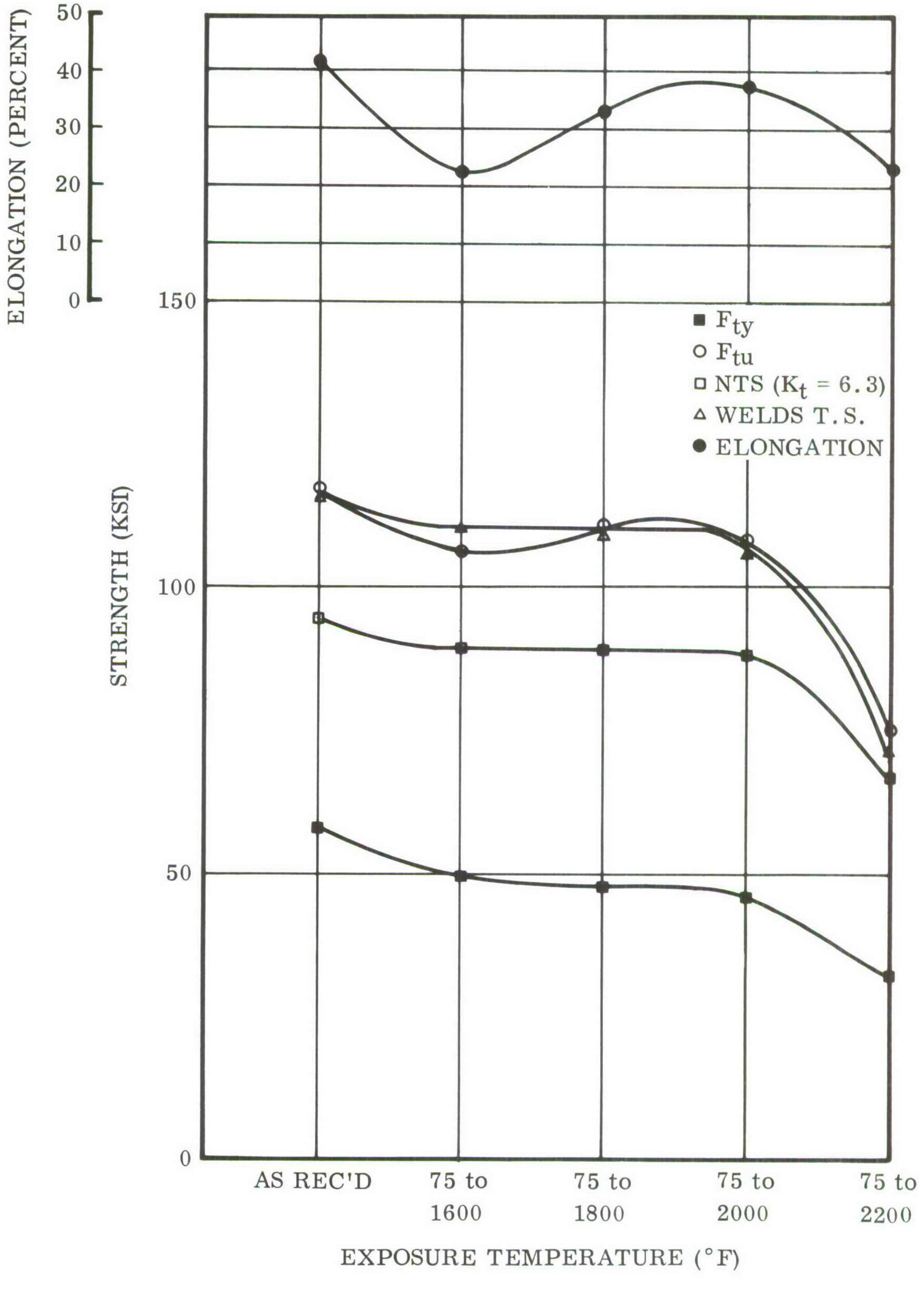
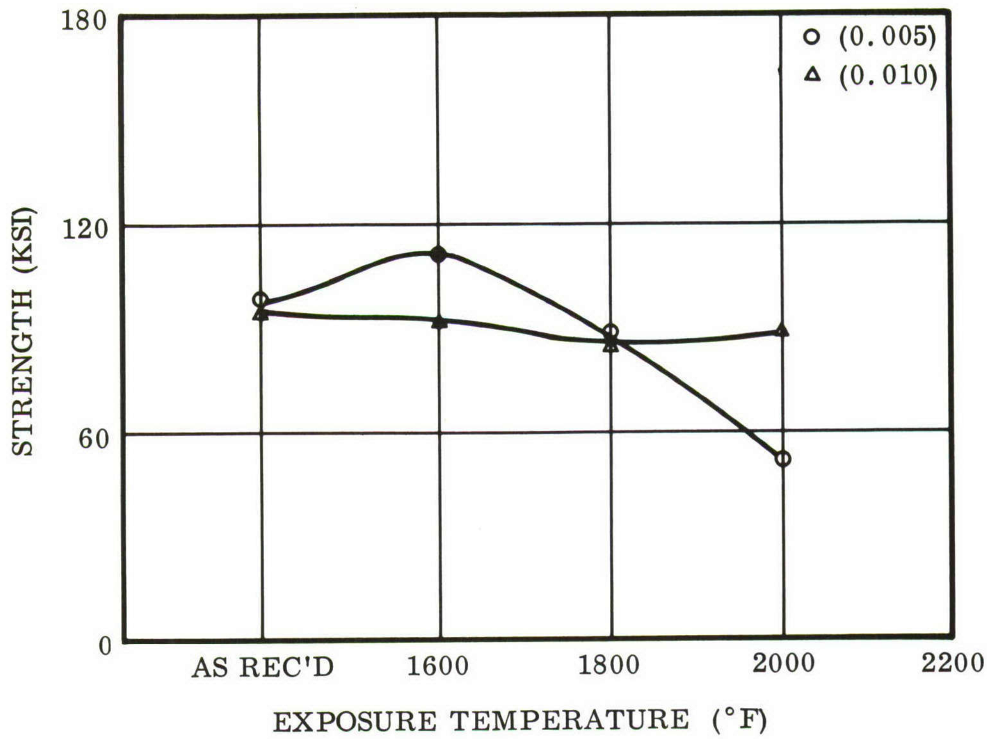
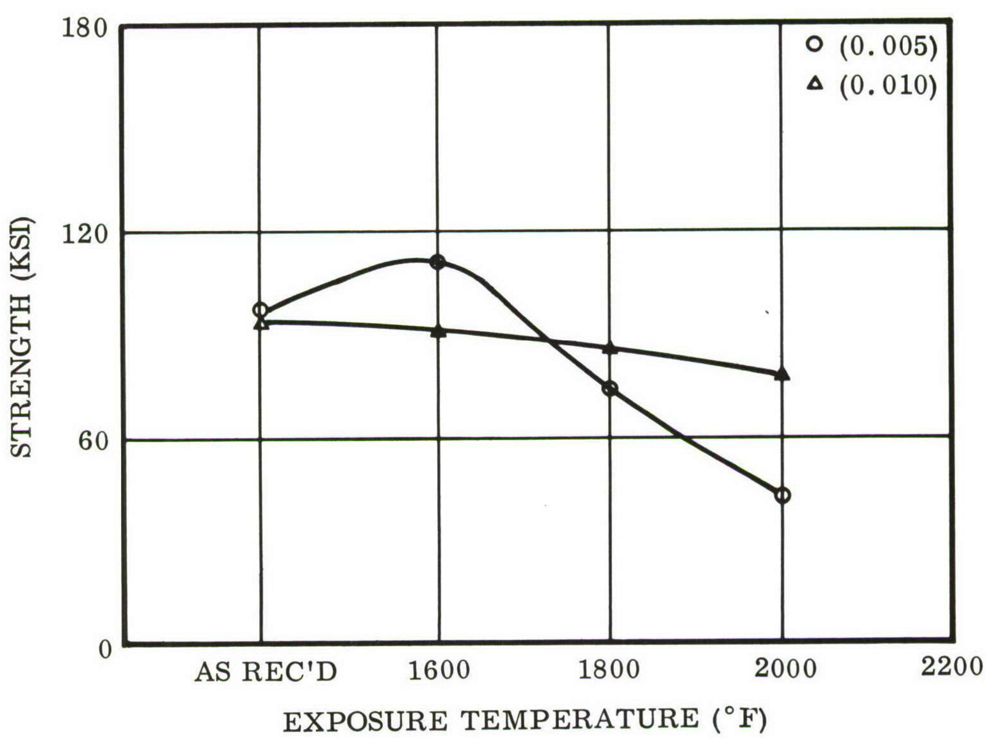


Figure 45. Mechanical Properties of Hastelloy X (at 75°F) after Thermal-Cyclic Exposures for 100 Cycles in Air (0.010 In. Thickness)

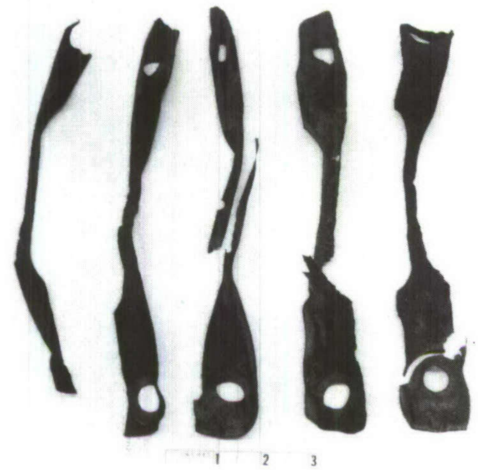


Hastelloy-X, Oxidation for 100 Hours (0.1 PSIG O_2)

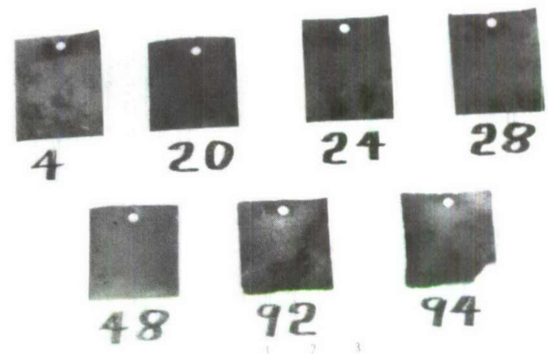


Hastelloy X, Oxidation for 100 Hours (1.0 PSIG O_2)

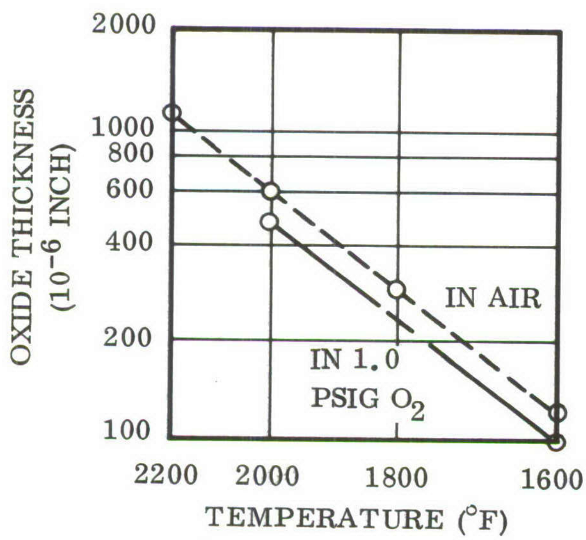
Figure 46. Notched Tensile Properties of Hastelloy X (at 75°F) after Oxidation Exposures for 100 Hours in Reduced Partial Pressures of Oxygen Gas



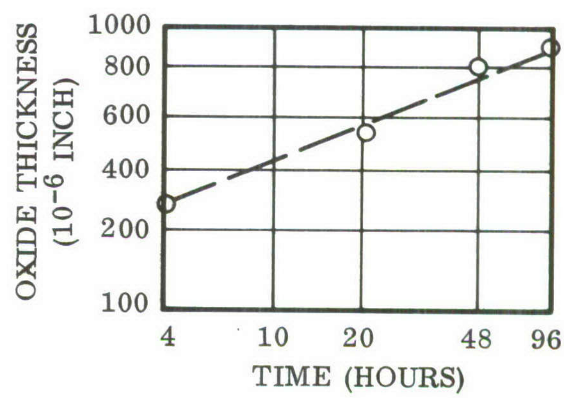
A. 0.005-Inch Thick Hastelloy X Specimens after 100 Hour Thermal Exposure at 2200°F in Air



B. 0.010-Inch Thick Hastelloy X Specimens after Thermal Exposure at 2200°F in Air for Times as Indicated, in Hours

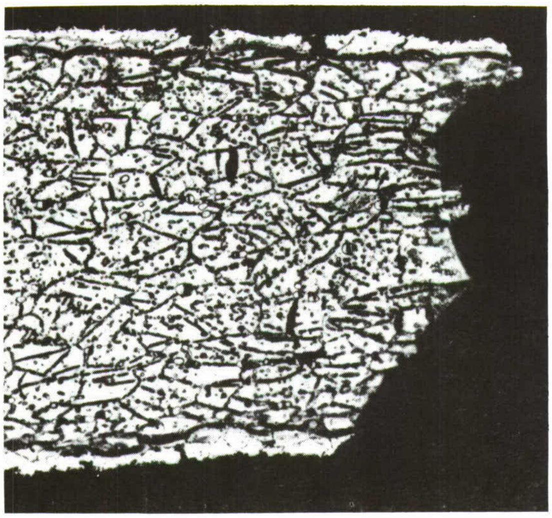


C. Total Oxide Thickness as a Function of Temperature after 100 Hour Exposure

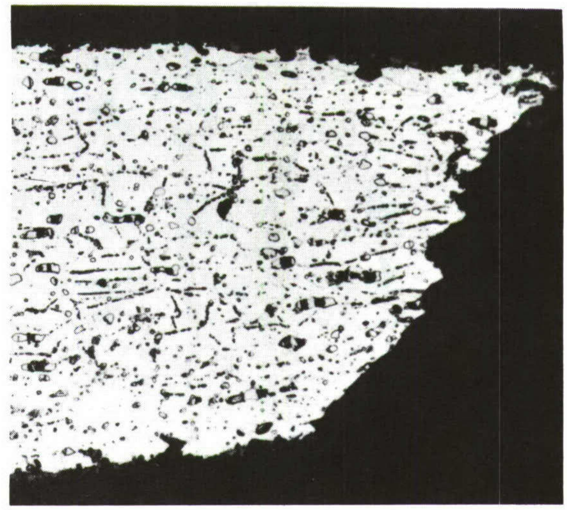


D. Thickness of Oxide Layer as a Function of Time of Exposure at 2200°F in Air

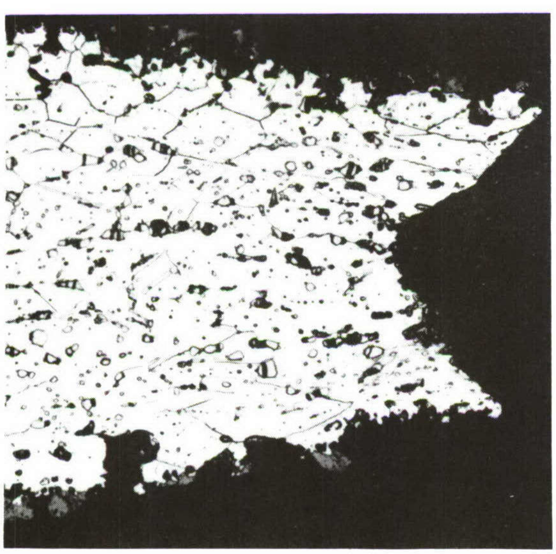
Figure 47. Photographs and Oxidation Curves of Hastelloy X after Various Exposures



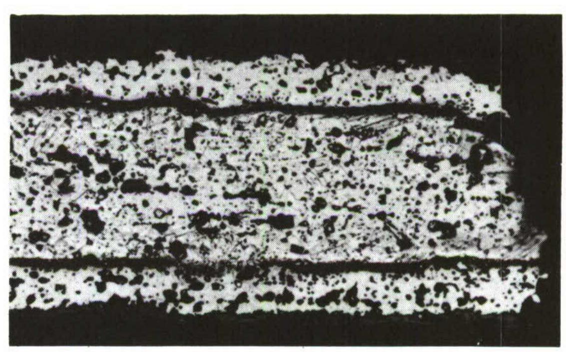
A. 0.010-Inch Thick Base Metal
Exposure: 1600°F in Air for 100 Hours
Etchant: 10% Oxalic, Electrolytic
Magnification: 250 X



B. 0.010-Inch Thick Base Metal
Exposure: 1800° F in Air for 100 Hours
Etchant: 10% Oxalic, Electrolytic
Magnification: 250 X

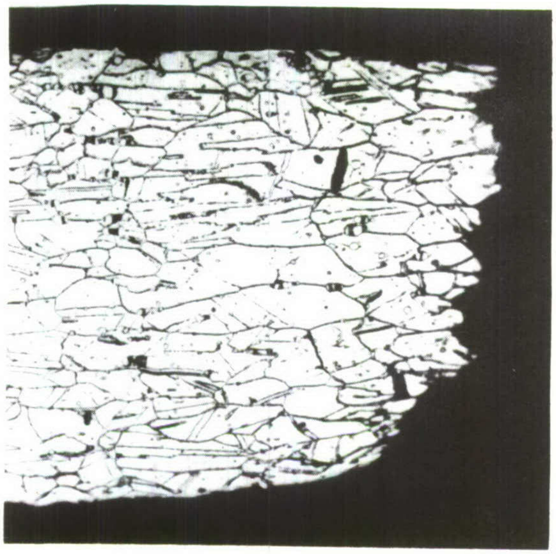


C. 0.010-Inch Thick Base Metal
Exposure: 2000°F in Air for 100 Hours
Etchant: 10% Oxalic, Electrolytic
Magnification: 250 X

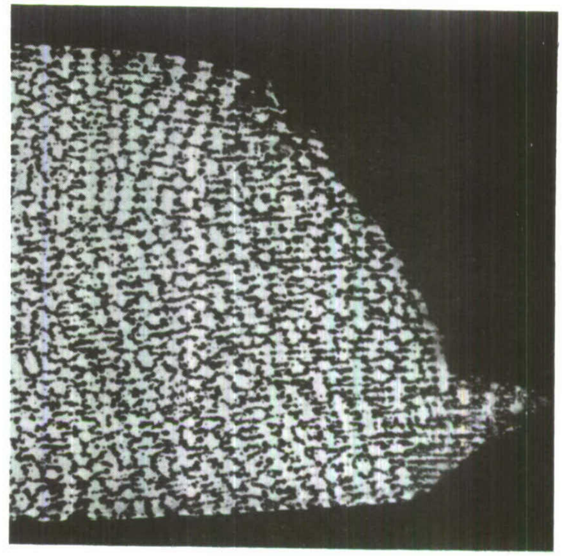


D. 0.005-Inch Thick Base Metal
Exposure: 1800°F in Air for 100 Hours
Etchant: 10% Oxalic, Electrolytic
Magnification: 250 X

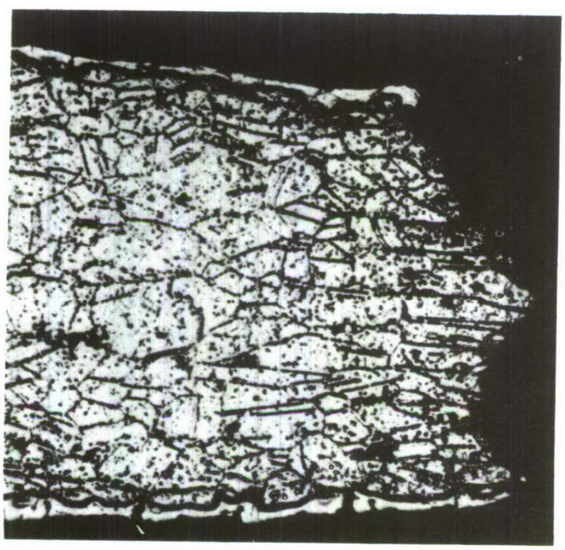
Figure 48. Photomicrographs of Hastelloy X Sheet Material (Sheet 1 of 2)



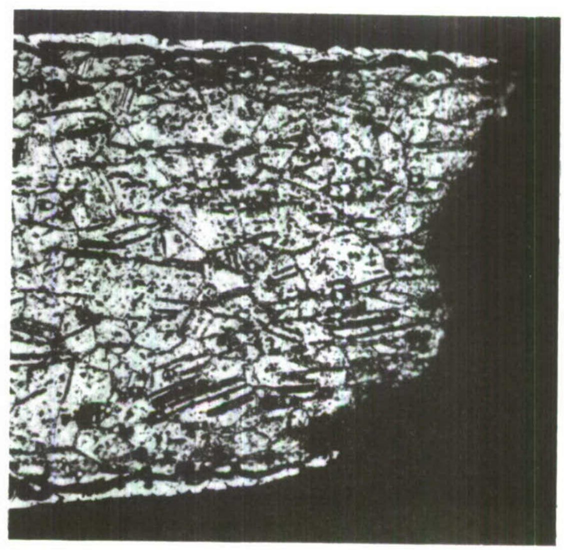
E. 0.010-Inch Thick Base Metal
Exposure: 100 Cycles from 75° to 1600°F
Etchant: 10% Oxalic, Electrolytic
Magnification: 250 X



F. 0.010-Inch Thick Weld Metal
Exposure: 100 Cycles from 75° to 1800°F
Etchant: 10% Oxalic, Electrolytic
Magnification: 250 X



G. 0.010-Inch Thick Base Metal
Exposure: 1600° F in 0.1 psig O_2 for 100 Hours
Etchant: 10% Oxalic, Electrolytic
Magnification: 250 X



H. 0.010-Inch Thick Base Metal
Exposure: 1600°F in 1.0 psig O_2 for 100 Hours
Etchant: 10% Oxalic, Electrolytic
Magnification: 250 X

Figure 48. Photomicrographs of Hastelloy X Sheet Material (Sheet 2 of 2)

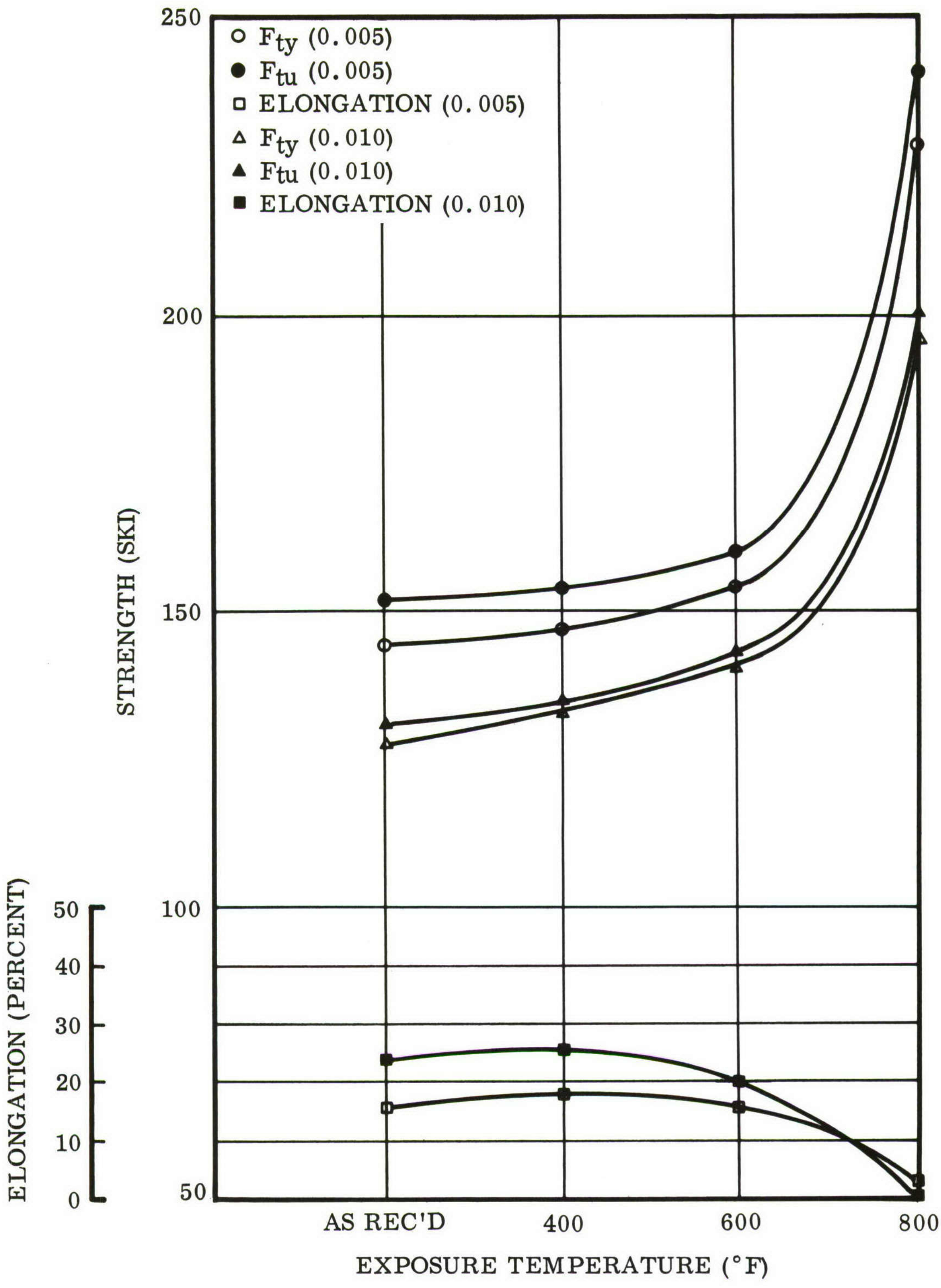


Figure 49. Mechanical Properties of Titanium-13V-11Cr-3Al Alloy (at 75° F) after Thermal Exposures for 100 Hours in Air

