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PROPERTIES OF CRYOGENICALLY WORKED MATERIALS

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by

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MARTIN MARIETTA CORPORATION

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center

Contract NAS3-12028

James R. Faddoul, Project Manager

NOTICE

NASA CR-72798

Final Report

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R. G. Herzog, S. H. Osgood, and D. Lighty

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NASA Lewis Research Center
Cleveland, Ohio

James R. Faddoul, Project Manager

FOREWORD

The work described herein, which was conducted by the Martin Marietta Corporation, Denver Division, was performed under NASA Contract NAS3-12028. The work was done under the management of the NASA Project Manager, Mr. James R. Faddoul, Liquid Rocket Technology Branch, NASA-Lewis Research Center.

ABSTRACT

Screening tests conducted on 15 alloys indicated that only two, PH 14-8 Mo and MP 35 N, developed significantly higher strengths when strained at cyrogenic temperatures than when strained at room temperature. From additional testing of PH 14-8 Mo it was determined that this material can be cryostrained and aged to higher strengths than those achieved through industry standard treatments. Through combined cryostrain-aging treatments it is possible to strengthen PH 14-8 Mo to obtain yield strength to density ratios in excess of 1×10^6 inches. Although further study is necessary before a final determination can be made the indications are that PH 14-8 Mo cryostrained and aged to above normal strengths will have sufficient toughness and corrosion resistance to be a useful structural material.

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PROPERTIES OF CRYOGENICALLY WORKED MATERIALS FINAL REPORT

By R. G. Herzog, S. H. Osgood and D. Lighty

SUMMARY

During the first year of the two-year program conducted under Contract NAS3-12028, 15 alloys were selected and tested to determine those for which cryoworking is a potentially useful strengthening process. The test materials were procured in the form of sheet or strip, in the range of 0.050 inch (0.127 cm) to 0.100 inch (0.254 cm) thick. With the exception of the magnesium alloy LA 141 A, the test materials were procured in the annealed or solution treated condition. LA 141 A was procured in the stabilized (-T7) condition and strained in that condition. Three other alloys, the 2219 and 6061 aluminum alloys, and the titanium alloy 6Aℓ-4V ELI, although procured in the annealed condition were strained in the solution treated condition. The materials were cryoworked by straining them in uniaxial tension while they were immersed in and at thermal equilibrium with a cryogen (cryostraining).

The materials tested were: aluminum alloys, 2219, 6061, and 5456; beryllium copper (CDA 172); cobalt alloy, L-605; cobalt-nickel alloy, MP 35 N; magnesium alloy, LA 141 A; nickel alloys, Inconel 718 and Nickel 440; steel, A-286, PH 14-8 Mo, 21-6-9, and TRIP steel; and the titanium alloys, 5Aℓ-2.5 Sn ELI, and 6Aℓ-4V ELI. At the conclusion of the first year's work it was determined that cryoworking was a potentially useful method of strengthening only two of the alloys tested: PH 14-8 Mo and MP 35 N.

For another seven alloys cryostraining was found to be a more effective method of strengthening than room temperature straining. These alloys have a higher uniform strain capability at cryogenic temperatures than at room temperature. Consequently, they can be strained and worked more at cryogenic temperatures than at room temperature, thus developing higher strengths through cryostraining. However, the magnitude of the strength increase that is possible by working these alloys at cryogenic temperatures is proportionally so small an increase with respect to strengths developed through room temperature working that cryostraining does not merit consideration as a practical method of strengthening them. The seven alloys in this category are: 6061, 5456, Inconel 718, Nickel 440, beryllium copper, A-286, and 21-6-9.

For the other alloys tested it was found that cryostraining has no advantage over room temperature straining with respect to developing higher strengths.

The first phase of the second year's work consisted of a continuation of the screening tests begun during the first year. However, only three alloys, all semiaustenitic precipitation hardening stainless steels; PH 14-8 Mo, PH 15-7 Mo, and 17-7 PH were tested. The purpose of these tests was to determine, on the

basis of comparative response to cryoworking, the alloy to make the subject of more detailed study during the remainder of the program. PH 14-8 Mo was ultimately selected for this purpose.

From the results of tests conducted during the second year of the program it was concluded that cryostraining is an effective method for strengthening each of the three alloys tested. All three steels can be cryostrained and aged to develop tensile strengths above 300 000 psi (206 900 N/cm^2). None of the steels evidenced significant anisotropy. PH 15-7 Mo developed higher strength per unit of strain than the other alloys; however, test results also indicated that PH 15-7 Mo was not as tough as the others after comparable cryostraining.

PH 14-8 Mo was selected for additional testing and study because it developed higher strengths per unit of strain than 17-7 PH, was found to have higher postweld strain capability than 17-7 PH or PH 15-7 Mo, and, although no specific tests were conducted, there were indications that PH 14-8 Mo was somewhat tougher than the other two steels after cryostraining and aging.

Conclusions drawn from the results of tests conducted on PH 14-8 Mo are:

1) Cryostrained PH 14-8 Mo can be aged to maximum strength per strain level at temperatures from 800°F (700°K) to 950°F (783°K). Aging times must, however, be adjusted to compensate for differences in aging temperatures: as aging temperature increases the time at temperature to achieve maximum strength decreases.

2) The toughness of cryostrained PH 14-8 Mo is slightly better, at equal strengths, after aging at 950°F (783°K) than after aging at 900°F (756°K) or at 800°F (700°K).

3) Cryostrained and aged, room temperature strained and aged, or annealed PH 14-8 Mo are more resistant to corrosion by an aqueous 3.5 NaCℓ solution than PH 14-8 Mo SRH 950 or PH 14-8 Mo SRH 1050.

4) The tensile properties of PH 14-8 Mo developed by cryostraining are relatively insensitive to strain rate.

5) Due to the Bauschinger effect, the compression yield strength of cryostrained (in tension) and unaged PH 14-8 Mo is much lower than its tensile yield strength.

6) Aging, even for short periods of time at 800°F (700°K), provides sufficient stress relief so that the Bauschinger effect is eliminated and compression yield strengths equal to or slightly exceeding the tensile yield strengths of comparably conditioned PH 14-8 Mo are achieved.

7) The data indicate that PH 14-8 Mo cryostrained and aged to above normal strengths will retain sufficient toughness and corrosion resistance to serve as a structural material. More comprehensive study is required, however, before a final determination can be made.

I. INTRODUCTION

Pure metals and many common structural metallic alloys, for example, the 300 series austenitic stainless steels and the non-heat-treatable aluminum alloys, cannot be strengthened by thermal treatment, but they do develop higher strengths through cold working. Cold working is the plastic deformation of a metal or metallic alloy at a temperature below its recrystallization temperature (Ref. 1). Metals and alloys are generally cold worked at temperatures above room temperature. In recent years, however, the working of metallic alloys at temperatures below room temperature has attracted sufficient interest and study so that some processes have been developed for working materials at cryogenic temperatures. For example, Arde Inc., has developed and patented the Ardeform Process (Ref. 2), a method of producing high-performance pressure vessels by cryogenic stretch forming. The process involves the controlled plastic deformation at -320°F (78°K) of pressure vessels made from 301 stainless steel (Ref. 3). Also, the Foster Wheeler Corp., has been awarded a patent (Ref. 4) for a unique method of forming pressure vessels from 301 stainless steel. This method includes a technique for explosively forming the 301 steel at -320°F (78°K).

The Ardeform Process and the Foster Wheeler methods exploit the austenite-to-martensite transformation that can be induced in metastable 301 stainless steel by plastically working the material at -320°F (78°K). At this temperature the transformation is strain-induced and strain-dependent, that is, the amount of martensite formed increases as strain is increased (Ref. 3). The 301 is hardened and strengthened by the transformation, with the increase in these properties dependent upon the final martensite-to-austenite ratio (Ref. 3). The forming methods developed by Arde and Foster Wheeler then are processes for strengthening metastable 301 stainless steel by straining the material at -320°F (78°K) to induce the austenite to martensite transformation.

Mangonon and Thomas (Ref. 5 and 6) report on transformations induced in 304 stainless steel by straining it at cryogenic temperatures, and the additional effects produced by subsequent thermal treatments. It is reported that by appropriate mechanical-thermal treatments, room temperature tensile yield strengths of 200 000 psi (137 900 N/cm^2) and greater, and elongations of up to 10 percent, are developed. The developed properties are shown to be related to the percentage of martensite in the mechanical-thermally treated structure.

The behavior of materials at cryogenic temperatures has been, and continues to be, the subject of many investigations (Ref. 7). The working of materials at cryogenic temperatures (cryoworking or cryostraining), has not been as extensively investigated, however. This program was conducted to determine how the room-temperature tensile properties of selected metallic alloys are affected by cryoworking. The two-year program was divided into two one-year segments. During the first year a screening program was conducted to test 15 selected metallic alloys. The purpose of the screening program was to identify the alloys that were most significantly affected, that is, strengthened by cryoworking. Data developed during the first year were used to select three alloys for the screening tests conducted during the first technical task of the second year. One of the alloys was then subjected to more detailed study during the remainder of the program. The objective of the program was to find at least one alloy that can be cryoworked to significantly increase its tensile strength without suffering too severe a degradation of ductility, toughness, and corrosion resistance.

The Technical Task outline of the entire program is:

- Task I - Materials Selection;
- Task II - Preparation of Baseline and Cryosoaked Specimens;
- Task III - Preparation of Cryoworked Specimens;
- Task IV - Room Temperature Testing;
- Task V - Evaluation of Results;
- Task VI - Selection of a Promising Alloy;
- Task VII - Thermal Response Tests;
- Task VIII - Toughness, Stress Corrosion, High Energy Rate Straining Tests, and Compression Tests;
- Task IX - Analysis.

The first year's program consisted of Tasks I through V. The results of these Tasks are compiled in the Contract Interim Report, (Ref. 8). Tasks VI through IX were conducted during the second year.

II. SYNOPSIS OF THE INTERIM REPORT

The results of the testing performed during the first year of the program are contained in an interim report, CR-72638. This chapter contains a summary of that report and an outline of the second year's program.

The work accomplished during the first year of the program was divided into five technical tasks, namely:

- Task I – Materials Selection;
- Task II – Preparation of Baseline and Cryosoaked Specimens;
- Task III – Preparation of Cryoworked Specimens;
- Task IV – Room Temperature Testing;
- Task V – Evaluation of Results.

TASK I - MATERIAL SELECTION

The objective of the program was to find a metallic alloy that is appreciably strengthened by cryostraining, yet retains sufficient ductility, toughness, and corrosion resistance so that its utility as a structural material is not lost. To achieve this objective it was necessary to select and test materials with a high potential for use in critical structural applications, particularly aerospace structures and airborne pressure vessels. Consequently, in selecting materials for testing in Tasks II, III, and IV, priority was given to structural materials, particularly those suitable for high performance airborne tankage. Other factors considered were:

1) Contract requirements - to select and test a minimum of fifteen alloys, with no more than five alloys from any one base metal system;
2) A material's properties and characteristics, specifically:
    a) Crystal Structure,
    b) Strain Hardening Characteristics,
    c) Thermal Hardening Characteristics,
    d) Phase Transformations,
    e) Properties at Cryogenic Temperatures, Particularly Ductility,
    f) Weldability,
    g) Formability,
    h) Availability in Sheet or Strip Form.

After a review of data collected from three literature searches (National Aeronautics and Space Administration, Department of Defense, and the National Bureau of Standards), and consultation with authoritative personnel in the metal-producing and metal-working industries, the following alloys were selected and tested:

Aluminum Alloys	-	2219, 5456, and 6061,
Cobalt Alloy	-	L-605,
Cobalt-Nickel Alloy	-	MP 35 N,
Copper Alloy	-	Beryllium Copper,
Magnesium Alloy	-	LA 141 A,
Nickel Alloys	-	Inconel 718, Nickel 440,
Steels	-	A-286, PH 14-8 Mo, TRIP, 21-6-9,
Titanium Alloys	-	Ti-6Aℓ-4V ELI, Ti-5Aℓ-2.5Sn ELI.

Not all of these alloys are entirely consistent with the premise of selecting materials with a high potential for structural applications. However, the requirement to select 15 alloys, with no more than 5 from any one alloy system, provided the opportunity to include several alloys on the basis of academic interest, rather than for structural potential.

TASKS II, III, AND IV

Tasks II, III, and IV were conducted as consecutive tasks; in Tasks II and III specimens were prepared for the tests conducted in Task IV. The objective of the combined Tasks was to determine those alloys among the 15 tested, for which cryostraining is a potentially practical strengthening process. The plan developed to achieve this objective was based on the following factors:

1. The test materials would be procured in the form of sheet or strip, as appropriate for each alloy;
2. The test materials would be strained in the annealed, solution-annealed, or solution-treated condition, as appropriate for each alloy. Consequently, all the materials would be procured in one of these conditions and strained in that condition, with the exception of the magnesium-lithium alloy, LA 141 A, the aluminum alloys, 2219 and 6061, and the titanium alloy, Ti-6Aℓ-4V ELI. The last three would be procured in the annealed condition and then be solution-heat-treated before straining. LA 141 A, would be procured and strained in the -T7 (stabilized) condition;
3. The materials would be strained in uniaxial tension, using standard tensile test machines and standard tensile test specimens (consistent with ASTM E8-69 specifications).

4. A strain rate of 0.050 inch per inch per minute (0.050 cm/cm/min) would be used in straining all specimens.
5. Specimens of each alloy would be strained at room temperature, -110°F (198°K), -320°F (78°K), and -423°F (20°K).
6. At each temperature some specimens of each alloy would be given a low strain, some an intermediate strain, and some a high strain. The low, intermediate, and high strains would be designated as strain levels A, B, and C, respectively. The strain levels would vary with alloy and also with temperature, being dependent and proportional to an alloy's capability to strain uniformly at a temperature.
7. Some specimens of each alloy would only be exposed to (soaked at) the cryogenic temperatures. These cryosoaked specimens would be identified as: 0% strained at -- (the appropriate temperature).
8. Some specimens of each alloy, baseline specimens, would be identified by the self-explanatory description: 0% strained at room temperature.
9. For the heat-treatable alloys one-half of each lot of baseline, cryosoaked, and cryostrained specimens would be given industry standard aging treatments; the remaining specimens of each lot would remain unaged.
10. Specimens prepared as described in items 2 through 9 would be tensile tested at room temperature to obtain ultimate tensile strength, tensile yield strength (0.2% offset), and percent elongation in 2 inches.

The screening program was divided into three separate, yet related technical tasks: Task II, Task III and Task IV. During Task II, the baseline and cryosoaked specimens were prepared. Also, preliminary testing was conducted to determine each alloy's capability for uniform straining at each of the four temperatures. The cryoworked (cryostrained) specimens were prepared during Task III, while the room temperature testing of baseline, cryosoaked, and cryostrained specimens was accomplished during Task IV.

More detailed descriptions of the work accomplished during each of the three tasks follows.

TASK II - PREPARATION OF BASELINE AND CRYOSOAKED SPECIMENS

Specimen Production

With the exception of the specimens strained at -423°F (20°K), specimens used in Tasks II and III were the flat friction-loaded type shown in Figure 1. Pin-loaded specimens of the type shown in Figure 2 were used for straining at -423°F (20°K).

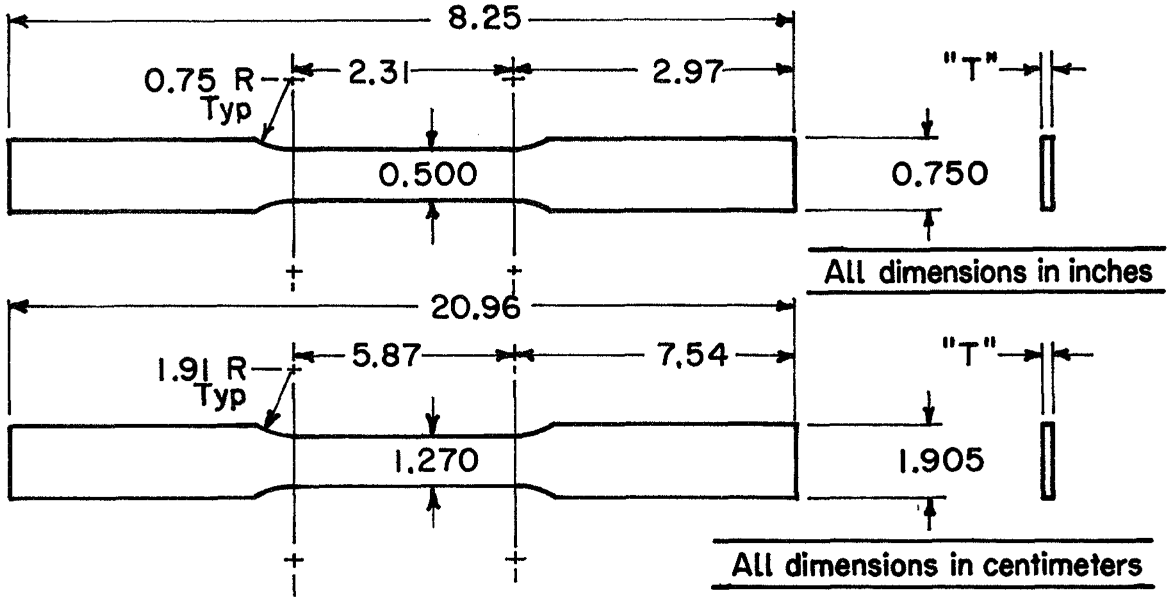


Figure 1. Configuration of Specimens Tested or Strained at Room Temperature, -110°F (194°K), -320°F (78°K)

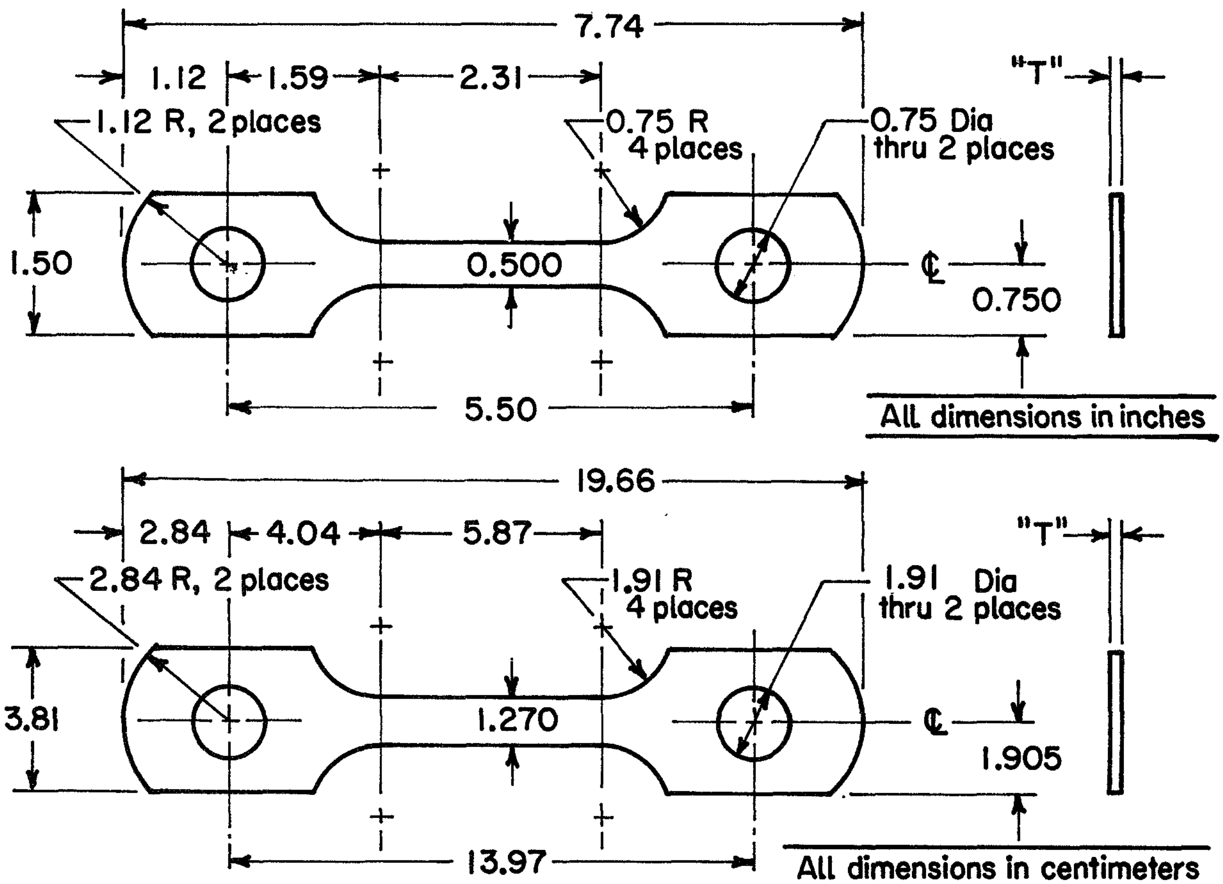


Figure 2. Configuration of Specimens Strained or Tested at -423°F (20°K)

In regard to making the specimens, the procedure followed was to first apply, by photographic process, a 0.100 in. (0.254 cm) square grid pattern (Fig. 3) to one side of the sheet or strip material. The sheet or strip was then sheared into blanks for machining: t x 7/8 in. (2.22 cm) wide x 8 in. (20.32 cm) long for the friction-loaded specimens; t x 1-5/8 in. (4.13 cm) wide x 8 in. (20.32 cm) long for the pin-loaded specimens. The blanks were then machined to specimen configuration in packs of 20 pieces minimum, depending upon material thickness. For all the specimens used in Tasks II, III and IV the longitudinal grain direction of the material was parallel to the longitudinal axis of the specimen.

Uniform Strain Capability (USC) Determination

During Task II, a preliminary and yet vital set of tests was conducted. The purpose of these tests was to determine each alloy's capability to strain uniformly at each of the four straining temperatures. To obtain these data a minimum of two specimens of each alloy were tension tested to failure at each temperature. For all alloys, these tension test specimens were tested in the condition (e.g., annealed) in which other specimens of the alloy were subsequently cryosoaked or cryostrained. The properties measured in these tests were: ultimate tensile strength; total elongation over a gage length of two inches; and uniform elongation over a one-inch gage length. When practical, tensile yield strength was also measured. Total elongation was measured across the fracture (Figure 4), while uniform elongation was measured over a one-inch gage in an area on one side of the fracture. Care was taken to measure uniform elongation only over a portion of each specimen's initial gage section that was unaffected by localized strain (necking) or by transition radius (Figure 4). Elongations were measured with a 6-inch rule having 0.010 inch graduations, and a 10X magnifying glass. The lines of the grid pattern served as strain measurement datum lines. The average value of the uniform elongations measured on specimens of an alloy tested to failure at a particular temperature was established as an alloy's uniform strain capability (USC) at that temperature. A USC was established for each alloy at each straining temperature.

Establishment of Strain Levels

The strain levels that were established for each alloy at each straining temperature were based on the USCs as follows:

Level A - 40% of an alloy's USC at that temperature at which the alloy had the least USC,

Level B - 60% of an alloy's USC at the straining temperature,

Level C - 80% of an alloy's USC at the straining temperature.

Thus for any alloy, Level A was the same value at all straining temperatures, while the values of Levels B and C varied with temperature.

