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FINAL REPORT

on

DETERMINATION OF STRUCTURAL ENGINEERING PROPERTIES OF INCOLOY 903 AND CTX-1 ALLOYS

to

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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by

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DETERMINATION OF STRUCTURAL ENGINEERING
PROPERTIES OF INCOLOY 903 AND CTX-1 ALLOYS

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SUMMARY

Incoloy 903 sheet, 1.55 m (0.062 inch) thick, and CTX-1 bar, 2.54 x 7.62 cm (1 x 3 inch), were evaluated. Both materials had been vacuum induction and vacuum arc remelted. Incoloy 903 was tested in two conditions:

(1) Annealed - 1200 K (1700 F), A.C. ("as received")

(2) Precipitation heat treated - 991 K (1325 F)/8 hours, F.C. 311 K (100 F)/hour to 894 K (1150 F)/8 hours, A.C.

CTX-1 was evaluated in two heat-treat conditions:

(1) Heat Treatment A: 1116 K (1550 F)/1 hour, A.C. + 991 K (1325 F)/8 hours, F.C. 311 K (100 F)/hour to 894 K (1150 F)/8 hours, A.C. (nonrecrystallized)

(2) Heat Treatment B: 1228 K (1750 F)/1 hour, A.C. + 991 K (1325 F)/8 hours, F.C. 311 K (100 F/hour to 894 K (1150 F)/8 hours, A.C. (recrystallized).

Tension, notched tension, compression, density, thermal conductivity, and thermal expansion tests were conducted on Incoloy 903 over the temperature range 20 K (-423 F) through 1033 K (1400 F). Fracture toughness tests were performed at room temperature (RT). Creep and rupture tests were conducted at 811 K (1000 F), 922 K (1200 F), and 1033 K (1400 F) for this alloy. Transverse unnotched and notched fatigue tests at R = 0.1 were performed at RT and 922 K (1200 F). The effects of welding on Incoloy 903 were evaluated utilizing tension, notched tension, fracture toughness, s well as unnotched and notched fatigue specimens. The elevated temperature stability of Incoloy 903 was investigated by exposing unstressed tension, notched tension (welded and nonwelded), and plane stress fracture toughness (welded and nonwelded) specimens at 922 K (1200 F) for 10 hours in air. After exposure, specimens were tested at various temperatures.

For CTX-1 alloy, tension, Charpy V-notch impact, density, thermal conductivity, and thermal expansion tests were conducted over the temperature range 20 K (-423 F) through 1033 K (1400 F). Poisson's ratio was determined at RT, 811 K (1000 F), 922 K (1200 F), and 1033 K (1400 F). Notched tension and compression tests were performed at 20 K (-423 F), RT, and 922 K (1200 F). Plane strain fracture toughness tests were conducted at RT, 77 K (-320 F), and 20 K (-423 F). Creep and rupture tests were performed at 811 K (1000 F), 922 K (1200 F), and 1033 K (1400 F). Longitudinal unnotched and notched fatigue tests at R = 0.1 were conducted at RT and 922 K (1200 F). The elevated temperature stability of CTX-1 was investigated by exposing unstressed tension, notched tension, Charpy V-notch, and fracture toughness specimens at 922 F (1200 F) for 10 hours in air. After exposure, specimens were tested at various temperatures.

A literature and industrial survey was also conducted to obtain additional data for both alloys.

INTRODUCTION

Incoloy 903 and CTX-1 are newly developed high-strength superalloys that maintain much of their strength up to 922 K (1200 F). Incoloy 903 is a product of Huntington Alloys while CTX-1 was developed by Carpenter Technology Corporation. The austenitic Fe-Ni-Co alloys, exhibiting Curie temperature behavior, are ferromagnetic at temperatures below approximately 728 K (850 F). The alloys are strengthened by precipitation of the intermetallic phase FCC-γ'-$Ni_3(Al, Ti)$. In addition, Ni_3Cb and Ni_3Ti phases are present in these alloys and are useful for structure and property control.

In addition to their attractive mechanical properties, the alloys exhibit nearly constant low coefficient of thermal expansion, which should provide excellent thermal fatigue resistance, and an almost constant modulus of elasticity over a wide temperature range. Also, the two materials are immune to embrittlement from high-pressure gaseous hydrogen. For this reason, the materials are being used in the space shuttle main engines[1]. Because of the nearly constant low coefficient of thermal expansion in combination with

(1) Lewis, Jack R., "Materials and Processes for Space Shuttle's Engines", Metal Progress (March 1975).

other attractive properties, the alloys are also being considered for use in aircraft gas turbine engines.

Since the alloys were recently introduced to the market in 1973, there is little published information available concerning their properties. Consequently, it was desirable to conduct a comprehensive engineering property characterization of these alloys.

OBJECTIVE

The objective of this program is to determine the engineering properties of Incoloy 903 and CTX-1 over the temperature range of 20 K (-423 F) through 1033 K (1400 F).

EXPERIMENTAL PROCEDURES

Materials

Incoloy 903 sheet in the recrystallize-annealed condition was selected for evaluation since this was the only sheet material available for immediate delivery. Three sheets of Incoloy 903, 1.55 mm x 0.914 m x 3.048 m (0.062 x 36 x 120 inches) were procured from Huntington Alloy Products Division for evaluation. The material was from heat HH21A20K which had been vacuum induction melted and electroflux remelted with the remelted ingot size 30.5 x 106.7 cm x length (12 x 42 inches x length). The sheet had been continuously solution treated at 1200 K (1700 F) in hydrogen atmosphere and air cooled. The chemical composition, as reported by the supplier, is shown in Table 1.

Alloy CTX-1 bar, 2.54 x 7.62 cm (1 x 3 inches), was obtained from Carpenter Technology Corporation for this investigation. The material was from heat 88893 which had been vacuum induction melted and vacuum arc remelted. Ingots had been press cogged to intermediate billets, 8.9 cm x 8.9 cm x 1.5 m (3½ inches x 3½ inches x 5 feet). The final 30 percent reduction was accomplished on a 40.6 cm (16 inch) hand mill using a 1144 K (1600 F) furnace temperature. The bar was supplied in the "as rolled" nonrecrystallized condition. The chemical composition, as reported by the supplier, is shown in

Table 1. Mechanical properties of the bar, as determined by the supplier, are shown in the first table of Appendix B.

Although similar, there is a slight variation in the chemical composition of the two alloys as shown in Table 1. Alloy CTX-1 has slightly higher percentages of cobalt, aluminum, and titanium. Consequently, trade names for these alloys have been used throughout this report.

Heat Treatment

Two heat treatment schedules, depending on the application, have been developed for Incoloy 903 and CTX-1. For tensile limited applications at low to moderate temperatures, the solution treatment temperature is 1228 K (1750 F); for creep-rupture limited applications, the solution treatment temperature is 1116 K (1550 F). After solution treatment the alloys are precipitation hardened by heating to 991 K (1325 F) for 8 hours, furnace cooling 311 K (100 F) per hour to 894 K (1150 F), holding for 8 hours, and air cooling. For creep-rupture applications, the alloys are very sensitive to thermomechanical working and should not be exposed to temperatures above 1144 K (1600 F) (which cause recrystallization) during fabrication or heat treatment; otherwise, the materials are notch sensitive in stress rupture.

The Incoloy 903 sheet was tested in (1) the "as received" (solution treated at 1200 K (1700 F) and air cooled) condition, and (2) in the heat treated condition. Precipitation hardening was accomplished in a vacuum (1.2×10^{-4} mm/Hg) furnace by heating at 991 K (1325 F) for 8 hours, furnace cooling 311 K (100 F) per hour at 894 K (1150 F), holding for 8 hours, and air cooling. Incoloy 903 was tested in the "as received" condition since it was thought that the alloy might have attractive low temperature properties in the annealed condition.

The CTX-1 alloy was tested in two heat conditions as follows:

Heat Treatment A: 1116 K (1550 F) for 1 hour, air cool plus 991 K (1325 F) for 8 hours, furnace cool 311 K (100 F) per hour to 894 K (1150 F) and hold for 8 hours and air cool.

Heat Treatment B: 1228 K (1750 F) for 1 hour, air cool plus 991 K (1325 F) for 8 hours, furnace cool 311 K (100 F) per hour to 894 K (1150 F) and hold for 8 hours and air cool.

Heat treatment of CTX-1 specimen blanks was performed in an air furnace.

The microstructures of the heat treated alloys as well as the "as received" (solution treated) Incoloy 903 were examined metallographically and found to be typical. The "as received" and heat treated Incoloy 903 sheet, shown in Figures 1 and 2, respectively, displayed a recrystallized microstructure. The CTX-1 bar, heat treatment A, displayed a deformed microstructure, Figure 3, while heat treatment B produced recrystallization, Figure 4. The alloys tended to pit during polishing and etching as evidenced in Figure 2.

Test Plan

The test plan to determine the engineering properties of Incoloy 903 and CTX-1 is outlined in Tables 2 and 3. Each alloy was tested in two heat treat conditions as described under Heat Treatment. Incoloy 903 was tested principally in the long transverse grain direction, which is most critical, with room-temperature tests only in the longitudinal direction. For economy, the CTX-1 bar was tested primarily in the longitudinal grain direction with room-temperature tests in the long transverse direction except for impact tests which were vice-versa. Three test specimens were tested for each condition.

The test plan provides for the determination of the effect of temperature on various mechanical and physical properties, the effect of thermal exposure (at 922 K (1200 F) for 10 hours) on the various mechanical properties at various temperatures, the effect of welding on certain mechanical properties of Incoloy 903 at various temperatures, and the effect of grain direction at room temperature.

Specimen Preparation

Rocketdyne Division of Rockwell International Corporation reported that Incoloy 903 sheet was very susceptible to oxygen contamination during solution treatment and that this condition adversely affected formability (ductility) and weldability. Rocketdyne had found it necessary to remove a superficial layer of material by abrasive belt sanding or grinding before forming or welding. Consequently, all Incoloy 903 specimens were ground to remove 0.076 m (0.003 inch) from each surface after heat treatment as described in Heat Treatment section. The location of the Incoloy 903 specimens is shown in Figure 5.

Specimen blanks were machined from the CTX-1 bar and heat treated in accordance with the procedures described in Heat Treatment section. After heat treatment, the specimens were finish machined. This procedure provided for the complete removal of all material subject to surface reactions during heat treatment. The location of the CTX-1 specimens is shown in Figure 6.

Incoloy 903 weldments were fabricated as shown in Figure 7. The sheet details were fully heat treated and ground to remove all surface contamination before welding. The sequence of welding in the fully heat treated condition with no subsequent thermal stress relief was selected to simulate certain applications on the space shuttle. For the welded fracture toughness specimen, the surface of the sheet was ground only in the area to be welded as shown in Figure 8. After welding, tensile, notched tensile, unnotched fatigue, and notched fatigue specimens were machined from the weldment shown in Figure 7. The weld bead was removed by grinding flush with the surface of the specimen.

Tungsten-inert-gas welding was performed according to the recommendations of Rockwell International - Rocketdyne Division. Rocketdyne reported that the weldability of Incoloy 903 was similar to Inco 718 but that Incoloy 903 was very susceptible to oxygen contamination during welding. Consequently, provisions were made to insure good back-up shielding using argon. Welding was accomplished utilizing strips sheared from ground sheet since welding wire was not commercially available. Welding was accomplished with automatic torch travel at 15 cm (6 inches) per minute with filler rod fed by hand using stringer bead technique. Back-up gas flow rate was 0.71 cubic meters (25 cubic feet) per hour. Preheat and postheat were not used. Weld bead was ground after each pass followed by cleaning with acetone. Thermal stress relief was not performed after welding. Several small cracks in the weld bead were encountered. These were repaired and the weldments were penetrant inspected again. For successful welding of this alloy, good back-up shielding and cleanliness (including the removal of heat treat contaminated surfaces) appeared paramount in importance.

Much difficulty was encountered in machining of the notch in the notched tensile specimens after heat treatment due to the small root radius of the notch. Originally a stress concentration factor of K_t = 10 had been selected. Initial attempts at machining the notch were unsuccessful due to cutter failure. Subsequent attempts to grind the notch were also nonproductive due to excessive wear of the grinding wheel. Consequently, it was necessary to resort to electrical discharge machining which was successful after increasing the notch root radius to 0.625 mm (0.0025 inch), resulting in a reduction in K_t from 10 to 8. In general, the machinability of Incoloy 903 and CTX-1 appeared similar to Inco 718.

In order to determine the effect of thermal exposure on various mechanical properties, selected finish machined specimens were exposed unstressed in air at 922 K (1200 F) for 10 hours. Except for the air environment, this treatment simulated the maximum thermal exposure conditions for the life of space shuttle rocket engines. The oxide layer was not removed from the exposed specimens.

Test Description

All test measurements were made using United States common engineering units. Throughout the report International (SI) units, obtained by conversion, are shown as well as the United States units.

Tensile Tests

Tensile tests were conducted using Baldwin Universal test machines. These machines were calibrated at frequent intervals in accordance with ASTM Method E4 to assure loading accuracy within ± 0.2 percent. The machines were equipped with integral automatic strain pacers and automatic load-strain recorders.

Tensile testing was performed according to ASTM Methods E8 and E21. Pin-loaded specimens, Figure A-1 (Appendix A)--conforming to ASTM Method E8, were used for Incoloy 903 sheet. Round specimens, 0.250-inch diameter, Figure A-2--conforming to ASTM Method E8, were utilized for CTX-1 bar.

For elevated temperature tests, three thermocouples were attached to the specimen gage length to insure the temperature of the specimen was constant during loading. Using the middle thermocouple as the control reading, specimens were held at test temperature before loading for at least 15 minutes after the other two thermocouples indicated the same temperature as the control thermocouple. The specimens were heated in a Satec split furnace. ASTM Class B extensometers with extensions to locate the linear differential transformer unit outside the furnace were used for elevated-temperature tests with appropriate autographic recorders to plot load-strain curves to slightly above yield load. The extensometer-recorder combination was calibrated regularly as a unit.

For low-temperature tests, specimens were immersed during testing in a Dewar flask containing either liquid nitrogen to obtain 77 K (-321 F) or liquid hydrogen to obtain 20 K (-423 F).

All tensile specimens were tested at a strain rate of approximately 0.005 cm/cm/min. (0.005 in./in./min.), as controlled by a strain pacer, until the 0.2 percent yield strength was exceeded and at a strain rate of approximately 0.75 cm/cm/min. (0.75 in./in./min.) above yield strength to fracture. For all tensile tests, the ultimate tensile strength, tensile yield strength at 0.2 percent offset, elongation, reduction of area for CTX-1 alloy only, and modulus of elasticity were determined. The yield strength and modulus were obtained from the load-strain curves.

Notched Tensile Tests

Tensile tests at various temperatures were conducted on Incoloy 903 notched-sheet specimens with a stress concentration factor, K_t, of 8, Figure A-3, and on CTX-1 notched-round specimens with a $K_t = 5$, Figure A-4. Notched tensile testing procedures were similar to those used for unnotched tensile tests.

Compression Tests

Compression testing was conducted in accordance with ASTM Methods E9 and E31. Incoloy 903 sheet specimens were tested using a Rockwell International type compression fixture. The configuration of compression sheet specimens is shown in Figure A-5. A compressometer was attached to the specimen at very small notches spanning a 5.08 cm (2-inch-gage) length. The strain signal was generated by a linear differential transformer which was part of the extensometer with readout on an autographic recorder. Round compression specimens, Figure A-6, were used for the CTX-1 bar. Fixturing was used to maintain alignment during testing.

Testing procedures and strain rates were similar to those used for tensile tests. The compressive yield strength at 0.2 percent offset, and the compressive modulus of elasticity were determined from the load-strain curves.

Impact Tests

Charpy V-notch impact tests were conducted on the CTX-1 alloy in accordance with ASTM Method E23 using a Reihle impact machine. The test machine was calibrated frequently by using standardized specimens obtained from the Army Materials and Mechanics Research Center. The specimen configuration is shown in Figure A-7. For low test temperatures, specimens were placed in individual paper "boats" and immersed in the proper cryogen. The "boat" containing the specimen was transferred to the test machine and tested within five seconds so that there was no significant temperature rise in the specimen. For elevated temperature tests, the specimens were heated to a temperature above the test temperature to compensate for the heat loss during transfer from the furnace to the impact test machine. The degree of elevation required at each test temperature was determined empirically by using a surplus impact specimen with imbedded thermocouple.

Poisson's Ratio Tests

Poisson's ratio was determined for CTX-1 only since Huntington Alloys[(2)] has published values for Incoloy 903. Poisson s ratio was determined at room temperature, 811 K (1000 F), 922 K (1200 F) and 1033 K (1400 F) using a cylindrical test specimen as shown in Figure A-8. Longitudinal and diametral strains were measured utilizing special extensometers which had been designed, developed, and constructed by Battelle's Columbus Laboratories. These special extensometers provided a convenient method of determining Poisson's ratio at elevated temperatures.

The longitudinal extensometer, as shown in Figure 9, was attached to the specimen with a 1.3 cm (0.50-inch) gage length. It consisted of two probes of high-purity alumina connected to twin beam supports and hinged by means of a spring-steel leaf spring. Changes in axial displacement were mechanically multiplied by a factor of 1.25 before they were measured by a

(2) Huntington Alloys Technical Brochure on Incoloy 903.

sensitive and magnetically shielded linear variable differential transformer (LVDT). The output signal obtained from the LVDT was proportional to the displacement over the gage length of the specimen.

The diametral extensometer, Figure 10, consisted of adjustable sensing arms of high-purity alumina connected to a bracket made of two parallel beams joined by a flexible ligament that acted as an elastic hinge. Diameter changes were magnified three times before they were measured at the other end by a LVDT. The transformer and armature of the LVDT were mounted on opposite beams and the position of the armature relative to the transformer was adjusted after the test specimen had been heated to the desired temperature. The output signal obtained from the LVDT was proportional to the diameter change in the specimen.

Loads were applied using an electrohydraulic servocontrolled testing machine. The load cell was calibrated prior to testing by utilization of a reference load cell. The extensometers were calibrated by employing a mechanical micrometer capable of 25.4×10^{-4} cm (10×10^{-4} inches) resolution.

Prior to making test measurements, loads were applied to the longitudinal specimens with the diametral extensometer in different orientations to check for anisotropy. It was found that the CTX-1 alloy was anisotropic. The end of the specimen was polished metallographically and etched to reveal the grain structure. Marks identifying the long transverse and short transverse grain directions were placed on the specimen. With the diametral extensometer orientated in either the long transverse or short transverse grain directions, a cyclic load from +97 MPa (+14 ksi) to -97 MPa (-14 ksi) was applied. The longitudinal strain, indicated by the longitudinal extensometer, was plotted simultaneously against the transverse strain, indicated by the diametral extensometer.

Fracture Toughness Tests

For CTX-1 alloy, plane-strain fracture toughness testing was conducted in accordance with ASTM Method E399 utilizing compact tension specimens, Figure A-9, having appropriate dimensions. After fatigue precracking, specimens were tested in Baldwin Universal test machines using procedures similar to those used for tensile testing. Since the room-temperature plane-strain (K_{Ic}) value of precipitation hardened Incoloy 903 was reported by Huntington Alloys[2] to be 110.5 MPa$\sqrt{m}$ (100.6 ksi$\sqrt{in.}$), CTX-1 was expected to exhibit a similar value. Consequently, plane-strain fracture toughness tests were not conducted at elevated temperatures since the K_{Ic} values at elevated temperatures were expected to be higher than the room-temperature value and it was unlikely that a valid K_{Ic} could be determined.

For Incoloy 903, plane-stress fracture toughness tests were conducted in accordance with MIL-HDBK-5B[3] by utilizing 45.7 cm (18 inch) wide center through-crack tension panels, Figure A-10, to obtain K_{app} values at room temperature.

The thin sheet center through-crack tension panels were initially saw-cut and then precracked in constant amplitude fatigue loading. In order to maintain a flat fatigue crack and not plastically strain the uncracked section, the maximum stresses were adjusted to keep the applied stress-intensity factor less than one-third of that anticipated at fracture. This usually involved stepping down the stresses as the cracking proceeded. The crack was extended to approximately one-quarter of the panel width. Buckling guides were attached and a clip-type compliance gage was mounted in the central notch. The panels were fractured in a rising load test at a stress rate in the range

$$0.002\ E < \dot{S} < .005\ E\ \text{MPa/min. (ksi/min.)}\ ,$$

which corresponds nominally to the gross strain rate of standard tensile testing. The test set-up showing the specimen in the electrohydraulic-servocontrolled test machine is shown in Figure 11. Elevated temperature plane stress fracture toughness tests were not conducted for the reasons previously given and low temperature tests were not performed due to the excessive cost of fixtures and the attendant safety hazard.

Creep and Stress-Rupture Tests

Standard creep testing frames, utilizing dead-weight loading of the specimen, were employed. These machines were calibrated and conformed to the requirements of ASTM Method E139. Chromel A and platinum heater wire furnaces

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(3) Section 9.5.1.5, "Plane-Stress and Transitional Fracture Toughness", MIL-HDBK-5B, Change Notice 2 (15 August 1974).

with taps along the side that allow for correcting small temperature differences along the gage length of the specimen were utilized. Temperature variations were maintained at less than ± 2 degrees. Windows in the front or back of the furnaces permitted creep measurements to be made optically using platinum strip extensometers that were attached directly to the gage section of sheet specimens and to the shoulder of cylindrical specimens. The microscopes used for these optical measurements were fitted with filar eyepieces whose smallest division corresponded on a 2.54 cm (1-inch) gage length to a strain of 0.005 percent. Zero reading was taken after the specimen had reached the test temperature with no stress applied. The initial deformation was obtained by applying the entire stress as rapidly as possible. "Foxboro" temperature controllers that operate on high-low power input controlled the test temperature to within ± 2 degrees of the intended temperature. Three thermocouples were attached to the gage section of each specimen. The thermocouples were made from calibrated wire and new thermocouples were used for each test. Creep and rupture tests were conducted at 811 K (1000 F), 922 K (1200 F), and 1033 K (1400 F) for both Incoloy 903 and CTX-1 in accordance with ASTM Method E139. Creep specimen configurations are shown in Figures A-11 and A-12.

Fatigue Tests

Fatigue tests were conducted using electrohydraulic-servocontrolled testing machines. These machines operate with closed-loop deflection, strain or load control. Under load control used in this program, cyclic loads were automatically maintained (regardless of the required amount of ram travel) by means of load-cell feedback signals. The calibration and alignment of each machine were checked periodically. In each case, the dynamic load-control accuracy was within ± 3 percent of the test load.

For elevated temperature studies, an induction heating coil controlled by a Lepel induction heater was used. A thermocouple placed on the center of the specimen controlled temperature to ± 5 degrees.

After machining and heat treating (when required), the edges of all sheet and plate specimens were polished according to Battelle-Columbus' standard practice prior to testing. The unnotched sheet specimens were held against a rotating drum covered with emery paper and polished using a kerosene lubricant. Successively finer grits of emery paper were used, as required, to produce a surface of approximately 10 RMS. Unnotched round specimens were polished using a Battelle-Columbus polishing apparatus. This machine utilizes a rotating belt sander driven rectilinearly along the specimen test section while the specimen is being rotated. The belt speed and specimen speed are adjusted so that polishing marks on the specimen are in the longitudinal direction. The surface finish was approximately 10 RMS. The machined notched specimens were not polished. A shadowgraph optical comparator was used for measuring the test sections of all polished specimens and for inspection of the root radius in the case of the notched specimens.

Configurations of fatigue test specimens are shown in Figures A-13 through A-16. The stress ratio for all specimens was R = 0.1 and the speed of testing was 20 Hz. Stresses for notched (K_t = 3.0) and unnotched specimens were selected so that S-N curves were defined between 10^3 and 10^7 cycles. Fatigue tests were conducted at room temperature and 922 K (1200 F).

Thermal Expansion

Thermal expansion was measured on longitudinal Incoloy 903 specimens in the heat treated condition and on longitudinal CTX-1 specimens with heat treatment A. Due to the wide test temperature range, 20 K (-423 F) - 1033 K (1400 F), two different apparatus were employed.

To measure thermal expansion at low temperatures from 20 K (-423 F) to 300 K (80 F), a fused silica dilatometer was employed wherein length changes were measured with a LVDT. Great care was taken to insure that the fused silica pushrod and the sample tube were of the same material (i.e., same manufacturer, heat treatment, etc.). The LVDT was calibrated periodically to insure linearity and a run made with no specimen present to check the integrity of all mechanical couplings, etc., over the entire temperature range.

The sample tube and pushrod were housed in the sample space of a liquid helium throttling dewar. This dewar provided control at any temperature in the range of 4.2 to 300 K (-452 to 80 F). Thermocouples were mounted directly on specimen and at regular intervals along the length and radius of the sample tube. A constant temperature region of about 25.4 cm (10 inches) along the length of the tube was achievable at any given throttle setting. Measurements were also taken to insure that the pushrod and sample tube temperatures were the same at any position along the length of the assembly.

Specimen length was 5.08 cm (2 inches). The accuracy of measurement on the 5.08 cm (2-inch) specimen was better than 1 percent, based on measurements of standard materials such as copper and nickel. The reproducibility of a given experiment over the entire range is about 15 to 25 x 10^{-5} mm.

To measure thermal expansion at elevated temperatures, 300 K (80 F) to 1033 K (1400 F), the technique and apparatus described below were used.

Measurements were made on both heating and cooling utilizing an automatic recording dilatometer. In this dilatometer, the nominal 5.08 cm (2-inch) long specimen was positioned between members of a quartz structure located on the axis of a tube furnace. As the specimen length changed due to temperature change, the relative positions of the quartz members changed. This displacement was sensed by an LVDT, the output of which was plotted on one axis of an X-Y recorder. The specimen temperature, sensed by a thermocouple, was plotted on the other axis. The furnace heating rate was controlled to achieve uniform temperature over the length of the specimen. The system was capable of displaying dilations of 0.01 percent over 2.54 cm (1 inch) of recorder chart with overall accuracy checked by means of measurements on reference standard materials obtained from the National Bureau of Standards.

Thermal Conductivity

Thermal conductivity was measured on longitudinal Incoloy 903 specimens in the heat treated condition and on longitudinal CTX-1 specimens with heat treatment A. Due to the extremes in testing temperatures, two different apparatus and techniques were utilized to improve accuracy.

For the temperature range 20 K (-423 F) to 300 K (80 F), thermal conductivity measurements were obtained by the absolute steady-state method. In this method, a temperature gradient is established along the length of a specimen, usually a cylindrical rod, by attaching one end to a controlled temperature heat sink, and adding a measured quantity of heat to the other end by means of an electric resistance heater. Conductivity is then calculated using a form of the Fourier equation:

$$\lambda = \frac{P}{A} \frac{L}{\Delta T} , \qquad (1)$$

where λ = thermal conductivity

q/A = heat flow per unit across section area

L = specimen length across which temperature gradient is measured

ΔT = temperature gradient across L.

In the Battelle apparatus, the heater was a 3-lead unit wound of Evanohm wire which has a nearly zero temperature coefficient of resistance. A constant current source was used to power the gradient heater. The temperature gradient set up in the specimen after a steady-state condition had been reached was measured using either gold cobalt versus "normal" silver differential thermocouples, or miniature platinum resistance thermometers. The ambient temperature was precisely controlled (± 0.05 K) during a measurement using the output of a Keithly 150 B null detector, the signal to which came from a copper-constantan thermopile mounted on the specimen container, and a low-temperature modified West controller. The temperature gradient across the specimen was measured by a Keithley 147 nonovoltmeter.

The measurements were carried out in a liquid helium throttling dewar. This dewar provided a degree of ambient temperature control in itself in that by suitably adjusting the throttle value (which admits helium through a capillary to the dewar sample chamber) and the vaporization heater voltage (which allows the liquid helium to vaporize before entering the sample chamber), the cold helium gas flowing past the specimen fixture (which is highly evacuated) could be controlled to within one degree K. This greatly reduced the burden on the independent ambient temperature control device used in the specimen fixture.

The accuracy of the thermal conductivity measurements described above was approximately ± 5 percent. The accuracy figure was based on measurements of various copper alloys and a thermal conductivity "round-robin" carried out by NBS-Boulder and Battelle-Columbus on Armco iron, which was characterized at Battelle-Columbus. This latter material is now fully recognized as a reference standard in the intermediate range of thermal conductivities.

To obtain thermal conductivity values at elevated temperatures, 300 K (80 F) to 1033 K (1400 F), the method outlined below was used.

Of the various techniques available for determination of thermal conductivity of metal alloys, the approach selected was measurement of thermal diffusivity and calculation of conductivity as the product of diffusivity, density, and specific heat. This approach was chosen because it bypasses some sources of potential error usually associated with direct, steady-state measurements, and is better suited to cases where relatively large specimens are not available. In addition, it is capable of accuracy comparable to that of steady-state methods. Measurements of specific heat were not included in the work scope since it was assumed that published specific heat values[2] would be adequate.

Thermal diffusivity was measured by the flash-laser technique. In this technique, a thin disk-shaped specimen was positioned in the isothermal zone of a furnace and the front face was heated with a short-duration pulse from a ruby laser. As the heat pulse traveled through the specimen, the back-face temperature rise was recorded as a function of time. This temperature-time history of the back face is directly related to the thermal diffusivity of the specimen as

$$\alpha = \frac{\omega_{\frac{1}{2}} L^2}{t_{\frac{1}{2}}} , \qquad (2)$$

where α = thermal diffusivity

L = specimen thickness

$t_{\frac{1}{2}}$ = time required for back face of specimen to reach one-half its maximum temperature rise

$\omega_{\frac{1}{2}}$ = theoretical parameter of the method which includes the effects of heat losses from the specimen surface.

This relationship involves several simplifying assumptions:

(1) The heat flow is one-dimensional from the front face directly to the back face.

(2) The incident heat pulse is of negligible duration compared to the time required for significant heat propagation through the specimen.

(3) The incident heat pulse is uniformly absorbed on the front face of an opaque specimen.

(4) The temperature rise within the specimen is small enough to consider the thermal properties as constant.

In the present case, all assumptions were justified.

Figure 12 is a section drawing of the Battelle-Columbus thermal diffusivity apparatus. The specimen was held in a tantalum holder inside a double-walled tantalum tube heater. Thermal radiation shielding surrounded the heater. The specimen and heater were protected by argon at less than atm 'ic pressure. Specimen temperatures were measured with a chromel-alumel thermocouple, the bead of which was in contact with the specimen holder.

The radiation detector is shown in position to view the back face of the specimen through a lens system. An indium-antimonide device was used as the radiation detector. The detector is placed in one arm of a biasing circuit, the unbalance of which is displayed on an oscilloscope and photographed by a camera. The time required for the back-face temperature to reach one-half its maximum, and data for ascertaining $\omega_{\frac{1}{2}}$ are obtained from measurements of the photograph. These parameters and the specimen thickness were used to calculate thermal diffusivity using Equation (2).

Based on experience with standard materials, the potential error of measured thermal diffusivity values was believed not to exceed ± 5 percent.

Density

Room-temperature densities of heat treated Incoloy 903 sheet and CTX-1 bar with heat treatment A were calculated from weight and dimension measurements on multiple regular-shaped samples of each alloy. Weights were determined by analytical balance, and dimensions by micrometer. Each dimension of each sample was measured approximately five times and the average of these was utilized in the calculation.

Discussion of Test Results

Tensile Properties

The tensile properties of annealed Incoloy 903 sheet are shown in Table 4. At room temperature the material appeared to be anisotropic since the yield strength, ultimate strength, and modulus of elasticity were significantly higher in the long transverse direction than in the longitudinal direction. The annealed material displayed attractive tensile properties at 77 K (-321 F) and 20 K (-423 F). The tensile ductility at 77 K (-321 F) was higher than at room temperature and at 20 K (-423 F) was equivalent to room-temperature elongation. The tensile yield and ultimate strengths at 922 K (1200 F) were higher than at room temperature indicating that precipitation hardening had occurred from elevated-temperature exposure during testing.

Elongation decreased with increasing temperature to 14.7 percent at 1033 K (1400 F). The modulus of elasticity values determined from load-strain curves appeared fairly constant from 20 K (-423 F) through 922 K (1200 F). Curves showing the effect of temperature on the tensile properties of annealed Incoloy 903 sheet are shown in Figure 13.

The tensile properties of heat treated Incoloy 903 sheet are shown in Table 5. Longitudinal tensile specimens taken from each of the three sheets of material used in this evaluation indicated that sheet #1 displayed slightly lower strengths than the other two sheets. A comparison of longitudinal and long transverse properties for sheet #1 showed the material was also anisotropic in the heat treated condition with the long transverse tensile strengths higher than longitudinal. Heat treated Incoloy 903 displayed very high strengths at low temperatures with higher elongations at 20 K (-423 F) and 77 K (-321 F) than at room temperature. The alloy maintained its strength very well through 922 K (1200 F) exhibiting minimum elongation (10.3 percent) at 922 K (1200 F). The modulus of elasticity appeared fairly constant from 20 K (-423 F) through 77 K (1200 F). Curves showing the effect of temperature on the tensile properties of heat treated Incoloy 903 sheet are shown in Figure 14.

The tensile properties of CTX-1 bar, resulting from heat treatment A, are shown in Table 6. The room temperature tensile yield and ultimate strengths in the long transverse grain direction were slightly higher than those in the longitudinal direction accompanied by lower elongation and reduction of area. This heat treatment produced high strengths at low temperatures with higher elongations at 20 K (-423 F) and 77 K (-321 F) than at room temperature, although the reduction of areas were lower than at room temperature. This heat treatment displayed good strength and excellent ductility at elevated temperatures. The modulus of elasticity was constant over the temperature range from 20 K (-423 F) through 922 K (1200 F). Curves showing the effect of temperature on the tensile properties of CTX-1 bar, heat treatment A, are shown in Figure 15.

The tensile properties of CTX-1 alloy, resulting from heat treatment B, are shown in Table 7. The room temperature tensile yield and ultimate strengths produced by heat treatment B were similar to those from heat treatment A except elongation and reduction of area were higher. Also, heat treatment B yielded more isotropic properties than heat treatment A. This improvement would be expected from a recrystallized microstructure. The low temperature tensile properties from heat treatment B were very good with elongation and reduction of area higher than those produced by heat treatment A. However, at 922 K (1200 F) and 1033 K (1400 F) the recrystallized material displayed very low elongations and reduction of areas. The modulus of elasticity was constant over the temperature range from 20 K (-423 F) through 922 K (1200 F). Curves showing the effect of temperature on the tensile properties of CTX-1 bar, heat treatment B, are shown in Figure 16.

Representative tensile stress-strain curves for Incoloy 903 sheet and CTX-1 bar at various temperatures are shown in Figures 17 through 22. These curves were constructed using average values for modulus of elasticity and yield strength. The Ramberg-Osgood shape parameter was determined utilizing a typical stress-strain curve selected for each test condition. The determination of the shape parameter was based upon the graphical relationship between Ramberg-Osgood exponent, n, and stress or load ratio as described in MIL-HDBK-5B[4].

Notched Tensile Properties

The notched tensile properties of annealed Incoloy 903 sheet are included in Table 4. The long transverse notched/unnotched ratio was 0.92 at room temperature with little difference between grain directions. This ratio decreased slightly at 20 K (-423 F), 77 K (-321 F), and 811 K (1000 F) but increased at 922 K (1200 F) and 1033 K (1400 F). Curves showing the effect of temperature on the notched tensile strength and notched/unnotched tensile strength ratio of annealed Incoloy 903 sheet are depicted in Figure 23.

The notched tensile properties of heat treated Incoloy 903 sheet are shown in Table 5. There was no significant difference in the longitudinal and long transverse notched/unnotched tensile strength ratios of heat treated Incoloy 903 sheet at room temperature. The long transverse notched/unnotched ratio at room temperature was 0.99 which was higher than corresponding values for annealed material. The ratio decreased slightly at 20 K (-423 F) and 77 K (-321 F), but increased at 811 K (1000 F), 922 K (1200 F), and 1033 K (1400 F). Curves showing the effect of temperature on the notched tensile

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(4) Section 9.3.2.4, "Ramberg-Osgood Method", MIL-HDBK-5B, Change Notice 3 (15 August 1974).

strength and notched/unnotched tensile strength ratio for heat treated Incoloy 903 sheet are shown in Figure 24.

The notched/unnotched tensile strength ratio for CTX-1 bar at room temperature was similar for both heat treat conditions, Tables 6 and 7. The ratios decreased at 20 K (-423 F) in a similar manner for both heat treat conditions. At 922 K (1200 F) the notched/unnotched ratio produced by heat treatment A was higher than at room temperature while the ratio for recrystallized (heat treatment B) material was 30.4 percent lower than at room temperature indicating severe notch sensitivity at 922 K (1200 F) for the recrystallized material. Curves showing the effect of temperature on the notched tensile strength and notched/unnotched tensile strength ratio for CTX-1 bar are depicted in Figure 25.

Compressive Properties

The compressive properties of Incoloy 903 sheet and CTX-1 bar are shown in Tables 8 through 11. The compressive strengths for the two alloys were higher than the tension strengths. The compressive yield strengths of annealed Incoloy 903 sheet indicated that precipitation hardening had occurred from elevated-temperature exposure during testing at 922 K (1200 F) and 1033 K (1400 F). The effect of temperature on the compressive yield strength and compressive modulus of elasticity is shown in Figures 26 and 27. Representative compressive stress-strain and compressive-tangent-modulus curves for Incoloy 903 and CTX-1 are shown in Figures 28 through 35. The procedures used for constructing compressive stress-strain curves was similar to those used for tensile stress-strain curves.

Impact Properties

Charpy V-notch impact values for CTX-1 bar, heat treatment A, are shown in Table 12. This heat treatment displayed anisotropic behavior with a long transverse impact value of 15.1 J (11.2 ft. lbs.) compared to a longitudinal value of 29.2 J (21.5 ft. lbs.). Except at 1033 K (1400 F), the Charpy V-notch impact values were not greatly different over the entire temperature range tested.

Charpy V-notch impact values for CTX-1 bar, heat treatment B, are shown in Table 13. The recrystallized material displayed about the same degree of anisotropy as the nonrecrystallized material. However, the impact values for the recrystallized material were significantly higher than the nonrecrystallized material over the entire temperature range. In general, the Charpy V-notch values increased with increasing temperature. The notch sensitivity of the recrystallized material at elevated temperatures was not manifested by the impact test. The effect of temperature in the Charpy V-notch impact values for CTX-1 bar is shown in Figure 36.

Fracture Toughness

The results of the thin sheet fracture toughness tests at room temperature for heat treated Incoloy 903 sheet are shown in Table 14. The apparent fracture toughness, K_{app}, values were calculated from the expression,[5]

$$K_{app} = S_{max}\sqrt{\pi a_0} \quad . \tag{3}$$

A finite width correction was not included since its effect is less than three percent for these crack sizes. The heat treated (recrystallized) Incoloy exhibited good fracture toughness, $K_{app} = 188$ MPa$\sqrt{m}$ (171 ksi$\sqrt{in.}$) at room temperature. Thermal exposure (see Effect of Thermal Exposure section) reduced the tensile yield strength somewhat and increased K_{app} to 196 MPa$\sqrt{m}$ (178 ksi$\sqrt{in.}$).

Plane-strain fracture toughness tests were conducted on CTX-1 with heat treatment A (nonrecrystallized) only. All of the candidate K_Q values, shown in Table 15, were valid K_{Ic} values by existing ASTM Method E399 criteria and the K_{Ic} values for each test condition were very consistent. Fracture toughness of CTX-1 did not decrease at 77 K (-321 F) or 20 K (-423 F), Figure 37. The room temperature K_{Ic} value of 58 MPa$\sqrt{m}$ (53 ksi$\sqrt{in.}$) for the T-L direction was much lower than expected. However, if testing were conducted in the L-T direction, the toughness may be significantly higher since the CTX-1 alloy with heat treatment A (nonrecrystallized) was strongly anisotropic with regard to other mechanical properties.

(5) Section 9.5.1.5, "Plane-Stress and Transitional Fracture Toughness", MIL-HDBK-5B, Change Notice 3 (15 August 1974).

Creep and Stress Rupture

Creep and stress rupture test data for annealed Incoloy sheet are shown in Table 16 and depicted graphically in Figures 38 and 39. As expected, the annealed recrystallized material exhibited very erratic creep behavior with some specimens showing very poor ductility. At 922 K (1200 F) one specimen failed through the loading hole indicative of severe notch sensitivity. Various degrees of precipitation hardening apparently occurred at 811 K (1000 F), 922 K (1200 F), and 1033 K (1400 F) during testing.

Table 17 contains creep and stress rupture test data for heat treated Incoloy sheet. Graphical representation is shown in Figures 40 and 41. The heat treated recrystallized Incoloy 903 creep behavior was somewhat more predictable but specimens tested at 811 K (1000 F) and 922 K (1200 F) displayed very low elongations.

Creep and stress rupture test data for CTX-1 bar, heat treatment A (nonrecrystallized), is shown in Table 18 and graphically in Figures 42 and 43. This material exhibited normal creep-rupture behavior with good ductility.

Table 19 lists the creep and stress rupture test data for CTX-1 bar, heat treatment B (recrystallized). Graphical representations are shown in Figures 44 and 45. The recrystallized CTX-1 alloy exhibited extreme notch sensitivity at 811 K (1000 F) and 922 K (1200 F) as evidenced by thread failures (Table 19). Two of three specimens tested at 811 K (1000 F) failed in the threads. At 922 K (1200 F), two specimens were tested with one failing in threads and one fracturing at fillet radius. Because of this extreme notch sensitivity, creep-rupture testing at these two temperatures was discontinued. The extreme notch sensitivity of the recrystallized CTX-1 bar displayed at 811 K (1000 F) and 922 K (1200 F) was not evident at 1033 K (1400 F) since no thread failures were experienced and the 1033 K (1400 F) elongations were not greatly different from those of the nonrecrystallized material. The creep-rupture strength of the recrystallized CTX-1 bar at 1033 K (1400 F) was similar to that of the nonrecrystallized material.

Fatigue Properties

Notched ($K_t = 3$) and unnotched axial load fatigue test data for Incoloy 903 sheet and CTX-1 bar are listed in Tables 20 through 27. All specimens were tested at a stress ratio of $R = 0.1$. Figures 46 through 53 depict the fatigue data in the form of S-N curves. The room temperature unnotched fatigue strength of CTX-1, heat treatment A and heat treatment B, and heat treated Incoloy 903 appeared similar. At 922 K (1200 F) the unnotched fatigue properties of CTX-1, heat treatment A, and heat treated Incoloy 903 were similar while CTX-1, heat treatment B, appeared inferior. In some cases the fatigue strength curves at 922 K (1200 F) were higher than the room-temperature curves. This apparent anomaly is attributed to fatigue scatter. The room-temperature notched ($K_t = 3$) fatigue strength of CTX-1, heat treatment A and heat treatment B, were similar while heat treated Incoloy 903 sheet was slightly superior. At 922 K (1200 F) the notched ($K_t = 3$) fatigue strength of CTX-1, heat treatment A, was superior to CTX-1, heat treatment B and heat treated Incoloy 903. There was little difference in the notched ($K_t = 3$) fatigue strength of annealed and heat treated Incoloy 903 sheet. For unnotched specimens, annealed Incoloy 903 sheet displayed significantly lower fatigue strength than the heat treated condition.

Effect of Welding

The tensile and notched tensile properties of heat treated and welded Incoloy 903 sheet are shown in Table 28 and graphically in Figure 54. The welded tensile yield and ultimate strengths were slightly lower than the annealed strengths. Weld elongations were greatly reduced compared to either annealed or heat treated values. Weld elongations at 20 K (-423 F) were very low. Welded notched/unnotched tensile strength ratios were about the same as annealed ratios and lower than heat treated ratios. The effect of welding on fracture toughness of Incoloy 903 sheet is shown in Table 14. The toughness values, K_{app}, of heat treated and welded Incoloy 903 were not valid since the net section fracture strength exceeded the tensile yield strength. The results of fatigue testing heat treated and welded Incoloy 903 sheet are shown in Tables 29 and 30 and graphically in Figures 55 and 56. The unnotched, welded fatigue strengths were significantly lower than the unnotched annealed fatigue strengths. In contrast, the notched, welded fatigue strengths were not appreciably different from the notched annealed fatigue strengths. This was most likely caused by the geometric notch masking the effect of the metallurgical (weld) notch.

Effect of Thermal Exposure

The effect of unstressed thermal exposure in air at 922 K (1200 F) on the tensile and notched tensile properties of annealed Incoloy 903 sheet is shown in Table 4 and Figures 13 and 23. Exposure caused an increase in the room-temperature tensile yield and ultimate strengths with a corresponding decrease in ductility. The 922 K (1200 F) exposure for 10 hours apparently caused precipitation hardening which produced tensile yield and ultimate strengths slightly lower than those obtained using the standard precipitation heat treatment. The same effect was manifested by exposed annealed specimens at the other test temperatures. Exposure had no significant effect upon modulus of elasticity. The notched/unnotched tensile strength ratios of exposed annealed specimens at the various temperatures were similar to annealed ratios. The notched tensile strengths of exposed, heat treated and welded, Incoloy 903 specimens, as shown in Table 28 and Figure 54, were much higher than nonexposed welded specimens indicating that the heat affected zone had apparently undergone precipitation hardening during exposure producing quasi heat treated properties. The effect of exposure on the fracture toughness of welded Incoloy 903 sheet is shown in Table 14. The K_{app} value for exposed, heat treated, and welded Incoloy 903 sheet was slightly higher than the K_{app} value for heat treated sheet and commensurate with the lower yield strength of the exposed welded specimens. It is interesting to note that for one exposed weld metal test (specimen 2-6T), one crack tip propagated from weld metal into parent metal which had lower fracture toughness. The K_{app} value for this specimen agreed closely with the K_{app} values for parent metal.

The effect of unstressed thermal exposure on heat treated Incoloy 903 sheet is shown in Table 5 and Figure 14. Exposure caused a slight decrease in the room-temperature tensile yield and ultimate strengths with a corresponding increase in elongation indicative of slight overaging. The same effect was evident at other test temperatures. Exposure had no significant effect upon modulus of elasticity. There was no significant difference in the notched/unnotched tensile strength ratios for exposed and unexposed heat treated Incoloy 903 at various temperatures. The effect of exposure on the fracture toughness of heat treated Incoloy 903 sheet is shown in Table 28. The K_{app} value for exposed heat treated sheet was slightly higher than unexposed material corresponding to the lower yield strength of the exposed material.

Exposure of CTX-1 tensile specimens in both heat treat conditions caused a slight decrease in the tensile yield and ultimate strengths with little change in elongation and reduction in area as shown in Tables 6 and 7 and graphically in Figures 15 and 16. Modulus of elasticity was not significantly affected by exposure. Exposure had no significant effect on the notched tensile strength ratios for both heat treat conditions, Tables 6 and 7 and Figure 25. For heat treatment A, exposure had no significant effect on the Charpy V-notch impact strength of CTX-1 at room temperature and 20 K (-423 F), Table 12 and Figure 36. Exposure caused a slight increase in the Charpy V-notch impact strength of CTX-1, heat treatment B, at the same temperatures, Table 13 and Figure 36. The effect of exposure on the fracture toughness of CTX-1, heat treatment A, is shown in Table 15. At room temperature exposure resulted in a slight increase in K_{Ic} values while at 20 K (-423 F), there was no significant difference, Figure 37.

Poisson's Ratio

Poisson's ratio was determined from the slope of the line generated from the plot of longitudinal strain versus transverse strain for CTX-1, heat treatment A. Four measurements were made for each test condition and the average slope used to determine Poisson's ratio. For the elevated-temperature values, the strain measurements were adjusted to compensate for thermal expansion. The results of the tests are shown in Table 31 and Figure 57. The anisotropy of CTX-1 bar, heat treatment A, displayed by mechanical properties, was very pronounced for Poisson's ratio as evidenced by the large difference between the long transverse and short transverse values.

Thermal Expansion

The thermal expansion curves for the Incoloy 903 are shown in Figure 58 and for CTX-1 in Figure 59.

Figure 58 illustrates a significant change in slope of the expansion curve for Incoloy 903 at approximately 672 K (750 F). This could be a result of a magnetic transformation since the alloys exhibit Curie temperature behavior. Transformation effects for this alloy were also observed in the thermal diffusivity measurements, reported later, and in a brief thermal analysis study by differential scanning calorimeter. In both cases, the transformation was again indicated to occur near 672 K (750 F). The expansion curve for CTX-1, Figure 59, is very similar to that for Incoloy 903, except that the transformation occurs near 722 K (840 F). Again, the transformation was confirmed by thermal diffusivity data, as reported later. Both alloys exhibited low thermal expansion characteristics.

Coefficients of linear expansion for the two alloys may be computed directly for any temperature range within that investigated, simply by reading appropriate values from the curves and performing the calculation.

Thermal Conductivity

For the low temperature range, 20 K (-423 F) to 300 K (80 F), thermal conductivity test results for the two alloys are shown in Tables 32 and 33 and graphically in Figure 60.

Results of thermal diffusivity measurements over the temperature range 300 K (80 F) - 1033 K (1400 F) are presented in Tables 34 and 35, in the order measured. Figures 61 and 62 are plots of the diffusivity data for Incoloy 903 and CTX-1, respectively. The curves were fitted visually. The transformations indicated by the thermal expansion curves are again evident here; the curves through these regions are dashed to indicate obvious uncertainties.

The similarities in their thermal expansion and thermal diffusivity characteristics, suggest that the specific heats of the two alloys, needed to calculate conductivity from the above measurement data, are also similar, and that reliable data for either one can be used for both in the calculation. The only specific heat data[2] found for either alloy were those reported for Incoloy 903 by Huntington Alloy Products Division of The International Nickel Company. However, these data were calculated from chemical composition and it is believed that these data are not reliable because they do not show the transformation effects observed in test measurements. The calculated specific heat data indicate a linear relationship with temperature; this is very unlikely.

As a further check, a cursory differential scanning calorimetry run was made on a sample of the Incoloy 903. This run showed a definite thermal excursion at near 672 K (750 F), confirming again that transformation occurs, and that the specific heat of the alloy undergoes an excursion in this range.

For these reasons, and because the task scope did not allow for accurate determinations of specific heat, accurate thermal conductivity values could not be presented for this temperature range. When accurate specific heat data are available, these measurements can be applied to diffusivity and density data in this report to derive thermal conductivities above room temperature.

Density

Based on measurements of five specimens, the average density of heat treated Incoloy 903 was 8.059 Mg/m^3 (0.291 $lb/in.^3$). Maximum deviations from this value among the five specimens were ± 0.18 percent.

Based on measurements of three specimens, the average density of CTX-1, heat treatment A, was 8.101 Mg/m^3 (0.293 $lb/in.^3$). The deviations from the average were +0.46 and -0.06 percent.

LITERATURE AND INDUSTRIAL SURVEY

The files of Metals and Ceramics Information Center at Battelle's Columbus Laboratories were searched for additional information on Incoloy 903 and CTX-1. This search was unproductive. Mechanical property data were solicited from the two material suppliers. Incoloy 903 data from Huntington Alloys are contained in the technical bulletin in Appendix B. Data from Carpenter Steel Division on CTX-1 are included in Appendix B. Thermal conductivity data for Incoloy 903 were supplied by Rocketdyne Division of Rockwell International and are also contained in Appendix B. Very little information was available for these two alloys in the open literature.