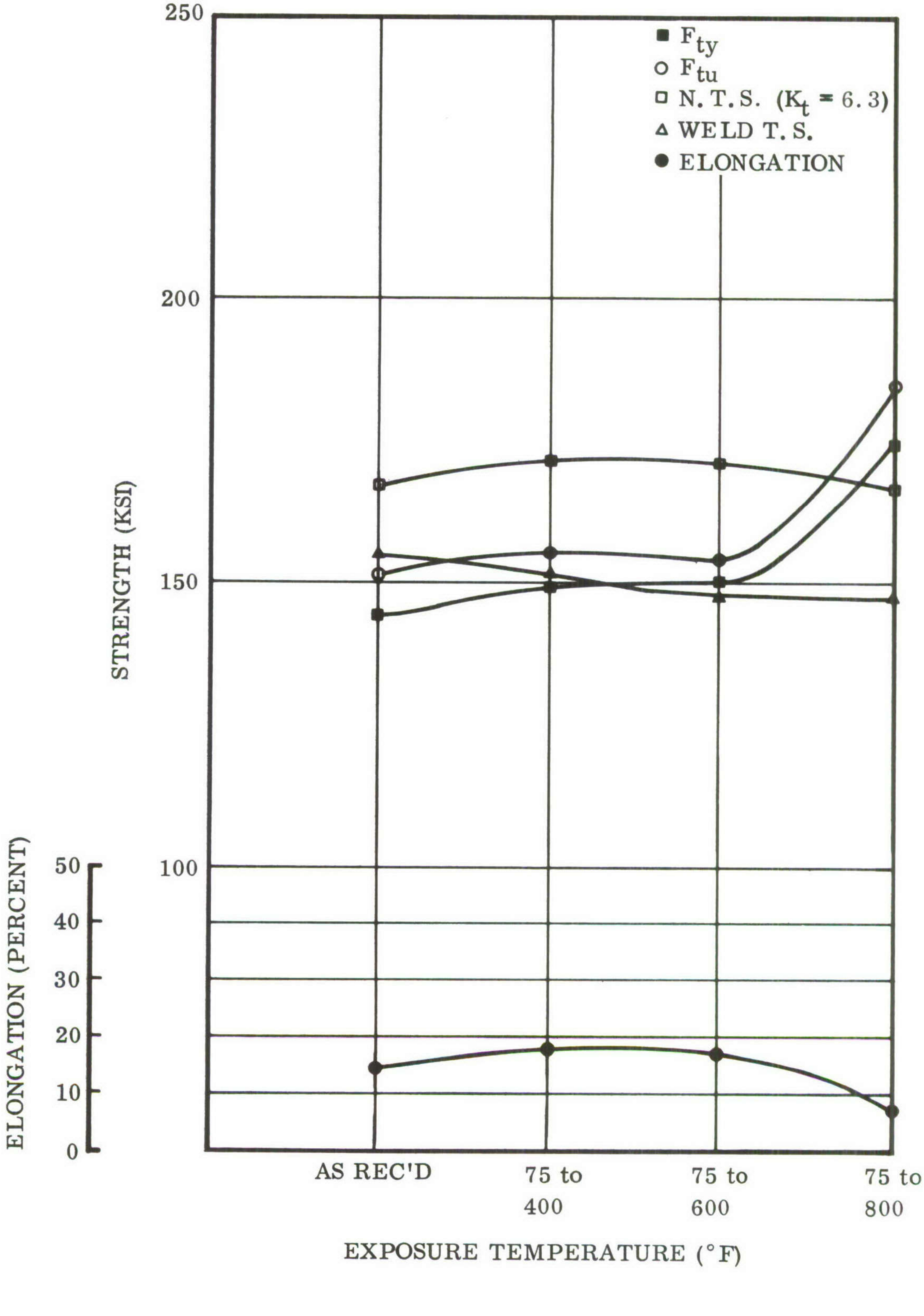


Figure 50. Mechanical Properties of Titanium-13V-11Cr-3Al Alloy (at 75°F) after Thermal Cyclic Exposures for 100 Cycles in Air (0.005 In. Thickness)

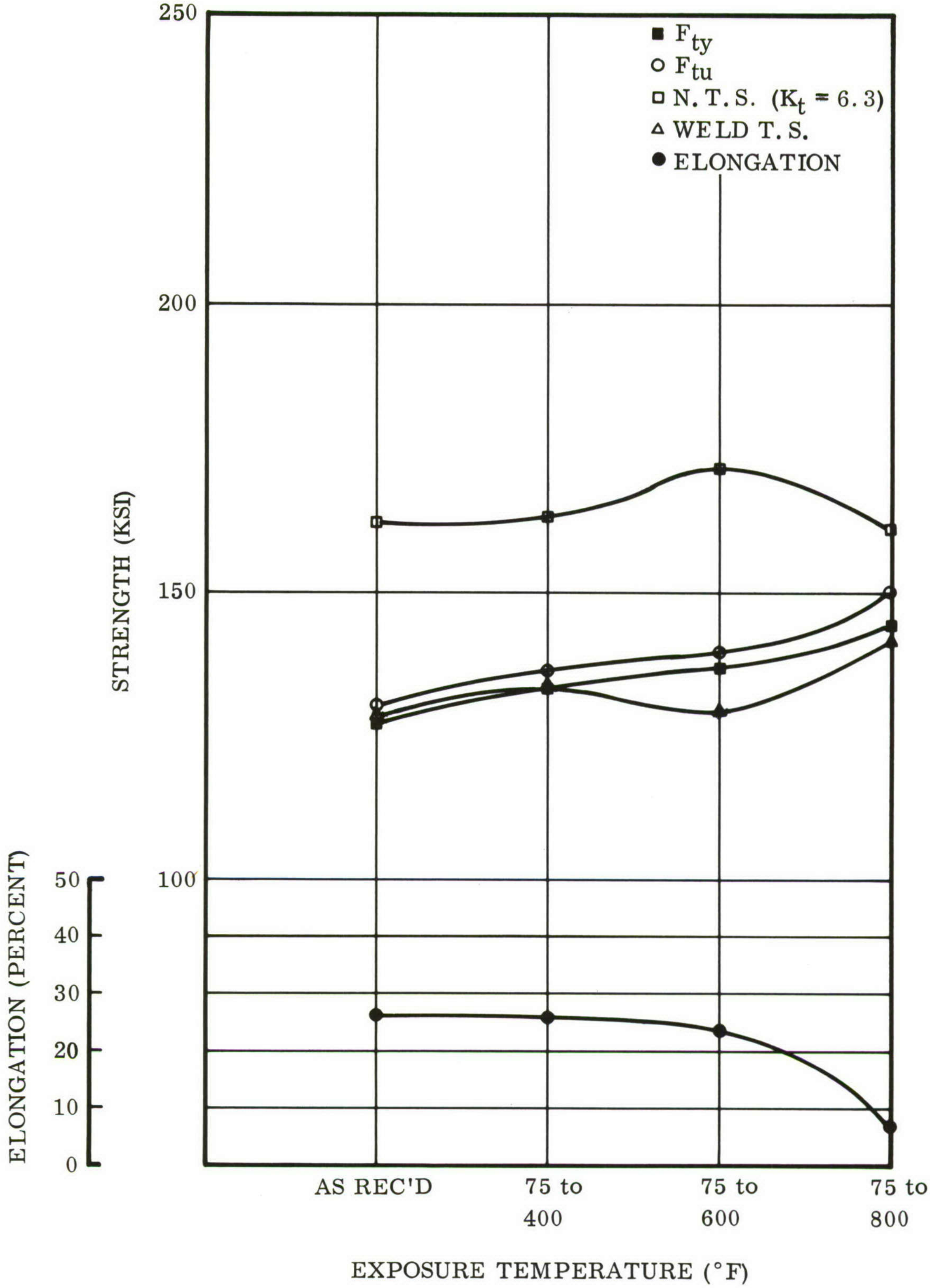
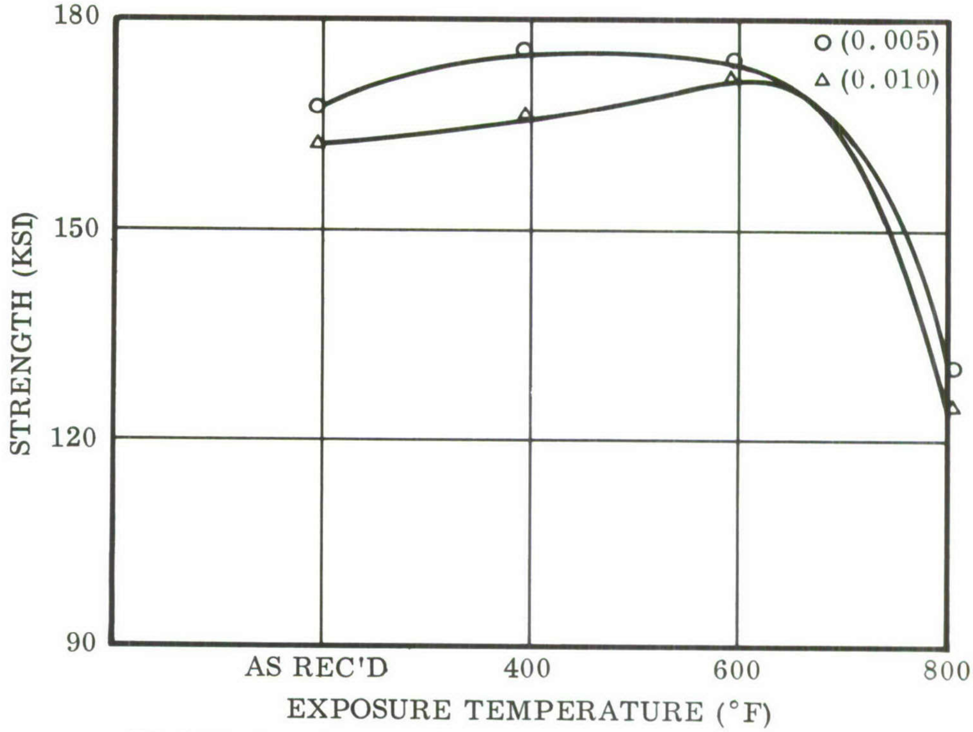
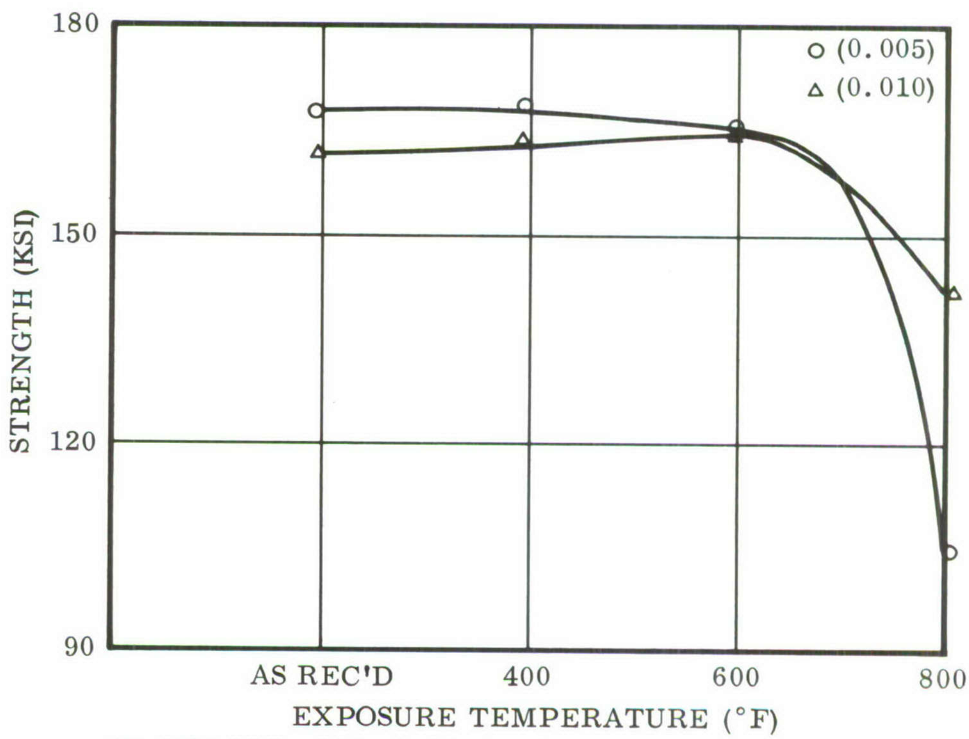


Figure 51. Mechanical Properties of Titanium-13V-11Cr-3Al Alloy (at 75°F) after Thermal Cyclic Exposures for 100 Cycles in Air (0.010 In. Thickness)

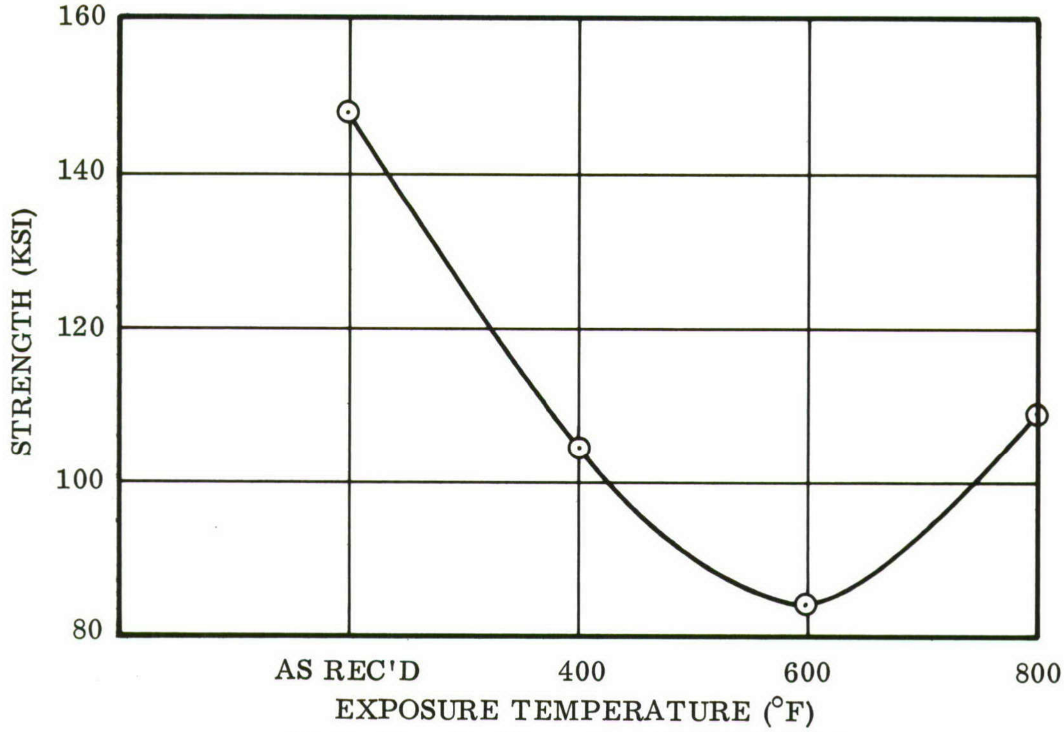


Ti-13V-Cr-3Al, Oxidation for 100 Hours (1.0 PSIG O_2)

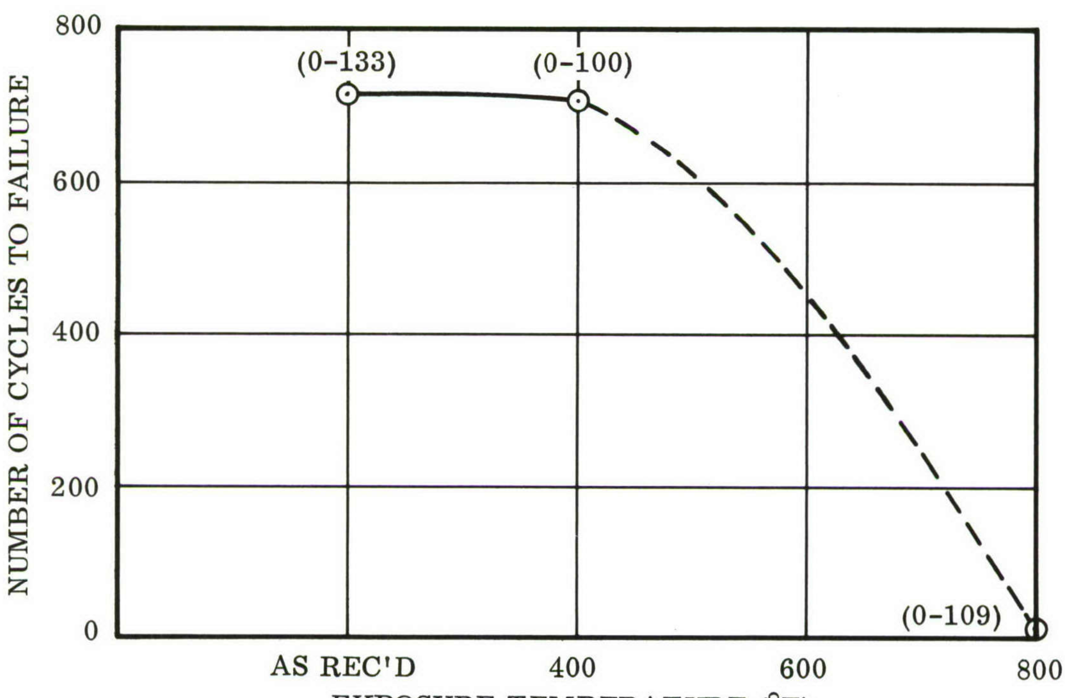


Ti-13V-11Cr-3Al, Oxidation for 100 Hours (0.1 PSIG O_2)

Figure 52. Notched Tensile Properties of Titanium-13V-11Cr-3Al Alloy (at 75°F) after Oxidation Exposures for 100 Hours in Reduced Partial Pressures of Oxygen Gas

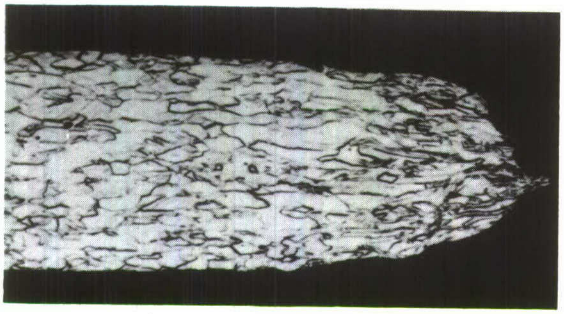


Static Tensile Strength of Welded Joints

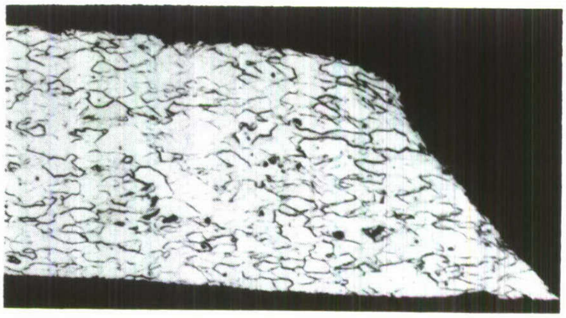


Axial Fatigue Properties of Welded Joints

Figure 53. Static and Fatigue Properties of Welded Joints of the Titanium-13V-11Cr-3Al Alloy (at 75°F) after Thermal Exposures for 100 Hours in Air

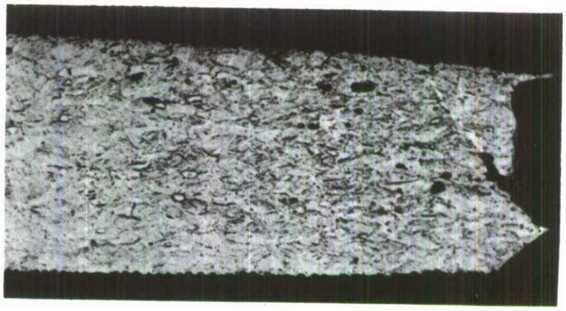


A. Base Metal
Exposure: As Received
Etchant: Kroll's
Magnification: 250 X



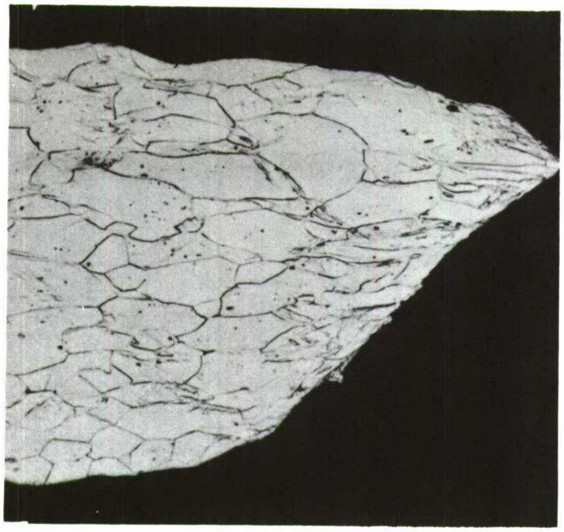
B. Base Metal
Exposure: 600°F in 1.0 psig O_2 for 100 Hours
Etchant: Kroll's
Magnification: 250 X

C. Weld Metal
Exposure: 100 Cycles from 75° to 600°F
Etchant: Kroll's
Magnification: 250 X

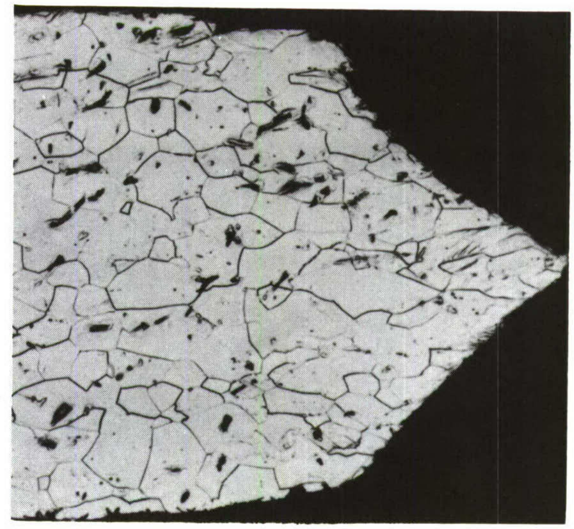


D. Base Metal
Exposure: 800°F in Air for 100 Hours
Etchant: Kroll's
Magnification: 250 X

Figure 54. Photomicrographs of Titanium-13V-11Cr-3Al Sheet Material (0.005-Inch Thickness)

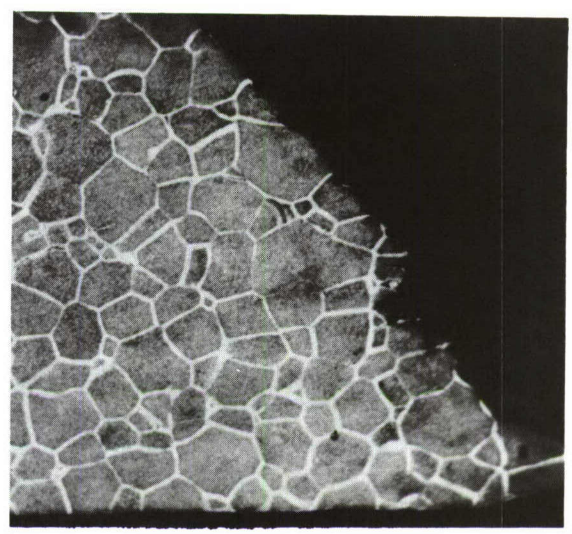


A. Base Metal
Exposure: As Received
Etchant: Kroll's
Magnification: 250 X



B. Base Metal
Exposure: 600° in Air for 100 Hours
Etchant: Kroll's
Magnification: 250 X

C. Heat Affected Zone of Weld
Exposure: 100 Cycles from 75° to 800° F
Etchant: Kroll's
Magnification: 250 X



D. Base Metal
Exposure: 800°F in 1.0 psig O_2 for 100 Hours
Etchant: Kroll's
Magnification: 250X

Figure 55. Photomicrographs of Titanium-13V-11Cr-3Al Sheet Material (0.010-Inch Thickness)

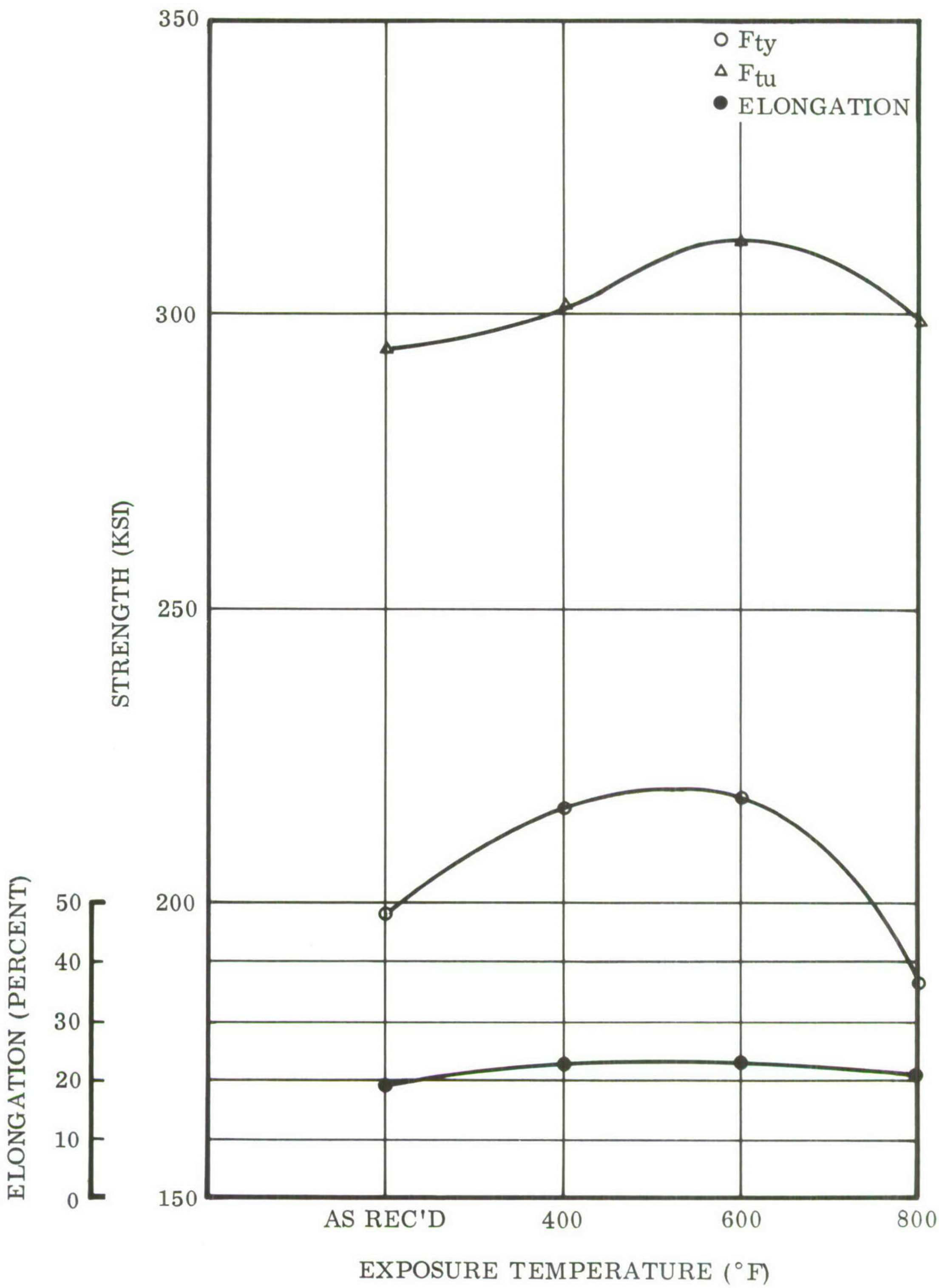


Figure 56. Mechanical Properties of 301-Stainless Steel (at -320°F) after Thermal Exposures for 100 Hours in Air (0.003 In. Thickness)