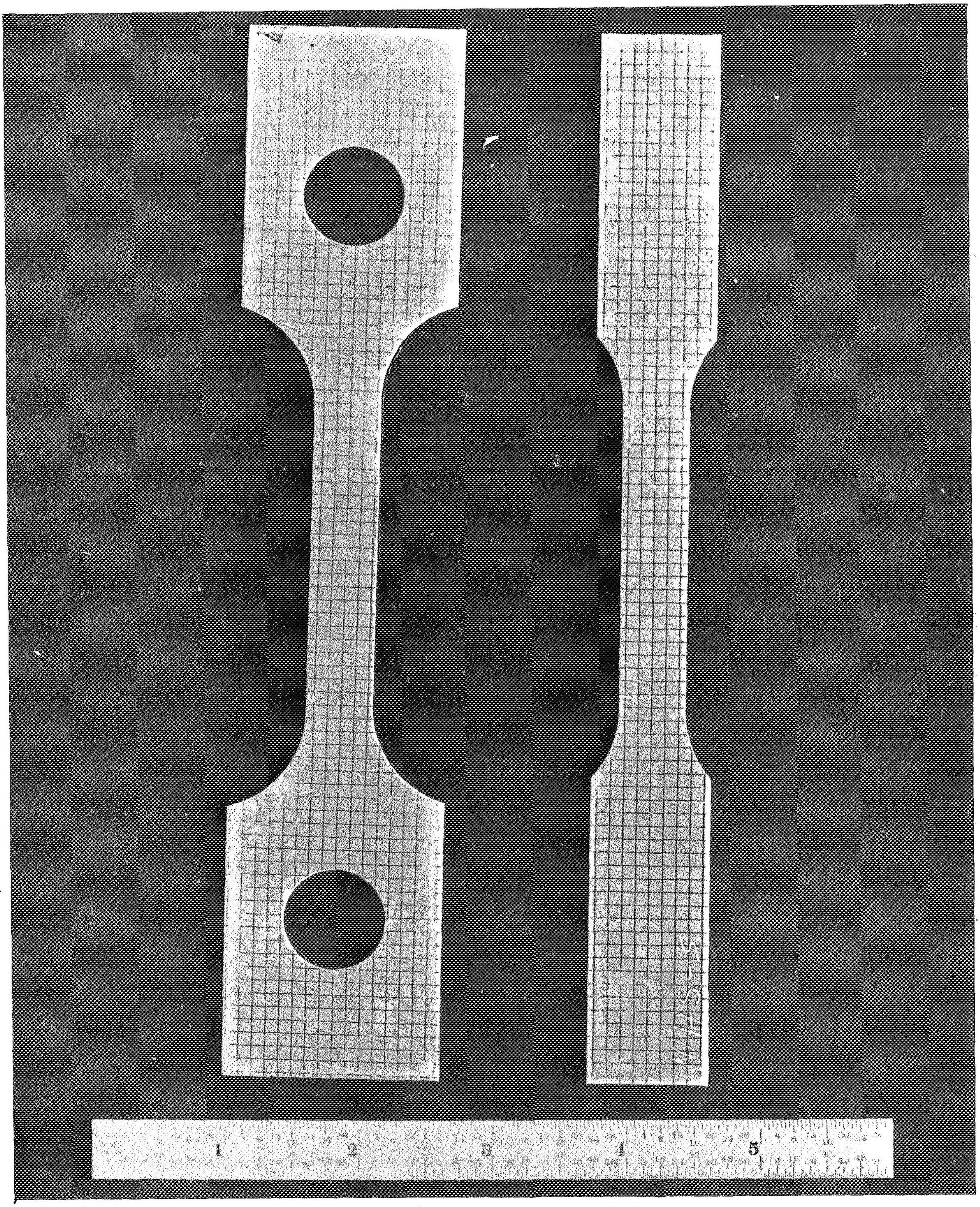


Figure 3. Specimens Used in Task II and Task III with the 0.100-inch (0.254-cm) Square Photogrid Pattern on the Surfaces.

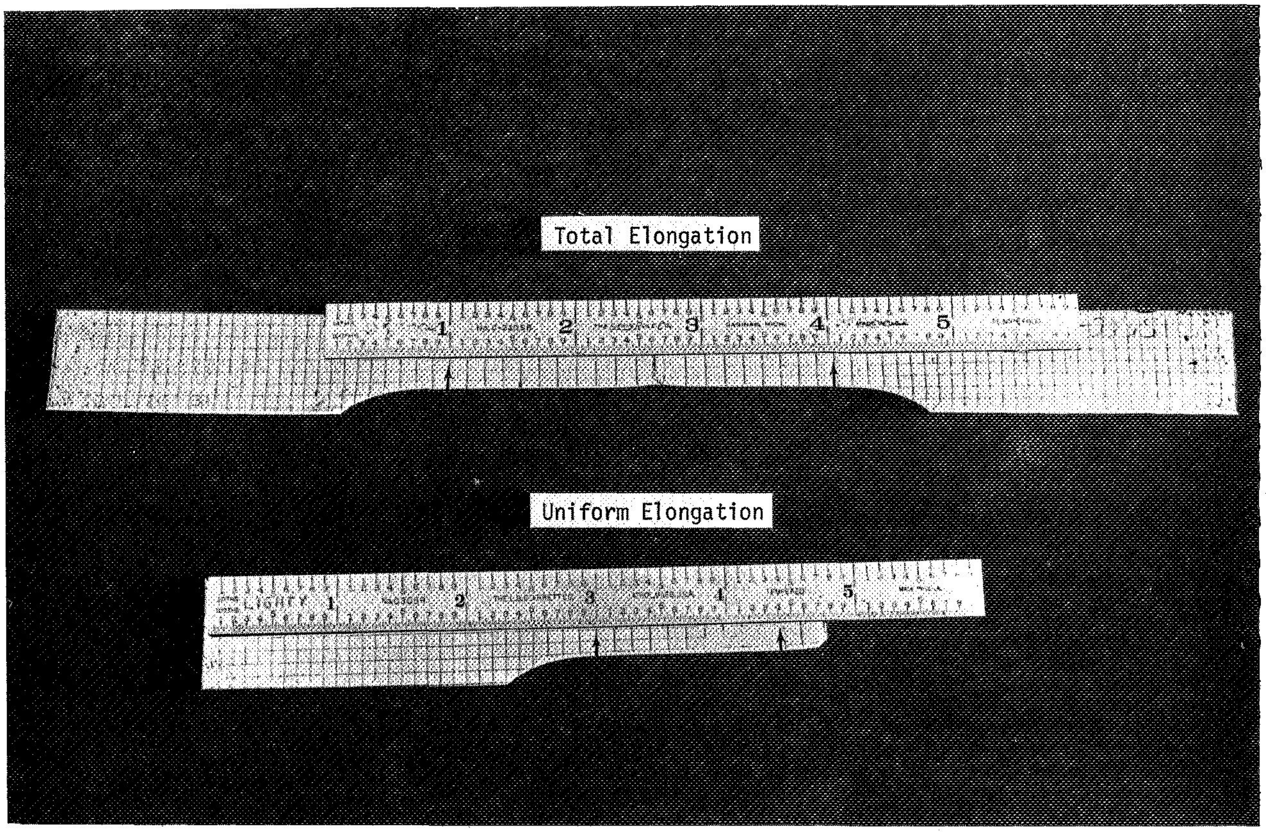


Figure 4. Measurement of Total and Uniform Elongations

Preparation of Baseline and Cryosoaked Specimens

During Task II, the baseline specimens and the cryosoaked specimens were prepared for testing in Task IV. Eleven of fifteen alloys were procured in the annealed or solution annealed condition and were strained and cryosoaked in the same condition. The four exceptions were: (1) the magnesium-lithium alloy, LA 141 A, which was procured and used in the -T7 (stabilized) condition; (2) aluminum alloy 2219 and (3) aluminum alloy 6061, which were procured in the annealed condition, but were solution-treated and then refrigerated to retard natural aging (specimens of these alloys were drawn from the refrigerator and, when necessary, brought up to room temperature just before they were cryosoaked, strained, or tested for baseline properties); and (4) alloy Ti-6Aℓ-4V ELI, which was procured in the annealed condition and then solution-treated to condition it for cryosoaking and straining.

Baseline Specimens

For non-heat-treatable alloys, the preparation of baseline specimens merely involved the selection and identification of five friction-loaded specimens for alloy. These were then stored and subsequently tested in Task IV. For each heat treatable alloy, ten specimens were selected and identified. Five of the ten specimens were then given an industry standard aging treatment, after which the ten specimens were stored until tested in Task IV.

During Tasks II, III, and IV, all of the aging treatments selected for the heat treatable alloys were industry standard treatments. Strain hardening accelerates the response of many of the alloys to aging treatments; consequently, when necessary, the aging treatment given unstrained specimens was different from that given strained specimens. Also, for several alloys, two aging treatments were used for strained specimens: (1) a treatment appropriate for highly strained materials, and (2) a treatment more suitable for lesser strained materials. When two aging treatments were used, one was selected as the primary treatment and the majority of the strained specimens were given that treatment.

Cryosoaked Specimens

Cryosoaked specimens were included in the program to determine whether or not the room temperature tensile properties of any of the alloys were affected by short term exposure to any of the cryogenic straining temperatures. It was necessary to develop these data because during the cryostraining operations there would be a delay from the time a specimen first came in contact with a cryogen until actual straining of the specimen could begin. For the straining at -110°F (194°K), and at -320°F (78°K) open end cryostats would be used. For this equipment a five minute delay period was anticipated from immersion of a specimen and load linkage until straining could be started. In actual practice, the five minute delay proved to be adequate. It was also a sufficient period for the specimen and bath to reach thermal equilibrium (less than two minutes). For straining at -423°F (20°K), with LH_2 as the cryogen, the use of a closed remotely controlled and operated system was necessary to meet rigid safety standards. With this system a 30 minute delay was anticipated from the time a specimen first contacted the LH_2 until straining could be started.

Therefore, based on the anticipated delay periods, the following soak times were established and used in preparing cryosoaked specimens:

1) At -100°F (194°K) and at -320°F (78°K), a soak period of 5 minutes was used;

2) At -423°F (20°K), a soak period of 30 minutes was used.

For non-heat-treatable alloys, cryosoaked specimens were prepared by immersing five friction loaded specimens of an alloy in the appropriate cryogen for the necessary period of time. The cryogens were: -110°F (194°K), a mixture of isopropyl alcohol and dry ice; -320°F (78°K), liquid nitrogen; -423°F (20°K), liquid hydrogen. Therefore, for each non-heat treatable alloy, fifteen cryosoaked specimens were prepared: five soaked at -110°F (194°K); five soaked at -320°F (78°K); and five soaked at -423°F (20°K). For each heat-treatable alloy, thirty cryosoaked specimens were prepared, ten soaked at each of the three temperatures. Five of each set of ten soaked specimens were aged after soaking.

All cryosoaked specimens (including those that were aged) were stored until tested during Task IV.

TASK III - PREPARATION OF CRYOSTRAINED SPECIMENS

Straining Schedule

Specimens of each alloy were prepared and strained according to the basic straining schedule, shown in Table 1. These specimens were tested in Task IV.

Table 1 - Task III Straining Schedule

Straining Temperature	Quantity of Specimens Strained Per Alloy					
	Strain Level A		Strain Level B		Strain Level C	
	Heat Treatable Alloy	Nonheat Treatable Alloy	Heat Treatable Alloy	Nonheat Treatable Alloy	Heat Treatable Alloy	Nonheat Treatable Alloy
Room Temp	10	5	10	5	10	5
-110°F (194°K)	10	5	10	5	10	5
-320°F (78°K)	10	5	10	5	10	5
-423°F (20°K)	10	5	10	5	10	5

Straining Procedures

For straining at room temperature, -110°F (194°K), and -320°F (78°K), friction-loaded specimens (Figure 1) were used and strained on one of two tensile machines: a 5000 lb (22 200N) capacity machine, or a 50 000 lb (222 400N) capacity machine. At -423°F (20°K) a 50 000 lb (222 400N) machine and pin-loaded specimens (Fig. 2) were used. All materials were strained at a rate of 0.050 in./in./min (0.050 cm/cm/min), except 6Aℓ-4V ELI titanium, which was strained at a rate of 0.005 in./in./min (0.005 cm/cm/min).

Room Temperature Straining

When specimens were strained at room temperature, strain was measured directly by holding a 4 in. long scale (0.010 in. divisions) against the gridded surface of a specimen as it was being strained. Strain was measured over a gage of 2 in. (5.08 cm) initial length. After a specimen had been strained and removed from the tensile machine the actual amount of strain was measured and recorded. Strain was measured over a gage of 2 in. (5.08 cm) initial length, using the grid marks, a 6 in. scale (0.010 in. divisions) and a 10X magnifying glass.

Cryostraining

Straining at -110°F (194°K) and at -320°F (78°K) was done on the same tensile machines that were used to strain specimens at room temperature. Open top cyostats and linkage systems (Figure 5) were also required. For -110°F (194°K) the cryogen was a mixture of dry ice and isopropyl alcohol, for -320°F (78°K) LN_2 was used. Whenever a setup was made for straining at either -110°F (194°K) or -320°F (78°K), the procedure included cooling the specimen grips to bath temperature by immersing them in the bath. When the grips had cooled and a specimen had been loaded into them, the whole assembly was connected to the cryostat and tensile machine. The level of the cryogen in the cryostat was controlled so that the upper grip was always completely immersed. A specimen was never strained until it had been in the bath for at least 5 minutes. The 5 minute delay from immersion to straining was sufficient as determined by experimentation, to assure that thermal equilibrium between specimen and bath had been achieved. A dial indicator was used to measure platen travel, which had been correlated to strain through experimentation. After a specimen was strained at -110°F (194°K) or -320°F (78°K) it was warmed to room temperature and the actual strain was measured and recorded the same as it had been on room temperature strained specimens.

Straining at -423°F (20°K) was done in LH_2. To meet rigid safety requirements, it was necessary to use equipment at the Liquid Hydrogen Laboratory. This equipment included a remotely operated 50 000 lb (222 400N) capacity tensile machine, a closed cryostat, and a remotely operated closed system for filling, draining and purging the cryostat. Each strain cycle consisted of: loading specimens into the load linkage connected to the empty and purged cryostat; closing the system; filling the cryostat with LH_2; straining (platen travel was measured); draining and purging the cryostat; and removing the specimens. Because of the complexity of this cycle, pin-loaded specimens were used. Their use permitted more than one specimen to be strained at a time. Usually five specimens were strained simultaneously, but the exact quantity was dependent on the strength of the material and the 50 000 lb (222 400N) capacity of the tensile machine. After being strained, specimens were warmed to room temperature and the actual strain was measured and recorded as it had been for room-temperature strained specimens.

Aging

As with the cryosoaked and baseline specimens, for the heat-treatable alloys, five of each set of ten room-temperature strained or cryostrained specimens were aged after straining.

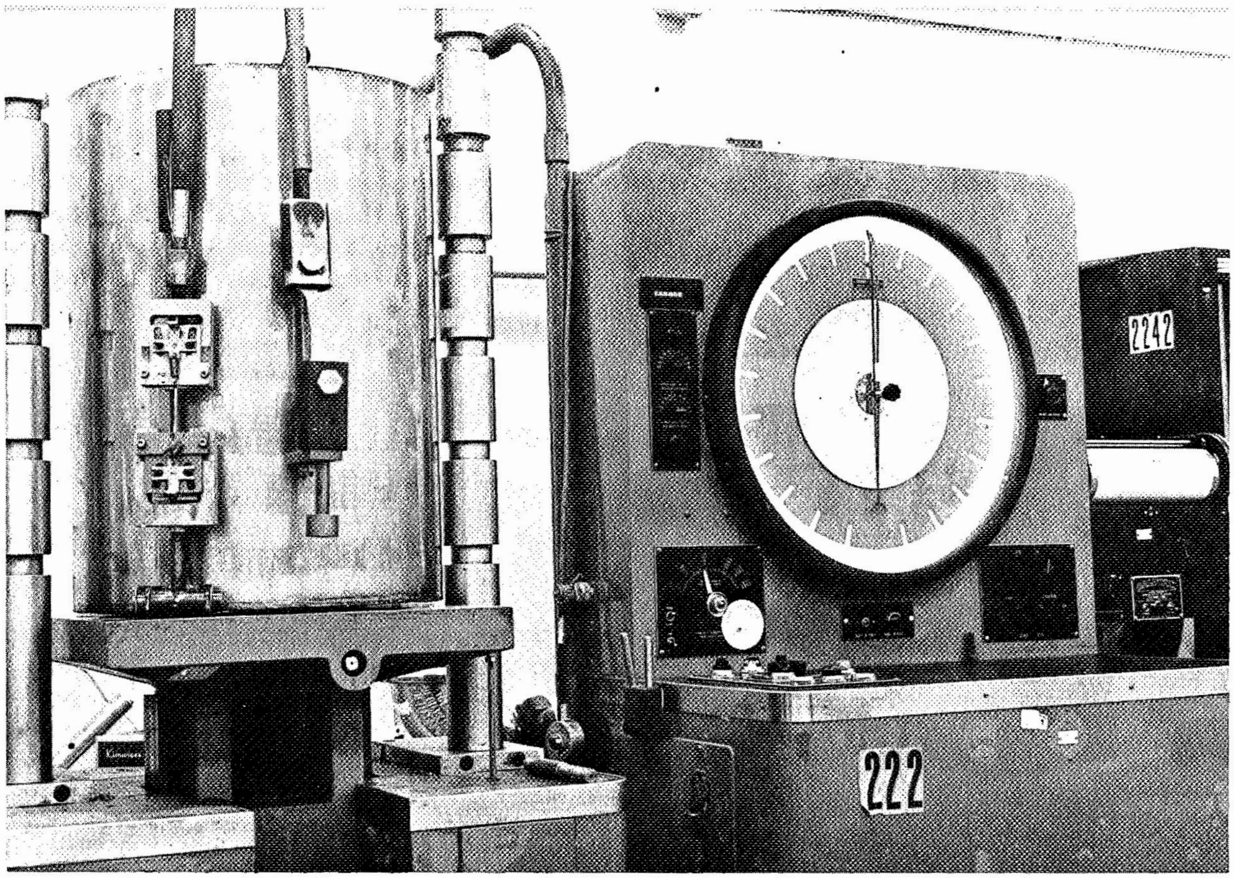


Figure 5. - Cryostat and Linkage Systems Used for Straining at -110°F (194°K) and -320°F (78°K).

TASK IV - ROOM TEMPERATURE TENSILE TESTS

During Task IV, the specimens prepared in Tasks II and III were subjected to standard room temperature tensile tests, conducted in accordance with the requirements of ASTM E8-69. As previously discussed, for heat treatable alloys one-half of each set of soaked or strained specimens were given an appropriate aging treatment before they were tested. The other half of each set were tested in the as-strained or as-soaked condition, as were the specimens of the nonheat treatable alloys.

The specimens were tested at room temperature on either a 5000 lb (22 200N) capacity, or a 50 000 lb (222 400N) capacity tensile machine, depending on the strength of the material. A load-strain curve was autographically recorded for each test. For this purpose, an extensometer with a 2-in. (5.08 cm) gage together with appropriate strain-magnifying and plotting devices were used. The properties determined from each test were: ultimate tensile strength; tensile yield strength, 0.2% offset; and total elongation, percent in 2 in. (5.08 cm).

TASK V - EVALUATION

Analysis of the results of Tasks I through IV led to the following conclusions:

1. Cryostraining was found to be a more effective strengthening treatment than room temperature straining for only two of the 15 alloys studied. The two alloys are: PH 14-8 Mo, a precipitation hardening semi-austenitic stainless steel, and MP 35 N, a cobalt-nickel multiphase alloy. Both of these alloys are strengthened by phase transformation. PH 14-8 Mo in Condition A (solution treated) has an austenitic structure. The austenite can be transformed to martensite either by thermal treatment or by cold working. The structure of annealed MP 35 N is face-centered cubic. When it is strained, platelets of a close-packed hexagonal phase form within the original structure. The test results indicated that compared with room temperature straining effects, straining at cryogenic temperatures enhanced the strain induced phase transformation of each alloy.

2. Seven other alloys, 6061 aluminum, 5456 aluminum, Inconel 718, Nickel 440, Beryllium Copper, A-286, and 21-6-9 can be strained greater amounts when the straining is done at cryogenic temperatures rather than at room temperature. Because of additional strain capability at the cryogenic temperatures, these alloys can be strain hardened to higher strengths at those temperatures than at room temperature. However, the magnitude of the strength increase that can be achieved by straining these alloys at cryogenic temperatures is so small (proportionally) that cryo-straining does not merit serious consideration as a practical method of strengthening them.

3. For the other five alloys cryostraining is not beneficial.

The results of the tests conducted on all the alloys are in the Interim Report, Ref. 8. However, for convenience, data obtained from testing the two responsive alloys, PH 14-8 Mo and MP 35 N, are summarized here.

PH 14-8 Mo

PH 14-8 Mo is a semi-austenitic precipitation hardening steel. In the solution treated (Condition A) condition, the structure of this steel is austenitic. Transformation of austenite to martensite can be accomplished in either of two ways, by thermal treatment or by cold working.

The thermal transformation treatment for PH 14-8 Mo requires the material be heated to and held at 1700°F (1200°K) for 1 hour to condition it for transformation. Then it must be cooled to -100°F (200°K) and held at that temperature for 8 hours to transform the austenite to martensite. An aging treatment, at either 950°F (782°K) or 1050°F (840°K) follows the transformation treatment. The conditions after aging are identified as SRH 950 and SRH 1050, respectively.

The cold-work treatment is normally a mill treatment. PH 14-8 Mo Condition A material is transformed to martensite by heavy cold reduction. It is then aged at 900°F (755°K) for 1 hour. The condition after aging is designated as CH 900. For this program a CH type treatment was used because the material could be strained in the highly workable austenitic condition, Condition A, and then aged.

The test stock obtained for use in Tasks II through IV was a sheet 0.070 x 36 x 120 inches (0.178 x 91 x 305 cm), Condition A, procured to North American Aviation Materials Specification MB0160-015. The chemical composition of this sheet is given in the following table:

Element	Percent by Weight	Element	Percent by Weight
C	0.038	Ni	8.31
Mn	0.10	Mo	2.15
P	0.003	Aℓ	1.17
S	0.004	N	0.005
Si	0.10	Fe	Balance
Cr	14.95		

The density of PH 14-8 Mo is 0.283 lb/cu in. (7.325 gm/cc). Its typical mechanical properties are shown in the following tabulation:

Condition (vacuum induction melted)	Ultimate Tensile Strength		Tensile Yield Strength, 0.2% Offset		Elongation, % in 2 in. (5.08 cm)
	psi	N/cm^2	psi	N/cm^2	
A	125 000	86 000	55 000	38 000	25.0
SRH 950	230 000	156 000	215 000	148 000	6.0
CH 900	280 000	193 000	270 000	186 000	1.5

The results of the tests conducted on PH 14-8 Mo during Tasks II through IV are listed in Tables 2 and 3 and summarized in Figures 6 through 11.

The test results indicate that straining at cryogenic temperatures enhances the austenite to martensite transformation in PH 14-8 Mo and possibly increases the aging response. Cryostraining is a process by which the room temperature tensile strength of PH 14-8 Mo can be increased. However, although the toughness of this alloy decreases as its strength increases, it is reasonable to anticipate that cryostraining procedures can be developed for the alloy to achieve a satisfactory compromise of strength and toughness. That is, the material's strength will be satisfactorily increased but its toughness will not be so seriously degraded that it cannot be used in structural applications.

MP 35 N

MP 35 is a cobalt-nickel multiphase alloy combining high strength with good ductility, toughness, and excellent corrosion resistance. It is a strain-hardening alloy that is additionally strengthened by poststrain aging. It has a face-centered cubic matrix of cobalt and nickel in which the alloying elements chromium and molybdenum are soluble at elevated temperatures. The face-centered cubic structure is retained when the material cools to room temperature. A local shear transformation is induced, however, when MP 35 N is worked at temperatures below the equilibrium transformation temperature, approximately 850°F (728°K). Small platelets of a hexagonal close packed structure form locally within the face centered cubic matrix. Unlike the martensite transformation that occurs in many steels, this transformation does not appear to have an M_s temperature at which it occurs spontaneously on cooling. The percentage of the original structure that is transformed to the hexagonal close packed phase is strain dependent, and the transformed product is stable.

The density of MP 35 N is 0.304 lb/cu in. (8.41 gm/cc). Its typical mechanical properties are shown in the following tabulation:

Condition	Ultimate tensile strength		Tensile yield strength, 0.2% offset		Elongation % in 2 in. (5.08 cm)
	psi	N/cm^2	psi	N/cm^2	
Annealed	132 000	91 000	53 000	37 000	68.0
Work-strengthened and aged	300 000	207 000	290 000	200 000	9.0

For testing in Tasks II through IV, a sheet of annealed MP 35 N, 0.060 x 30 x 48 in. (0.152 x 76 x 122 cm), of the composition given in the following tabulation was procured to commercial requirements:

Element	Percent by Weight
Ni	33.5
Co	38.9
Cr	18.6
Mo	7.2
Other	1.8

Because of the comparatively small size of the MP 35 N sheet available for the program, it was necessary to strain less than the usual amount of specimens at each temperature. Normally, for a heat-treatable alloy, 40 specimens were conditioned at each temperature, for MP 35 N this number was reduced to 30.

The results of the tests conducted on the MP 35 N material are given in Tables 4 and 5 and summarized in Figures 12 through 17. As the data show, cryostraining is a more effective means of strengthening MP 35 N than is room-temperature straining. However, high strains, regardless of the straining temperature, severely reduce the elongation of the MP 35 N, and it is likely that its toughness is proportionally degraded.

SUMMARY

In summary, the results of the testing conducted in Task IV indicated that only PH 14-8 Mo and MP 35 N developed sufficiently higher room-temperature tensile strengths through cryostraining than through room-temperature straining to merit consideration as candidate materials for further testing in Task VI. It was initially planned to test both alloys during Task VI; however, MP 35 N was reluctantly dropped from the program when it was found that the required quantity of sheet could not be obtained in time to meet program schedule requirements.