An industrial survey was made in an effort to obtain the latest information on these two alloys. In addition to the two material suppliers, three companies currently using or testing these two materials were contacted by telephone. Most of the developmental data or information which had been obtained by the user companies, as well as specific applications, were considered proprietary and requests to obtain these data were unsuccessful. However, general comments received from these contacts are summarized below.

Hot Workability. These alloys can be hot worked like many of the Fe-Ni-base superalloys. Forgeability is good. The alloys are normally hot worked from 1311 K (1900 F) and finish forged or rolled (warm worked) slightly below 1144 K (1600 F). A reduction of 25 - 30 percent at temperatures below 1144 K (1600 F) is required to provide good elevated temperature ductility and creep-rupture properties. For recrystallized material, thermomechanical working below 1144 K (1600 F) is not required.

Heat Treatment. Two different solution treatment temperatures are being used for these alloys. For maximum elevated temperature ductility and good creep-rupture properties, a solution treatment temperature of 1116 - 1444 K (1550 - 1600 F) followed by air cool is used. Precipitation hardening consists of 991 K (1325 F) for 8 hours, furnace cool at 311 K (100 F) per hour to 894 K (1150 F) for 8 hours and air cool. For room temperature, moderate short time elevated temperature, and low temperature applications, a 1200 - 1228 K (1700 - 1750 F) solution treatment temperature is used followed by the same precipitation hardening treatment. For brazed assemblies, higher solution temperatures are used. Solution treating temperatures above 1144 K (1600 F) produce a recrystallized microstructure. The microstructure and resulting mechanical properties are greatly dependent upon thermomechanical processing. Final deformation or heat treatment at temperatures above 1144 K (1600 F) results in elevated temperature notch sensitivity and poor rupture ductility.

Rocketdyne Division, Rockwell International, has discovered that the alloys are very susceptible to oxygen penetration at the grain boundaries during solution heat treatment in air. This contamination extends to a depth of 2 to 3 mm and causes some loss in ductility and formability. In order to prevent this contamination, solution treatment should be performed in hydrogen, argon, or vacuum or affected surface layer removed after heat treatment.

Corrosion Resistance. Because the alloys do not contain chromium, the corrosion and oxidation resistance is inferior to many of the Fe-Ni-Cr superalloys. Under high humidity conditions, the alloys form a red oxide at room temperature. The alloys have poor oxidation resistance, inferior to 400 series stainless steel as determined by one investigator. For extended elevated temperature exposure in air, the consensus was that coatings would be required for protection.

<u>Surface Treatments</u>. Several coatings have been investigated for the protection of these alloys from corrosion and oxidation. Electrolytic chromium was found to provide good protection but the process has limited throwing power. Diffused pack aluminide coatings have been tested and have provided adequate protection. However, these coatings require further evaluation to determine whether they cause a loss in rupture ductility.

<u>Formability</u>. Rocketdyne has encountered some cracking problems in forming Incoloy 903 sheet in annealed (solution treated) condition. It was found that the formability had been impaired by oxygen contamination during solution heat treatment. The problem was overcome by abrasive belt grinding to remove the contaminated surface layer prior to forming.

<u>Machineability</u>. The machineability of the alloys is similar to Inco 718.

<u>Weldability</u>. According to Rocketdyne, in general, the weldability of Incoloy 903 is similar to Incoloy 718. Since the alloy is very susceptible to oxygen contamination, good shielding is the utmost in importance. (Also, surfaces to be welded must be free from oxygen contamination from heat treatment.) They have been very successful in automatic welding at 15 - 30 cm (6 - 8 inches) per minute using Incoloy 903 filler wire. Specifically, their procedure is to weld without preheat using stringer bead technique. The weld is ground after each pass; this operation is very important. Cleaning with acetone is performed after each grinding pass. Stress relief is not required after welding. Rocketdyne is welding some assemblies in the fully heat treated condition and has experienced no cracking problems using the above procedure.

The welding of nonrecrystallized material is of some concern to other investigators since areas of the heat affected zone would recrystallize and would be expected to be notch sensitive at elevated temperatures.

<u>Specifications</u>. There are no public specifications for these alloys.

<u>Applications</u>. These alloys are being used in the space shuttle main engines (SSME) for transition rings, turbine inlet housing support strut

ring (turbopump), heat exchanger liner, and hot gas manifold liner(1). These alloys are being used in the SSME because of their unique combiration of properties, which include low thermal expansion, low elastic modulus, high strength, and resistance to embrittlement from high-pressure gaseous hydrogen. The alloys are also being evaluated for use in advanced aircraft gas turbine engines. Because of their low, nearly constant thermal expansion, the alloys are being evaluated for compressor cases to provide blade tip seal clearance control. The alloys are also being considered for other gas turbine engine applications.

CONCLUSIONS

(1) For the single heats tested, the CTX-1 bar had similar yield and ultimate strengths for both heat treat conditions (nonrecrystallized and recrystallized) while Incoloy 903 sheet in heat treated (recrystallized) condition exhibited somewhat higher yield and ultimate strengths. Both alloys maintained their strength very well through 922 K (1200 F). CTX-1 bar in the recrystallized, heat treated condition had slightly higher elongation and reduction of area at room and low temperatures but exhibited a decrease in these properties at 811 K (1000 F) with minimum ductility at 922 K (1200 F) while the nonrecrystallized heat treatment showed increasing elongation and reduction of area at 922 K (1200 F) and 1033 K (1400 F). Elongation values did not decrease at low temperatures although reduction of area values for CTX-1 bar declined at low temperatures. Tensile modulus of elasticity was nearly constant from 20 K (-423 F) through 922 K (1200 F) for both alloys.

(2) The effect of temperature on the notched tensile strength, $K_t = 8$ for Incoloy 903 and $K_t = 5$ for CTX-1, was, in general, similar to the effect on tensile ultimate strength. The notched/unnotched tensile strength ratio was higher for heat treated than annealed Incoloy 903. The notched tensile strength of recrystallized CTX-1 bar was inferior to nonrecrystallized material at 922 K (1200 F). The notched/unnotched tensile strength ratio of recrystallized CTX-1 was very low at 922 K (1200 F).

(3) The compressive yield strengths were higher than the tensile yield strengths. Compressive modulus of elasticity was nearly constant from 20 K (-423 F) through 922 K (1200 F). Tensile and compressive modulus of elasticity values were similar for CTX-1 bar.

(4) The Charpy V-notch impact values of recrystallized CTX-1 bar were significantly higher than the nonrecrystallized material over the entire temperature range. The impact values increased gradually with increasing temperature with a large increase at 1033 K (1400 F). The notch sensitivity of the recrystallized material at elevated temperatures was not manifested by the Charpy V-notch impact test.

(5) Heat treated (recrystallized) Incoloy 903 sheet exhibited good fracture toughness at room temperature with $K_{app} = 188$ MPa$\sqrt{m}$ (171 ksi$\sqrt{in.}$). Heat treated (nonrecrystallized) CTX-1 bar had a K_{Ic} value of 58 MPa$\sqrt{m}$ (53 ksi$\sqrt{in.}$) at room temperature for T-L direction and this value did not decrease at low temperatures.

(6) As expected, annealed (recrystallized) Incoloy 903 sheet displayed very erratic creep behavior with some specimens showing poor ductility. Heat treated (recrystallized) Incoloy 903 showed poor creep ductility at 811 K (1000 F) and 922 K (1200 F). Heat treated (nonrecrystallized) CTX-1 bar displayed very good creep and rupture properties with good ductility. Heat treated (recrystallized) CTX-1 bar exhibited extreme notch sensitivity at 811 K (1000 F) and 922 K (1200 F) as evidenced by thread failures.

(7) The room temperature unnotched fatigue strengths of CTX-1, in both non-recrystallized and recrystallized heat treatments, and heat treated (recrystallized) Incoloy 903 were similar. At 922 K (1200 F) the unnotched fatigue properties of nonrecrystallized CTX-1 and heat treated (recrystallized) Incoloy 903 were similar while recrystallized CTX-1 was inferior. There was no significant difference in the room temperature notched ($K_t = 3$) fatigue strength of CTX-1 bar in both heat treat conditions while heat treated (recrystallized) Incoloy 903 sheet was slightly superior. At 922 K (1200 F) the notched ($K_t = 3$) fatigue strength of nonrecrystallized CTX-1 was superior to recrystallized CTX-1 and Incoloy 903. Unnotched annealed Incoloy 903 sheet had significantly lower fatigue strength than heat treated sheet but there was little difference in the notched ($K_t = 3$) fatigue strength of annealed and heat treated conditions.

(8) Poisson's ratio for CTX-1 bar in nonrecrystallized condition varied greatly with grain direction.

(9) Both materials were anistropic. Anistropy was somewhat reduced by the recrystallization heat treatment as evidenced by the tensile properties of CTX-1.

(10) Heat treated and welded Incoloy 903 sheet had yield and ultimate strengths slightly lower than annealed strengths. The elongation of welded specimens was greatly reduced compared to either annealed or heat treated values. Weld ductility at 20 K (-423 F) was very low. Welded notched/unnotched tensile strength ratios were about the same as annealed ratios and lower than heat treated ratios. The net section fracture strength of heat treated and welded fracture toughness specimens exceeded the tensile yield strength indicative of excellent toughness. Unnotched, welded fatigue strengths were significantly lower than unnotched annealed fatigue strengths while the notched, welded fatigue strength was similar to the annealed fatigue strength.

(11) Unstressed exposure of annealed as well as heat treated and welded Incoloy 903 at 922 K (1200 F) for 10 hours in air caused precipitation hardening with an attendant increase in tensile strength and decrease in ductility. The fracture toughness of exposed, heat treated, and welded Incoloy 903 was slightly higher than for heat treated sheet commensurate with the lower yield strength of the exposed welded specimens. Except for a slight reduction in tensile strengths (due to overaging), unstressed exposure had no deleterious effect upon heat treated Incoloy 903 and CTX-1 in both heat treat conditions.

(12) Incoloy 903 and CTX-1 have low, nearly constant thermal expansion from 20 K (-423 F) through 922 K (1200 F). Thermal expansion characteristics for the two alloys were similar.

(13) Thermal conductivity over the range, 300 K (80 F) - 1033 K (1400 F), was not computed from thermal diffusivity and density measurements because published specific heat data are believed to be unreliable.

(14) The densities were for Incoloy 903, 8.059 Mg/m^3 (0.291 $lb/in.^3$), and for CTX-1, 8.101 Mg/m^3 (0.293 $lb/in.^3$).

RECOMMENDATIONS

(1) The engineering properties of Incoloy 903 should be determined in the nonrecrystallized heat treated condition.

(2) Weld properties of Incoloy 903 should be evaluated in the annealed, welded, solution heat treated, and aged (recrystallized) condition as well as the solution (recrystallized), welded and aged condition. The weld properties of CTX-1 bar should also be evaluated.

(3) The fracture toughness of nonrecrystallized CTX-1 bar in the L-T grain direction should be determined at room and low temperatures. Also, the fracture toughness of recrystallized CTX-1 bar in the T-L and L-T grain directions should be determined at room and low temperatures.

(4) Since the published specific heat data for Incoloy 903 is believed to be unreliable, specific heat measurements should be made on Incoloy 903 and CTX-1 bar.

TABLE 1. CHEMICAL COMPOSITION OF INCOLOY 903 AND CTX-1

Element	Incoloy 903 Heat HH21A2UK	CTX-1 Heat 88893
Nickel	37.89	37.77
Cobalt	15.15	15.96
Aluminum	0.66	0.97
Titanium	1.54	1.78
Columbium Plus Tantalum	3.00	3.05
Silicon	0.28	0.10
Phosphorus	--	0.002
Sulfur	0.004	0.003
Manganese	0.16	0.04
Chromium	--	0.09
Carbon	0.02	0.021
Molybdenum	--	0.13
Copper	--	0.19
Boron	--	0.007
Iron	41.28	39.86

TABLE 2. TEST PLAN FOR INCOLOY 903 SHEET

Property	Test Temperature 20K -423F	77K -321F	RT RT	811K 1000F	922K 1200F	1033K 1400F	Specimens per Heat-Treat Condition	Number of Heat-Treat Conditions	Total Specimens
Tension (L)			3				3	2	6
Tension (LT)	3	3	3	3	3	3	18	2	36
Notched Tension (L)			3				3	2	6
Notched Tension (LT)	3	3	3	3	3	3	18	2	36
Compression (L)			3				3	2	6
Compression (LT)	3	3	3	3	3	3	13	2	36
Exposure (922K for 10 hours)									
Tension (LT)	3		3		3		9	2	18
Notched Tension (LT)	3		3		3		9	2	18
Weldments									
Tension (LT)	3		3		3		9	1	9
Notched Tension (LT)	3		3		3		9	1	9
Exposed Notched Tension (LT)	3		3		3		9	1	9
Fracture Toughness, K_c									
Unexposed (LT)			3				3	1	3
Exposed (LT)			3				3	1	3
Weld Unexposed (LT)			3				3	1	3
Weld Exposed (LT)			3				3	1	3
Creep and Stress Rupture (LT)				5	5	5	15	2	30
Fatigue (LT)									
Unnotched			8		8		16	2	32
Notched			8		8		16	2	32
Weld Unnotched			4		4		8	1	8
Weld Notched			4		4		8	1	8
Density			3				3	1	3
Thermal Conductivity	←		1			→	1	1	1
Thermal Expansion	←		1			→	1	1	1

TABLE 3. TEST PLAN FOR CTX-1 BAR

Property	Test Temperature 20K -423F	77K -321F	RT RT	811K 1000F	922K 1200F	1033K 1400F	Specimens per Heat-Treat Condition	Number of Heat-Treat Conditions	Total Specimens
Tension (T)			3				3	2	6
Tension (L)	3	3	3	3	3	3	18	2	36
Poisson's Ratio			1	1	1	1	4	1	4
Notched Tension (L)	3		3		3		9	2	18
Compression (T)			3				3	2	6
Compression (L)	3		3		3		9	2	18
Impact (L)			3				3	2	6
Impact (T)	3	3	3	3	3	3	18	2	36
Exposure (922K for 10 hours)									
Tension (L)	3		3		3		9	2	18
Notched Tension (L)	3		3		3		9	2	18
Impact (T)	3		3				6	2	12
Fracture Toughness, K_{Ic}									
Unexposed (L)	3	3	3				9	1	9
Exposed (L)	3		3				6	1	6
Creep and Stress-Rupture (L)				5	5	5	15	2	30
Fatigue (L)									
Unnotched			8		8		16	2	32
Notched			8		8		16	2	32
Density			3				1	1	3
Thermal Conductivity	←	←	1	→	→	→	1	1	1
Thermal Expansion	←	←	1	→	→	→	1	1	1

TABLE 4. TENSILE AND NOTCHED TENSILE PROPERTIES OF ANNEALED INCOLOY 903 SHEET AT VARIOUS TEMPERATURES INCLUDING PRIOR EXPOSURE

Temperature K	Temperature F	Prior Exposure	Grain Direction	Specimen Identification	Yield Strength (0.2% Offset) MPa	Yield Strength (0.2% Offset) Ksi	Ultimate Strength MPa	Ultimate Strength Ksi	Elongation in 5.08 cm (2 in.), percent	Modulus of Elasticity GPa	Modulus of Elasticity Ksi x 10^3	Specimen Identification	Notch Strength K_t = 8.0 MPa	Notch Strength K_t = 8.0 Ksi	Notched/Unnotched Ratio
RT	RT	None	L	1-1L	507	73.5	849.4	123.2	31.0	147	21.4	1-1LN	(a)	(a)	
				1-2L	503	73.0	848.1	123.0	30.5	149	21.6	1-2LN	754	109.3	
				1-3L	503	72.9	850.1	123.3	33.0	149	21.6	1-3LN	760	110.2	
				Average	504	73.1	849.2	123.2	31.5	148	21.5	Average	757	109.8	0.89
		None	LT	1-7T	603	87.4	881.8	127.9	32.0	170	24.6	1-7TN	812	117.8	
				1-8T	590	85.6	877.0	127.2	31.5	178	25.9	1-8TN	806	116.9	
				1-9T	593	86.0	878.4	127.4	28.0	170	24.6	1-9TN	816	118.4	
				Average	595	86.3	879.1	127.5	30.5	173	25.0	Average	811	117.7	0.92
		922.0 K (1200 F) for 10 hours	LT	1-22T	1185	171.9	1435	208.1	13.0	188	27.3	1-22TN	1373	199.1	
				1-23T	1189	172.4	1431	207.5	13.5	(b)	(b)	1-23TN	1349	195.6	
				1-24T	1180	171.2	1433	[illegible]	13.0	156	22.6	1-24TN	1367	198.3	
				Average	1185	171.8	1433	207.8	13.2	172	25.0	Average	1363	197.7	0.95
20	-423	None	LT	1-1T	871.5	126.4	1324	192.1	29.0	207	30.0	1-1TN	1160	168.2	
				1-2T	871.5	126.4	1324	192.1	34.0	(b)	(b)	1-2TN	1141	165.5	
				1-3T	863.9	125.3	1320	191.4	28.5(c)	184	26.7	1-3TN	1142	165.6	
				Average	869.0	126.0	1323	191.9	30.5	195	28.3	Average	1148	166.4	0.87
		922.0 K (1200 F) for 10 hours	LT	1-19T	1440	208.8	1917	277.5	20.5	179	26.0	1-19TN	1631	236.5	
				1-20T	1440	208.8	1916	277.9	14.0(d)	193	28.0	1-20TN	1622	235.2	
				1-21T	1431	207.6	1905	276.3	20.5(e)	190	27.5	1-21TN	1609	233.4	
				Average	1437	208.4	1911	277.2	18.3	187	27.2	Average	1621	235.0	0.85
77	-321	None	LT	1-4T	794.3	115.2	1220	177.0	40.0	203	29.5	1-4TN	1056	153.1	
				1-5T	795.6	115.4	1220	176.9	38.5	216	31.3	1-5TN	1061	153.9	
				1-6T	786.6	114.1	1220	176.9	38.0	215	31.2	1-6TN	1019	147.8	
				Average	792.2	114.9	1220	176.9	38.8	211	30.7	Average	1045	151.6	0.86
811	1000	None	LT	1-10T	520	75.4	819.1	118.8	32.0	185	26.9	1-10TN	676	98.1	
				1-11T	525	76.1	839.8	121.8	32.0	192	27.9	1-11TN	687	99.6	
				1-12T	515	74.7	825.3	119.7	33.0	190	27.6	1-12TN	695.7	100.9	
				Average	520	75.4	828.1	120.1	32.3	189	27.5	Average	686	99.5	0.83
922	1200	None	LT	1-13T	744.6	108.0	859.8	124.7	16.0	180	26.1	1-13TN	817.7	118.6	
				1-14T	748.1	108.5	868.0	125.9	23.0	177	25.7	1-14TN	841.2	122.0	
				1-15T	751.5	109.0	864.6	125.4	17.0	178	25.9	1-15TN	859.8	124.7	
				Average	748.1	108.3	864.1	125.3	18.7	178	25.9	Average	839.7	121.8	0.97
		922.0 K (1200 F) for 10 hours	LT	1-25T	903.9	131.1	980.4	142.2	8.0	178	25.8	1-25TN	912.9	132.4	
				1-26T	917.7	133.1	974.9	141.4	6.0	177	25.7	1-26TN	969.4	140.6	
				1-27T	901.1	130.7	968.7	140.5	6.0	178	25.8	1-27TN	907.3	131.6	
				Average	907.5	131.6	974.6	141.4	6.7	178	25.8	Average	929.9	134.9	0.95
1033	1400	None	LT	1-16T	523	75.8	534	77.4	18.0	130	18.9	1-16TN	625	90.7	
				1-17T	489	70.9	489	70.9	12.0	133	19.3	1-17TN	614	89.0	
				1-18T	537	77.9	540	78.4	14.0	134	19.4	1-18TN	637	92.4	
				Average	516	74.9	521	75.6	14.7	132	19.2	Average	625	90.7	1.20

(a) Specimen lost.
(b) Load-strain curve not suitable for modulus determination.
(c) Failed outside gage marks.
(d) Portion of fracture may have been missing.
(e) Specimen fractured in two places.

TABLE 5. TENSILE AND NOTCHED TENSILE PROPERTIES OF HEAT TREATED INCOLOY 903 SHEET AT VARIOUS TEMPERATURES INCLUDING PRIOR EXPOSURE

Temperature K	Temperature F	Prior Exposure	Grain Direction	Specimen Identification	Yield Strength (0.2% Offset) MPa	Yield Strength (0.2% Offset) Ksi	Ultimate Strength MPa	Ultimate Strength Ksi	Elongation in 5.08 cm (2 in.), percent	Modulus of Elasticity GPa	Modulus of Elasticity Ksi x 10³	Specimen Identification	Notch Strength K_t = 8 MPa	Notch Strength K_t = 8 Ksi	Notched/Unnotched Ratio
RT	RT	None	L	1-4LH	1189	172.5	1433	207.8	12.0	153	22.2	1-4LNH	1451	210.5	
				1-5LH	1190	172.7	1440	208.9	13.0	157	22.8	1-5LNH	1446	209.8	
				1-6LH	1180	171.1	1435	208.2	13.0	154	22.3	1-6LNH	1466	212.7	
				Avg. (Sht. 1)	1186	172.1	1436	208.3	12.7	155	22.4	Average	1454	211.0	1.01
				2-1LH	1251	181.4	1486	215.6	12.0	165	24.0				
				2-2LH	1275	185.0	1504	218.1	11.5	165	24.0				
				Avg. (Sht. 2)	1263	183.2	1495	216.8	11.7	165	24.0				
				3-1LH	1275	184.9	1502	217.9	12.0	162	23.5				
				3-2LH	1298	188.3	1515	219.8	11.0	163	23.6				
				Avg. (Sht. 3)	1286	186.6	1508	218.8	11.5	162.5	23.5				
			LT	1-34TH	1289	187.0	1459	211.6	12.5	176	25.5	1-34TNH	1431	207.6	
				1-35TH	1288	186.8	1457	211.4	13.0	178	25.9	1-35TNH	1473	213.6	
				1-36TH	1283	186.1	1459	211.6	13.0	178	25.8	1-36TNH	1445	209.6	
				Average	1287	186.6	1458	211.5	12.8	177	25.7	Average	1450	210.3	0.99
		922 K (1200 F) for 10 hours	LT	1-49TH	1222	177.2	1427	207.0	14.5	178	25.8	1-49TNH	1405	203.8	
				1-50TH	1224	177.6	1388	201.3	14.0	(a)	(a)	1-50TNH	1384	200.8	
				1-51TH	1261	182.9	1384	200.7	13.0	191	27.7	1-51TNH	1412	204.8	
				Average	1236	179.2	1400	203.0	13.8	184	26.7	Average	1400	203.1	1.00
20	-423	None	LT	1-28TH	1575	228.5	1962	284.6	13.0	195	28.3	1-28TNH	1701	246.7	
				1-29TH	1593	231.0	1979	287.1	13.0	195	28.3	1-29TNH	1736	251.8	
				1-30TH	1593	231.1	2002	290.4	16.5	187	27.2	1-30TNH	1644	238.4	
				Average	1587	230.2	1981	287.4	14.2	192	28.0	Average	1697	245.6	0.85
		922 K (1200 F) for 10 hours	LT	1-46TH	1480	214.7	1890	274.2	18.5	181	26.2	1-46TNH	1632	236.7	
				1-47TH	1493	216.5	1893	274.5	16.0	176	25.6	1-47TNH	1649	239.[illegible]	
				1-48TH	1500	217.6	1891	274.3	16.0	177	25.7	1-48TNH	1644	238.4	
				Average	1491	216.3	1891	274.3	16.8	178	25.8	Average	1642	238.1	0.87
77	-321	None	LT	1-31TH	1505	218.3	1829	265.3	18.5	194	23.2	1-31TNH	1678	243.4	
				1-32TH	1512	219.2	1837	266.5	19.0	184	26.7	1-32TNH	1687	244.7	
				1-33TH	1511	219.1	1834	266.0	18.5	187	27.2	1-33TNH	1673	242.6	
				Average	1509	218.9	1833	265.9	18.7	188	27.4	Average	1679	243.6	0.92
811	1000	None	LT	1-37TH	1083	157.1	1262	183.0	11.0	181	26.3	1-37TNH	1537	223.0	
				1-38TH	1075	156.0	1262	183.0	10.0	192	27.9	1-38TNH	1634	237.0	
				1-39TH	1077	156.2	1266	183.6	16.0	179	26.0	1-39TNH	1558	226.0	
				Average	1078	156.4	1263	183.2	12.3	184	26.7	Average	1576	228.7	1.25
922	1200	None	LT	1-40TH	942.5	136.7	964.6	139.9	10.0	161	23.4	1-40TNH	1004	145.7	
				1-41TH	950.1	137.8	969.4	140.6	11.0	162	23.5	1-41TNH	1007	146.0	
				1-42TH	931.5	135.1	931.5	137.2	10.0	161	23.4	1-42TNH	1027	149.0	
				Average	941.4	136.5	955.1	139.2	10.3	161	23.4	Average	1013	146.9	1.05
		922.0 K (1200 F) for 10 hours	LT	1-52TH	927.3	134.5	948.7	137.6	10.0	153	22.2	1-52TNH	963.2	139.7	
				1-53TH	930.8	135.0	952.9	138.2	10.0	161	23.3	1-53TNH	989.4	143.5	
				1-54TH	915.6	132.8	948.0	137.5	8.0	154	22.4	1-54TNH	1001	145.2	
				Average	924.6	134.1	949.9	137.8	9.3	156	22.6	Average	984.5	142.8	1.04
1033	1400	None	LT	1-43TH	478	69.4	503	72.9	18.0	104	15.1	1-43TNH	539	78.2	
				1-44TH	470	68.2	516	74.8	16.0	121	17.6	1-44TNH	589	85.4	
				1-45TH	472	68.5	480	69.6	14.0	103	14.9	1-45TNH	586	85.0	
				Average	473	68.7	500	72.4	16.0	109	15.9	Average	571	82.9	1.15

(a) Load-strain curve not suitable for modulus determination.

TABLE 6. TENSILE AND NOTCHED TENSILE PROPERTIES OF CTX-1 BAR, HEAT TREATMENT A, AT VARIOUS TEMPERATURES INCLUDING PRIOR EXPOSURE

Temperature K	Temperature F	Prior Exposure	Grain Direction	Specimen Identification	Yield Strength (0.2% Offset) MPa	Yield Strength (0.2% Offset) Ksi	Ultimate Strength MPa	Ultimate Strength Ksi	Elongation in 2.54 cm (1 in.), percent	Reduction in Area, percent	Modulus of Elasticity GPa	Modulus of Elasticity Ksi x 10^3	Specimen Identification	Notch Strength $K_t = 5$ MPa	Notch Strength $K_t = 5$ Ksi	Notched/Unnotched Ratio
	RT	None	LT	4-1TA	1200	174.0	1391	201.7	14.0	30.4	159	23.1				
				4-2TA	1196	173.5	1397	202.6	12.0	31.4	156	22.7				
				4-3TA	1177	170.7	1375	199.5	12.5	33.1	157	22.8				
				Average	1191	172.7	1374	201.3	12.8	31.6	157	22.9				
			L	4-7LA	1140	165.4	1365	198.0	16.0	45.8	152	22.1	4-4LNA	1652	239.6	
				4-8LA	1140	165.3	1349	195.6	16.0	47.4	149	21.6	4-5LNA	1664	241.3	
				4-9LA	1142	165.6	1364	197.9	16.0	43.4	154	22.3	4-6LNA	1646	238.8	
				Average	1141	165.4	1359	197.2	16.0	45.5	152	22.0	Average	1654	239.9	1.22
		922 K (1200 F) for 10 hours	L	4-22LA	1106	160.4	1307	189.6	17.0	45.5	155	22.5	4-13LNA	1610	233.6	
				4-23LA	1120	162.4	1350	195.8	16.0	43.4	159	23.0	4-14LNA	1575	228.4	
				4-24LA	1105	160.3	1322	191.7	17.0	47.2	156	22.6	4-15LNA	1575	238.5	
				Average	1110	161.0	1326	192.4	16.7	45.4	157	22.7	Average	1587	233.5	1.21
20	-423	None	L	4-1LA	1458	211.5	1896	275.1	18.0	16.2	148	21.5	4-1LNA	1926	279.3	
				4-2LA	1477	214.2	1914	277.6	13.0	19.1	150	21.8	4-2LNA	1935	280.7	
				4-3LA	1472	213.5	1935	280.7	19.0	17.0	143	20.8	4-3LNA	1917	278.0	
				Average	1469	213.1	1882	277.8	16.7	17.4	147	21.4	Average	1926	279.3	1.01
		922 K (1200 F) for 10 hours	L	4-19LA	1422	206.2	1824	264.6	21.0	17.7	130	18.8	4-10LNA	1993	289.1	
				4-20LA	1413	205.0	1822	264.2	19.0	25.1	132	19.1	4-11LNA	1890	274.2	
				4-21LA	1373	199.1	1766	256.1	21.5	22.0	126	18.3	4-12LNA	1909	276.9	
				Average	1403	203.4	1804	261.6	20.5	21.6	129	18.7	Average	1931	280.1	1.07
77	-321	None	L	4-4LA	1349	195.6	1705	247.3	20.0	28.1	155	22.5				
				4-5LA	1387	201.2	1762	255.6	22.0	30.1	148	21.5				
				4-6LA	1295	187.9	1662	241.0	19.0	24.8	158	22.9				
				Average	1344	194.9	1710	248.0	20.3	27.7	154	22.3				
811	1000	None	L	4-10LA	955.6	138.6	1175	170.4	17.0	38.0	187	27.1				
				4-11LA	990.8	143.7	1192	172.9	17.0	38.2	174	25.3				
				4-12LA	977.0	141.7	1190	172.6	16.0	40.9	161	23.4				
				Average	974.5	141.3	1186	172.0	16.7	39.0	174	25.3				
922	1200	None	L	4-13LA	904.5	131.2	977.0	141.7	26.0	62.3	162	23.5	4-7LNA	1215	176.3	
				4-14LA	882.5	128.0	952.2	138.1	25.0	55.9	170	24.6	4-8LNA	1202	174.3	
				4-15LA	881.8	127.9	959.7	139.2	25.0	48.4	162	23.5	4-9LNA	1208	175.2	
				Average	889.6	129.0	963.0	139.7	25.3	55.5	165	23.9	Average	1208	175.3	1.25
		922 K (1200 F) for 10 hours	L	4-25LA	894.9	129.8	961.8	139.5	30.0	45.8	159	23.1	4-16LNA	1101	159.7	
				4-26LA	860.5	124.8	903.9	131.1	21.0	54.8	157	22.4	4-17LNA	1107	160.6	
				4-27LA	853.6	123.8	926.7	134.4	24.0	47.6	158	[illegible]	4-18LNA	1196	173.5	
				Average	869.7	126.1	9308	135.0	25.0	49.4	158	22.9	Average	1134	164.6	1.22
1033	1400	None	L	4-16LA	550	79.8	574	83.3	28.0	65.7	130	18.9				
				4-17LA	574	83.3	556	80.7	33.0	62.9	127	18.5				
				4-18LA	540	78.4	540	78.4	32.0	68.5	132	19.1				
				Average	555	80.5	557	80.8	31.0	65.7	130	18.8				

TABLE 7. TENSILE AND NOTCHED TENSILE PROPERTIES OF CTX-1 BAR, HEAT TREATMENT B, AT VARIOUS TEMPERATURES INCLUDING PRIOR EXPOSURE

Temperature		Prior Exposure	Grain Direction	Specimen Identification	Yield Strength (0.2% Offset)		Ultimate Strength		Elongation in 2.54 cm (1 in.), percent	Reduction in Area, percent	Modulus of Elasticity		Specimen Identification	Notch Strength $K_t = 5$		Notched/ Unnotched Ratio
K	F				MPa	Ksi	MPa	Ksi			GPa	Ksi x 10^3		MPa	Ksi	
RT	RT	None	LT	4-1TB	1157	167.8	1400	203.1	17.0	41.0	153	22.2				
				4-2TB	1153	167.2	1398	202.8	16.0	40.6	152	22.0				
				4-3TB	1153	167.2	1396	202.5	16.0	41.8	162	23.5				
				Average	1154	167.4	1398	202.8	16.3	41.1	156	22.6				
			L	4-7LB	1141	165.5	1402	203.3	18.0	48.6	148	21.4	4-4LNB	1709	247.9	
				4-8LB	1111	161.1	1371	198.9	19.0	51.1	145	21.1	4-5LNB	1728	250.6	
				4-9LB	1131	164.0	1395	202.3	18.0	50.0	149	21.6	4-6LNB	1770	256.8	
				Average	1128	163.5	1389	201.5	18.3	49.9	144	21.4	Average	1739	251.8	1.25
		922 K (1200 F) for 10 hours	L	4-22LB	1088	157.8	1366	198.1	20.0	51.9	156	22.7	4-13LNB	1737	252.0	
				4-23LB	1086	157.5	1368	198.4	20.0	49.0	158	22.9	4-14LNB	1706	247.4	
				4-24LB	1099	159.4	1372	199.0	21.0	50.5	163	23.6	4-15LNB	1715	249.8	
				Average	1091	158.2	1369	198.5	20.3	50.5	159	23.1	Average	1719	249.7	1.26
20	-423	None	L	4-1LB	1362	197.6	1932	280.2	24.0	25.4	127	18.4	4-1LNB	1964	284.9	
				4-2LB	1365	198.0	1946	282.3	25.0	27.0	134	19.5	4-2LNB	1974	286.3	
				4-3LB	1371	198.8	1940	281.4	25.0	25.3	145	21.1	4-3LNB	1993	289.0	
				Average	13[illegible]	198.1	1939	281.3	24.7	25.9	135	19.7	Average	1977	286.7	1.02
		922 K (1200 F) for 10 hours	L	4-19LB	1289	187.0	1857	269.3	24.0	25.5	[illegible]	20.0	4-10LNB	1926	279.3	
				4-20LB	1306	189.4	1884	273.3	24.0	29.7	137	19.9	4-11LNB	1955	283.5	
				4-21LB	1259	184.0	1886	273.5	22.5	25.6	148	21.4	4-12LNB	1945	282.1	
				Average	1288	186.8	1876	272.0	23.5	26.9	141	20.4	Average	1942	281.6	1.04
77	-321	None	L	4-4LB	1306	189.4	1784	258.7	23.0	36.3	159	23.1				
				4-5LB	1306	189.4	1767	256.3	25.0	35.2	156	22.7				
				4-6LB	1313	190.4	1797	260.7	23.0	33.9	163	23.7				
				Average	1308	189.7	1783	258.6	23.7	35.1	159	23.2				
811	1000	None	L	4-10LB	881.1	127.8	1190	172.6	17.0	30.2	185	26.8				
				4-11LB	886.0	128.5	1205	174.8	15.0	31.5	194	28.1				
				4-12LB	875.6	127.0	1190	172.6	15.0	33.3	205	29.7				
				Average	880.9	127.8	1198	173.3	15.7	31.7	195	28.2				
922	1200	None	L	4-13LB	818.4	118.7	961.1	139.4	4.0	8.3	182	26.4	4-7LNB	833.6	120.9	
				4-14LB	841.8	122.1	979.7	142.1	5.0	8.8	173	25.1	4-8LNB	894.2	129.7	
				4-15LB	815.0	118.2	947.3	137.4	3.0	5.6	168	24.4	4-9LNB	782.5	113.5	
				Average	825.1	119.7	962.7	139.6	4.0	7.6	174	25.3	Average	836.8	121.4	0.87
		922 K (1200 F) for 10 hours	L	4-25LB	833.6	120.9	964.6	139.9	3.0	8.1	160	23.2	4-16LNB	826.0	119.8	
				4-26LB	832.9	120.8	963.2	139.7	4.0	6.9	154	22.4	4-17LNB	786.0	114.0	
				4-27LB	812.2	117.8	946.6	137.3	4.0	10.9	154	22.4	4-18LNB	822.5	119.3	
				Average	826.2	119.8	958.1	139.0	3.7	8.6	156	22.7	Average	811.5	117.7	0.85
1033	1400	None	L	4-16LB	554	80.3	577	83.7	6.0	17.6	129	18.7				
				4-17LB	560	81.3	599	86.9	7.0	13.9	130	18.9				
				4-18LB	553	80.2	586	85.0	5.0	15.8	129	18.7				
				Average	556	80.6	587	85.2	6.0	15.8	129	18.8				

TABLE 8. COMPRESSIVE PROPERTIES OF ANNEALED INCOLOY 903 SHEET AT VARIOUS TEMPERATURES

Temperature		Grain Direction	Specimen Identification	Yield Strength (0.2% Offset)		Modulus of Elasticity	
K	F			MPa	Ksi	GPa	Ksi x 10^3
RT	RT	L	1-1L	563	81.7	172	25.0
			1-2L	554	80.3	172	24.9
			1-3L	559	81.1	172	25.0
			Avg.	558	81.0	172	25.0
		LT	1-7T	578	83.9	193	28.0
			1-8T	580	84.2	195	28.3
			1-9T	577	83.7	192	27.8
			Avg.	578	83.9	193	28.0
20	-423	LT	1-1T	881.1	127.8	(a)	(a)
			1-2T	(b)	(b)	(b)	(b)
			1-3T	867.4	125.8	(a)	(a)
			Avg.	874.7	126.8		
77	-321	LT	1-4T	783.2	113.6	194	28.1
			1-5T	794.3	115.2	196	28.4
			1-6T	823.2	119.4	205	29.7
			Avg.	800.6	116.1	198	28.4
811	1000	LT	1-10T	475	68.9	154	22.3
			1-11T	468	67.9	161	23.3
			1-12T	467	67.8	173	25.1
			Avg.	470	68.2	163	23.6
922	1200	LT	1-13T	757.7	109.9	183	26.5
			1-14T	787.4	114.2	(a)	(a)
			1-15T	719.8	104.4	184	26.7
			Avg.	755.0	109.5	183.5	26.6
1033	1400	LT	1-16T	526	76.3	117	17.0
			1-17T	549	79.7	109	15.8
			1-18T	543	78.8	113	16.4
			Avg.	539	78.3	113	16.4

(a) Load strain curve not suitable for modulus determination.

(b) Specimen inadvertently overloaded.

TABLE 9. COMPRESSIVE PROPERTIES OF HEAT TREATED INCOLOY 903 SHEET AT VARIOUS TEMPERATURES

Temperature K	Temperature F	Grain Direction	Specimen Identification	Yield Strength (0.2% Offset) MPa	Yield Strength (0.2% Offset) Ksi	Modulus of Elasticity GPa	Modulus of Elasticity Ksi x 10^3
RT	RT	L	1-4LH	1304	189.1	176	25.6
			1-5LH	1292	187.4	176	25.5
			1-6LH	1282	186.0	171	24.8
			Avg.	1293	187.5	174	25.3
		LT	1-25TH	1397	202.6	197	28.5
			1-26TH	1406	204.0	198	28.7
			1-27TH	1395	202.3	196	28.4
			Avg.	1399	203.0	197	28.5
20	-423	LT	1-19TH	1803	261.5	205	29.7
			1-20TH	1788	259.4	206	29.9
			1-21TH	1767	256.3	191	27.7
			Avg.	1786	259.1	201	29.1
77	-321	LT	1-22TH	1683	244.1	204	29.6
			1-23TH	1675	243.0	206	29.9
			1-24TH	1677	243.3	202	29.3
			Avg.	1678	243.1	204	29.6
811	1000	LT	1-28TH	1120	162.4[(a)]	190	27.6
			1-29TH	(b)	(b)	179	26.0
			1-30TH	(b)	(b)	176	25.5
			Avg.	1120	162.4	182	26.4
922	1200	LT	1-31TH	1004	145.7	166	24.1
			1-32TH	1009	146.4	167	24.2
			1-33TH	1003	145.5	161	23.4
			Avg.	1005	145.9	165	23.9
1033	1400	LT	1-34TH	515	74.7	97.9	14.2
			1-35TH	504	73.1	(c)	(c)
			1-36TH	500	72.5	97.9	14.2
			Avg.	506	73.4	97.9	14.2

(a) Load-strain curve extrapolated to obtain yield load.

(b) Specimen buckled before yielding.

(c) Load-strain curve not suitable for modulus determination.

TABLE 10. COMPRESSIVE PROPERTIES OF CTX-1 BAR, HEAT TREATMENT A

Temperature K	Temperature F	Grain Direction	Specimen Identification	Yield Strength (0.2% Offset) MPa	Yield Strength (0.2% Offset) Ksi	Modulus of Elasticity GPa	Modulus of Elasticity Ksi x 10³
RT	RT	LT	4-1TA	1377	199.7	163	23.7
			4-2TA	1370	198.7	158	23.0
			4-3TA	1346	195.2	172	24.9
			Avg.	1364	197.9	164	23.9
		L	4-4LA	1318	191.1	160	23.2
			4-5LA	1303	189.0	158	22.9
			4-6LF	1303	189.0	170	24.7
			Avg.	1308	189.7	167	23.6
20	-423	L	4-1LA	1631	236.6	145	21.1
			4-2LA	1567	227.3	(a)	(a)
			4-3LA	1644	238.5	(a)	(a)
			Avg.	1614	234.1	145	21.1
922	1200	L	4-7LA	1017	147.3	167	24.3
			4-8LA	1010	146.5	169	24.5
			4-9LA	1038	150.5	166	24.1
			Avg.	1022	148.1	167	24.3

(a) Load-strain curve not suitable for modulus determination.

TABLE 11. COMPRESSIVE PROPERTIES OF CTX-1 BAR, HEAT TREATMENT B

Temperature K	Temperature F	Grain Direction	Specimen Identification	Yield Strength (0.2% Offset) MPa	Yield Strength (0.2% Offset) Ksi	Modulus of Elasticity GPa	Modulus of Elasticity Ksi x 10³
RT	RT	LT	4-1TB	1343	194.8	158	22.9
			4-2TB	1354	196.4	161	23.3
			4-3TB	1365	198.0	165	23.9
			Avg.	1354	196.4	161	23.4
		L	4-4LB	1269	184.0	147	21.3
			4-5LB	1276	185.1	145	21.1
			4-6LB	1295	187.9	144	20.9
			Avg.	1280	185.7	145	21.1
20	-423	L	4-1LB	1486	215.5	163	23.6
			4-2LB	(a)	(a)	(a)	(a)
			4-3LB	1542	223.7	158	22.9
			Avg.	1514	219.6	161	23.2
922	1200	L	4-7LB	960.4	139.3	145	21.1
			4-8LB	951.5	138.0	140	20.3
			4-9LB	944.6	137.0	145	21.0
			Avg.	952.2	138.1	143	20.8

(a) Specimen inadvertently overloaded.

TABLE 12. CHARPY V-NOTCH IMPACT VALUES FOR CTX-1 BAR, HEAT TREATMENT A, INCLUDING PRIOR EXPOSURE

Temperature K	Temperature F	Prior Exposure	Grain Direction	Specimen Identification	Charpy V-Notch Energy J	Charpy V-Notch Energy Ft. Lbs.
RT	RT	None	L	4-1LA	28.5	21.0
				4-2LA	29.2	21.5
				4-3LA	29.8	22.0
				Avg.	29.2	21.5
			LT	4-7TA	14.2	10.5
				4-8TA	13.5	10.0
				4-9TA	17.6	13.0
				Avg.	15.1	11.2
		922 K (1200 F) for 10 hours	LT	4-22TA	12.9	9.5
				4-23TA	15.6	11.5
				4-24TA	15.6	11.5
				Avg.	14.7	10.8
20	-423	None	LT	4-1TA	13.5	10.0
				4-2TA	12.9	9.5
				4-3TA	14.2	10.5
				Avg.	13.5	10.0
		922 K (1200 F) for 10 hours	LT	4-19TA	12.9	9.5
				4-20TA	12.9	9.5
				4-21TA	14.9	11.0
				Avg.	13.6	10.0
77	-321	None	LT	4-4TA	12.9	9.5
				4-5TA	12.2	9.0
				4-6TA	13.5	10.0
				Avg.	12.9	9.5
811	1000	None	LT	4-10TA	14.9	11.0
				4-11TA	15.6	11.5
				4-12TA	15.6	11.5
				Avg.	15.4	11.3
922	1200	None	LT	4-13TA	15.6	11.5
				4-14TA	(a)	(a)
				4-15TA	16.3	12.0
				Avg.	15.9	11.7
1033	1400	None	LT	4-16TA	27.8	20.5
				4-17TA	24.4	18.0
				4-18TA	24.4	18.0
				Avg.	25.5	18.8

(a) Specimen positioned improperly in testing machine.

TABLE 13. CHARPY V-NOTCH IMPACT VALUES FOR CTX-1 BAR, HEAT TREATMENT B, INCLUDING PRIOR EXPOSURE

Temperature K	Temperature F	Prior Exposure	Grain Direction	Specimen Identification	Charpy V-Notch Energy J	Charpy V-Notch Energy Ft. Lbs.
RT	RT	None	L	4-1LB	42.0	31.0
				4-2LB	41.3	30.5
				4-3LB	40.0	29.5
				Avg.	41.1	30.3
			LT	4-7TB	19.0	14.0
				4-8TB	19.6	14.5
				4-9TB	21.0	15.5
				Avg.	19.9	14.7
		922K (1200 F) for 10 hours	LT	4-22TB	20.3	15.0
				4-23TB	24.4	18.0
				4-24TB	21.7	16.0
				Avg.	22.1	16.3
20	-423	None	LT	4-1TB	17.6	13.0
				4-2TB	20.3	15.0
				4-3TB	18.3	13.5
				Avg.	18.7	13.8
		922 K (1200 F) for 10 hours	LT	4-19TB	21.7	16.0
				4-20TB	25.8	19.0
				4-30TB	20.3	15.0
				Avg.	22.6	16.7
77	-321	None	LT	4-4TB	18.3	13.5
				4-5TB	20.3	15.0
				4-6TB	17.6	13.0
				Avg.	18.7	13.8
811	1000	None	LT	4-10TB	26.4	19.5
				4-11TB	25.1	18.5
				4-12TB	26.4	19.5
				Avg.	26.0	19.2
922	1200	None	LT	4-13TB	27.1	20.0
				4-14TB	23.7	17.5
				4-15TB	26.4	19.5
				Avg.	25.7	19.0
1033	1400	None	LT	4-16TB	40.0	29.5
				4-17TB	38.6	28.5
				4-18TB	38.6	28.5
				Avg.	39.1	28.8

TABLE 14. ROOM TEMPERATURE FRACTURE TOUGHNESS PROPERTIES OF HEAT TREATED INCOLOY 903 SHEET, T-L CRACK ORIENTATION

Specimen Identification	Thickness, B		Width, W		Maximum Stress, S_{max}		Initial Precrack, $2a_o$		Apparent Toughness, K_{app}		Net Section Stress, S_n	
	mm	inches	cm	inches	MPa	Ksi	cm	inches	MPa-m$^{1/2}$	Ksi-in.$^{1/2}$	MPa	Ksi
Unexposed Parent Metal, TYS = 1287 MPa (186.6 ksi) and TUS = 1458 MPa (211.5 ksi)												
3-4T	1.4	0.056	45.36	17.86	503	73.0	7.87	3.10	177	161	609	88.3
3-5T	1.4	0.055	45.31	17.84	521	75.6	9.04	3.56	197	179	651	94.4
3-6T	1.4	0.056	45.31	17.84	497	72.1	9.32	3.67	190	173	626	90.8
Avg.									188	171		
Exposed[a] Parent Metal, TYS = 1236 MPa (179.2 ksi) and TUS = 1400 MPa (203.0 ksi)												
2-1T	1.4	0.056	45.36	17.86	505	73.3	9.83	3.87	199	181	645	93.6
2-2T	1.4	0.056	45.34	17.85	500	72.5	9.22	3.63	190	173	627	91.0
2-3T	1.4	0.054	45.31	17.84	521	75.6	9.25	3.64	199	181	655	95.0
Avg.									196	178		
Unexposed Weld Metal[b], TYS = 533 MPa (77.3 ksi) and TUS = 719 MPa (104.3 ksi)												
3-1T	1.4	0.054	45.31	17.84	557	80.8	9.07	3.57	210	191[c]	696	101.0
3-2T	1.3	0.053	45.42	17.88	545	79.1	8.86	3.49	203	185[c]	678	98.3
3-3T	1.3	0.051	45.34	17.85	537	78.0	9.07	3.57	203	185[c]	672	97.5
Avg.									205	187[c]		
Exposed Weld Metal[d], TYS = 1062 MPa (154 ksi, est.) and TUS = 1172 MPa (170 ksi, est.)												
2-4T	1.3	0.051	45.34	17.85	614	89.0	9.27	3.65	234	213	771	111.9
2-5T	1.3	0.051	45.34	17.85	631	91.6	9.27	3.65	241	219	793	115.1
2-6T	1.5	0.058	45.34	17.85	496	71.9	9.27	3.65	189[e]	172	623	90.4
Avg.									237	216		

(a) 922 K (1200 F) for 10 hours.

(b) Heat treated and welded with no subsequent thermal treatment.

(c) Not valid since S_n > TYS.

(d) Heat treated, welded and exposed at 922 K (1200 F) for 10 hours.

(e) On one side, crack ran through adjacent parent metal, not included in average.

TABLE 15. **FRACTURE TOUGHNESS PROPERTIES OF C1X-1 BAR, HEAT TREATMENT A, T-L CRACK ORIENTATION**

Specimen Identification	Test Temperature K	Test Temperature F	Exposure	W cm	W inches	B cm	B inches	A cm	A inches	P_Q(a) MN	P_Q(a) lbs.	K_Q(b) MPa$\sqrt{m}$	K_Q(b) Ksi$\sqrt{in.}$
			TYS (LT) = 1374 MPa (201.3 ksi), TYS (LT) = 1191 MPa (172.7 ksi)										
1	RT	RT	None	5.08	2.00	2.54	1.00	3.28	1.29	20.59	4630	58.7	53.4
2	RT	RT	None	5.08	2.00	2.54	1.00	2.54	1.00	34.12	7670	56.9	51.8
3	RT	RT	None	5.08	2.00	2.54	1.00	2.67	1.05	32.81	7375	59.1	53.8
Avg.												58.2	53.0
			TUS (L) = 1326 MPa (192.4 ksi), TYS (L) = 1110 MPa (161.0 ksi)										
4	RT	RT	922 K (1200 F) 10 hours	5.08	2.00	2.54	1.00	2.64	1.04	34.87	7840	61.9	56.3
5	RT	RT	922 K (1200 F) 10 hours	5.08	2.00	2.54	1.00	2.67	1.05	33.63	7560	60.7	55.2
6	RT	RT	922 K (1200 F) 10 hours	5.08	2.00	2.54	1.00	2.64	1.04	36.12	8120	64.2	58.4
Avg.												62.3	56.6
			TUS (L) = 1710 MPa (248.0 ksi), TYS (L) = 1344 MPa (194.9 ksi)										
7	77	-321	None	5.08	2.00	2.54	1.00	2.59	1.02	32.25	7250	55.5	50.5
8	77	-321	None	5.08	2.00	2.54	1.00	2.69	1.06	32.65	7340	59.8	54.4
9	77	-321	None	5.08	2.00	2.54	1.00	2.67	1.05	33.89	7620	61.1	55.6
Avg.												58.8	53.5
			TUS (L) = 1882 MPa (277.8 ksi), TYS (L) = 1469 MPa (213.1 ksi)										
10	20	-423	None	5.08	2.00	2.54	1.00	2.64	1.04	33.36	7500	59.2	53.9
11	20	-423	None	5.08	2.00	2.54	1.00	2.67	1.05	34.47	7750	62.2	56.6
12	20	-423	None	5.08	2.00	2.54	1.00	2.77	1.09	34.03	7650	65.5	59.6
Avg.												62.3	56.7
			TUS (L) = 1804 MPa (261.6 ksi), TYS (L) = 1403 MPa (203.4 ksi)										
13	20	-423	922 K (1200 F) 10 hours	5.08	2.00	2.54	1.00	2.69	1.06	34.70	7800	63.6	57.9
14	20	-423	922 K (1200 F) 10 hours	5.08	2.00	2.54	1.00	2.67	1.05	33.36	7500	60.2	54.8
15	20	-423	922 K (1200 F) 10 hours	5.08	2.00	2.54	1.00	2.69	1.06	36.25	8150	66.5	60.5
Avg.												63.4	57.7

(a) $P_Q = P_{max}$

(b) Candidate K_Q values are valid K_{Ic} values by existing ASTM criteria (E399).