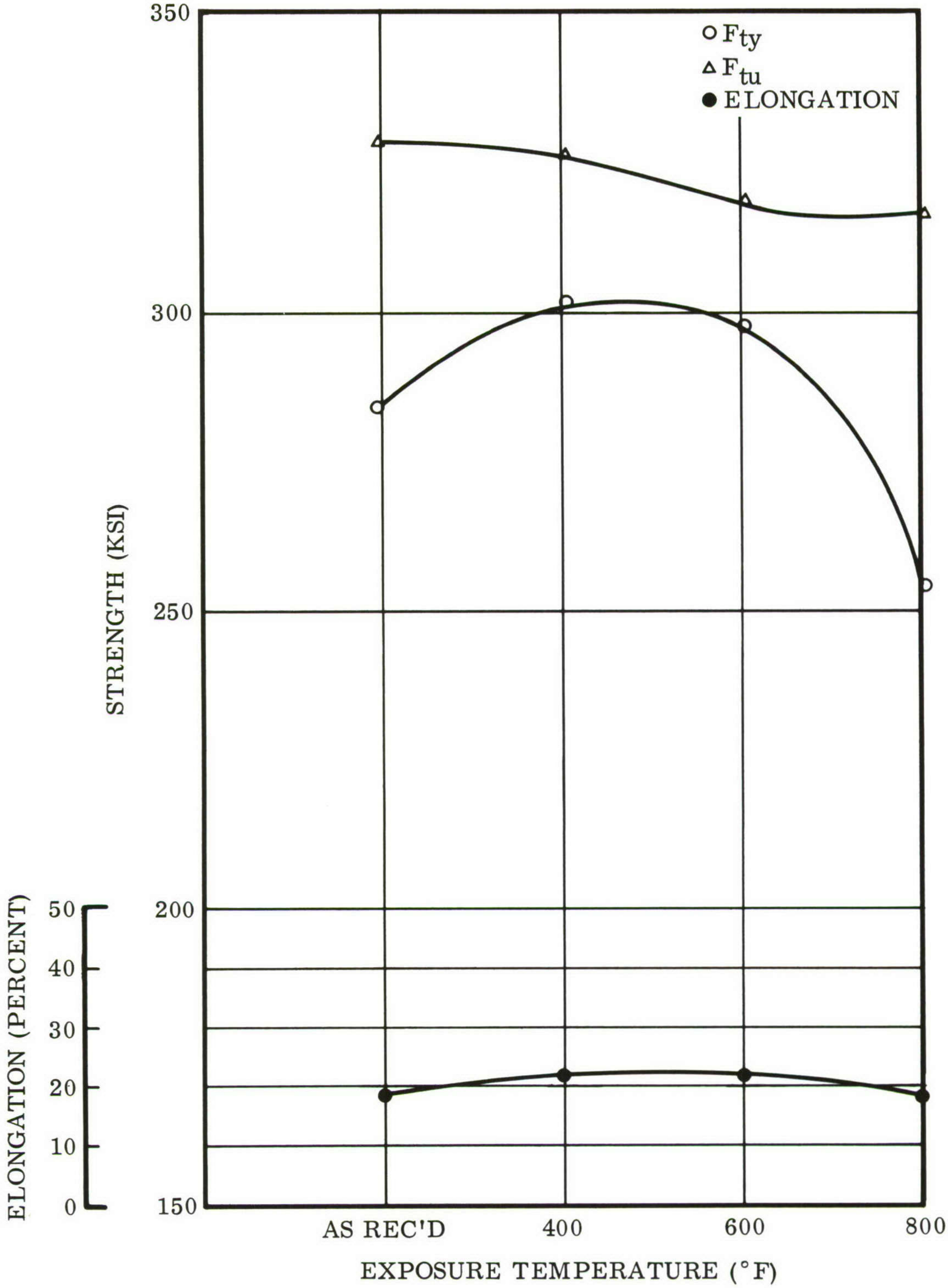


Figure 57. Mechanical Properties of 301-Stainless Steel (at -320°F) after Thermal Exposures for 100 Hours in Air (0.006 In. Thickness)

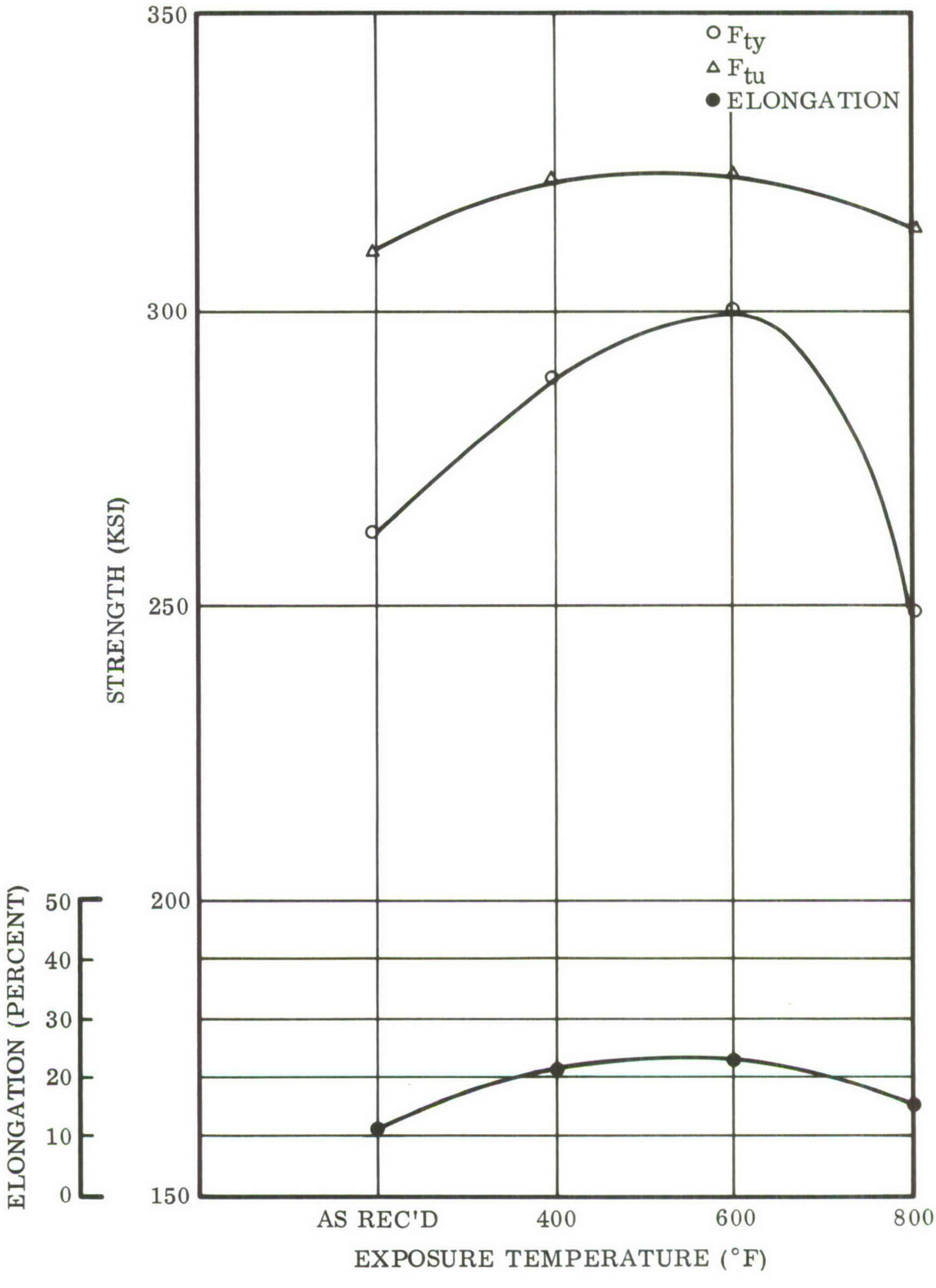


Figure 58. Mechanical Properties of 301-Stainless Steel (at -320°F) after Thermal Exposures for 100 Hours in Air (0.010 In. Thickness)

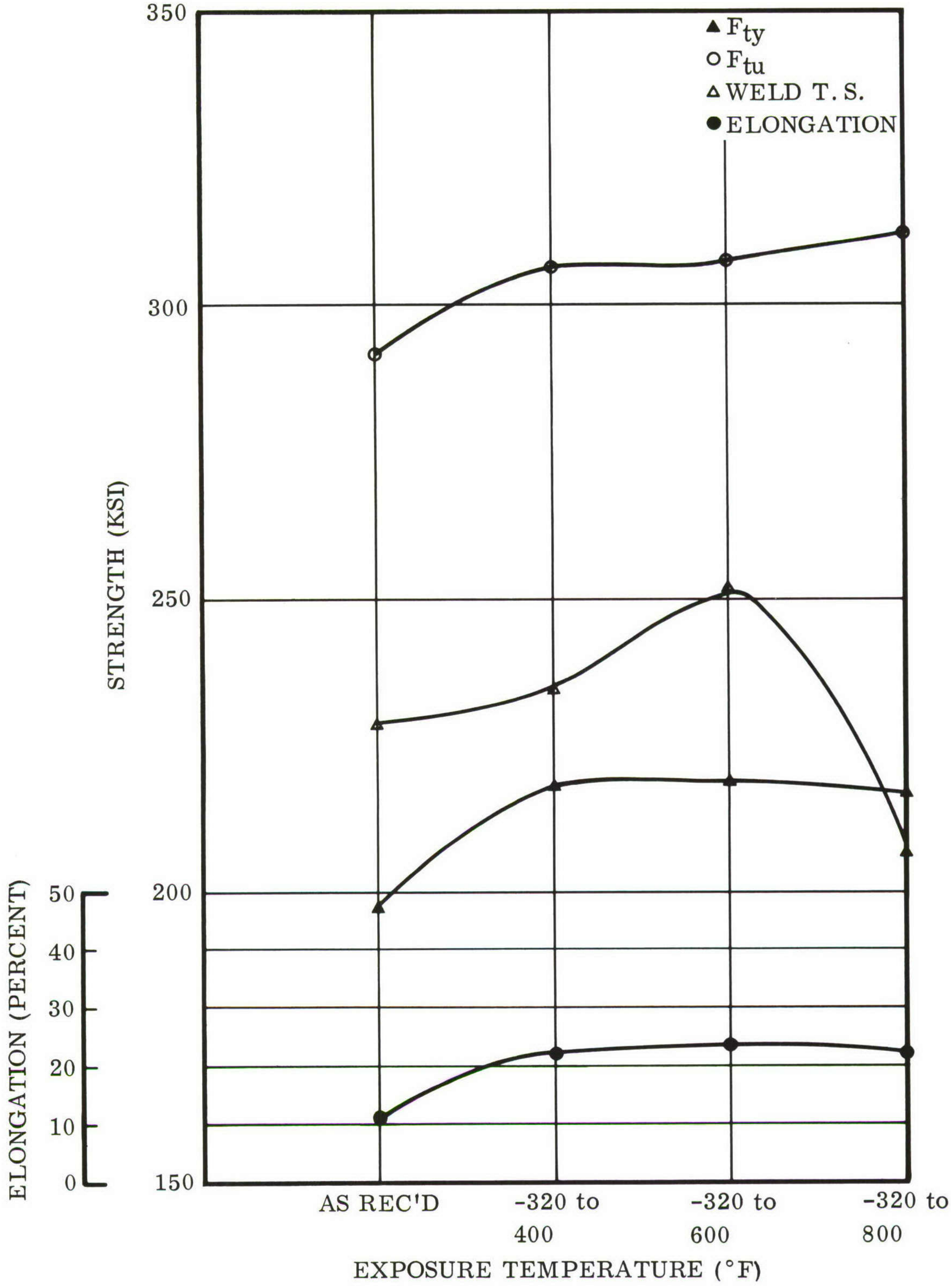


Figure 59. Mechanical Properties of 301-Stainless Steel (at -320°F) after Thermal Cyclic Exposures for 100 Cycles (0.003 In. Thickness)

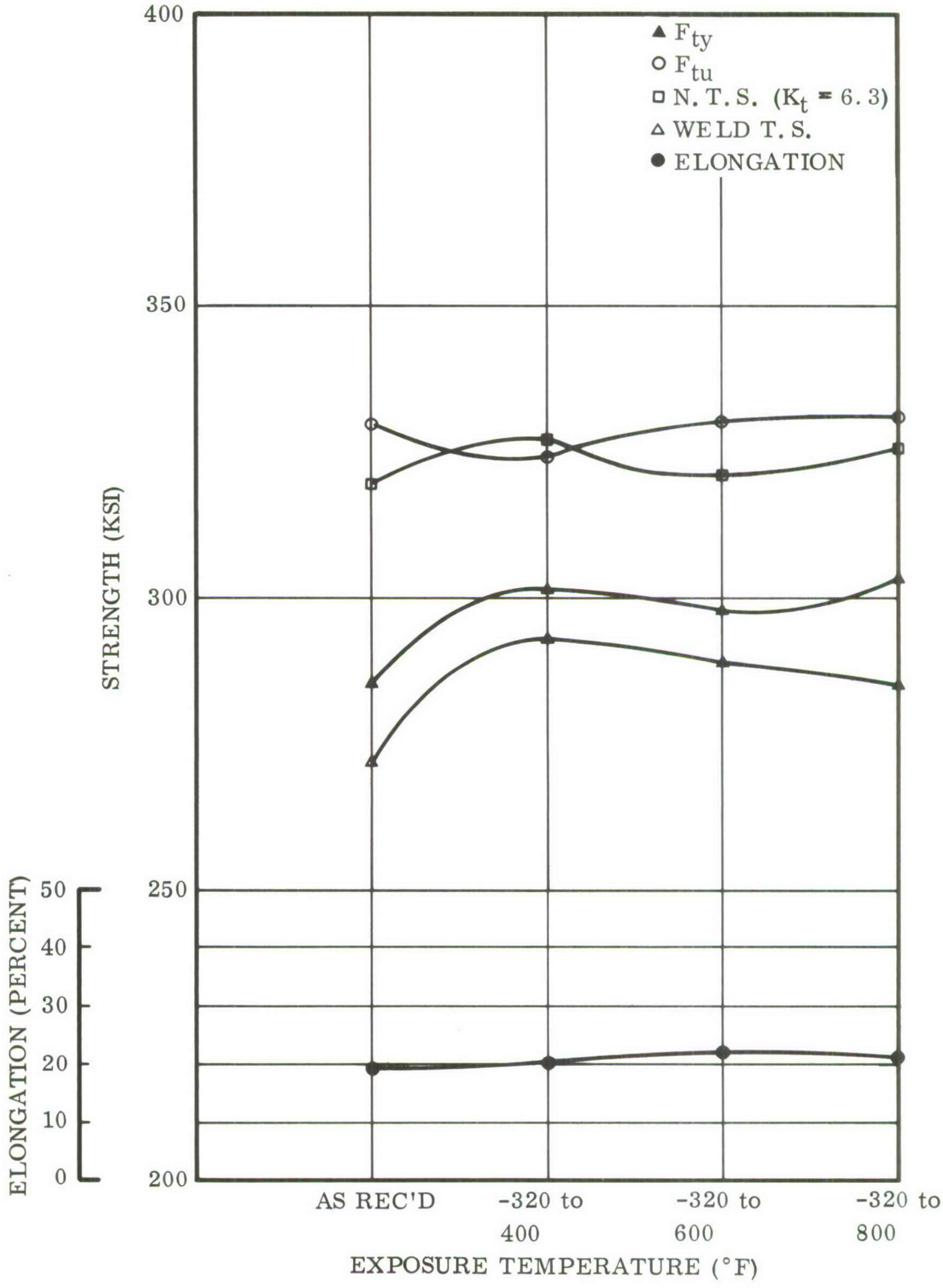


Figure 60. Mechanical Properties of 301-Stainless Steel (at -320°F) after Thermal Cyclic Exposures for 100 Cycles (0.006 In. Thickness)

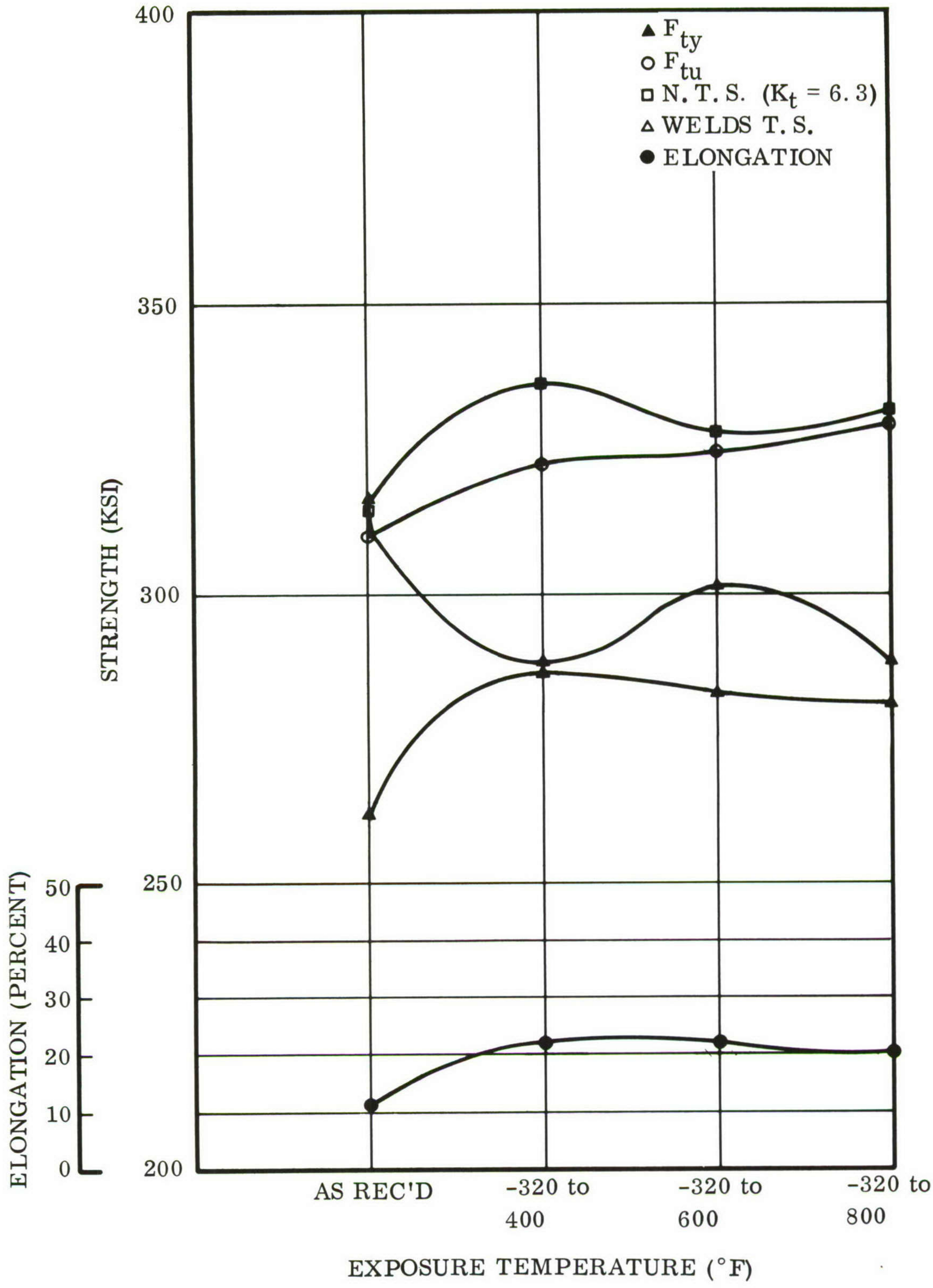
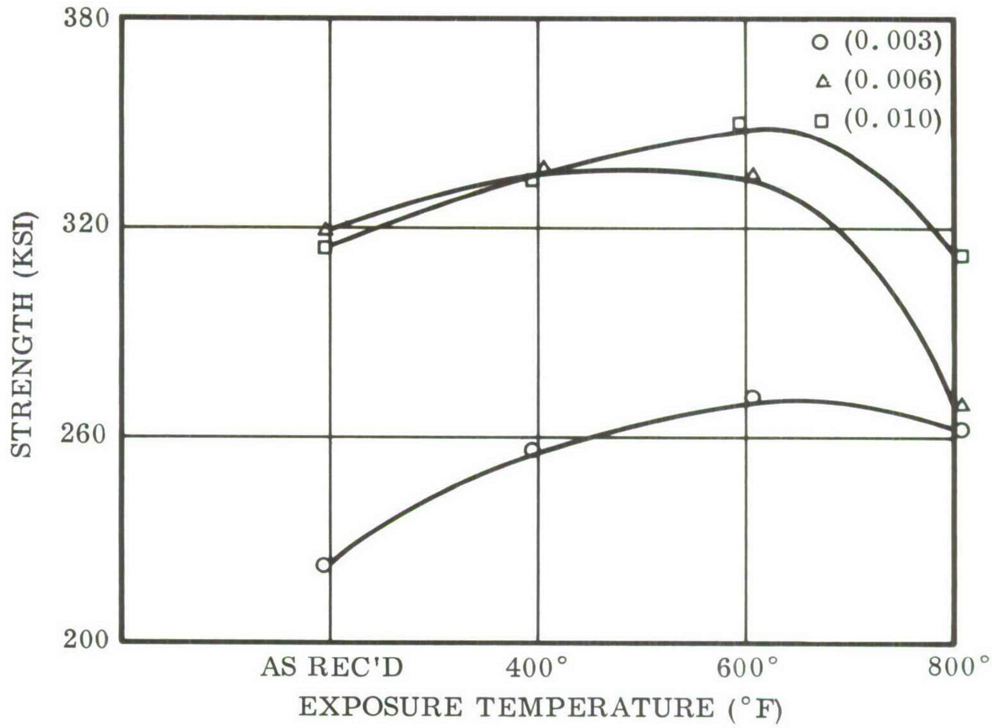
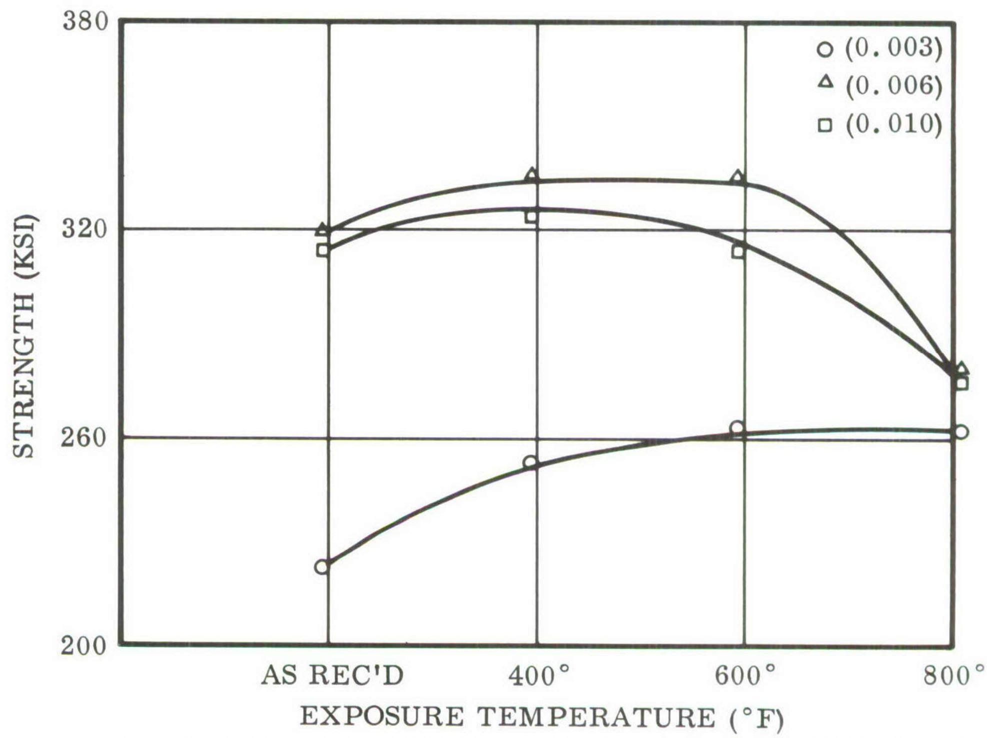


Figure 61. Mechanical Properties of 301-Stainless Steel (at -320°F) after Thermal Cyclic Exposures for 100 Cycles (0.010 In. Thickness)

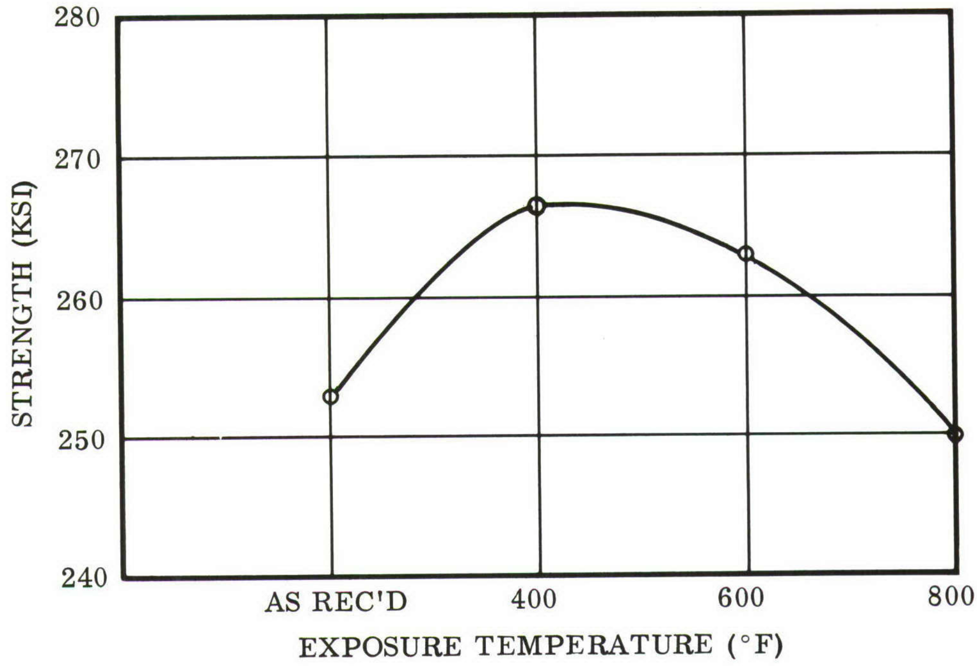


301 Stainless Steel Oxidation for 100 Hours (1.0 PSIG O_2)

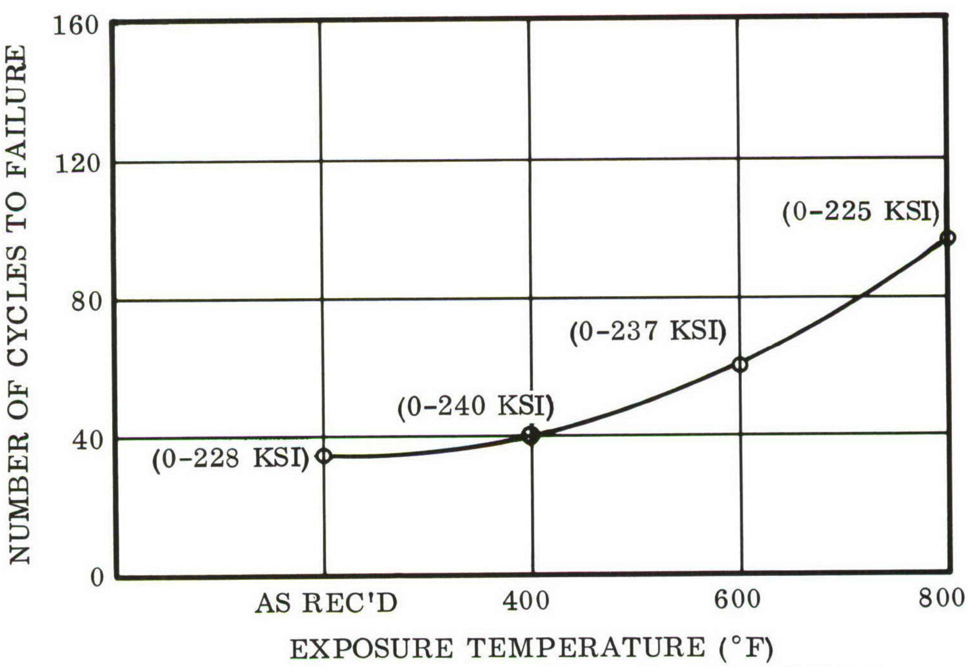


301 Stainless Steel Oxidation for 100 Hours (0.1 PSIG O_2)

Figure 62. Notched Tensile Properties of 301-Stainless Steel (at -320°F) after Oxidation Exposures for 100 Hours in Reduced Partial Pressures of Oxygen Gas