Table 2 Tensile Properties of PH 14-8 Mo Corrosion Resistant Steel Sheet[a]

(Unstrained and prestrained conditions[b])

Test temperature, °F	Exposure or prestrain temperature, °F	Uniform strain capability at temperature, percent in 2 in.	Target prestrain, percent in 2 in.	Measured prestrain, percent in 2 in.	Tensile properties			
					Ultimate strength, psi	Yield strength, 0.2% offset, psi	Elongation, percent in 2 in. Total	Uniform
RT[c]	---	---	---	---	135 400	55 700	26.0	21.0
-110[c]	---	---	---	---	185 900	66 500	17.0	13.0
-320[c]	---	---	---	---	289 200	80 500	22.5	18.5
-423[c]	---	---	---	---	324 400	---	17.0	15.0
RT[d]	RT	21.0	0	0	130 600	55 000	26.5	---
RT[e]			0	0	127 800	54 700	28.0	---
RT[f]			5.5	5.5	141 400	71 000	19.5	---
RT[g]			5.5	5.5	139 900	87 400	27.5	---
RT[f]			13.5	13.0	150 800	135 200	12.0	---
RT[g]			13.5	13.5	199 700	197 600	10.0	---
RT[f]			17.5	17.5	167 000	167 000	5.0	---
RT[g]	RT	21.0	17.5	17.5	231 400	231 100	4.0	---
RT[d]	-110	13.0	0	0	130 700	55 000	27.5	---
RT[e]			0	0	129 400	55 400	28.0	---
RT[f]			5.5	5.5	175 600	109 100	10.5	---
RT[g]			5.5	5.5	214 800	195 300	7.0	---
RT[f]			8.0	7.0	182 400	168 900	7.5	---
RT[g]			8.0	7.0	249 700	247 500	7.0	---
RT[f]			10.5	10.5	195 400	194 700	4.0	---
RT[g]	-110	13.0	10.5	10.0	271 700	271 700	6.5	---
RT[d]	-320	18.5	0	0	130 300	55 600	27.0	---
RT[e]			0	0	130 300	54 000	27.5	---
RT[f]			5.5	6.0	217 200	110 900	9.5	---
RT[g]	-320	18.5	5.5	6.0	250 500	181 800	6.5	---

Table 2 Tensile Properties of PH 14-8 Mo Corrosion Resistant Steel Sheet[a] - Concluded

(Unstrained and prestrained conditions[b])

Test temperature, °F	Exposure or prestrain temperature, °F	Uniform strain capability at temperature, percent in 2 in.	Target prestrain, percent in 2 in.	Measured prestrain, percent in 2 in.	Tensile properties			
					Ultimate strength, psi	Yield strength, 0.2% offset, psi	Elongation, percent in 2 in.	
							Total	Uniform
RT[f]	-320	18.5	11.0	10.0	228 300	214 900	8.0	---
RT[g]			11.0	10.5	305 400	298 700	6.0	---
RT[f]			14.5	15.0	250 500	241 800	3.5	---
RT[g]	-320	18.5	14.5	14.5	329 400	326 800	5.0	---
RT[d]	-423	15.0	0	0	127 000	54 000	26.5	---
RT[e]			0	0	130 400	54 100	27.5	---
RT[f]			5.5	6.5	218 500	121 200	9.0	---
RT[g]			5.5	4.5	164 900	76 600	8.0	---
RT[f]			9.0	7.0	214 600	110 600	10.0	---
RT[g]			9.0	8.0	260 000	217 900	10.0	---
RT[f]			12.0	9.8	225 600	189 500	8.0	---
RT[g]	-423	15.0	12.0	10.0	284 300	261 200	7.0	---

[a]Sheet, 0.070 inch thick.

[b]All specimens were machined from annealed material.

[c]Condition: Annealed.

[d]Condition: Annealed and exposed to the indicated temperature.

[e]Condition: Same as "d" except after exposure to temperature the specimens were aged (1 hour at 900°F.)

[f]Condition: Annealed and prestrained at the indicated temperature.

[g]Condition: Same as "f" except after prestraining the specimens were aged (1 hour at 900°F.)

Table 3 Tensile Properties of PH 14-8 Mo Corrosion Resistant Steel Sheet[a]

(Unstrained and prestrained conditions[b])

Test temperature, °K	Exposure or prestrain temperature, °K	Uniform strain capability at temperature, percent in 5.08 cm	Target prestrain, percent in 5.08 cm	Measured prestrain, percent in 5.08 cm	Tensile properties: Ultimate strength, N/cm^2	Tensile properties: Yield strength, 0.2% offset, N/cm^2	Elongation, percent in 5.08 cm: Total	Elongation, percent in 5.08 cm: Uniform
RT[c]	---	---	---	---	93 400	38 400	26.0	21.0
194[c]	---	---	---	---	128 200	45 900	17.0	13.0
78[c]	---	---	---	---	199 400	55 500	22.5	18.5
20[c]	---	---	---	---	223 700	---	17.0	15.0
RT[d]	RT	21.0	0	0	90 000	37 900	26.5	---
RT[e]			0	0	88 100	37 700	28.0	---
RT[f]			5.5	5.5	97 500	49 000	19.5	---
RT[g]			5.5	5.5	96 500	60 300	27.5	---
RT[f]			13.5	13.0	104 000	93 200	12.0	---
RT[g]			13.5	13.5	137 700	136 200	10.0	---
RT[f]			17.5	17.5	115 100	115 100	5.0	---
RT[g]	RT	21.0	17.5	17.5	159 600	159 300	4.0	---
RT[d]	194	13.0	0	0	90 100	37 900	27.5	---
RT[e]			0	0	89 200	38 200	28.0	---
RT[f]			5.5	5.5	121 100	75 200	10.5	---
RT[g]			5.5	5.5	148 100	134 700	7.0	---
RT[f]			8.0	7.0	125 800	116 500	7.5	---
RT[g]			8.0	7.0	172 200	170 700	7.0	---
RT[f]			10.5	10.5	134 700	134 200	4.0	---
RT[g]	194	13.0	10.5	10.0	187 300	187 300	6.5	---
RT[d]	78	18.5	0	0	89 800	38 300	27.0	---
RT[e]			0	0	89 800	37 200	27.5	---
RT[f]			5.5	6.0	149 800	76 500	9.5	---
RT[g]	78	18.5	5.5	6.0	172 700	125 400	6.5	---

Table 3 Tensile Properties of PH 14-8 Mo Corrosion Resistant Steel Sheet[a] - Concluded

(Unstrained and prestrained conditions[b])

Test temperature, °K	Exposure or prestrain temperature, °K	Uniform strain capability at temperature, percent in 5.08 cm	Target prestrain, percent in 5.08 cm	Measured prestrain, percent in 5.08 cm	Tensile properties			
					Ultimate strength, N/cm²	Yield strength, 0.2% offset, N/cm²	Elongation, percent in 5.08 cm	
							Total	Uniform
RT[f]	78	18.5	11.0	10.0	157 400	148 200	8.0	---
RT[g]			11.0	10.5	210 600	206 000	6.0	---
RT[f]			14.5	15.0	172 700	166 700	3.5	---
RT[g]	78	18.5	14.5	14.5	227 100	225 300	5.0	---
RT[d]	20	15.0	0	0	87 600	37 200	26.5	---
RT[e]			0	0	89 900	37 300	27.5	---
RT[f]			5.5	6.5	150 700	83 600	9.0	---
RT[g]			5.5	4.5	113 700	52 800	8.0	---
RT[f]			9.0	7.0	148 000	76 300	10.0	---
RT[g]			9.0	8.0	179 300	150 200	10.0	---
RT[f]			12.0	9.8	155 600	130 700	8.0	---
RT[g]	20	15.0	12.0	10.0	196 000	180 100	7.0	---

[a]Sheet, 0.178 cm thick.

[b]All specimens were machined from annealed material.

[c]Condition: Annealed.

[d]Condition: Annealed and exposed to the indicated temperature.

[e]Condition: Same as "d" except after exposure to temperature the specimens were aged (1 hour at 756°K.)

[f]Condition: Annealed and prestrained at the indicated temperature.

[g]Condition: Same as "f" except after prestraining the specimens were aged (1 hour at 756°K.)

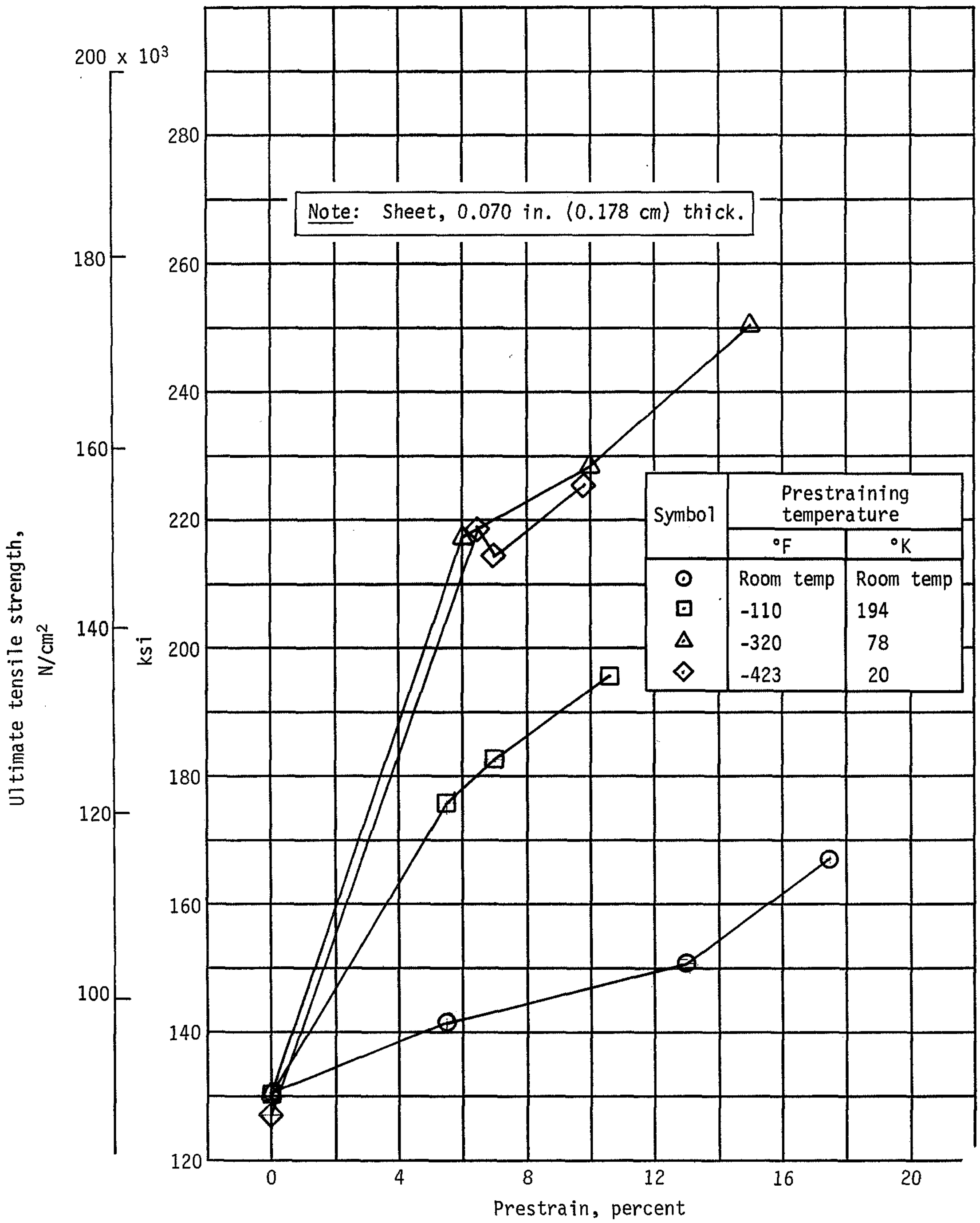


Figure 6.- Ultimate Tensile Strength of Prestrained PH 14-8 Mo Steel

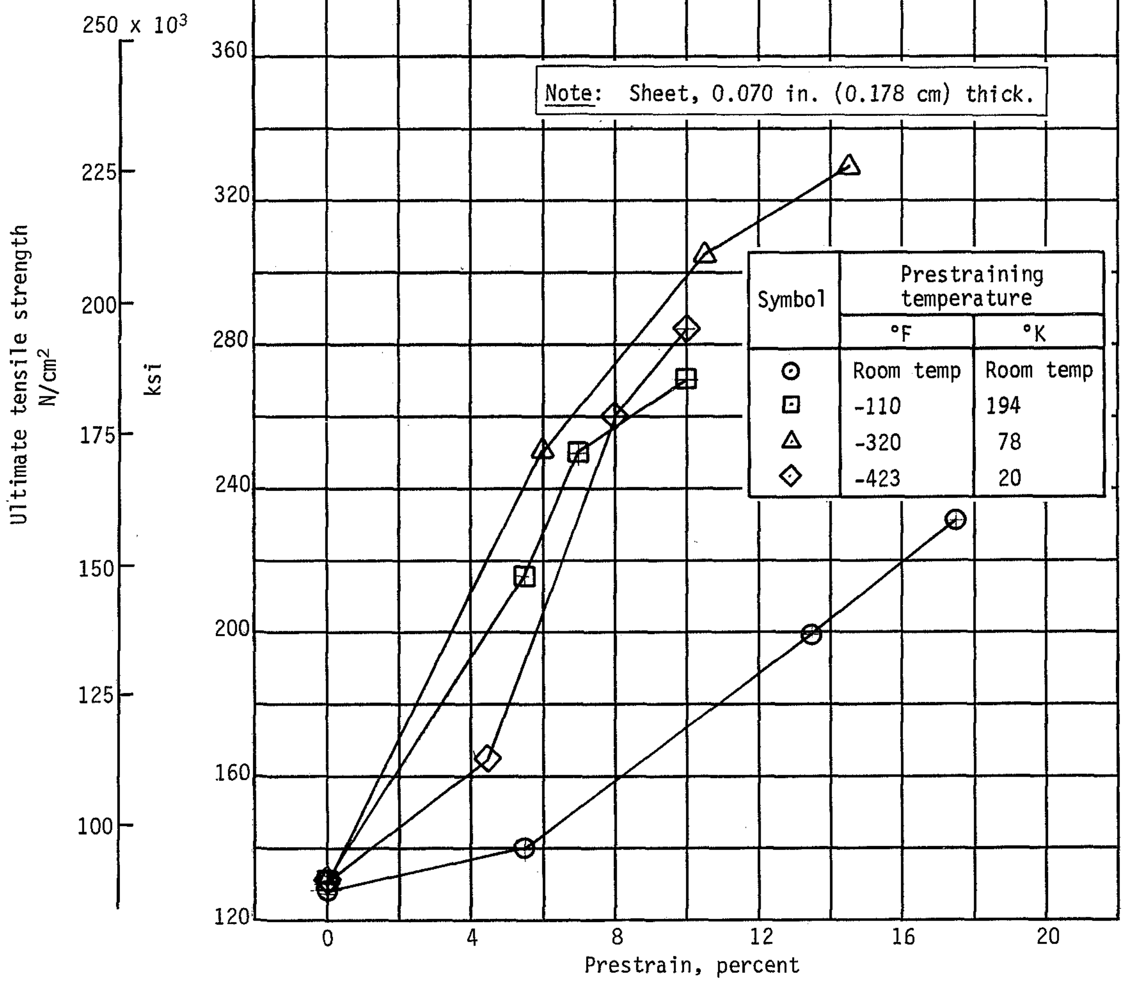


Figure 7.- Ultimate Tensile Strength of Prestrained PH 14-8 Mo Steel, Aged 1 hr at 900°F (756°K)

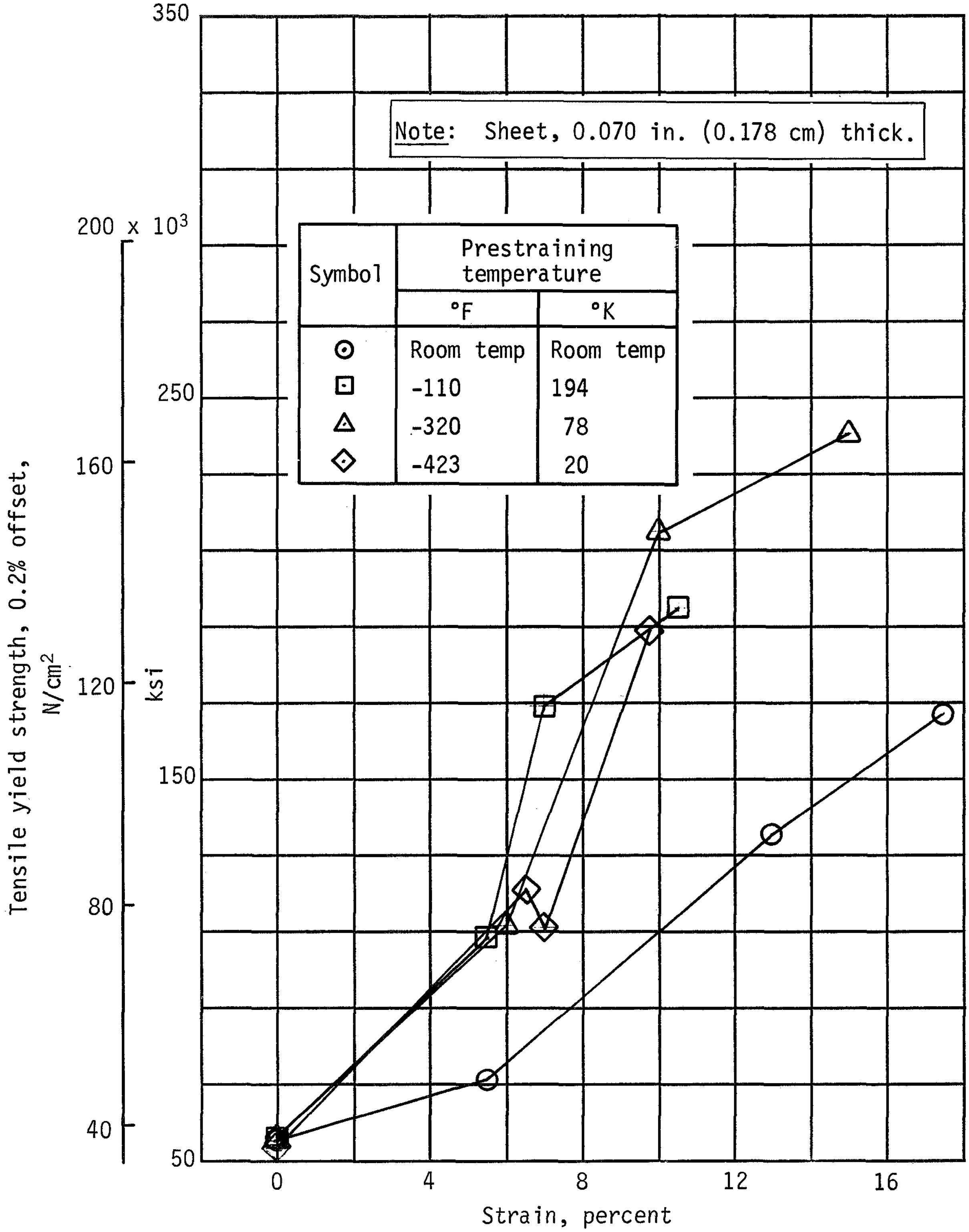


Figure 8.- Tensile Yield Strength of Prestrained PH 14-8 Mo Steel

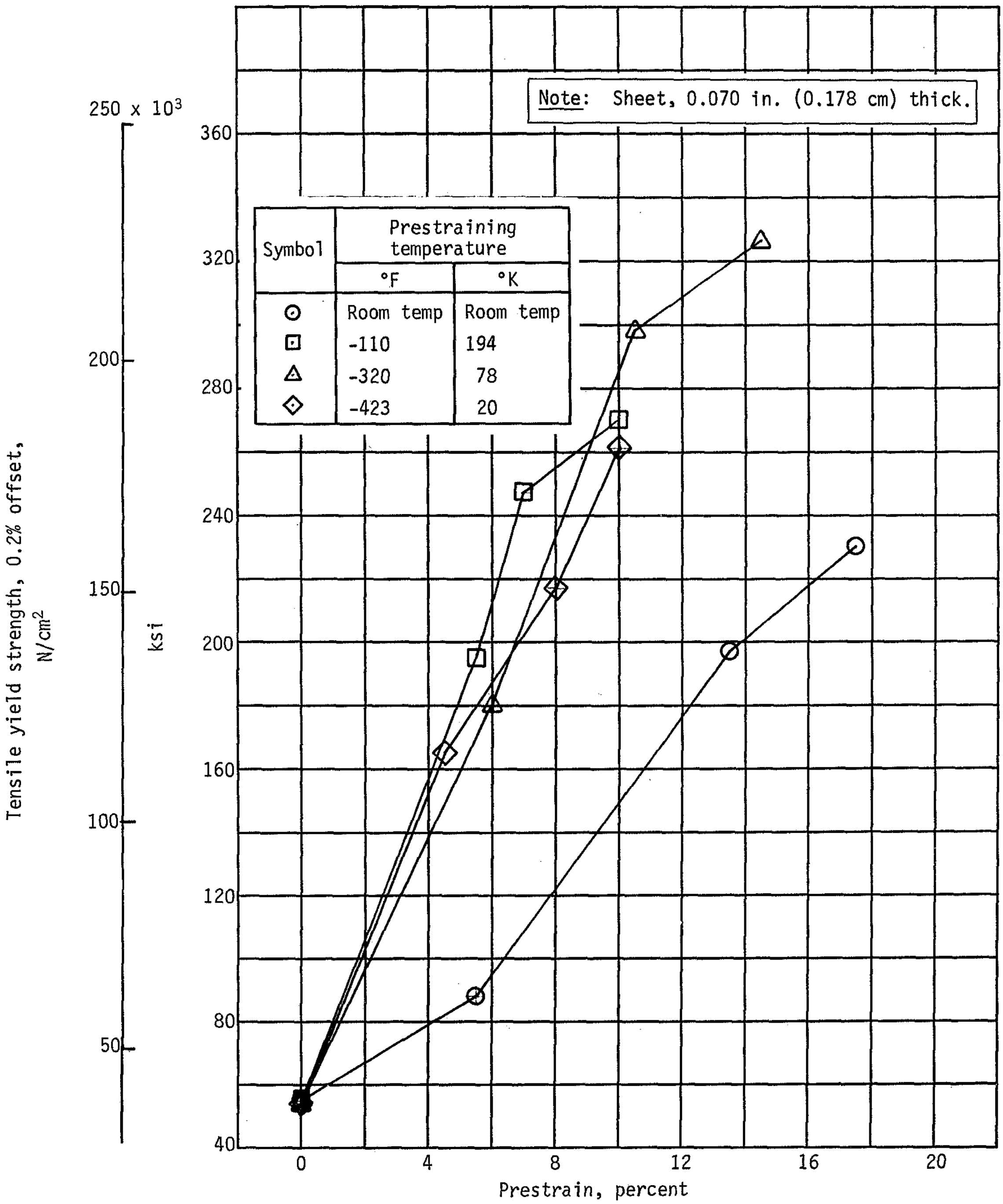


Figure 9.- Tensile Yield Strength of Prestrained PH 14-8 Mo Steel, Aged 1 hr at 900°F (756°K)