TABLE 16. SUMMARY DATA ON THE LONG TRANSVERSE CREEP AND RUPTURE PROPERTIES OF ANNEALED INCOLOY 903 SHEET

Specimen Identification	Stress		Test Temperature		Hours to Indicated Deformation, percent					Initial Strain, percent	Rupture Time, hour	Elongation 5.08 cm (2 in.), percent	Minimum Creep Rate, percent/hour
	MPa	Ksi	K	F	0.1	0.2	0.5	1.0	2.0				
1-1T	800	116	811	1000	--	--	--	--	--	--	On loading	37.3	--
1-2T	758	110	811	1000	0.1	0.4	--	--	--	12.052	17.7	13.6	0.015
1-3T	689	100	811	1000	0.1	0.4	--	--	--	18.134	36.7	17.7	0.0007
1-4T	621	90	811	1000	47	50[d]	--	--	--	2.307	52.4	4.1	0.0003
1-5T	483	70	811	1000	--	--	--	--	--	0.600	160.6	-0.4[a]	--
1-6T	689	100	922	1200	1.0	2.5	--	--	--	0.604	5.8[b]	0	0.06
1-7T	689	100	922	1200	1.5	4.7	--	--	--	0.548	5.6	0.9	0.036
1-8T	552	80	922	1200	--	--	--	--	--	0.341	3.0	0.9	0.015
1-9T	345	50	922	1200	30	75	180	275	375	0.370	802.8	17.3	0.0019
1-10T	207	30	922	1200	140	230	382	535	800[d]	0.286	571.8[c]	1.4	0.0006
1-11T	414	60	1033	1400	--	--	--	0.15	0.25	0.761	0.6	15.9	5.7
1-12T	345	50	1033	1400	--	--	--	0.15	0.25	0.364	0.8	16.8	5.5
1-13T	276	40	1033	1400	0.3	0.9	3.2	7.0	16	0.161	115.3	31.8	0.11
1-14T	207	30	1033	1400	0.1	0.3	1.0	1.6	3.6	0.341	17.8	22.3	0.50
1-15T	138	20	1033	1400	0.3	1.3	3.0	7.0	14	0.208	105.0	37.7	0.14

(a) Contraction occurred.

(b) Failed in pin hole.

(c) Test discontinued.

(d) Estimated.

TABLE 17. SUMMARY DATA ON THE LONG TRANSVERSE CREEP AND RUPTURE PROPERTIES OF HEAT-TREATED INCOLOY 903 ALLOY SHEET

Specimen Identification	Stress		Test Temperature		Hours to Indicated Deformation, percent					Initial Strain, percent	Rupture Time, hour	Elongation in 5.08 cm (2 in.), percent	Minimum Creep Rate, percent/hour
	MPa	ksi	K	F	0.1	0.2	0.5	1.0	2.0				
1-16TH	1227	178	811	1000	--	--	--	--	--	--	On loading	9.5	--
1-17TH	1034	150	811	1000	0.1	0.4	1.7	2.6	--	0.844	4.0	1.4	0.25
1-18TH	896	130	811	1000	15	--	--	--	--	0.818	27.7	0.9	0.0034
1-19TH	758	110	811	1000	--	--	--	--	--	0.457	66.3	0.5	0.00012
1-20TH	483	70	811	1000	--	--	--	--	--	0.209	1510.0(a)	0.222	0.000008
1-21TH	827	120	922	1200	0.04	0.09	0.22	0.38	0.56	0.584	0.7	3.6	2.2
1-22TH	589	100	922	1200	0.3	0.9	2.3	4.1	8.0	0.837	6.6	3.2	0.20
1-23TH	517	75	922	1200	2.2	10	27	46	70	0.327	89.8	4.1	0.016
1-24TH	345	50	922	1200	15	37	117	205	290	0.420	694.4	17.7	0.0035
1-25TH	138	20	922	1200	120	230	430	650(b)	900(b)	0.011	450.0(a)	0.548	0.0005
1-30TH	69	10	922	1200	340	540	1025(b)	1800(b)	--	0.064	697.9(a)	0.361	0.00012
1-26TH	276	40	1033	1400	0.07	0.13	0.43	0.92	2.0	0.311	7.7	24.1	1.0
1-27TH	172	25	1033	1400	0.15	0.35	1.4	3.2	7.0	0.130	46.1	39.5	0.27
1-28TH	48	7	1033	1400	1.6	4.5	19	44	100	0.071	1101.1	55.9	0.018
1-29TH	14	2	1033	1400	45	93	250	525	1100(b)	0.041	452.2	0.892	0.0018

(a) Test discontinued.

(b) Estimated.

TABLE 18. SUMMARY DATA ON THE LONGITUDINAL CREEP AND RUPTURE PROPERTIES OF CTX-1 ALLOY BAR, HEAT TREATMENT A

Specimen Identification	Stress		Test Temperature		Hours to Indicated Deformation, percent					Initial Strain, percent	Rupture Time, hour	Elongation in 2.54 cm (1 in.), percent	Reduction in Area, percent	Minimum Creep Rate, percent/hour
	MPa	Ksi	K	F	0.1	0.2	0.5	1.0	2.0					
1-1LA	1034	150	811	1000	--	0.05	0.15	0.5	1.4	1.433	7.5	17.8	48.5	1.1
1-10LA	965	140	811	1000	0.3	1.3	10	28	54	0.856	131.3	8.9	16.7	0.026
1-11LA	931	135	811	1000	2.0	4.0	35	80	132	0.837	236.3	8.2	11.8	0.010
1-15LA	896	130	811	1000	0.5	3.2	40	140	263	0.630	436.8	5.2	3.3	0.0057
1-3LA	827	120	811	1000	750	1600(a)	--	--	--	0.700	1000.6(b)	0.822	--	Nil
1-6LA	896	130	922	1200	--	--	--	--	0.05	1.150	0.2	20.0	48.1	--
1-4LA	689	100	922	1200	0.4	2.3	17	28	40	0.418	75.2	11.8	30.5	0.015
1-9LA	586	85	922	1200	20	70	175	260	340	0.381	424.2	13.3	28.0	0.002
1-7LA	483	70	922	1200	230	455	900(a)	--	--	0.355	522.8(b)	0.596	--	0.00018
1-13LA	448	65	922	1200	520	900	1500(a)	--	--	0.415	1005.0(b)	0.674	--	0.00014
1-2LA	345	50	1033	1400	0.6	2.0	6.0	10	15	0.333	25.1	24.4	52.6	0.08
1-5LA	207	30	1033	1400	8.0	17	40	65	85	0.230	135.9	16.3	57.4	0.013
1-8LA	103	15	1033	1400	42	80	130	180	305	0.056	1349.3	42.2	66.8	0.0025
1-12LA	48	7	1033	1400	75	120	300	--	--	0.026	527.5(b)	0.785	--	--
1-14LA	21	3	1033	1400	155	360	1700(a)	--	--	0.044	668.2(b)	0.315	--	0.00022

(a) Estimated.

(b) Test discontinued.

TABLE 19. SUMMARY DATA ON THE LONGITUDINAL CREEP AND RUPTURE PROPERTIES OF CTX-1 ALLOY BAR, HEAT TREATMENT B

Specimen Identification	Stress		Test Temperature		Hours to Indicated Deformation, percent					Initial Strain, percent	Rupture Time, hour	Elongation in 2.54 cm (1 in.), percent	Reduction in Area, percent	Minimum Creep Rate, percent/hour
	MPa	Ksi	K	F	0.1	0.2	0.5	1.0	2.0					
1-3LB	1034	150	811	1000	0.14	0.5	--	--	--	1.794	2.4	3.7	11.1	0.086
1-5LB	965	140	811	1000	1.3	--	--	--	--	1.295	4.3(a)	--	--	--
1-4LB	827	120	811	1000	--	--	--	--	--	0.644	10.8(a)	--	--	--
1-6LB	689	100	922	1200	--	--	--	--	--	0.548	1.7(b)	2.2	9.8	0.016
1-1LB	483	70	922	1200	--	--	--	--	--	0.511	5.3(a)	--	--	--
1-2LB	345	50	1033	1400	0.5	1.5	5	9	--	0.270	11.6	12.6	17.4	1.3
1-10LB	207	30	1033	1400	3	8	29	58	85	0.215	130.8	17.8	24.7	0.015
1-7LB	138	20	1033	1400	8	30	109	202	309	0.126	634.9	39.2	27.1	0.0034
1-8LB	48	7	1033	1400	140	315	225	1550(d)	--	0.026	620.1(c)	0.440	--	0.0004
1-9LB	21	3	1033	1400	470	1015	2700(d)	--	--	0	1098.4(c)	0.241	--	0.00018

(a) Failed in threads.

(b) Failed in fillet radius.

(c) Test discontinued.

(d) Estimated.

TABLE 20. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED ANNEALED INCOLOY 903 SHEET

(Transverse, R = 0.1)

Specimen Number	Maximum Stress, MPa	Maximum Stress, ksi	Lifetime, Cycles
	Room Temperature		
1-6T	862	125	125,500
1-7T	758	110	70,600
1-5T	689	100	129,400
1-8T	621	90	265,600
1-9T	552	80	559,800
1-11T	517	75	786,300
1-12T	500	72.5	10,000,000[(a)]
1-10T	483	70	10,000,000[(a)]
	922K (1200 F)		
1-16T	827	120	78,000
1-15T	758	110	110,000
1-40T	724	105	241,600
1-14T	689	100	270,000
1-39T	655	95	3,856,300
1-41T	655	95	4,967,200
1-17T	621	90	280,000
1-42T	621	90	2,306,600
1-13T	552	80	10,000,000[(a)]

(a) Did not fail.

TABLE 21. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED ANNEALED INCOLOY 903 SHEET

(Transverse, R = 0.1, K_t = 3.0)

Specimen Number	Maximum Stress, MPa	ksi	Lifetime, Cycles
	Room Temperature		
1-1TN	689	100	3,600
1-2TN	586	85	10,500
1-3TN	483	70	42,300
1-5TN	414	60	94,000
1-6TN	379	55	135,600
1-7TN	362	52.5	188,300
1-4TN	345	50	6,570,000
1-11TN	310	45	10,000,000[a]
	922K (1200 F)		
1-9TN	483	70	5,300
1-15TN	414	60	153,000
1-10TN	345	50	223,700
1-12TN	310	45	840,300
1-13TN	276	40	2,139,200
1-14TN	259	37.5	3,974,300
1-16TN	241	35	4,684,700
1-8TN	207	30	10,000,000[a]

(a) Did not fail.

TABLE 22. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED HEAT TREATED INCOLOY 903 SHEET

(Transverse, R = 0.1)

Specimen Number	Maximum Stress, MPa	ksi	Lifetime, Cycles
	Room Temperature		
1-18TH	1172	170	37,900
1-17TH	1103	160	52,600
1-19TH	1034	150	66,700
1-20TH	965	140	87,300
1-21TH	896	130	148,700
1-22TH	862	125	140,700
1-23TH	827	120	255,900
1-24TH	793	115	174,900
1-25TH	758	110	254,300
1-26TH	724	105	372,500
1-27TH	689	100	10,000,000(a)
	922K (1200 F)		
1-29TH	827	120	387,000
1-32TH	758	110	602,000
1-33TH	758	110	(b)
1-34TH	724	105	1,257,700
1-28TH	689	100	1,309,700
1-30TH	621	90	1,772,000
1-35TH	621	90	4,193,200
1-31TH	586	85	4,009,800
1-36TH	586	85	7,500,000

(a) Did not fail.
(b) Failed at thermocouple.

TABLE 23. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED HEAT TREATED INCOLOY 903 SHEET

(Transverse, R = 0.1, K_t = 3.0)

Specimen Number	Maximum Stress, MPa	Maximum Stress, ksi	Lifetime, Cycles
		Room Temperature	
1-17THN	827	120	3,900
1-18THN	689	100	9,500
1-19THN	621	90	18,100
1-20THN	552	80	37,100
1-21THN	483	70	75,200
1-22THN	414	60	177,500
1-23THN	345	50	10,000,000[(a)]
		922K (1200 F)	
1-25THN	552	[illegible]	7,000
1-30THN	483	70	32,000
1-26THN	414	60	160,000
1-31THN	379	55	230,000
1-27THN	345	50	1,100,000
1-28THN	310	45	1,550,000
1-29THN	276	40	2,200,000
1-24THN	241	35	4,400,000
1-32THN	207	30	10,000,000[(a)]

(a) Did not fail.

TABLE 24. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED CTX-1 BAR, HEAT TREATMENT A

(Longitudinal, R = 0.1)

Specimen Number	Maximum Stress, MPa	Maximum Stress, ksi	Lifetime, Cycles
		Room Temperature	
4-2LA	1103	160	31,190
4-1LA	965	140	45,900
4-15LA	827	120	108,670
4-14LA	758	110	249,920
4-4LA	689	100	541,080
4-5LA	621	90	459,490
4-3LA	552	80	14,700,000[(a)]
		922K (1200 F)	
4-8LA	965	140	9,850
4-11LA	896	130	181,000
4-6LA	827	120	328,800
4-9LA	758	110	562,300
4-10LA	689	100	1,055,850
4-7LA	621	90	2,123,600
4-12LA	483	70	5,600,000
4-13LA	414	60	11,800,000[(a)]

(a) Did not fail.

TABLE 25. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED CTX-1 BAR, HEAT TREATMENT A

(Longitudinal $R = 0.1$, $K_t = 3.0$)

Specimen Number	Maximum Stress, MPa	Maximum Stress, ksi	Lifetime, Cycles
	Room Temperature		
4-3LNA	689	100	9,050
4-2LNA	483	70	30,050
4-5LNA	345	50	95,050
4-7LNA	276	40	704,380
4-4LNA	207	30	1,492,240
4-6LNA	172	25	12,000,000[a]
	922K (1200 F)		
4-8LNA	621	90	8,800
4-10LNA	552	80	31,300
4-11LNA	483	70	113,100
4-12LNA	414	60	859,500
4-9LNA	345	50	4,270,200
4-13LNA	276	40	10,000,000[a]

(a) Did not fail.

TABLE 26. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED CTX-1 BAR, HEAT TREATMENT B

(Longitudinal, R = 0.1)

Specimen Number	Maximum Stress, MPa	ksi	Lifetime, Cycles
	Room Temperature		
4-1LB	1103	160	32,520
4-2LB	827	120	126,420
4-4LB	758	110	266,470
4-3LB	689	100	1,712,360
4-5LB	672	97.5	1,336,200
4-6LB	621	90	2,178,900
4-7LB	552	80	10,000,000[(a)]
	922K (1200 F)		
4-8LB	965	140	3,590
4-9LB	827	120	26,580
4-15LB	758	110	62,630
4-10LB	689	100	254,900
4-11LB	552	80	442,340
4-12LB	552	80	1,175,900
4-13LB	448	65	3,171,740
4-14LB	345	50	10,000,000[(a)]

(a) Did not fail.

TABLE 27. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED CTX-1 BAR, HEAT TREATMENT B

(Longitudinal, $R = 0.1$, $K_t = 3.0$)

Specimen Number	Maximum Stress, MPa	Maximum Stress, ksi	Lifetime, Cycles
	Room Temperature		
4-1LNB	827	120	5,240
4-2LNB	689	100	8,860
4-3LNB	483	70	24,760
4-4LNB	345	50	84,870
4-14LNB	276	40	192,750
4-5LNB	207	30	414,240
4-6LNB	138	20	12,000,000[a]
	922K (1200 F)		
4-9LNB	552	80	4,000
4-10LNB	483	70	6,900
4-7LNB	414	60	12,400
4-11LNB	345	50	77,300
4-12LNB	276	40	144,200
4-8LNB	207	30	2,687,500
4-13LNB	138	20	8,265,500
4-15LNB	121	17.5	10,000,000[a]

(a) Did not fail.

TABLE 28 TENSILE AND NOTCHED TENSILE PROPERTIES OF HEAT TREATED AND WELDED INCOLOY 903 SHEET INCLUDING PRIOR EXPOSURE

Temperature K	Temperature F	Prior Exposure	Grain Direction	Specimen Identification	Approximate Yield Strength(a) MPa	Approximate Yield Strength(a) Ksi	Ultimate Strength(b) MPa	Ultimate Strength(b) Ksi	Elongation in 5.08 cm (2 in.), percent	Modulus of Elasticity GPa	Modulus of Elasticity Ksi x 10^3	Specimen Identification	Notch Strength K_t = 8.0 MPa	Notch Strength K_t = 8.0 Ksi	Notched/ Unnotched Ratio
RT	RT	None	LT	W1-4TH W1-5TH W1-6TH Average	491 560 548 53[illegible]	71.2 81.3 79.5 7.3	703.9 717.7 735.7 719.1	102.1 104.1 106.7 104.3	6.0 7.0 5.0 6.0	194 179 173 182	28.2 25.9 25.[illegible] 26.4	W1-4TNH W1-5TNH W1-6TNH Average	642 640 587 623	93.2 92.8 85.2 90.4	0.87
RT	RT	922 K (1200 F) for 10 hours	LT									W1-13TNH W1-14TNH W1-15TNH Average	1122 1163 1095 1127	162.8 168.7 158.8 163.4	
20	-423	None	LT	W1-1TH W1-2TH W1-3TH Average	812.9 710.8 795.6 773.1	117.9 103.[illegible] 115.4 112.1	1111 1110 1119 1113	161.2 161.0 162.4 161.5	3.5 5.0 3.0 3.8	187 192 207 195	27.2 27.9 30.0 28.4	W1-1TNH W1-2TNH W1-3TNH Average	1041 944 893 913	151.0 137.0 129.6 139.2	0.86
20	-423	922 K (1200 F) for 10 hours	LT									W1-10TNH W1-11TNH W1-12TNH Average	1306 1274 1234 1271	189.5 184.8 179.0 184.4	
922	1200	None	LT	W1-7TH W1-8TH W1-9TH Average	543 580 605 576	78.7 84.1 87.7 83.5	634.3 659.1 657.1 650.1	92.0 95.6 95.3 94.3	5.0 5.0 5.0 5.0	185 218 148 184	26.9 31.6 21.5 26.7	W1-7TNH W1-8TNH W1-9TNH Average	570 596 678 615	82.7 86.4 98.4 89.2	0.95
922	1200	922 K (1200 F) for 10 hours	LT									W1-16TNH W1-17TNH W1-18TNH Average	749.5 741.9 739.1 736.8	108.7 107.6 107.2 107.8	

(a) Gage length included heat treated parent metal, fusion zone and heat affected zones.

(b) All failures occurred in heat affected zone.

TABLE 29. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED HEAT TREATED INCOLOY 903 SHEET, AS WELDED

(Transverse, R = 0.1)

Specimen Number	Maximum Stress, MPa	ksi	Lifetime, Cycles
	Room Temperature		
9W	689	100	29,400
11W	621	90	57,300
10W	517	75	333,800
12W	431	62.5	8,605,200
	922K (1200 F)		
13W	621	90	30,800
14W	483	70	342,900
15W	414	60	508,000
16W	379	55	10,000,000[a]

(a) Did not fail.

TABLE 30. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED HEAT TREATED INCOLOY 903 SHEET, AS WELDED

(Transverse, R = 0.1, K_t = 3.0)

Specimen Number	Maximum Stress, MPa	Maximum Stress, ksi	Lifetime, Cycles
	Room Temperature		
1-WN	586	85	3,600
4-WN	483	70	14,800
2-WN	414	60	31,100
3-WN	362	52.5	74,200
	922K (1200 F)		
6-WN	483	70	5,500
5-WN	379	55	450,000
8-WN	276	40	2,800,000
7-WN	276	40	(a)

(a) Failed at thermocouple.

TABLE 31. POISSON'S RATIO FOR CTX-1 BAR, HEAT TREATMENT A, AT VARIOUS TEMPERATURES

Temperature		Specimen	Poisson's Ratio[a]	
K	F	Identification	LT	ST
RT	RT		0.344	0.247
811	1000	CTX-1-3	0.352	0.264
922	1200		0.382	0.271
1033	1400		0.406	0.290

(a) Average of four measurements.

TABLE 32. THERMAL CONDUCTIVITY OF INCOLOY 903 IN THE TEMPERATURE RANGE 20 K (-423 F) TO 300 K (80 F)

T(K)	λ (watts/cmK)
300	0.161
245	0.157
150	0.155
110	0.148
77	0.145
50	0.135
20	0.128

TABLE 33. THERMAL CONDUCTIVITY OF CTX-1 IN THE TEMPERATURE RANGE 20 K (-423 F) TO 300 K (80 F)

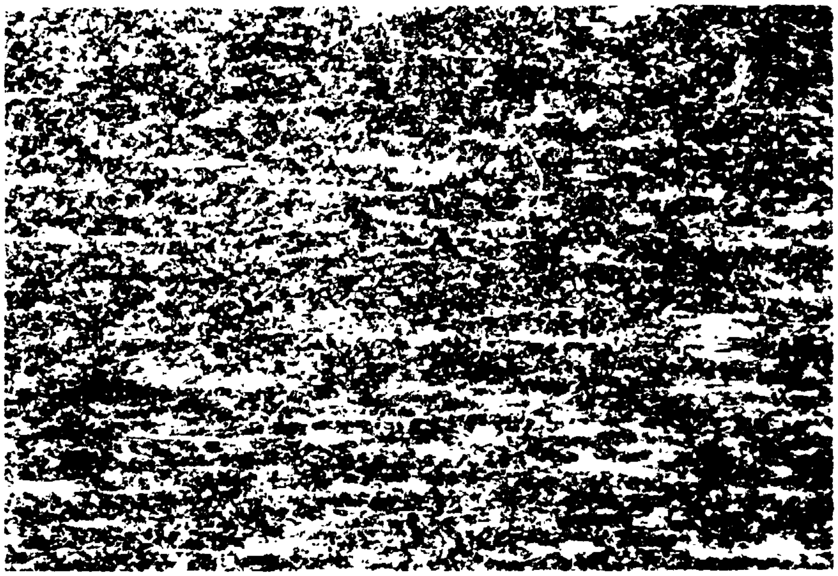
T(K)	λ (watts/cm K)
300	0.175
250	0.173
190	0.171
145	0.168
90	0.161
77	0.160
40	0.152
20	0.144

TABLE 34. THERMAL DIFFUSIVITY OF INCOLOY 903

Temperature			Thermal Diffusivity,
K	C	F	m^2 sec^{-1} x 10^4
296	23	73	0.0346
			0.0355
			0.0351
318	45	113	0.0358
			0.0374
			0.0360
382	109	228	0.0374
			0.0367
			0.0362
479	206	403	0.0387
			0.0384
			0.0377
581	308	586	0.0374
			0.0384
			0.0379
685	412	774	0.0416
			0.0409
			0.0417
766	493	919	0.0445
			0.0459
			0.0450
870	597	1107	0.0486
			0.0495
			0.0495
968	695	1283	0.0521
			0.0513
			0.0519
1033	760	1400	0.0512
			0.0510
			0.0[illegible]
873	600	1112	0.0485
			0.0493
			0.0484
684	411	772	0.0412
			0.0417
			0.0409
474	201	394	0.0370
			0.0374
			0.0379
294	21	70	0.0333
			0.0341
			0.0338

TABLE 35. THERMAL DIFFUSIVITY OF CTX-1

Temperature			Thermal Diffusivity, m^2 sec^{-1} x 10^4
K	C	F	
296	23	73	0.0382
			0.0400
			0.0384
320	47	117	0.0399
			0.0392
			0.0404
380	107	225	0.0404
			0.0404
			0.0400
482	209	408	0.0400
			0.0402
			0.0402
593	320	608	0.0382
			0.0382
			0.0393
689	416	781	0 0375
			0.0382
			0.0384
762	489	912	0.0444
			0.0443
			0.0435
869	596	1105	0.0470
			0.0470
			0.0465
971	698	1288	0.0472
			0.0481
			0.0478
1035	762	1404	0.0486
			0.0483
			0.0481
871	598	1108	0.0444
			0.0459
			0.0460
689	416	781	0.0378
			0.0376
			0.0380
289	16	61	0.0369
			0.0353
			0.0353
482	209	408	0.0385
			0.0394
			0.0394



100X

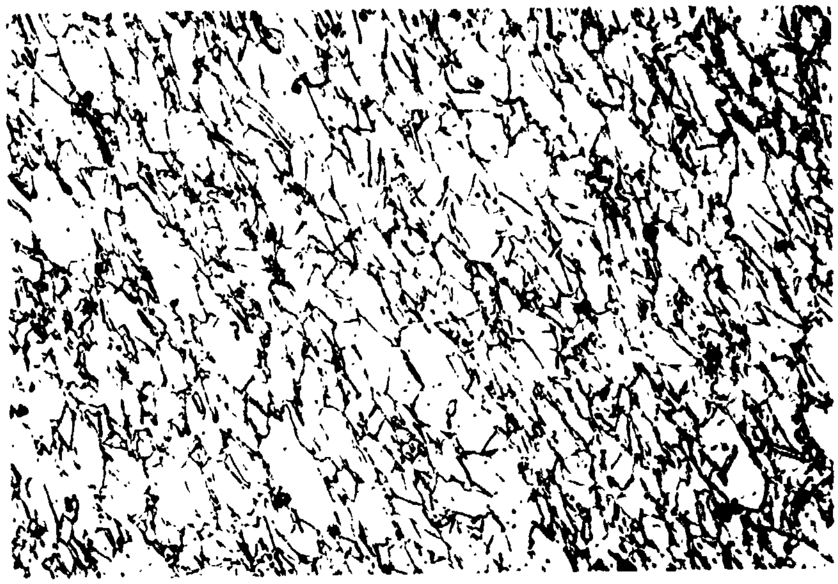
FIGURE 1. MICROSTRUCTURE OF ANNEALED INCOLOY 903 SHEET

Etchant: $FeCl_3$-HCl-HNO_3-H_2O

100X

FIGURE 2. MICROSTRUCTURE OF HEAT TREATED INCOLOY 903 SHEET

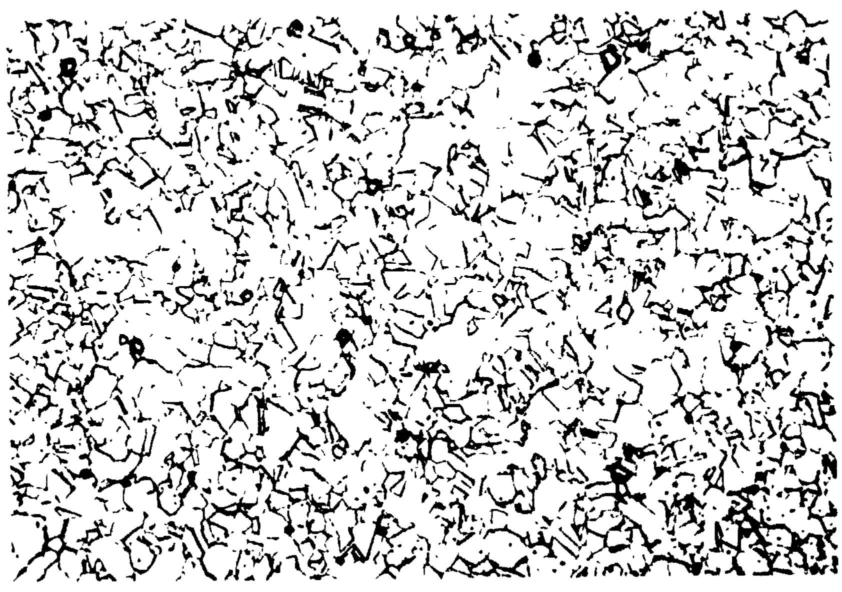
Etchant: $FeCl_3$-HCl-HNO_3-H_2O



100X

FIGURE 3. MICROSTRUCTURE OF CTX-1 BAR,
HEAT TREATMENT A

Etchant: $FeCl_3$-HCl-HNO_3-H_2O



100X

FIGURE 4. MICROSTRUCTURE OF CTX-1 BAR,
HEAT TREATMENT B

Etchant: $FeCl_3$-HCl-HNO_3-H_2O

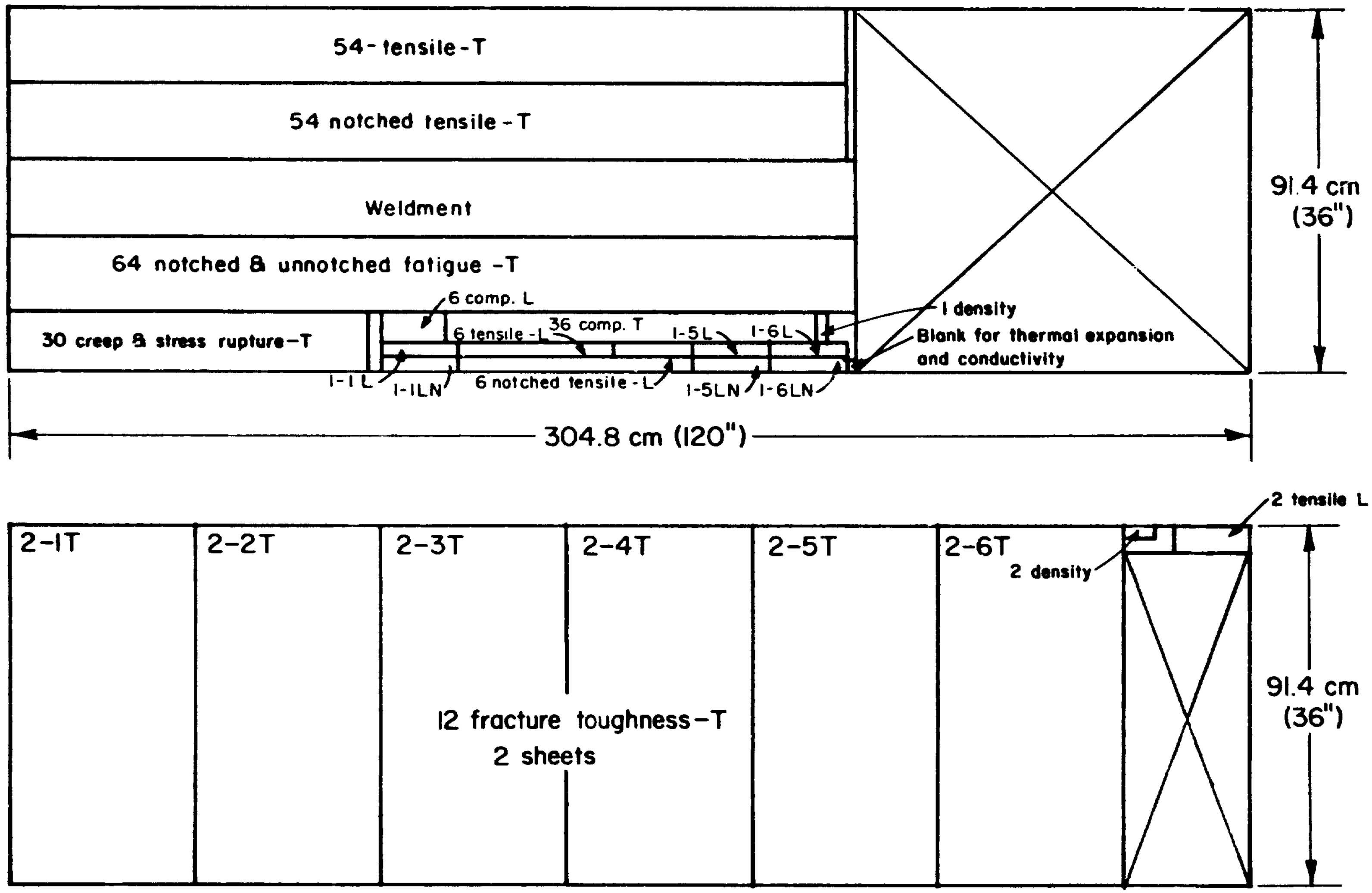


FIGURE 5. SPECIMEN LOCATION FOR INCOLOY 903 SHEET

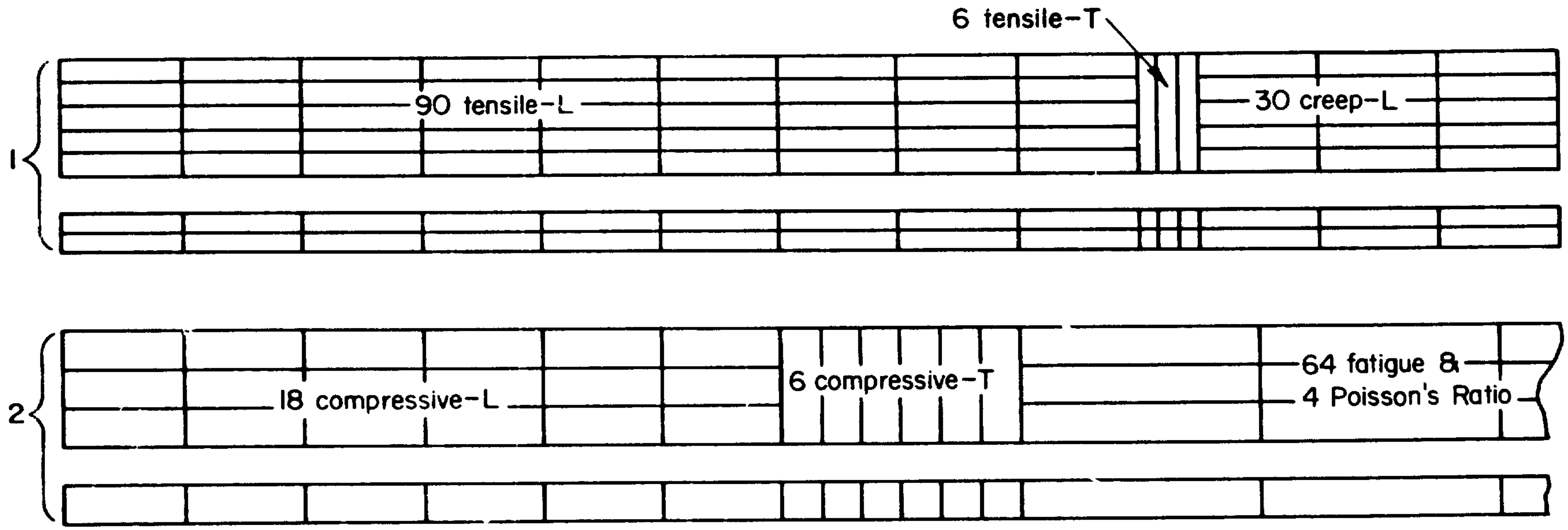


FIGURE 6. SPECIMEN LOCATION FOR CTX-1 BAR

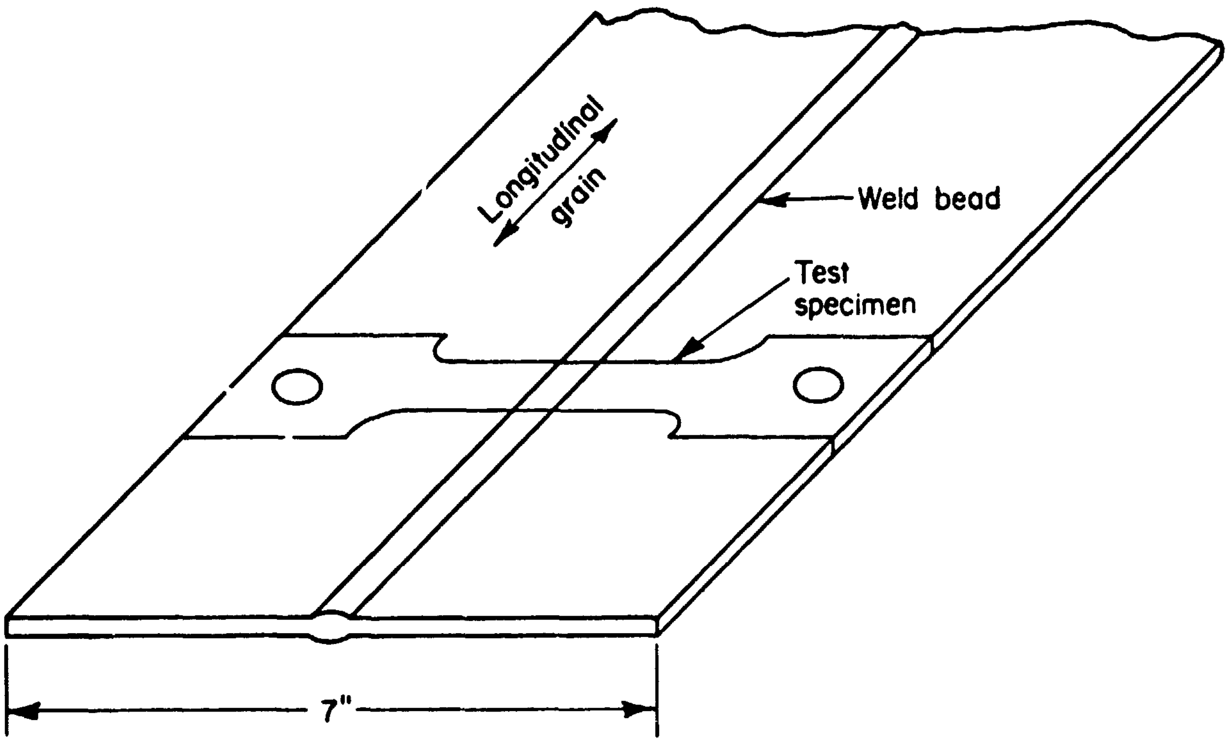


FIGURE 7. INCOLOY 903 SHEET WELDMENT

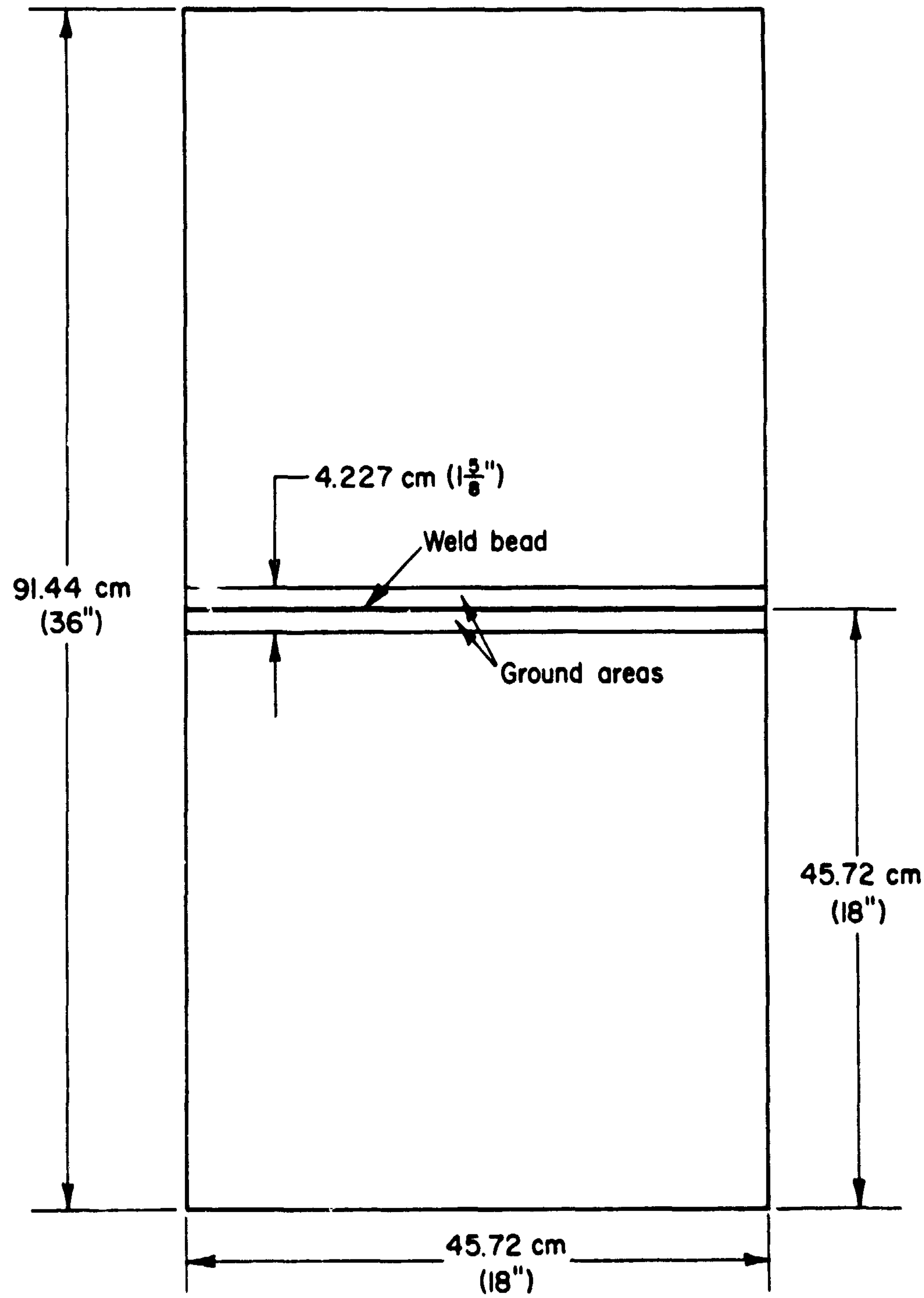


FIGURE 8. WELDED FRACTURE TOUGHNESS SPECIMEN

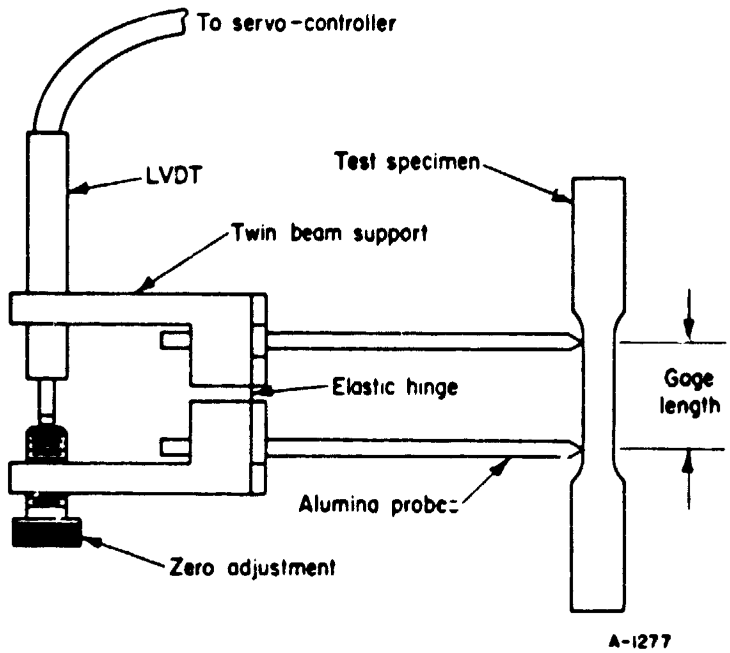


FIGURE 9. LONGITUDINAL EXTENSOMETER

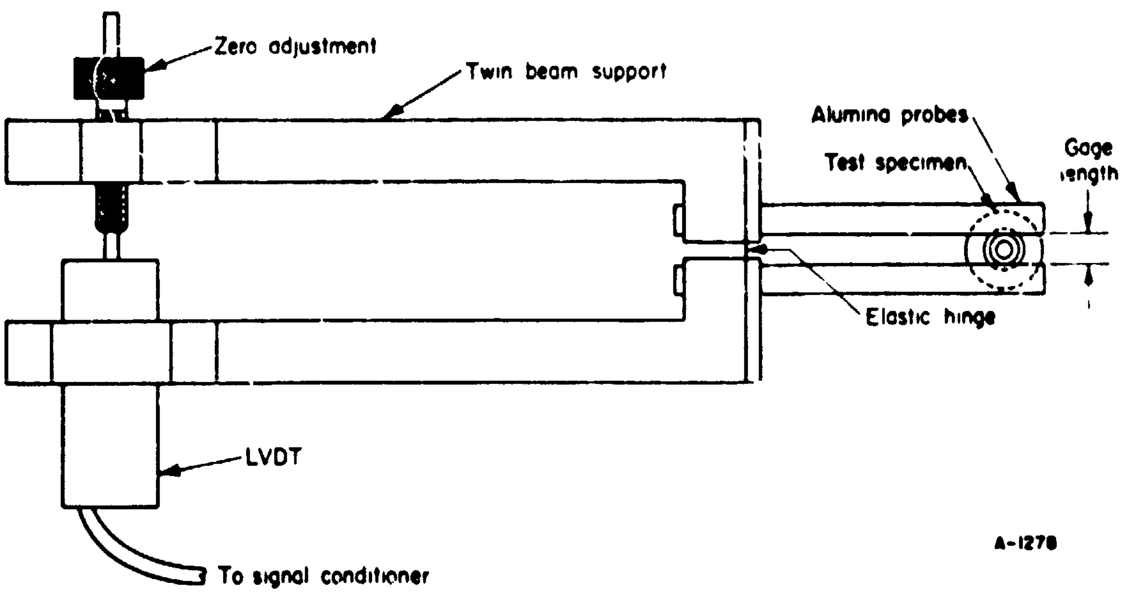


FIGURE 10. DIAMETRIAL EXTENSOMETER

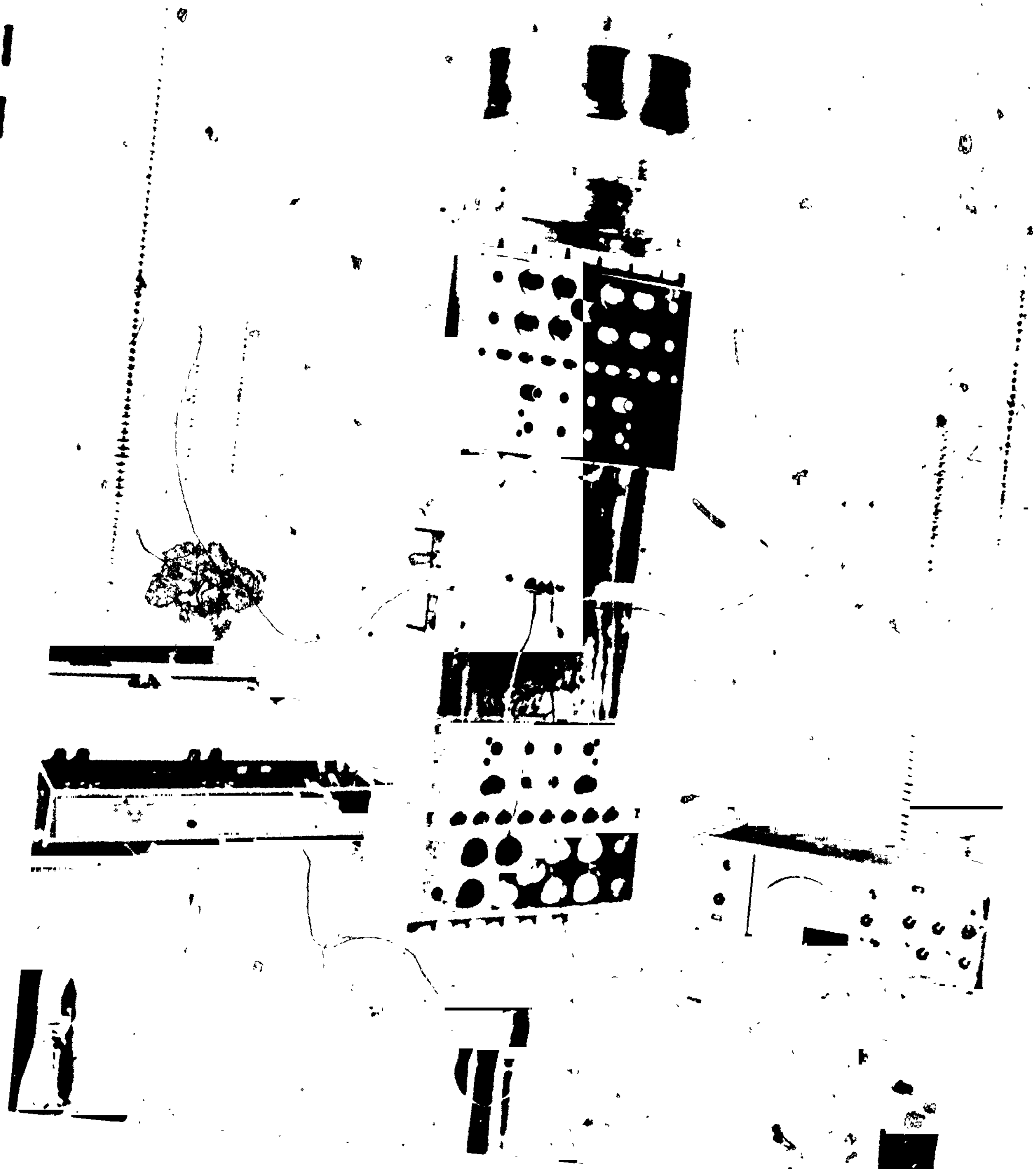


FIGURE 11. PLANE-STRESS FRACTURE TOUGHNESS TEST SET-UP

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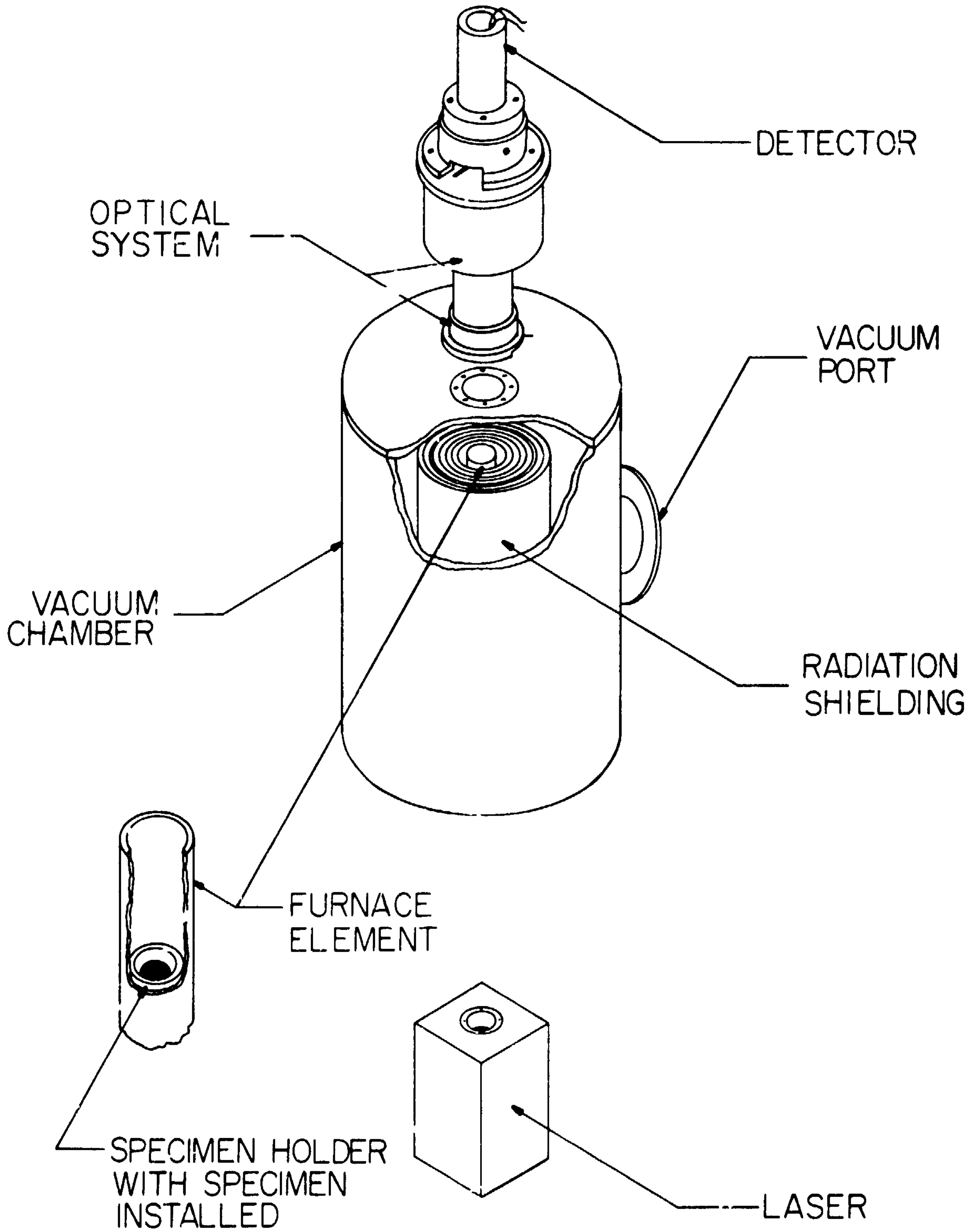