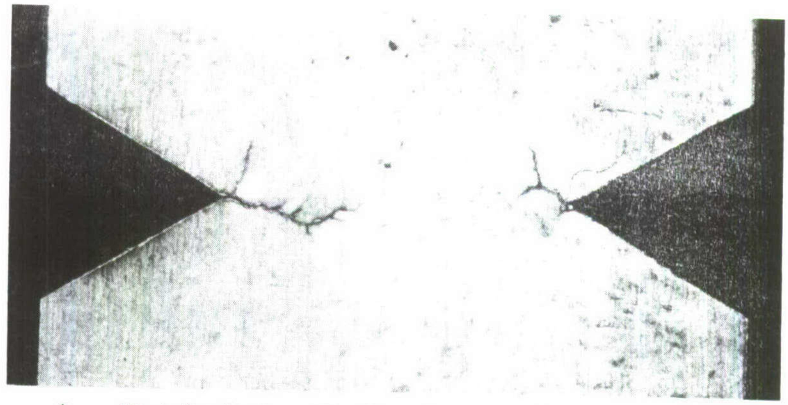


Static Tensile Strength of Complex Welded Joints

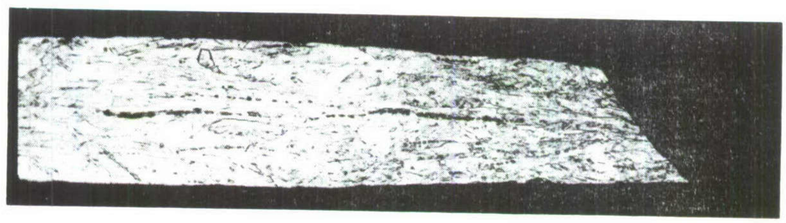


Axial Fatigue Properties of Complex Welded Joints

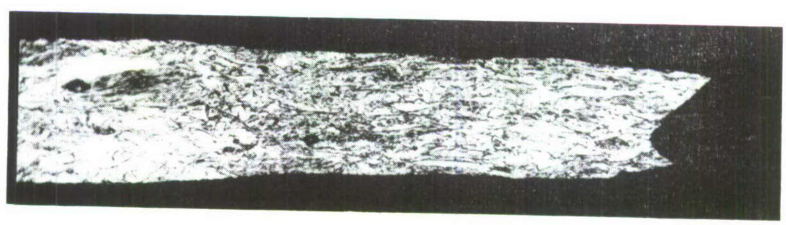
Figure 63. Static and Fatigue Properties of Complex Welded Joints of 301-Stainless Steel (at -320°F) after Thermal Exposures for 100 Hours in Air



A. Notched Tensile Speciment after 17 Cycles from -320°F to 600°F



B. 400°F

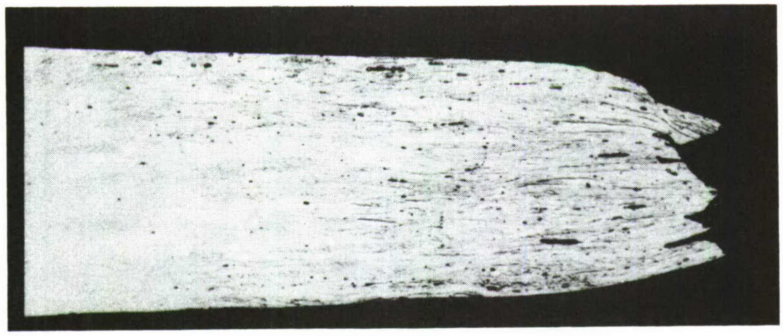


C. 600°F

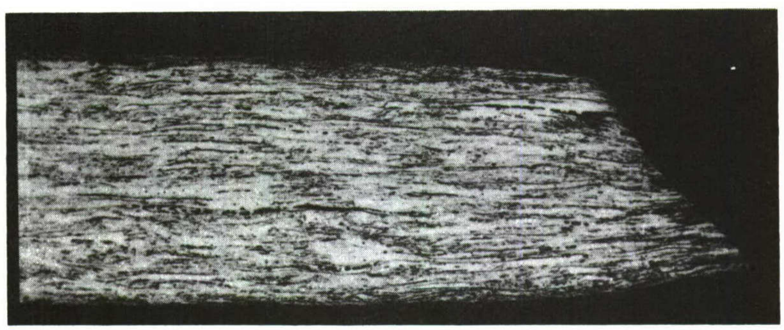
D. 800°F

Base Metal
Exposure: 100 Hours in 0.1 psig O_2 at Given Temperature
Etchant: 10% Oxalic, Electrolytic
Magnification: 250 X

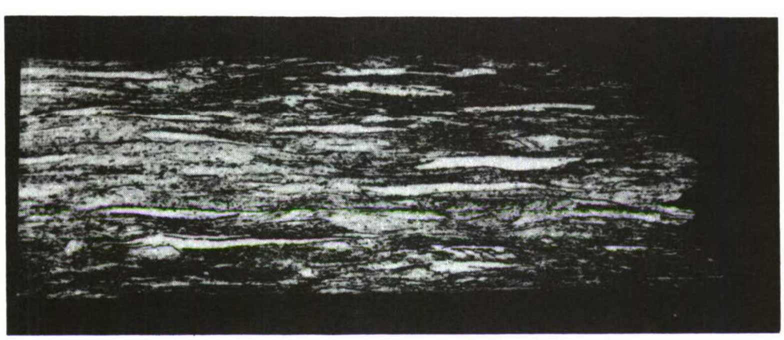
Figure 64. Photograph and Photomicrographs of Type 301-Stainless Steel after Various Exposures (0.003-Inch Thickness)



A. 400°F



B. 600°F



C. 800°F

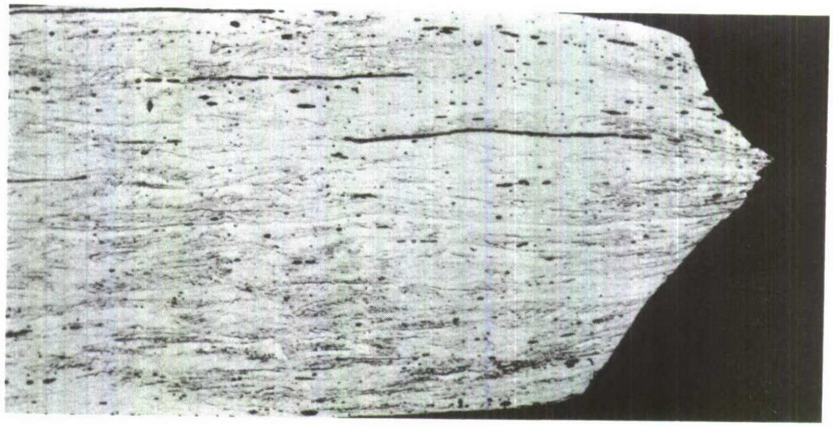
Base Metal

Exposure: 100 Hours in Air at Given Temperature

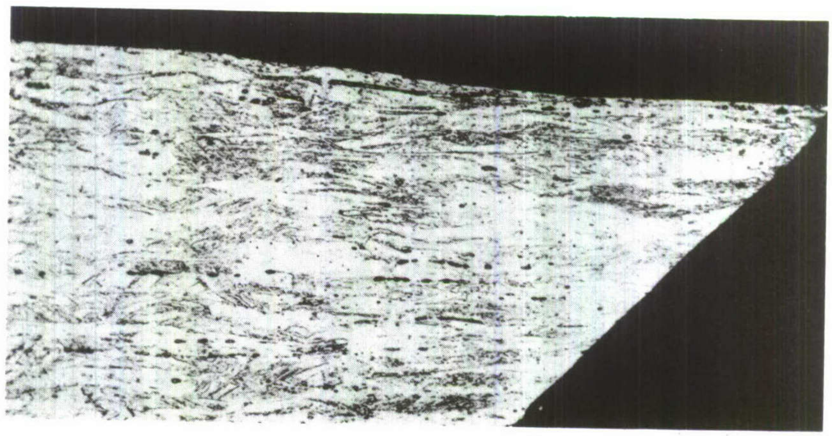
Etchant: 10% Oxalic, Electrolytic

Magnification: 250 X

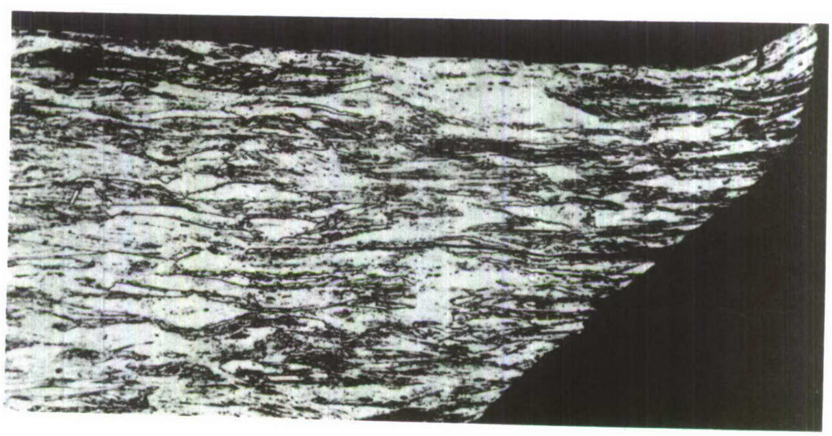
Figure 65. Photomicrographs of 301-Stainless Steel after Various Exposures (0.006 In. and 0.010 In. Thickness) (Sheet 1 of 3)



D. 400°F



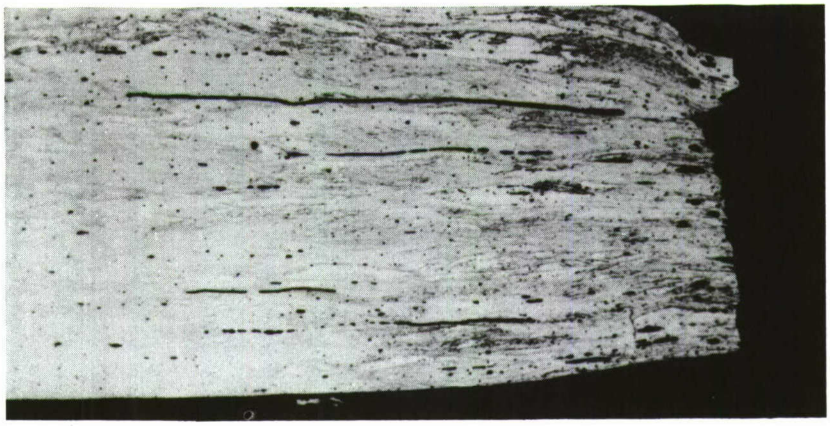
E. 600°F



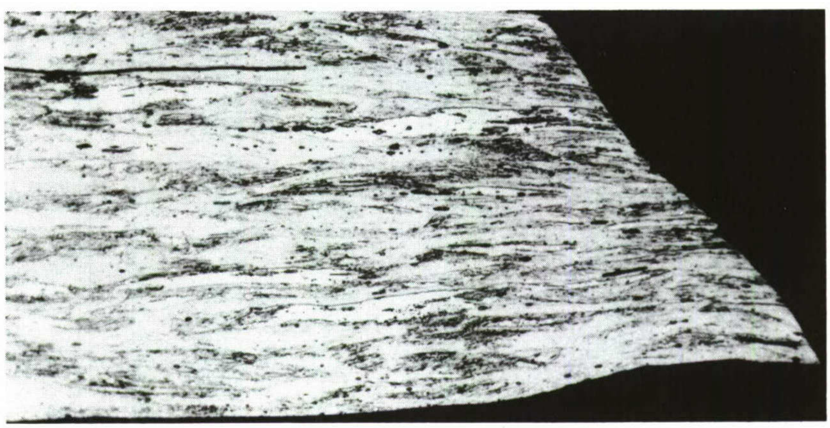
F. 800°F

Base Metal
Exposure: 100 Hours in 1.0 psig O_2 at Given Temperature
Etchant: 10% Oxalic, Electrolytic
Magnification: 250 X

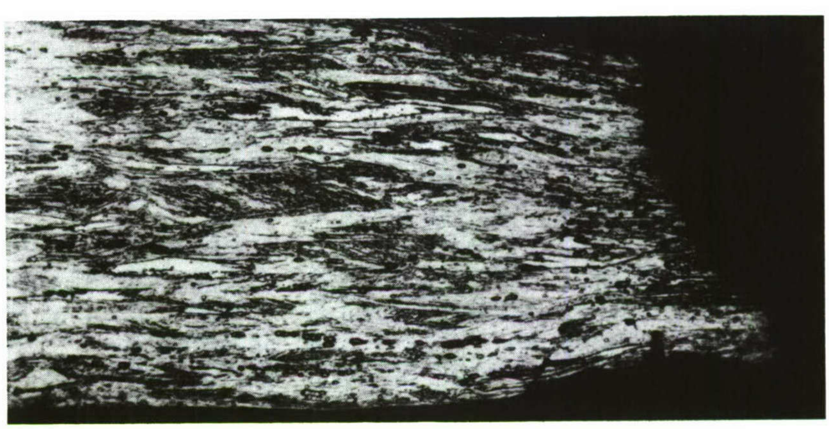
Figure 65. Photomicrographs of 301-Stainless Steel after Various Exposures (0.006 In. and 0.010 In. Thick) (Sheet 2 of 3)



G. -320° to 400°F



H. -320° to 600°F



I. -320° to 800°F

Base Metal

Exposure: 100 Cycles at Given Temperature

Etchant: 10% Oxalic, Electrolytic

Magnification: 250 X

Figure 65. Photomicrographs of 301-Stainless Steel after Various Exposures (0.006 In. and 0.010 In. Thick) (Sheet 3 of 3)

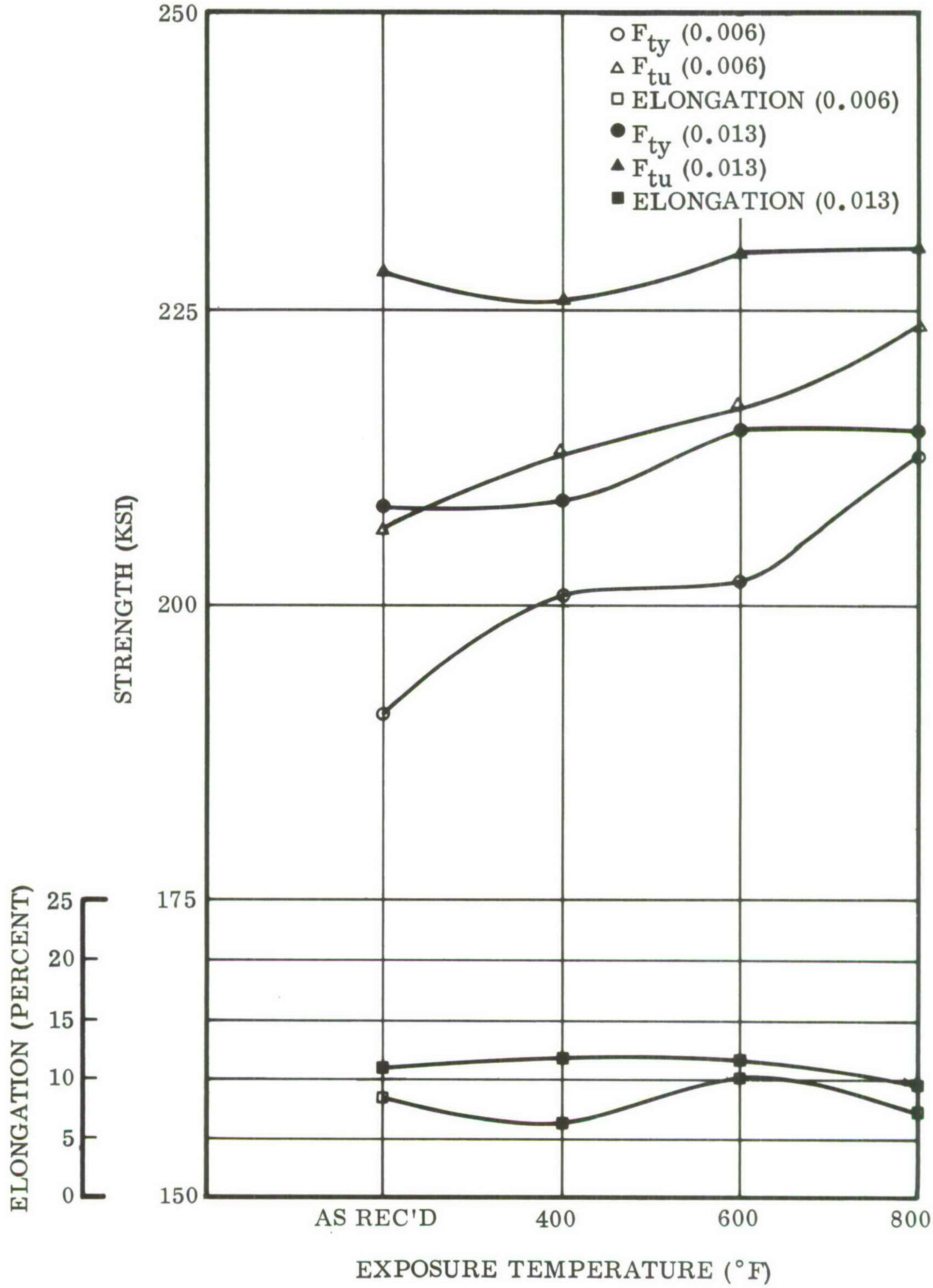


Figure 66. Mechanical Properties of Titanium-5Al-2.5Sn ELI Alloy (at -423°F) after Thermal Exposures for 100 Hours in Air

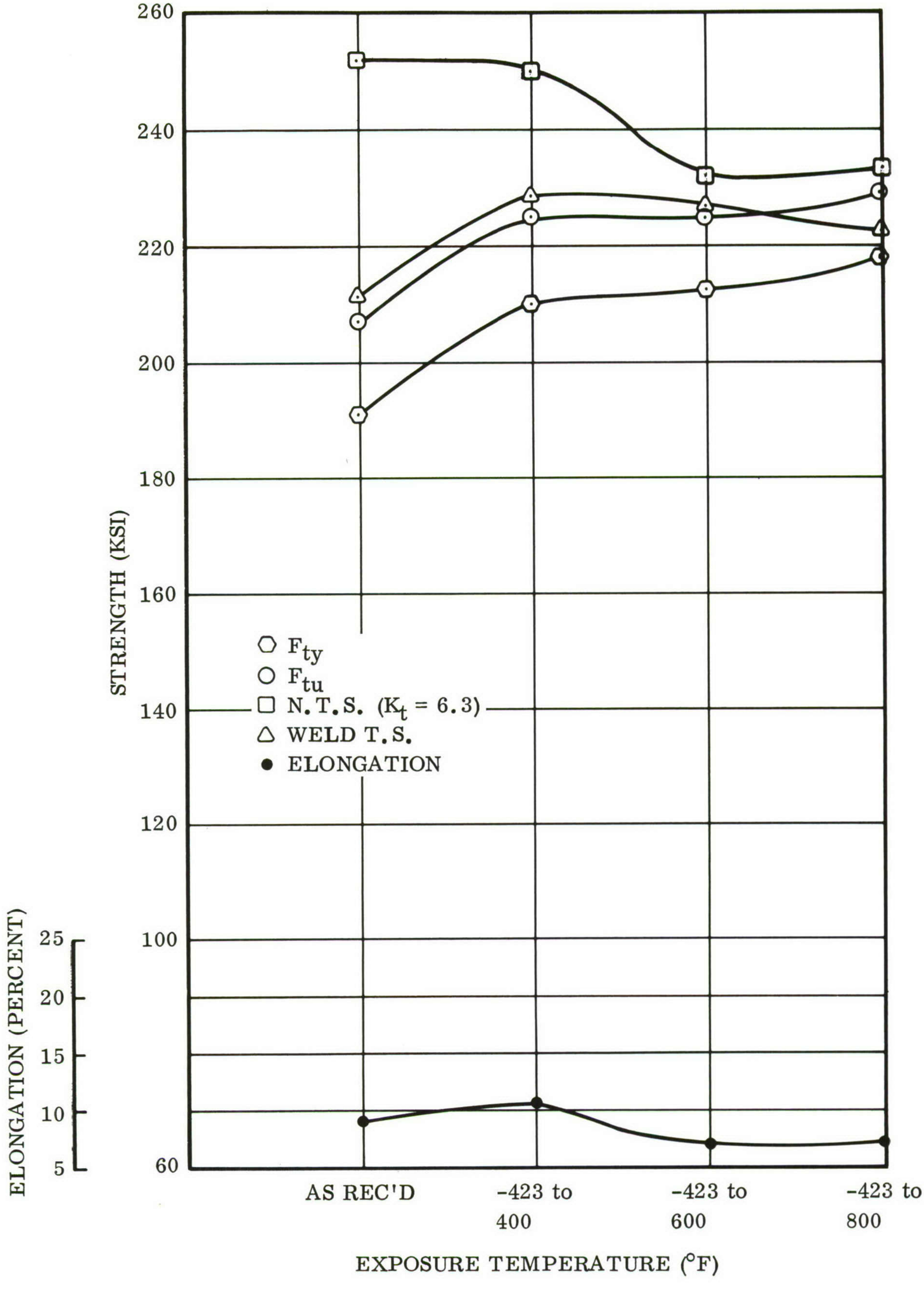


Figure 67. Mechanical Properties of Titanium-5Al-2.5Sn ELI Alloy (at -423°F) after Thermal Cyclic Exposures for 100 Cycles (0.006 In. Thickness)