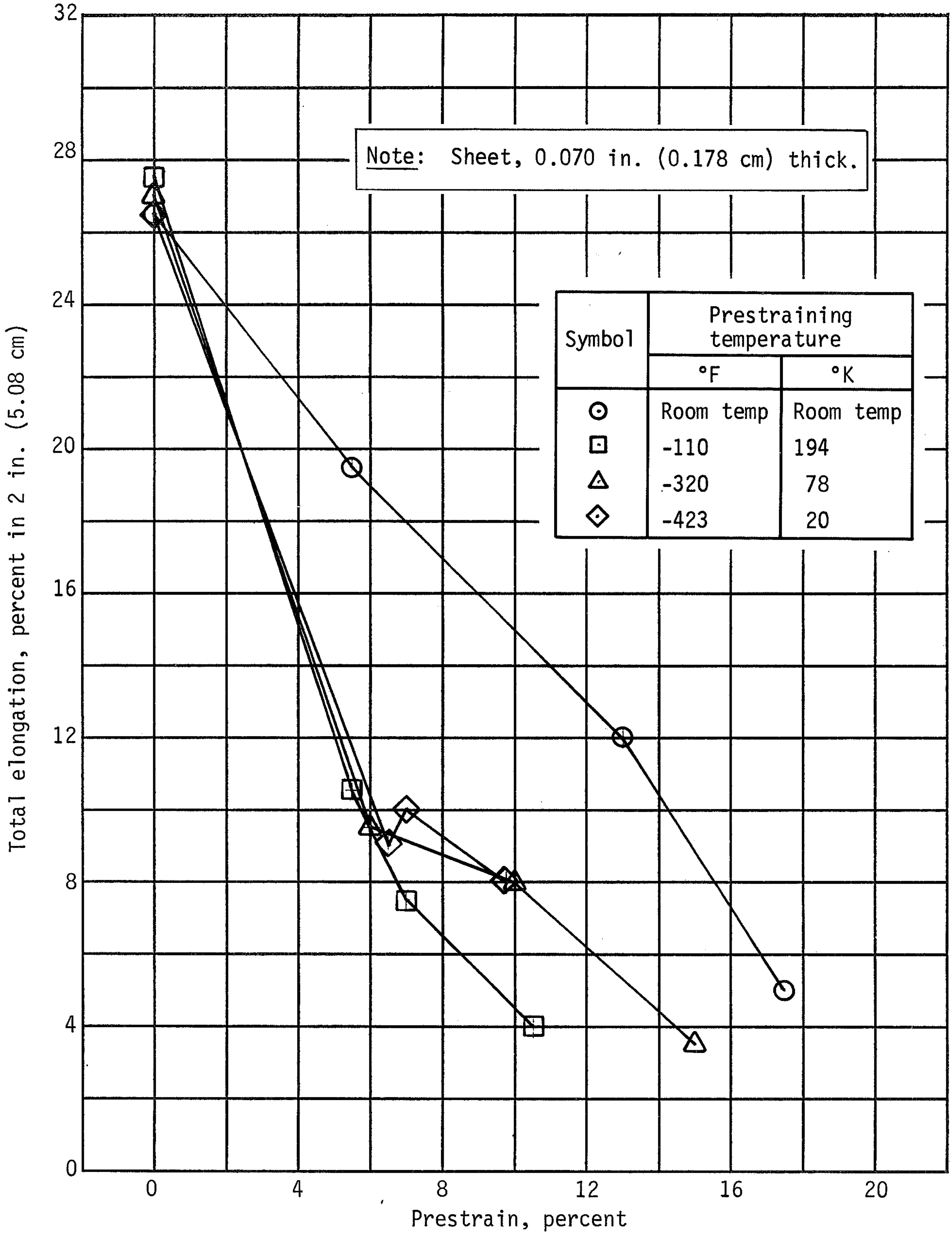


Figure 10 .- Total Elongation of Prestrained PH 14-8 Mo Steel

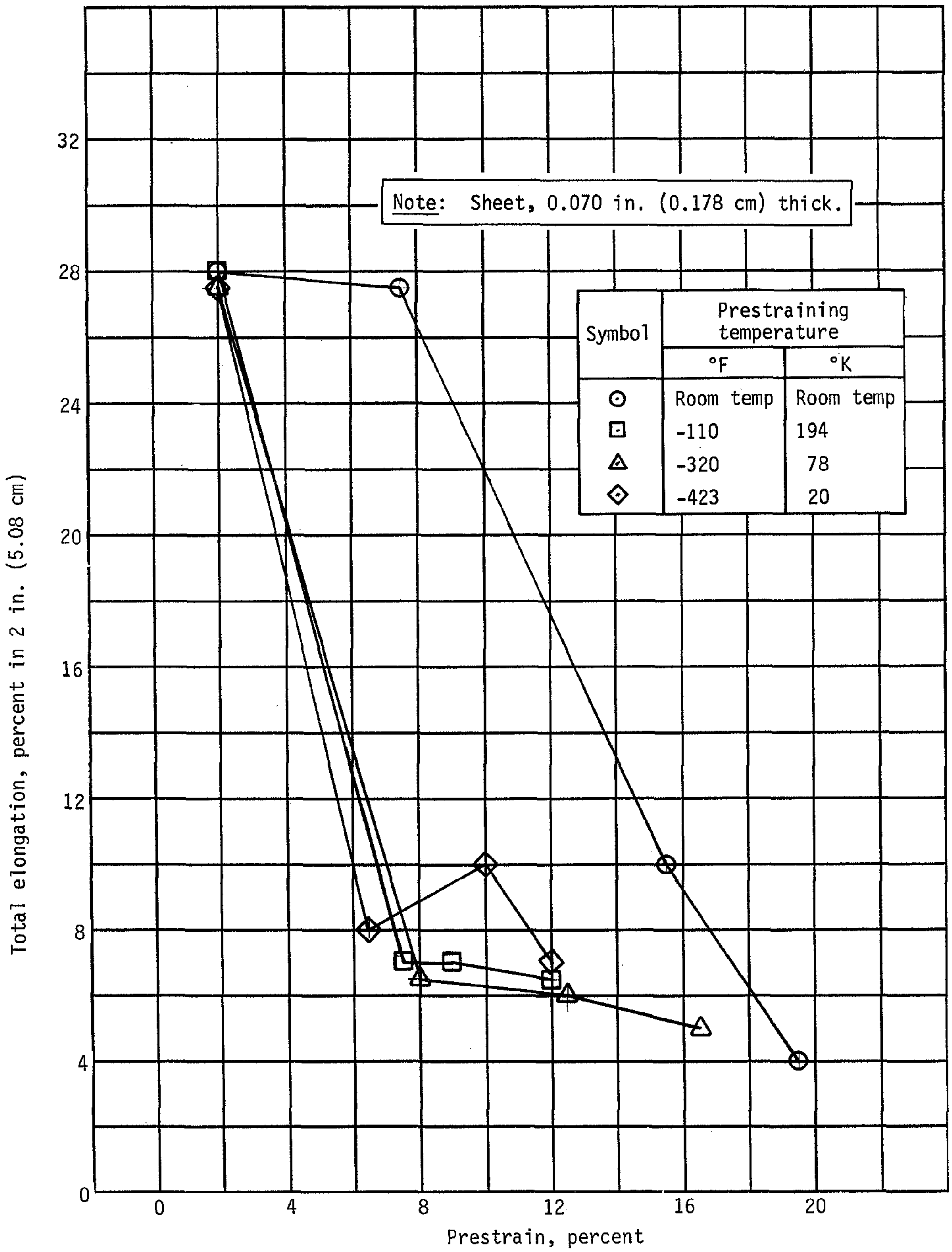


Figure 11.- Total Elongation of Prestrained PH 14-8 Mo Steel, Aged 1 hr at 900°F (756°K)

Table 4 Tensile Properties of MP 35 N Cobalt-Nickel Alloy Sheet[a]

(Unstrained and prestrained conditions[b])

Test temperature, °F	Exposure or prestrain temperature, °F	Uniform strain capability at temperature, percent in 2 in.	Target prestrain, percent in 2 in.	Measured prestrain, percent in 2 in.	Tensile properties			
					Ultimate strength, psi	Yield strength, 0.2% offset, psi	Elongation, percent in 2 in.	
							Total	Uniform
RT[c]	---	---	---	---	123 700	---	63.0	55.0
-110[c]	---	---	---	---	146 700	61 000	77.0	70.0
-320[c]	---	---	---	---	178 500	81 100	77.0	70.0
-423[c]	---	---	---	---	211 000	---	78.5	75.0
RT[d]	RT	55.0	0	0	121 700	48 600	62.0	---
RT[e]			0	0	127 000	50 500	69.0	---
RT[f]			22.0	22.0	152 200	127 500	32.0	---
RT[g]			22.0	22.0	155 600	128 900	33.0	---
RT[f]			33.0	34.0	163 300	154 200	26.0	---
RT[g]			33.0	32.5	161 200	147 600	22.5	---
RT[f]			44.0	44.0	177 600	171 000	18.0	---
RT[g]	RT	55.0	44.0	44.0	187 400	187 400	8.5	---
RT[d]	-110	70.0	0	0	124 800	49 600	62.5	---
RT[e]			0	0	126 200	49 600	64.5	---
RT[f]			22.0	25.5	159 400	137 800	27.5	---
RT[g]			22.0	22.5	159 400	136 600	30.5	---
RT[f]			42.0	42.0	186 000	170 800	15.0	---
RT[g]			42.0	42.0	193 600	190 600	6.0	---
RT[f]			56.0	54.5	209 300	187 800	5.5	---
RT[g]	-110	70.0	56.0	53.5	218 200	217 200	3.0	---
RT[d]	-320	70.0	0	0	125 600	50 100	66.0	---
RT[e]			0	0	126 200	50 100	64.5	---
RT[f]			22.0	23.5	159 100	126 400	28.0	---
RT[g]	-320	70.0	22.0	22.5	163 400	147 600	27.5	---

Table 4 Tensile Properties of MP 35 N Cobalt-Nickel Alloy Sheet[a] - Concluded
(Unstrained and prestrained conditions[b])

Test temperature, °F	Exposure or prestrain temperature, °F	Uniform strain capability at temperature, percent in 2 in.	*Target* prestrain, percent in 2 in.	*Measured* prestrain, percent in 2 in.	Tensile properties			
					Ultimate strength, psi	Yield strength, 0.2% offset, psi	Elongation, percent in 2 in.	
							Total	Uniform
RT[f]	-320	70.0	42.0	42.5	195 100	164 700	7.5	---
RT[g]			42.0	40.5	204 200	197 200	4.5	---
RT[f]			56.0	55.5	207 400	174 900	5.5	---
RT[g]	-320	70.0	56.0	56.5	241 300	224 400	2.0	---
RT[d]	-423	75.0	0	0	125 800	45 100	66.5	---
RT[e]			0	0	125 800	49 100	64.0	---
RT[f]			22.0	26.0	165 600	133 700	27.5	---
RT[g]			22.0	26.0	164 300	150 200	24.0	---
RT[f]			45.0	47.0	204 800	177 700	7.5	---
RT[g]			45.0	45.0	225 000	222 900	3.0	---
RT[f]			60.0	58.0	228 100	181 700	5.5	---
RT[g]	-423	75.0	60.0	60.0	260 100	258 900	2.0	---

[a]Sheet, 0.060 inch thick.

[b]All specimens were machined from annealed materal.

[c]Condition: Annealed.

[d]Condition: Annealed and exposed to the indicated temperature.

[e]Condition: Same as "d" except after exposure to temperature the specimens were aged (4 hours at 900°F.)

[f]Condition: Annealed and prestrained at the indicated temperature.

[g]Condition: Same as "f" except after prestraining the specimens were aged (4 hours at 900°F.)

Table 5 Tensile Properties of MP 35 N Cobalt-Nickel Alloy Sheet[a]
(Unstrained and prestrained conditions[b])

Test temperature, °K	Exposure or prestrain temperature, °K	Uniform strain capability at temperature, percent in 5.08 cm	Target prestrain, percent in 5.08 cm	Measured prestrain, percent in 5.08 cm	Tensile properties			
					Ultimate strength, N/cm²	Yield strength, 0.2% offset, N/cm²	Elongation, percent in 5.08 cm	
							Total	Uniform
RT[c]	---	---	---	---	85 300	---	63.0	55.0
194[c]	---	---	---	---	101 100	42 100	77.0	70.0
78[c]	---	---	---	---	123 100	55 900	77.0	70.0
20[c]	---	---	---	---	145 500	---	78.5	75.0
RT[d]	RT	55.0	0	0	83 900	33 500	62.0	---
RT[e]			0	0	87 600	34 800	69.0	---
RT[f]			22.0	22.0	105 000	87 900	32.0	---
RT[g]			22.0	22.0	107 300	88 900	33.0	---
RT[f]			33.0	34.0	112 600	106 300	26.0	---
RT[g]			33.0	32.5	111 100	101 800	22.5	---
RT[f]			44.0	44.0	122 500	117 900	18.0	---
RT[g]	RT	55.0	44.0	44.0	129 200	129 200	8.5	---
RT[d]	194	70.0	0	0	86 000	34 200	62.5	---
RT[e]			0	0	87 000	34 200	64.5	---
RT[f]			22.0	25.5	109 900	95 000	27.5	---
RT[g]			22.0	22.5	109 900	94 200	30.5	---
RT[f]			42.0	42.0	128 200	117 800	15.0	---
RT[g]			42.0	42.0	133 500	131 400	6.0	---
RT[f]			56.0	54.5	144 300	129 500	5.5	---
RT[g]	194	70.0	56.0	53.5	150 400	149 800	3.0	---
RT[d]	78	70.0	0	0	86 600	34 500	66.0	---
RT[e]			0	0	87 000	34 500	64.5	---
RT[f]			22.0	23.5	109 700	87 200	28.0	---
RT[g]	78	70.0	22.0	22.5	112 700	101 800	27.5	---

Table 5 Tensile Properties of MP 35 N Cobalt Nickel Alloy Sheet[a] - Concluded
(Unstrained and prestrained conditions[b])

Test temperature, °K	Exposure or prestrain temperature, °K	Uniform strain capability at temperature, percent in 5.08 cm	Target prestrain, percent in 5.08 cm	Measured prestrain, percent in 5.08 cm	Tensile properties: Ultimate strength, N/cm²	Tensile properties: Yield strength, 0.2% offset, N/cm²	Elongation, percent in 5.08 cm: Total	Elongation, percent in 5.08 cm: Uniform
RT[f]	78	70.0	42.0	42.5	134 500	113 600	7.5	---
RT[g]			42.0	40.5	140 800	136 000	4.5	---
RT[f]			56.0	55.5	143 000	120 600	5.5	---
RT[g]	78	70.0	56.0	56.5	166 400	154 700	2.0	---
RT[d]	20	75.0	0	0	86 700	31 100	66.5	---
RT[e]			0	0	86 700	33 900	64.5	---
RT[f]			22.0	26.0	114 200	92 200	27.5	---
RT[g]			22.0	26.0	113 300	103 600	24.0	---
RT[f]			45.0	47.0	141 200	122 500	7.5	---
RT[g]			45.0	45.0	155 100	153 700	3.0	---
RT[f]			60.0	58.0	157 300	125 300	5.5	---
RT[g]	20	75.0	60.0	60.0	179 300	178 500	2.0	---

[a]Sheet, 0.152 cm thick.

[b]All specimens were machined from annealed material.

[c]Condition: Annealed.

[d]Condition: Annealed and exposed to the indicated temperature.

[e]Condition: Same as "d" except after exposure to temperature the specimens were aged (4 hours at 756°K.)

[f]Condition: Annealed and prestrained at the indicated temperature.

[g]Condition: Same as "f" except after prestraining the specimens were aged (4 hours at 756°K.)

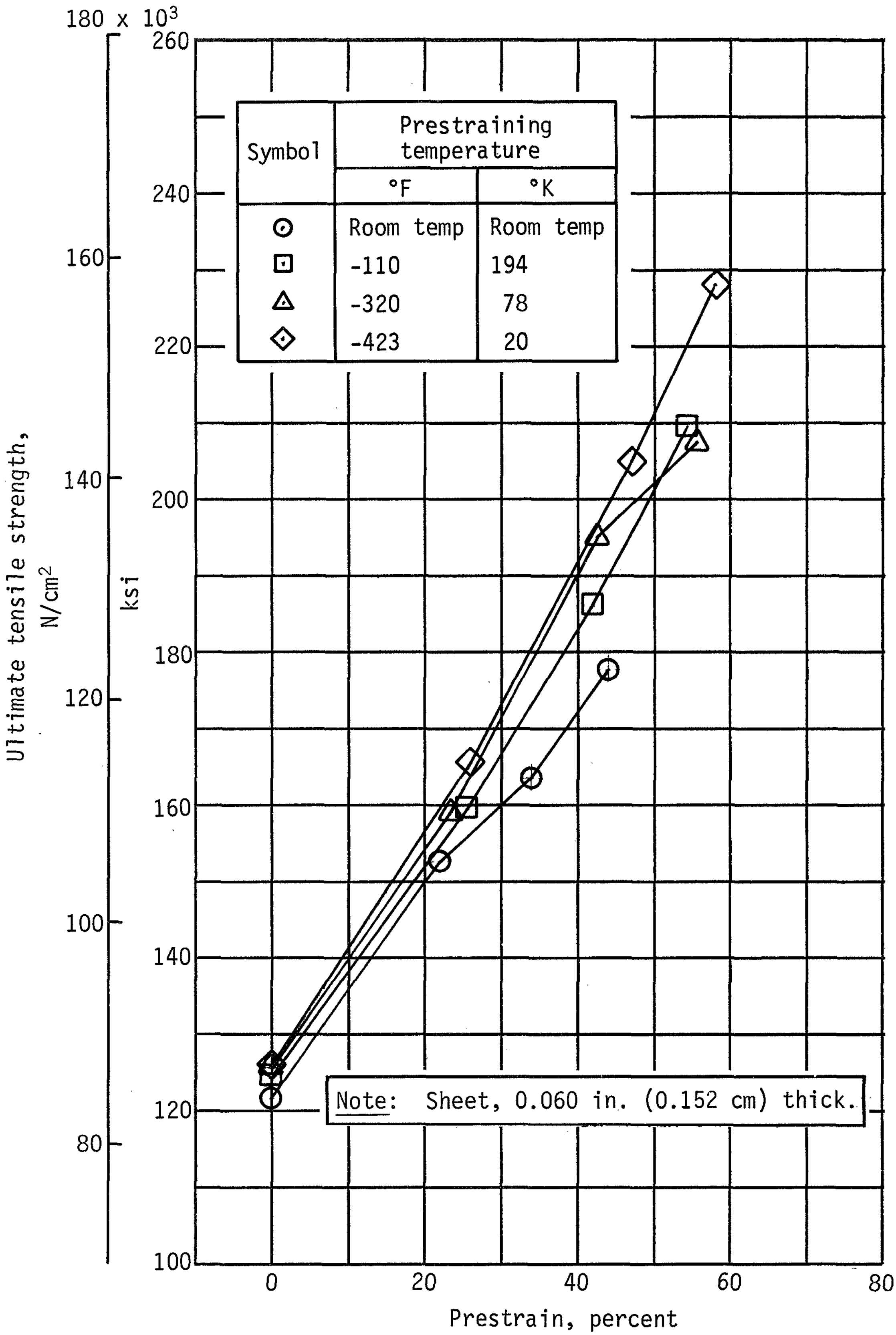


Figure 12.- Ultimate Tensile Strength of Prestrained MP 35 N Cobalt-Nickel Alloy

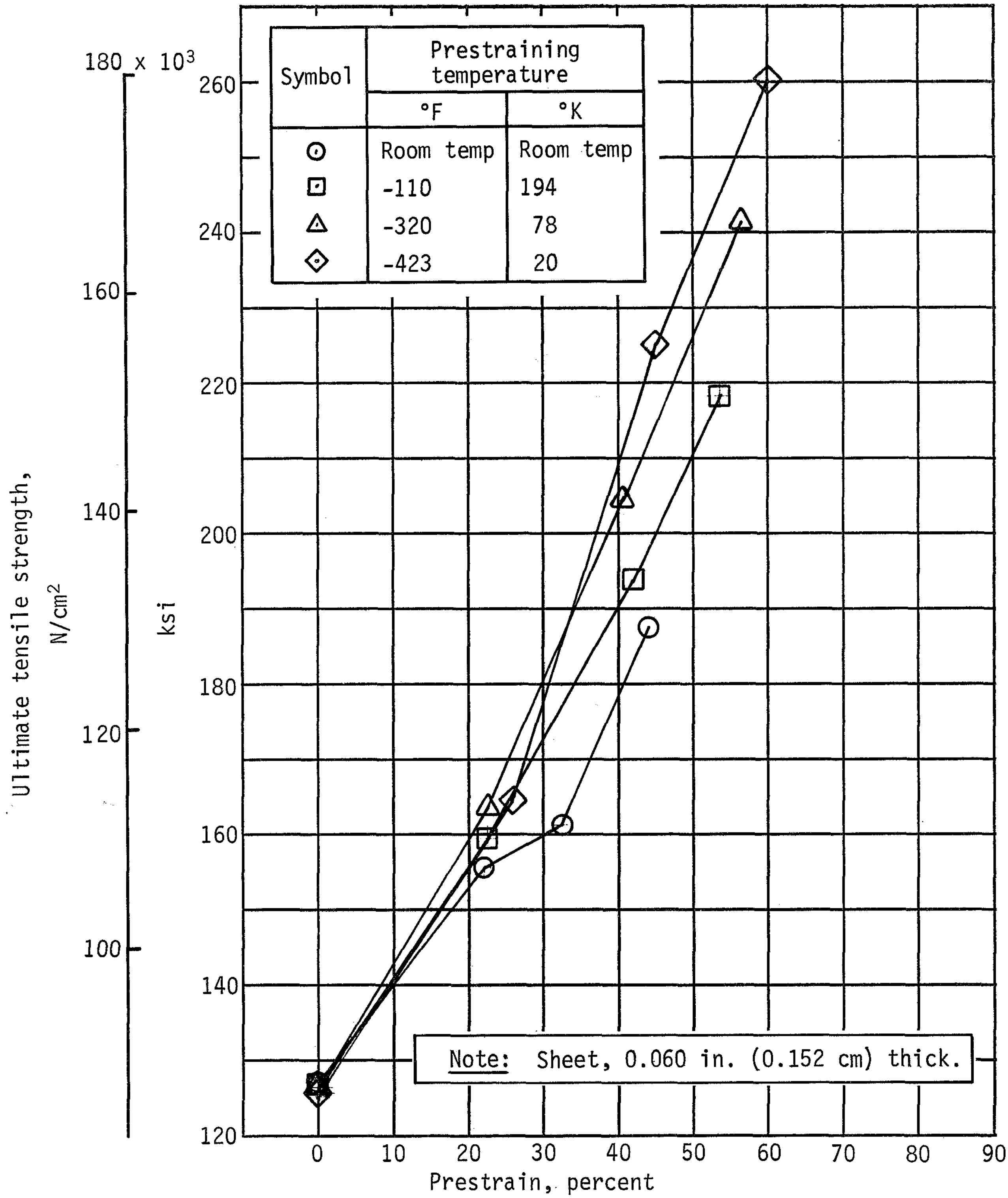


Figure 13.- Ultimate Tensile Strength of Prestrained MP 35 N Cobalt-Nickel Alloy, Aged 4 hr at 900°F (756°K)

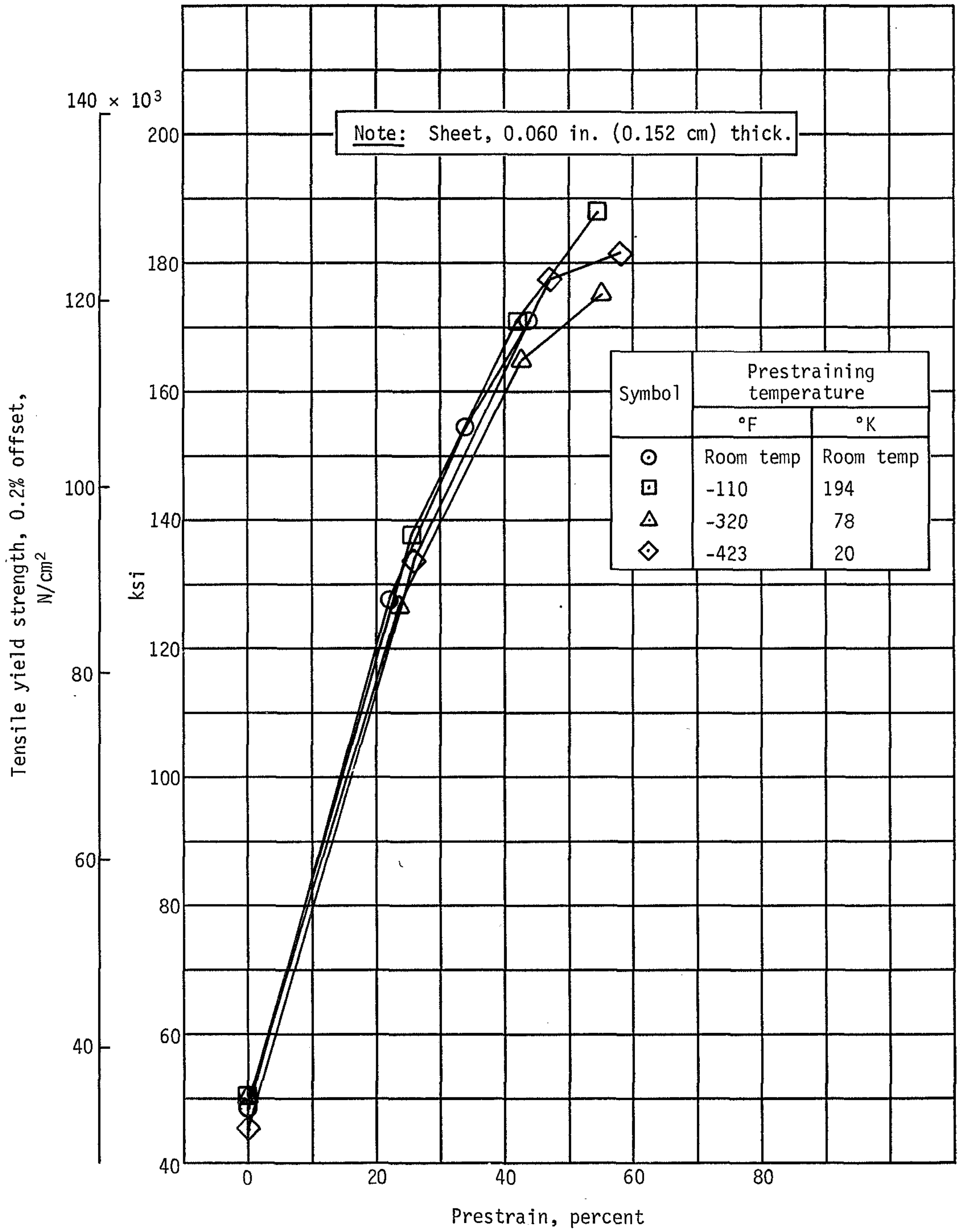


Figure 14.- Tensile Yield Strength of Prestrained MP 35 N Cobalt-Nickel Alloy

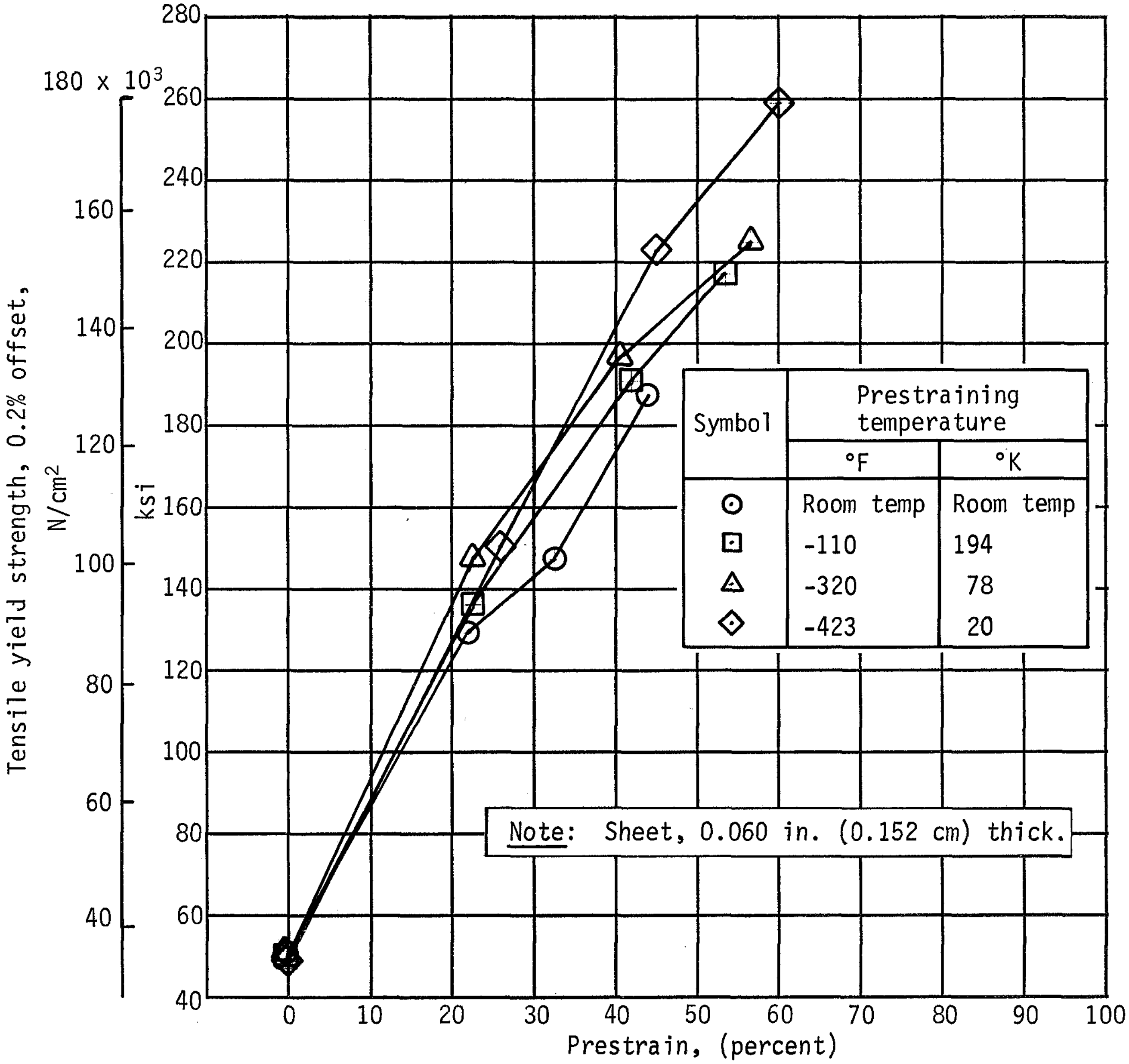


Figure 15.- Tensile Yield Strength of Prestrained MP 35 N Cobalt-Nickel Alloy, Aged 4 hr at 900°F (756°K)