FIGURE 12. LASER FLASH THERMAL DIFFUSIVITY MEASUREMENT APPARATUS

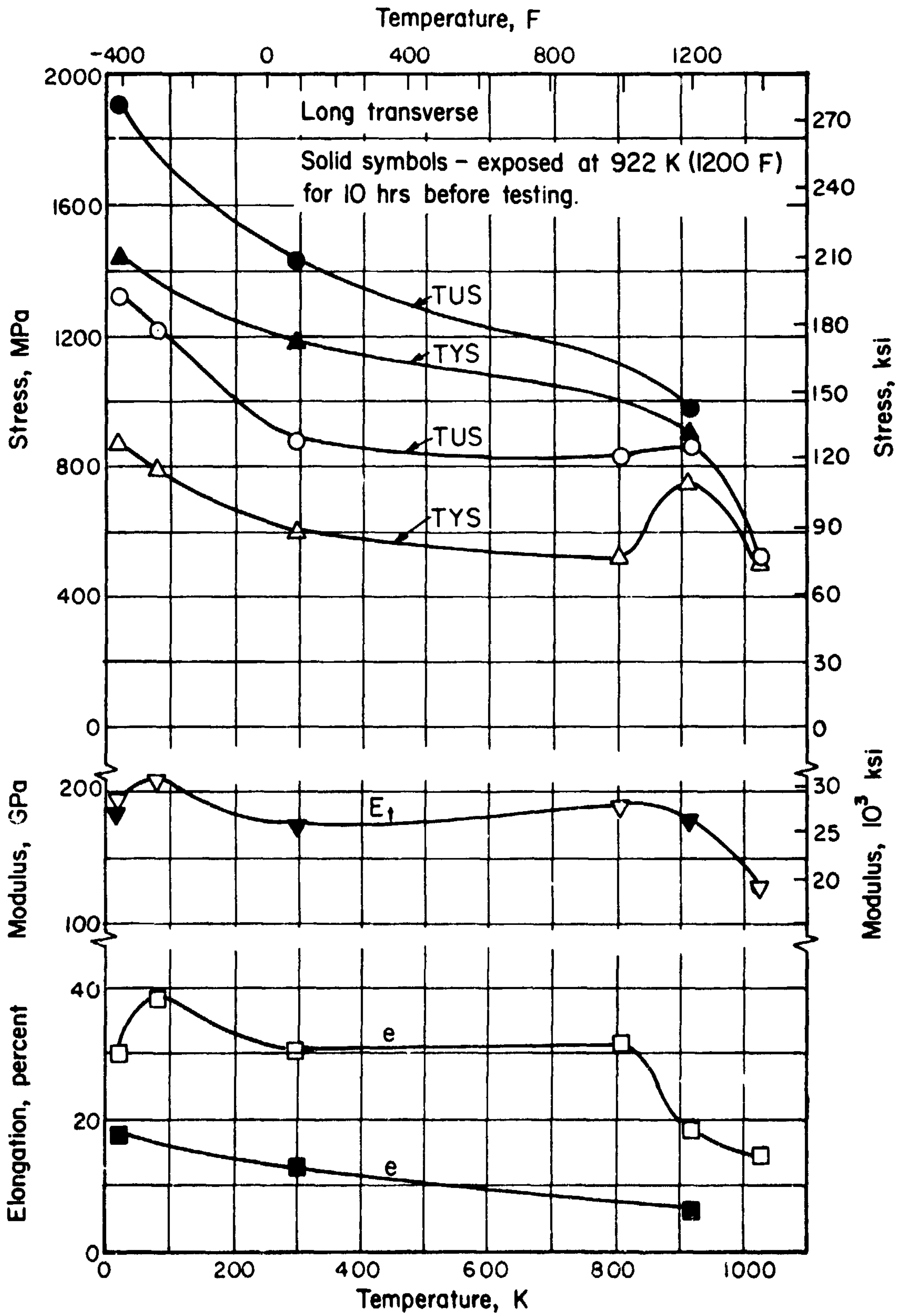


FIGURE 13. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED INCOLOY 903 SHEET

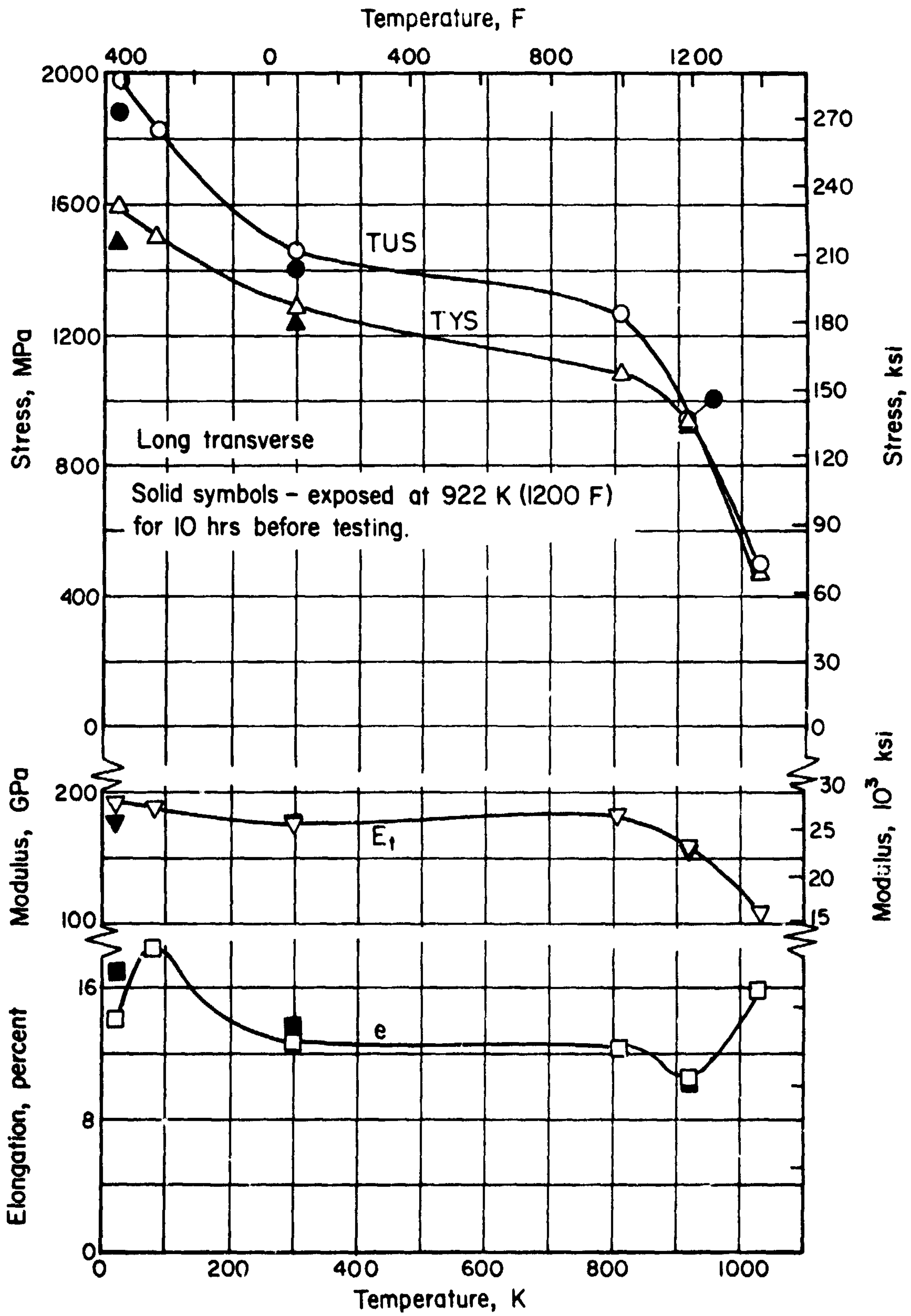


FIGURE 14. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF HEAT TREATED INCOLOY 903 SHEET

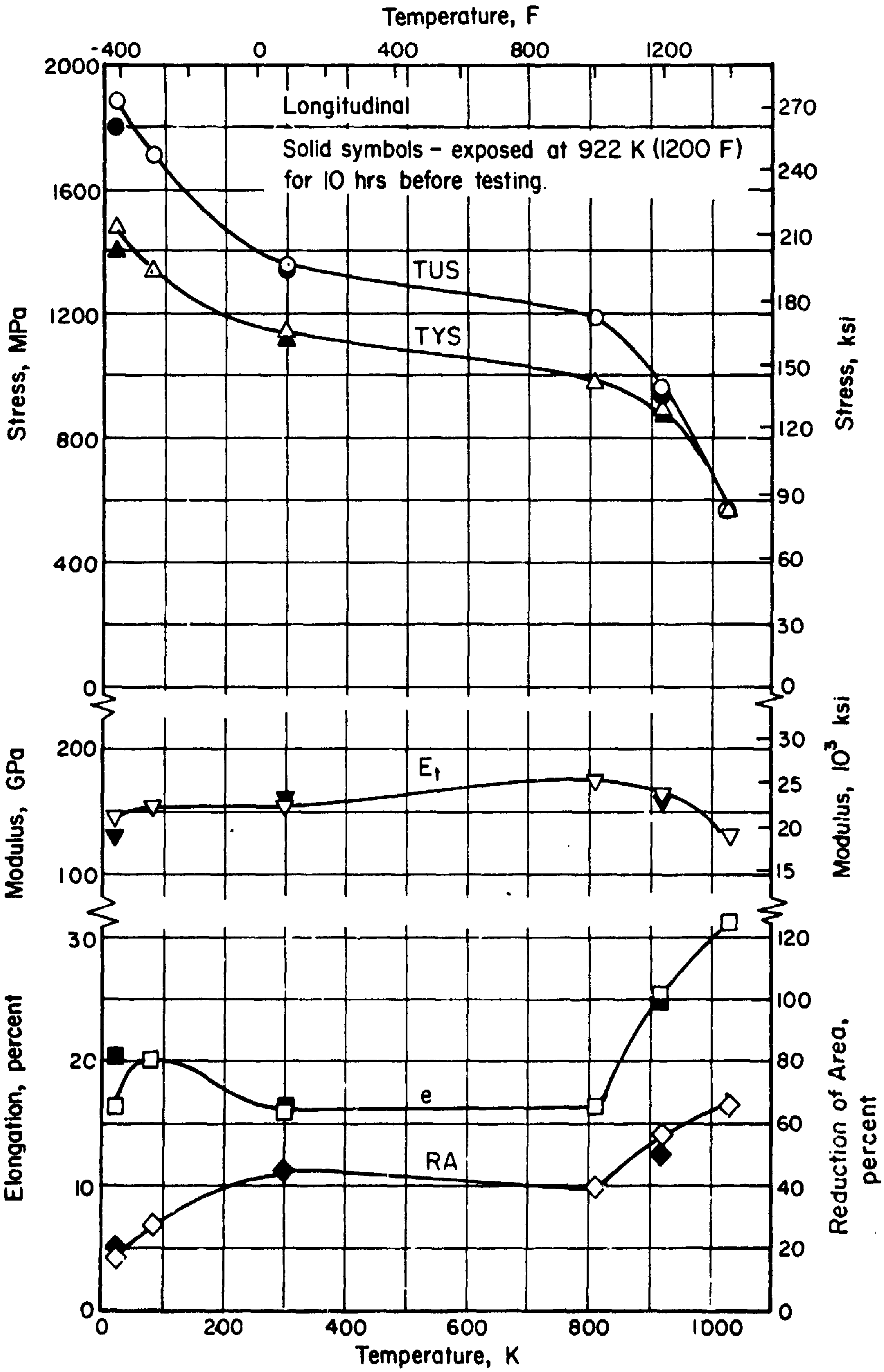


FIGURE 15. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF CTX-1 BAR, HEAT TREATMENT A

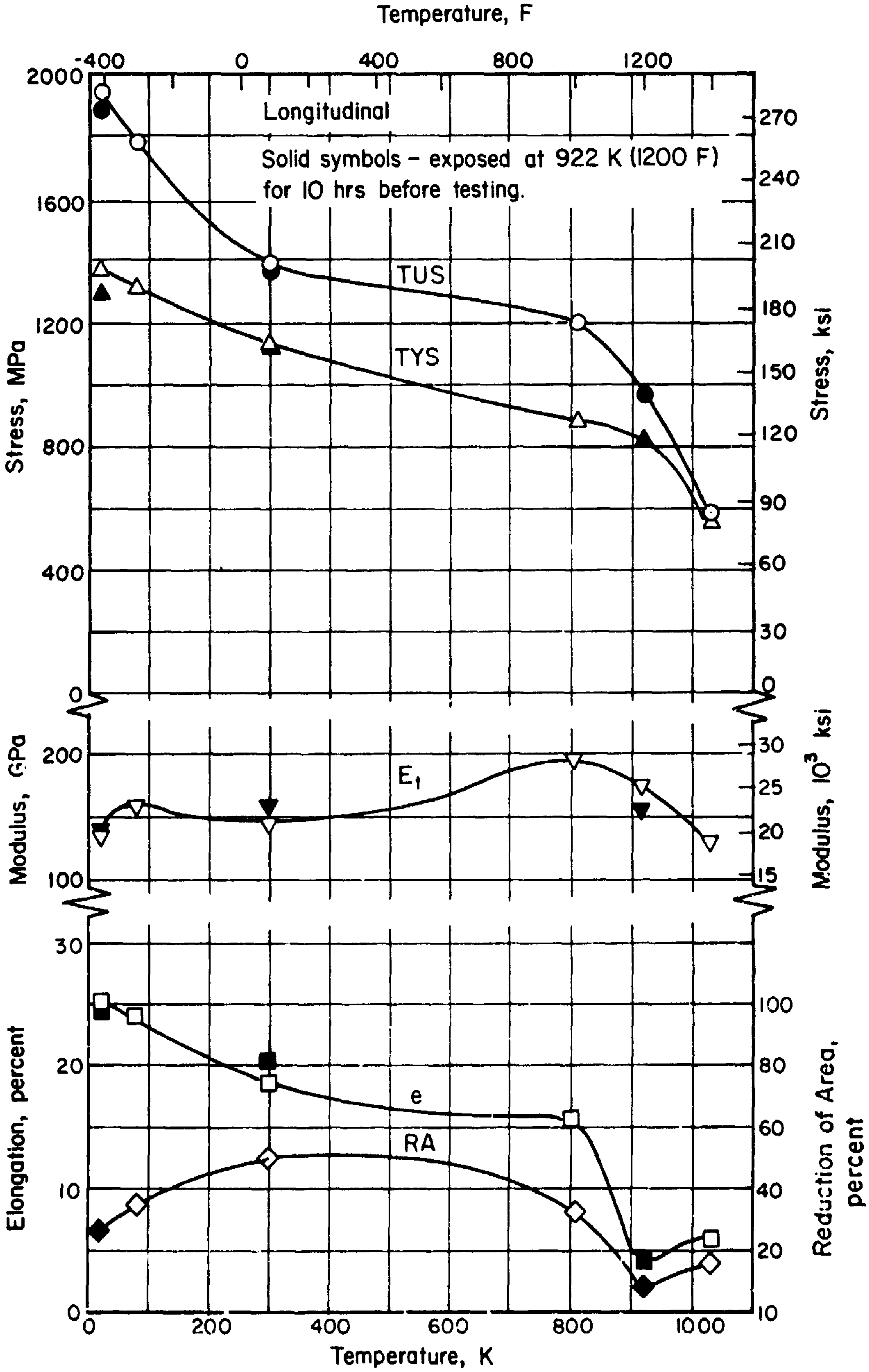


FIGURE 16. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF CTX-1 BAR, HEAT TREATMENT B

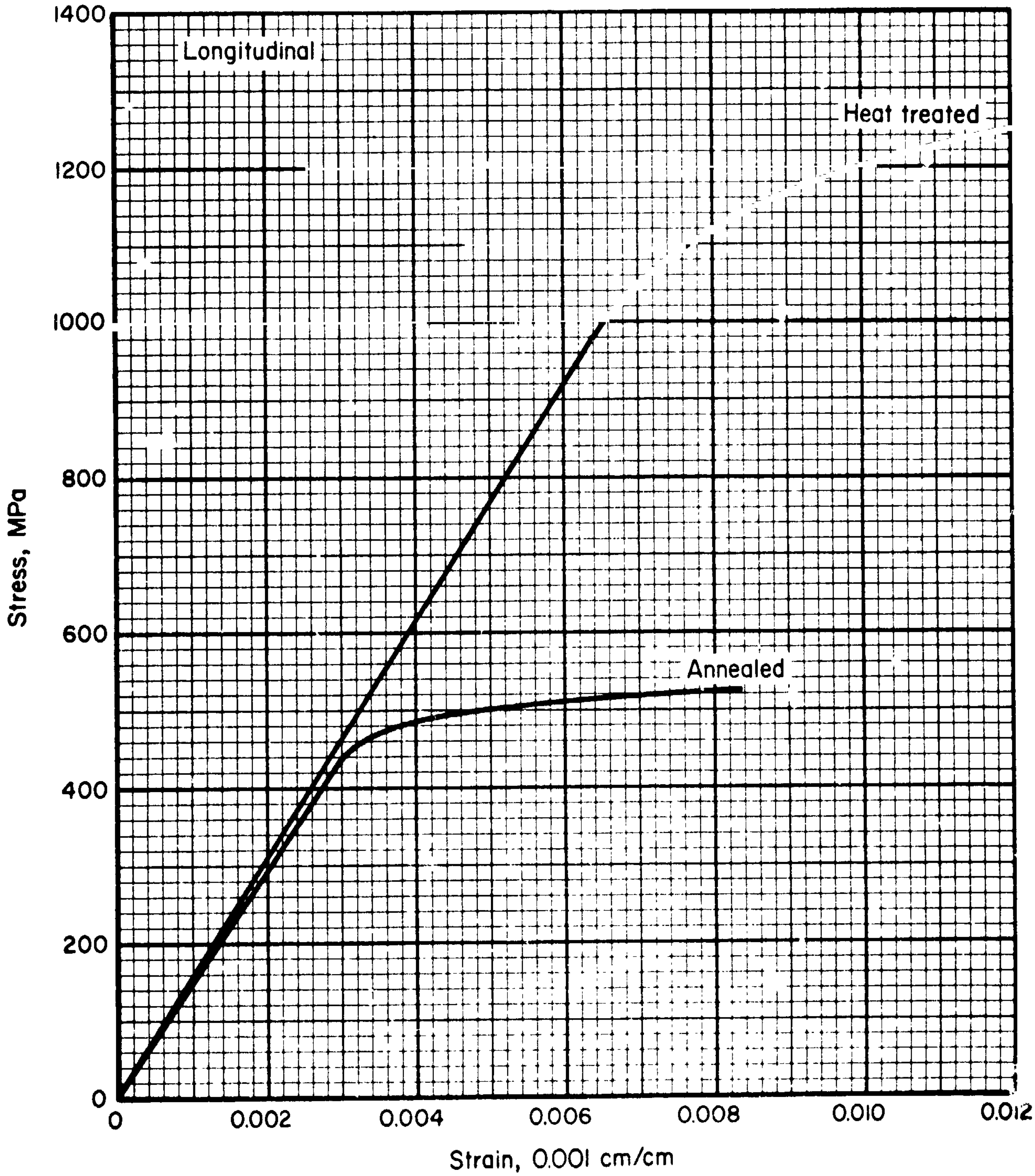


FIGURE 17. TYPICAL TENSILE STRESS-STRAIN CURVES FOR INCOLOY 903 SHEET AT ROOM TEMPERATURE

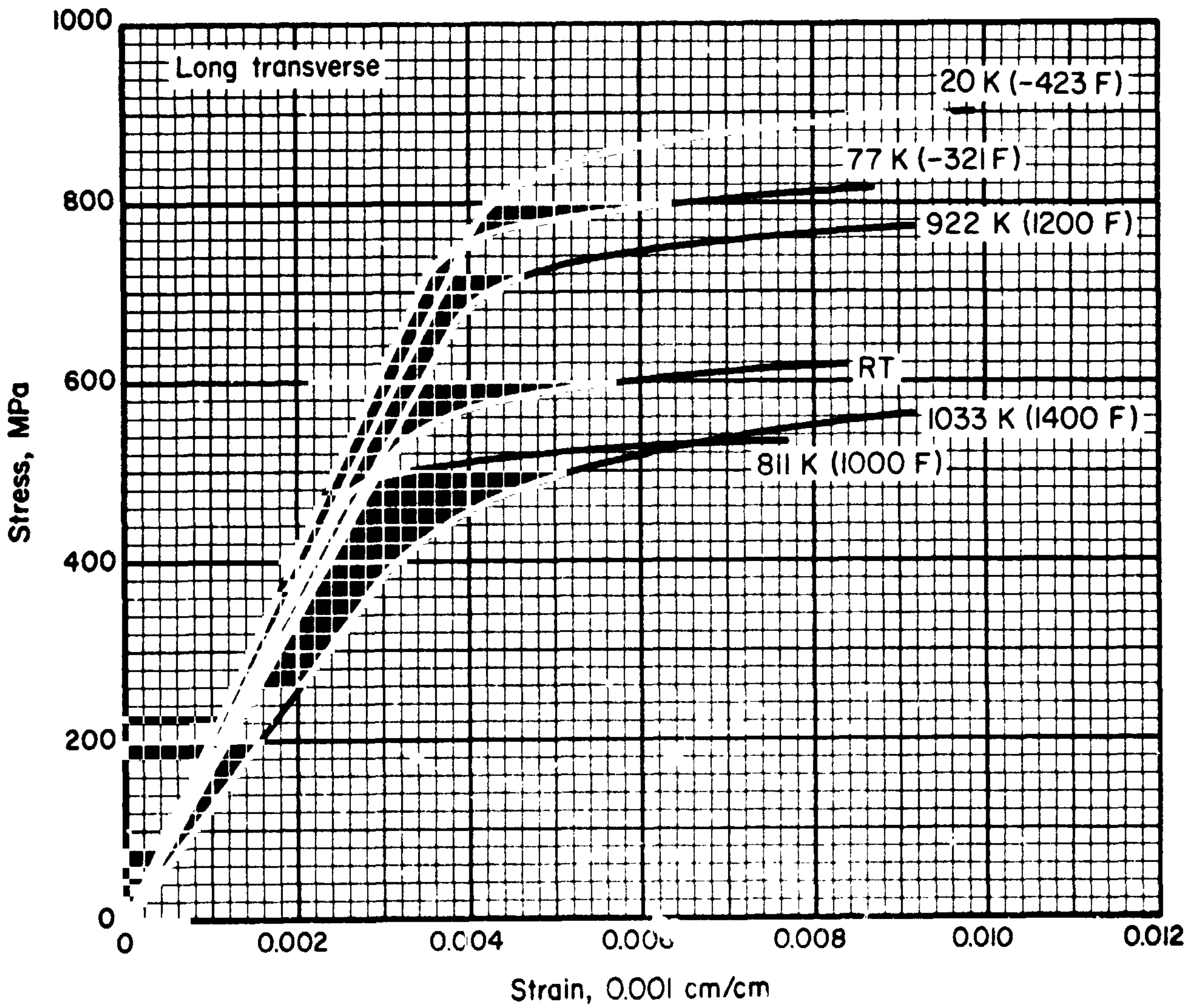


FIGURE 18. TYPICAL TENSILE STRESS-STRAIN CURVES FOR ANNEALED INCOLOY 903 SHEET AT VARIOUS TEMPERATURES

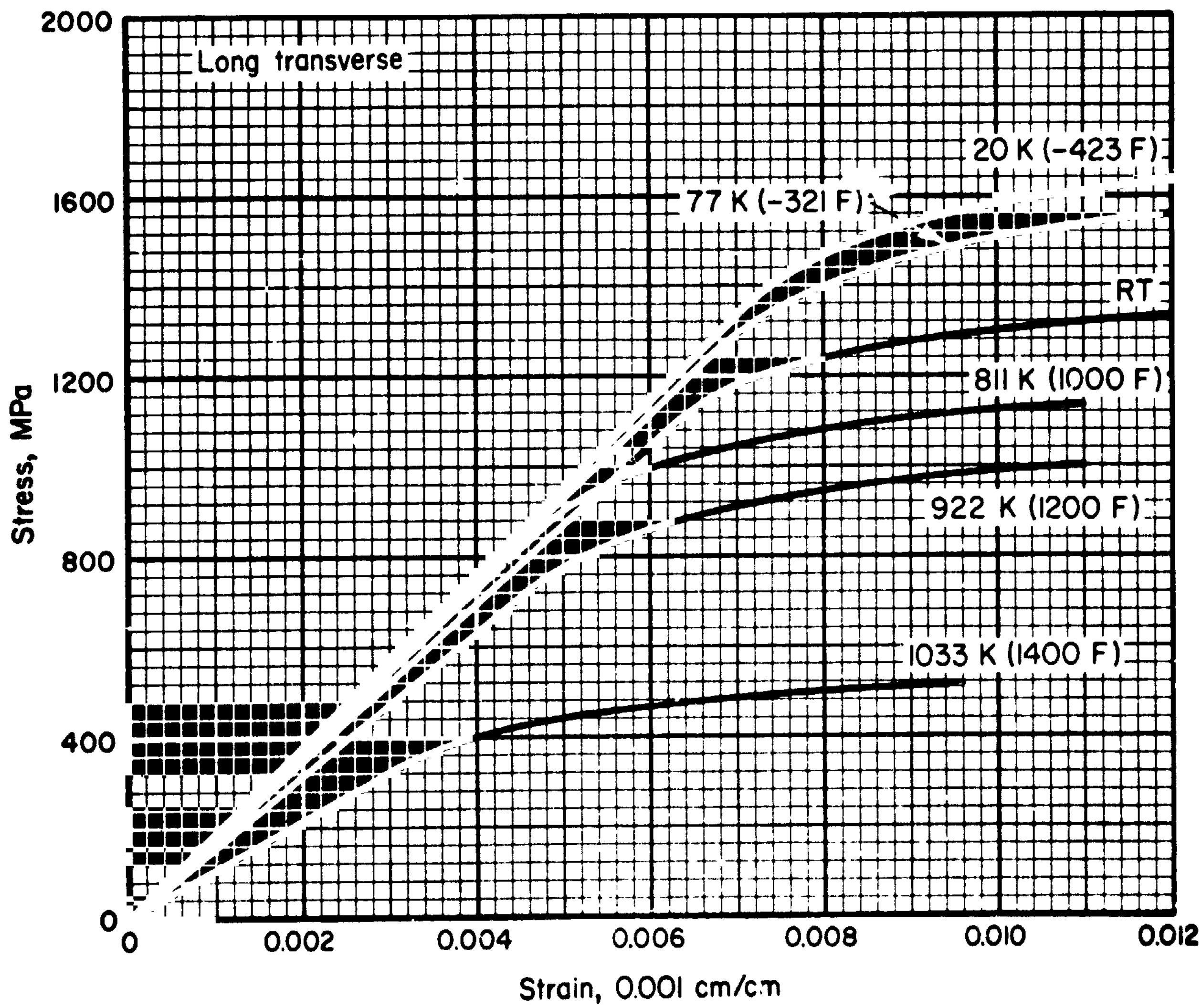


FIGURE 19. TYPICAL TENSILE STRESS-STRAIN CURVES FOR HEAT TREATED INCOLOY 903 SHEET AT VARIOUS TEMPERATURES

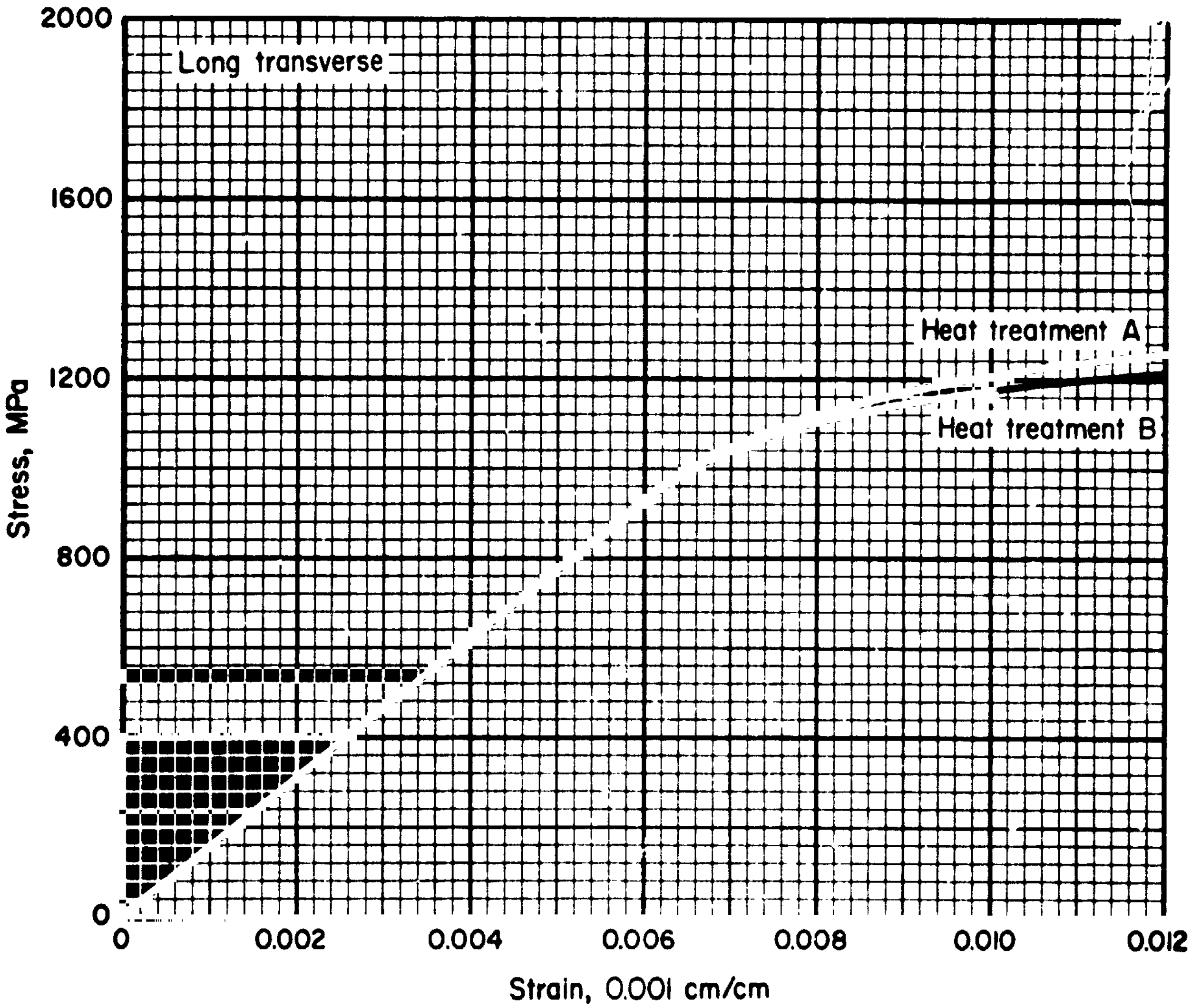


FIGURE 20. TYPICAL TENSILE STRESS-STRAIN CURVES FOR CTX-1 BAR AT ROOM TEMPERATURE

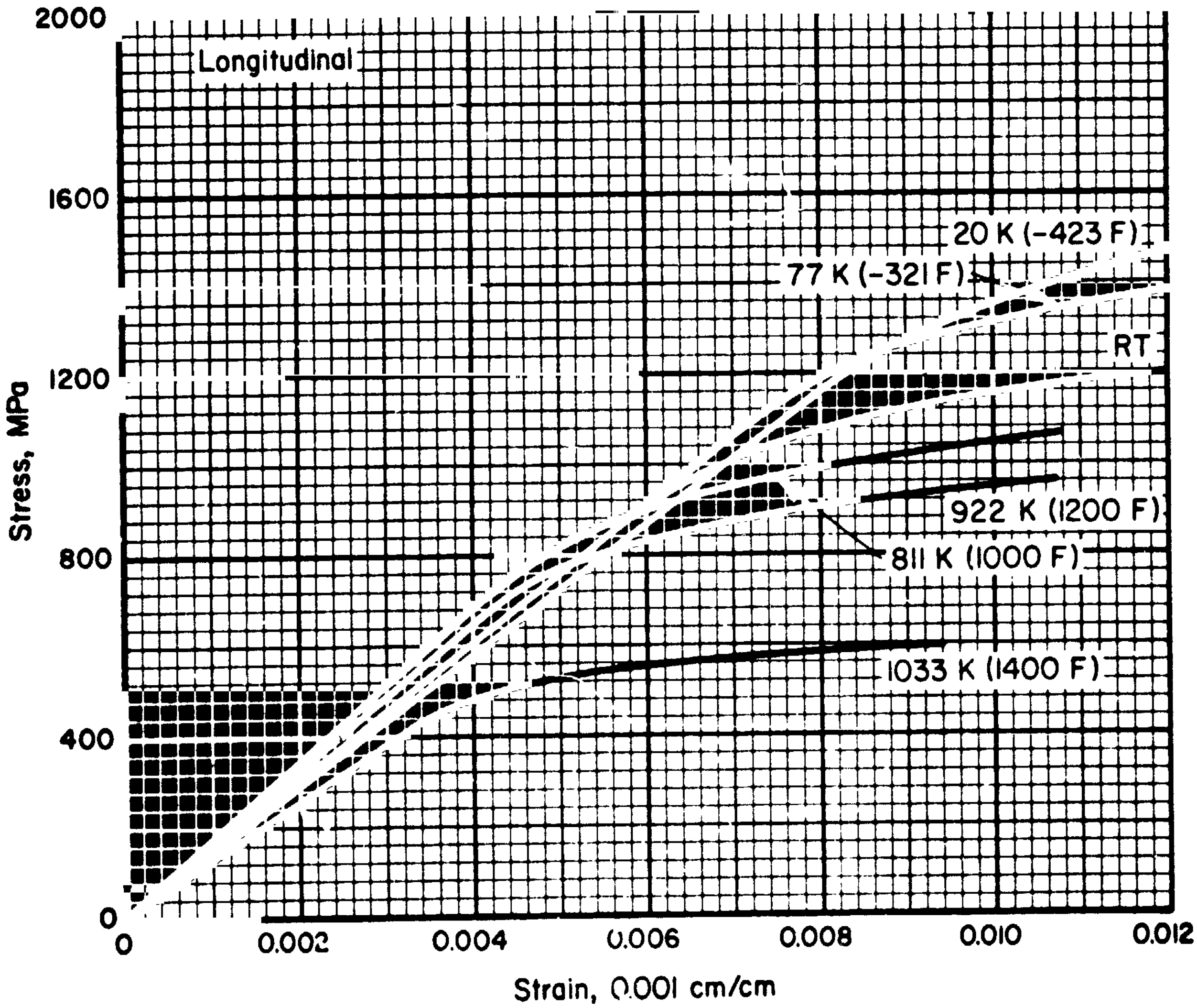


FIGURE 21. TYPICAL TENSILE STRESS-STRAIN CURVES FOR CTX-1 BAR, HEAT TREATMENT A, AT VARIOUS TEMPERATURES

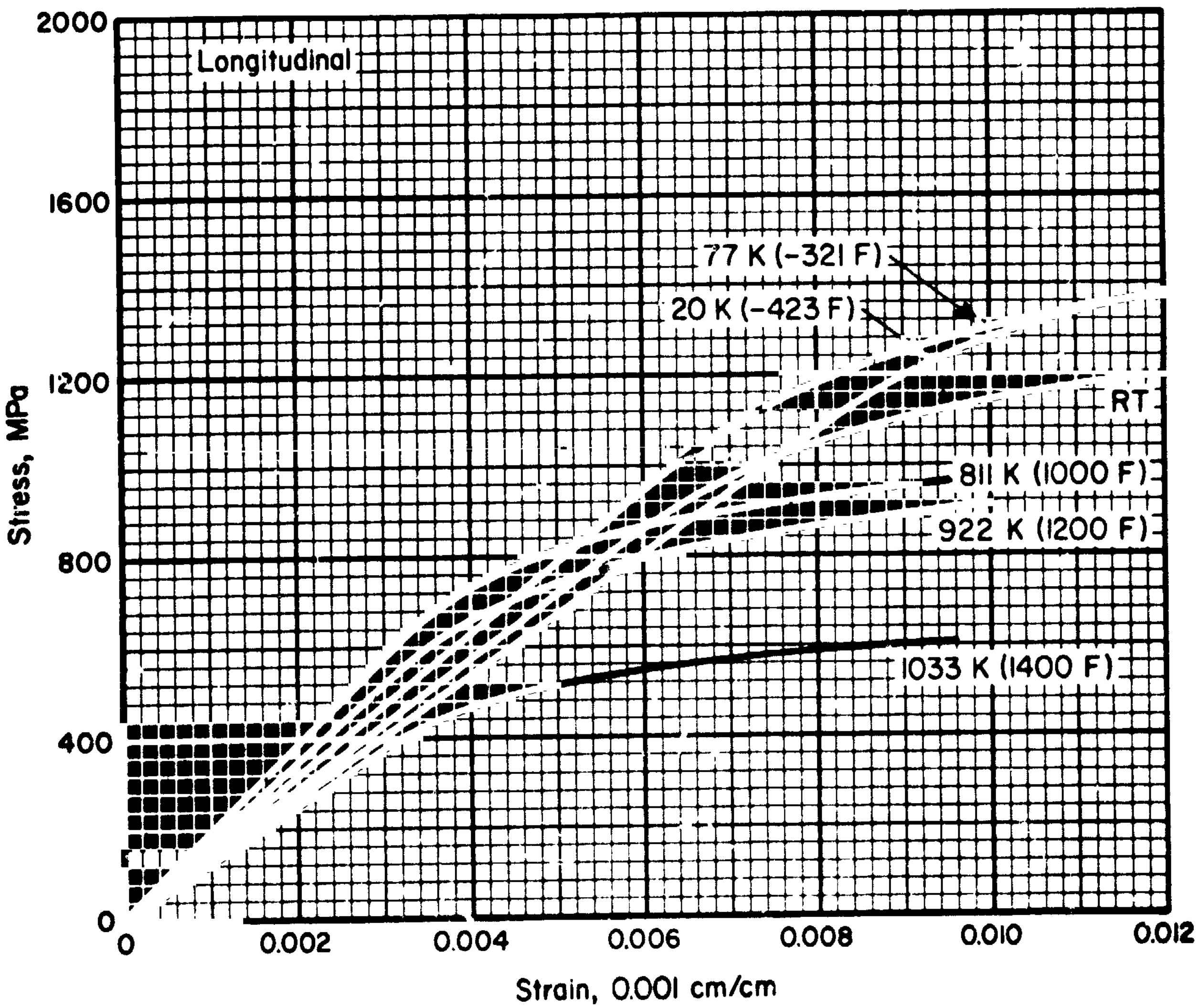


FIGURE 22. TYPICAL TENSILE STRESS-STRAIN CURVES FOR CTX-1 BAR, HEAT TREATMENT B, AT VARIOUS TEMPERATURES

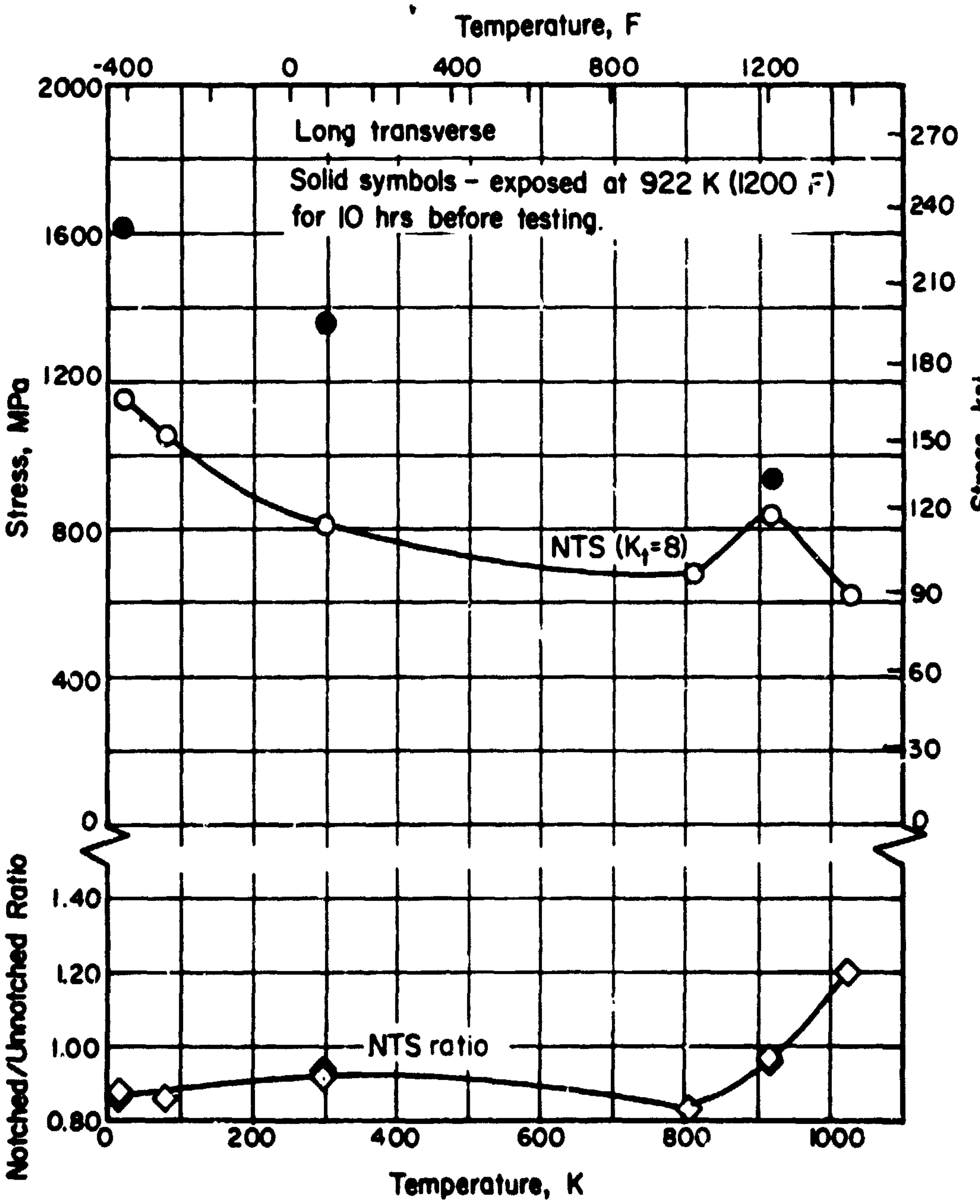


FIGURE 23. EFFECT OF TEMPERATURE ON THE NOTCHED TENSILE STRENGTH AND ON THE NOTCHED/UNNOTCHED TENSILE STRENGTH RATIO OF ANNEALED INCOLOY 903 SHEET

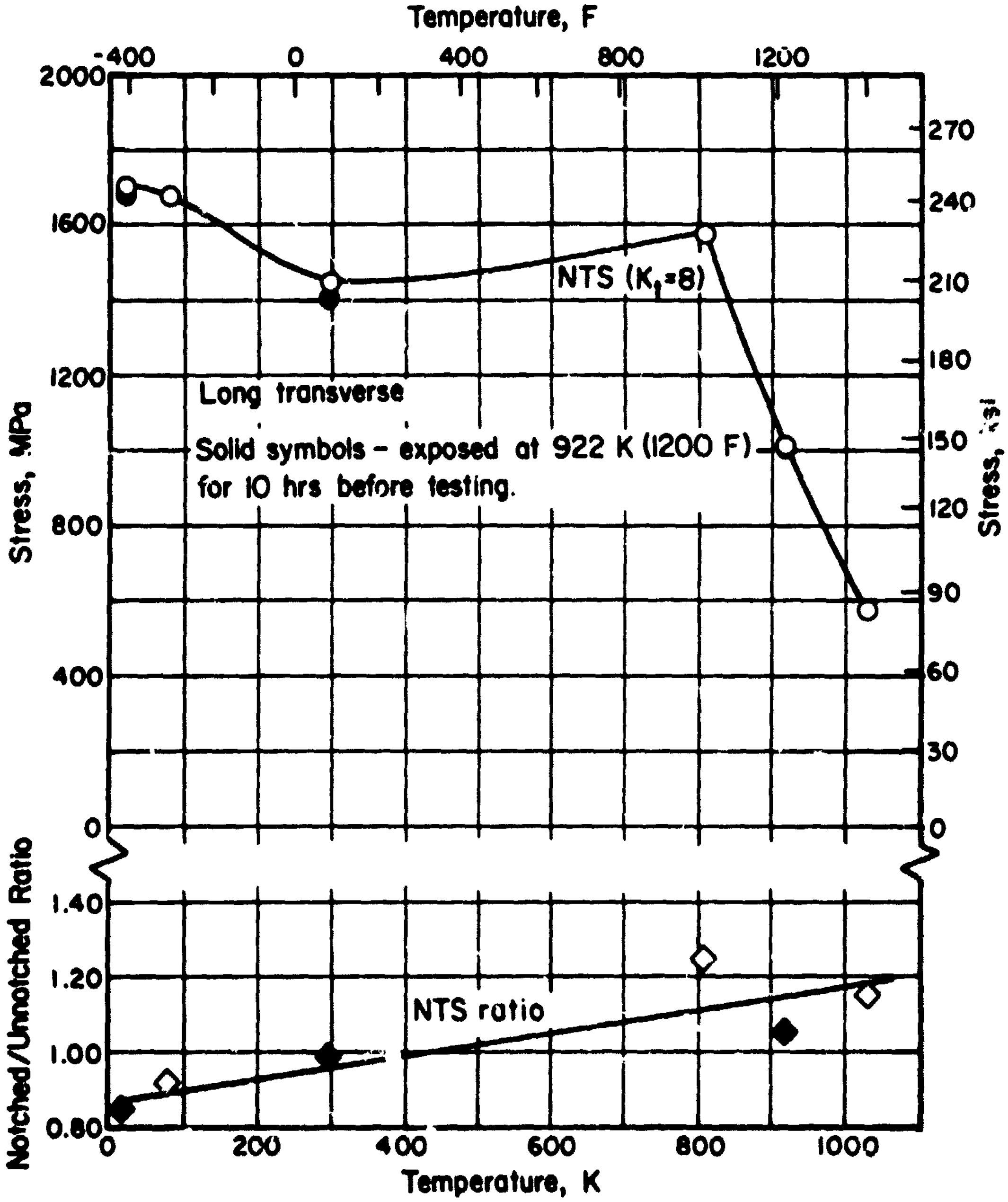


FIGURE 24. EFFECT OF TEMPERATURE ON THE NOTCHED TENSILE STRENGTH AND ON THE NOTCHED/UNNOTCHED TENSILE STRENGTH RATIO OF HEAT TREATED INCOLOY 903 SHEET