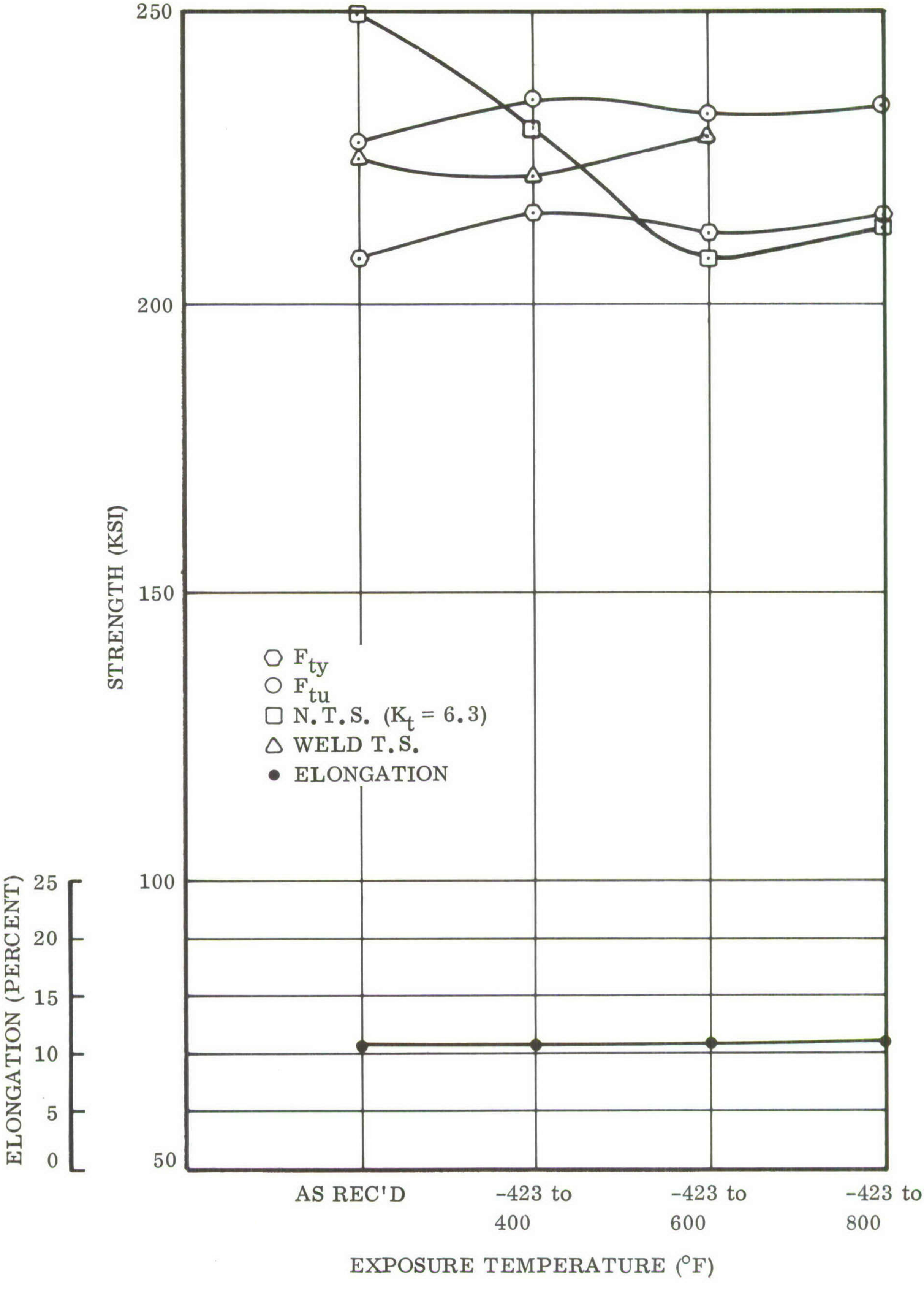
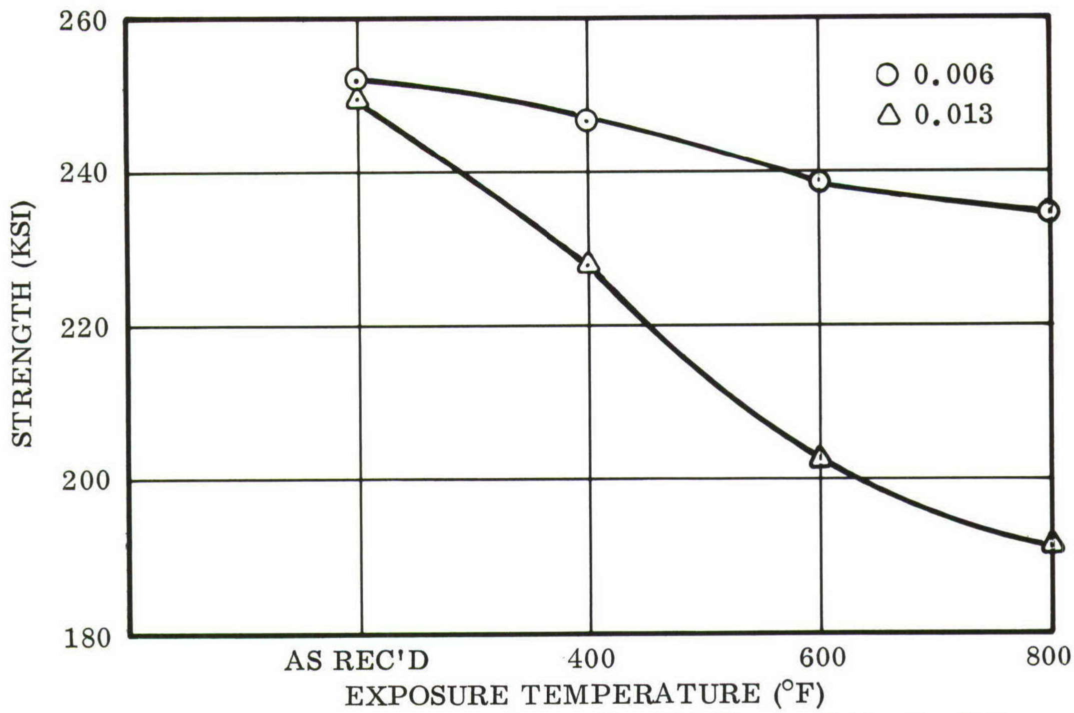
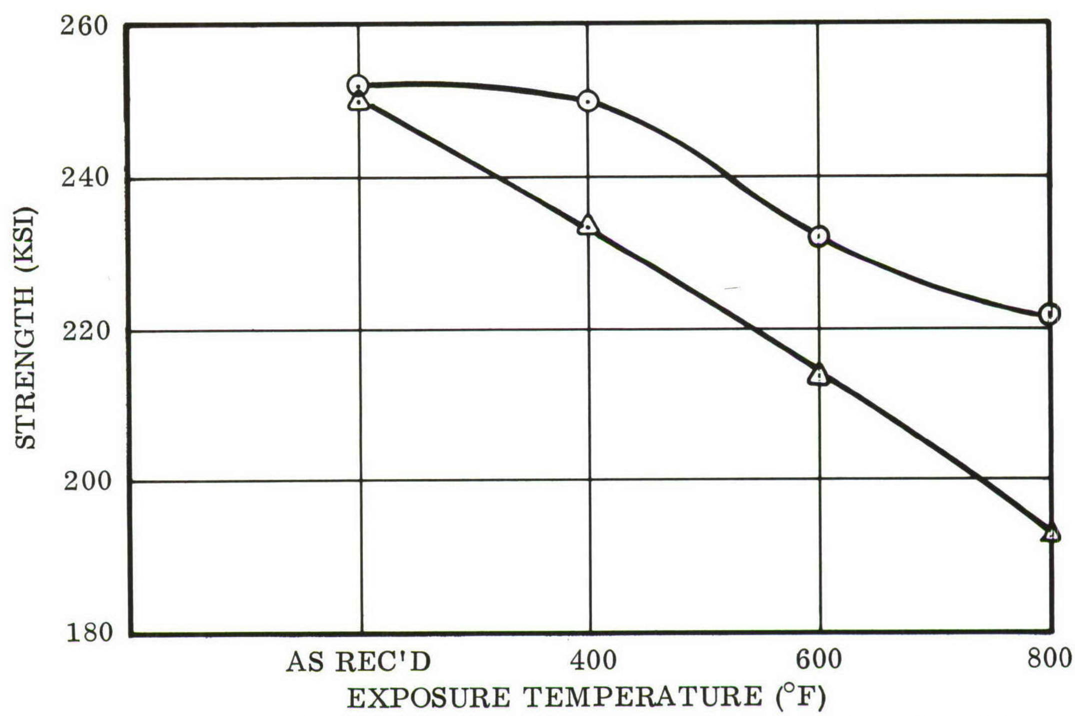


Figure 68. Mechanical Properties of Titanium-5Al-2.5Sn ELI Alloy (at -423°F) after Thermal Cyclic Exposures for 100 Cycles (0.013 In. Thickness)



Ti-5Al-2.5Sn ELI, Oxidation for 100 Hours (1.0 psig O_2)



Ti-5Al-2.5Sn ELI, Oxidation for 100 Hours (0.1 psig O_2)

Figure 69. Notched Tensile Properties of Titanium-5Al-2.5Sn ELI Alloy (at -423°F) after Oxidation Exposure for 100 Hours in Reduced Partial Pressures of Oxygen Gas

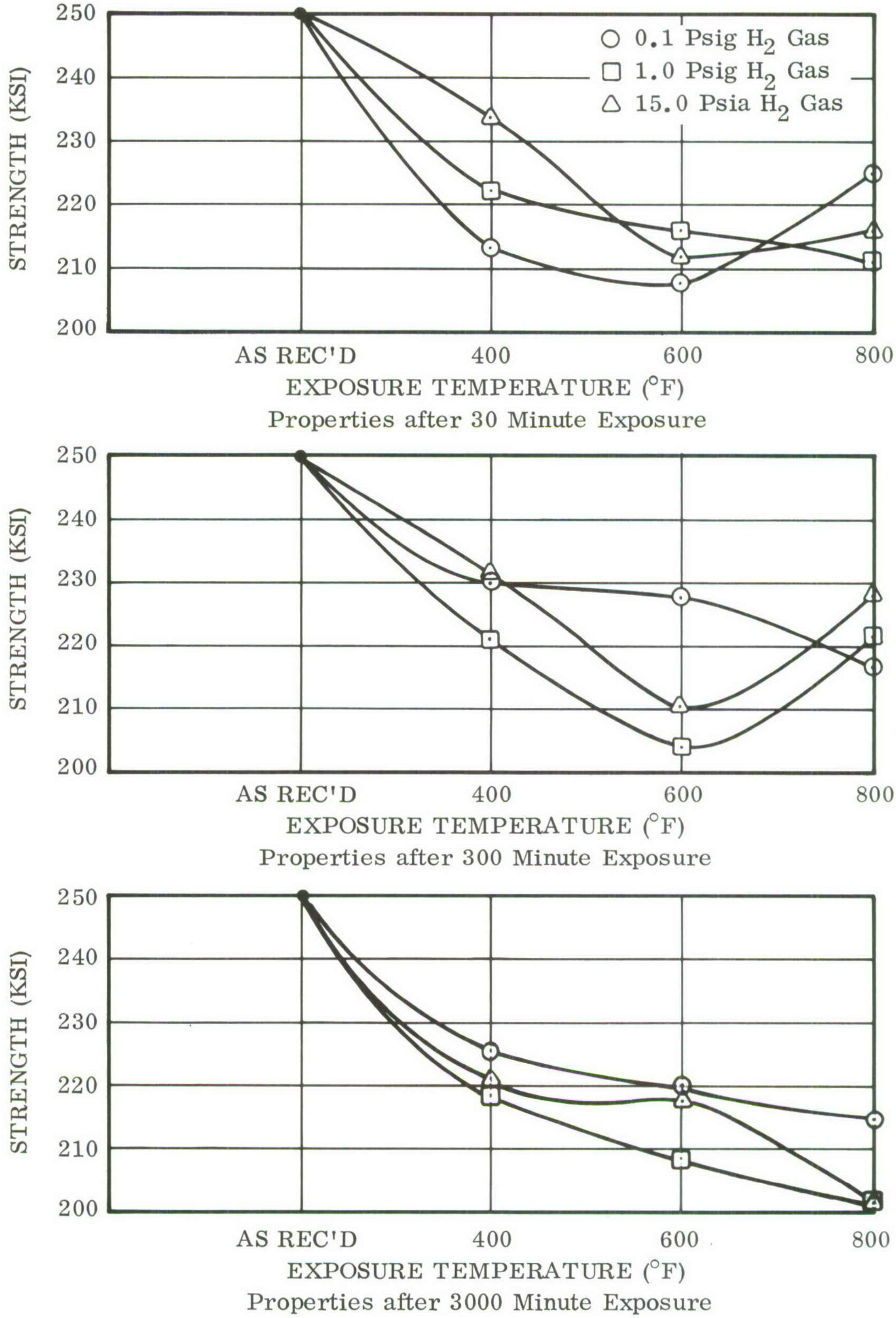
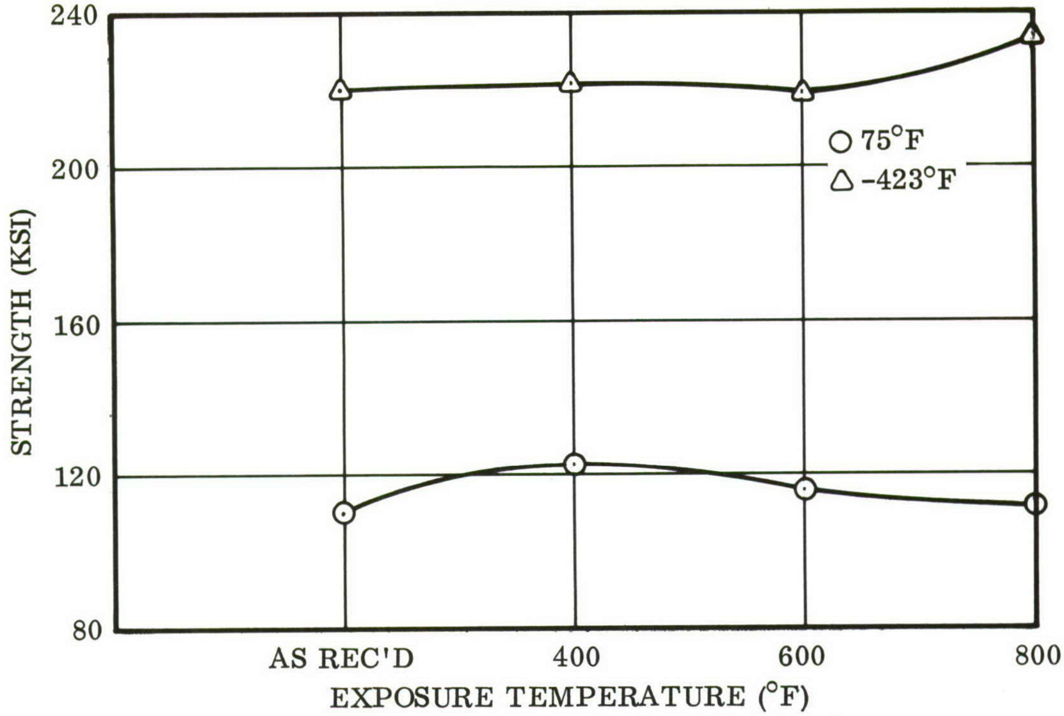
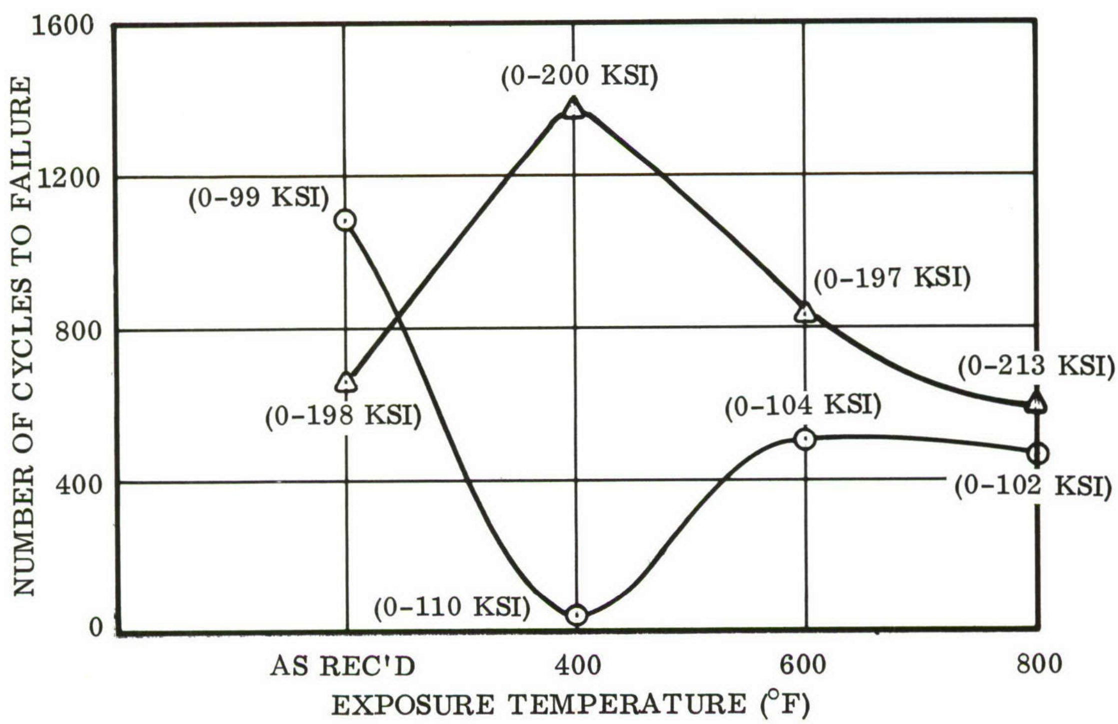


Figure 70. Notched Tensile Properties of Titanium-5Al-2.5Sn ELI Alloy (at -423°F) after Exposures in Various Pressures of Hydrogen Gas

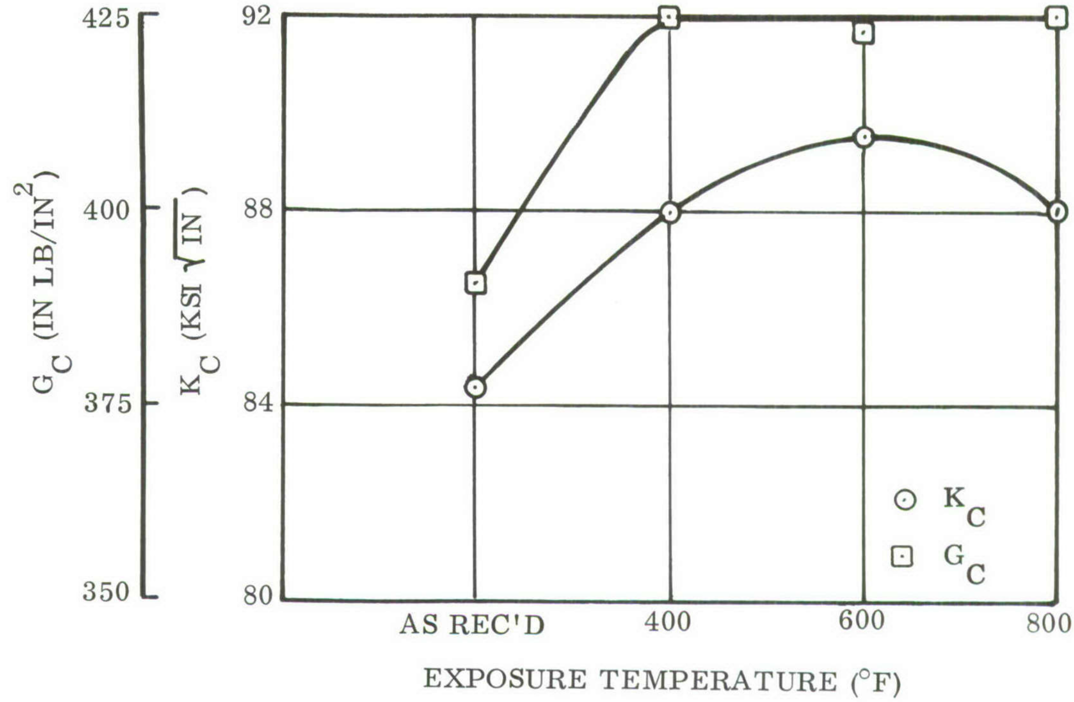


Static Tensile Strength of Welded Joints

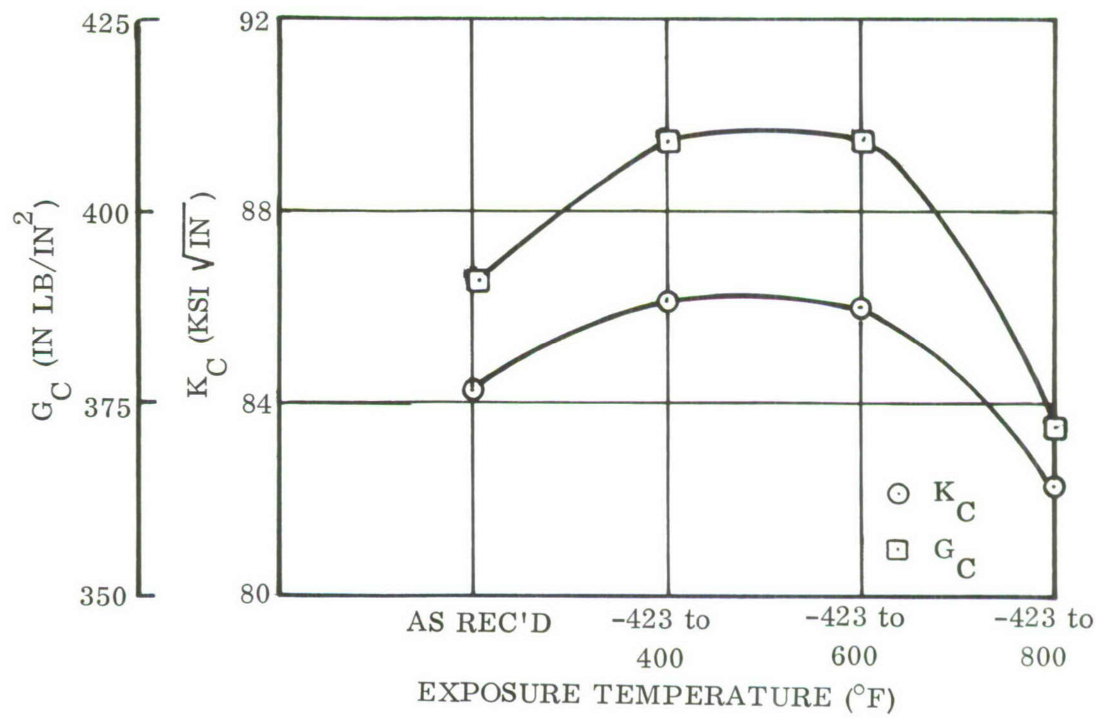


Axial Fatigue Properties of Welded Joints

Figure 71. Static and Fatigue Properties of Welded Joints of Titanium-5Al-2.5Sn ELI Alloy (at 75°F and -423°F) after Thermal Exposures for 100 Hours in Air

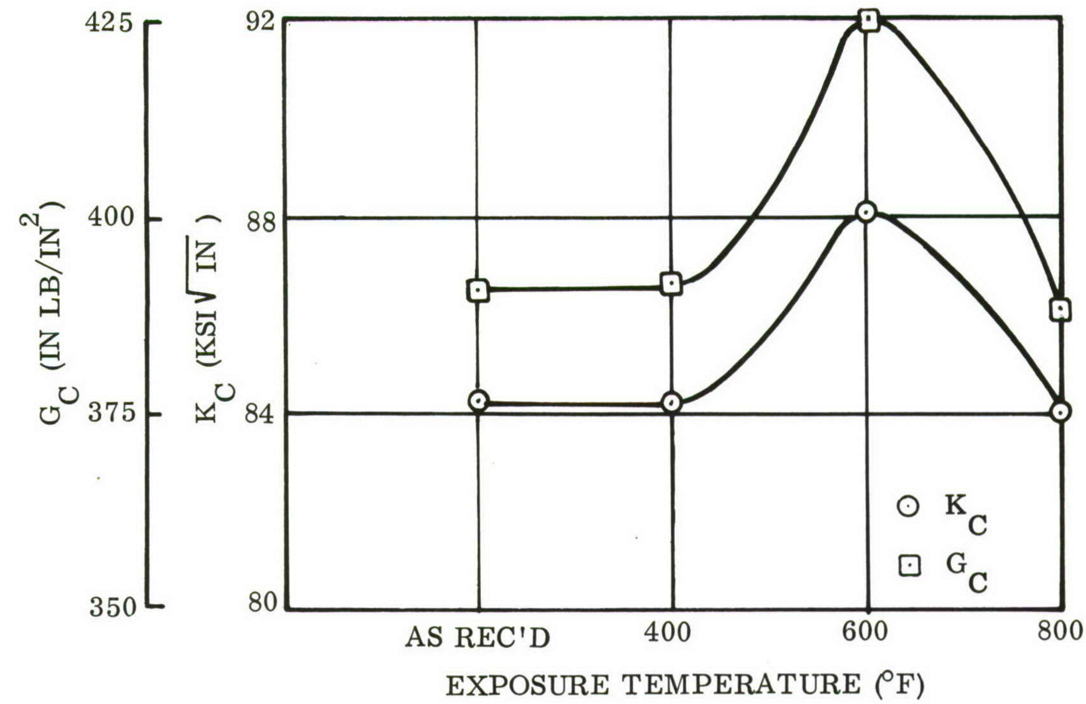


Properties After Thermal Exposures for 100 Hours in Air

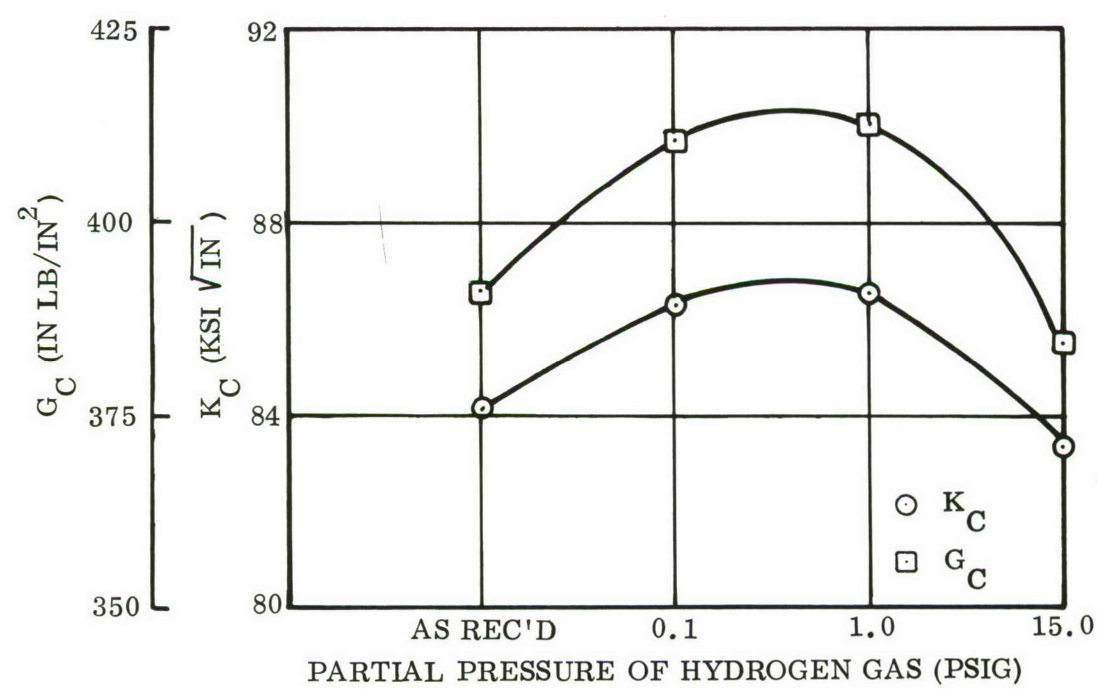


Properties After Cyclic Exposures for 100 Cycles in Air

Figure 72. Crack Propagation Properties of Titanium-5Al-2.5Sn ELI Alloy (at -423°F) after Various Exposures (Sheet 1 of 2)

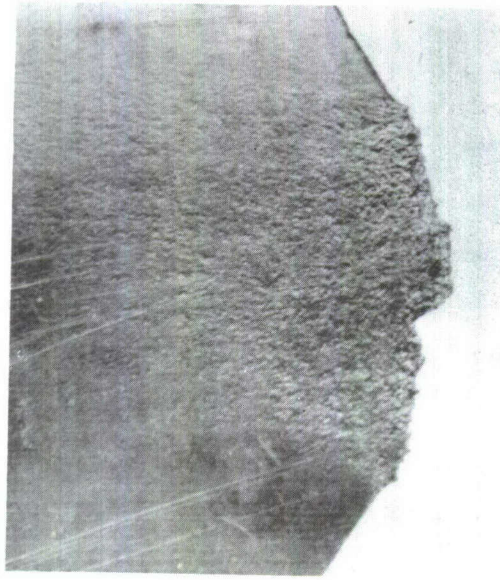


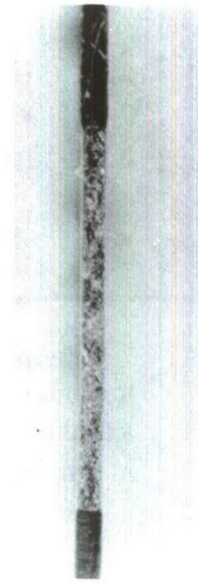
Properties After Oxidation Exposures for 100 Hours in 1.0 psig of Oxygen