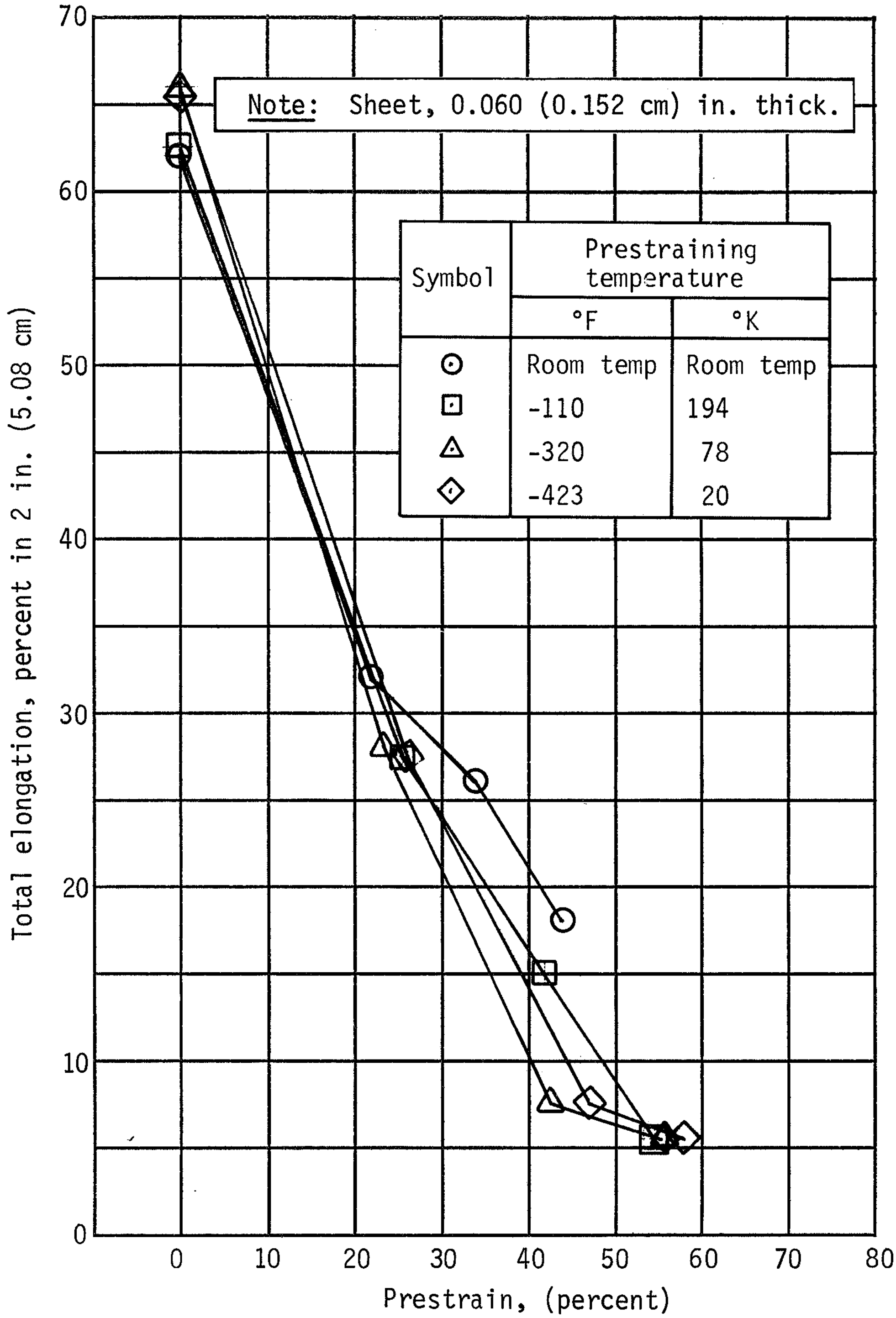


Figure 16.- Total Elongation of Prestrained MP 35 N Cobalt-Nickel Alloy

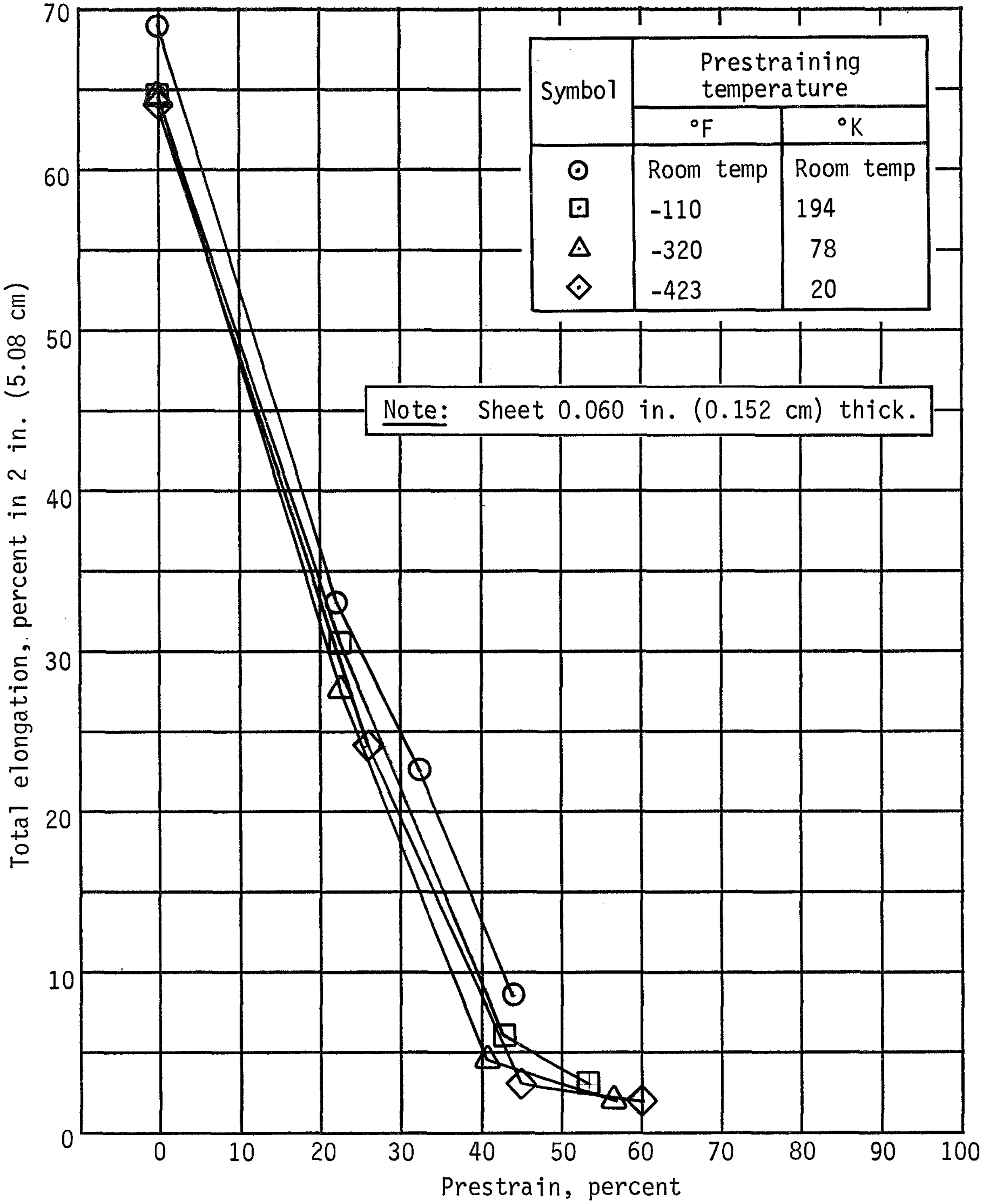


Figure 17.- Total Elongation of Prestrained MP 35 N Cobalt-Nickel Alloy, Aged 4 hr at 900°F (756°K)

THE SECOND YEAR'S PROGRAM

Before Task IV testing was completed and the results analyzed, it had been planned that nine alloys would be tested in Task VI, three from each of three alloy systems. These alloys were to have been chosen primarily on the basis of the Task IV test results. It was intended that only alloys with a high probability of being appreciably strengthened by cryostraining would be studied in Task VI. However, when the Task IV test results were analyzed and it was found that only two alloys were legitimate candidates for further study, the program had to be modified accordingly.

The second year's program was conducted according to the following plan.

1. The testing portion of the program was divided into three tasks:

   Task VI - Selection of a Promising Alloy;

   Task VII - Thermal Response Tests;

   Task VIII - Toughness, Stress Corrosion, High Energy Rate Straining Tests, and Compression Tests.

2. Two additional tasks:

   Task IX - Analysis;

   Task X - Reporting;

   completed the program.

3. Three alloys were tested in Task VI, all semi-austenitic precipitation hardening corrosion resistant steels: PH 14-8 Mo; PH 15-7 Mo; and 17-7 PH.

4. Cryostraining was done at one temperature, -320°F (78°K).

A report of the work done and the results obtained during the second year of the program is contained in the remaining chapters of this document.

III. MATERIALS

The results of previous testing, Tasks I through IV of the program (Ref 8), identified only two alloys, of the fifteen studied, as legitimate candidates for additional cryostraining studies. Initially, it was intended to test both alloys, PH 14-8 Mo and MP 35 N, in Task VI, along with PH 15-7 Mo and 17-7 PH. Unfortunately, an adequate supply of MP 35 N sheet could not be obtained in time to meet the program schedule requirements. Consequently, in Task VI, three alloys from the same alloy system were tested: PH 14-8 Mo, PH 15-7 Mo, and 17-7 PH. All are semi-austenitic precipitation hardening corrosion resistant steels.

The three semi-austenitic precipitation hardening steels tested are alloys developed by Armco Steel Corporation, Middletown, Ohio. The first of these to be developed was 17-7 PH. It is essentially a modified 301 stainless steel (Ref 9), the major changes being the addition of aluminum and the reduction of the permissible carbon and manganese contents. As a result, 17-7 PH, unlike 301, can be strengthened by thermal treatment. Development of PH 15-7 Mo and PH 14-8 Mo followed, in order, the development of 17-7 PH.

In Condition A, a mill-annealed condition often referred to as the solution-treated condition, the three alloys have an austenitic structure, are ductile, and can be formed by methods used to form the austenitic stainless steels. In this condition, because of their austenitic structure, the alloys retain good ductility at -320°F (78°K).

These steels are hardened by the austenite-to-martensite transformation, and by a precipitation hardening treatment (aging) following transformation. The aging treatment also serves to temper the martensite.

Transformation of the austenite to martensite in these steels is conventionally accomplished either by thermal treatment or by cold work (cold rolling at the mill) (Ref 10). A cold work method of transformation, substituting uniaxial tensile straining for cold rolling, was ideally suited to the program. Using this procedure, the materials were strained in the ductile condition (Condition A) to induce the transformation and were then aged for additional strengthening.

The materials procured for testing in Task VI are described below:

1. PH 14-8 Mo Vacuum Induction Melted

   Materials Specification: North American Specification, MB 160-015 E

   Sheet Size: .050 x 36 x 120 in. (0.127 x 91 x 305 cm)

   Surface Finish: 2D

   Temper: Condition A

Chemical Composition:

Element	% by weight	Element	% by weight
C	.039	Cr	15.18
Mn	.04	Ni	8.20
P	.003	Aℓ	1.27
S	.004	Mo	2.22
Si	.04	Cu	.05
		Fe	Remainder

Condition	Grain direction	Mechanical properties*					
		Ultimate tensile strength		Tensile yield strength (0.2% offset)		Elongation percent in 2 inches (5.08 cm)	Hardness Rockwell
		psi	N/cm^2	psi	N/cm^2		
A	L	129 800	89 500	58 300	40 200	30.0	B 89.0
A	T	125 600	86 600	56 600	39 000	31.5	B 89.0
SRH 950	L	227 500	156 900	203 900	140 600	9.0	C 49.0
SRH 950	T	229 000	157 900	204 500	141 000	7.0	C 49.0
SRH 1050	L	215 500	148 600	201 500	138 900	8.0	C 44.5
SRH 1050	T	215 800	148 800	200 200	138 000	5.5	C 44.5

* Reported and certified by the supplier.

2. PH 15-7 Mo

Materials Specification: Aerospace Materials Specification, AMS 5520A

Sheet Size: .050 x 36 x 120 in. (0.127 x 91 x 305 cm)

Surface Finish: 2D

Temper: Condition A

Chemical Composition:

Element	% by weight	Element	% by weight
C	.08	Cr	15.17
Mn	.60	Ni	7.26
P	.021	Aℓ	1.23
S	.019	Mo	2.27
Si	.034	Cu	.10
Co	.08	Fe	Remainder

Condition	Grain direction	Mechanical properties*					
		Ultimate tensile strength		Tensile yield strength (0.2% offset)		Elongation percent in 2 inches (5.08 cm)	Hardness Rockwell
		psi	N/cm^2	psi	N/cm^2		
A	L	123 800	85 400	59 200	40 800	41.5	B 91.0
A	T	122 200	84 300	60 300	41 600	37.5	B 91.0
TH 1050	L	210 000	144 800	201 500	138 900	10.0	C 45.0
TH 1050	T	217 800	150 200	204 800	141 200	7.0	C 45.0
RH 950	L	230 000	158 600	218 200	150 400	9.5	C 48.0
RH 950	T	236 400	163 000	220 100	151 800	7.0	C 48.0

* Reported and certified by the supplier.

3. 17-7 PH

Material Specification: MIL-S-25043C

Sheet Size: .050 x 36 x 120 in. (0.127 x 91 x 305 cm)

Surface Finish: 2D

Temper: Condition A

Chemical Composition:

Element	% by weight	Element	% by weight
C	.07	Cr	17.08
Mn	.49	Ni	7.44
P	.017	Aℓ	1.05
S	.018	Mo	.31
Si	.38	Cu	.28
Co	.07	Fe	Remainder

Condition	Grain direction	Mechanical properties*					
		Ultimate tensile strength		Tensile yield strength (0.2% offset)		Elongation percent in 2 inches (5.08 cm)	Hardness Rockwell
		psi	N/cm^2	psi	N/cm^2		
A	L	118 200	81 500	48 300	33 300	49.0	B 87.0
A	T	114 100	78 700	45 000	31 000	50.0	B 87.0
TH 1050	L	193 500	133 400	169 000	116 500	10.0	C 43.0
TH 1050	T	139 100	130 400	168 500	116 200	9.0	C 43.0
RH 950	L	221 000	152 400	203 500	140 300	10.0	C 48.0
RH 950	T	215 500	148 600	193 800	133 600	8.0	C 48.0

* Reported and certified by the supplier.

In addition to the sheet stock, weld wire was also procured for use in preparing the welded specimens tested in Task VI; characteristics of the weld wire are:

PH 14-8 Mo wire, 0.045 in. (0.114 cm) diameter; North American Specification LBO 160 117 C

Chemical Composition:

Element	% by weight	Element	% by weight
C	.038	Cr	14.43
Mn	.43	Ni	8.17
Si	.38	Mo	2.17
S	.003	Aℓ	1.23
P	.005	Fe	Remainder

W PH 15-7 Mo wire, 0.045 in. (0.114 cm) diameter, AMS 5813A

Chemical Composition:

Element	% by weight	Element	% by weight
C	.067	Cr	14.74
Mn	.41	Ni	7.50
Si	.34	Mo	2.23
S	.025	Aℓ	.95
P	.007	Fe	Remainder

W 17-7 PH wire, 0.045 in. (0.114 cm) diameter, SMX 7-59 B, Class 1

Chemical Composition:

Element	% by weight	Element	% by weight
C	.067	Cr	16.54
Mn	.44	Ni	7.40
Si	.20	Aℓ	.91
S	.012	Fe	Remainder
P	.010		

IV. PROCEDURES AND EQUIPMENT

TASK VI - SELECTION OF A PROMISING ALLOY

Task VI was conducted to develop data by which to compare the three alloys tested with respect to changes in room temperature tensile properties induced by straining at -320°F (78°K). The objective of this Task was to determine through a comparative evaluation of test results, the alloy of the three tested that should be tested in Tasks VII and VIII.

Task VI was divided into four sub-tasks:

1. Parent Metal Tests;
2. Weldment Tests;
3. Higher Strain-Rate Tests;
4. Roll-Straining Tests.

The test plan and the procedures and equipment used in conducting the Task VI tests are described in the following paragraphs by subtask.

Parent Metal Tests

Purpose: The purpose of this series of tests was to determine how uniform straining in uniaxial tension at -320°F (78°K) affected the room temperature tensile properties (both longitudinal and long transverse) of each alloy.

Approach: To develop the necessary data the following plan was followed:

1. Three longitudinal and three long transverse specimens of each alloy, in Condition A, were tensile tested to failure at room temperature. Like quantities of specimens of each alloy were similarly tested at -320°F (78°K). The properties measured were ultimate tensile strength, total elongation, and uniform elongation.
2. The average uniform elongation was calculated for each combination of alloy, grain direction, and temperature. These averages were established as uniform strain capability (USC) values.
3. Four target strain values (strain levels) were arbitrarily selected for each combination of alloy and grain direction. Four levels were selected to facilitate graphical presentation of the test results. The strain levels used are defined in Table 6.
4. Specimens of each alloy were prepared and tested in the conditions identified in Table 7.

Table 6. Strain Level Definitions, Task VI Parent Metal Tests

Strain Level	Definition
A(L)	40% of an alloy's USC[1] in the longitudinal[2] grain direction at -320°F (78°K).
B(L)	60% of an alloy's USC in the longitudinal[2] grain direction at -320°F (78°K).
C(L)	75% of an alloy's USC in the longitudinal[2] grain direction at -320°F (78°K).
D(L)	90% of an alloy's USC in the longitudinal[2] grain direction at -320°F (78°K).
A(T)	40% of an alloy's USC in the long transverse[2] grain direction at -320°F (78°K).
B(T)	60% of an alloy's USC in the long transverse[2] grain direction at -320°F (78°K).
C(T)	75% of an alloy's USC in the long transverse[2] grain direction at -320°F (78°K).
D(T)	90% of an alloy's USC in the long transverse[2] grain direction at -320°F (78°K).

NOTE: 1. USC = uniform strain capability.
2. Relative to final mill rolling.

Equipment: A Balwin Universal Test Machine, 50 000 lb (222 400N) capacity, Model FGT, and standard accessories were used for specimen straining and testing at room temperature. The same machine, an open-end cryostat, and special load linkage systems (Figure 5), were used for straining and testing at -320°F (78°K).

Cryogen: The cryogen used for specimen straining and testing at -320°F (78°K) was liquid nitrogen (LN_2).

Specimens: Specimens of the type shown in Figure 18 were used in the tensile testing of unstrained material at room temperature and -320°F (78°K).

Specimens of the type shown in Figure 19 were strained at room temperature and -320°F (78°K). After being strained the specimens were remachined to the configuration shown in Figure 20 for room temperature tensile testing.

One surface of each specimen of the types shown in Figures 18 and 19 had a 0.100 inch square grid pattern, of the type shown in Figure 3, applied (photographically) to one surface. The grid lines were used as datum lines for strain measurement.