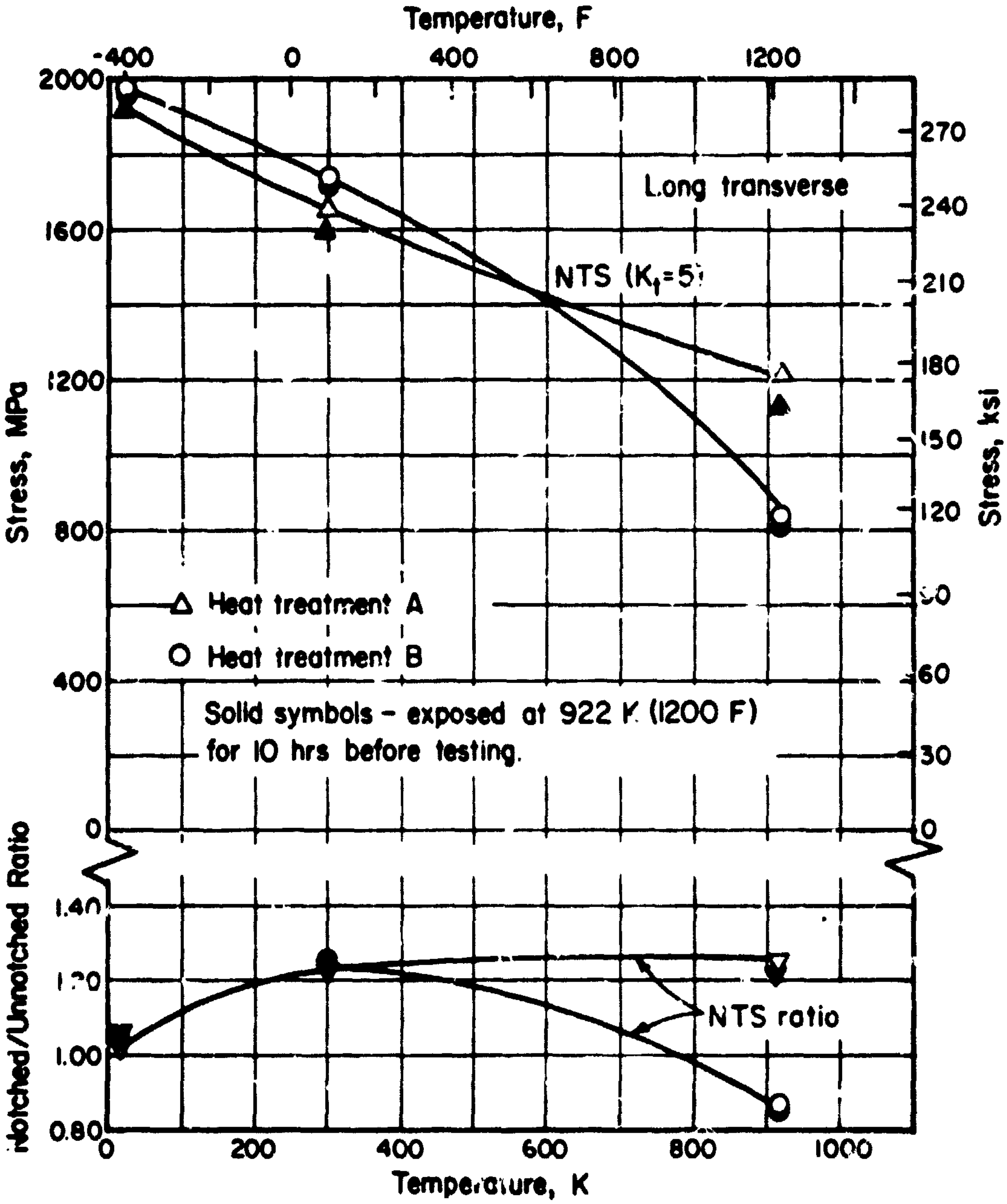


FIGURE 25. EFFECT OF TEMPERATURE ON THE NOTCHED TENSILE STRENGTH AND ON THE NOTCHED/UNNOTCHED TENSILE STRENGTH RATIO FOR CTX-1 BAR

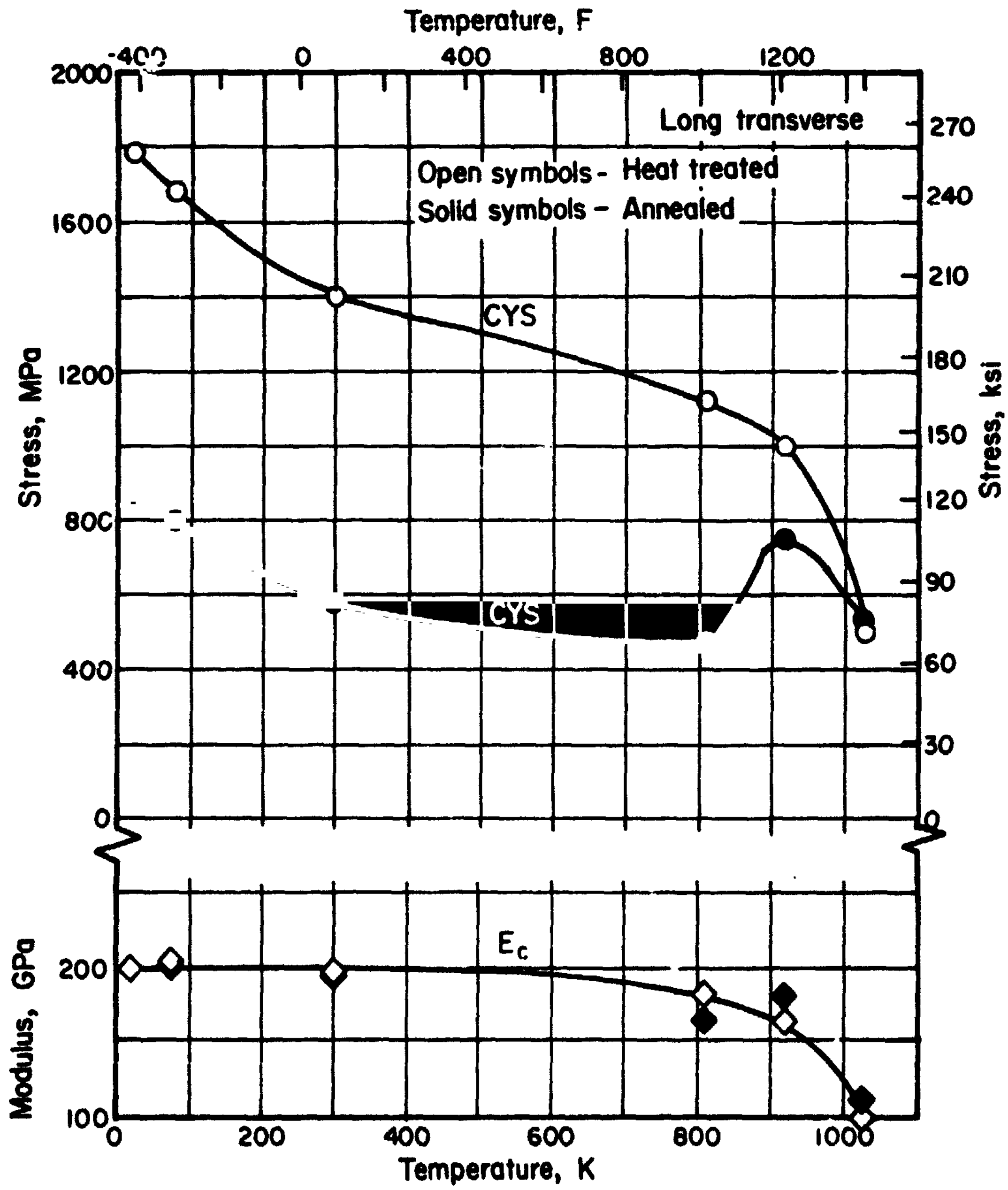


FIGURE 26. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF INCOLOY 903 SHEET

C-2

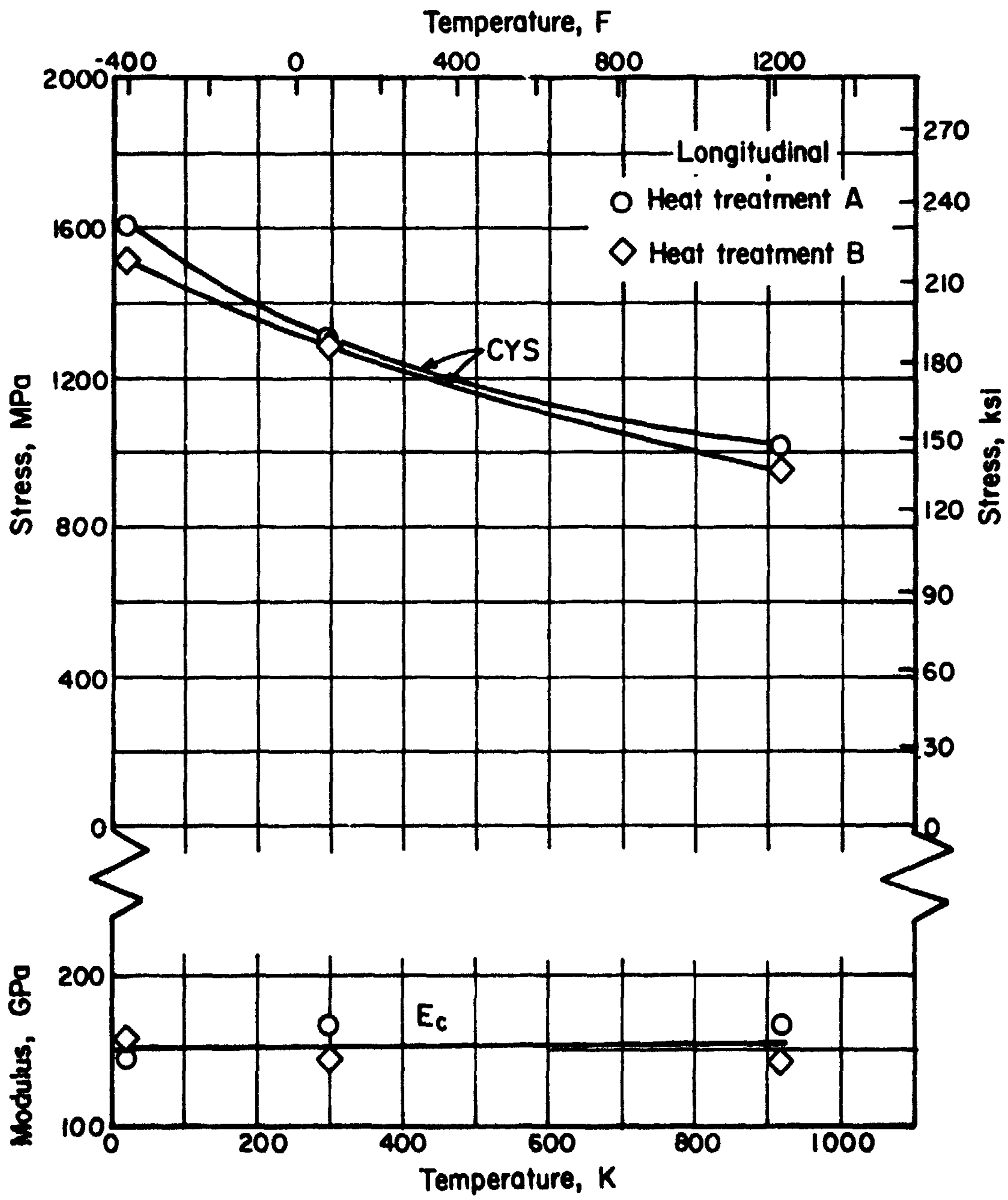


FIGURE 27. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF CTX-1 BAR

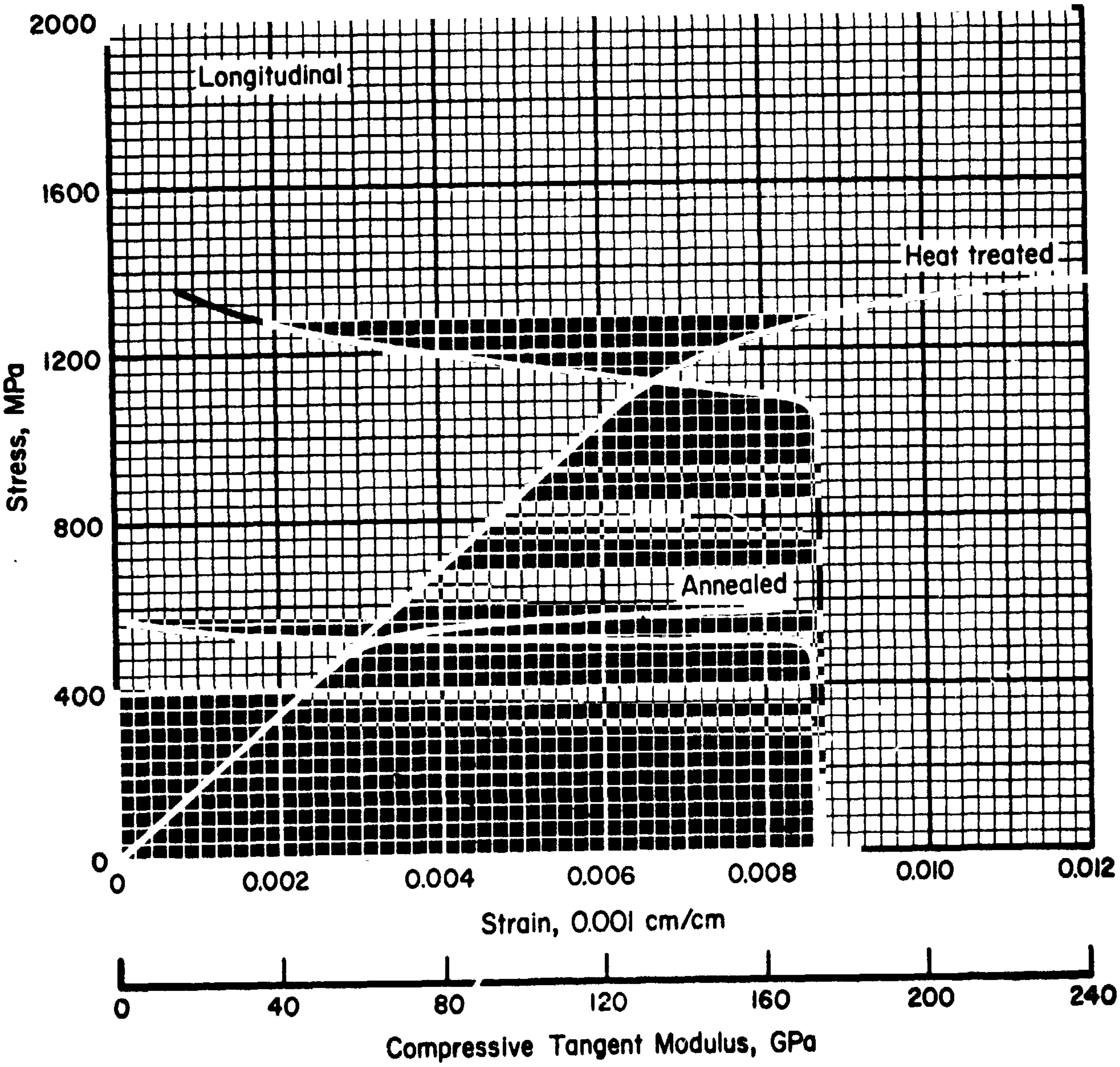


FIGURE 28. TYPICAL COMPRESSIVE STRESS-STRAIN AND COMPRESSIVE TANGENT MODULUS CURVES FOR INCOLOY 903 SHEET AT ROOM TEMPERATURE

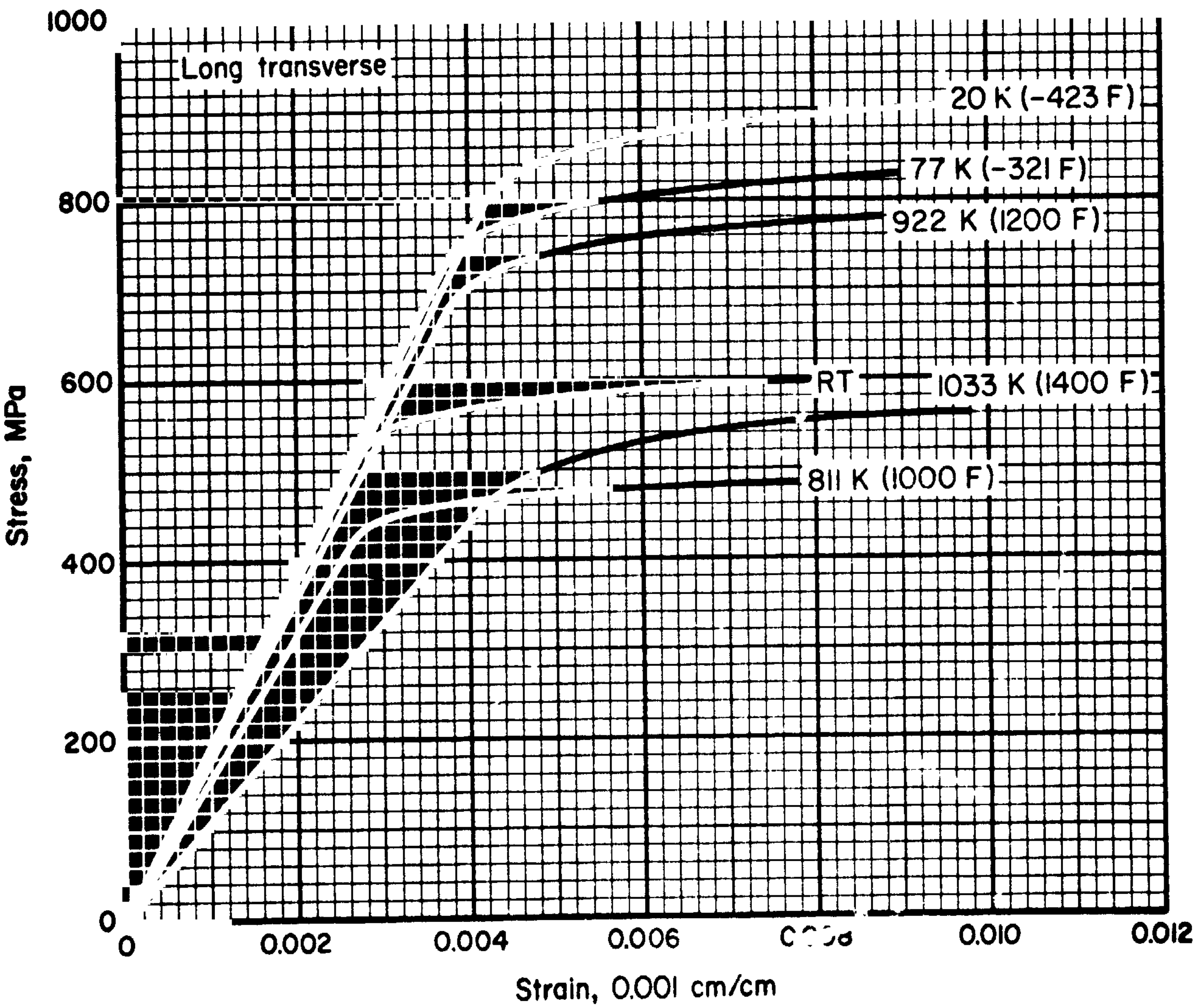


FIGURE 29. TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR ANNEALED INCOLOY 903 SHEET AT VARIOUS TEMPERATURES

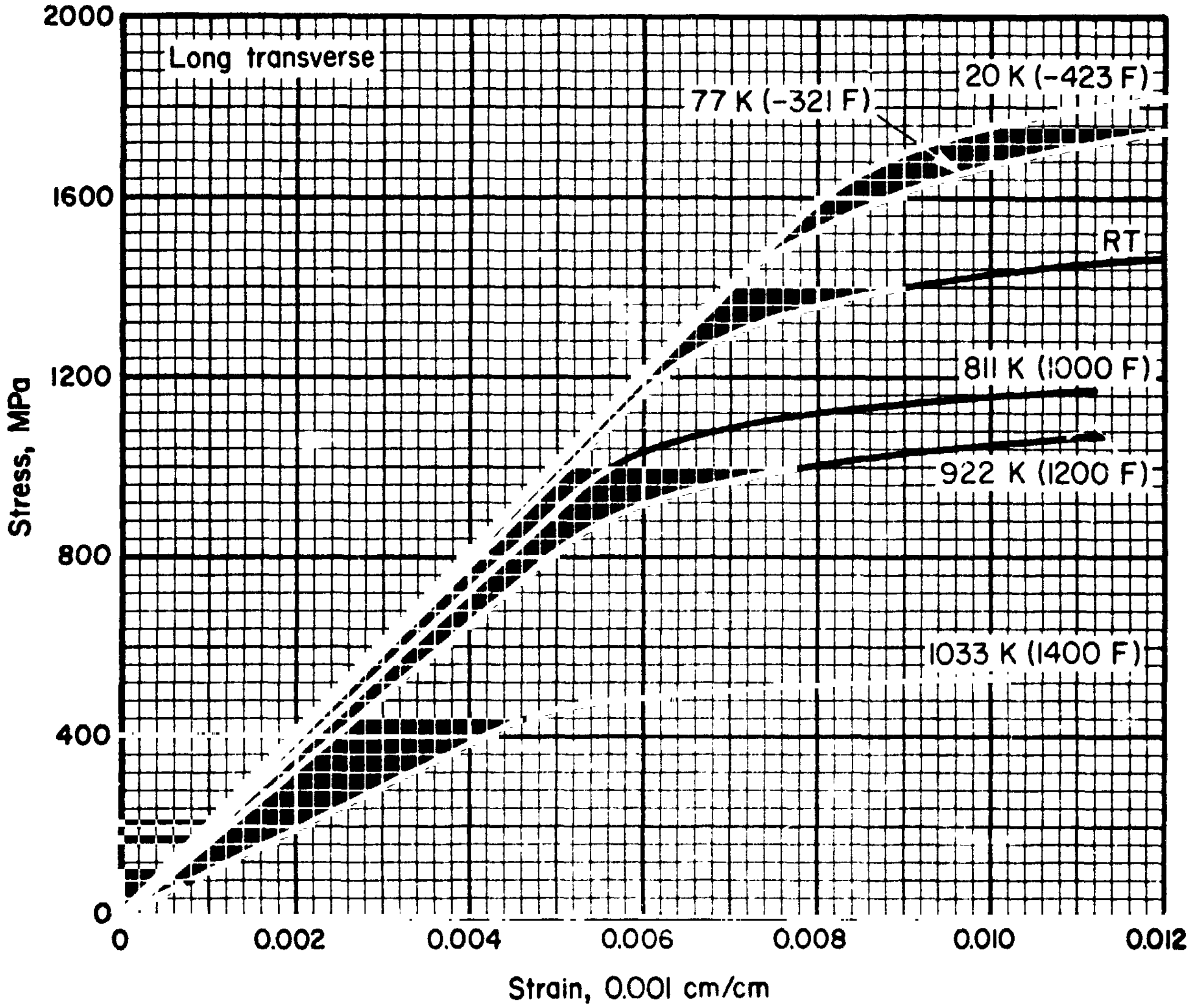


FIGURE 30. TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR HEAT TREATED INCOLOY 903 SHEET AT VARIOUS TEMPERATURES

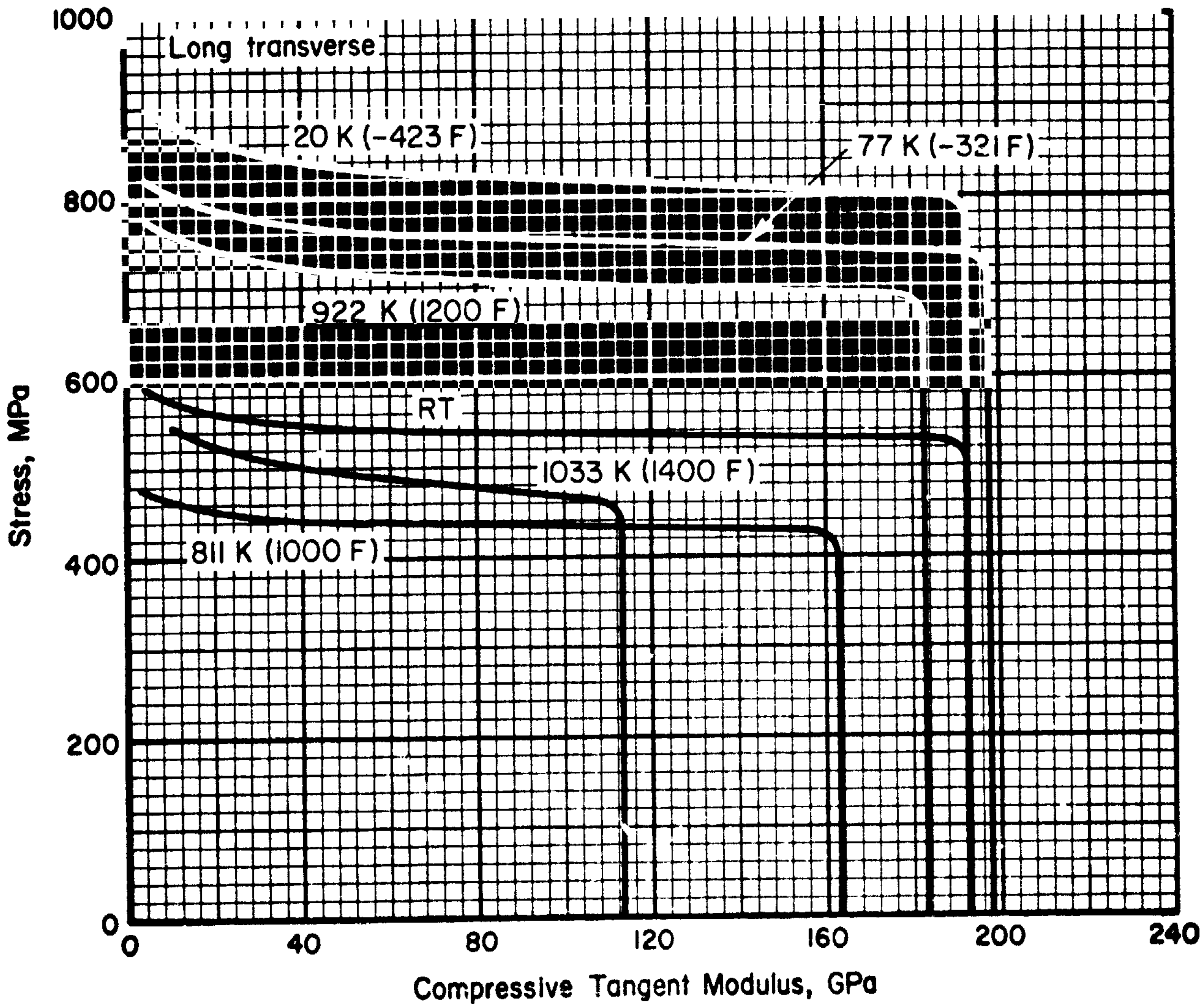


FIGURE 31. TYPICAL COMPRESSIVE TANGENT MODULUS CURVES FOR ANNEALED INCOLOY 903 SHEET AT VARIOUS TEMPERATURES

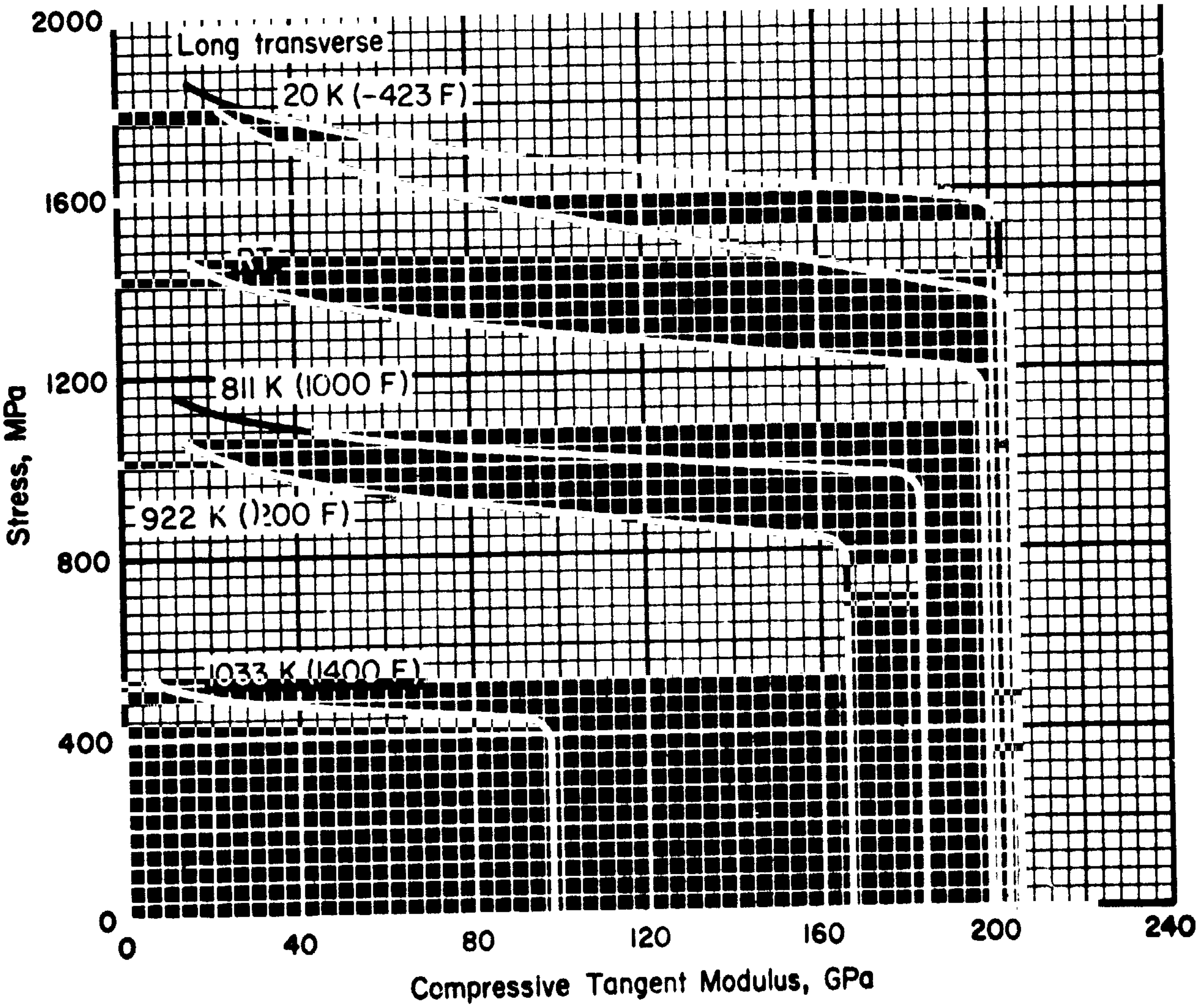


FIGURE 32. TYPICAL COMPRESSIVE TANGENT MODULUS CURVES FOR HEAT TREATED INCOLOY 903 SHEET AT VARIOUS TEMPERATURES

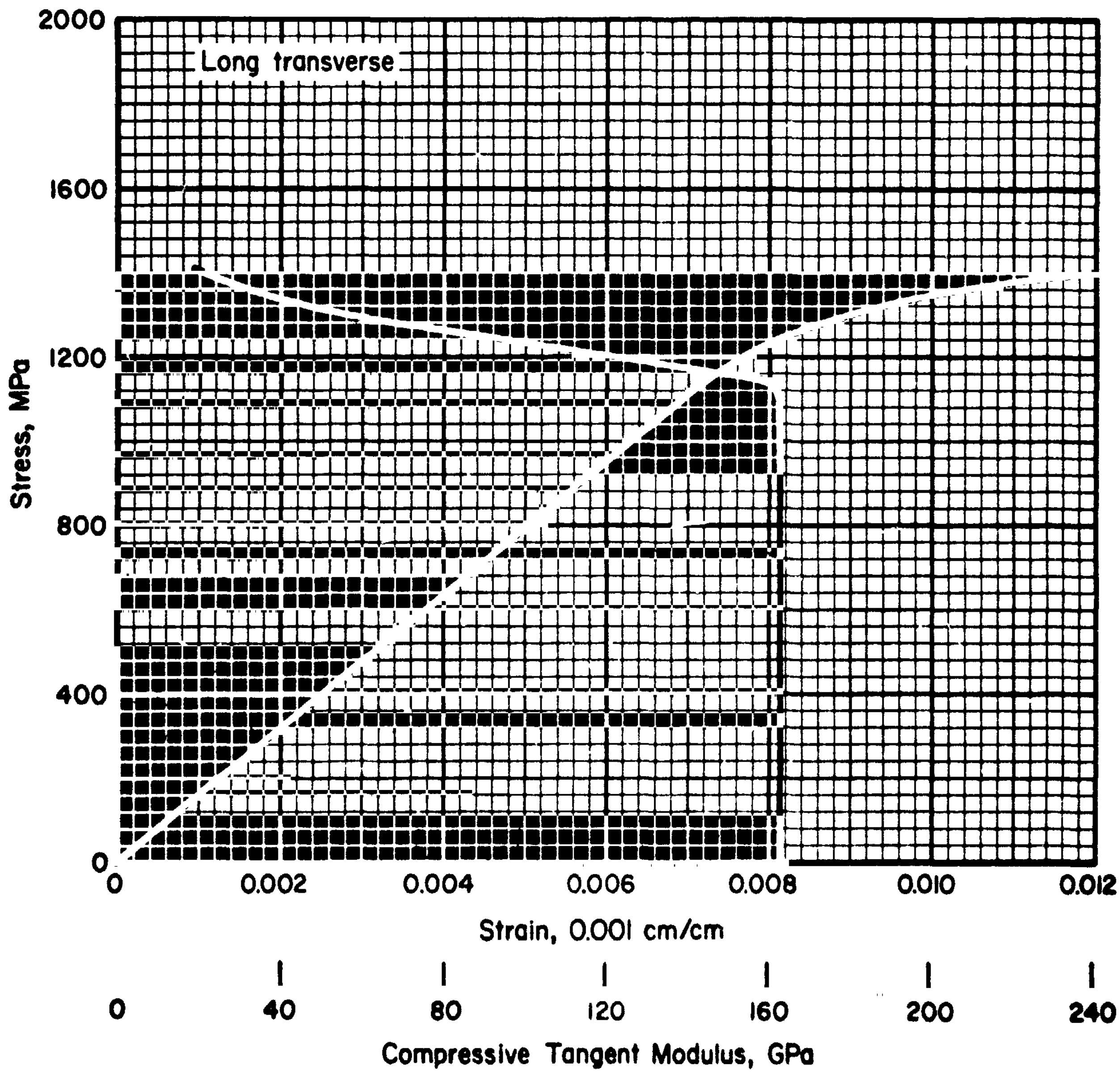


FIGURE 33. TYPICAL COMPRESSIVE STRESS-STRAIN AND COMPRESSIVE TANGENT MODULUS CURVES FOR CTX-1 BAR, HEAT TREATMENTS A AND B, AT ROOM TEMPERATURE

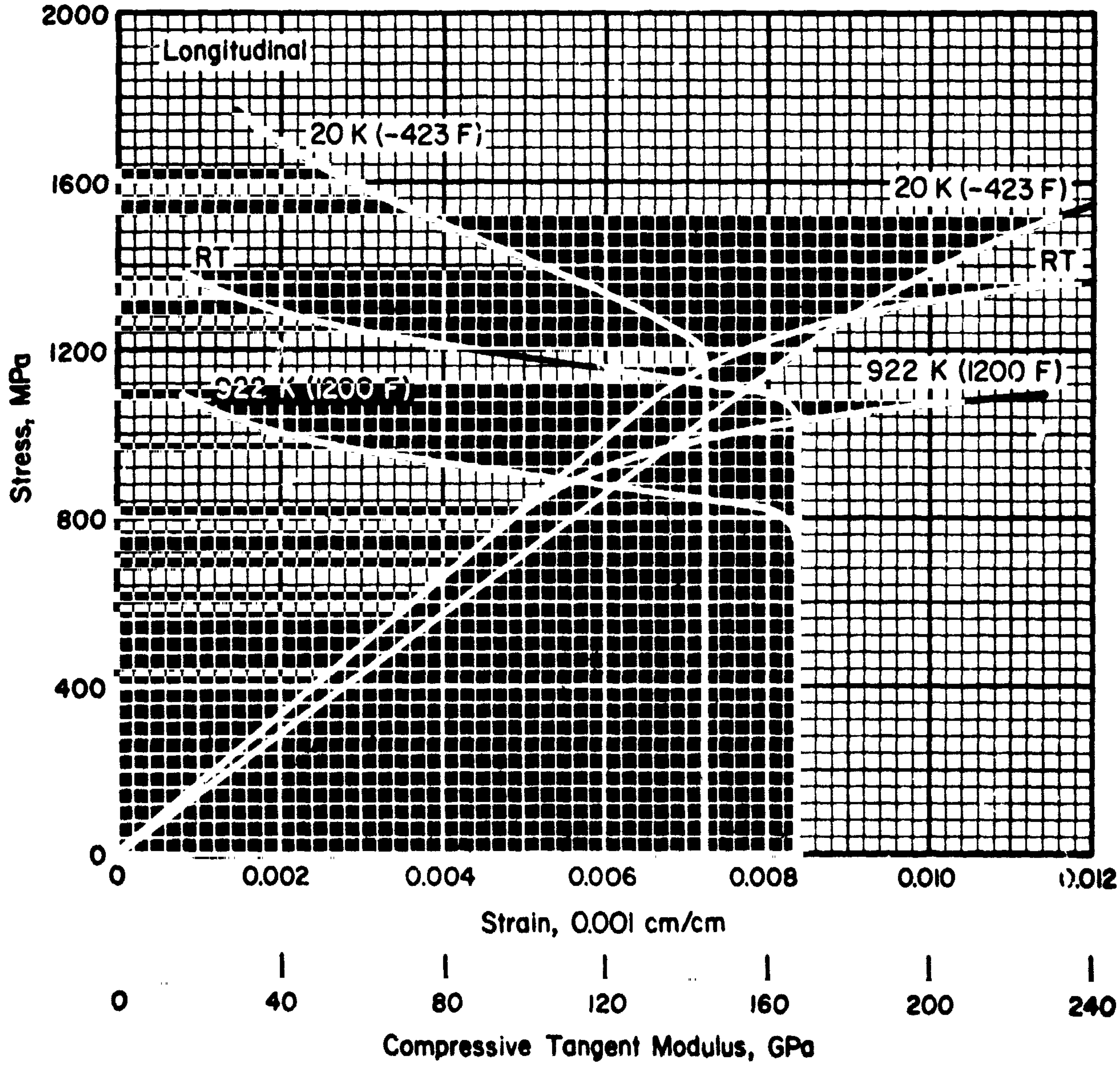


FIGURE 34. TYPICAL COMPRESSIVE STRESS-STRAIN AND COMPRESSIVE TANGENT MODULUS CURVES FOR CTX-1 BAR, HEAT TREATMENT A, AT VARIOUS TEMPERATURES

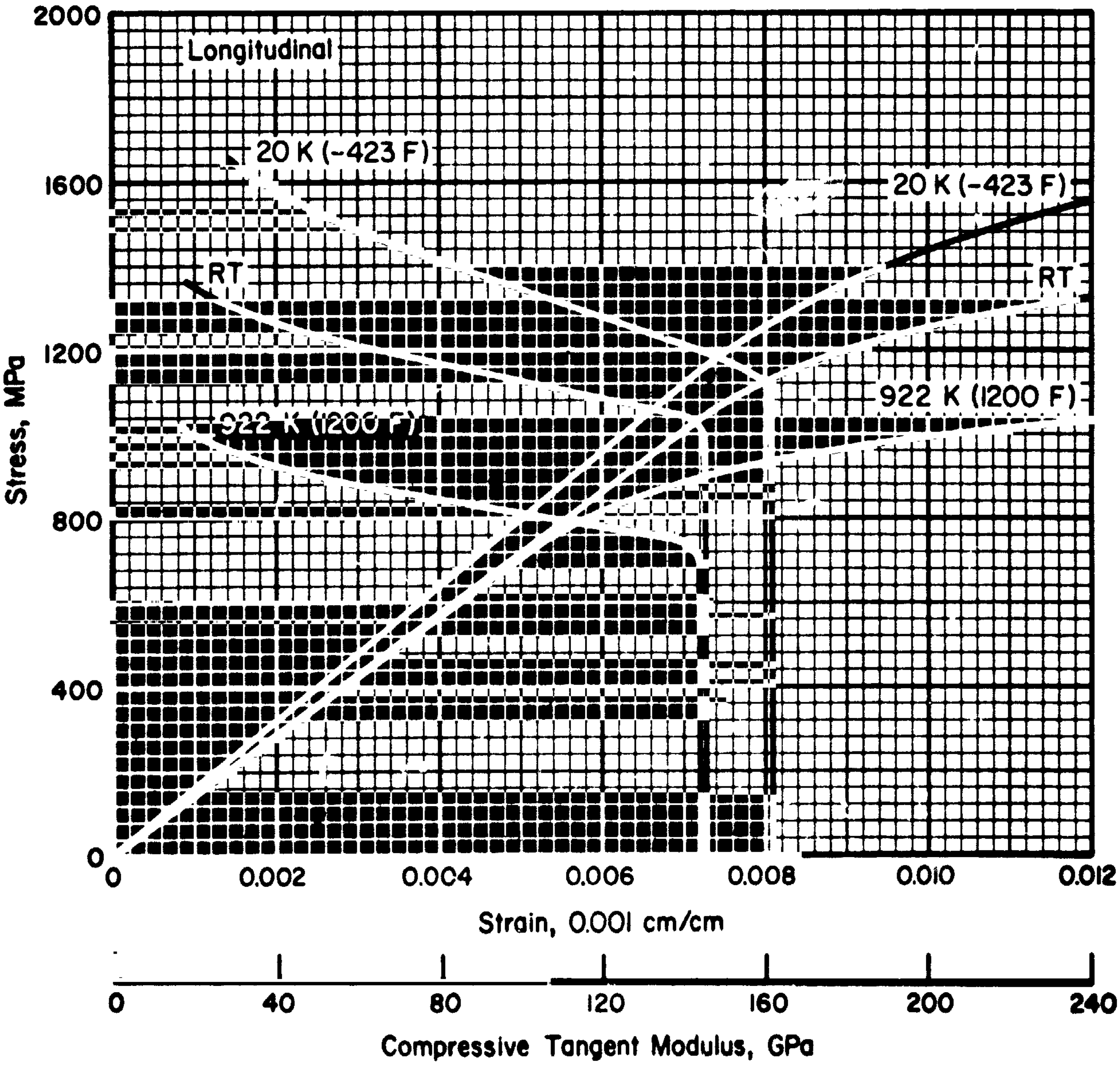


FIGURE 35. TYPICAL COMPRESSIVE STRESS-STRAIN AND COMPRESSIVE TANGENT MODULUS CURVES FOR CTX-1 BAR, HEAT TREATMENT B, AT VARIOUS TEMPERATURES

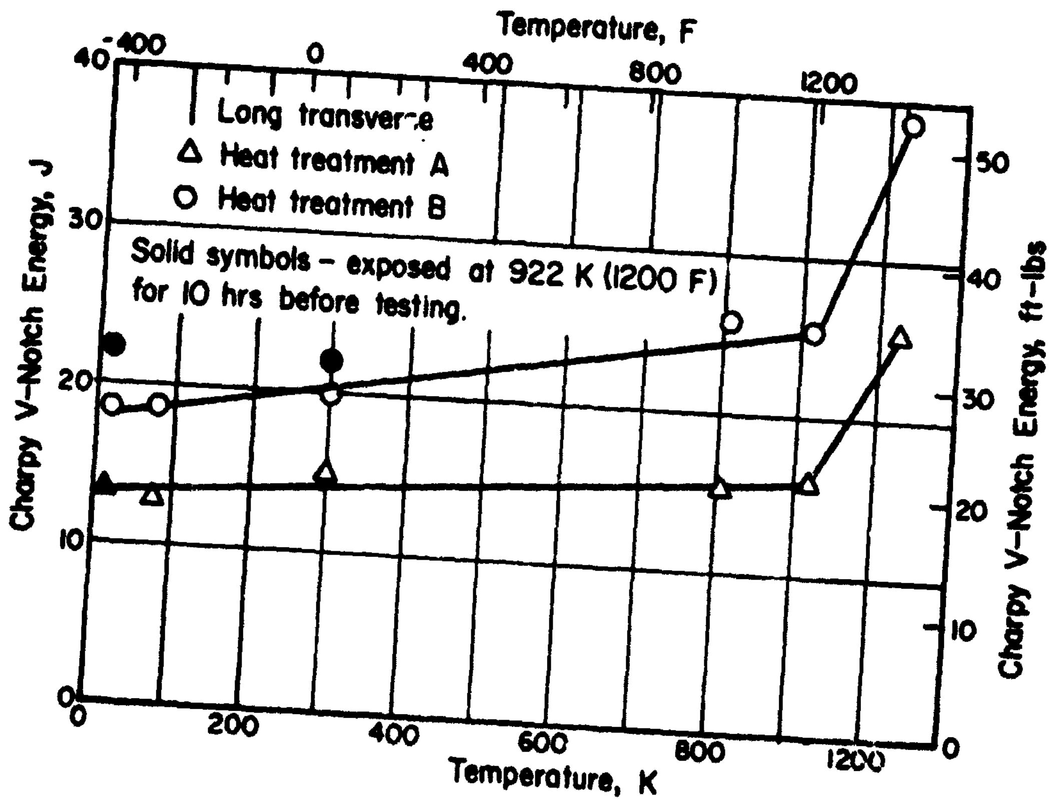


FIGURE 36. EFFECT OF TEMPERATURE ON THE CHARPY V-NOTCH IMPACT ENERGY OF CTX-1 BAR

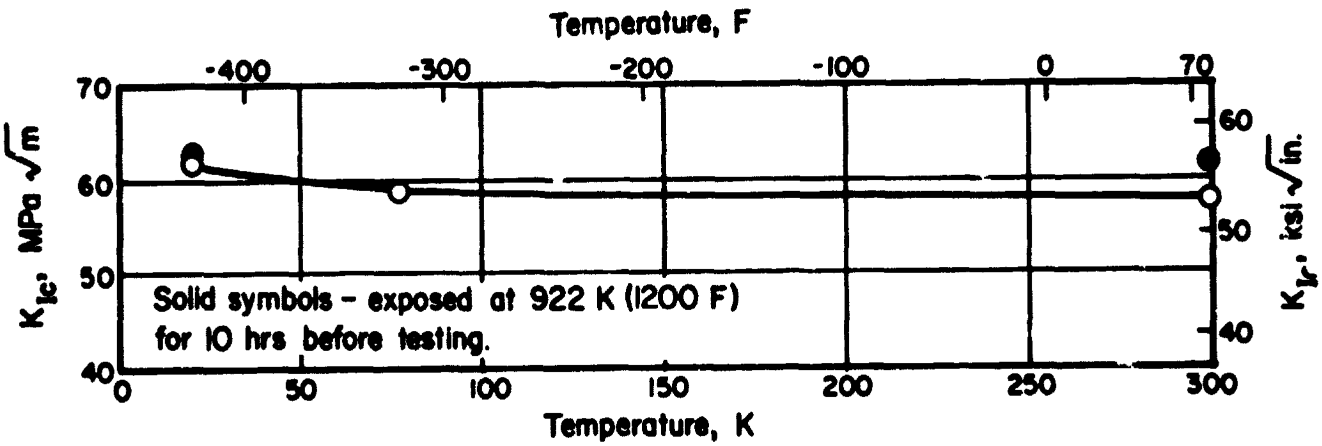


FIGURE 37. EFFECT OF TEMPERATURE ON THE FRACTURE TOUGHNESS OF CTX-1 ALLOY BAR, HEAT TREATMENT A (T-L DIRECTION)

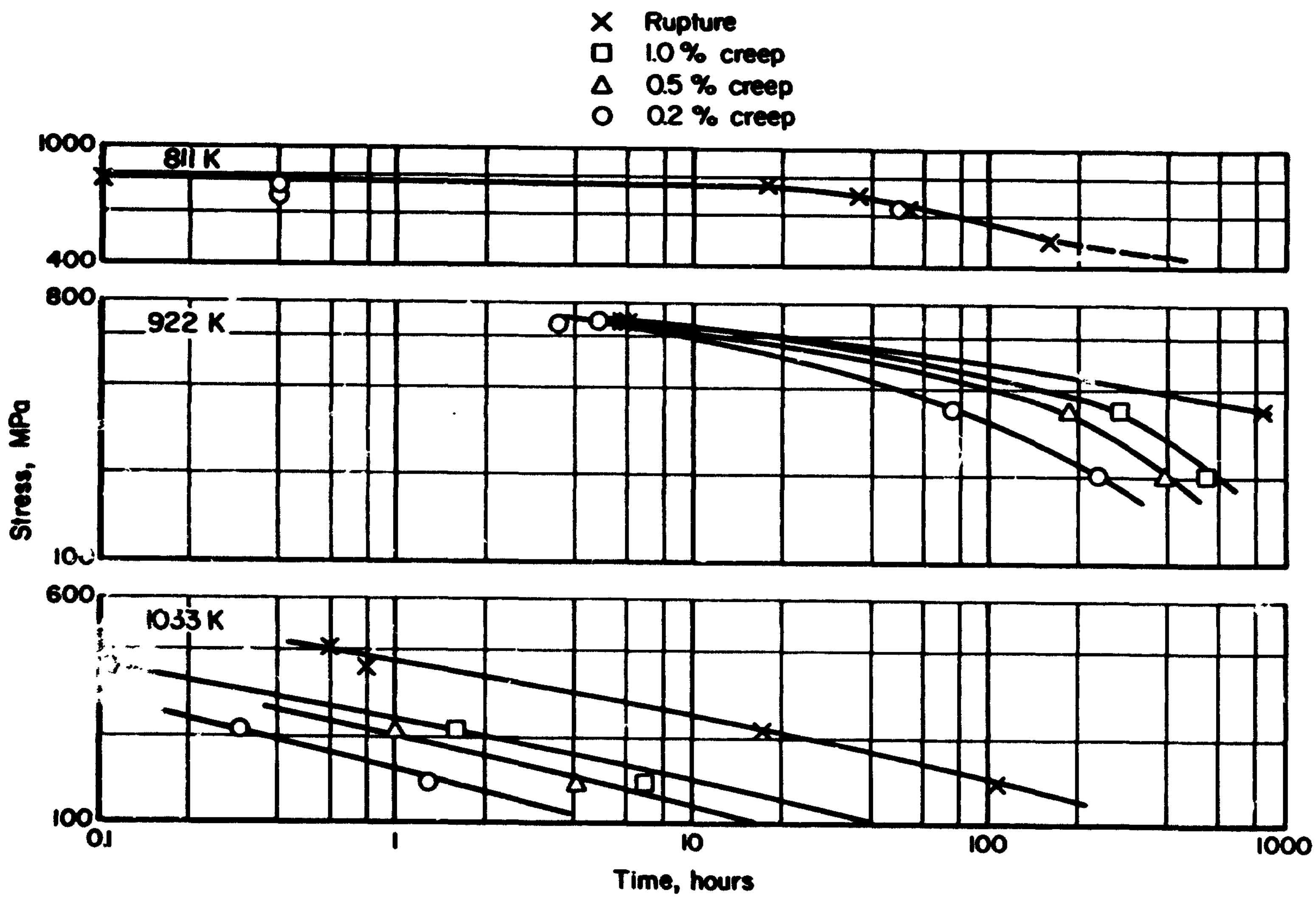


FIGURE 38. CREEP-RUPTURE CURVES FOR ANNEALED INCOLOY 903 SHEET (SI UNITS)