Properties After Hydrogen Gas Exposures for 50 Hours at 600 °F

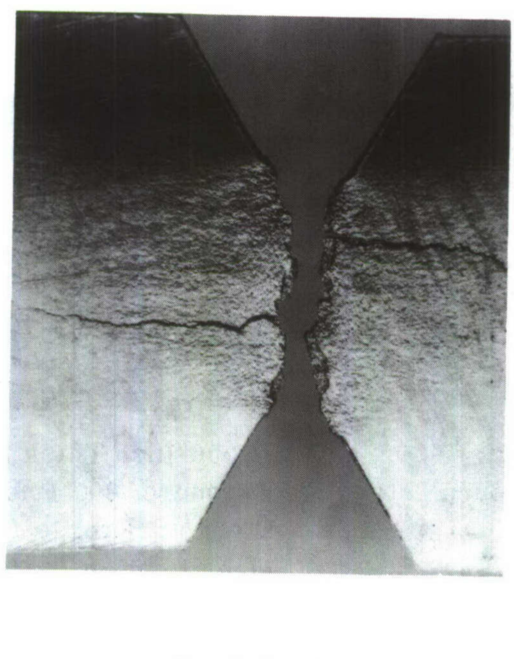
Figure 72. Crack Propagation Properties of Titanium-5Al-2.5Sn ELI Alloy (at -423° F) after Various Exposures (Sheet 2 of 2)

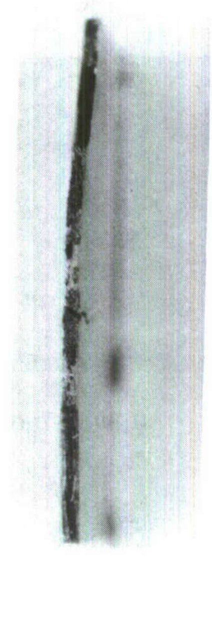




A. Side View B. Edge View

Typical Failure of Notched Tensile Specimens due to Exposure Under Load in Hydrogen Gas

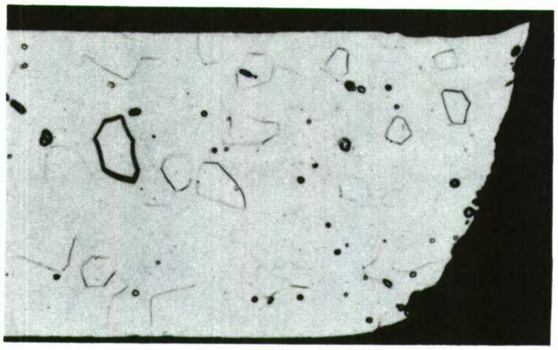




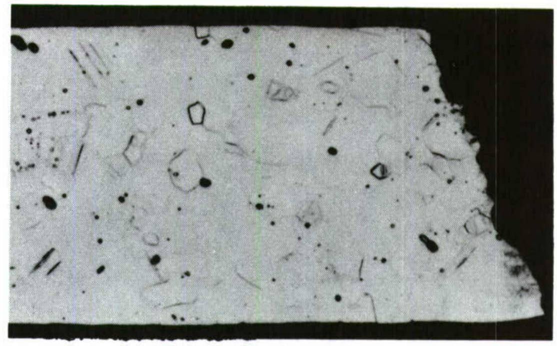
C. Side View D. Edge View

Failure, Showing Longitudinal Cracks, of Notched Tensile Specimens due to Exposure Under Load in Hydrogen Gas

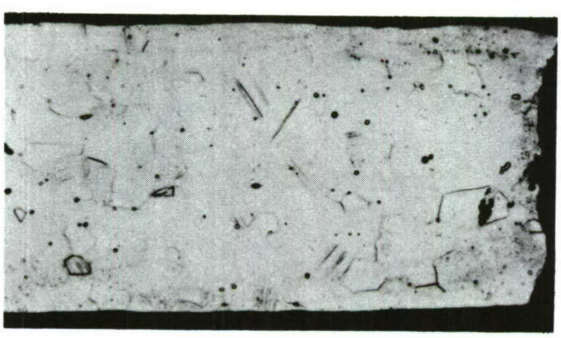
Figure 73. Photographs of Titanium-5Al-2.5Sn ELI Alloy after Hydrogen Gas Exposures



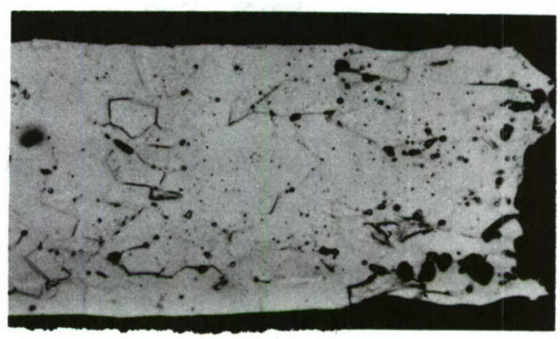
A. 0.006-Inch Thick Base Metal
Exposure: As Received
Etchant: Kroll's
Magnification: 250 X



B. 0.006-Inch Thick Base Metal
Exposure: 400°F for 100 Hours in Air
Etchant: Kroll's
Magnification: 250 X

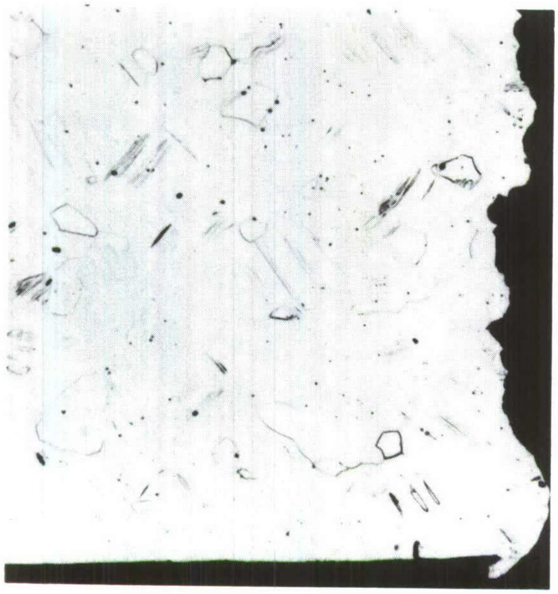


C. 0.006-Inch Thick Base Metal
Exposure: 600°F for 100 Hours in Air
Etchant: Kroll's
Magnification: 250 X

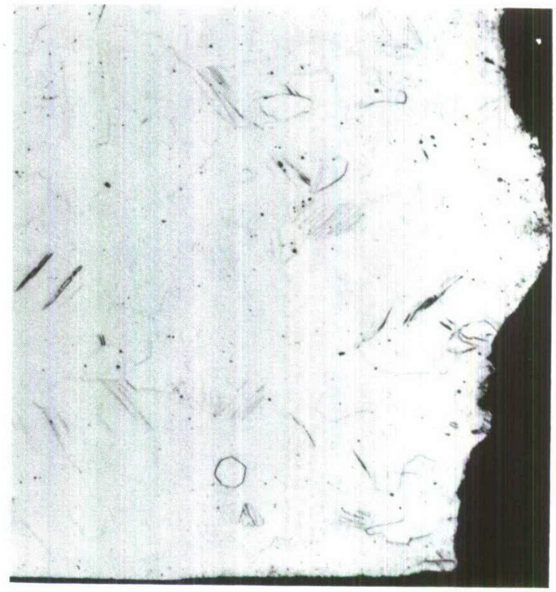


D. 0.006-Inch Thick Base Metal
Exposure: 800°F for 100 Hours in Air
Etchant: Kroll's
Magnification: 250 X

Figure 74. Photomicrographs of Titanium-5Al-2.5Sn ELI Sheet Material (Sheet 1 of 3)

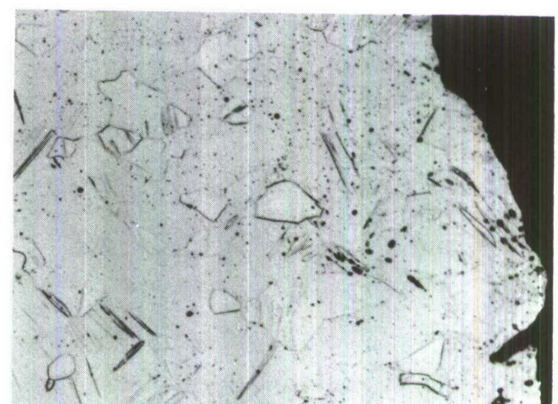


E. 0.013-Inch Thick Base Metal
Exposure: As Received
Etchant: Kroll's
Magnification: 250 X



F. 0.013-Inch Thick Base Metal
Exposure: 400°F for 100 Hours in Air
Etchant: Kroll's
Magnification: 250 X

G. 0.0013-Inch Thick Base Metal
Exposure: 600° F for 100 Hours in Air
Etchant: Kroll's
Magnification: 250 X

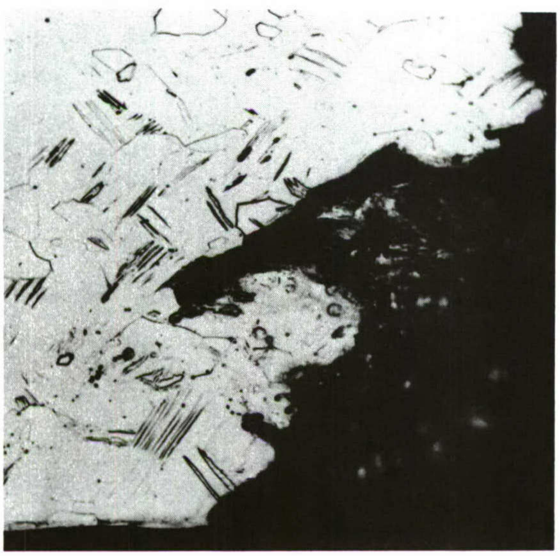


H. 0.013-Inch Thick Base Metal
Exposure: 800°F for 100 Hours in Air
Etchant: Kroll's
Magnification: 250 X

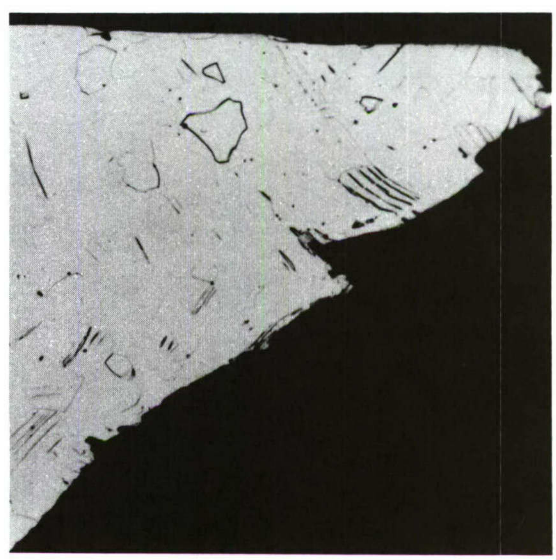
Figure 74. Photomicrographs of Titanium-5A1-2.5Sn ELI Sheet Material (Sheet 2 of 3)

I. 0.013-Inch Thick Base Metal
Exposure: As Received
Etchant: Kroll's
Magnification: 250 X

J. 0.013-Inch Thick Base Metal
Exposure: 400° F for 5 Hours in 0.1 psig H_2
Etchant: Kroll's
Magnification: 250 X



K. 0.013-Inch Thick Base Metal
Exposure: 400° F for 5 Hours in 1.0 psig H_2
Etchant: Kroll's
Magnification: 250 X



L. 0.013-Inch Thick Base Metal
Exposure: 400°F for 5 Hours in 15.0 psia H_2
Etchant: Kroll's
Magnification: 250 X

Figure 74. Photomicrographs of Titanium-5Al-2.5Sn ELI Sheet Material (Sheet 3 of 3)

TABLES

Table 1. History and Chemical Composition (Nominal) of Alloys Tested in Screening Program

Alloy	Haynes No. 25	Hastelloy X	Haynes R-41	Hastelloy R-235	Inconel 718	8Al-1Mo-1V Titanium	13V-11Cr-3Al Titanium	301XFH Stainless Steel	310FH Stainless Steel	5Al-2.5Sn Titanium-ELI
Temper	Cold Rolled 10%	Cold Rolled 10%	Annealed	Cold Rolled 10%	Annealed	Annealed	Annealed	Extra Full Hard	Full Hard	Annealed
Gauge (In.)	0.010	0.020	0.010	0.012	0.010	0.020	0.010	0.010	0.010	0.017
Supplier	Stellite	Stellite	Stellite	Stellite	Stellite	TMCA	TMCA	Washington	Washington	Republic
Heat No.	L1582	X4892	T28646	RV7403	8643	V1553	F9668	61945	43631	3960328
Chemistry (Wt. %)										
Ni	10.0	Bal.	Bal.	Bal.	52.50			7.00	20.50	
Cr	20.0	21.75	19.0	15.50	19.0		11.00	17.00	25.00	0.10
Co	Bal.	1.50	11.0	2.50						
V						1.00	13.50			0.10
Al			1.5	2.00	1.5	8.0	3.00			5.40
Ti			3.15	2.50	0.8	Bal.	Bal.			Bal.
Mo		9.0	9.75	5.50	3.1	1.00				0.10
Cb					5.625					
B			0.0065							
W	15.0	0.60								
Fe	3.00	18.50	5.00	10.00	Bal.	0.3		Bal.	Bal.	
Sn										2.50
Cu					0.75					
Si	1.00	1.00	0.50	0.60	0.75			1.00	1.50	
C	0.10	0.10	0.12	0.16	0.10	0.08	0.05	0.14	0.25	0.05
O							0.20			0.12
N						0.05	0.08			0.04
H						0.015	0.02			0.015
Mn	1.5	1.00	0.10	0.25	0.50			2.00	2.00	0.10
P				0.010					0.045	
S		0.015	0.030	0.03				0.03		

Table 2. History and Chemical Analysis of Alloys Tested in Phase II

Alloy	Hastelloy X	Hastelloy X	13V-11Cr-3Al Titanium	13V-11Cr-3Al Titanium	301 Stainless Steel	301 Stainless Steel	301 Stainless Steel	5Al-2.5Sn ELI Titanium
Gauge (In.)	0.005	0.010	0.005	0.010	0.003	0.006	0.010	0.013 and 0.006
Temper	Annealed	Annealed	Annealed	Annealed	EFH	EFH	EFH	Annealed
Supplier	Union Carbide Stellite	Union Carbide Stellite	Rodney Metals	Crucible Steel	Wallingford Steel	Wallingford Steel	Washington Steel	Titanium Metals Corp. of America
Heat No.	X-24806	X-24349	F-8276	F-9668	89361	36208	61945	D-3274
Coil No.							8693	
Specification	AMS 5536C	AMS 5536C			Mil-S-5059A	Mil-S-5059A	GD/A-0-71004	GD/A-0-71010
Chemistry (Wt. %)								
Al			3.3	3.4				5.2
C	0.10	0.11	0.04	0.04	0.11	0.11	0.10	0.026
Co	1.53	1.66				0.10		
Cr	21.87	22.09	11.5	10.4	17.93	16.64	17.02	
Cu					0.13	0.13	0.16	
Fe	19.1	18.9	0.26	0.17	Bal.	Bal.	Bal.	0.05
H								12 ppm
Mn	0.62	0.49			0.74	0.72	0.61	<0.006
Mo	9.02	8.88			0.20	0.13	0.18	
N			0.035	0.03				0.017
Ni	Bal.	Bal.			7.10	7.22	7.17	
O				0.11				0.080
P	0.019	0.014			0.021	0.020	0.026	
S	0.008	0.007			0.019	0.014	0.017	
Sn								2.5
Si	0.72	0.66			0.38	0.30	0.42	
Ti			Bal.	Bal.				Bal.
V			13.6	13.7				
W	0.54	0.52						

Table 3. Inert-Arc Straight-Line Fusion Weld Schedules

Material	Gauge (in.)	Filler	Amps	Volts*	Speed (in./min)	Backup Gas (ft^3/hr)	Torch Gas (ft^3/hr)	Clamp Pressure (psi)	Backup Bar (Room Temp)	Electrode (Tungsten-2% Thoriated) (in.)**
Hastelloy X	0.005	None	6	4	6.5	A/10	A/10	15	Copper	0.020
Hastelloy X	0.010	None	12	8	6.5	A/10	A/10	30	Copper	0.040
Ti-13V-11Cr-3Al	0.005	None	4	5	4	A/10 Trailing Shield	A/12 He/12	15	Copper	0.020
Ti-13V-11Cr-3Al	0.010	None	6	8	4	A/10 Trailing Shield	A/12 He/12	30	Copper	0.040
Type 301 S.S.	0.003	None	5	7	4	A/10	A/10	10	Copper	0.020
Type 301 S.S.	0.006	None	7	7	6	A/10	A/10	20	Copper	0.040
Type 301 S.S.	0.010	None	10	12	6	A/10	A/10	30	Copper	0.064
Ti-5Al-2.5Sn	0.006	None	4	5	4	A/10 Trailing Shield	A/12 He/12	15	Copper	0.020
Ti-5Al-2.5Sn	0.013	None	8	10	4	A/10 Trailing Shield	A/12 He/12	30	Copper	0.040

* Direct current, straight polarity
** All electrodes tapered 30 degrees

Table 4. Tensile Properties of Hastelloy X Alloy (0.005-In. Thickness)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength ($K_t = 6.3$) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
As-Received	75	83.3	133	17.0	93.5		118	15.0	
	75	80.7	127	17.0	94.0		114	14.5	
	75	82.5	130	17.0	96.9		107	15.0	
	75	81.7	130	17.5	91.8		108	15.5	
	75	83.4	130	16.5	95.9		108	14.0	
Avg.		82.3	130	17.0	94.4	0.72	111	14.8	85
Thermal Exposure,	75	72.2	127	16.5					
1600°F for 100	75	72.9	127	19.0					
Hours in Air	75	73.8	129	19.0					
	75	75.4	133	19.0					
	75	73.9	130	18.5					
Avg.		73.6	129	18.4					
Thermal Exposure,	75	53.2	93.0	8.0					
1800°F for 100	75	54.8	85.7	3.5					
Hours in Air	75	58.8	91.8	8.0					
	75	55.0	90.3	6.0					
	75	59.5	94.5	10.0					
Avg.		56.3	91.1	7.1					

Thermal Exposure,	75	*							
2000°F for 100	75	*							
Hours in Air	75	*							
	75	*							
	75	*							
Avg.									
Thermal Exposure,	75	*							
2200°F for 100	75	*							
Hours in Air	75	*							
	75	*							
	75	*							
Avg.									
Thermal Cycle,	75	81.1	138	21.0	111		130	16.5	
75°F to 1600°F	75	82.6	139	21.5	111		131	17.0	
100 Cycles in	75	82.6	138	16.5	111		126	15.5	
Air	75	81.4	137	20.0	113		132	15.0	
	75	83.3	135	20.0	113		133	16.0	
Avg.		82.2	137	19.8	112	0.82	130	16.0	95
Thermal Cycle,	75	74.1	130	25.0	112		118	21.0	
75°F to 1800°F	75	74.6	130	28.0	105		121	21.5	
100 Cycles in	75	74.8	130	25.0	104		121	21.5	
Air	75	73.4	129	26.0	106		123	22.0	
	75	70.9	123	25.0	107		110	16.5	
Avg.		73.5	128	25.8	107	0.84	119	20.5	93

*Specimen failed during exposure.

Table 4. (Cont)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
Thermal Cycle,	75	51.9	107	25.0	65.0		99.7	21.5	
75°F to 2000°F	75	55.8	107	25.0	76.5		101	22.0	
100 Cycles in Air	75	51.1	107	24.5	82.5		99.7	21.5	
	75	50.0	101	23.0	87.5		104	22.0	
	75	50.5	104	24.5	82.0		103	22.5	
Avg.		51.9	105	24.4	78.7	0.75	101	21.9	96
Thermal Cycle,	75	43.0	88.3	18.0	75.7		85.6	17.5	
75°F to 2200°F	75	45.4	88.0	18.5	81.8		90.6	18.0	
100 Cycles in Air	75	46.1	85.2	18.0	66.9		80.3	17.0	
	75	49.4	86.0	17.0	74.8		83.3	17.0	
	75	48.2	93.2	18.0	51.2		85.5	17.5	
Avg.		46.4	88.1	17.9	70.1	0.80	85.1	17.4	97
Oxidation, 0.1 psig	75				111				
O_2 at 1600°F for	75				111				
100 Hours	75				113				
	75				111				
	75				109				
Avg.									

Oxidation, 1.0 psig	75	112
O_2 at 1600°F for	75	113
100 Hours	75	112
	75	109
	75	115
Avg.		112
Oxidation, 0.1 psig	75	71.5
O_2 at 1800°F for	75	70.8
100 Hours	75	76.0
	75	80.4
	75	69.6
Avg.		73.6
Oxidation, 1.0 psig	75	77.1
O_2 at 1800°F for	75	89.8
100 Hours	75	92.5
	75	89.9
	75	91.5
Avg.		88.2
Oxidation, 0.1 psig	75	56.0
O_2 at 2000°F for	75	30.4
100 Hours	75	40.0
	75	27.0
	75	55.0
Avg.		41.7

Table 4. (Cont)

Exposure Condition	Test Temp ($^{\circ}F$)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength ($K_t = 6.3$) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
Oxidation, 1.0 psig	75				74.0				
O_2 at 2000°F for	75				58.5				
100 Hours	75				54.6				
	75				62.8				
	75				13.7				
Avg.					52.7				
Oxidation, 0.1 psig	75				*				
O_2 at 2200°F for	75				*				
100 Hours	75				*				
	75				*				
	75				*				
Avg.									
Oxidation, 1.0 psig	75				*				
O_2 at 2200°F for	75				*				
100 Hours	75				*				
	75				*				
	75				*				
Avg.									

*Specimen failed during exposure.

Spalling, 0.1 psig	75	101
O_2 75°F to 1800°F	75	104
100 Cycles at	75	103
30 minutes/cycle	75	105
	75	108
Avg.		104
Spalling, 1.0 psig	75	105
O_2 75°F to 1800°F	75	105
100 Cycles at	75	103
30 minutes/cycle	75	101
	75	101
Avg.		103

Table 5. Tensile Properties of Hastelloy X Alloy (0.010-In. Thickness)

Exposure Condition		Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
As-Received		75	59.0	116	43.0	94.2		120		
		75	59.1	117	42.5	95.1		121	38.5	
		75	59.7	117	42.0	94.3		120	36.0	
		75	58.0	115	42.0	94.4		121	39.5	
		75	58.7	115	40.0	94.1		94.8	11.0	
	Avg.		58.9	116	41.9	94.4	0.81	116	31.3	100
Thermal Exposure, 1600°F for 100 Hours in Air		75	46.3	110	26.5					
		75	46.1	110	26.0					
		75	46.7	111	27.0					
		75	47.2	110	25.5					
		75	47.1	109	26.5					
	Avg.		46.7	110	26.3					
Thermal Exposure, 1800°F for 100 Hours in Air		75	40.6	100	23.5					
		75	40.7	104	33.0					
		75	42.5	105	32.0					
		75	42.4	106	26.5					
		75	40.4	101	25.0					
	Avg.		41.3	103	28.0					

Thermal Exposure,	75	36.7	81.4	18.5					
2000°F for	75	37.5	81.8	27.5					
100 Hours in Air	75	34.0	80.9	27.0					
	75	30.9	81.4	22.5					
	75	41.6	85.1	26.5					
Avg.		36.1	82.1	24.4					
Thermal Exposure,	75	*							
2200°F for	75	*							
100 Hours in Air	75	*							
	75	*							
	75	*							
Avg.									
Thermal Cycle,	75	52.0	108	20.5	89.1		112	31.5	
75°F to 1600°F	75	51.1	106	19.0	88.3		111	30.0	
100 Cycles in Air	75	52.1	110	24.5	89.4		111	28.5	
	75	50.9	108	23.5	88.7		109	30.5	
	75	50.2	105	18.5	89.9		111	31.0	
Avg.		51.3	107	21.2	89.1	0.83	111	30.3	100
Thermal Cycle,	75	47.5	110	36.5	89.1		113	26.0	
75°F to 1800°F	75	47.8	111	36.0	90.8		111	29.0	
100 Cycles in Air	75	48.0	112	34.5	90.0		111	27.0	
	75	48.2	110	38.0	90.2		111	27.5	
	75	47.8	111	34.5	88.3		111	26.5	
Avg.		47.9	111	35.9	89.7	0.81	111	27.2	100

Table 5. (Cont)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
Thermal Cycle,	75	45.9	109	38.5	87.3		108	29.0	
75°F to 2000°F	75	46.8	109	37.5	84.9		110	24.0	
100 Cycles in Air	75	45.6	109	36.5	90.6		107	25.0	
	75	45.2	108	38.5	90.8		105	28.5	
	75	45.2	108	38.5	92.7		108	24.5	
Avg.		45.7	109	37.9	89.3	0.82	108	26.2	99
Thermal Cycle,	75	31.5	72.7	24.0	64.6		69.8	20.0	
75°F to 2200°F	75	33.4	85.5		64.7		72.7	16.5	
100 Cycles	75	31.0	75.2		60.2		68.8	23.5	
	75	31.1	72.1	24.0	71.6		83.4	26.0	
	75	31.9	68.6	21.0	70.4		71.1	25.0	
Avg.		31.8	74.8	23.0	66.3	0.89	73.2	22.2	98
Oxidation, 0.1 psig	75				91.4				
O_2 at 1600°F for	75				91.9				
100 Hours	75				91.4				
	75				89.6				
	75				91.4				
Avg.					91.2				

Oxidation, 1.0 psig	75	91.7
O_2 at 1600°F for	75	93.0
100 Hours	75	93.3
	75	92.5
	75	93.0
Avg.		92.7
Oxidation, 0.1 psig	75	86.2
O_2 at 1800°F for	75	84.4
100 Hours	75	84.7
	75	84.1
	75	84.1
Avg.		84.7
Oxidation, 1.0 psig	75	86.1
O_2 at 1800°F for	75	85.4
100 Hours	75	85.2
	75	86.9
	75	85.9
Avg.		85.9
Oxidation, 0.1 psig	75	77.7
O_2 at 2000°F for	75	76.4
100 Hours	75	83.8
	75	80.2
	75	76.6
Avg.		78.9

Table 5. (Cont)

Exposure Condition	Test Temp ($^{\circ}F$)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength ($K_t = 6.3$) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
Oxidation, 1.0 psig	75				89.4				
O_2 at 2000°F for	75				89.1				
100 Hours	75				90.5				
	75				89.7				
	75				91.6				
Avg.					90.1				
Oxidation, 0.1 psig	75				*				
O_2 at 2200°F for	75				*				
100 Hours	75				*				
	75				*				
	75				*				
Avg.									
Oxidation, 1.0 psig	75				*				
O_2 at 2200°F for	75				*				
100 Hours	75				*				
	75				*				
	75				*				
Avg.									

*Specimens failed during exposure.