Table 7 - Test Schedule, Task VI Parent Metal Tests

Type of Test	Material Condition	No. of Specimens per Alloy		Specimen Design	
		Longitud- inal	Trans- verse	Fig. 18	Fig. 19 + Fig. 20
Room temp tensile	Strained at room temp:				
	0% + aged	3	3	X	-
	Level A(L)	3	-	-	X
	Level A(L) + aged	3	-	-	X
	Level A(T)		3	-	X
	Level A(T) + aged		3	-	X
	Level B(L)	3	-	-	X
	Level B(L) + aged	3	-	-	X
	Level B(T)	-	3	-	X
	Level B(T) + aged	-	3	-	X
	Level C(L)	3	-	-	X
	Level C(L) + aged	3	-	-	X
	Level C(T)	-	3	-	X
	Level C(T) + aged	-	3	-	X
	Level D(L)	3	-	-	X
	Level D(L) + aged	3	-	-	X
	Level D(T)	-	3	-	X
	Level D(T) + aged	-	3	-	X
	Strained at -320°F (78°K):				
	0%	3	3	X	-
	0% + aged	3	3	X	-
	Level A(L)	3	-	-	X
	Level A(L) + aged	3	-	-	X
	Level A(T)	-	3	-	X
	Level A(T) + aged	-	3	-	X
	Level B(L)	3	-	-	X
	Level B(L) + aged	3	-	-	X
	Level B(T)	-	3	-	X
	Level B(T) + aged	-	3	-	X
	Level C(L)	3	-	-	X
	Level C(L) + aged	3	-	-	X
	Level C(T)	-	3	-	X
	Level C(T) + aged	-	3	-	X
	Level D(L)	3	-	-	X
	Level D(L) + aged	3	-	-	X
	Level D(T)	-	3	-	X
Room temp tensile	Level D(T) + aged	-	3	-	X

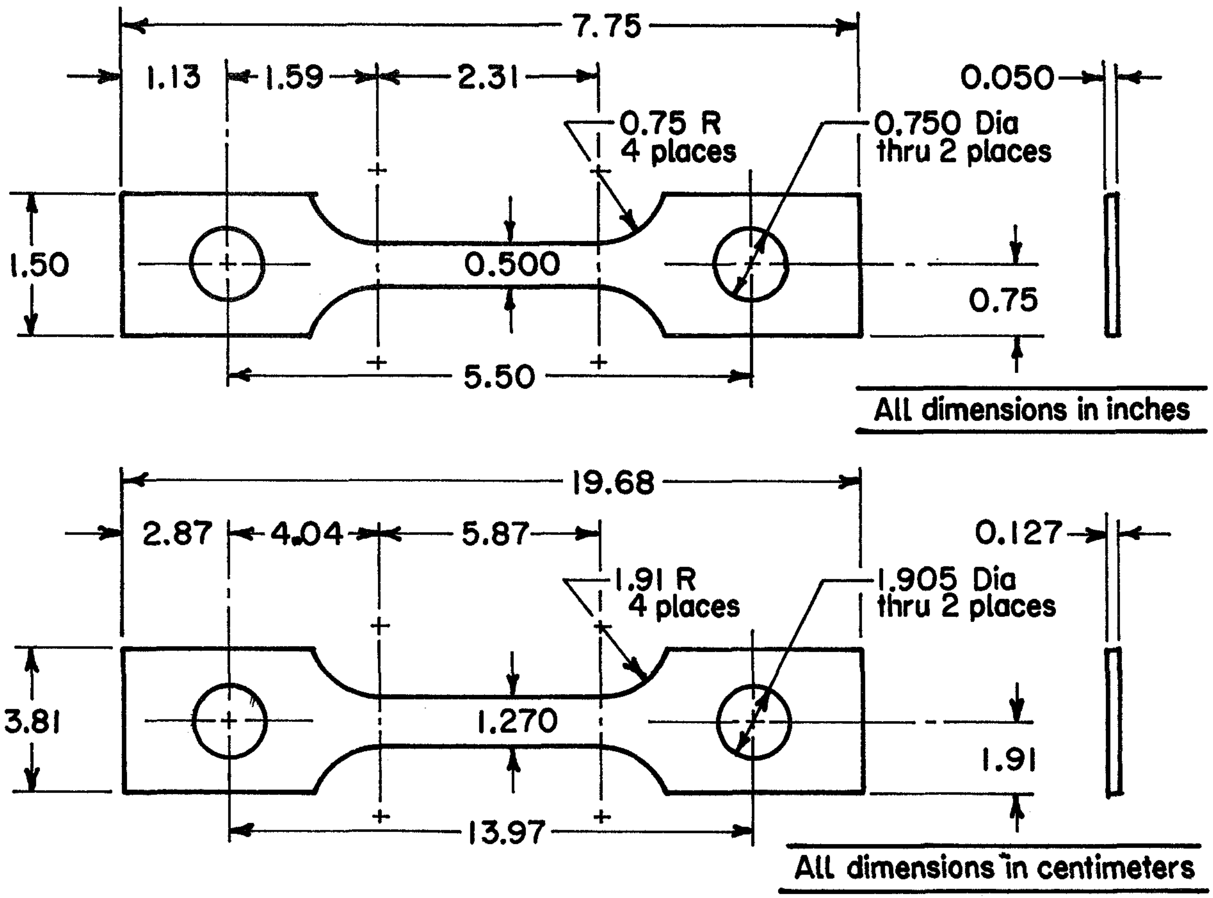
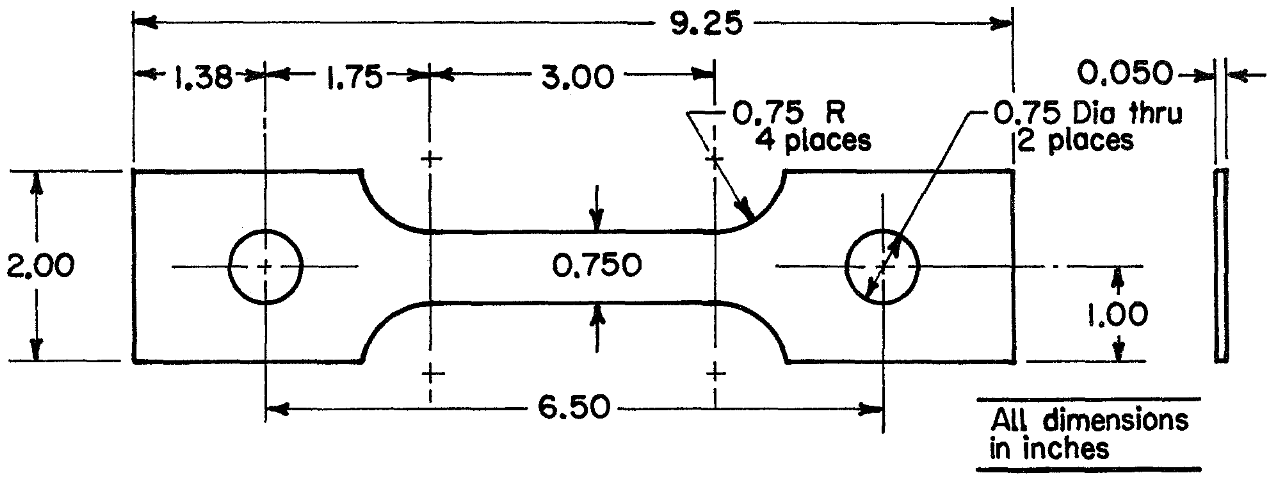


Figure 18 Tensile Specimen for Testing Unstrained Material.



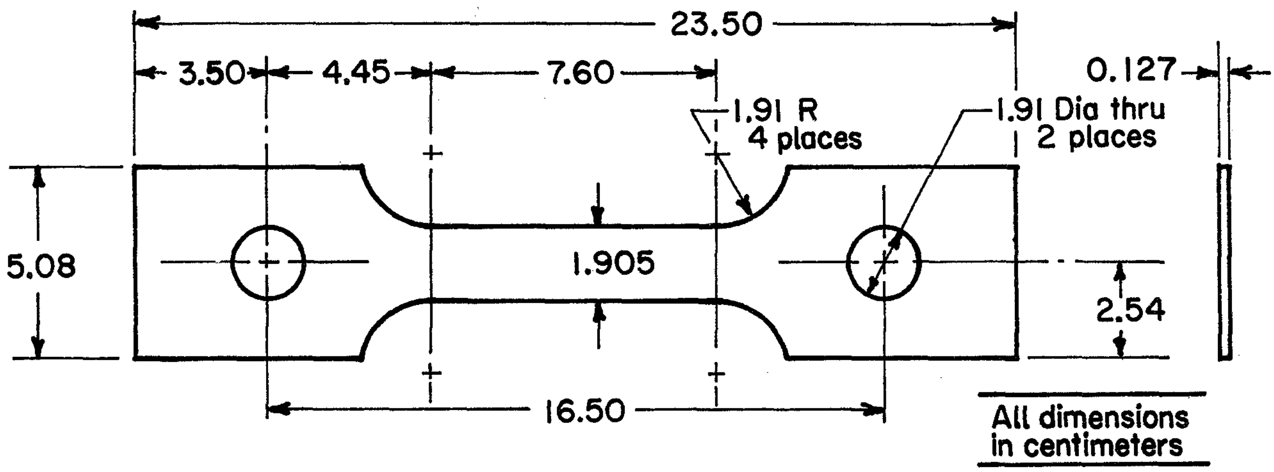


Figure 19 Configuration of Specimens Strained at Room Temperature and -320°F (78°K)

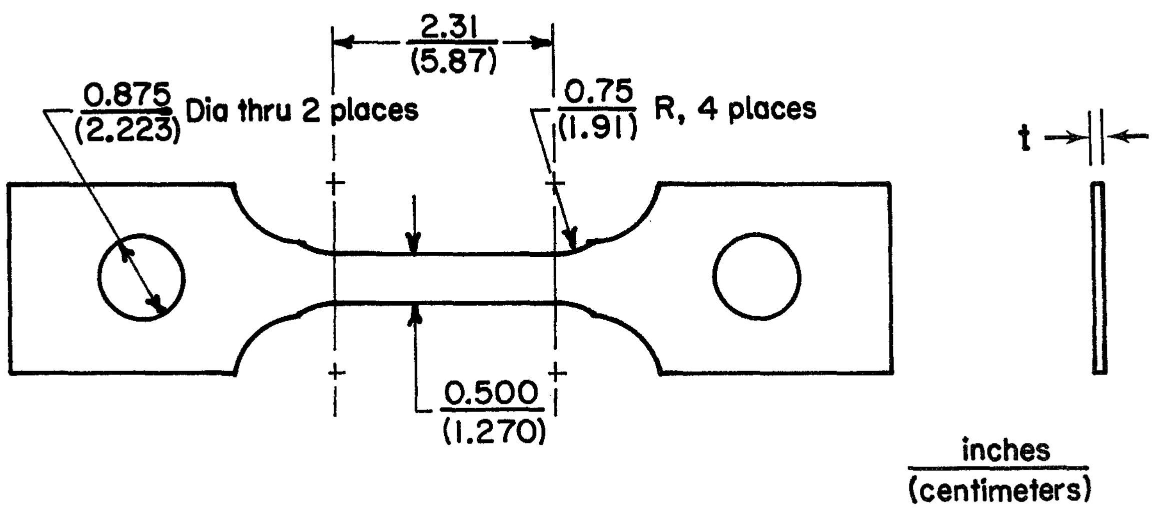


Figure 20 Configuration of Strained Specimens Remachined for Tensile Test

Tensile Testing: Tensile tests were conducted in accordance with the procedures and specifications of ASTM E8-69.

Straining: Specimens were strained at a rate of 0.050 inch per inch per minute (0.050 cm per cm per minute), regardless of the temperature at which the straining was done.

When specimens were strained to a given strain level at room temperature, strain was measured directly by means of the grid marks, a 10 power magnifying glass, and a 6-inch scale with 0.010 inch graduations. When the proper amount of strain was reached, the load was released.

Since the specimens strained at -320°F (78°K) were immersed in LN_2 when strained, direct measurement of strain was impractical. However, it was possible by experimentation (Ref. 8) to relate platen travel to specimen strain. Thus, for the specimens strained at -320°F (78°K), strain was measured indirectly by measuring platen travel with a dial indicator.

Aging: The industry standard aging treatment for developing the CH-900 condition in all three alloys is one hour at 900°F (756°K. This aging treatment was given all specimens that were aged in Task VI. Certified and calibrated furnaces were used. All specimens were thoroughly cleaned and coated with Turco-Pretreat before they were aged.

WELDMENT TESTS

Purpose: This series of tests was conducted to determine how each alloy was affected by welding before cryostraining.

Approach: Butt-welded test panels of the configuration shown in Figure 21 were prepared, one test panel per alloy. Specimens for testing and straining were made from each panel. Table 8 is the test schedule for the weldment tests, showing the number of specimens tested per alloy, and how each was conditioned for testing.

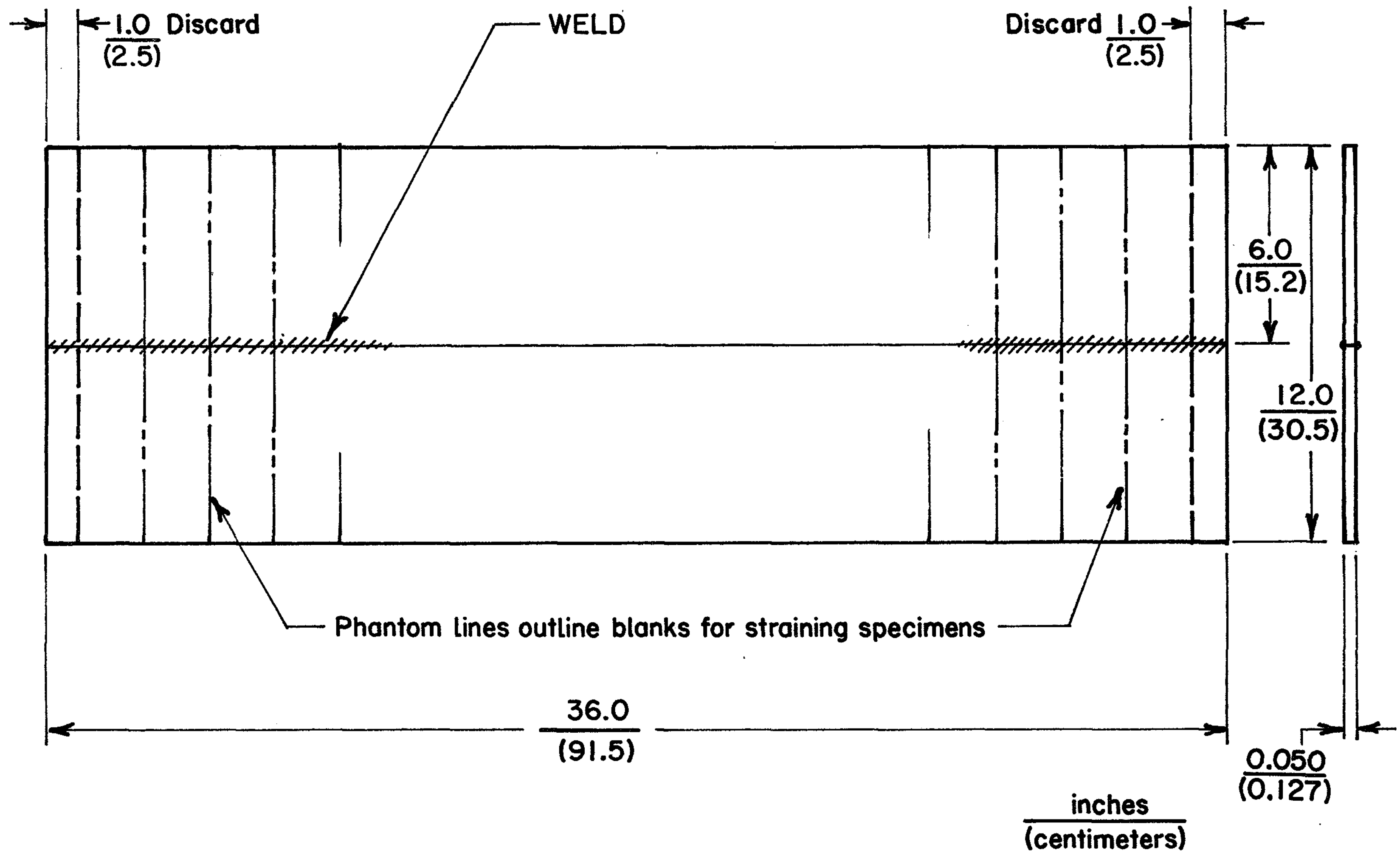


Figure 21 Butt Weld Test Panel

Table 8. Test Schedule, Task VI Weldment Tests

Type of Test	Material Condition	No. of Specimens (Per Alloy) Longitudinal Grain Direction
Room temperature tensile	As received + welded	3
-320°F (78°K) tensile	As received + welded	3
Room temperature tensile	As received + welded + strained* at room temp to Level E** + aged***	3
Room temperature tensile	As received + welded + strained* at -320°F (78°K) to Level E** + aged***	3
	Total	12
* Strain rate, 0.050 inch per inch per minute ** Level E - 60% of USC at -320°F (78°K) *** One hour at 900°F (756°K)		

For welded specimens the USC for each alloy was established as the average of the uniform strains measured on the welded specimens of the alloy that had been tested to failure at -320°F (78°K).

General: The equipment and procedures used in conducting the weldment tests were the same as those used in conducting the parent metal tests, except as specifically noted in the following paragraphs.

Welding: The test panels were welded by the tungsten-inert-gas method. The basic equipment used was: an airline fixture, Model No. 11312 HLZ with stainless steel hold down fingers and backup; Sciaky Controller, Model No. F18 DTX-W1000-S6; and an Airco power supply, Model No. 3AD-24HEPAB-B. The weld schedules used to weld the test panels were:

PH 14-8 Mo:

Material:	PH 14-8 Mo, 0.050 in. (0.127 cm) thick
Condition:	Condition A
Weld Wire:	WPH 14-8 Mo, 0.045 in. (0.114 cm) diameter
Gas:	Argon
Gas Flow:	Torch, 30 cf/hr (0.85 m^3/hr) Backup, 13 cf/hr (0.38 m^3/hr) Trailing shield 35 cf/hr (1.05 m^3/hr)
Volts:	8
Amperes:	72
Wire Feed:	17 in./min (43.18 cm/min)
Travel Speed:	8 in./min (20.32 cm/min)
Electrode:	0.093 inch (0.236 cm) diameter, tungsten.

PH 15-7 MO:

Material:	PH 15-7 Mo sheet, 0.050 in. (0.114 cm) thick
Condition:	Condition A
Weld Wire:	WPH 15-7 Mo
Gas:	Argon
Gas Flow:	Torch, 30 cf/hr (0.85 m^3/hr) Backup, 13 cf/hr (0.38 m^3/hr) Trailing shield, 35 cf/hr (1.05 m^3/hr)
Volts:	8.3
Amperes:	71
Wire Feed:	17 in./min (43.18 cm/min)
Travel Speed:	7.8 in./min (19.8 cm/min)
Electrode:	0.093 inch (0.236 cm) diameter, tungsten

17-7 PH:

Material:	17-7 PH sheet, 0.050 in. (0.127 cm) thick
Condition:	Condition A
Weld Wire:	W17-7 PH
Gas:	Argon
Gas Flow:	Torch, 30 cf/hr (0.85m^3/hr) Backup, 13 cf/hr (0.38 m^3/hr) Trailing shield, 35 cf/hr (1.05 m^3/hr)
Volts:	8.3
Amperes:	70
Wire Feed:	19.5 in./min (49.3 cm/min)
Travel Speed:	7.8 in./min (19.8 cm/min)
Electrode:	0.093 inch (0.236 cm) diameter, tungsten

Inspection: After welding, all panels were given visual, penetrant, and X-ray inspections.

Specimens:: Specimens of the type shown in Figure 22 were used in the tensile testing of unstrained weldments at room temperature and -320°F (78°K).

Specimens of the type shown in Figure 23 were strained at room temperature and at -320°F (78°K). After being strained, they were remachined to the configuration shown in Figure 24 for tensile testing at room temperature.

The weld specimens were not gridded because the weld bead, which was not removed, hampered the processing and degraded the accuracy of the pattern. Instead, one surface of the gage section of a specimen was painted with layout fluid and strain datum lines, 0.250 inch (0.635 cm) apart and transverse to the axis of the specimen, were scribed on the painted surface.

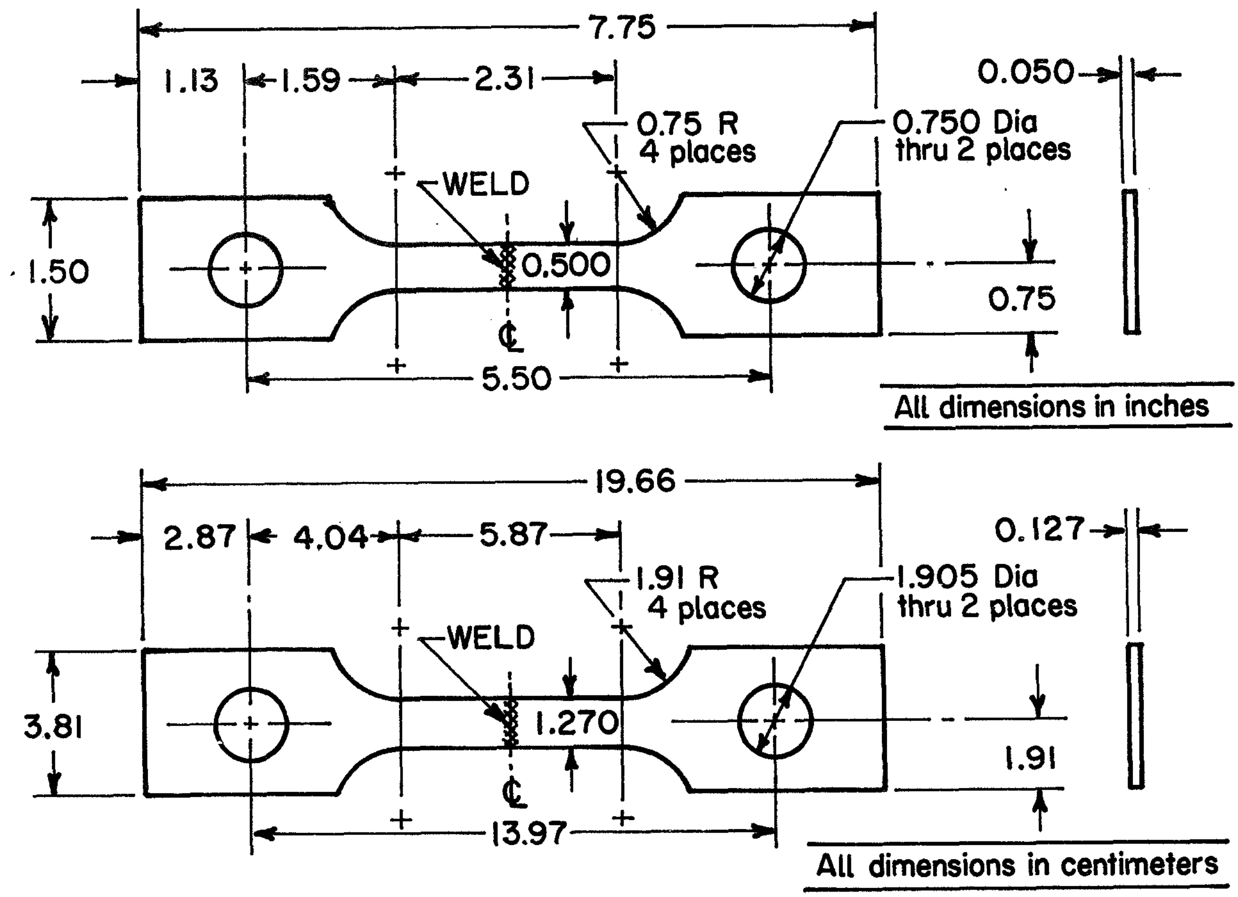
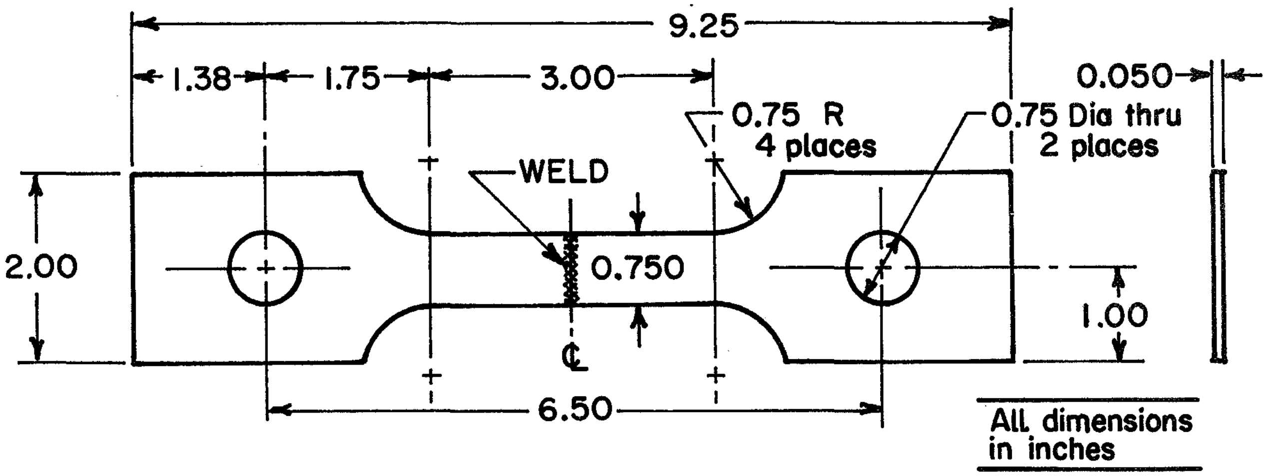


Figure 22 Tensile Specimen for Testing Unstrained Weldments



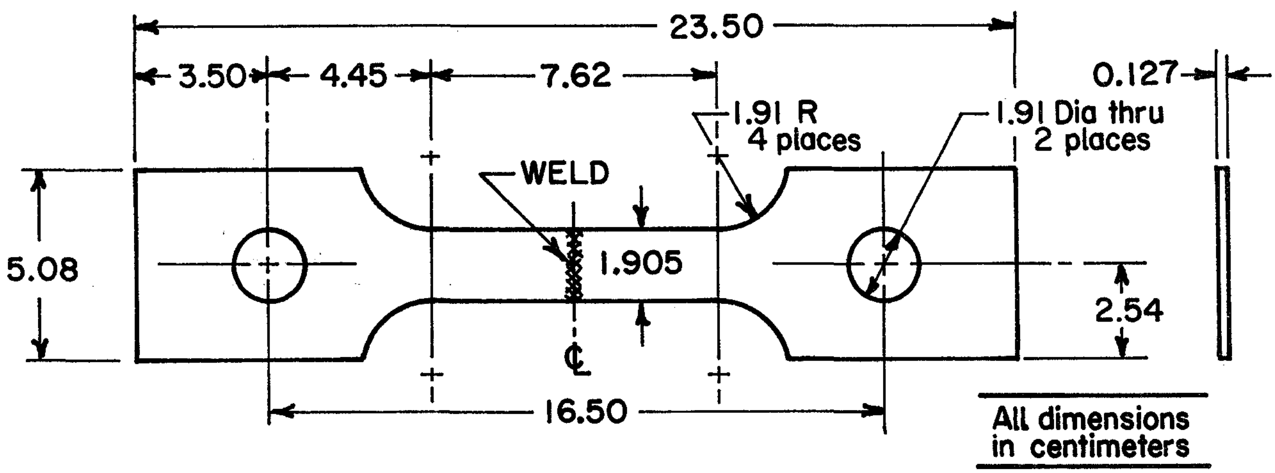


Figure 23 Configuration of Weldment Specimens Strained at Room Temperature and at -320°F (78°K)

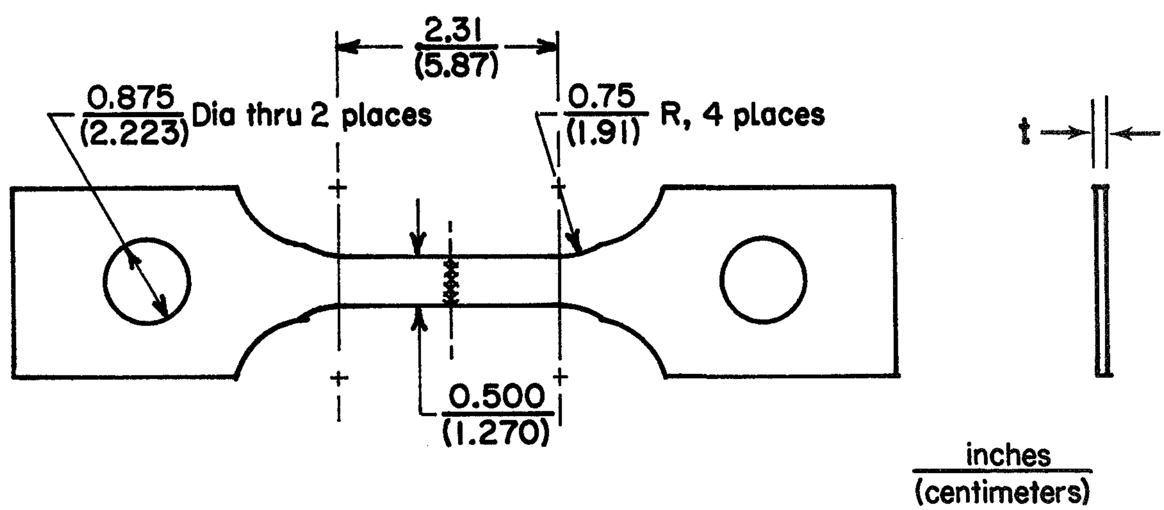


Figure 24 Configuration of Strained Weldment Specimens Remachined for Tensile Test

Straining: The techniques used for specimen straining and strain measurement in the parent metal test series were used in the weld test series.