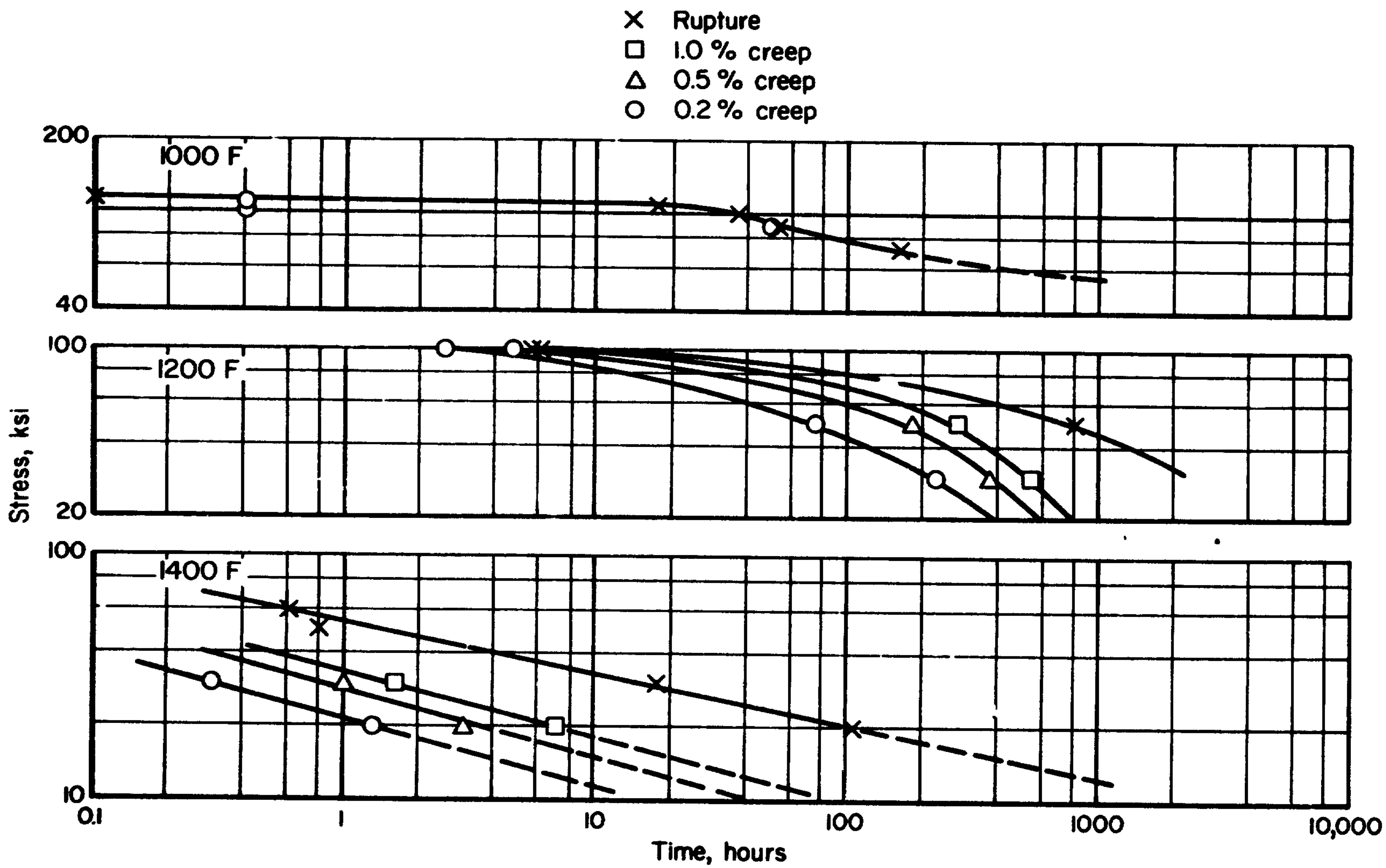


FIGURE 39. CREEP-RUPTURE CURVES FOR ANNEALED INCOLOY 903 SHEET

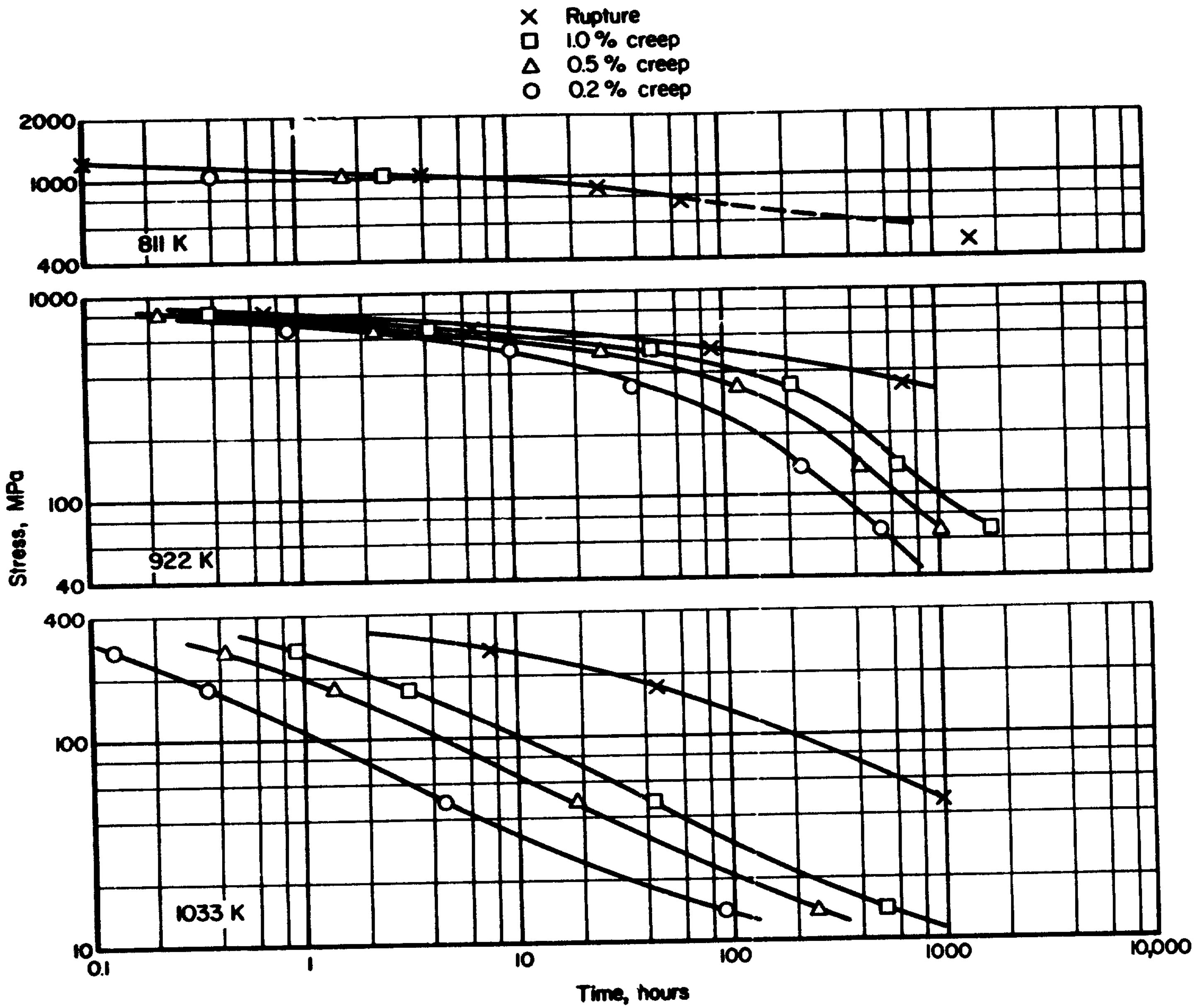


FIGURE 40. CREEP-RUPTURE CURVES FOR HEAT TREATED INCOLOY 903 SHEET (SI UNITS)

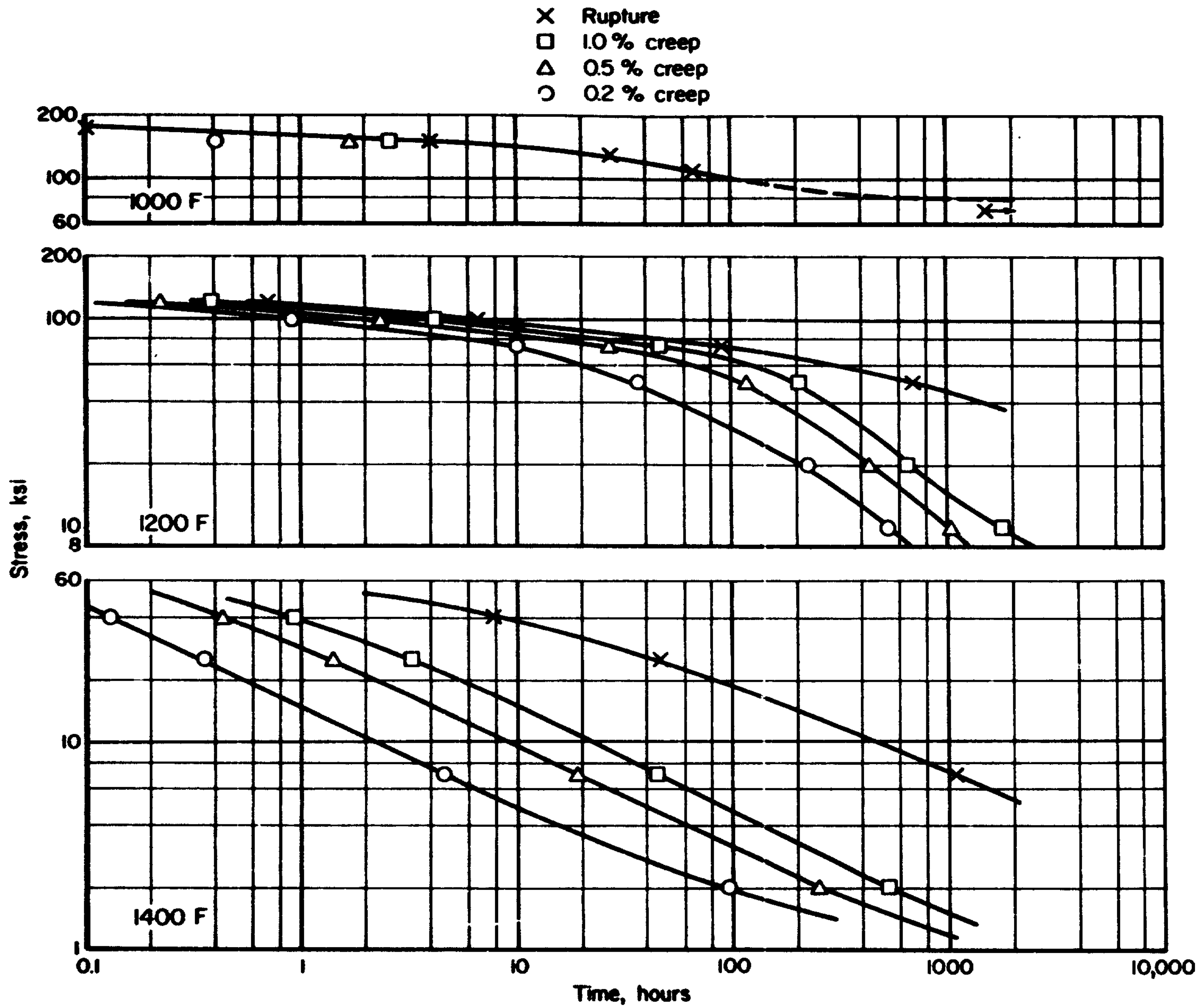


FIGURE 41. CREEP-RUPTURE CURVES FOR HEAT TREATED INCOLOY 903 SHEET

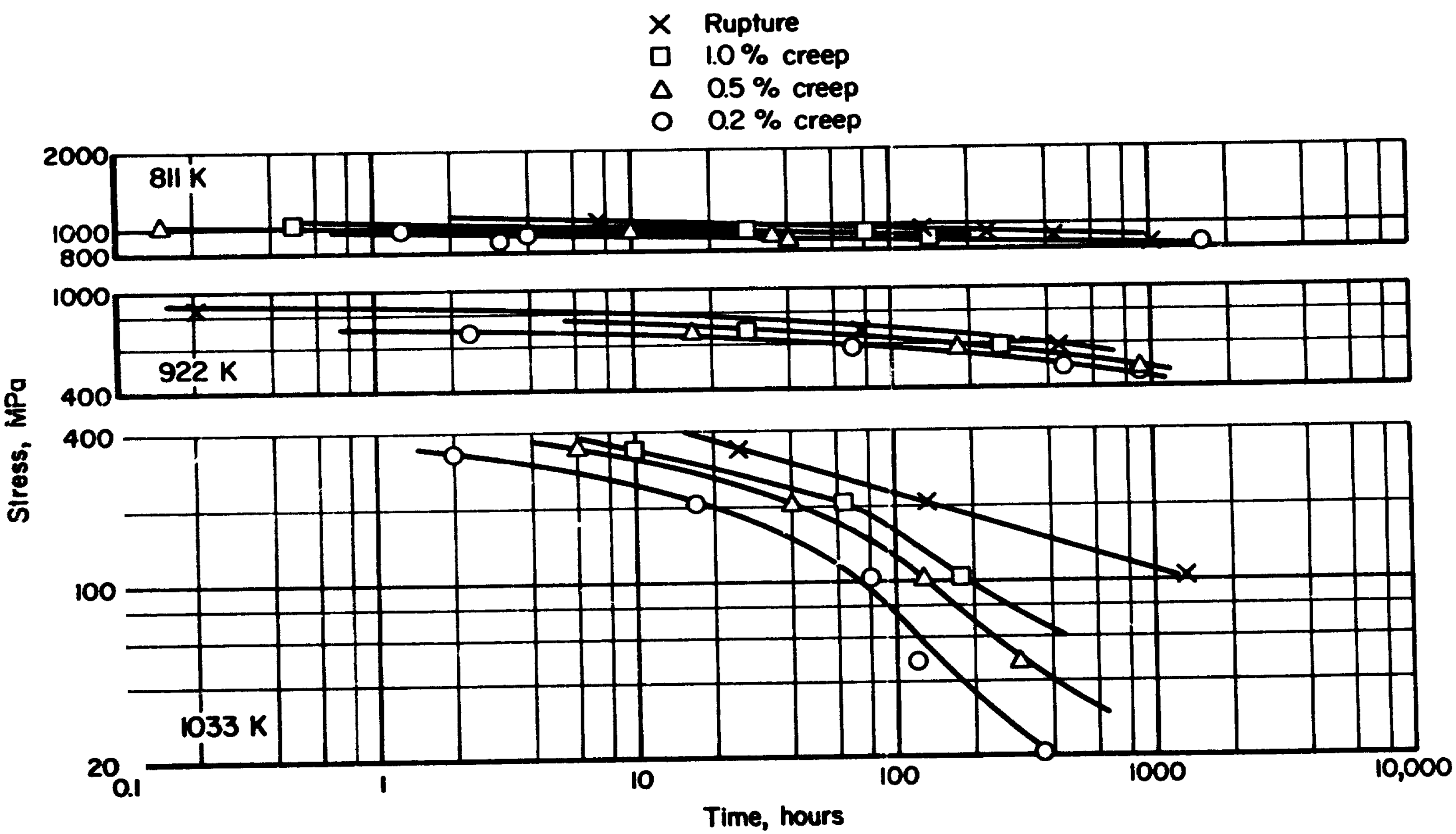


FIGURE 42. CREEP RUPTURE CURVES FOR CTX-1 BAR, HEAT TREATMENT A (SI UNITS)

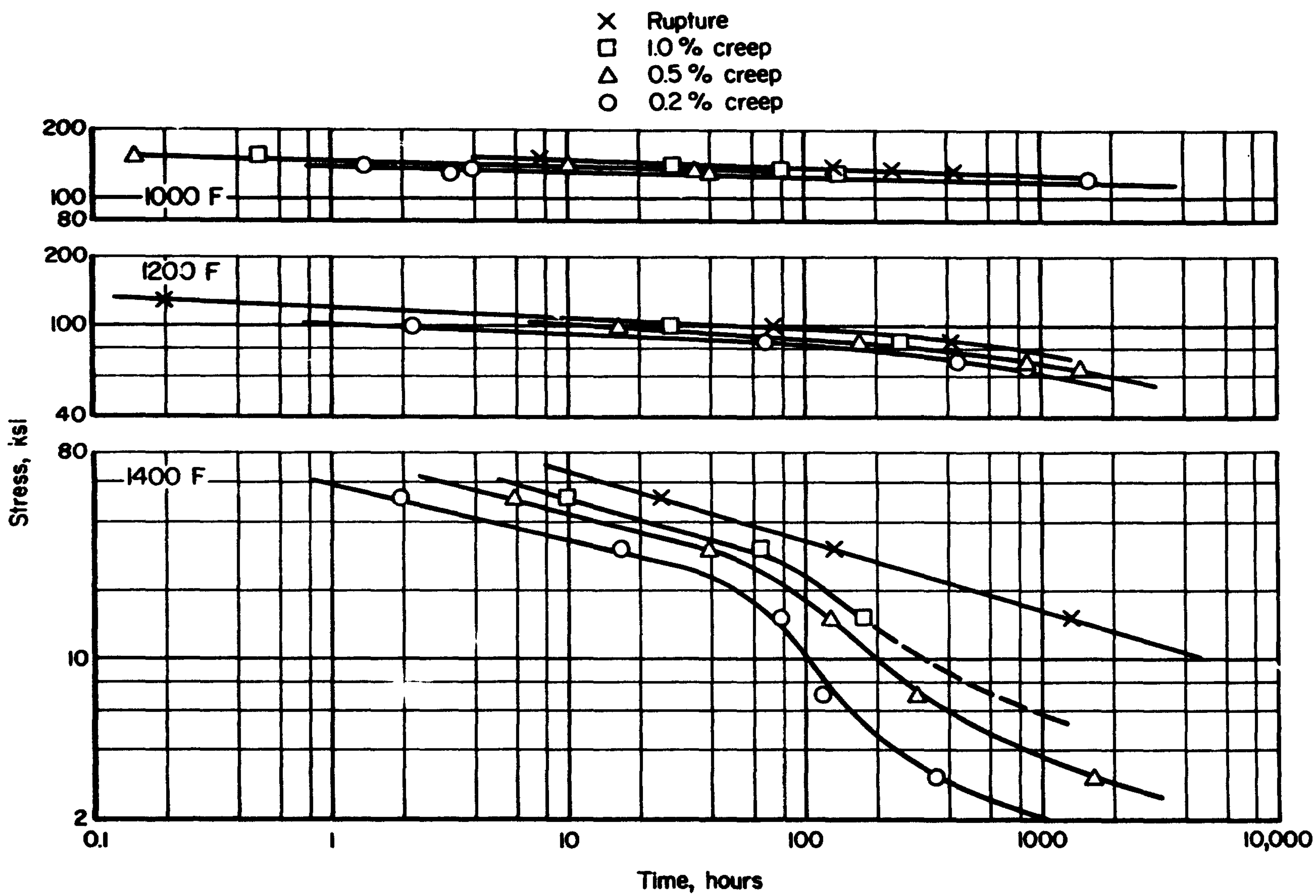


FIGURE 43. CREEP-RUPTURE CURVES FOR CTX-1 BAR, HEAT TREATMENT A

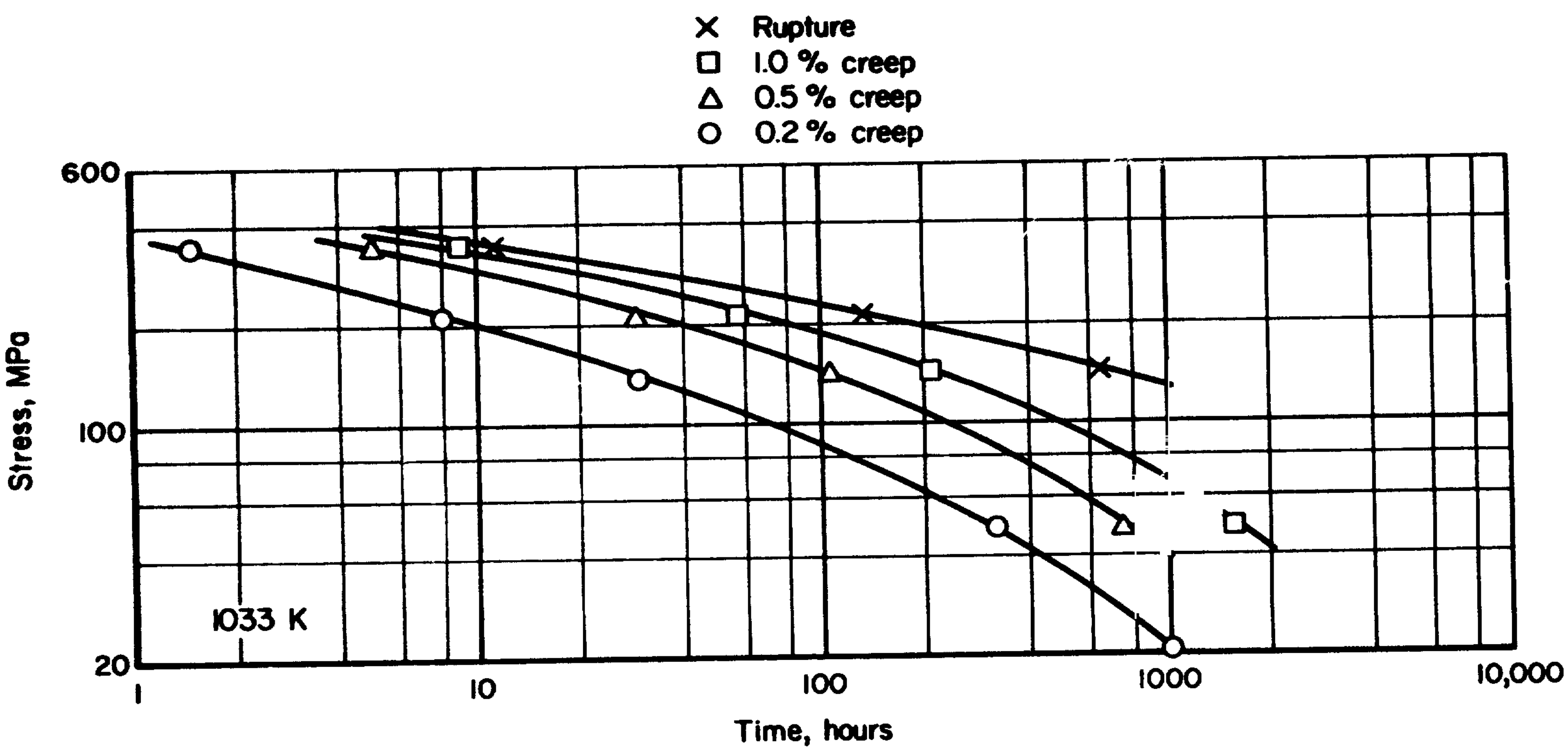


FIGURE 44. CREEP-RUPTURE CURVES FOR CTX-1 BAR, HEAT TREATMENT B (SI UNITS)