Spalling, 0.1 psig	75	91.1
O_2 75°F to 1800°F	75	91.3
100 Cycles at	75	89.0
30 minutes/cycle	75	90.0
	75	90.0
Avg.		90.3
Spalling, 1.0 psig	75	90.5
O_2 75°F to 1800°F	75	90.6
100 Cycles at	75	91.8
30 minutes/cycle	75	91.8
	75	93.1
Avg.		91.6

Table 6. Tensile Properties of Titanium-13V-11Cr-3Al Alloy (0.005-In. Thickness)

Exposure Condition		Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
As-Received		75	144	151	15.5	171		149	1.0	
		75	142	155	12.5	167		146	1.5	
		75	142	149	16.0	167		156	4.0	
		75	145	153	16.5	166		158	2.0	
		75	146	154	16.0	171		159	5.0	
	Avg.		144	152	15.3	168	1.11	154	2.7	100
Thermal Exposure,		75	149	155	16.5					
400°F for 100		75	150	156	18.0					
Hours in Air		75	142	148	16.5					
		75	149	155	18.5					
		75	149	155	17.5					
	Avg.		148	154	17.4					
Thermal Exposure,		75	154	160	16.5					
600°F for 100		75	155	162	16.0					
Hours in Air		75	154	160	13.0					
		75	157	163	16.0					
		75	154	160	17.0					
	Avg.		155	161	15.7					

Thermal Exposure,	75	220	230	1.5					
800°F for 100	75	228	240	2.0					
Hours in Air	75	233	247	3.5					
	75	229	242	4.0					
	75	233	246	4.0					
Avg.		229	241	3.0					
Thermal Cycle,	75	147	154	16.0	169		154	4.0	
75°F to 400°F	75	150	157	19.0	170		153	3.0	
100 Cycles in Air	75	148	154	17.5	173		152	2.5	
	75	149	156	16.5	174		151	2.5	
	75	150	158	16.5	173		149	2.0	
Avg.		149	156	17.1	172	1.10	152	2.8	97
Thermal Cycle,	75	154	156		168		152	4.0	
75°F to 600°F	75	147	153	18.0	169		138	1.5	
100 Cycles in Air	75	151	158	18.5	173		142	2.5	
	75	152	159	16.0	175		155	3.0	
	75	144	149	15.5	173		156	3.0	
Avg.		150	155	17.0	172	1.11	149	2.8	96
Thermal Cycle,	75	171	182	9.5	170		126	0.5	
75°F to 800°F	75	176	186	9.0	170		170	3.0	
100 Cycles in Air	75	176	186	8.5	161				
	75	177	188	8.0	176		127	1.0	
	75	177	188	7.5	182		169	2.0	
Avg.		175	186	8.5	172	0.92	148	1.6	80

Table 6. (Cont)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
Oxidation, 0.1 psig	75				168				
O_2 at 400°F for	75				168				
100 Hours	75				166				
	75				168				
	75				172				
Avg.					168				
Oxidation, 1.0 psig	75				173				
O_2 at 400°F for	75				177				
100 Hours	75				176				
	75				174				
	75				174				
Avg.					175				
Oxidation, 0.1 psig	75				168				
O_2 at 600°F for	75				165				
100 Hours	75				165				
	75				165				
	75				162				
Avg.					165				

Oxidation, 1.0 psig	75	172
O_2 at 600°F for	75	176
100 Hours	75	165
	75	174
	75	174
Avg.		172
Oxidation, 0.1 psig	75	111
O_2 at 800°F for	75	109
100 Hours	75	103
	75	107
	75	96.1
Avg.		105
Oxidation, 1.0 psig	75	137
O_2 at 800°F for	75	128
100 Hours	75	142
	75	126
	75	125
Avg.		132

Table 7. Tensile Properties of Titanium-13V-11Cr-3Al Alloy (0.010-In. Thickness)

Exposure Condition		Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Elongation (%)	Efficiency (%)
As-Received		75	129	132	26.0	161		120	5.0	
		75	127	129	26.0	163		136	4.5	
		75	129	132	28.0	161		136	5.0	
		75	126	128	26.5	163		128	4.0	
		75	129	132	26.5	164		132	5.0	
	Avg.		128	131	26.6	162	1.24	130	4.7	99
Thermal Exposure,		75	133	135	25.5					
400°F for 100		75	134	135	26.0					
Hours in Air		75	135	136	25.5					
		75	134	136	26.0					
		75	133	134	26.0					
	Avg.		134	135	25.8					
Thermal Exposure,		75	140	143	18.5					
600°F for 100		75	140	145	19.0					
Hours in Air		75	142	146	19.0					
		75	144	145	21.0					
		75	143	146	20.0					
	Avg.		142	145	19.5					

Thermal Exposure,	75	197	204	2.0					
800°F for 100	75	197	211	1.5					
Hours in Air	75	196	200	1.0					
	75		192	0.5					
	75		198	1.5					
Avg.		197	201	1.3					
Thermal Cycle,	75	136	138	26.5	163		137	5.0	
75°F to 400°F	75	133	135	28.5	163		139	4.0	
100 Cycles in Air	75	134	135	21.5	164		128	3.0	
	75	134	136	25.1	165		126	3.0	
	75	134	135	27.5	164		138	4.5	
Avg.		134	136	25.8	164	1.21	134	3.9	98
Thermal Cycle,	75	138	140	25.0	172		126	1.5	
75°F to 600°F	75	138	140	21.0	171		131	1.0	
100 Cycles in Air	75	139	141	25.0	173		133	1.0	
	75	138	139		173		139	1.0	
	75	139	141	23.5	170		127	1.0	
Avg.		138	140	23.6	172	1.23	131	1.1	94
Thermal Cycle,	75	143	148	10.5	171		144	1.0	
75°F to 800°F	75	148	152	7.5	162		132	1.0	
100 Cycles in Air	75	145	150	9.5	154		146	1.0	
	75	148	151	4.0	160		148	1.5	
	75	143	148	4.0	161		142	3.0	
Avg.		145	150	7.1	162	1.08	142	1.3	95

Table 7. (Cont)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength ($K_t = 6.3$) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Elongation (%)	Efficiency (%)
Oxidation, 0.1 psig	75				162				
O_2 at 400°F for	75				163				
100 Hours	75				163				
	75				162				
	75				164				
Avg.					163				
Oxidation, 1.0 psig	75				166				
O_2 at 400°F for	75				167				
100 Hours	75				166				
	75				166				
	75				166				
Avg.					166				
Oxidation, 0.1 psig	75				164				
O_2 at 600°F for	75				166				
100 Hours	75				166				
	75				164				
	75				164				
Avg.					165				

Oxidation, 1.0 psig	75	173
O_2 at 600°F for	75	173
100 Hours	75	174
	75	172
	75	176
Avg.		174
Oxidation, 0.1 psig	75	123
O_2 at 800°F for	75	129
100 Hours	75	151
	75	157
	75	150
Avg.		142
Oxidation, 1.0 psig	75	126
O_2 at 800°F for	75	128
100 Hours	75	123
	75	124
	75	116
Avg.		123

Table 8. Fatigue Properties of Titanium-13V-11Cr-3Al Alloy (0.010-In. Thickness)

Exposure Condition	Joint Config	Direction	Test Temp (°F)	Specimen Number	Stress Range (ksi)	No. of Cycles to Failure	Static Strength (ksi)	Remarks
As-Received	1	Long.	75	S-1			149	Failed in base material
	1	Long.	75	S-2			147	Failed in base material
	1	Long.	75	F-3	0-133	1052		Failed in base material
	1	Long.	75	F-4	0-133	879		Failed in base material
	1	Long.	75	F-5	0-133	215		Failed in weld
Avg.						715	148	
Thermal Exposure, 100 Hours at 400°F in Air	1	Long.	75	S-6			111	Failed in weld
	1	Long.	75	S-7			111	Failed in weld
	1	Long.	75	F-8	0-100	933		Failed in weld
	1	Long.	75	F-9	0-100	216		Failed in weld
	1	Long.	75	F-10	0-100	964		Failed in base material
Avg.						704	111	
Thermal Exposure, 100 Hours at 600°F in Air	1	Long.	75	S-11				Specimen damaged
	1	Long.	75	S-12			84.2	Failed in weld
	1	Long.	75	F-13			83.8	Failed in weld
	1	Long.	75	F-14	0-75.6		60.4	Failed in weld
	1	Long.	75	F-15	0-75.6		73.3	Failed in weld
Avg.							75.4	

Thermal Exposure, 100 Hours at 800°F in Air	1	Long.	75	S-16			137	Failed in weld
	1	Long.	75	S-17			104	Failed in weld
	1	Long.	75	F-18	0-109		108	Failed in weld during first cycle
	1	Long.	75	F-19	0-109		85.8	Failed in weld during first cycle
	1	Long.	75	F-20	0-109	9		Failed in weld
Avg.						9	109	

Table 9. Tensile Properties of Type 301 Stainless Steel (0.003-In. Thickness)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notched Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
As-Received	75	170	192	16.0	195		136	1.0	
	75	178	184		205		128	1.0	
	75	185	202	20.5	201		140	1.0	
	75	178	195	20.0	197		144	1.0	
	75	180	197	20.0	195			1.0	
Avg.		178	194	19.1	199	1.03	137	1.0	71
	-320				226		255	0.5	
	-320	200	288	17.0	226		229	0	
	-320	198	299	22.5	226		203	0	
	-320	203	288	15.0	223		244	0.5	
	-320	192	300	22.0	220		212	0	
Avg.		198	294	19.1	224	0.76	229	0.2	78
Thermal Exposure,	-320	217	309	22.5					
400°F for 100	-320	215	298	22.5					
Hours in Air	-320	218	301	22.5					
	-320	219	300	23.0					
	-320	214	298	22.5					
Avg.		217	301	22.6					

Thermal Exposure,	-320	217	313	23.0				
600°F for 100	-320	228	314	24.0				
Hours in Air	-320	226	313	23.0				
	-320	217	312	24.0				
	-320	212	312	23.0				
Avg.		220	313	23.4				
Thermal Exposure,	-320	207	300	17.5				
800°F for 100	-320	186	293	17.5				
Hours in Air	-320	160	303	22.5				
	-320	186	303	22.0				
	-320	191	303	22.5				
Avg.		186	300	20.4				
Thermal Cycle,	-320	218	306	22.5	*	227	8.0	
-320° to 400°F	-320	222	309	22.0	*	263	9.5	
100 Cycles in Air	-320	214	307	20.5	*	170	9.5	
	-320	223	304	22.5	*	265		
	-320	222	310	23.0	*	250		
Avg.		220	307	22.1		235	9.0	77
Thermal Cycle,	-320	223	309	24.0	*	209	3.5	
-320°F to 600°F	-320	224	314	23.5	*	270	10.0	
100 Cycles in Air	-320	223	309	23.5	*	270	9.0	
	-320	219	307	23.5	*	249	9.0	
	-320	208	307	23.5	*	259	8.5	
Avg.		219	309	23.6		252	8.0	81

*Failed during thermal cycle.

Table 9. (Cont)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notched Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
Thermal Cycle,	-320		315	25.0	*		214	0.5	
-320°F to 800°F	-320	214	314	22.5	*		219	1.5	
100 Cycles in Air	-320	211	312	23.0	*		218	1.0	
	-320	223	312	21.0	*		212	1.5	
	-320	224	314	23.0	*		169	0.5	
Avg.		218	313	22.9			206	1.2	66
Oxidation, 0.1 psig	-320				246				
O_2 at 400°F for	-320				249				
100 Hours	-320				252				
	-320				249				
	-320				259				
Avg.					251				
Oxidation, 1.0 psig	-320				262				
O_2 at 400°F for	-320				254				
100 Hours	-320				250				
	-320				254				
	-320				254				
Avg.					255				

Oxidation, 0.1 psig	-320	262
O_2 at 600°F for	-320	259
100 Hours	-320	262
	-320	255
	-320	262
Avg.		261
Oxidation, 1.0 psig	-320	273
O_2 at 600°F for	-320	264
100 Hours	-320	269
	-320	272
	-320	266
Avg.		269
Oxidation, 0.1 psig	-320	255
O_2 at 800°F for	-320	265
100 Hours	-320	258
	-320	265
	-320	265
Avg.		262
Oxidation, 1.0 psig	-320	265
O_2 at 800°F for	-320	262
100 Hours	-320	260
	-320	261
	-320	265
Avg.		263

*Failed during thermal cycle.

Table 10. Tensile Properties of Type 301 Stainless Steel (0.006-In. Thickness)

Exposure Condition		Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notched Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Elongation (%)	Efficiency (%)
As-Received		75	239	249	1.5	257		155	1.5	
		75	245	257	0.5	257		151	2.0	
		75	239	243	0.5	241		157	2.0	
		75	240	252	1.0	259		151	1.5	
		75	222	244	0.5	259		148	1.5	
	Avg.		237	249	0.8	255	1.02	152	1.7	61
		-320	299	329	18.0	321		276	5.5	
		-320	291	327	18.0	331		273	5.0	
		-320				320		275	5.0	
		-320	271	332	20.0	320		256	4.5	
		-320	277	327	*	307		279	4.5	
	Avg.		285	329	18.7	320	0.97	272	4.9	83
Thermal Exposure,		-320	304	329	21.5					
400°F for 100		-320	296	326	21.0					
Hours in Air		-320								
		-320	296	327	23.5					
		-320	309	323	21.0					
	Avg.		301	326	21.8					

Thermal Exposure,	-320		334	22.5					
600°F for 100	-320	288	309	*					
Hours in Air	-320		310	*					
	-320	305	310	*					
	-320	304	327	20.0					
Avg.		299	318	21.3					
Thermal Exposure,	-320	236	307	16.5					
800°F for 100	-320	262	320	18.5					
Hours in Air	-320	265	321	19.5					
	-320	262	319	21.5					
	-320	250	319	17.5					
Avg.		255	317	18.7					
Thermal Cycle,	-320	304	329	20.0	324		295	4.0	
-320°F to 400°F	-320	304	309	*	333		296	3.0	
100 Cycles in Air	-320		329	21.0	334		290	5.5	
	-320	297	325	18.0	327		290	2.0	
	-320		332	21.0	318		296		
Avg.		302	325	20.0	327	1.01	293	3.6	90
Thermal Cycle,	-320	303	333	22.0	319		295	4.0	
-320°F to 600°F	-320	292	319	*	323		282	3.5	
100 Cycles in Air	-320	296	334	22.0	335		285	3.5	
	-320	304	338	22.5	312		291	4.0	
	-320	299	329	19.0	320		294	4.5	
Avg.		299	331	21.4	322	0.97	289	3.9	87

*Fractured outside gauge marks.

Table 10. (Cont)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notched Tensile Strength ($K_t = 6.3$) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Elongation (%)	Efficiency (%)
Thermal Cycle,	-320	298	333	22.0	330		291	2.5	
-320°F to 800°F	-320	308	336	22.0	328		283	2.5	
100 Cycles in Air	-320	307	332	16.5	326		275	2.5	
	-320		328	20.0	321		290	2.5	
	-320	304	334	22.0	326		291		
Avg.		304	333	20.5	326	0.98	286	2.5	86
Oxidation, 0.1 psig	-320				338				
O_2 at 400°F for	-320				330				
100 Hours	-320				334				
	-320				337				
	-320				337				
Avg.					335				
Oxidation, 1.0 psig	-320				328				
O_2 at 400°F for	-320				338				
100 Hours	-320				338				
	-320				337				
	-320				337				
Avg.					336				

Oxidation, 0.1 psig	-320	340
O_2 at 600°F for	-320	326
100 Hours	-320	335
	-320	335
	-320	340
Avg.		335
Oxidation, 1.0 psig	-320	338
O_2 at 600°F for	-320	340
100 Hours	-320	343
	-320	334
	-320	324
Avg.		336
Oxidation, 0.1 psig	-320	264
O_2 at 800°F for	-320	290
100 Hours	-320	276
	-320	272
	-320	282
Avg.		277
Oxidation, 1.0 psig	-320	266
O_2 at 800°F for	-320	263
100 Hours	-320	267
	-320	284
	-320	270
Avg.		270

Table 11. Tensile Properties of Type 301 Stainless Steel (0.010-In. Thickness)

Exposure Condition		Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
As-Received		75	231	236	*	261		181	1.0	
		75	228	233	9.0	263		185	0.5	
		75	223	229	15.0	261		183	1.0	
		75	227	234	17.0	263		180	1.0	
		75	233	237	16.0	265		166	1.0	
	Avg.		228	234	14.2	263	1.12	179	0.9	77
		-320	256	321	11.5	320		322	9.0	
		-320	270	307	10.5	320		309	8.5	
		-320	265	310	12.5	315		320	8.0	
		-320	250	299	10.0	305		316	8.0	
		-320	274	317	10.5	316		317	7.5	
	Avg.		263	311	11.0	315	1.01	317	8.2	100
Thermal Exposure,		-320	291	322	22.0					
400°F for 100		-320	287	324	22.0					
Hours in Air		-320	290	319	21.0					
		-320	288	324	21.5					
		-320	285	321	20.5					
	Avg.		288	322	21.4					

Thermal Exposure,	-320	298	328	*					
600°F for 100	-320	298	316	*					
Hours in Air	-320	301	321	21.0					
	-320	303	323	22.0					
	-320	302	327	24.0					
Avg.		300	323	22.3					
Thermal Exposure,	-320	242	324	17.5					
800°F for 100	-320	255	314	12.5					
Hours in Air	-320	243	291	10.0					
	-320	253	323	20.5					
	-320	254	323	19.0					
Avg.		249	315	15.9					
Thermal Cycle,	-320	288	327	22.0	337		284	4.5	
-320°F to 400°F	-320	288	315	22.0	338		293	2.0	
100 Cycles in Air	-320	286	324	21.5	337		284	4.5	
	-320	283	323	21.0	333		288	1.5	
	-320	288	328	22.0	334		288	3.0	
Avg.		287	323	21.7	336	1.04	287	5.1	89
Thermal Cycle,	-320	293	327	22.5	330		295	15.5	
-320°F to 600°F	-320	280	324	22.5	327		293	13.0	
100 Cycles in Air	-320	288	327	22.0	327		290	11.0	
	-320	283	324	21.0	330		313	12.0	
	-320	274	322	22.5	328		318	12.5	
Avg.		284	325	22.1	328	1.01	302	12.8	

*Fractured outside gauge marks.

Table 11. (Cont)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
Thermal Cycle,	-320	287	324	21.0	329		306	1.5	
-320°F to 800°F	-320	280	332	20.5	333		285	8.0	
100 Cycles in Air	-320	278	329	22.5	330		278	2.0	
	-320	284	332	20.0	336		298	7.5	
	-320	281	331	20.0	328		278	4.0	
Avg.		282	330	20.8	331	1.00	289	4.6	88
Oxidation, 0.1 psig	-320				320				
O_2 at 400°F for	-320				336				
100 Hours	-320				335				
	-320				328				
	-320				317				
Avg.					327				
Oxidation, 1.0 psig	-320				337				
O_2 at 400°F for	-320				334				
100 Hours	-320				337				
	-320				337				
	-320				337				
	-320				337				
Avg.					336				

Oxidation, 0.1 psig	-320	322
O_2 at 600°F for	-320	319
100 Hours	-320	311
	-320	322
	-320	306
Avg.		316
Oxidation, 1.0 psig	-320	349
O_2 at 600°F for	-320	355
100 Hours	-320	347
	-320	347
	-320	347
Avg.		349
Oxidation, 0.1 psig	-320	294
at 800°F for	-320	291
100 Hours	-320	266
	-320	278
	-320	264
Avg.		278
Oxidation, 1.0 psig	-320	315
at 800°F for	-320	316
100 Hours	-320	312
	-320	311
	-320	306
Avg.		312

Table 12. Fatigue Properties of Type 301 Stainless Steel (0.010-In. Thickness)

Exposure Condition	Joint Config	Direction	Test Temp (°F)	Specimen Number	Stress Range (ksi)	No. of Cycles to Failure	Static Strength (ksi)	Remarks
As-Received	2	Long.	-320	S-1			252	Failed at outer row of spot welds
	2	Long.	-320	S-2			254	Failed at outer row of spot welds
	2	Long.	-320	F-3	0-228	20		Failed at outer row of spot welds
	2	Long.	-320	F-4	0-228	40		Failed at outer row of spot welds
	2	Long.	-320	F-5	0-228	46		Failed at outer row of spot welds
Avg.						35	253	
Thermal Exposure, 100 Hours at 400°F in Air	2	Long.	-320	S-6			264	Failed at outer row of spot welds
	2	Long.	-320	S-7			270	Failed at outer row of spot welds
	2	Long.	-320	F-8	0-240	33		Failed at outer row of spot welds
	2	Long.	-320	F-9	0-240	66		Failed at outer row of spot welds
	2	Long.	-320	F-10	0-240	23		Failed at outer row of spot welds
Avg.						41	267	
Thermal Exposure, 100 Hours at 600°F in Air	2	Long.	-320	S-11			266	Failed at outer row of spot welds
	2	Long.	-320	S-12			259	Failed at outer row of spot welds
	2	Long.	-320	F-13	0-237	71		Failed at outer row of spot welds
	2	Long.	-320	F-14	0-237	40		Failed at outer row of spot welds
	2	Long.	-320	F-15	0-237	70		Failed at outer row of spot welds
Avg.						60	263	

Thermal Exposure,	2	Long.	-320	S-16			252	Failed at outer row of spot welds
100 Hours at	2	Long.	-320	S-17			248	Failed at outer row of spot welds
800°F in Air	2	Long.	-320	F-18	0-225	116		Failed at outer row of spot welds
	2	Long.	-320	F-19	0-225	125		Failed at outer row of spot welds
	2	Long.	-320	F-20	0-225	49		Failed at outer row of spot welds
Avg.						97	250	

Table 13. Crack Propagation Properties of Type 301 Stainless Steel (0.010-In. Thickness)

Exposure Condition	Direction	Test Temp (°F)	Width/ Thickness (In.)	Initial Notch Length (In.)	Critical Load (lb)	Critical Crack Length-2a (In.)	Gross Stress- σ_G (ksi)	Net Stress- σ_N (ksi)	Fracture Toughness-K_C (ksi $\sqrt{In.}$)	Strain Energy Release Rate-G_C (In. lb/In.^{2})
As-Received	Long.	-320	4.00/0.0098	1.24	3540	1.75	90.4	161	164	947
	Long.	-320	4.00/0.0098	1.24	3020	1.70	77.1	133	137	663
	Long.	-320	4.00/0.0100	1.24	3025	1.90	75.7	144	145	740
	Long.	-320	4.00/0.0100	1.25	3335	1.72	83.4	146	149	782
	Long.	-320	4.00/0.0098	1.24	3170	1.65	80.8	138	141	700
Avg.			4.00/0.0099	1.24	3214	1.74	81.5	144	147	766
As-Received	Trans.	-320	4.00/0.0101	1.26	1815	1.40	45.0	69.1	70.7	167
	Trans.	-320	4.00/0.0101	1.25	1780	1.26	44.1	64.4	64.8	140
	Trans.	-320	4.00/0.0101	1.24	1910	1.24	47.3	68.5	69.0	159
	Trans.	-320	4.00/0.0100	1.23	1840	1.40	46.0	70.8	72.2	174
Avg.			4.00/0.0101	1.25	1836	1.33	45.6	68.2	69.2	160
Thermal Exposure,	Long.	-320	4.00/0.0101	1.23	2955	1.35	73.2	110	112	442
800°F for 100	Long.	-320	4.00/0.0100	1.23	2810	1.33	70.4	105	107	403
Hours in Air	Long.	-320	4.00/0.0102	1.23	2660	1.57	65.2	107	110	424
	Long.	-320	4.00/0.0100	1.22	2950	1.33	73.9	111	112	442
	Long.	-320	4.00/0.0099	1.25	2650	1.52	67.0	108	110	429
Avg.			4.00/0.0100	1.23	2805	1.42	69.9	108	110	428
Thermal Exposure,	Trans.	-320	3.98/0.0100	1.23	1520	1.23	38.2	54.9	55.4	102
800°F for 100	Trans.	-320	3.99/0.0106	1.24	1930	1.30	45.7	67.5	68.5	157
Hours in Air	Trans.	-320	3.99/0.0105	1.23	2125	1.38	50.8	77.4	78.6	206
	Trans.	-320	3.98/0.0106	1.23	1820	1.23	43.1	62.2	62.5	130
	Trans.	-320	3.97/0.0102	1.24	1765	1.24	43.8	62.7	63.9	136
Avg.			3.98/0.0104	1.23	1832	1.30	44.3	64.9	65.8	146

Thermal Cycle,	Long.	-320	4.01/0.0100	1.26	4000	1.67	99.8	172	175	1080
-320°F to 800°F	Long.	-320	4.00/0.0102	1.24	3860	1.80	94.7	172	175	1080
100 Cycles in Air	Long.	-320	4.00/0.0101	1.24	4060	1.60	100	167	171	1030
	Long.	-320	4.00/0.0102	1.23	4140	1.58	101	168	171	1030
	Long.	-320	4.00/0.0100	1.23	3800	1.68	95.1	164	167	984
Avg.			4.00/0.0101	1.24	3972	1.67	98.1	169	172	1041
Thermal Cycle,	Trans.	-320	4.00/0.0102	1.23	2200	1.23	53.9	78.0	78.1	203
-320°F to 800°F	Trans.	-320	4.00/0.0100	1.24	2080	1.40	52.0	80.0	81.6	200
100 Cycles in Air	Trans.	-320	4.00/0.0102	1.23	2280	1.33	55.9	83.8	85.0	240
	Trans.	-320	4.00/0.0102	1.23	2520	1.30	61.8	91.8	92.6	286
	Trans.	-320	4.00/0.0101	1.25	2280	1.36	56.4	85.4	86.8	250
Avg.			4.00/0.0101	1.24	2272	1.32	56.0	83.8	84.8	236
Oxidation, 1.0 psig	Long.	-320	4.00/0.0100	1.23	2900	1.23	72.6	105	105	409
O_2 at 800°F for	Long.	-320	4.00/0.0100	1.23	2580	1.40	64.5	99.2	101	360
100 Hours	Long.	-320	4.01/0.0101	1.24	2440	1.46	60.0	95.0	96.4	328
	Long.	-320	4.00/0.0102	1.24	2740	1.54	67.1	109	111	435
	Long.	-320	4.01/0.0102	1.23	3020	1.39	73.9	114	115	466
Avg.			4.00/0.0101	1.23	2736	1.40	67.6	104	106	400
Oxidation, 1.0 psig	Trans.	-320	4.00/0.0100	1.24	2000	1.24	50.0	72.5	72.9	187
O_2 at 800°F for	Trans.	-320	4.00/0.0100	1.25	1960	1.33	49.0	73.5	74.4	185
100 Hours	Trans.	-320	4.00/0.0101	1.26	2020	1.26	50.0	73.7	73.6	181
	Trans.	-320	4.00/0.0101	1.23	1960	1.30	48.6	71.9	72.8	177
	Trans.	-320	4.00/0.0101	1.23	1960	1.23	48.6	70.0	70.4	165
Avg.			4.00/0.0101	1.24	1980	1.27	49.2	72.3	72.8	179