HIGHER STRAIN RATE TESTS

Purpose: Until this series of tests was conducted, all of the specimens that had been strained, except the Ti 6Aℓ-4V specimens strained in Task III, had been strained at a program standard rate of 0.050 inch per inch per minute (0.050 cm/cm/min). Therefore, this series of tests was conducted to determine whether or not cryostraining at a faster rate would cause any or all of the three alloys to develop significantly different room temperature tensile properties than those developed by cryostraining at the program standard rate.

Approach: The same procedures, techniques, and types of specimens used in conducting the parent metal test series were used in conducting the higher strain rate tests, except that specimens were strained at a faster rate.

The test schedule for the higher strain rate tests is shown in Table 9.

Table 9 Test Schedule, Task VI Higher Strain Rate Tests

Type of Test	Material Condition	No. of Specimens (Per Alloy) Longitudinal Grain Direction
Room temp tensile 1.5 in./in./min (1.5 cm/cm/min) strain rate	As received	3
-320°F (78°K) tensile 1.5 in./in./min (1.5 cm/cm/min) strain rate	As received	3
Room temp tensile 0.005 in./in./min(0.005 cm/cm/min) strain rate	Strained at room temp 1.5 in./in./min (1.5 cm/cm/min) to:	
	Level X*	3
	Level X*+ aged	3
	Level Y**	3
	Level Y**+ aged	3
Room temp tensile 0.005 in./in./min(0.005 cm/cm/min) strain rate	Strained at -320°F (78°K) 1.5 in./in./min (1.5 cm/cm/min) to:	
	Level X*	3
	Level X*+aged	3
	Level Y**	3
	Level Y**+ aged	3
	Total	30

*Level X, 50% of the alloy's uniform strain capability at -320°F (78°K)

** Level Y, 75% of the alloy's uniform strain capability at -320°F (78°K)

Straining: All specimens strained for the higher strain rate tests were strained at a rate of 1.5 in./in./min (1.5 cm/cm/min).

ROLL STRAINING TESTS

Purpose: The purpose of these tests was to determine how the room temperature tensile properties of the three alloys were affected by roll-straining at -320°F (78°K).

Approach: To develop the required data, samples of each alloy were rolled at room temperature and others at -320°F (78°K). The materials were rolled until a reduction in thickness of 10 to 20 percent was achieved. Tensile bars were made from the roll-strained materials and tensile tested at room temperature. The roll strain test schedule is shown in Table 10.

Table 10 Test Schedule, Task VI Roll Strain Tests

Type of Test	Material Condition	No. of Specimen (Per Alloy) Longitudinal Grain Direction
Room temp tensile	As received + roll strained* at room temp,	3
	+ aged	3
	As received + roll strained* at -320°F (78°K)	3
	+ aged	3
	Total	12
*Thickness reduction - approximately 10 to 20%.		

Equipment: A Stanat rolling mill, Model TA-215 was used to roll-strain the materials.

For tensile testing and aging, the same equipment that had been used in the parent metal test series was used.

Procedures: The blanks for roll straining were 3 inch (7.6 cm) x 5 inch (12.70 cm) pieces of sheet material, with the longitudinal grain direction parallel to the 5 inch (12.70 cm) length. When the room temperature rolling operations were performed, the blanks were rolled in repeated passes until the desired reduction in thickness was achieved. When the materials were rolled at -320°F (78°K), the blanks were immersed in LN_2 for a minimum of 5 minutes, passed through the rolls, again immersed in LN_2 for a minimum of 5 minutes, and again passed through the rolls. This sequence was repeated until the desired thickness reduction was achieved. Becaused the blanks were small they were easily and quickly handled. In practice, it required less than ten seconds, to remove a blank from the LN_2, feed it into and pass it through the rolls, and return it to the LN_2.

Specimens of the type shown in Figure 1 were made from the rolled blanks and tested at room temperature.

ANALYSIS

The results of all the tests conducted during Task VI were analyzed. Based on a comparative evaluation of the overall performance of the three alloys, PH 14-8 Mo was selected for testing in Tasks VII and VIII.

TASK VII - THERMAL PROCESSING STUDIES

Purpose: PH 14-8 Mo is usually procured in either of two conditions: Condition A, the solution treated condition, or Condition CH-900, cold rolled at the mill to approximately a 60 percent reduction, and aged one hour at 900°F (756°K).

During the preceding tasks, whenever PH 14-8 Mo specimens were aged, the CH-900 aging treatment, one hour at 900°F (756°K) was used. Task VII was conducted to study the effects produced by other aging treatments on room temperature tensile properties developed by cryostrained PH 14-8 Mo. The objective of Task VII was to select twenty combinations of cryostrain-aging treatments for study in the Task VIII stress corrosion and toughness tests.

Approach: The basic plan for Task VII is defined in Tables 11 and 12, the straining and aging schedules. Four groups of specimens were strained. Three groups were strained at -320°F (78°K) to each of three strain levels, identified as P, Q, and N, in order of increased strain. The fourth group of specimens was strained at room temperature to a strain equal to level N at -320°F (78°K). Then, as indicated in Table 12, specimens were given various aging treatments. After being aged the specimens were remachined and room temperature tensile tests were conducted to obtain ultimate tensile strength, tensile yield strength, and elongation. Based on these test results twenty combinations of cryostrain and aging treatments (temperature and time) were selected for use in the Task VIII tests.

Table 11 - Straining Schedule, Task VII

Number of Specimens	Uniform Strain Capability (USC) at -320°F (78°K)	Strain Level: Designation	Strain Level: Percent of USC at -320°F (78°K)	Target Strain, Percent	Strain Temp °F (°K)
60	20.0	P	50.0	10.0	-320 (78)
60	20.0	Q	65.0	13.0	-320 (78)
60	20.0	N	80.0	16.0	-320 (78)
18	20.0	S	80.0	16.0	RT

Specimens: The specimens used throughout in Task VII were gridded specimens of the type shown in Figure 19. After being strained, the specimens were remachined to the configuration shown in Figure 20, and then aged in accordance with the schedule given in Table 12 on the following page.

Procedures: For operations common to Task VI and Task VII, such as cryo-straining, strain measurement, and aging, the techniques and procedures used in Task VI were also used in Task VII.

Table 12 - Aging Schedule, Task VII

Aging Temp	Aging Time (hr)	No. of Specimens			
		Strain Level			
		P (10%)	Q (13%)	N (16%)	S (16%)
800°F (700°K)	0.5	2	2	2	-
	1	2	2	2	-
	2	2	2	2	-
	4	3	3	3	-
	6	3	2	2	-
	8	2	2	2	-
	12	1	-	2	-
900°F (756°K)	0.5	2	2	2	-
	1	2	3	3	2
	2	3	3	2	-
	4	3	2	2	-
	4.5	3	4	2	-
	5	2	2	2	-
	5.5	2	3	2	-
	6	2	2	2	-
	7	-	-	-	2
	8	2	2	2	-
	16	1	1	1	-
950°F (783°K)	0.5	2	2	2	-
	1	2	2	2	2
	2	2	3	2	-
	4	3	3	2	-
	6	2	1	2	-
	7	-	-	-	2
	8	2	1	2	-
	16	1	1	1	-
1000°F (811°K)	0.5	2	2	2	-
	1	2	2	3	2
	2	2	2	2	-
	4	2	2	2	-
	7	-	-	-	2
1050°F (839°K)	1	-	-	-	2
	7	-	-	-	2
1100°F (866°K)	0.5	2	2	2	-

ANALYSIS

The data from the Task VII tests were analyzed to determine which combinations of strain level and aging temperatures and times should be used in the Task VIII toughness and stress corrosion tests. The following combinations were selected and used for the 10% and 15% prestrained materials.

AGING		
TEMPERATURE		TIME
°F	°K	(hr)
800	700	1, 4, 8
950	783	1, 4, 8
900	756	1, 2, 4, 8

TASK VIII - TOUGHNESS, STRESS CORROSION, HIGH ENERGY RATE STRAINING AND COMPRESSION TESTS

Purpose: Task VIII was conducted to determine how cryostraining at -320°F (78°K) affected the toughness, stress corrosion resistance, and compressive yield strength of PH 14-8 Mo; and to investigate the effects of straining PH 14-8 Mo at -320°F (78°K) using a high energy rate (explosive) technique.

Approach: Task VIII was divided into four subtasks that will be discussed separately. In general, however, many operations conducted in Task VIII were similar to operations performed in preceding tasks. For example, gridding of specimen stock, straining, strain measurement, and heat treatment. The techniques and procedures used in Task VIII to perform operations common to other tasks were the same as those used in the preceding tasks.

At the end of Task VII, twenty combinations of cryostrain, aging temperature, and aging time, were selected as specimen conditioning treatments for the toughness and stress corrosion studies scheduled for Task VIII. The basic plan for both the toughness and stress corrosion tests was to subject specimens representative of each of the twenty conditions to equivalent toughness and corrosion tests to develop data for comparative evaluation of the conditioning treatments.

The plan for the high energy rate straining tests was to explosively strain samples of the PH 14-8 Mo at room temperature and other samples at -320°F (78°K). Tensile specimens were prepared from the strained material, aged, and tensile tested at room temperature to obtain data for comparison with data from the Task VI Parent Metal and Higher Strain Rate tests.

The compression tests were conducted to determine how prestraining in uniaxial tension affected the room temperature compressive yield strength of PH 14-8 Mo. For this purpose compressive test specimens were prepared from PH 14-8 Mo sheet stock that had been prestrained at -320°F (78°K) or at room temperature. These specimens were tested at room temperature, some in the prestrained and unaged condition, others after having been given one of several aging treatments selected for the study. Equal quantities of longitudinal and long transverse specimens were prepared and tested. Also, for comparison, tensile specimens were prepared from prestrained material, aged along with the compression specimens, and tested at room temperature. However, where specimens with corresponding prestrain, or prestrain and aging treatments had been tested in the Task VI Parent Metal test series, the Task VI data were used for comparsion. Also, compression tests were conducted on specimens prepared from stock that had been heat treated to the SRH 950 and SRH 1050 conditions.

TOUGHNESS TESTS

Purpose: This series of tests was conducted to develop data to compare the toughness of PH 14-8 Mo in various cryostrained-aged conditions.

Approach: The toughness series of tests consisted of the following:

1. Room temperature tensile test (control specimens).
2. Room temperature notched-tensile tests.
3. Room temperature center cracked toughness tests.

The toughness test schedule, including baseline testing, is shown in Table 13.

Procedures:

Control Specimen Tests: Unnotched specimens of the type that had been used in Task VII (Figures 19 and 20) were used as control or baseline specimens for the notched tensile tests. These specimens were strained and then remachined in the same way that the Task VII specimens had been processed. After straining and remachining these specimens were stored until the notched tensile specimens had been strained and were ready for aging. The notched and unnotched specimens were then aged together, in accordance with the schedule, Table 13. Room temperature tensile tests were then conducted on the unnotched control specimens. The properties measured in these tests were ultimate tensile strength, tensile yield strength, and elongation in 2 inches.

Notched Tensile Tests: Specimens of this type shown in Figure 25 were appropriately strained, either at room temperature or at -320°F (78°K), in accordance with the test schedule. The usual procedures and techniques were used to strain these specimens, except that because of their size, the 150 000 lb (667 500 N) capacity Baldwin universal test machine and a large cryostat were used (Figure 26). In all other respects the usual straining procedures were followed.

After being strained, the specimens were notched as shown in Figure 27. The electrical discharge machining (EDM) process was used for this operation. The machine used was a Cincinnati Milling Machine Company EDM, Model No. 250. The setup for producing the notches is shown in Figure 28.

It was necessary to remove the scale that formed on the notch surfaces during the EDM process by hand filing. After this was done, the notch radii were measured and found to range from 0.003 in. (0.008 cm) to 0.005 in. (0.012 cm). A notch radius of 0.001 in. (0.003 cm) maximum was needed to achieve the desired stress concentration factor (K_t) of 16 or greater (Ref. 12). Therefore, each notch radius was hand dressed to 0.001 in. (0.003 cm).

A Bausch & Lomb 20-inch (50.8 cm) optical comparator, Model No. 38-13-20 was used to measure critical dimensions of the notched specimens. The dimensions

Table 13 - Test Schedule, Task VIII Toughness Test Series

Material condition	Aging treatment			Number of specimens		
	Temperature		Time (hours)	Unnotched tensile *	Notched tensile	Fracture toughness
	°F	°K				
Baseline Conditions						
SRH 1050	-		-	1	-	-
SRH 950	-		-	1	-	-
Strained at RT						
10%	900	756	1	1	2	2
15%	900	756	1	1	2	2
Strained at -320°F (78°K) 10% Level A-A	800	700	1	1	2	2
	800	700	4			
	800	700	8			
	900	756	1			
	900	756	2			
	900	756	4			
	900	756	8			
	950	783	1			
	950	783	4			
	950	783	8	1	2	2
Strained at -320°F (78°K) 15% Level B-B	800	700	1	1	2	2
	800	700	4			
	800	700	8			
	900	756	1			
	900	756	2			
	900	756	4			
	900	756	8			
	950	783	1			
	950	783	4			
	950	783	8	1	2	2

*Aged with the notched specimens to serve as control specimens.

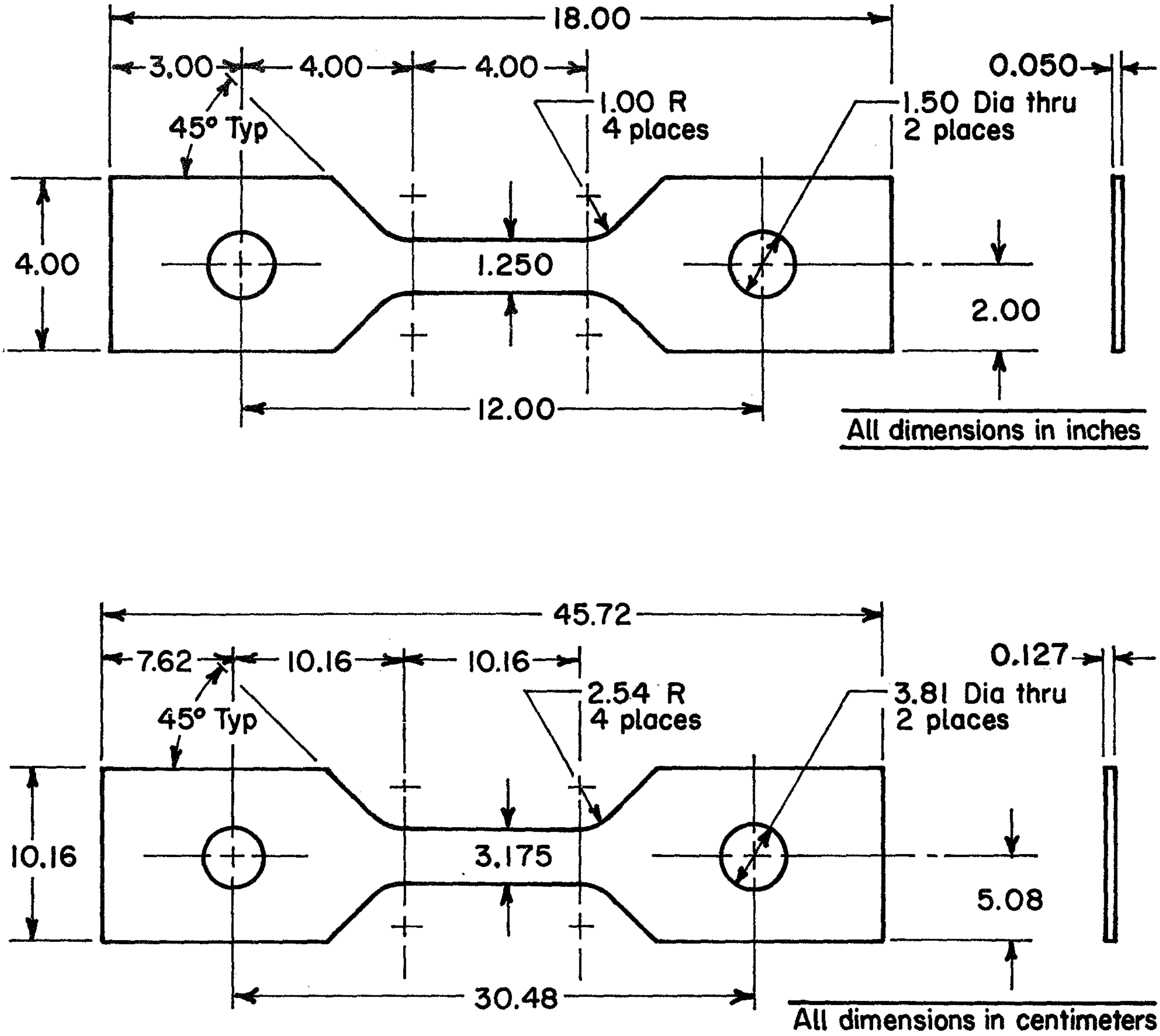


Figure 25 Configuration of Straining Blank for Notched Tensile Specimen

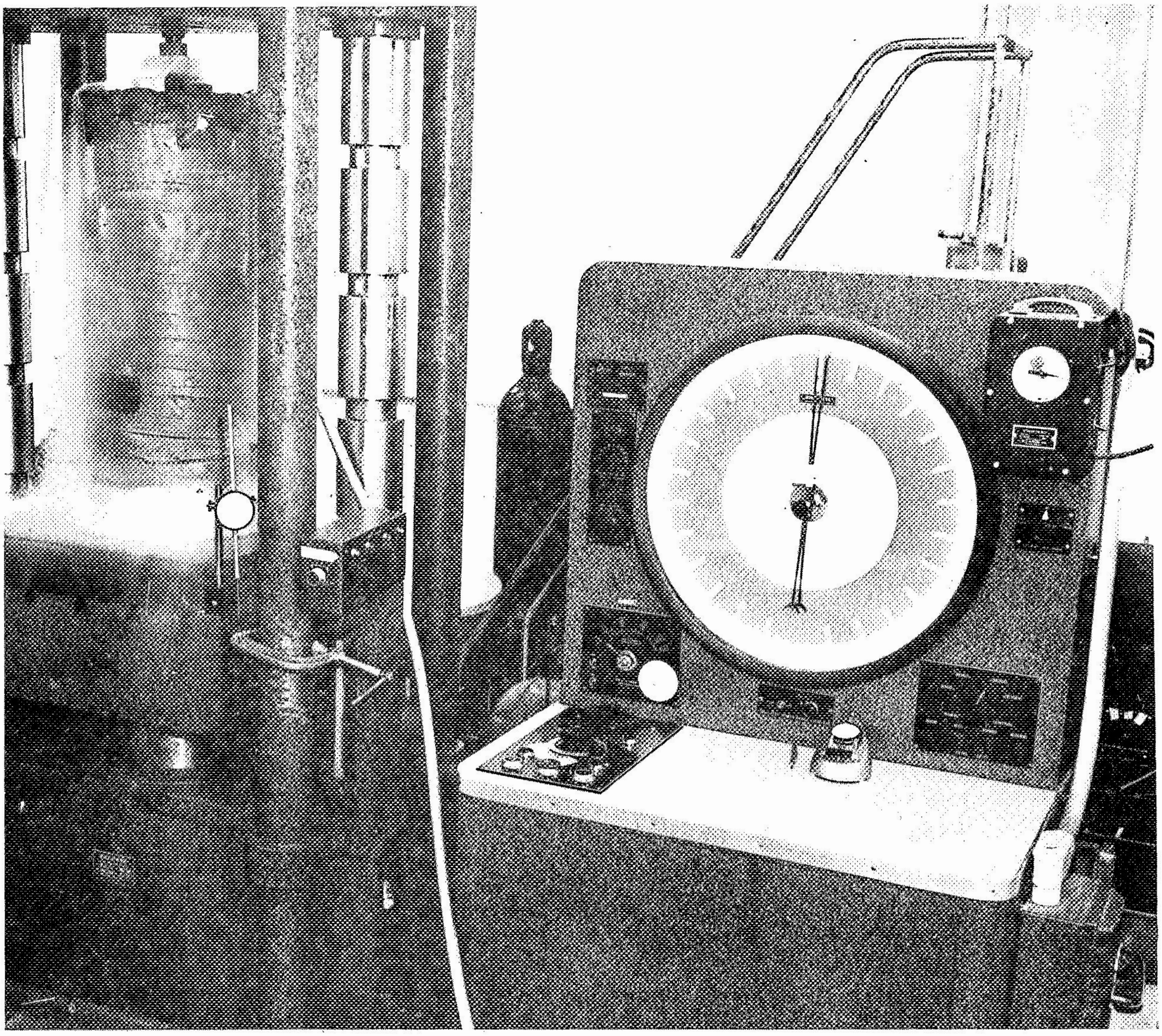


Figure 26 Setup for Straining the Notched Tensile and Toughness Blanks

measured (at 20X magnification) on each specimen were:

1. The width of the specimen at the notches.
2. The depth of both notches.
3. The distance between the two notches.
4. The radius of each notch.

The specimens were then tested to failure in tension at room temperature. The properties measured were ultimate tensile strength, and elongation in 2 inches (5.08 cm).

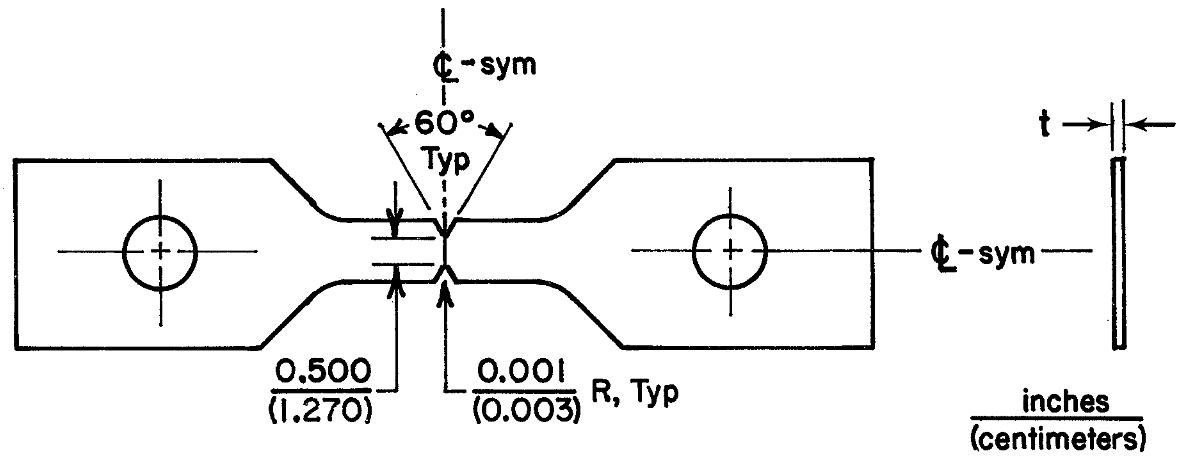


Figure 27 Configuration of Notched Tensile Specimen

Center Cracked Tests: The specimens strained to the 10 percent and 15 percent strain levels at room temperature and to the 10 percent level at -320°F (78°K) (Table 13) were of the type shown in Figure 28. Doublers were required in the grip portions of this type specimen to prevent bearing failure during straining. The doublers were attached by spotwelding. This method of attaching the doublers was satisfactory for room temperature straining and for straining 10 percent at -320°F (78°K). However, to achieve 15 percent strain at -320°F (78°K), it was necessary to use mechanical fasteners (huck-bolts) to attach the doublers, and also to modify the design of the straining specimen. The specimens strained 15 percent at -320°F (78°K) were the type shown in Figure 29.