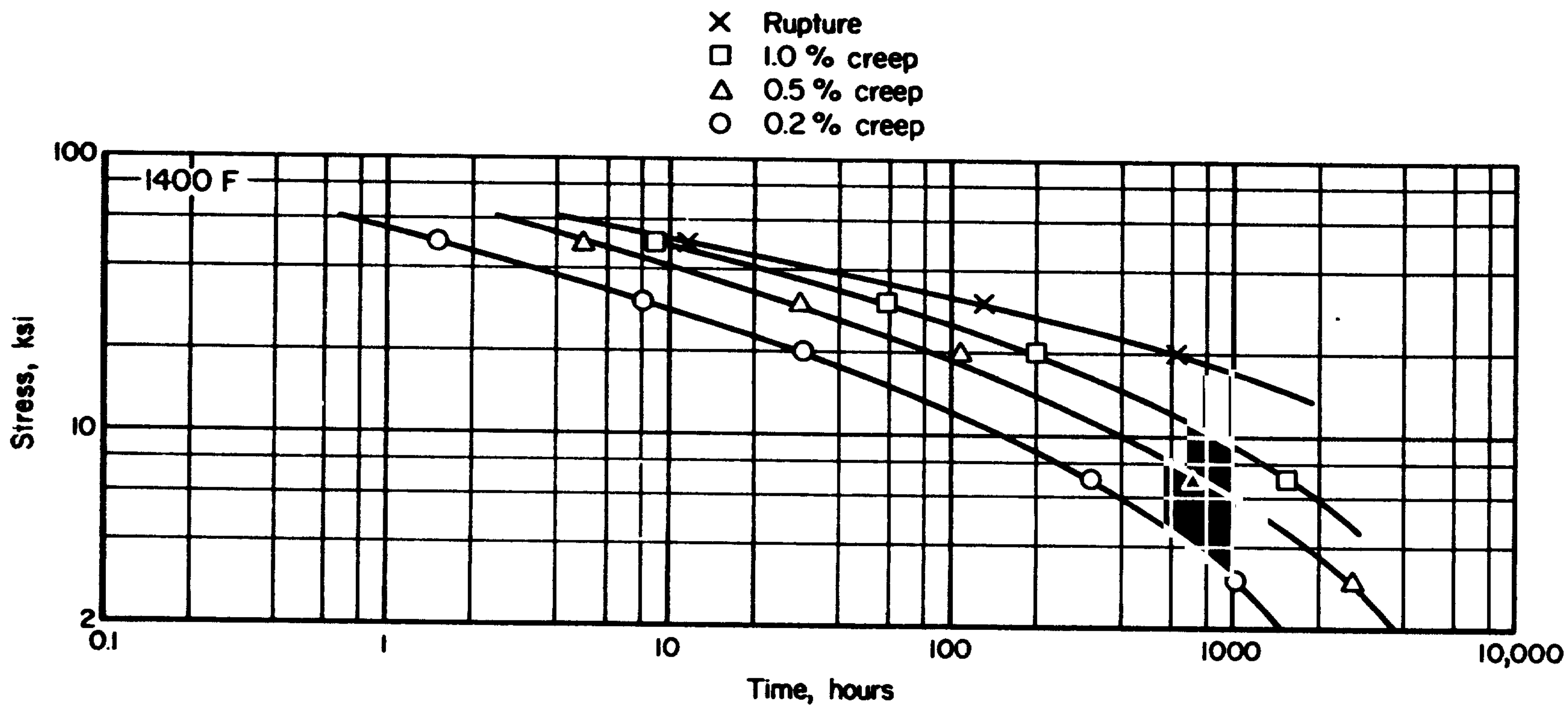


FIGURE 45. CREEP-RUPTURE CURVES FOR CTX-1 BAR, HEAT TREATMENT B

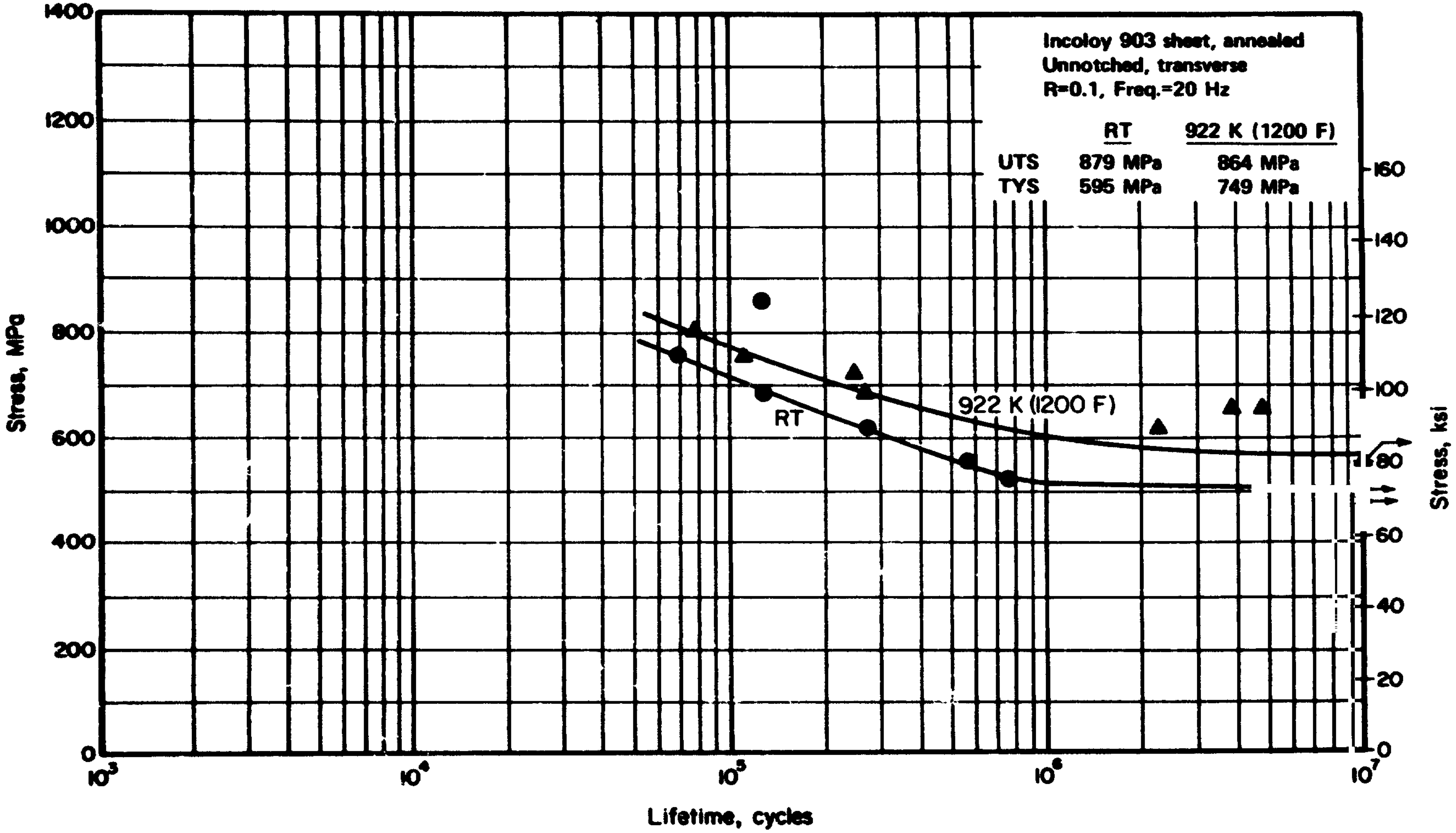


FIGURE 46. AXIAL LOAD S/N FATIGUE CURVES FOR UNNOTCHED ANNEALED INCOLOY 903 SHEET

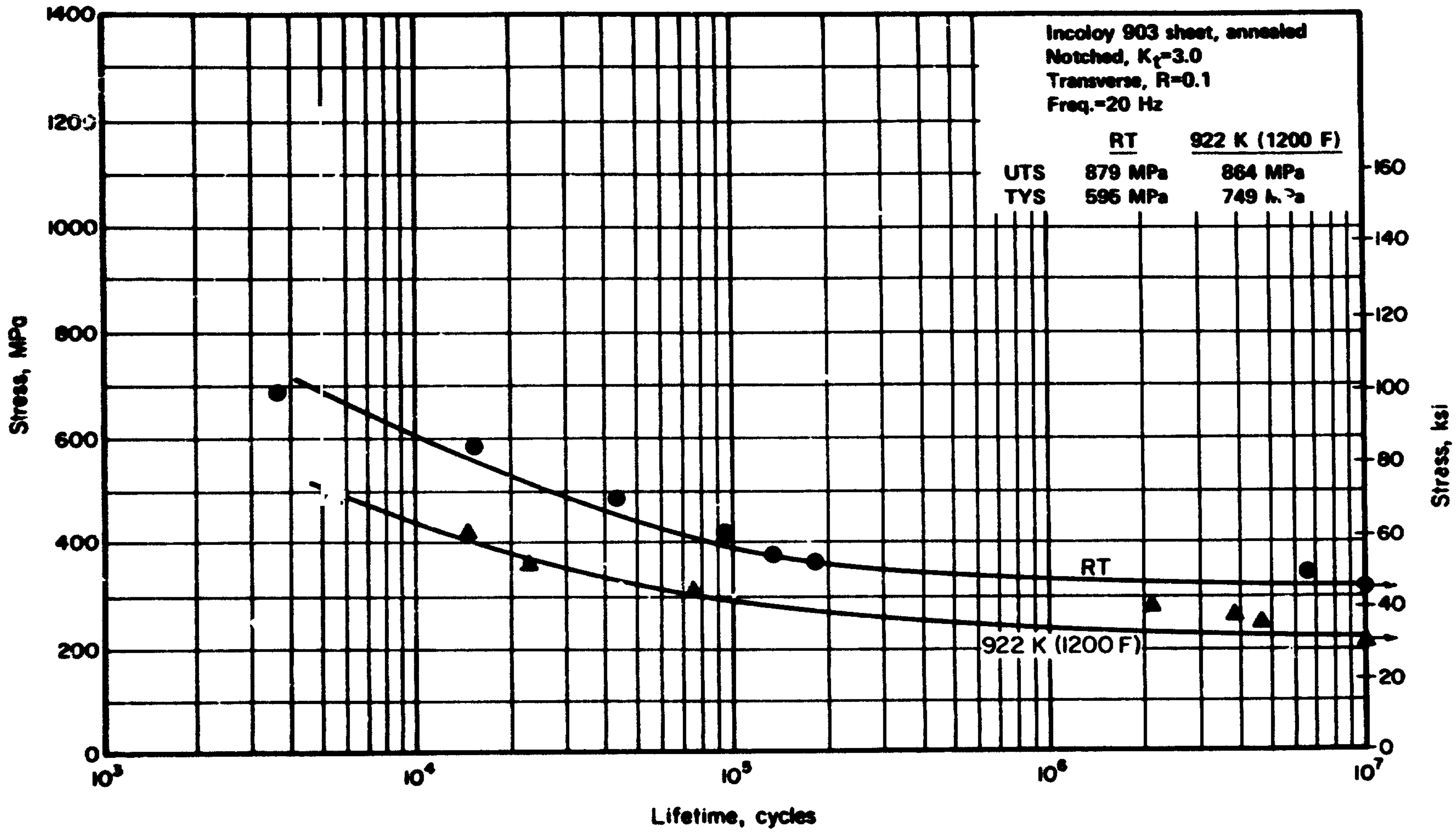


FIGURE 47. AXIAL LOAD S/N FATIGUE CURVES FOR NOTCHED ANNEALED INCOLOY 903 SHEET

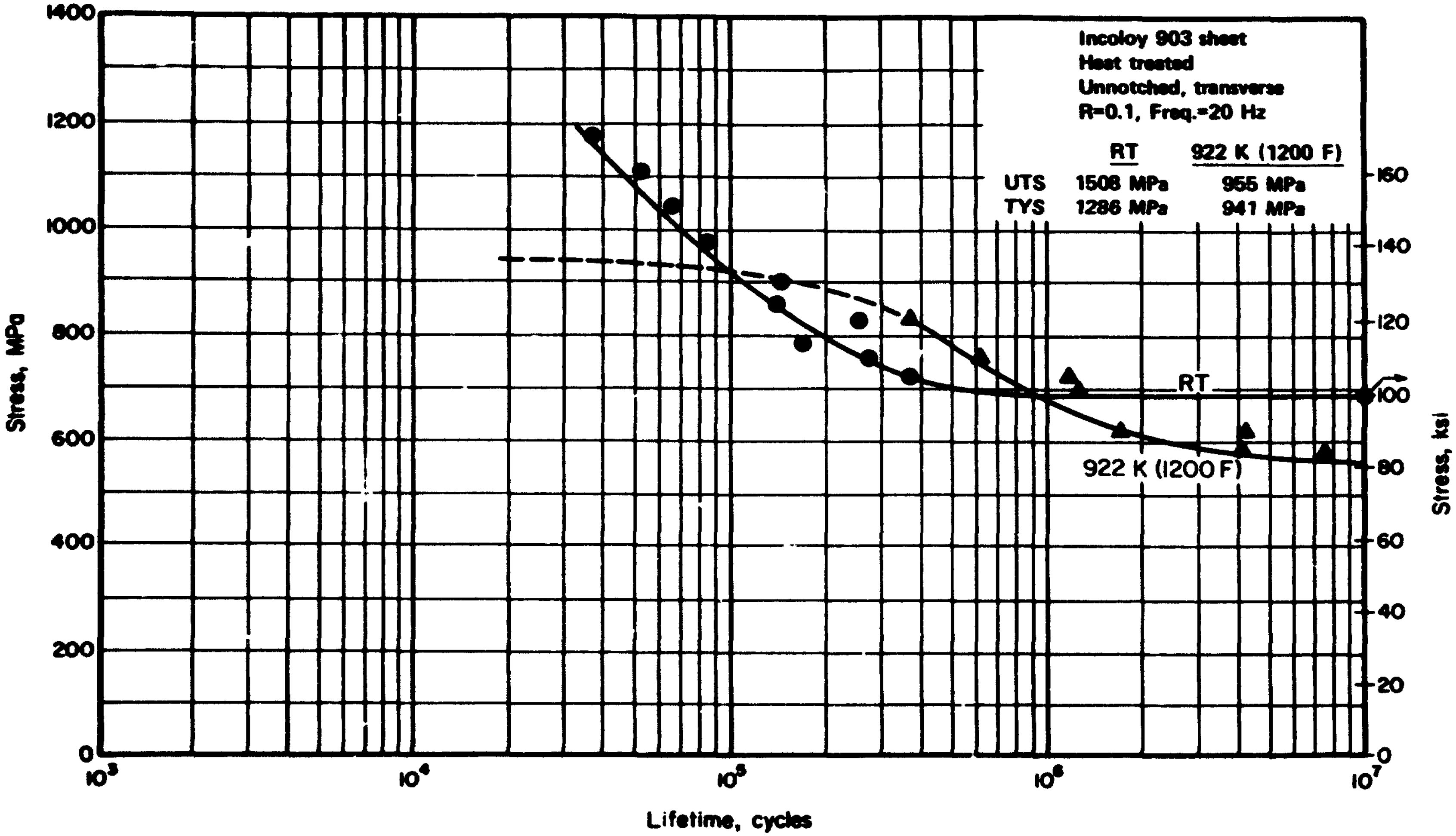


FIGURE 48. AXIAL LOAD S/N FATIGUE CURVES FOR UNNOTCHED HEAT TREATED INCOLOY 903 SHEET

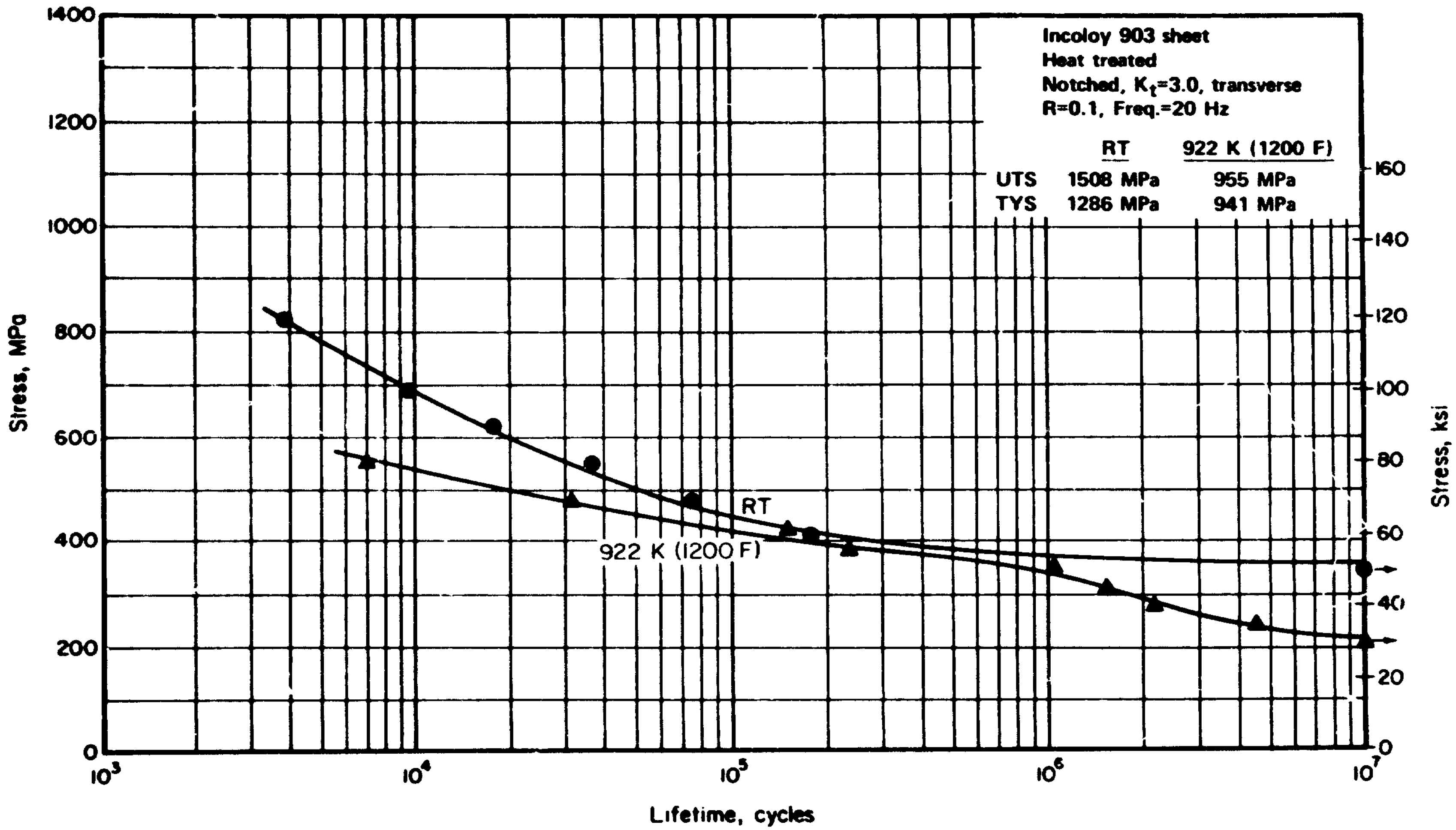


FIGURE 49. AXIAL LOAD S/N FATIGUE CURVES FOR NOTCHED HEAT TREATED INCOLOY 903 SHEET

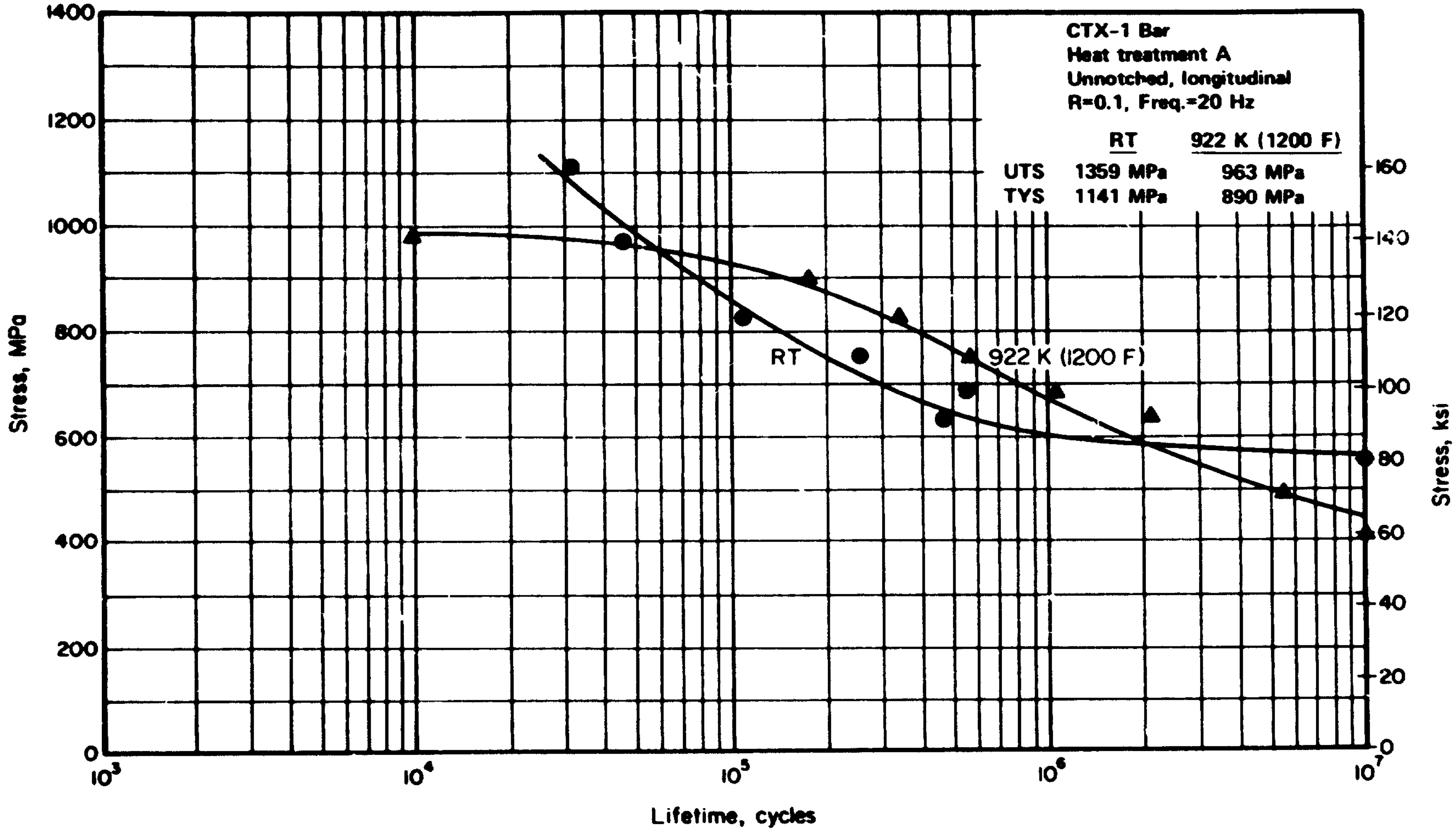


FIGURE 50. AXIAL LOAD S/N FATIGUE CURVES FOR UNNOTCHED CTX-1 BAR, HEAT TREATMENT A

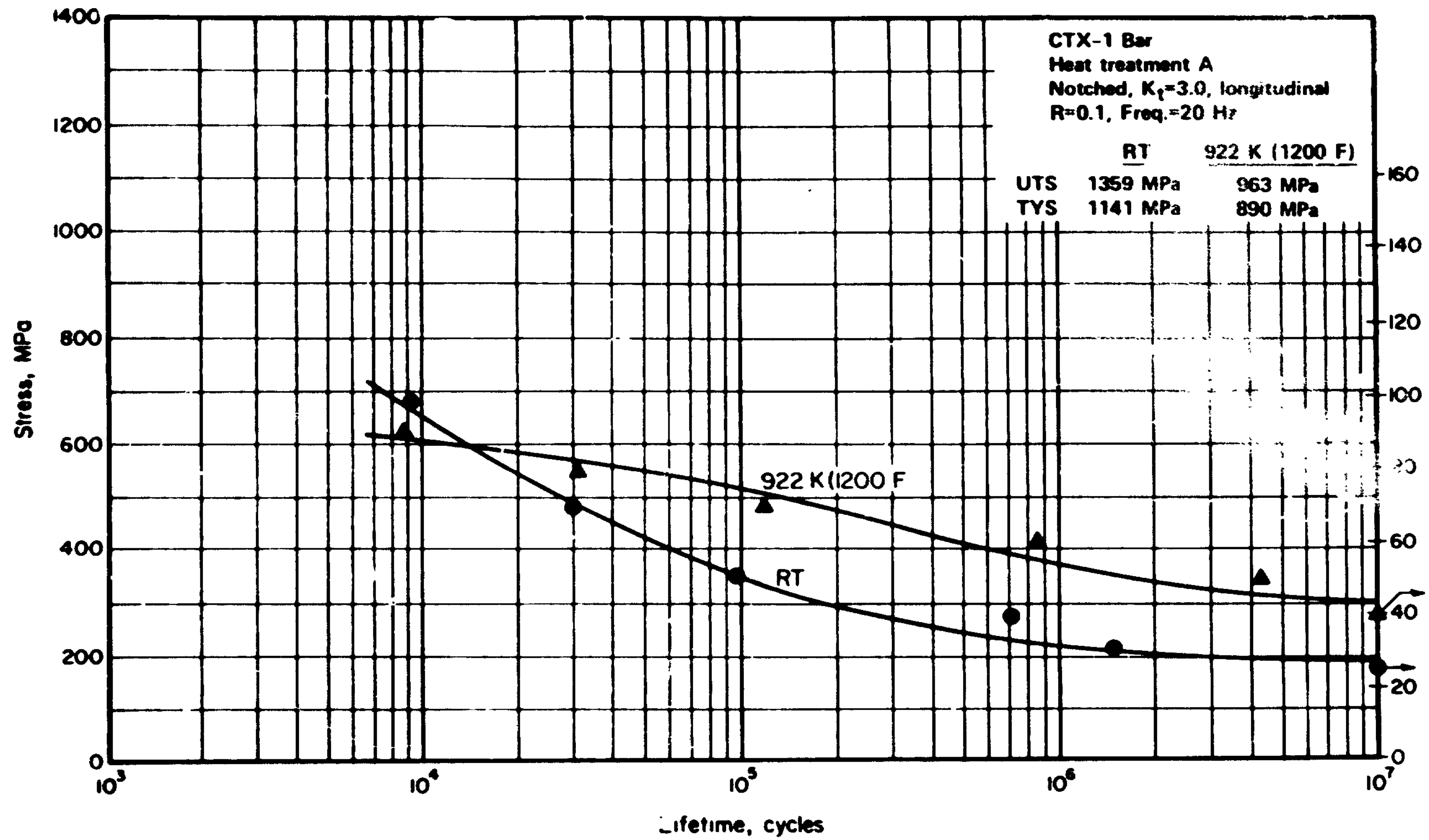


FIGURE 51. AXIAL LOAD S/N FATIGUE CURVES FOR NOTCHED CTX-1 BAR, HEAT TREATMENT A

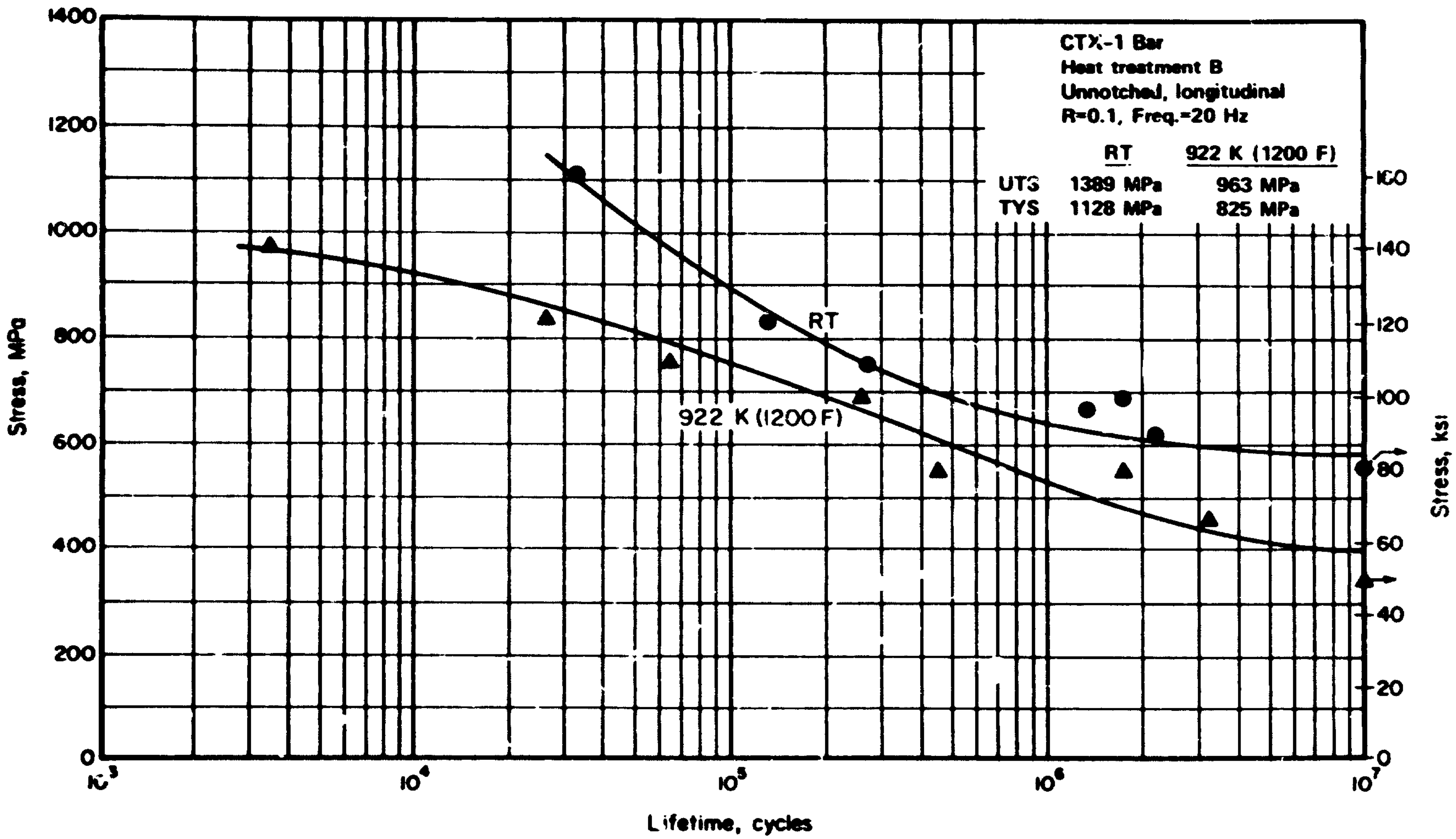


FIGURE 52. AXIAL LOAD S/N FATIGUE CURVES FOR UNNOTCHED CTX-1 BAR, HEAT TREATMENT B

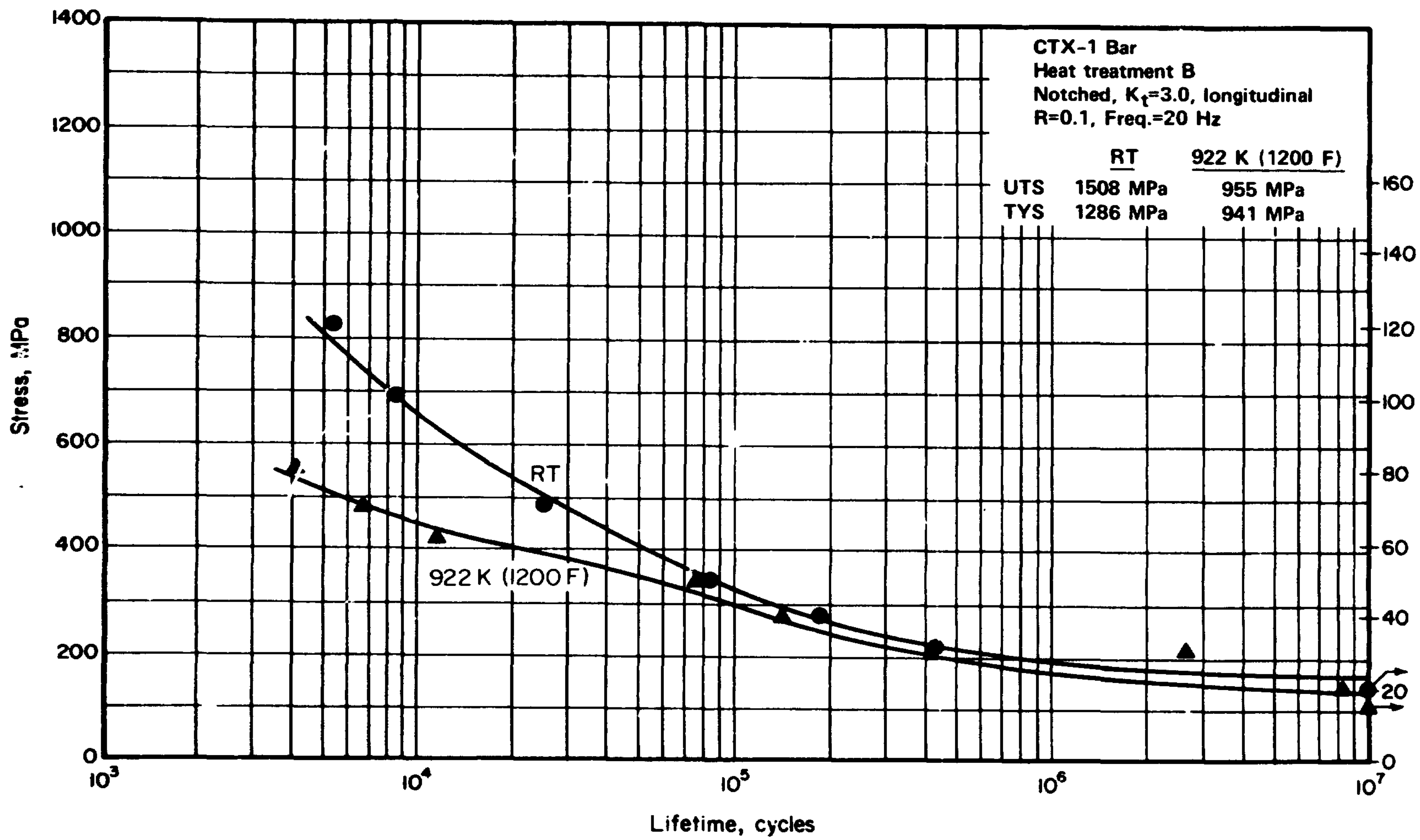


FIGURE 53. AXIAL LOAD S/N FATIGUE CURVES FOR NOTCHED CTX-1 BAR, HEAT TREATMENT B

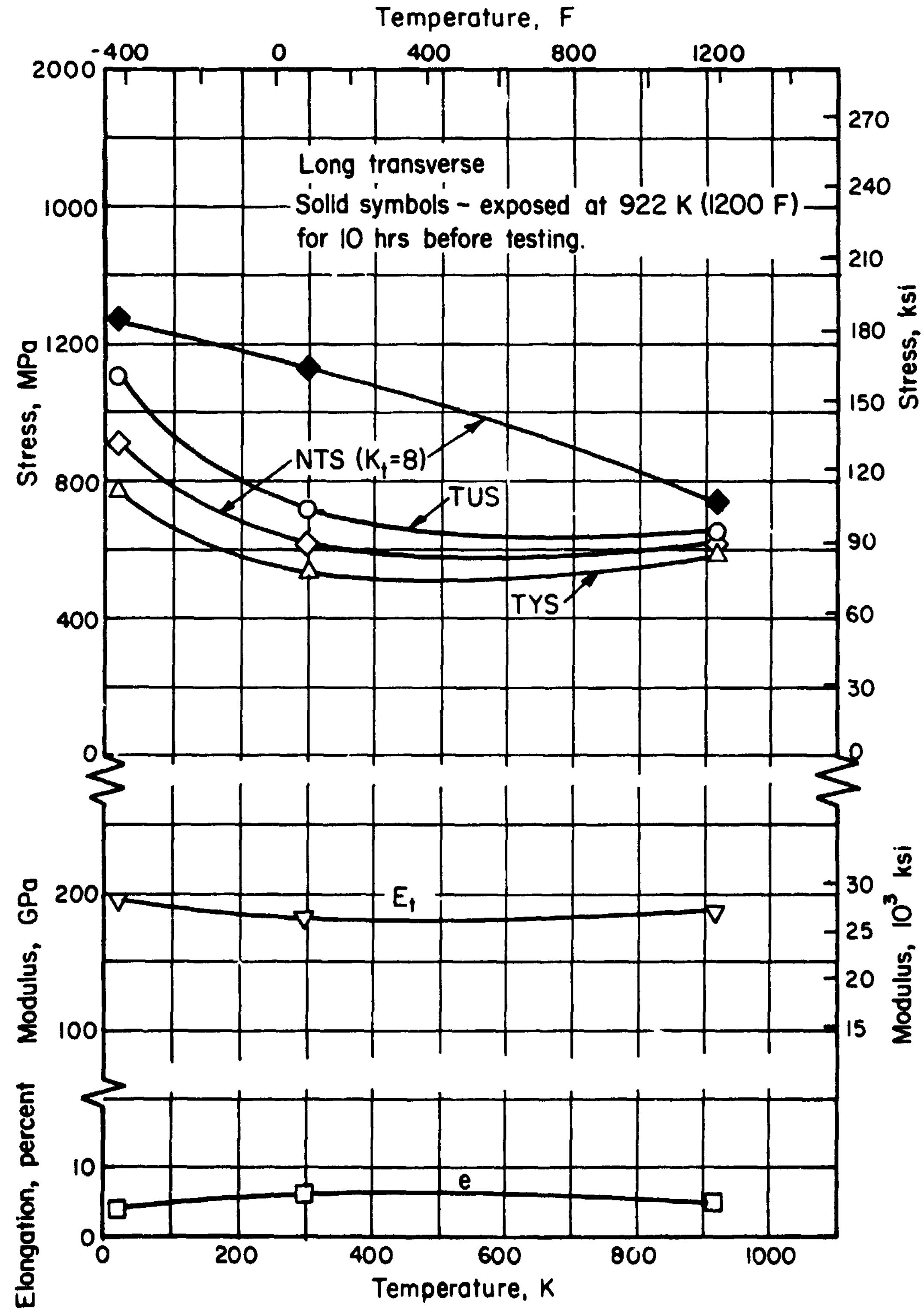


FIGURE 54. EFFECT OF TEMPERATURE ON TENSILE, NOTCHED TENSILE STRENGTH, AND NOTCHED/UNNOTCHED TENSILE STRENGTH RATIO FOR HEAT TREATED AND WELDED INCOLOY 903

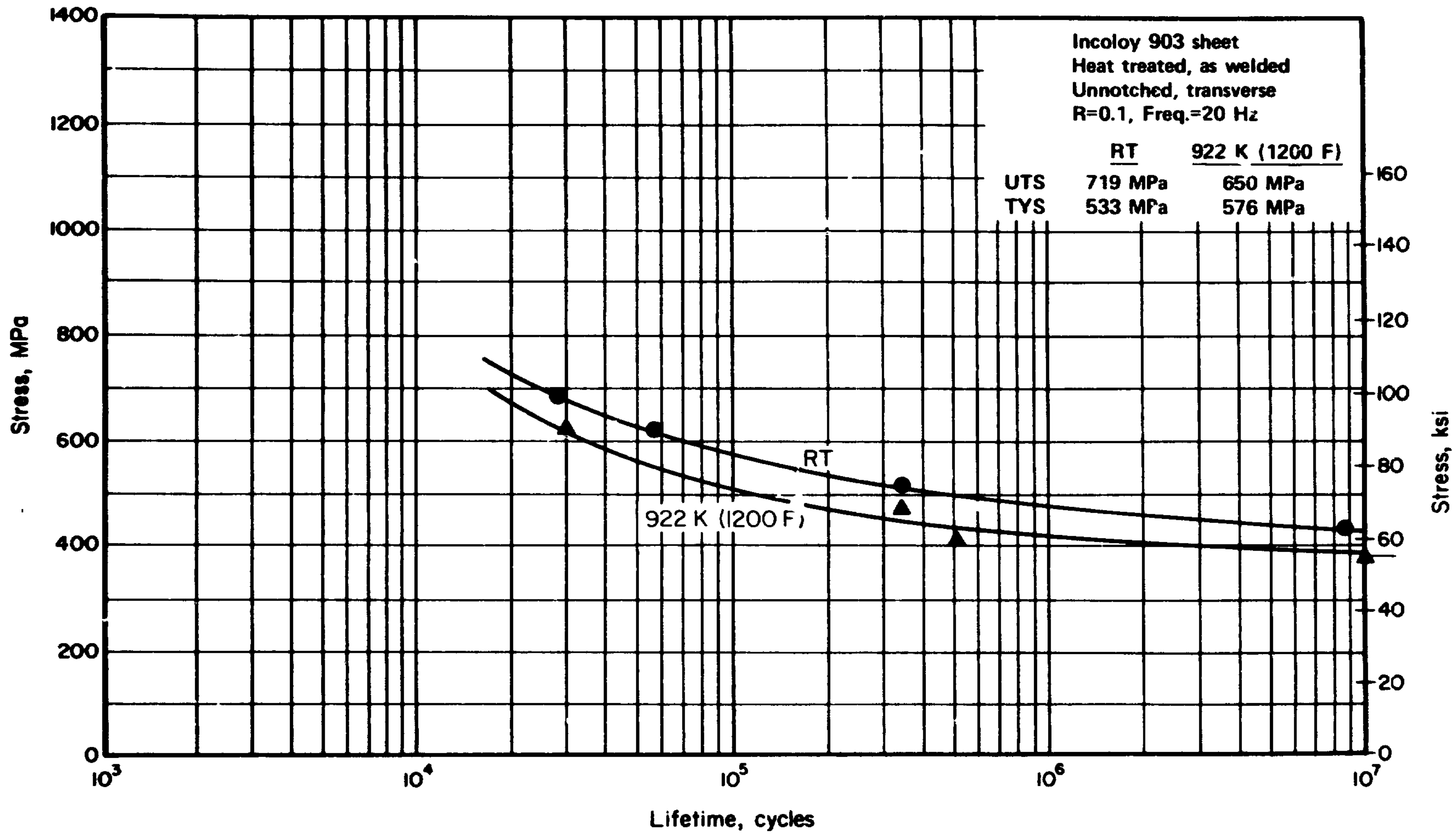


FIGURE 55. AXIAL LOAD S/N FATIGUE CURVES FOR UNNOTCHED HEAT TREATED INCOLOY 903 SHEET, AS WELDED

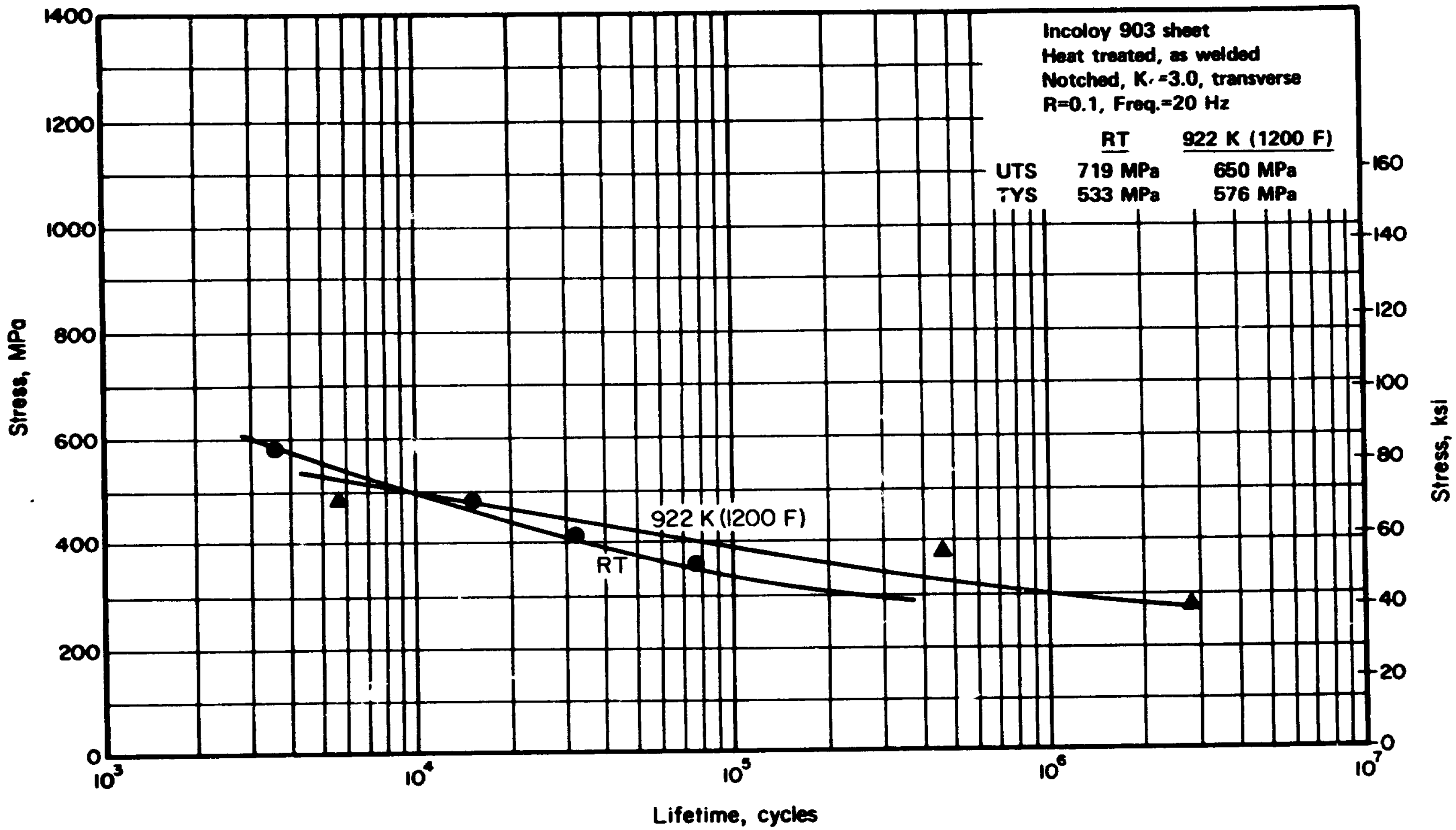


FIGURE 56. AXIAL LOAD S/N FATIGUE CURVES FOR NOTCHED HEAT TREATED INCOLOY 903 SHEET, AS WELDED

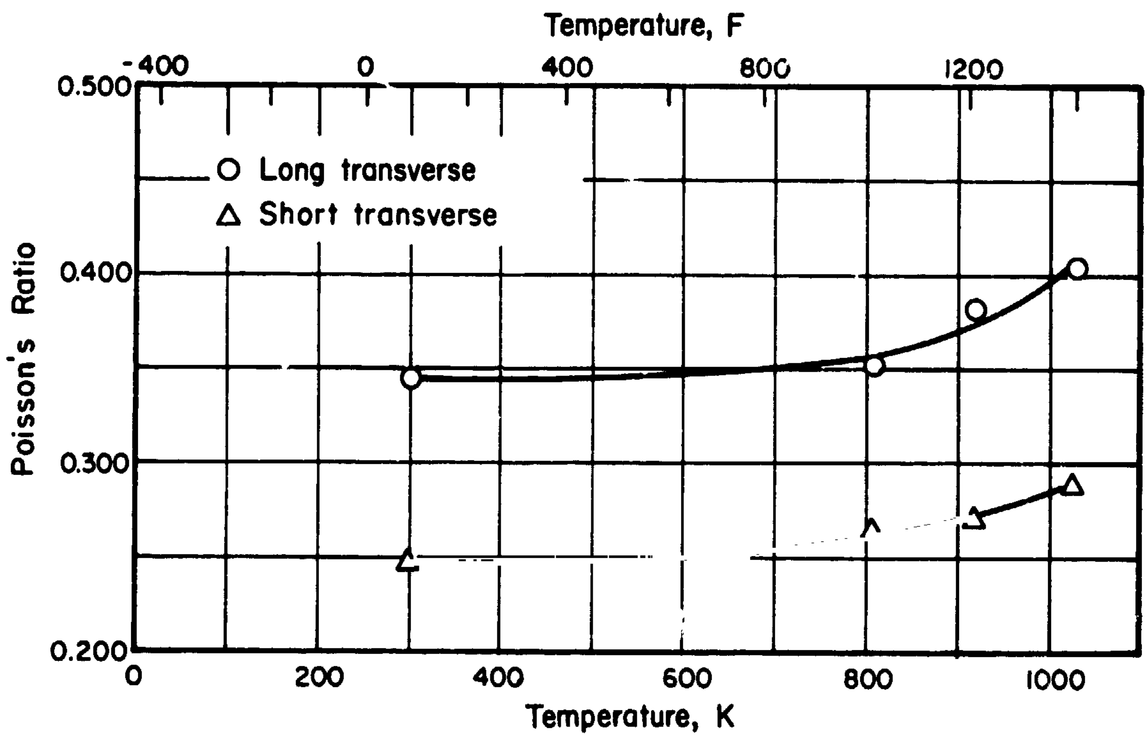


FIGURE 57. EFFECT OF TEMPERATURE ON POISSON'S RATIO FOR CTX-1 BAR, HEAT TREATMENT A

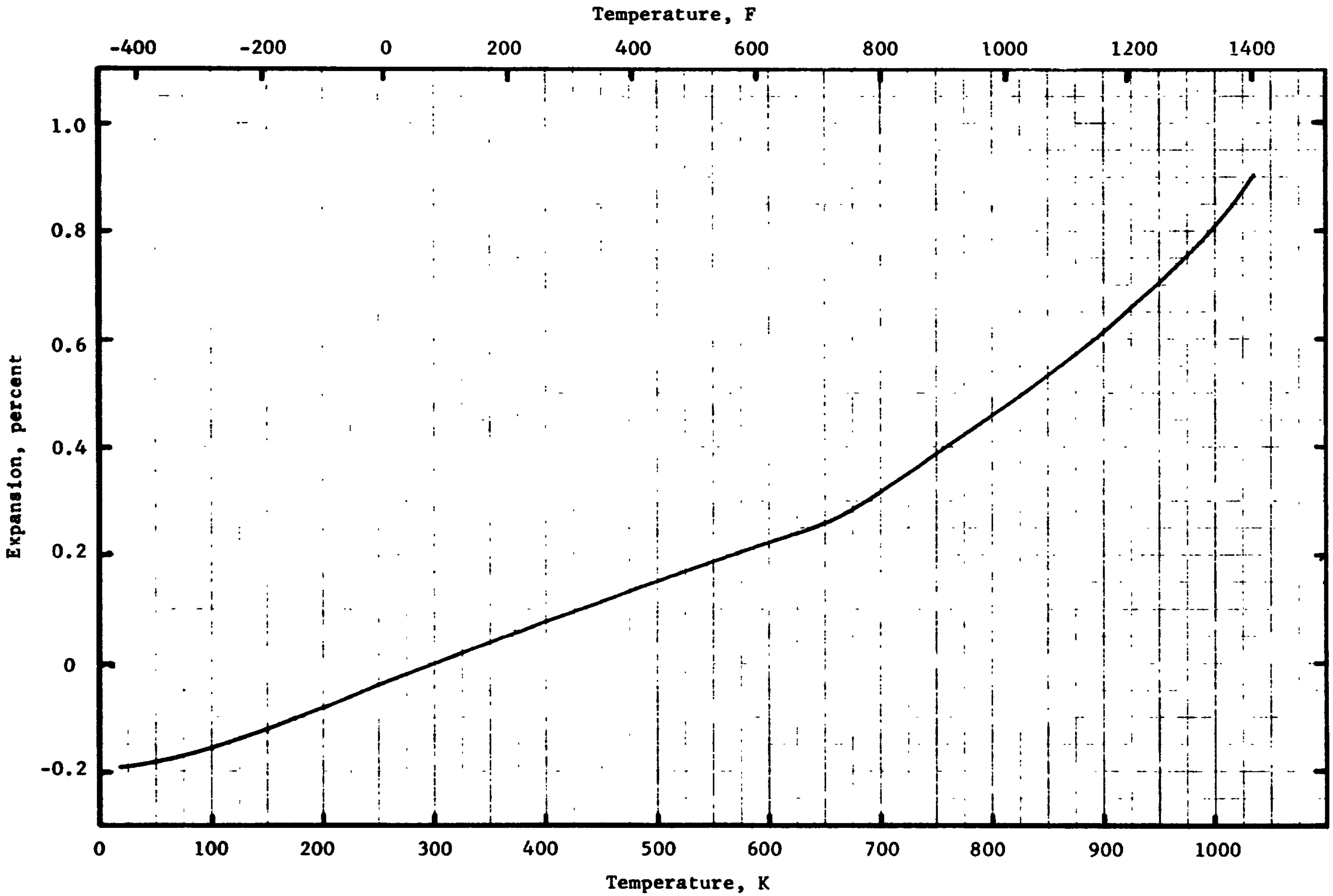


FIGURE 58. LINEAR THERMAL EXPANSION OF HEAT TREATED INCOLOY 903

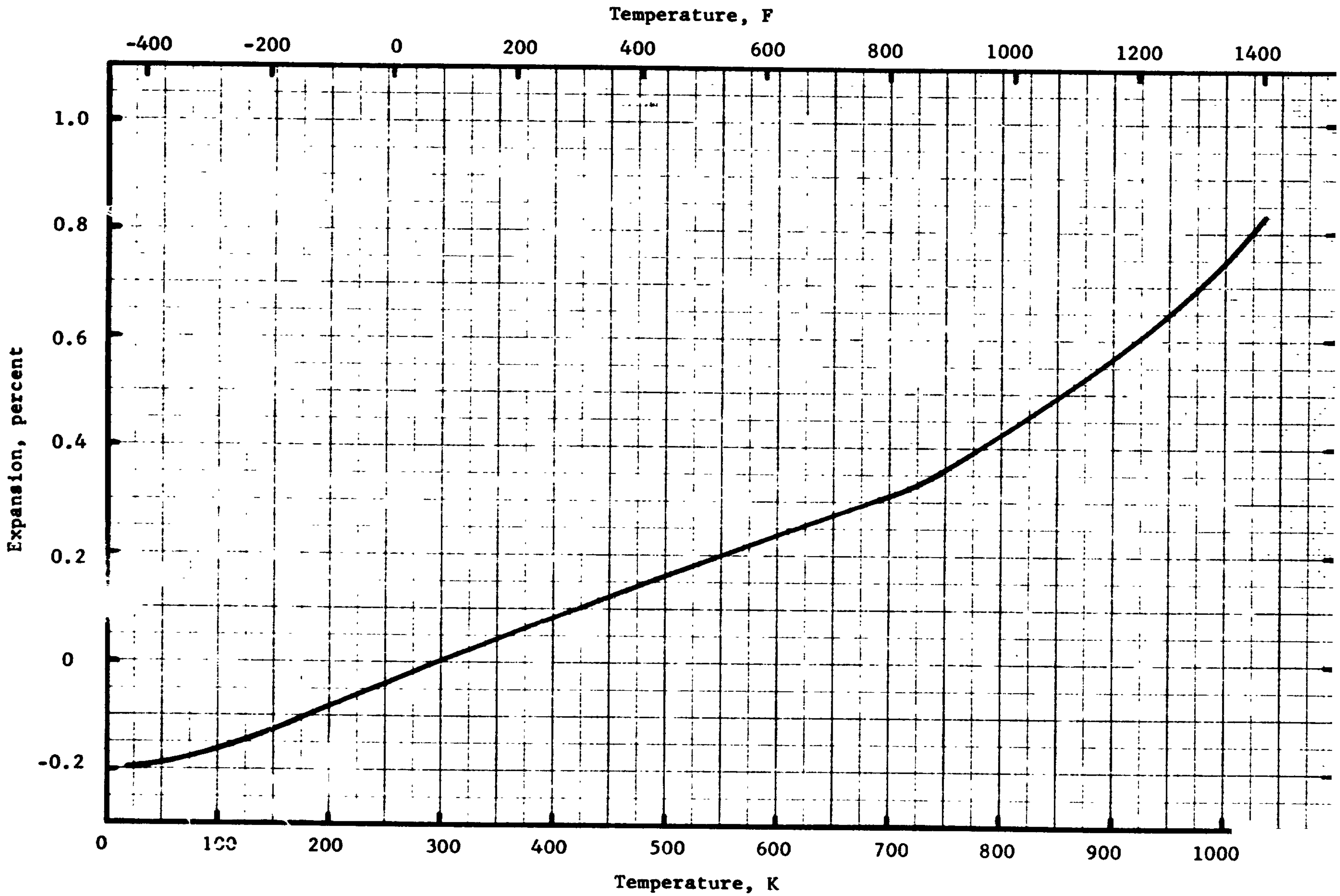


FIGURE 59. LINEAR THERMAL EXPANSION OF CTX-1 BAR, HEAT TREATMENT A

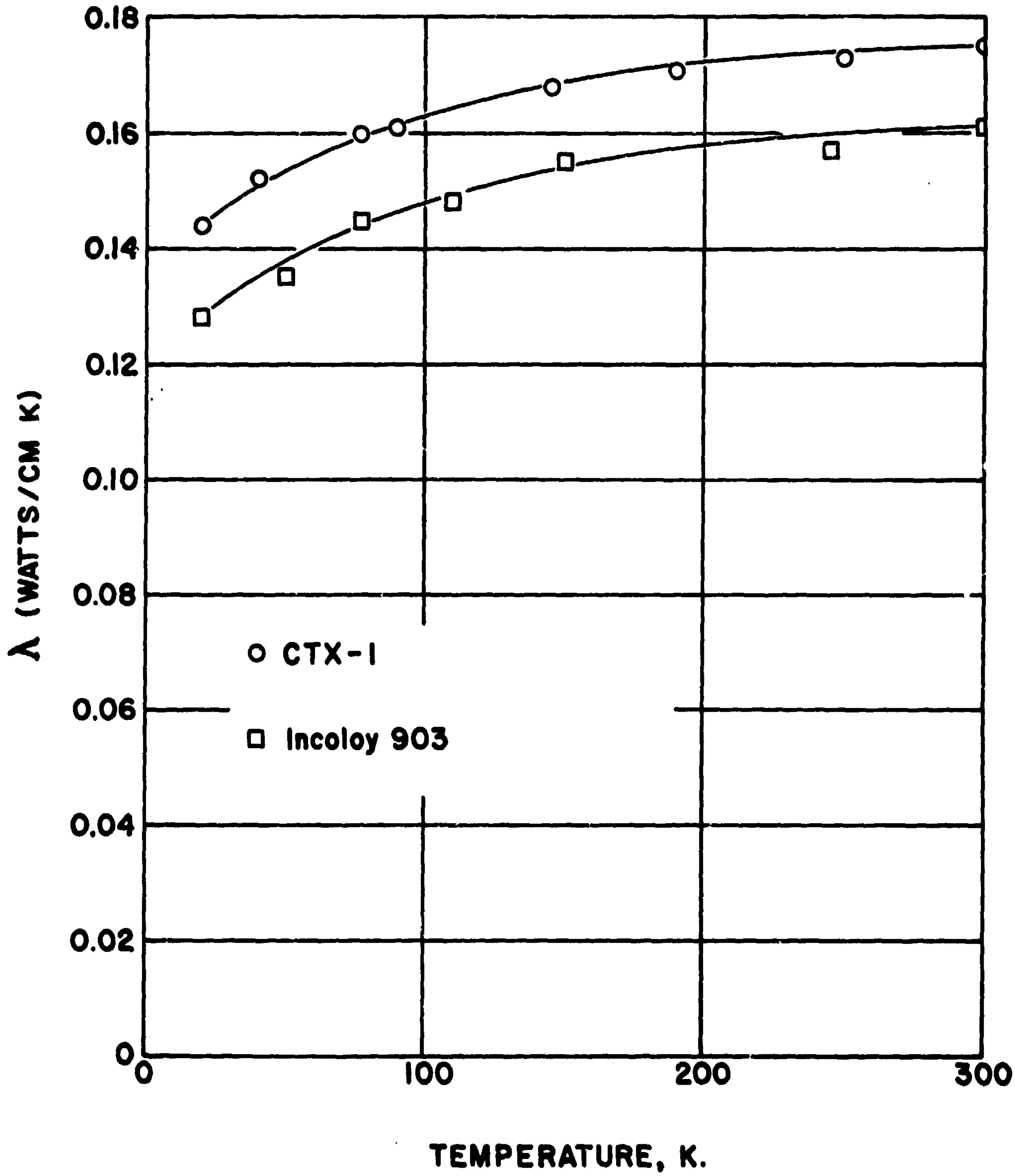


FIGURE 60. THERMAL CONDUCTIVITY OF INCOLOY 903 and CTX-1 IN THE TEMPERATURE RANGE 20 K (-423 F) TO 300 K (80 F)

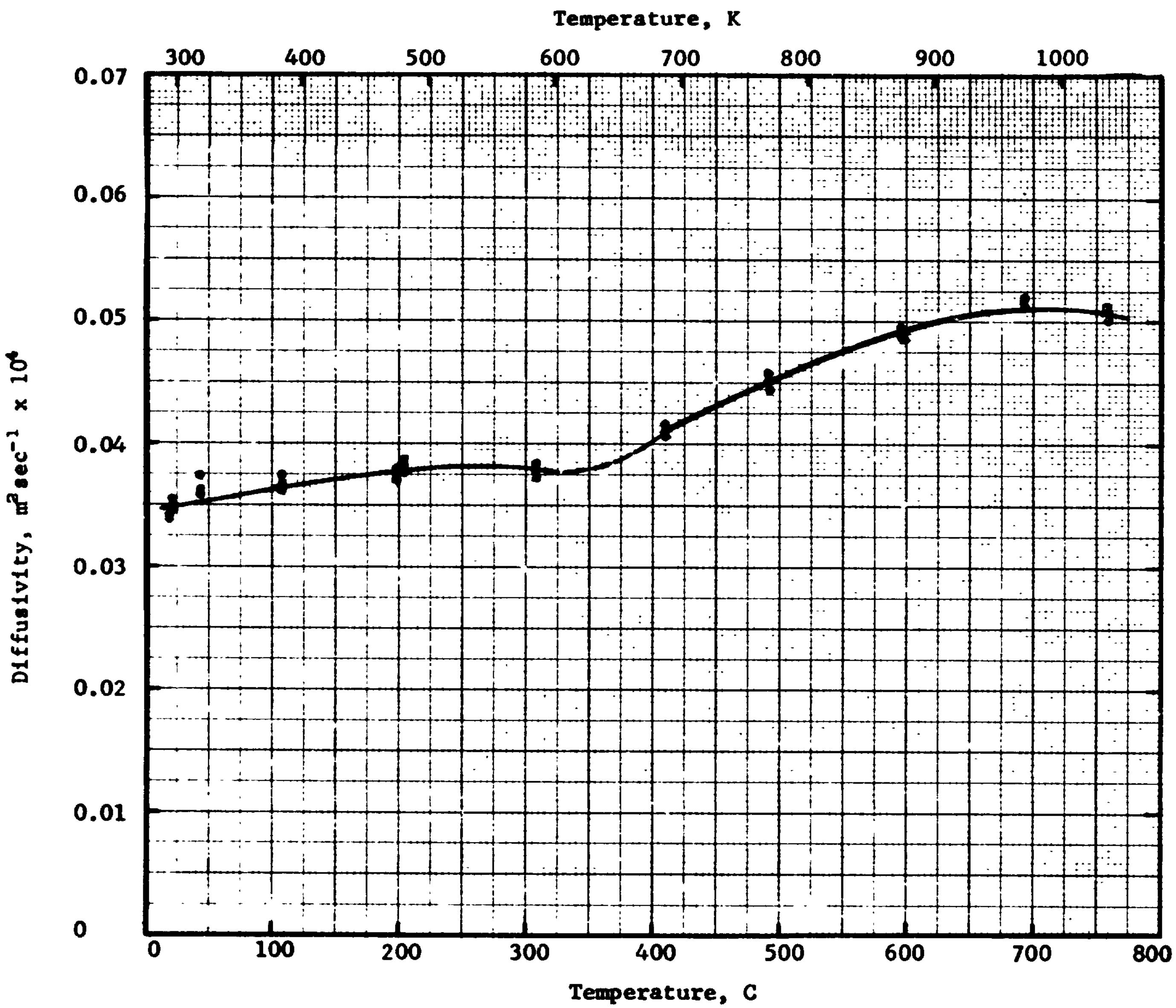


FIGURE 61. THERMAL DIFFUSIVITY OF INCOLOY 903

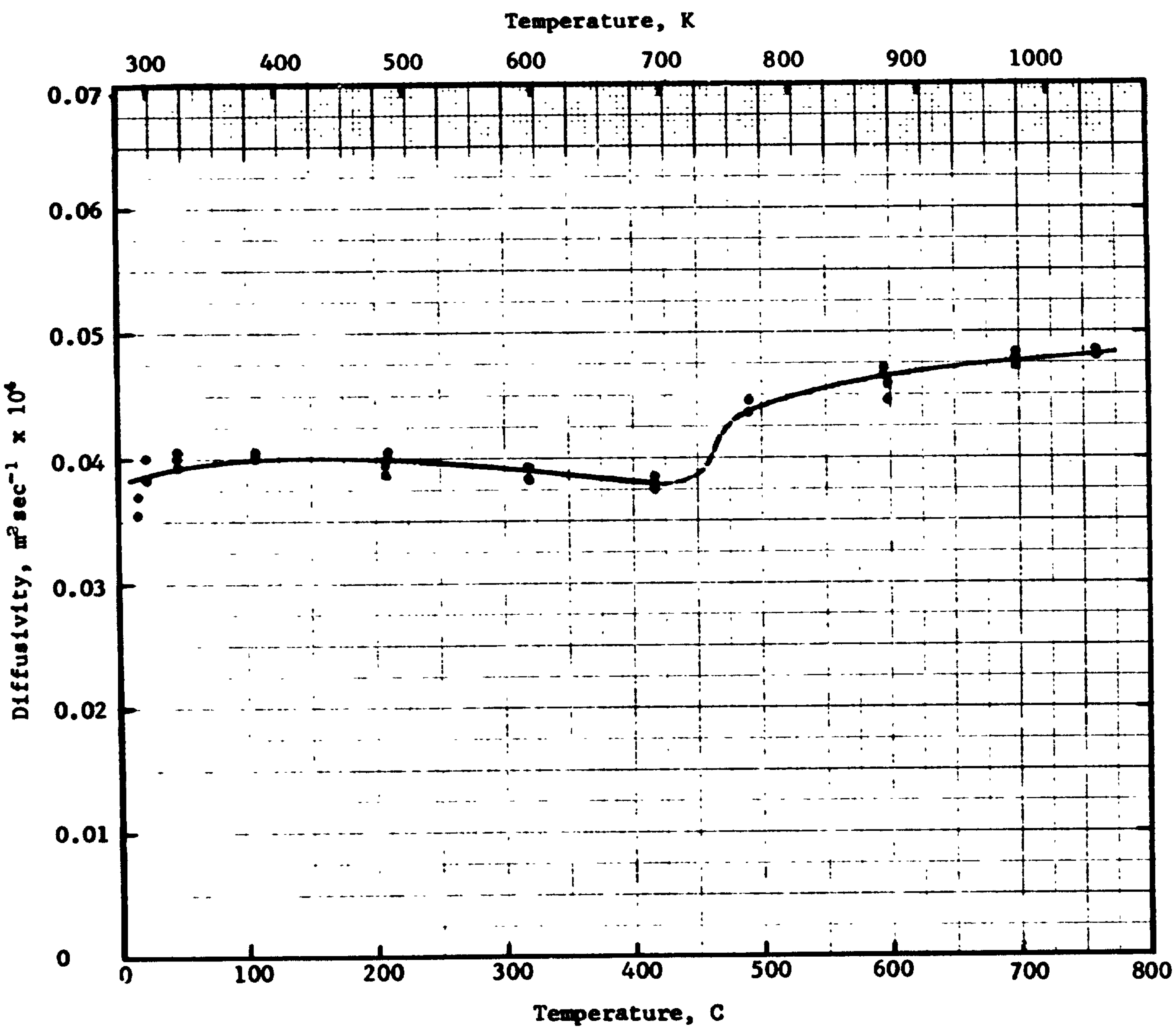


FIGURE 62. THERMAL DIFFUSIVITY OF CTX-1

APPENDIX A

SPECIMEN CONFIGURATIONS

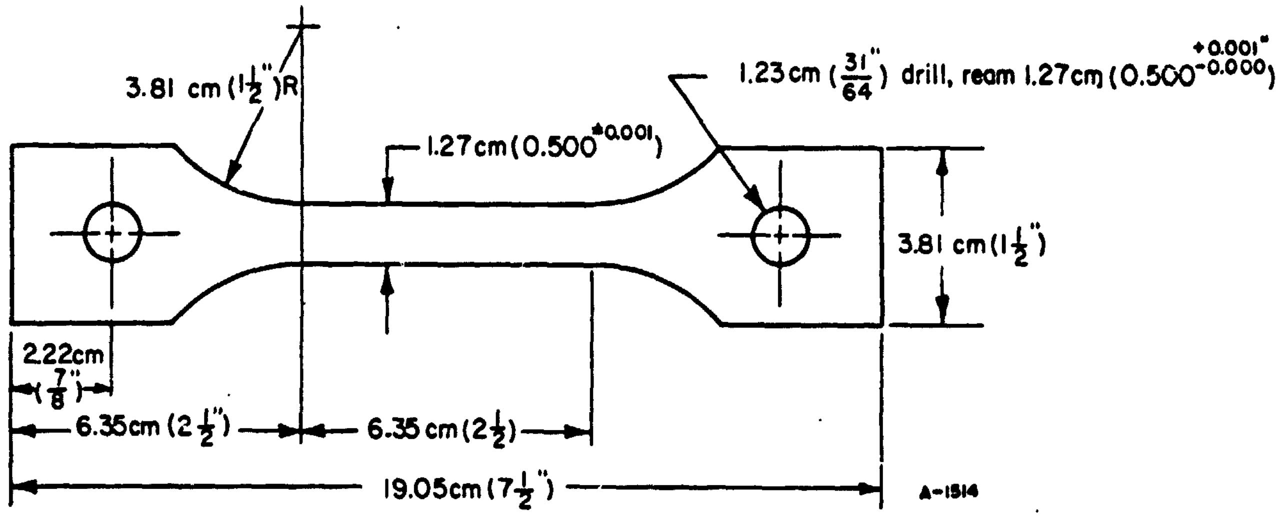


FIGURE A-1. SHEET TENSILE SPECIMEN

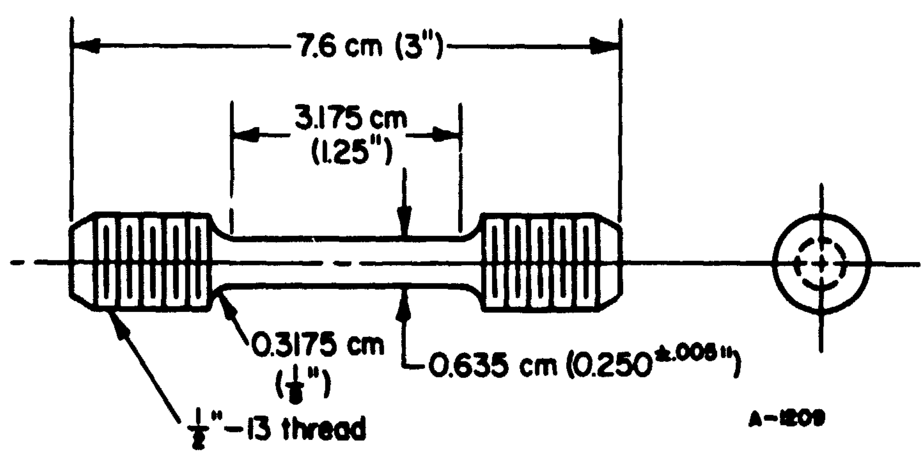


FIGURE A-2. ROUND TENSILE SPECIMEN

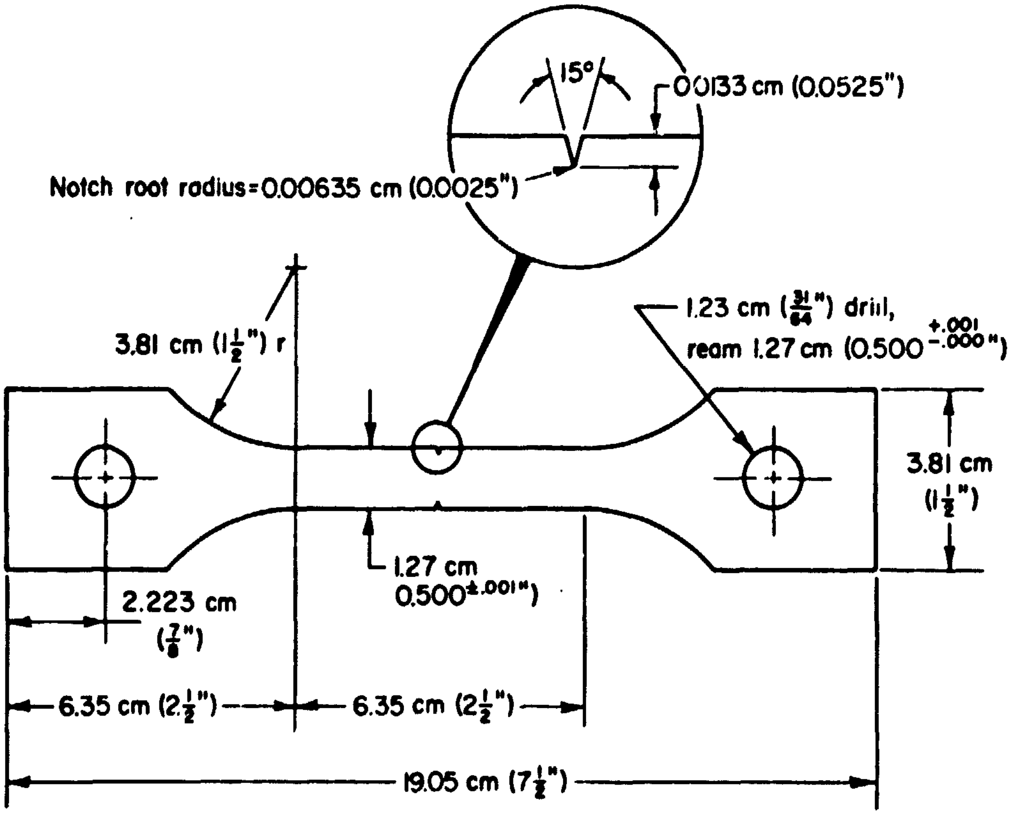


FIGURE A-3. SHEET NOTCHED TENSILE SPECIMEN, K_t = 8

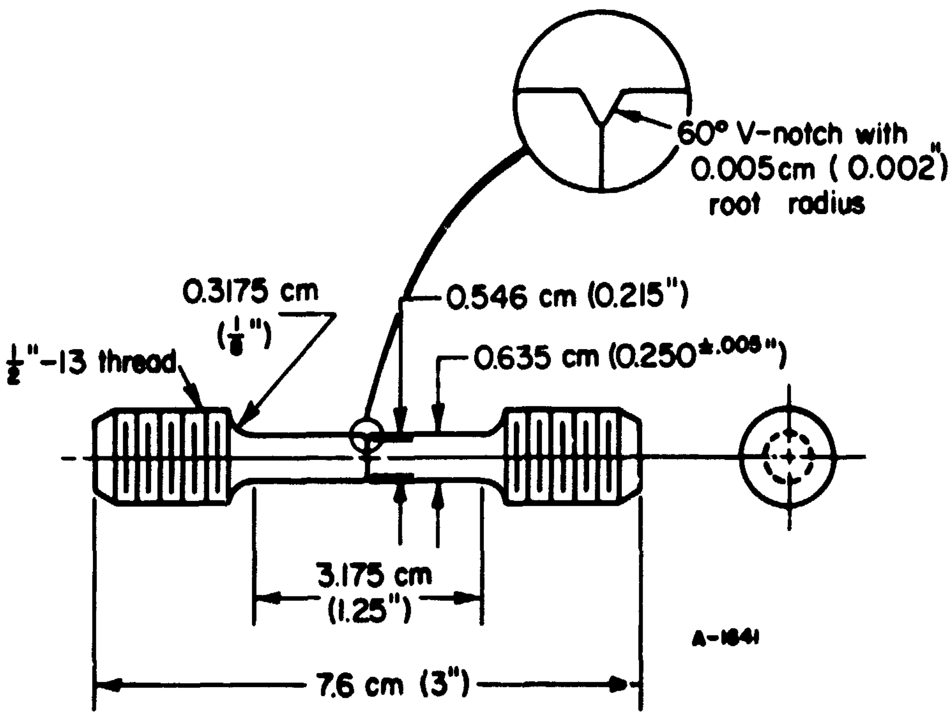
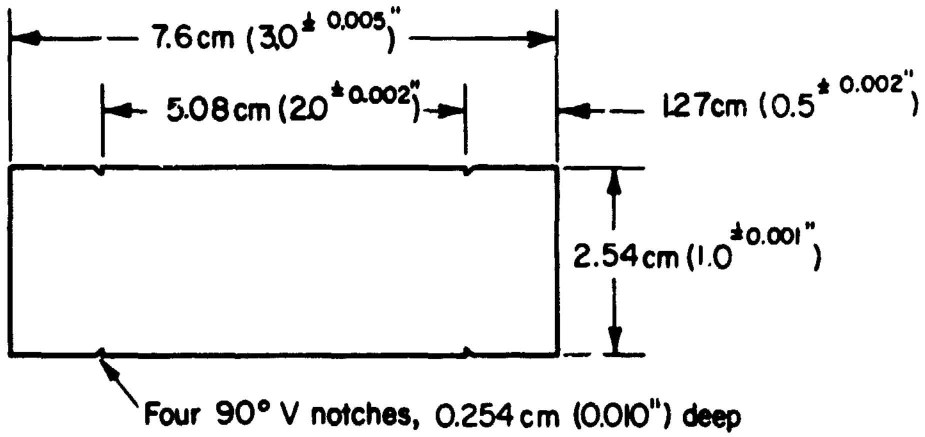


FIGURE A-4. ROUND NOTCHED TENSILE SPECIMEN, K_t = 5

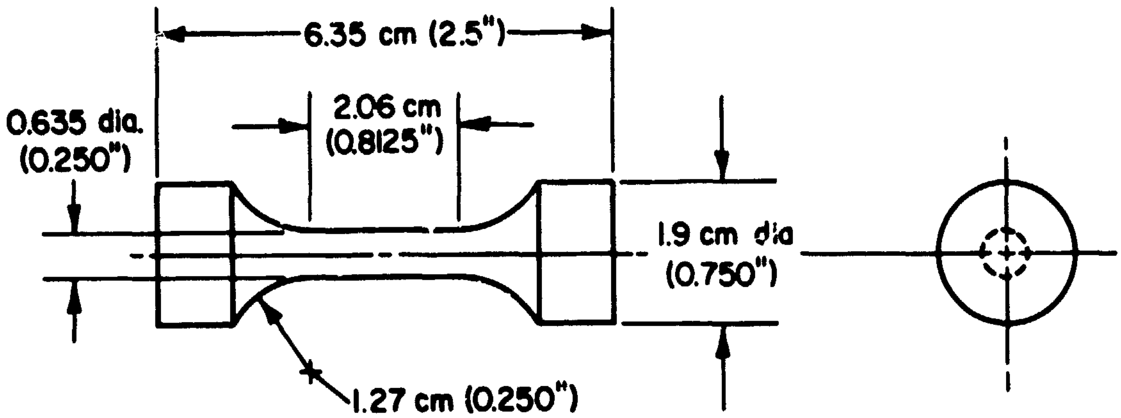


Notes: 1. Ends must be flat and parallel to within 0.0002".

2. Surface must be free from nicks and scratches.

A-1516

FIGURE A-5. SHEET COMPRESSION SPECIMEN



Note: Grind or machine ends of specimen so that ends of specimen shall be plane and perpendicular to the axis of the specimen within 0.25 degree. The ends shall be parallel within 0.0005".