Table 14. Tensile Properties of Titanium-5Al-2.5Sn ELI Alloy (0.006-In. Thickness)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
As-Received	75	95.1	103	17.5	138		102	13.5	
	75	94.6	103	18.0	140		106	14.0	
	75	97.7	105	18.0	141		106	15.0	
	75	96.7	104	18.0	138		-	-	
	75	97.6	105	18.5	138		-	-	
Avg.		96.3	104	18.0	139	1.33	105	14.2	100
	-423	197	208	7.5	243		220	2.0	
	-423	192	212	10.0	266		205	0.5	
	-423	186	205	10.5	254		209	3.0	
	-423	192	201	6.0	240		217	6.0	
	-423	191	209	6.5	258		203	1.0	
Avg.		191	207	8.1	252	1.22	211	2.5	100
Thermal Exposure, 400°F for 100 Hours in Air	-423	201	204	5.0					
	-423	203	212	2.5					
	-423	204	215	2.0					
	-423	198	216	11.5					
	-423	201	216	11.0					
Avg.		201	213	6.4					

Thermal Exposure,	-423	204	219	12.0					
600°F for 100	-423	201	218	-					
Hours in Air	-423	201	214	5.0					
	-423	205	221	13.0					
	-423	197	215	11.0					
Avg.		202	217	10.3					
Thermal Exposure,	-423	212	222	3.5					
800°F for 100	-423	216	230	10.0					
Hours in Air	-423	212	222	7.0					
	-423	210	222	6.0					
	-423	214	225	10.0					
Avg.		213	224	7.3					
Thermal Cycle,	-423	205	220	8.5	248		228	3.0	
-423°F to 400°F	-423	211	225	12.0	241		233	10.0	
100 Cycles in Air	-423	211	226	11.5	242		229	3.5	
	-423	216	229	10.0	270		221	0	
	-423	205	-	-	244		-	-	
Avg.		210	225	10.5	249	1.10	228	4.1	100
Thermal Cycle,	-423	211	227	10.5	217		230	4.0	
-423°F to 600°F	-423	217	224	4.0	267		224	1.5	
100 Cycles in Air	-423	211	223	5.5	229		233	7.5	
	-423	218	229	8.5	219		228	3.0	
	-423	214	221	-	227		-	-	
Avg.		214	225	7.1	232	1.03	226	4.0	100

Table 14. (Cont)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
Thermal Cycle,	-423	213	226	6.5	229		233	3.5	
-423°F to 800°F	-423	217	231	11.0	247		219	3.0	
100 Cycles in Air	-423	214	227	9.5	241		202	6.0	
	-423	228	236	4.5	242		202	-	
	-423	216	225	5.0	213		231	-	
Avg.		218	229	7.3	234	1.02	221	4.1	96
Oxidation, 0.1 psig	-423				263				
O_2 at 400°F for	-423				241				
100 Hours	-423				-				
	-423				238				
	-423				257				
Avg.					250				
Oxidation, 1.0 psig	-423				239				
O_2 at 400°F for	-423				255				
100 Hours	-423				248				
	-423				250				
	-423				243				
Avg.					247				

Oxidation, 0.1 psig	-423	220
O_2 at 600°F for	-423	229
100 Hours	-423	228
	-423	252
	-423	-
Avg.		232
Oxidation, 1.0 psig	-423	249
O_2 at 600°F for	-423	227
100 Hours	-423	257
	-423	247
	-423	216
Avg.		239
Oxidation, 0.1 psig	-423	218
O_2 at 800°F for	-423	219
100 Hours	-423	210
	-423	236
	-423	-
Avg.		221
Oxidation, 1.0 psig	-423	209
O_2 at 800°F for	-423	252
100 Hours	-423	232
	-423	234
	-423	253
Avg.		236

Table 15. Tensile Properties of Titanium-5Al-2.5Sn ELI Alloy (0.013-In. Thickness)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength ($K_t = 6.3$) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
As-Received	75	98.2	109	18.0	143		112	15.0	
	75	98.0	109	17.5	143		109	16.0	
	75	98.8	111	18.5	145		110	14.5	
	75	99.3	111	18.5	143		111	16.5	
	75	99.1	111	18.5	143		111	14.0	
Avg.		98.7	110	18.2	143	1.30	111	15.2	100
	-423	208	228	13.5	246		228	2.0	
	-423	206	225	8.0	232		227	3.5	
	-423	208	224	5.0	253		229	4.0	
	-423	209	230	13.0	249		219	1.0	
	-423	210	231	14.5	270		221	0.8	
Avg.		208	228	10.8	250	1.10	225	2.3	99
Thermal Exposure,	-423	211	227	7.0					
400°F for 100	-423	208	220						
Hours in Air	-423	209	228	13.0					
	-423	211	229	12.0					
	-423	205	229	13.0					
Avg.		209	226	11.3					

Thermal Exposure,	-423	209	221	10.0					
600°F for 100	-423	217	236	14.0					
Hours in Air	-423	211	232	12.5					
	-423	211	228	4.0					
	-423	227	234	15.0					
Avg.		215	230	11.1					
Thermal Exposure,	-423	222	237	12.5					
800°F for 100	-423	212	230	12.5					
Hours in Air	-423	212	227	4.5					
	-423	213	231	10.5					
	-423	213	229	7.5					
Avg.		215	231	9.5					
Thermal Cycle,	-423	217	238	11.0	224		227	2.0	
-423°F to 400°F	-423	215	234	10.0	208		229	2.5	
100 Cycles in Air	-423	217	233	10.0	223		201	1.5	
	-423	214	236	11.0	238		231	2.0	
	-423	215	234	13.0	256				
Avg.		216	235	11.0	230	0.98	222	2.0	
Thermal Cycle,	-423	208	234	9.5	201		223	1.0	
-423°F to 600°F	-423	211	232	14.0	218		216	0.5	
100 Cycles in Air	-423	212	233	11.0	215		232	0.5	
	-423	217	230	7.5	203		241	0.0	
	-423	211	235	14.0	204		234	2.0	
Avg.		212	233	11.2	208	0.89	229	0.8	98

Table 15. (Cont

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
Thermal Cycle,	-423	210	233	12.0	221				
-423°F to 800°F	-423	210	233	13.5	230				
100 Cycles in Air	-423	214	233	8.0	195				
	-423	215	233	10.0	208				
	-423	224	236	11.5	212				
Avg.		215	234	11.0	213	0.91			
Oxidation, 0.1 psig	-423				244				
O_2 at 400°F for	-423				242				
100 Hours	-423				223				
	-423				226				
	-423								
Avg.					234				
Oxidation, 1.0 psig	-423				228				
O_2 at 400°F for	-423				239				
100 Hours	-423				215				
	-423				221				
	-423				238				
Avg.					228				

Oxidation, 0.1 psig	-423	225
O_2 at 600°F for	-423	220
100 Hours	-423	201
	-423	205
	-423	217
Avg.		214
Oxidation, 1.0 psig	-423	197
O_2 at 600°F for	-423	190
100 Hours	-423	211
	-423	198
	-423	223
Avg.		204
Oxidation, 0.1 psig	-423	178
O_2 at 800°F for	-423	191
100 Hours	-423	197
	-423	194
	-423	206
Avg.		193
Oxidation, 1.0 psig	-423	175
O_2 at 800°F for	-423	182
100 Hours	-423	201
	-423	203
	-423	199
Avg.		192

Table 15. (Cont)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
Hydrogen Exposure,	-423				210				
0.1 psig H_2 at	-423				210				
400°F for 30	-423				220				
minutes	-423				211				
	-423				216				
Avg.					213				
Hydrogen Exposure,	-423				242				
0.1 psig H_2 at	-423				222				
400°F for 300	-423				231				
minutes	-423				224				
	-423				232				
Avg.					230				
Hydrogen Exposure,	-423				232				
0.1 psig H_2 at	-423				202				
400°F for 3000	-423				262				
minutes	-423				214				
	-423				213				
Avg.					225				

Hydrogen Exposure,	-423	217
1.0 psig H_2 at	-423	217
400°F for 30	-423	225
minutes	-423	227
Avg.		222
Hydrogen Exposure,	-423	220
1.0 psig H_2 at	-423	219
400°F for 300	-423	221
minutes	-423	213
	-423	234
Avg.		221
Hydrogen Exposure,	-423	211
1.0 psig H_2 at	-423	224
400°F for 3000	-423	234
minutes	-423	219
	-423	200
Avg.		218
Hydrogen Exposure,	-423	193
15.0 psig H_2 at	-423	257
400°F for 30	-423	238
minutes	-423	268
	-423	214
Avg.		234

Table 15. (Cont)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength ($K_t = 6.3$) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
Hydrogen Exposure,	-423				231				
15.0 psig H_2 at	-423				243				
400°F for 300	-423				211				
minutes	-423				231				
	-423				238				
Avg.					231				
Hydrogen Exposure,	-423				225				
15.0 psig H_2 at	-423				230				
400°F for 3000	-423				226				
minutes	-423				197				
	-423				226				
Avg.					221				
Hydrogen Exposure,	-423				224				
0.1 psig H_2 at	-423				209				
600°F for 30	-423				222				
minutes	-423				214				
	-423				219				
Avg.					218				

Hydrogen Exposure,	-423	227
0.1 psig H_2 at	-423	223
600°F for 300	-423	234
minutes	-423	229
Avg.		228
Hydrogen Exposure,	-423	219
0.1 psig H_2 at	-423	220
600°F for 3000	-423	211
minutes	-423	224
	-423	224
Avg.		220
Hydrogen Exposure,	-423	207
1.0 psig H_2 at	-423	241
600°F for 30	-423	216
minutes	-423	199
Avg.		216
Hydrogen Exposure,	-423	199
1.0 psig H_2 at	-423	217
600°F for 300	-423	190
minutes	-423	211
Avg.		204

Table 15. (Cont)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
Hydrogen Exposure,	-423				225				
1.0 psig H_2 at	-423				201				
600°F for 3000	-423				212				
minutes	-423				203				
	-423				201				
Avg.					208				
Hydrogen Exposure,	-423				202				
15.0 psig H_2 at	-423				208				
600°F for 30	-423				217				
minutes	-423				211				
	-423				224				
Avg.					212				
Hydrogen Exposure,	-423				223				
15.0 psig H_2 at	-423				194				
600°F for 300	-423				214				
minutes	-423				213				
	-423				205				
Avg.					210				

Hydrogen Exposure,	-423	233
15.0 psig H_2 at	-423	208
600°F for 3000	-423	218
minutes	-423	216
	-423	216
Avg.		218
Hydrogen Exposure,	-423	230
0.1 psig H_2 at	-423	215
800°F for 30	-423	228
minutes	-423	234
	-423	218
Avg.		225
Hydrogen Exposure,	-423	224
0.1 psig H_2 at	-423	214
800°F for 300	-423	225
minutes	-423	213
	-423	209
Avg.		217
Hydrogen Exposure,	-423	214
0.1 psig H_2 at	-423	220
800°F for 3000	-423	225
minutes	-423	207
	-423	203
Avg.		214

Table 15. (Cont)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength ($K_t = 6.3$) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
Hydrogen Exposure,	-423				200				
1.0 psig H_2 at	-423				209				
800°F for 30	-423				226				
minutes	-423				203				
	-423				219				
Avg.					211				
Hydrogen Exposure,	-423				245				
1.0 psig H_2 at	-423				203				
800°F for 300	-423				234				
minutes	-423				224				
	-423				206				
Avg.					222				
Hydrogen Exposure,	-423				214				
1.0 psig H_2 at	-423				206				
800°F for 3000	-423				196				
minutes	-423				187				
Avg.					201				

Hydrogen Exposure, 15.0 psig H_2 at 800°F for 30 minutes	-423	220
	-423	197
	-423	223
	-423	222
Avg.		216
Hydrogen Exposure, 15.0 psig H_2 at 800°F for 300 minutes	-423	209
	-423	225
	-423	232
	-423	240
	-423	232
Avg.		228
Hydrogen Exposure, 15.0 psig H_2 at 800°F for 3000 minutes	-423	196
	-423	229
	-423	162
	-423	218
Avg.		201
Hydrogen Exposure, 0.1 psig H_2 at 600°F for 30 minutes with 10 ksi Applied Load	-423	192
	-423	214
	-423	208
	-423	201
Avg.		204

Table 15. (Cont)

Exposure Condition	Test Temp (°F)	F_{ty} (ksi)	F_{tu} (ksi)	Elongation (%)	Notch Tensile Strength (K_t = 6.3) (ksi)	Notch/Unnotched Tensile Strength Ratio	Weld Tensile Strength (ksi)	Weld Elongation (%)	Joint Efficiency (%)
Hydrogen Exposure, 0.1 psig H_2 at 600°F for 300 minutes with 10 ksi Applied Load		ALL SPECIMENS FAILED AFTER 50 MINUTES EXPOSURE TIME							
Hydrogen Exposure, 0.1 psig H_2 at 600°F for 3000 minutes with 5 ksi Applied Load		ALL SPECIMENS FAILED AFTER 480 MINUTES EXPOSURE TIME							
Hydrogen Exposure,	-423				234				
1.0 psig H_2 at 600°F	-423				210				
for 30 minutes with	-423				211				
10 ksi Applied Load	-423				225				
	-423				210				
Avg.					218				
Hydrogen Exposure, 1.0 psig H_2 at 600°F for 300 minutes with 10 ksi Applied Load		ALL SPECIMENS FAILED AFTER 120 MINUTES EXPOSURE TIME							

Hydrogen Exposure, 1.0 psig H_2 at 600°F for 3000 minutes with 10 ksi Applied Load		ALL SPECIMENS FAILED AFTER 150 MINUTES EXPOSURE TIME
Hydrogen Exposure,	-423	224
15.0 psig H_2 at	-423	217
600°F for 30	-423	223
minutes with 10 ksi	-423	213
Applied Load	-423	228
Avg.		221
Hydrogen Exposure,	-423	235
15.0 psig H_2 at	-423	213
600°F for 300	-423	233
minutes with 10 ksi	-423	208
Applied Load	-423	233
Avg.		224
Hydrogen Exposure,	-423	234
15.0 psig H_2 at	-423	235
600°F for 3000	-423	228
minutes with 5 ksi	-423	249
Applied Load	-423	238
Avg.		237

Table 16. Fatigue Properties of Titanium-5Al-2.5Sn ELI Alloy (0.013-In. Thickness)

Exposure Condition	Joint Config	Direction	Test Temp (°F)	Specimen Number	Stress Range (ksi)	No. of Cycles to Failure	Static Strength (ksi)	Remarks
As-Received	1	Long.	75	S-1			110	Failed in base metal
	1	Long.	75	S-2			110	Failed in base metal
	1	Long.	75	F-3	0-99	945		Failed in end doubler
	1	Long.	75	F-4	0-99	1598		Failed in end doubler
	1	Long.	75	F-5	0-99	695		Failed in weld
Avg.						1079	110	
	1	Long.	-423	S-6			218	Failed in base metal
	1	Long.	-423	S-7			222	Failed in base metal
	1	Long.	-423	F-8	0-198	1049		Failed in end doubler
	1	Long.	-423	F-9	0-198	745		Failed in weld
	1	Long.	-423	F-10	0-198	183		Failed in weld
Avg.						659	220	
Thermal Exposure, 100 Hours at 400°F in Air	1	Long.	75	S-11			132	Failed in base metal
	1	Long.	75	S-12			113	Failed in weld
	1	Long.	75	F-13	0-110	27		Failed in base metal
	1	Long.	75	F-14	0-110	11		Failed in base metal
	1	Long.	75	F-15	0-110	3		Failed in weld
Avg.						14	123	
	1	Long.	-423	S-16			222	Failed in base metal
	1	Long.	-423	S-17			221	Failed in weld
	1	Long.	-423	F-18	0-200	1756		Failed in end doubler
	1	Long.	-423	F-19	0-200	790		Failed in weld
	1	Long.	-423	F-20	0-200	1504		Failed in weld
Avg.						1350	222	

Thermal Exposure,	1	Long.	75	S-21			116	Failed in base metal
100 Hours at	1	Long.	75	S-22			116	Failed in base metal
600°F in Air	1	Long.	75	F-23	0-104	687		Failed in weld
	1	Long.	75	F-24	0-104	484		Failed in weld
	1	Long.	75	F-25	0-104	308		Failed in weld
Avg.						493	116	
	1	Long.	-423	S-26			217	Failed in base metal
	1	Long.	-423	S-27			220	Failed in base metal
	1	Long.	-423	F-28	0-197	614		Failed in weld
	1	Long.	-423	F-29	0-197	883		Failed in weld
	1	Long.	-423	F-30	0-197	1001		Failed in weld
Avg.						833	219	
Thermal Exposure,	1	Long.	75	S-31			114	Failed in weld
100 Hours at	1	Long.	75	S-32			112	Failed in weld
800°F in Air	1	Long.	75	F-33	0-102	1012		Failed in weld
	1	Long.	75	F-34	0-102	282		Failed in weld
	1	Long.	75	F-35	0-102	72		Failed in weld
Avg.						455	113	
	1	Long.	-423	S-36			248	Failed in base metal
	1	Long.	-423	S-37			226	Failed in weld
	1	Long.	-423	F-38	0-213	976		Failed in weld
	1	Long.	-423	F-39	0-213	164		Failed in weld
Avg.						570	237	

Table 17. Crack Propagation Properties of Titanium-5Al-2.5Sn ELI Alloy (0.013 Thickness)

Exposure Condition	Direction	Test Temp (°F)	Width/ Thickness (In.)	Initial Notch Length (In.)	Critical Load (lb)	Critical Crack Length-2a (In.)	Gross Stress- σ_G (ksi)	Net Stress- σ_N (ksi)	Fracture Toughness-K_C (ksi$\sqrt{\text{In.}}$)	Strain Energy Release Rate-G_{C_2} (In. lb/In.^{2})
As-Received	Long.	-423	4.000/0.0130	1.24	2930	1.42	56.3	87.5	89.0	435
	Long.	-423	3.990/0.0130	1.24	2655	1.41	51.2	79.3	80.6	357
	Long.	-423	3.990/0.0130	1.24	2790	1.38	53.8	82.3	83.4	382
	Long.	-423	3.990/0.0131	1.24	2835	1.46	54.2	85.6	86.3	419
	Long.	-423	4.000/0.0131	1.25	2825	1.32	53.9	80.5	81.4	364
Avg.			3.994/0.0130	1.24	2807	1.40	53.9	83.0	84.3	391
Thermal Exposure,	Long.	-423	3.990/0.0131	1.27	2955	1.37	56.4	86.2	86.5	411
400°F for 100 Hours	Long.	-423	3.990/0.0130	1.25	2830	1.50	54.6	87.5	89.0	436
in Air	Long.	-423	3.980/0.0130	1.22	2700	1.50	52.3	83.9	85.2	399
	Long.	-423	4.000/0.0130	1.26	2805	1.51	54.0	86.1	88.5	431
	Long.	-423	4.000/0.0130	1.24	2905	1.49	56.0	89.2	90.9	454
Avg.			3.992/0.0130	1.25	2839	1.47	54.7	86.6	88.0	426
Thermal Exposure,	Long.	-423	3.990/0.0131	1.25	2875	1.48	55.1	87.6	89.2	438
600°F for 100 Hours	Long.	-423	4.000/0.0132	1.25	2820	1.35	53.4	80.6	82.0	369
in Air	Long.	-423	3.980/0.0130	1.24	2875	1.37	55.6	84.8	85.8	405
	Long.	-423	3.990/0.0130	1.24	2980	1.57	57.4	94.9	96.6	512
	Long.	-423	3.980/0.0131	1.25	2870	1.33	55.1	82.7	83.8	386
Avg.			3.988/0.0131	1.25	2884	1.42	55.3	86.1	89.5	422

Thermal Exposure,	Long.	-423	4.000/0.0130	1.25	3090	1.34	59.5	89.4	91.1	456
800°F for 100 Hours	Long.	-423	3.980/0.0128	1.28	2775	1.48	54.4	86.7	88.0	426
in Air	Long.	-423	3.980/0.0131	1.25	2760	1.52	53.0	85.8	87.3	419
	Long.	-423	3.990/0.0130	1.23	2835	1.55	54.7	89.4	91.2	460
	Long.	-423	3.980/0.0130	1.26	2760	1.36	53.4	81.0	82.2	371
Avg.			3.986/0.0130	1.25	2844	1.45	55.0	86.5	88.0	426
Thermal Cycle,	Long.	-423	4.020/0.0127	1.27	3040	1.27	59.5	87.1	87.8	424
-423°F to 400°F	Long.	-423	4.040/0.0126	1.23	2940	1.25	57.8	83.5	84.7	394
100 Cycles in Air	Long.	-423	3.990/0.0126	1.22	2970	1.32	59.0	88.4	89.1	436
	Long.	-423	3.990/0.0122	1.24	2700	1.26	55.4	81.1	81.4	364
	Long.	-423	3.990/0.0125	1.26	2850	1.37	57.1	86.9	88.2	427
Avg.			4.006/0.0125	1.24	2900	1.29	57.8	85.4	86.2	409
Thermal Cycle,	Long.	-423	4.000/0.0130	1.25	2905	1.45	55.9	87.7	89.4	442
-423°F to 600°F	Long.	-423	3.980/0.0131	1.24	2925	1.30	56.1	83.4	84.2	390
100 Cycles in Air	Long.	-423	3.990/0.0131	1.25	2710	1.40	51.8	79.7	81.4	362
	Long.	-423	4.000/0.0130	1.26	2980	1.55	57.4	94.9	95.8	504
	Long.	-423	3.980/0.0130	1.24	2670	1.35	51.6	78.0	79.2	345
Avg.			3.990/0.0130	1.25	2838	1.41	54.6	84.7	86.0	409
Thermal Cycle,	Long.	-423	3.980/0.0130	1.25	2685	1.44	51.9	81.4	82.5	374
-423°F to 800°F	Long.	-423	3.990/0.0131	1.25	2730	1.33	52.2	78.2	79.3	345
100 Cycles in Air	Long.	-423	4.000/0.0131	1.24	2725	1.32	52.0	77.6	78.5	339
	Long.	-423	4.000/0.0130	1.25	2900	1.43	55.8	86.8	88.4	429
	Long.	-423	3.990/0.0130	1.27	2840	1.32	54.8	81.8	82.6	375
Avg.			3.992/0.0130	1.25	2776	1.37	53.3	81.2	82.3	372

Table 17. (Cont)

Exposure Condition	Direction	Test Temp (°F)	Width/ Thickness (In.)	Initial Notch Length (In.)	Critical Load (lb)	Critical Crack Length-2a (In.)	Gross Stress-σ_G (ksi)	Net Stress-σ_N (ksi)	Fracture Toughness-K_C (ksi$\sqrt{In.}$)	Strain Energy Release Rate-G_{C_2} (In. lb/In.^{2})
Oxidation, 1.0 psig	Long.	-423	3.930/0.0129	1.24	2490	1.58	49.1	82.2	83.0	379
O_2 at 400°F for	Long.	-423	3.980/0.0129	1.25	2565	1.54	50.0	81.4	83.0	379
100 Hours	Long.	-423	3.970/0.0129	1.24	2675	1.55	52.2	85.7	87.2	418
	Long.	-423	3.990/0.0132	1.25	2815	1.41	53.4	82.6	84.1	389
	Long.	-423	3.980/0.0130	1.25	2900	1.32	56.1	83.8	84.7	394
Avg.			3.970/0.0130	1.25	2689	1.48	52.2	83.1	84.4	392
Oxidation, 1.0 psig	Long.	-423	3.997/0.0123	1.21	2625	1.47	53.7	85.2	86.7	413
O_2 at 600°F for	Long.	-423	3.950/0.0126	1.24	2780	1.26	55.8	82.0	82.0	369
100 Hours	Long.	-423	3.950/0.0126	1.26	2980	1.30	59.8	89.2	89.7	442
	Long.	-423	3.958/0.0125	1.21	2990	1.38	60.4	92.9	93.6	481
	Long.	-423	3.985/0.0125	1.23	2850	1.37	57.2	87.1	88.4	429
Avg.			3.968/0.0125	1.23	2845	1.36	57.4	87.3	88.1	427
Oxidation, 1.0 psig	Long.	-423	3.990/0.0128	1.21	2725	1.37	53.3	81.3	82.3	372
O_2 at 800°F for	Long.	-423	3.999/0.0125	1.22	3015	1.25	60.3	87.6	88.3	428
100 Hours	Long.	-423	3.992/0.0125	1.22	2785	1.29	55.8	82.4	83.1	379
	Long.	-423	3.998/0.0124	1.18	2580	1.43	52.0	81.1	82.4	373
Avg.			3.995/0.0125	1.21	2776	1.34	55.4	83.1	84.0	388
Hydrogen Exposure,	Long.	-423	4.000/0.0130	1.26	3000	1.55	57.7	94.0	96.4	511
0.1 psig H_2 at 600°F	Long.	-423	4.000/0.0129	1.24	2810	1.36	54.5	82.4	83.9	387
for 50 Hours	Long.	-423	3.980/0.0129	1.29	2775	1.42	54.1	84.1	85.5	402
	Long.	-423	3.990/0.0130	1.25	2730	1.45	52.6	82.7	84.2	390
	Long.	-423	3.990/0.0127	1.26	2580	1.45	50.9	79.9	81.4	364
Avg.			3.992/0.0129	1.26	2779	1.45	54.0	84.6	86.3	411

Hydrogen Exposure,	Long.	-423	3.990/0.0127	1.23	2865	1.35	56.5	85.5	86.7	413
1.0 psig H_2 at 600°F	Long.	-423	3.910/0.0126	1.22	3025	1.41	61.3	96.0	96.5	512
for 50 Hours	Long.	-423	3.992/0.0125	1.22	2705	1.22	54.2	78.0	78.0	334
	Long.	-423	3.997/0.0126	1.23	2825	1.34	56.1	84.3	85.8	405
	Long.	-423	3.997/0.0126	1.11	2990	1.22	59.3	85.4	85.4	401
Avg.			3.977/0.0126	1.20	2882	1.31	57.5	85.8	86.5	413
Hydrogen Exposure,	Long.	-423	3.980/0.0129	1.26	2875	1.36	56.0	85.1	86.2	408
15.0 psig H_2 at 600°F	Long.	-423	3.990/0.0128	1.25	2580	1.36	50.5	76.6	77.8	333
for 50 Hours	Long.	-423	3.990/0.0129	1.24	2710	1.28	52.6	77.4	77.8	333
	Long.	-423	3.990/0.0130	1.24	2970	1.42	57.2	88.9	90.4	449
	Long.	-423	3.980/0.0131	1.23	2890	1.34	55.5	83.5	84.9	396
Avg.			3.986/0.0129	1.24	2805	1.35	54.4	82.3	83.4	384

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2. Effects of thermal exposures on mechanical properties
3. Properties at cryogenic temperatures
4. Tensile, notched tensile, weld tensile, fatigue, and crack propagation properties

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II. Contract AF 33(657)-9445
III. General Dynamics/ Astronautics, San Diego, California
IV. Christian, J. L., and Kerr, J. R.
V. Secondary Rpt. No. AE62-0867-3
VI. Avl fr OTS
VII. In ASTIA collection

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