FIGURE A-6. ROUND COMPRESSION SPECIMEN

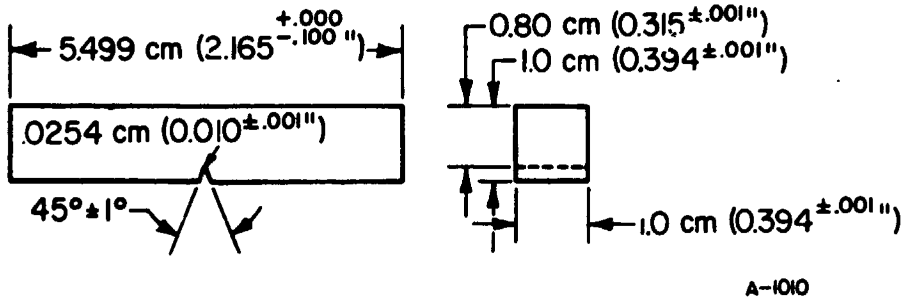


FIGURE A-7. CHARPY V-NOTCH IMPACT SPECIMEN

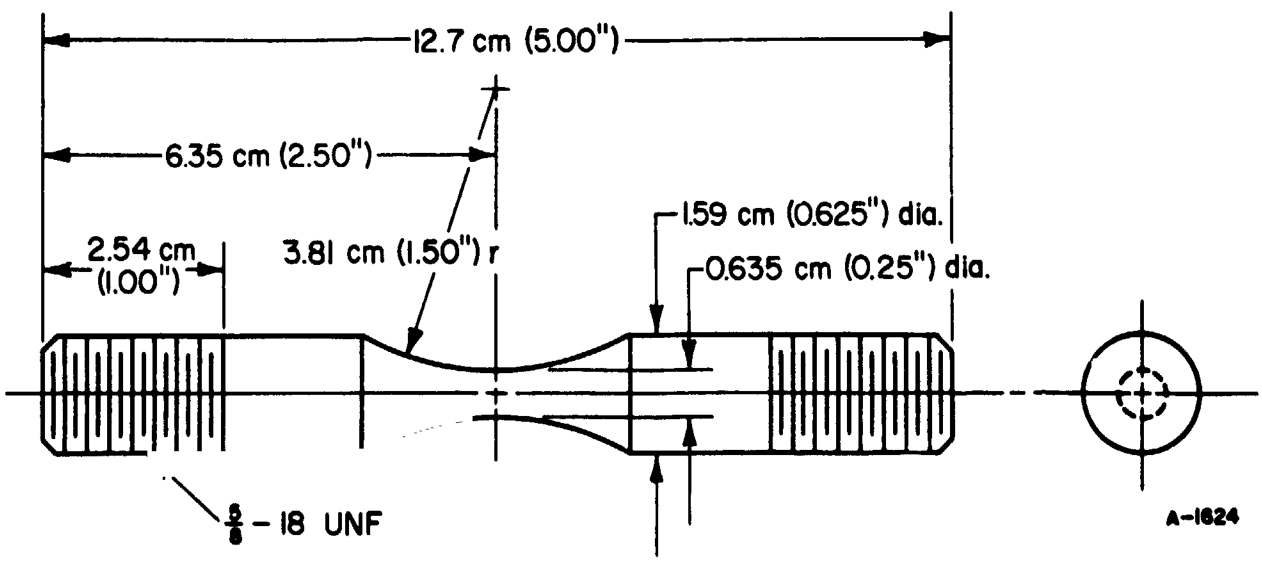


FIGURE A-8. POISSON'S RATIO SPECIMEN

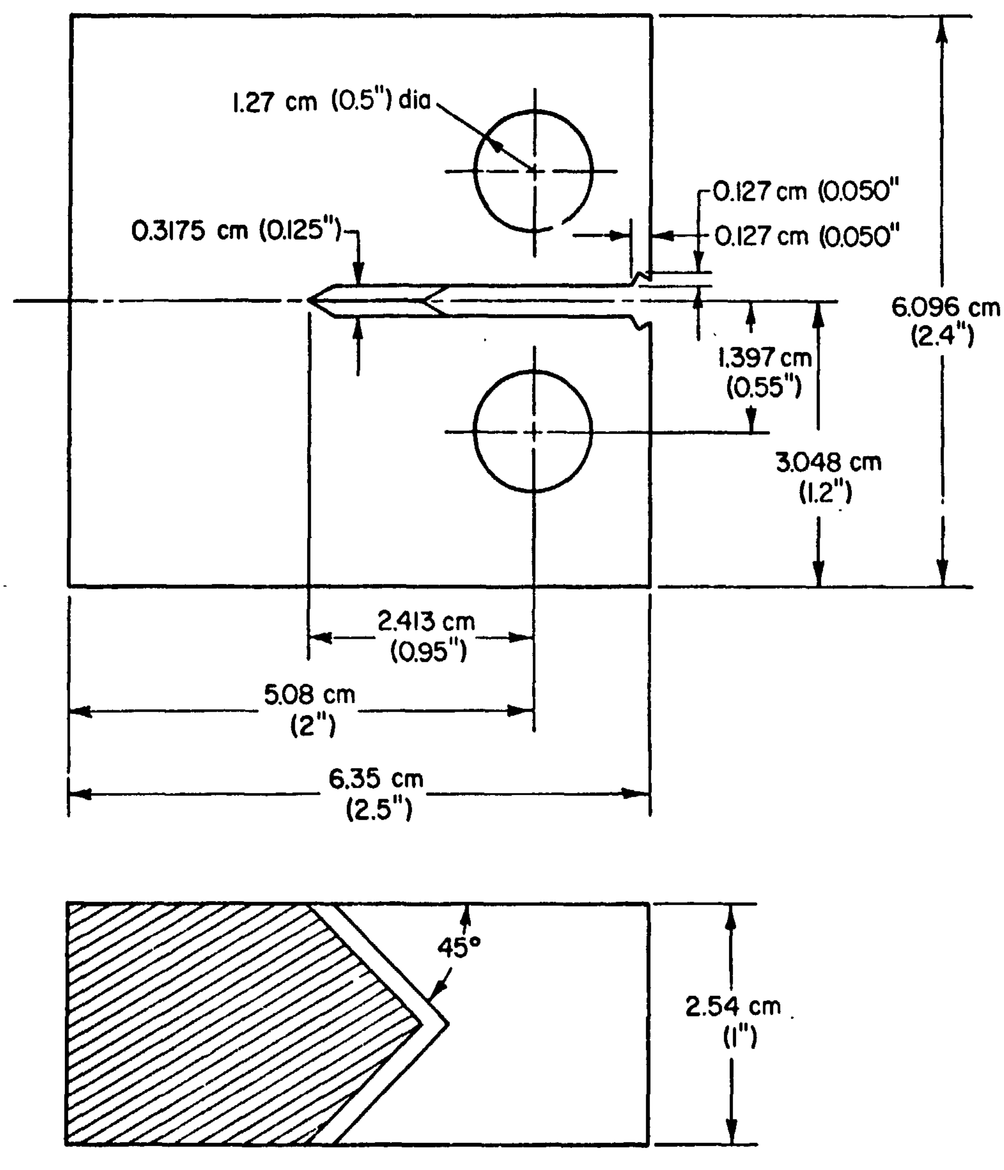


FIGURE A-9. COMPACT TENSION SPECIMEN

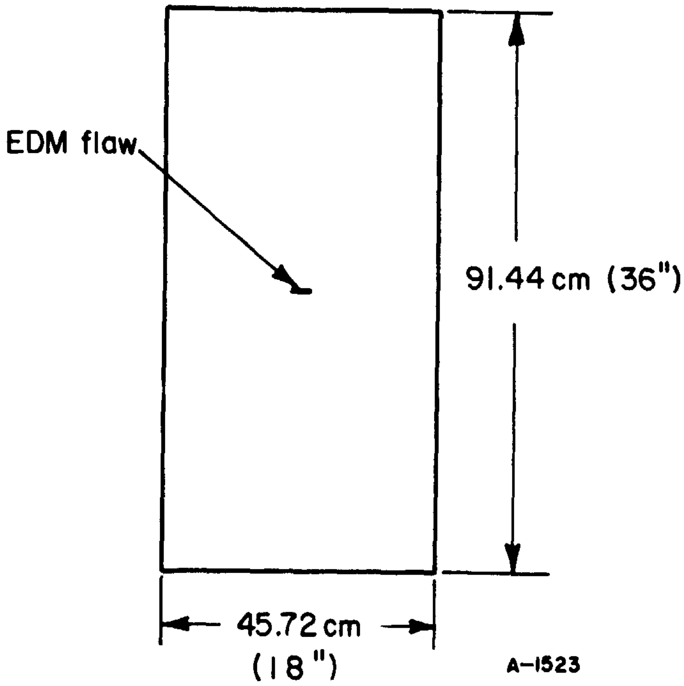


FIGURE A-10. CENTER-CRACKED SHEET FRACTURE TOUGHNESS SPECIMEN

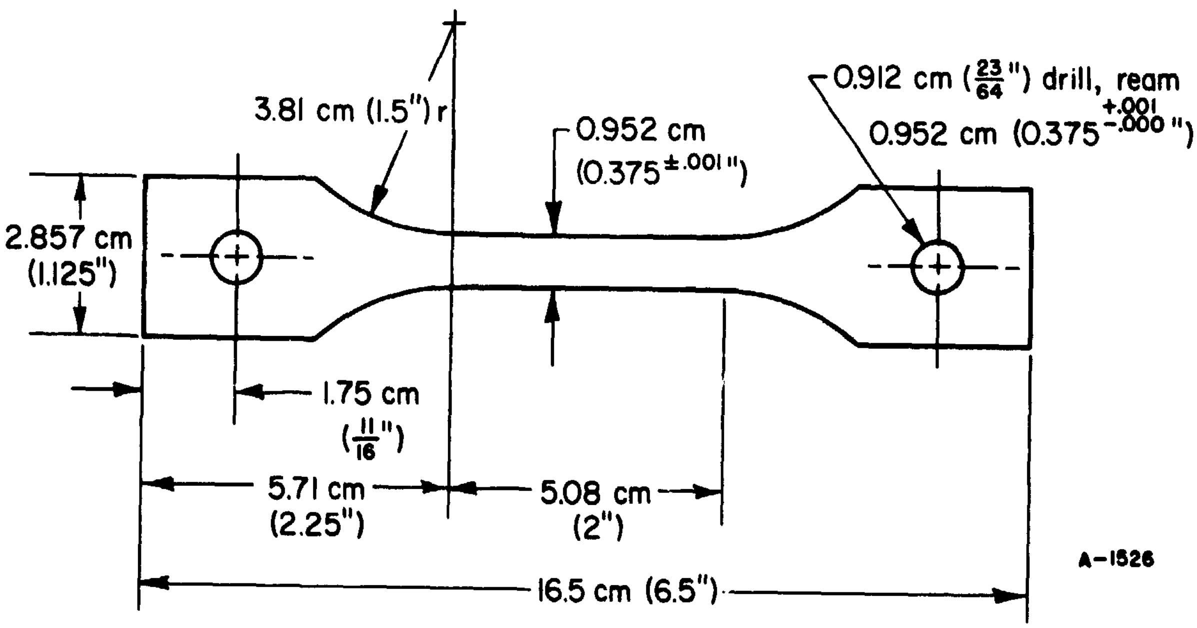


FIGURE A-11. SHEET CREEP AND STRESS-RUPTURE SPECIMEN

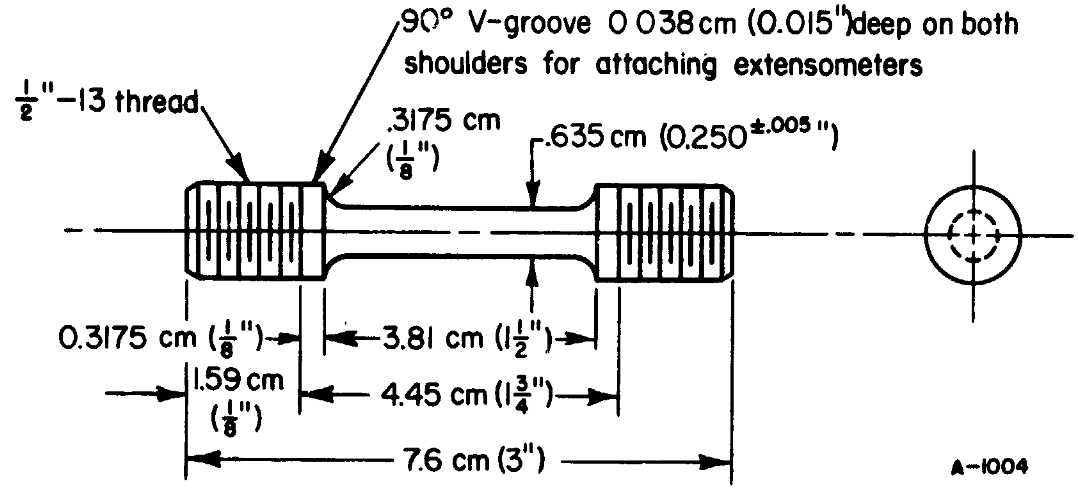


FIGURE A-12. ROUND CREEP AND STRESS-RUPTURE SPECIMEN

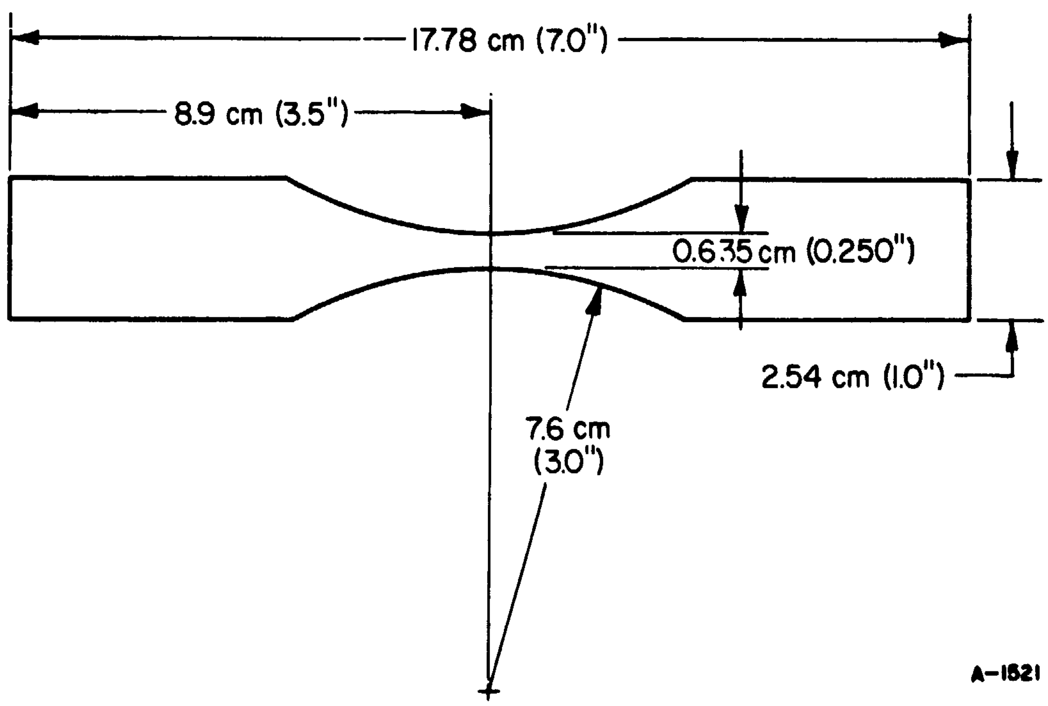


FIGURE A-13. UNNOTCHED SHEET FATIGUE SPECIMEN

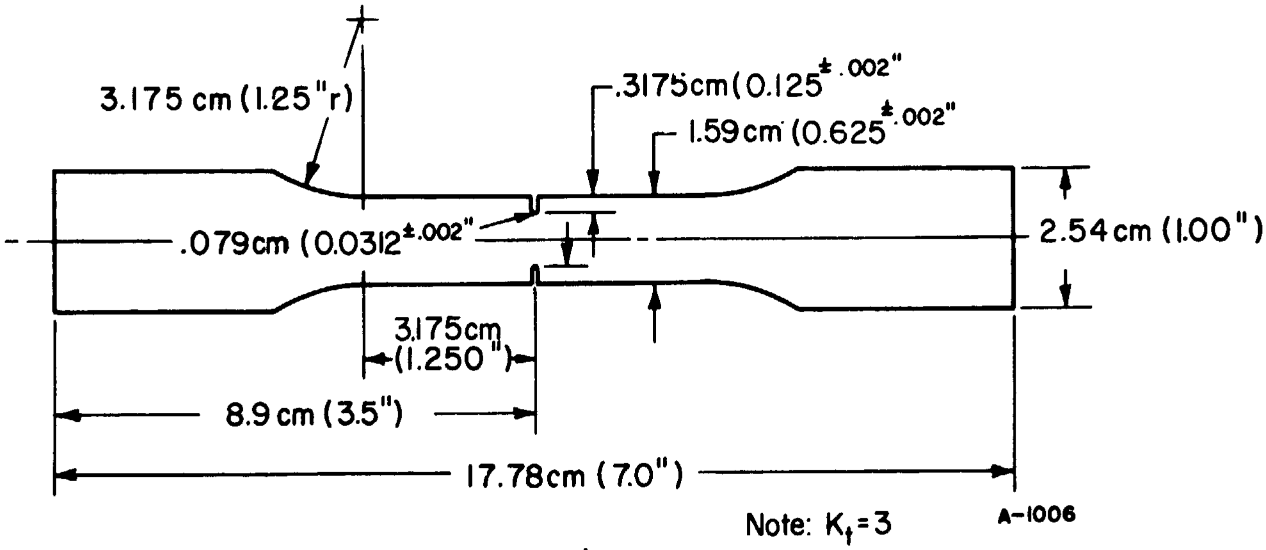


FIGURE A-14. NOTCHED SHEET FATIGUE SPECIMEN

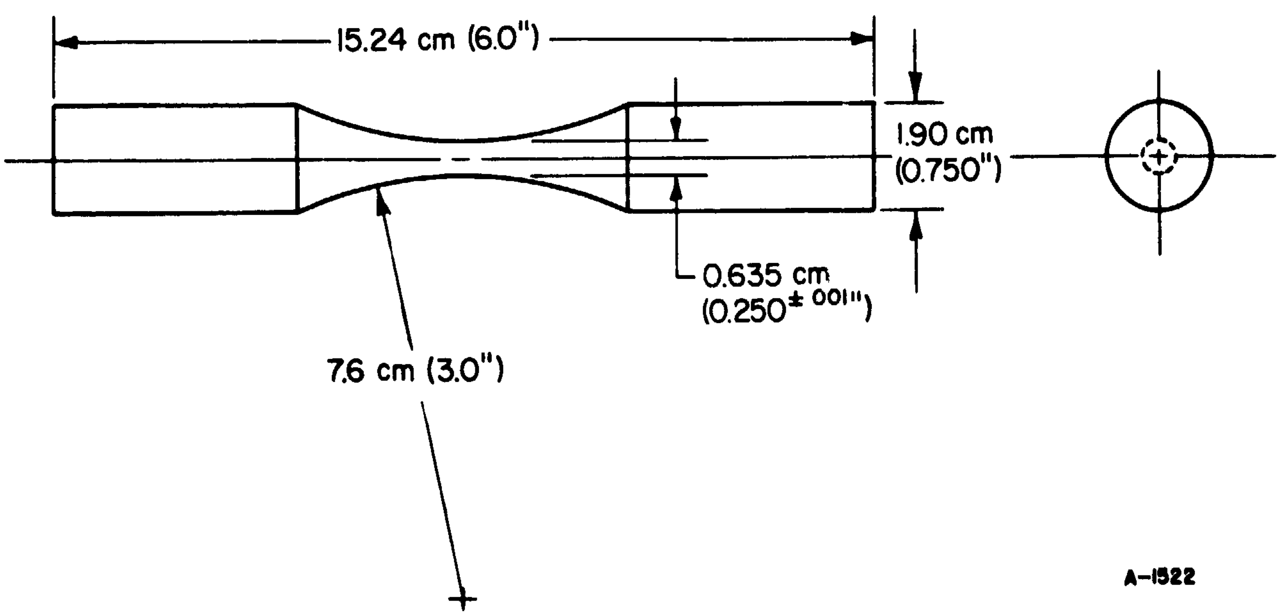


FIGURE A-15. UNNOTCHED ROUND FATIGUE SPECIMEN

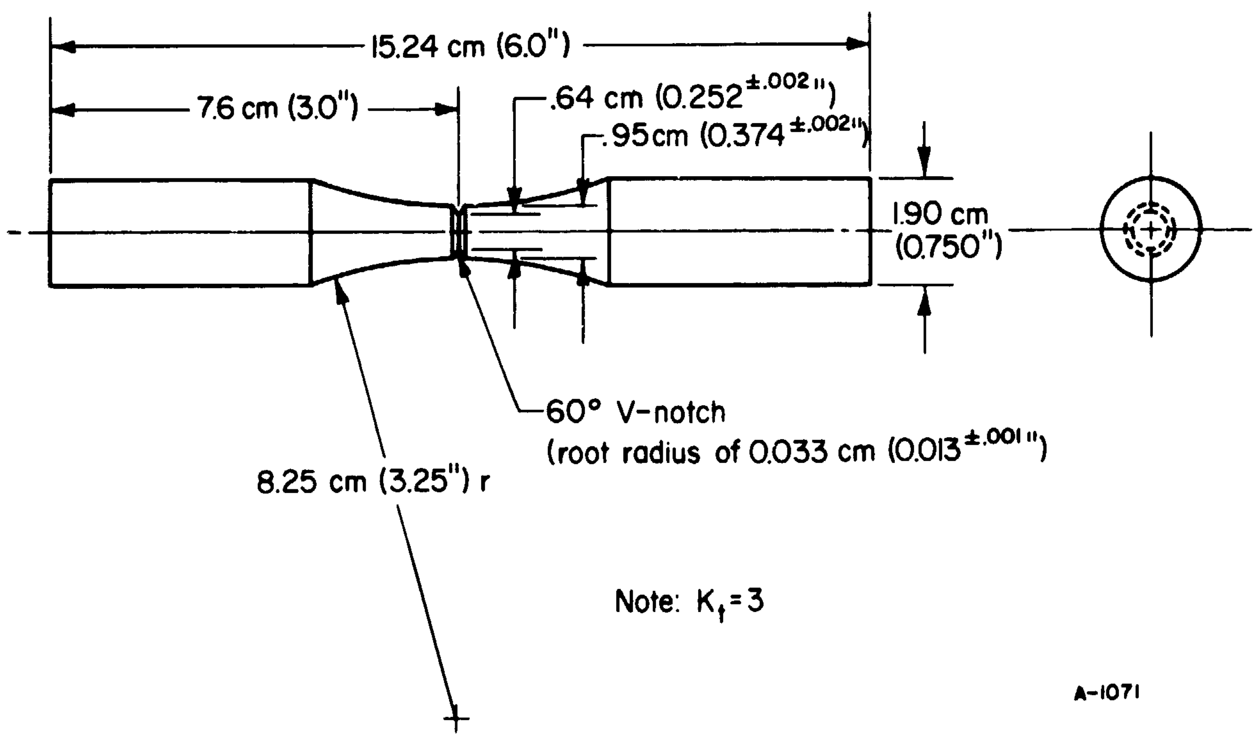


FIGURE A-16. NOTCHED ROUND FATIGUE SPECIMEN

APPENDIX B

DATA COLLECTED FROM INDUSTRIAL SURVEY

- Table I -

Properties of As-Shipped Bar (CTX-1)

Order	Heat	Size	Bar	Room Temperature Tensile Data: .2% Y.S. Ksi	U.T.S. Ksi	% El	%R.A.	Stress Rupture Data*: Test Temp.	Load Ksi	% El	%R.A.	Hours
M85129	88893	3" x 1"	1A	179.0	215.0	12.1	34.1	1200°F	95.0	7.5	25.2	261.2
			2A	181.0	216.5	12.1	32.3	1200°F	95.0	7.0	27.6	240.0
			2A0	182.0	216.0	14.0	40.2	1200°F	95.0	6.5	13.6	340.5

*Combination Smooth/Notch Stress Rupture samples with a .178" gage diameter.

All test samples are longitudinal. Heat Treatment - 1550°F/1 hr./O.T.
+
1325°F/8 hrs./F.C. 100°F/hr.
to 1150°F/hold 8 hrs./A.C.

Data supplied by Carpenter Technology Corporation
Reading, Pennsylvania
April 15, 1975

TABLE I

CAPABILITY MECHANICAL TEST DATA FOR CARPENTER CTX-1 ALLOY

Heat	Solution Temperature, °F/1 hr.	Room Temperature Tensile Data				1200°F Tensile Data				1200°F Stress Rupture Data			
		0.2% Y.S., ksi	Ult. T.S., ksi	El %	R.A., %	0.2% Y.S., ksi	Ult. T.S., ksi	El., %	R.A., %	Load, ksi	Life, hours	El., %	R.A. %
82202	1600	178.5	216.0	10.0	53.1	143.0	166.7	22.2	63.4	90.0	42.5	26.0	66.5
82719	1600	175.0	210.0	9.2	19.6	139.0	158.0	18.7	60.1	90.0	203.1	17.6	36.1
84814	1600	180.0	210.5	13.4	35.8	132.6	154.9	20.0	57.2	90.0	105.5	9.8	26.5
86675	1575	190.0	216.0	15.3	44.5	143.8	155.0	22.7	52.5	95.0	334.5	4.2	17.6
87390	1550	190.5	214.5	15.0	45.6	141.5	154.0	20.7	51.0	95.0	383.5	8.4	21.6
87390	1550	180.0	207.5	15.0	45.4	144.0	154.8	21.8	54.8	95.0	322.4	13.3	44.4
88893	1550	177.5	208.5	15.6	43.6	122.1	143.0	22.1	58.0	95.0	125.0	7.0	19.8
89584	1550	178.0	204.0	14.0	47.0	144.0	158.5	20.7	55.5	85.0	450.4	16.0	56.4
89791	1575	178.0	206.5	13.0	34.0	138.3	156.0	20.9	55.5	95.0	229.9	15.4	46.8
91178	1575	179.0	207.0	12.0	33.0	141.0	158.0	20.0	57.7	95.0	74.3	22.8	58.0

Age: 1325°F/8 hrs./Cooled 100°F/hr. to 1150°F/8 hrs./A.C.

All test samples taken from 3/4" sq. forged coupons.

All stress rupture samples are combination smooth/notch .178" gage diameter.

Data supplied by Carpenter Technology Corporation
Reading, Pennsylvania
August 14, 1974 and April 15, 1975

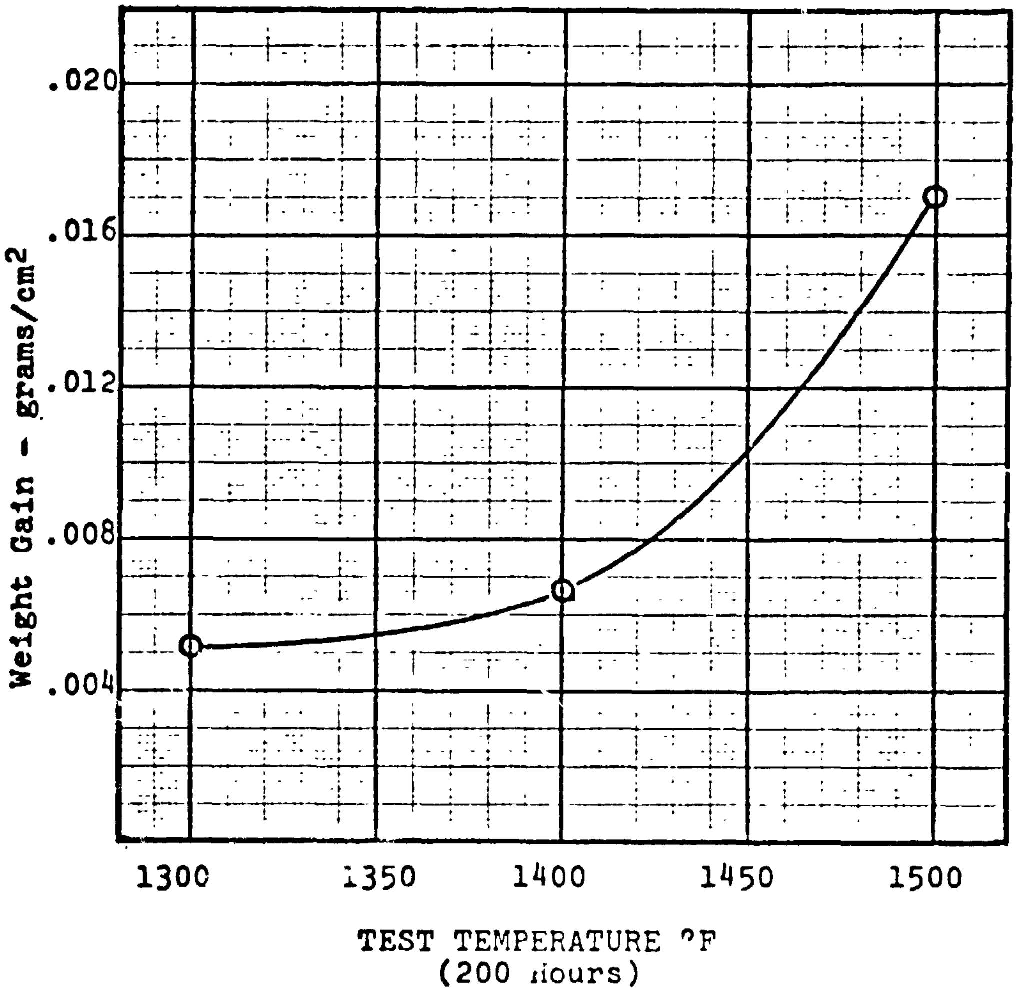


Figure 1. OXIDATION TEST DATA - CARPENTER CTX-1.
(Electric Furnace -- Static Air)

Test Temp. (°F)	Weight Gain grams/cm^2
1300	.0051
1400	.0066
1500	.0170

Heat Treatment:
Solution: 1600°F/1 hr./A.C.
Aged: 1325°F/8 hrs./cool 100°F per hr. to 1150°F/8 hrs./A.C.

Re: C.32.73
Carpenter Technology Corp.
Reading, Pa.
8/14/74

CARPENTER TECHNOLOGY CORPORATION
READING, PENNSYLVANIA

Suggested Chemistry and Property Levels
to be Included in Specification
for Controlled Thermal Expansion Superalloy

C	Mn	Si	P	S	Cr
.05 Max.	.20 Max.	.20 Max.	.015 Max.	.015 Max.	.20 Max.
Ni	**Mo**	**Cu**	**Cb+Ta**	**Ti**	**Al**
36.5/38.5	.20 Max.	.50 Max.	2.50/3.50	1.60/1.80	.50/1.15
		B	**Co**	**Fe**	
		.010 Max.	14.00/17.00	Balance	

Heat Treatment #1

Solution Treatment - 1550°F/1575°F ± 25°F/1 hr. at heat Air Cool or faster.
Precipitation Treatment - 1325°F ± 15°F, hold at heat for 8 hours, furnace cool at maximum rate of 100°F per hour to 1150°F ± 15°F/8 hrs. Air Cool.

Grain Size after Heat Treatment: Average of ASTM #3 or finer.

Properties after Precipitation Heat Treatment:

Tensile Properties

Test Temp.	.2% Y.S. (KSI)	U.T.S. (KSI)	%El.	%R.A.
Room	160.0 Min.	195.0 Min.	10	20
1200°F	120.0 Min.	140.0 Min.	12	30

Stress Rupture

Test Temp.	Load (KSI)	%El.	Life (Hrs.)
1200°F	95.0*	4.0 Min.	23 Hrs. Min.

*OK to overload at a rate of 5.0 KSI every 8 hours after a minimum life of 48 hours.

CARPENTER TECHNOLOGY CORPORATION
READING, PENNSYLVANIA

Heat Treatment #2

Solution Treatment - 1750°F ± 25°F/1 hr. at heat Air Cool or faster.
Precipitation Treatment - 1325°F ± 15°F, hold at heat for 8 hours, furnace cool at maximum rate of 100°F per hour to 1150°F ± 15°F/8 hrs. Air Cool.

Grain Size after Heat Treatment: Average of ASTM 3 or finer.

Properties after Precipitation Heat Treatment

Tensile Properties

Test Temp.	.2% Y.S. (KSI)	U.T.S. (KSI)	%El.	%R.A.
Room	150.0	180.0	10	20
1200°F	110.0	125.0	8	12

No Stress Rupture for this heat treatment.

Thermal Expansion

Temperature Range °F	Total Thermal Expansion in mils/inch	Average Linear Coefficient of Thermal Expansion in/in/°F X 10^{-6}
Room - 700°F	2.2/3.0	3.5/4.8
Room - 900°F	3.2/4.0	3.8/4.8

CARPENTER TECHNOLOGY CORPORATION
CONTROLLED THERMAL EXPANSION SUPERALLOYS
PRELIMINARY INFORMATION
MARCH 26, 1973

Studies at the CarTech Research and Development Center have revealed a series of high-strength superalloy-type compositions in which both mechanical and thermal expansion characteristics can be controlled and varied over wide ranges. The alloys exhibit Curie temperature behavior, having an α_1 [coefficient of thermal expansion from room temperature to the Curie temperature] which is lower than α_2 [coefficient of thermal expansion above the Curie temperature]. This means that although the alloys are fully austenitic, they are ferromagnetic at ambient temperature. A wide range of α, and Tc [Curie temperature] are possible - depending upon exact composition.

Two alloys are presented, Table I. CTX-1 exhibits an excellent combination of strength and ductility. Depending on heat treatment, the alloy can develop a wide range of strength and ductilities. However, due to relatively low solvus temperatures of precipitated phases, CTX-1 must be forged and heat treated at relatively low temperatures. For example, maximum forging temperature of CTX-1 is usually held to 1900°F. CTX-1 is a stronger version which is less ductile. It too, can be processed to a wide range of property capability. Higher forging temperatures (e.g. 2050°F) and solution treating temperature are possible for wider latitude in process control.

Table II shows some typical properties for CTX-1 and EX 00035. These properties were developed for conditions requiring best 1200°F stress-rupture ductilities. Alternate hot work/heat treat sequences are possible.

TABLE I

CHEMISTRIES OF CARTECH DEVELOPMENT CONTROLLED THERMAL EXPANSION SUPERALLOYS

	CTX-1	EX 00035
C	.03	.03
Ni	37.50	40.70
Co	16.00	16.00
Ti	1.75	3.00
Al	1.00	1.25
Cb	3.00	4.70
B	.0075	.0075
Fe	Balance	Balance

Carpenter Technology Corporation
Reading, Pa., 19603
March 26, 1973

TABLE II

PRELIMINARY DATA ON CARTECH DEVELOPMENT CONTROLLED THERMAL EXPANSION SUPERALLOYS

Alloy Names	Solution Temp. (°F)	70°F Tensile .2% YS (ksi)	70°F Tensile UTS (ksi)	70°F Tensile El. (%)	70°F Tensile R.A. (%)	1200°F Tensile .2% YS (ksi)	1200°F Tensile UTS (ksi)	1200°F Tensile El. (%)	1200°F Tensile R.A. (%)	Stress Rupture Life (Hrs)	Stress Rupture El. (%)	Stress Rupture R.A. (%)	Thermal Expansion Coefficient (in/in/°F)
CTX-1	1575	180/185	205/210	11/14	35/40	145/150	160/165	17/20	55/60	150*	8/10	38/40	75°F to Inflection (~840°F) = 4/5 x 10⁻⁶
"	1600	182/187	210/215	11/14	40/45	145/150	160/165	19/22	55/60	225*	12/14	35/38	75°F to 1300°F = 5.5/6.5 x 10^{-6}
"	1625	182/187	210/215	11/14	40/45	145/150	162/167	19/22	55/60	300*	10/12	25/30	
"	1650	-	-	-	-	135/140	160/165	13/15	18/22	5*	1/3	1/3	
"	1675	-	-	-	-	130/135	155/160	10/12	18/20	3*	1/3	1/3	
EX 00035	1775	205/210	240/245	5/10	8/12	165/170	190/195	12/15	20/25	1000**	5/8	13/15	75°F to Inflection (~800°F) = 4/5 x 10^{-6}
"	1825	220/225	240/245	5/10	18/22	-	-	-	-	5**	1/3	3/5	

*1150°F and 110 ksi
**1200°F and 90 ksi

All Age Treatments
1325°F/8 hrs./cool 100°F/hr. to 1150°F/8 hrs./A.C.

Carpenter Technology Corporation
Reading, Pa. 19603
March 26, 1973

TABLE II

THERMAL EXPANSION COEFFICIENT (in/in/°F)

CTX-1 - 75°F to 840°F = 4/5 x 10^{-6}

75°F to 1300°F = 5.5/6.5 x 10^{-6}

EX 00035 - 75°F to 800°F = 4/5 x 10^{-6}

TABLE 1. THERMAL CONDUCTIVITY FOR INCOLOY 903[a]

Temperature, F	Annealed, BTU/FT, FT^2/HR/F	Heat Treated, BTU/FT, FT^2/HR/F
-200	6.5	8.0
0	7.7	8.6
200	8.7	9.3
400	9.5	10.0
800	11.3	11.5
1200	13.0	13.0
1600	14.8	14.8

[a] Data supplied by Rockwell International-Rockedyne Division.

HUNTINGTON ALLOYS

INCOLOY alloy 903

INCOLOY alloy 903 is a precipitation-hardenable nickel-iron-cobalt alloy whose outstanding characteristics are a constant low coefficient of thermal expansion, a constant modulus of elasticity, and high strength. The nominal composition of alloy 903 is shown in Table 1.

The alloy's characteristics make it an excellent candidate for applications such as rocket-engine thrust chambers, steam-turbine bolts, springs, gage blocks, and ordnance hardware.

Values reported in this publication are representative of the alloy, but they are not suitable for specifications.

Units of measure in this publication are shown in customary United States units along with corresponding values in the International System of Units (SI). The SI unit of stress is the pascal (Pa). The pascal is the SI designation for newton per square metre (N/m^2). Its approximate relationship to the pound per square inch (psi) is 1 Pa ($1 N/m^2$) = 0.0001450 psi, or 1 psi = 6,895 Pa. Because of the disparity in magnitude between the two units, multiples of the pascal are normally used for converted values. Frequently used multiples are kilopascal (kPa), megapascal (MPa), and gigapascal (GPa), which are magnitudes of 10^3, 10^6, and 10^9, respectively. A value of 1000 psi (1 ksi) would be converted to an SI equivalent as follows:

1000 X 6,895 = 6,895,000 Pa or 6.895 MPa

As illustrated by the above example, 1 ksi is equivalent to approximately 7 MPa.

PHYSICAL CONSTANTS AND THERMAL PROPERTIES

Some physical constants for INCOLOY alloy 903 are listed in Table 2. Thermal properties for the alloy are shown in Table 3. Physical properties are reported for precipitation-hardened material.

Table 1 – Nominal Composition of INCOLOY alloy 903

Element	Weight %
Nickel	38.0
Cobalt	15.0
Aluminum	0.7
Titanium	1.4
Columbium	3.0
Iron	Balance

Table 2 – Physical Constants of Age-Hardened INCOLOY alloy 903

Density	
lb/cu in	0.294
Mg/m^3	8.14
Curie Temperature	
°F	780-880
°C	416-471
Melting Range	
°F	2405-2539
°C	1318-1393

INCONEL and INCOLOY are Registered Trademarks of The International Nickel Company, Inc.

Table 3 – Thermal Properties of Age-Hardened INCOLOY alloy 903

Temperature	Specific Heat[a]	Electrical Resistivity	Thermal Conductivity[b]
°F	Btu/lb-°F	ohm-circ mil/ft	Btu-in./ft²-hr-°F
100	0.105	379	117
200	0.108	433	119
400	0.115	532	124
600	0.122	626	128
800	0.129	692	134
1000	0.136	728	145
1200	0.143	734	158
°C	J/kg-°C	µΩ-m	W/m-°C
50	441.7	0.650	16.9
100	454.3	0.735	17.2
200	481.5	0.880	17.9
300	506.6	1.020	18.3
400	531.7	1.135	19.0
500	558.9	1.195	20.3
600	584.1	1.220	21.9

[a]Calculated from chemical composition.
[b]Calculated from electrical resistivity.

THERMOELASTIC PROPERTIES

The composition of INCOLOY alloy 903 is designed to provide a constant low coefficient of thermal expansion. Figure 1 shows expansion curves for four different samples. As shown by the curves, the alloy typically exhibits a coefficient of expansion of about 4.0 x 10^{-6} in./in./° F (7.2 μ m/m−° C) from room temperature to around 800° F (425° C).

The expansion characteristics of alloy 903 are highly reproducible both in static and cyclic exposure to temperature. It exhibited no change in coefficient of expansion after exposure for 500 hours at 1100° F (595° C). Fifty cycles of heating to 1200° F (650° C), holding at temperature for 15 min, and air cooling resulted in a reproducibility of expansion within 1%.

INCOLOY alloy 903 maintains its rigidity over a wide temperature range. As shown in Table 4, the modulus of elasticity remains virtually constant from −320° F (−196° C) to 1200° F (650° C).

Because of alloy 903's low coefficient of thermal expansion and constant modulus of elasticity, it is highly resistant to thermal fatigue and thermal shock.

Table 4 – Modulus of Elasticity[a] of Age-Hardened INCOLOY alloy 903

Temperature	Tensile Modulus	Torsional Modulus	Poisson's Ratio[b]
° F	10^6 psi	10^6 psi	
-320	21.59	–	–
-200	21.42	–	–
-100	21.34	–	–
0	21.29	–	–
100	21.30	8.63	0.234
200	21.35	8.56	0.247
300	21.42	8.62	0.242
400	21.52	8.75	0.230
500	21.67	8.84	0.226
600	21.84	8.88	0.230
700	22.00	8.89	0.237
800	22.18	8.84	0.255
900	22.34	8.65	0.291
1000	22 10	8.41	0.314
1100	21.75	8.10	0.343
1200	21.43	7.64	0 402
° C	GPa	GPa	Poisson's Ratio[b]
-196	148.9	–	–
-100	147.4	–	–
- 50	146.9	–	–
0	146.8	–	–
50	146.9	59.3	0.239
100	147.2	59.0	0.247
150	147.8	59.5	0.242
200	148 4	60.3	0.231
250	149 3	60.9	0.226
300	150 2	61.2	0.227
350	151 3	61.2	0.236
400	152.4	61.4	0.241
450	153 5	60.3	0.27[illegible]
500	153.9	59 2	0.300
550	151.8	57.6	0.318
600	149.8	55 4	0.352

[a] Determined by dynamic method.
[b] Calculated from moduli of elasticity.

MECHANICAL PROPERTIES

INCOLOY alloy 903 has high mechanical properties at room temperature and retains much of its strength up to around 1200° F (650° C). Typical room-temperature and 1200° F (650° C) tensile properties for the alloy are shown in Table 5. Typical room-temperature mechanical properties for the alloy after 1000-hr exposure to elevated temperatures are listed in Table 6. As indicated by the impact strength, no deleterious phases were present in the alloy. A comparison of notch- and smooth-bar tensile strength is shown in Figure 2. All properties are reported for age-hardened material.

Stress-rupture properties of the alloy are governed by thermo-mechanical processing. Typical stress to produce rupture in 100 hr of age-hardened material at 1200° F (650° C) is 85,000 psi (586 MPa).

Room-temperature plane-strain fracture toughness (K_{IC}) of precipitation-hardened alloy 903 is 100,600 psi $\sqrt{in.}$ (111 36 MPa · $\sqrt{m}$) (average of three tests).

Table 5 – Typical Tensile Properties[a]

Temperature		Yield Strength (0.2% Offset)		Tensile Strength		Elongation,	Reduction of Area,
° F	° C	1000 psi	MPa	1000 psi	MPa	%	%
70	21	160	1103	190	1310	14	40
1200	650	130	896	145	1000	18	55

[a] Material heat treated 1550° F (845° C)/1 hr, W Q + 1325° F (720° C)/8 hr, F C 100° F (56° C)/hr to 1150° F (620° C)/8 hr, A C

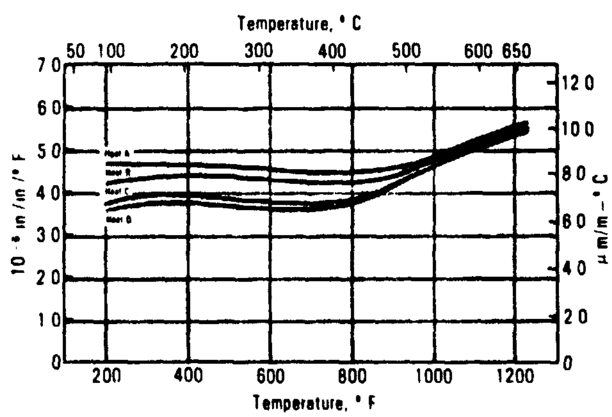


Figure 1. Typical coefficients of thermal expansion (room temperature to temperature shown) of INCOLOY alloy 903.

METALLOGRAPHY

INCOLOY alloy 903 derives much of its high strength from the precipitation of gamma prime during heat treatment This phase results from alloying additions of aluminum, titanium, and columbium

A typical microstructure of alloy 903 in the solution-treated and precipitation-hardened condition is shown in Figure 3

OXIDATION RESISTANCE

The static oxidation resistance of INCOLOY alloy 903 is shown in Table 7 Testing was conducted for 500 hr at 1000° F (540° C), 1100° F (595° C) and 1200° F (650° C)

Cyclic oxidation resistance of alloy 903 is shown in Table 8. The specimens were alternately exposed to the test temperature for 15 min and cooled in air for 5 min

Because alloy 903 contains no chromium, oxidation resistance may become a consideration for some high-temperature applications In such cases, protective coatings may be desirable

Table 6—Room-Temperature Tensile Properties After 1000 Hours of Exposure to Elevated Temperatures[a]

Exposure Temperature		Yield Strength (0.2% Offset)		Tensile Strength		Elongation, %	Reduction of Area, %	Impact Strength	
°F	°C	1000 psi	MPa	1000 psi	MPa			ft-lbs	J
70	21	165.5	1141	198 5	1369	17	43	24	32.5
1100	595	169.5	1169	200 5	1382	16	44	25	33 9
1200	650	149 0	1027	185 0	1276	19	47	26	35 3
1300	705	107.0	738	149 0	1027	20	41	–	–

[a] Material heat treated 1550° F (845° C)/1 hr, W Q + 1325° F (720° C)/8 hr, F C 100° F (56° C)/ hr to 1150° F (620° C)/8 hr, A C

Table 7—500-hr Static Oxidation Resistance of INCOLOY alloy 903

Test Temperature		Weight Gain[a]	Depth of Attack	
°F	°C	mg/cm²	in.	cm
1000	540	0 7	0 0015	0.0038
1100	595	2.2	0.0025	0 0064
1200	650	2 7	0 0040	0 0102

[a] No scaling evident

Table 8—Cyclic Oxidation Resistance of INCOLOY alloy 903

Cyclic[a] Exposure Time, hr	Weight Gain, mg/cm²		
	1000° F (540° C)	1100° F (595° C)	1200° F (650° C)
100	0 32	0 6	1 1
200	0 38	0 7	1 9
300	0 40	0 9	2 4
400	0 43	1 0	3 0
500	0 48	1 1	3.6

[a] 15 min heating and 5 min cooling in air

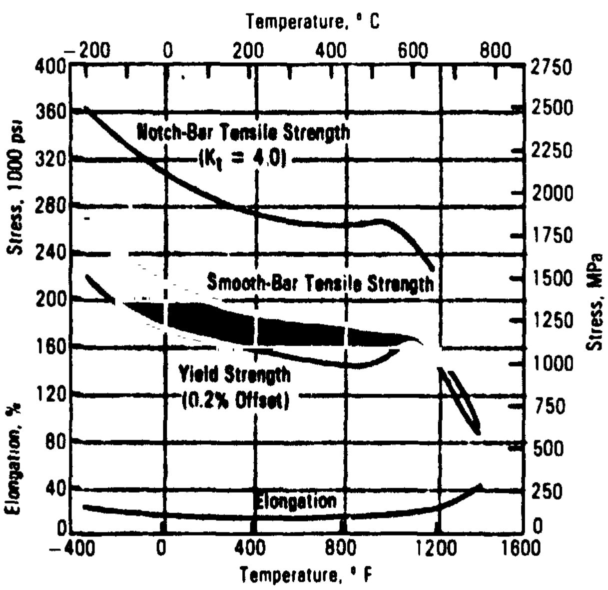


Figure 2. Tensile properties of smooth and notched specimens of solution-treated and age-hardened INCOLOY alloy 903.

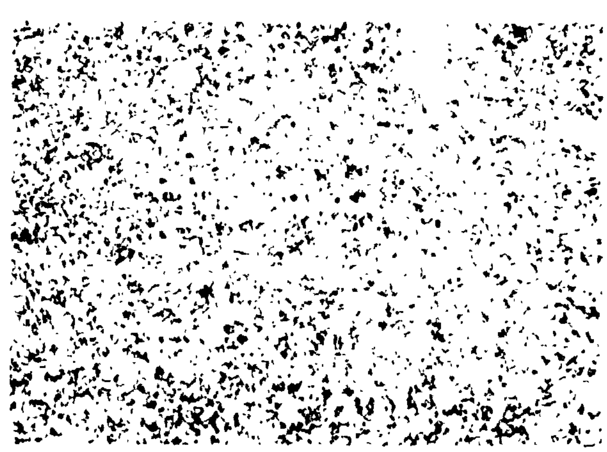


Figure 3. Typical microstructure of INCOLOY alloy 903 in the solution-treated and age-hardened condition Etchant Glyceregia 100X

FABRICATION

Hot Forming

INCOLOY alloy 903 should be hot worked in the 1500-2050° F (815-1120° C) temperature range. For applications in which high stress-rupture properties are required, the alloy should be given a minimum of 25%, and preferably 50%, reduction at temperatures of 1500 to 1600° F (816-871° C). When tensile properties govern, alloy 903 should be worked in the same manner as INCONEL alloy X-750. Details are given in "Fabricating Huntington Alloys". Since INCOLOY alloy 903 is softer than alloy X-750 between 1600-2000° F (870-1095° C), forming forces are lower.

Machining

In either the solution-treated or age-hardened condition, INCOLOY alloy 903 should be machined with the tooling and procedures recommended for Group D-2 alloys in "Huntington Alloys: Machining".

Joining

INCOLOY alloy 903 is readily joined by the gas-tungsten-arc process. Consult Technical Service for specific welding recommendations.

Heat Treatment

Solution treatment before age hardening should be performed in the 1500-1800° F (815-980° C) range, depending on the product and prior condition. For optimum mechanical properties, a precipitation-hardening treatment of 1325° F (720° C)/8 hr, F.C. 100° F (56° C)/hr to 1150° F (620° C) 8 hr, A.C. is recommended.

AVAILABLE PRODUCTS

INCOLOY alloy 903 is available as sheet, plate, rod, bar, and forging stock. For information, consult the nearest Huntington Alloys office.

2M 10-74 S-51

Litho in USA