The strained specimens were made into test specimens of the type shown in Figure 30 (Ref. 13 and 14). These specimens were made by shearing and machining the gage sections of the strained specimens into rectangular blanks 3 inches (7.62 cm) x 12 inches (30.48 cm). The blanks were then identified and appropriately aged (Table 13). Next, three holes, as shown in Figure 30, were added by the EDM process. Then, after the holes had been hand dressed to remove scale formed during the EDM operation, the center notches were extended by fatigue cracking. For this purpose the specimens were loaded in axial tension in a Baldwin universal fatigue testing machine, Type SF-10-4, 10 000 lb (44 500 N) capacity.

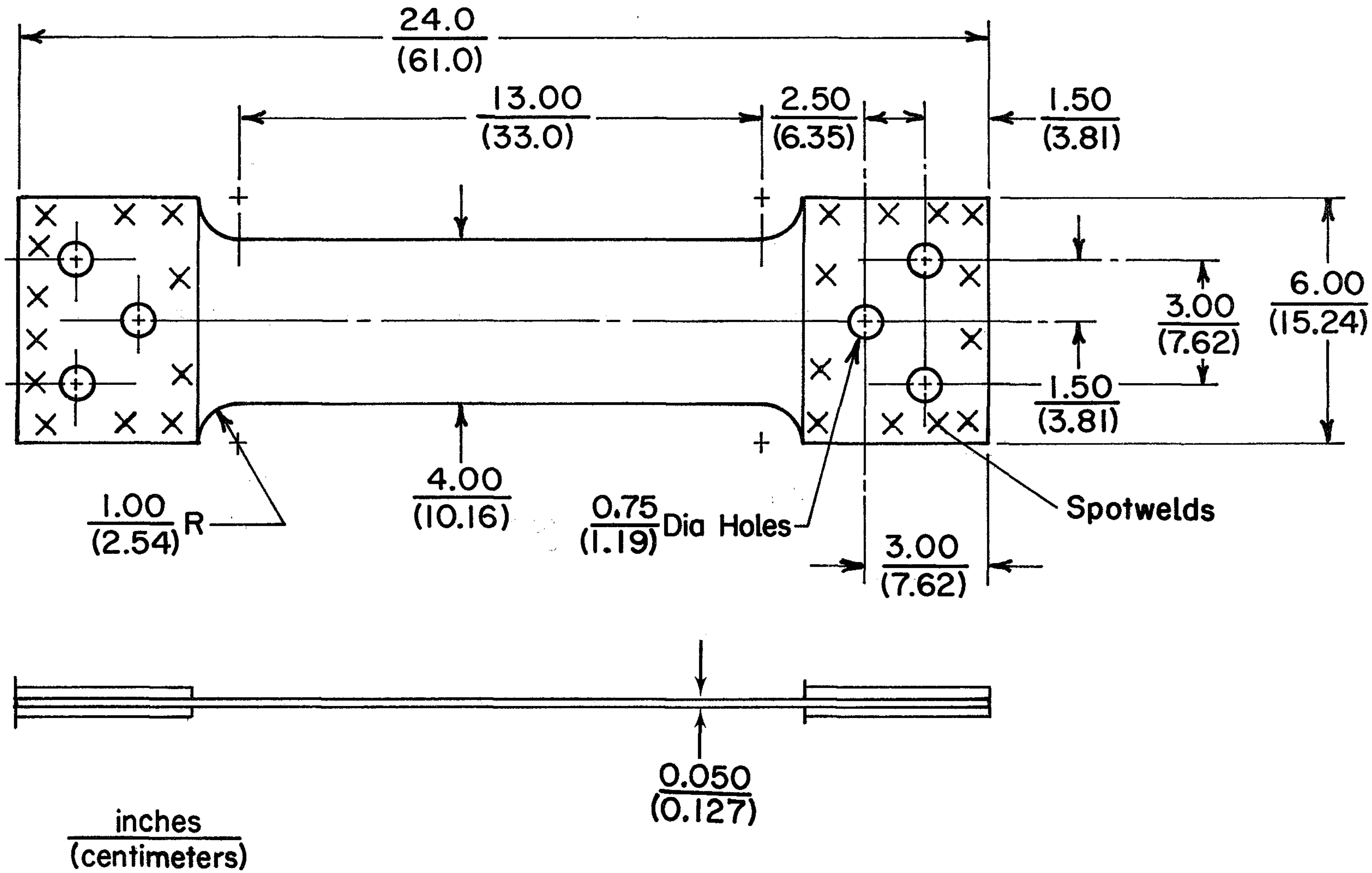


Figure 28 Configuration of the Center-Cracked Specimen Straining Blank Strained 10% and 15% at Room Temperature and 10% at -320°F (78°K)

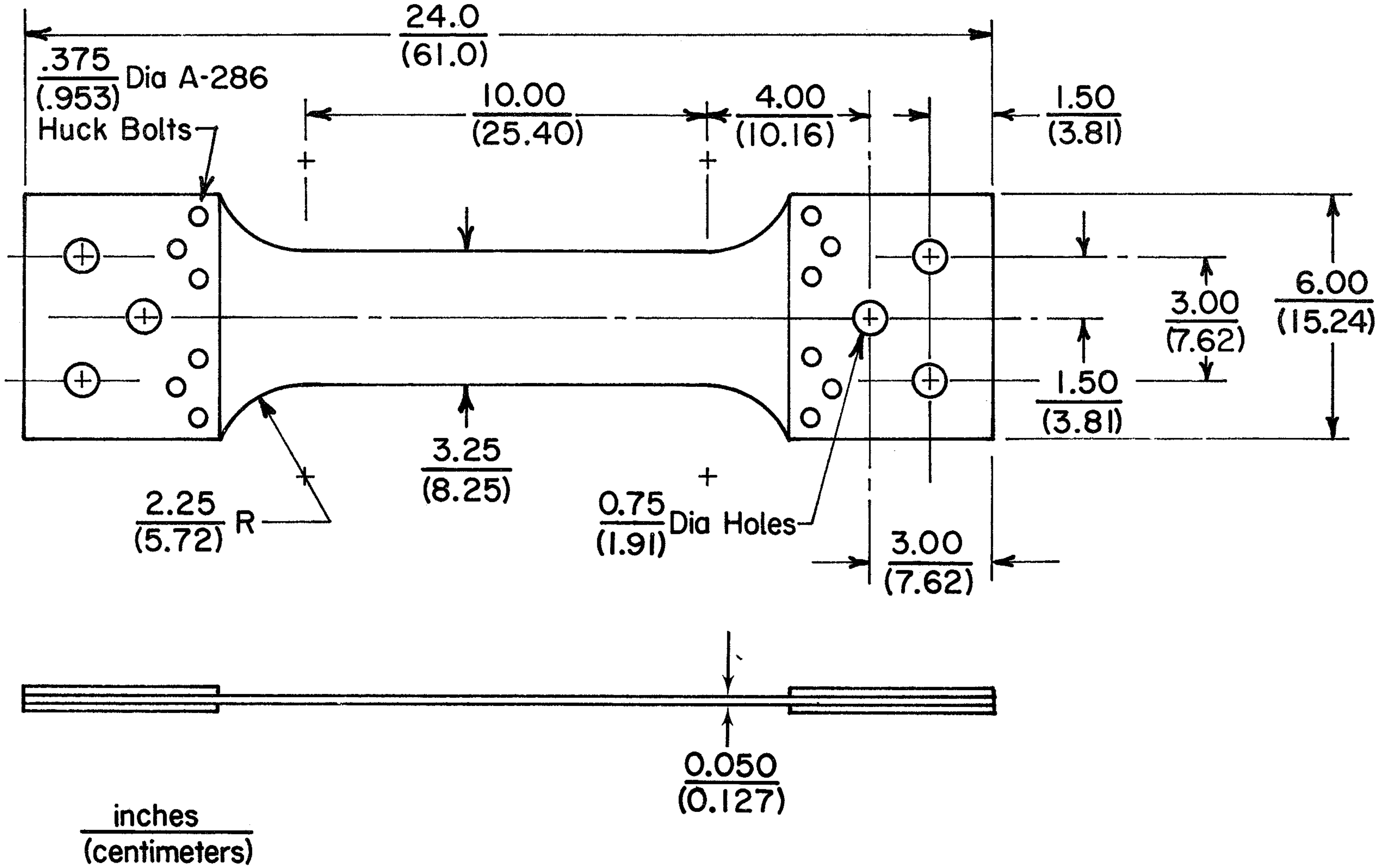


Figure 29 Configuration of the Center-Cracked Specimen Straining Blank Strained 15% at -320^{o}F (78^{o}K)

The center cracked specimens were tested on the 150 000 lb (667 500 N) capacity Baldwin universal test machine. An Instron extensometer, G51-13, was used as a compliance gage. This was attached to the specimen, spanning the center crack at its midpoint. Strain was measured over a 0.500 inch (1.27 cm) gage length. An X-Y recorder was used to autographically plot a load-strain curve for each test.

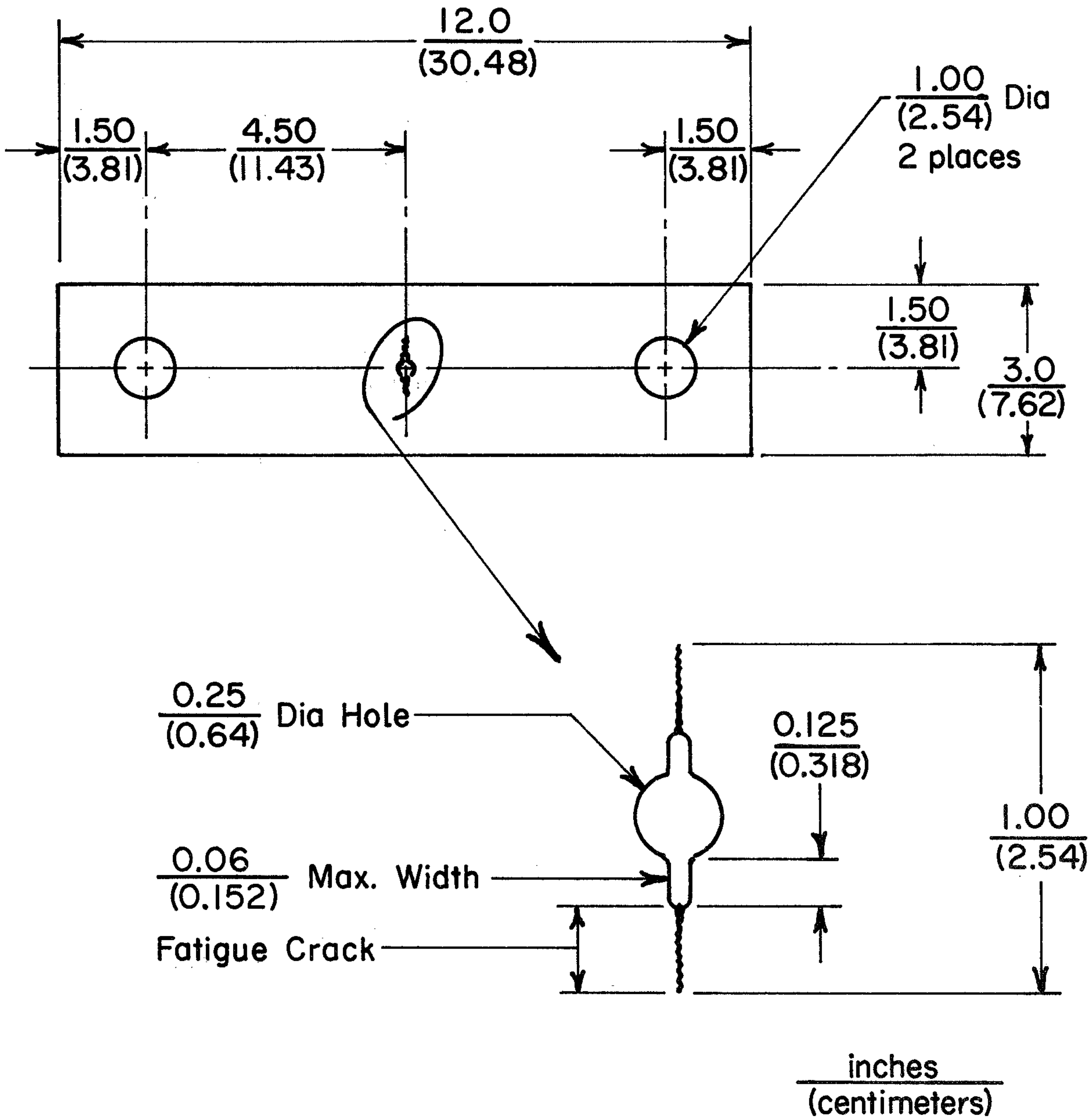


Figure 30 Configuration of the Center-Cracked Specimens

STRESS CORROSION TESTS

Purpose: This series of tests was conducted to determine how PH 14-8 Mo in various strained and unstrained conditions was affected by alternate immersion in an aqueous 3.5 percent NaCl solution.

Approach: The stress corrosion test schedule is given in Table 14. Specimens of the PH 14-8 Mo sheet material were prepared in the conditions and quantities indicated and exposed to 500 cycles of alternate immersion in an aqueous 3.5 percent NaCl solution. During each immersion cycle the specimens were submerged in the solution for 10 minutes and out for 50 minutes.

All the specimens exposed to the solution in a stressed condition (Table 14) were so prepared that the outer fiber tensile stress was applied in the long transverse grain direction.

Procedures: Corrosion specimens of room temperature strained and cryostrained material were prepared as follows:

1. 20 blanks of the type shown in Figure 31 were strained to level A-A (target strain 10%) at -320°F (78°K). The usual straining procedures were followed.
2. 20 blanks of the same type were strained to level B-B (target strain 15%) at -320°F (78°K).
3. 2 blanks were strained to level A-A (target strain 10%) at room temperature.
4. 2 blanks were strained to level B-B (target strain 15%) at room temperature.
5. 3 corrosion specimens t x 0.250 inches (0.635 cm) wide x 5.312 inches (13.44 cm) long were made from the gage section of each of the strained blanks (Figure 32).
6. The corrosion specimens were aged in accordance with the Test Schedule (Table 14).

Six corrosion specimens of the type shown in Figure 32 were made from a 3 inch (7.62 cm) x 5.312 inch (13.44 cm) piece of the PH 14-8 Mo sheet material that had been heat treated to the SRH-950 condition. The following heat treatment was used:

> The material was cleaned and coated with Turco Pretreat. It was heated to 1700°F (1200°K) and held at that temperature for one hour, air cooled to room temperature and immediately cooled to -100°F (200°K). It was held at -100°F (200°K) for 8 hours and then aged one hour at 950°F (783°K) and air cooled to room temperature.

Six corrosion specimens of the type shown in Figure 32 were made from a 3 inch (7.62 cm) x 5.312 inch (13.44 cm) piece of the PH 14-8 Mo sheet material that had been heat treated to the SRH-1050 condition. The heat treatment for this material was the same as for the piece heat treated to SRH-950, except that the aging temperature was 1050°F (839°K) rather than 950°F (783°K).

Six corrosion specimens of the type shown in Figure 32 were made from the PH 14-8 Mo Condition A material.

As shown in the test schedule (Table 14) one-third of the total quantity of corrosion specimens were exposed to the corrosive medium in the free, unstressed condition. Specimens of this type were prepared for exposure as follows:

1. The Turco Pretreat used in the heat treating operations was removed from the surfaces of the specimens by hand dressing with a commercial cleanser.
2. The specimens were thoroughly cleaned. The cleaning included vapor degreasing followed by a series of water rinses, then alkaline cleaning and thorough rising in deionized water. The specimens were then thoroughly dried and sealed in plastic envelopes until needed.
3. To prepare them for exposure the specimens were removed from the protective envelopes and, with nylon cord, were suspended from the specimen holding rack of the alternate immersion test machine.

All other corrosion specimens were exposed to the corrosive medium in a stressed state. As indicated in Table 14, one-third of the total quantity of specimens were stressed to 50 percent of tensile yield strength, one-third to 80 percent of tensile yield strength, and exposed in those conditions. To stress the specimens for exposure, they were loaded in four-point bending as shown in Figure 33. Since tensile yield strength varied with strain level and aging treatment, the deflection to develop the required outer fiber stress was calculated for each stressed specimen (Table 14).

These specimens were handled in the same manner as unstressed specimens, through cleaning and protective packaging. Installation of this type of specimen into the four-point loading fixture was accomplished as follows:

1. A fixture and specimen were assembled into the device shown in Figure 34. This device held the fixture in position so that after the dial indicator had been zeroed to the properly positioned but undeflected specimen, the required deflection could be set by adjusting the set-screw activated loading block to the proper position. Deflection was measured with the dial indicator.

Table 14 Test Schedule, Task VIII Stress Corrosion Tests

Material condition	Straining blank N^{o}	Test specimen No.	Aging Treatment: Time (hr)	Aging Treatment: Temperature ^{o}F (^{o}K)	Midpoint deflection: in.	Midpoint deflection: cm	Outer fiber stress: % of tensile yield	Outer fiber stress: psi	Outer fiber stress: N/cm^2
Level A-A strained 10% at -320^{o}F (78^{o}K)	AA-1N	AA-1N-1	1	800 (700)	0	0	0	0	0
		-2	1		0.374	0.950	50	124 000	85 500
		-3	1		0.598	1.52	80	198 000	137 000
	AA-2N	AA-2N-1	1		0	0	0	0	0
		-2	1		0.374	0.950	50	124 000	85 500
		-3	1		0.598	1.52	80	198 000	137 000
	AA-3N	AA-3N-1	4		0	0	0	0	0
		-2	4		0.405	1.03	50	134 000	92 500
		-3	4		0.646	1.64	80	214 000	148 000
	AA-4N	AA-4N-1	4		0	0	0	0	0
		-2	4		0.405	1.03	50	134 000	92 500
		-3	4		0.646	1.64	80	214 000	148 000
	AA-5N	AA-5N-1	8		0	0	0	0	0
		-2	8		0.405	1.03	50	134 000	92 500
		-3	8		0.646	1.64	80	214 000	148 000
	AA-6N	AA-6N-1	8		0	0	0	0	0
		-2	8		0.405	1.03	50	134 000	92 500
		-3	8	800 (700)	0.646	1.64	80	214 000	148 000
	AA-7N	AA-7N-1	1	900 (756)	0	0	0	0	0
		-2	1		0.405	1.03	50	134 000	92 500
		-3	1		0.646	1.64	80	214 000	148 000
	AA-8N	AA-8N-1	1		0	0	0	0	0
		-2	1		0.405	1.03	50	134 000	92 500
		-3	1		0.646	1.64	80	214 000	148 000
	AA-9N	AA-9N-1	2		0	0	0	0	0
		-2	2		0.411	1.04	50	136 000	93 700
		-3	2		0.658	1.67	80	218 000	150 000
	AA-10N	AA-10N-1	2		0	0	0	0	0
		-2	2		0.411	1.04	50	136 000	93 800
		-3	2		0.658	1.67	80	218 000	150 000
	AA-11N	AA-11N-1	4		0	0	0	0	0
		-2	4		0.414	1.05	50	137 000	94 500
		-3	4		0.661	1.68	80	219 000	151 000
	AA-12N	AA-12N-1	4		0	0	0	0	0
		-2	4		0.414	1.05	50	137 000	94 500
		-3	4		0.661	1.68	80	219 000	151 000
	AA-13N	AA-13N-1	8		0	0	0	0	0
		-2	8		0.417	1.06	50	138 000	95 100
		-3	8		0.667	1.70	80	221 000	152 000
	AA-14N	AA-14N-1	8		0	0	0	0	0
		-2	8		0.417	1.06	50	138 000	95 100
		-3	8	900 (756)	0.667	1.70	80	221 000	152 000
	AA-15N	AA-15N-1	1	950 (783)	0	0	0	0	0
		-2	1		0.423	1.07	50	140 000	96 500
		-3	1		0.676	1.72	80	224 000	155 000
	AA-16N	AA-16N-1	1		0	0	0	0	0
		-2	1		0.423	1.07	50	140 000	96 500
		-3	1		0.676	1.72	80	224 000	155 000
	AA-17N	AA-17N-1	4		0	0	0	0	0
		-2	4		0.417	1.06	50	138 000	95 100
		-3	4		0.664	1.68	80	220 000	152 000
	AA-18N	AA-18N-1	4		0	0	0	0	0
		-2	4		0.417	1.06	50	138 000	95 100
		-3	4		0.664	1.68	80	220 000	152 000
	AA-19N	AA-19N-1	8		0	0	0	0	0
		-2	8		.408	1.04	50	135 000	93 100
		-3	8		0.652	1.66	80	216 000	149 000
	AA-20N	AA-20N-1	8		0	0	0	0	0
		-2	8		0.408	1.04	50	135 000	94 000
		-3	8	950 (783)	0.652	1.66	80	216 000	149 000

Table 14 (cont)

Material condition	Straining blank No.	Test specimen No.	Aging Treatment: Time (hr)	Aging Treatment: Temperature °F (°K)	Midpoint deflection: in.	Midpoint deflection: cm	Outer fiber stress: % of tensile yield	Outer fiber stress: psi	Outer fiber stress: N/cm²
Level B-B strained 15% at -320°F (78°K)	BB-1N	BB-1N-1	1	800 (700)	0	0	0	0	0
		-2	1		0.487	1.24	50	157 000	108 000
		-3	1		0.781	1.98	80	252 000	174 000
	BB-2N	BB-2N-1	1		0	0	0	0	0
		-2	1		0.487	1.24	50	157 000	108 000
		-3	1		0.781	1.98	80	252 000	174 000
	BB-3N	BB-3N-1	4		0	0	0	0	0
		-2	4		0.498	1.25	50	159 000	110 000
		-3	4		0.787	2.00	80	254 000	175 000
	BB-4N	BB-4N-1	4		0	0	0	0	0
		-2	4		0.493	1.25	50	159 000	110 000
		-3	4		0.787	2.00	80	254 000	175 000
	BB-5N	BB-5N-1	8		0	0	0	0	0
		-2	8		0.527	1.34	50	170 000	117 000
		-3	8		0.843	2.14	80	272 000	188 000
	BB-6N	BB-6N-1	8		0	0	0	0	0
		-2	8		0.527	1.34	50	170 000	117 000
		-3	8	800 (700)	0.843	2.14	80	272 000	188 000
	BB-7N	BB-7N-1	1	900 (756)	0	0	0	0	0
		-2	1		0.474	1.20	50	153 000	106 000
		-3	1		0.760	1.93	80	245 000	169 000
	BB-8N	BB-8N-1	1		0	0	0	0	0
		-2	1		0.474	1.20	50	153 000	106 000
		-3	1		0.760	1.93	80	245 000	169 000
	BB-9N	BB-9N-1	2		0	0	0	0	0
		-2	2		0.515	1.31	50	166 000	115 000
		-3	2		0.828	2.10	80	267 000	184 000
	BB-10N	BB-10N-1	2		0	0	0	0	0
		-2	2		0.515	1.31	50	166 000	115 000
		-3	2		0.828	2.10	80	267 000	184 000
	BB-11N	BB-11N-1	4		0	0	0	0	0
		-2	4		0.499	1.27	50	161 000	111 000
		-3	4		0.800	2.03	80	258 000	178 000
	BB-12N	BB-12N-1	4		0	0	0	0	0
		-2	4		0.499	1.27	50	161 000	111 000
		-3	4		0.800	2.03	80	258 000	178 000
	BB-13N	BB-13N-1	8		0	0	0	0	0
		-2	8		0.487	1.24	50	157 000	108 000
		-3	8		0.781	1.98	80	252 000	174 000
	BB-14N	BB-14N-1	8		0	0	0	0	0
		-2	8		0.487	1.24	50	157 000	108 000
		-3	8	900 (756)	0.781	1.98	80	252 000	174 000
	BB-15N	BB-15N-1	1	950 (783)	0	0	0	0	0
		-2	1		0.508	1.29	50	164 000	113 000
		-3	1		0.812	2.03	80	262 000	181 000
	BB-16N	BB-16N-1	1		0	0	0	0	0
		-2	1		0.508	1.29	50	164 000	113 000
		-3	1		0.812	2.03	80	262 000	181 000
	BB-17N	BB-17N-1	4		0	0	0	0	0
		-2	4		0.496	1.26	50	160 000	110 000
		-3	4		0.797	2.02	80	257 000	176 000
	BB-18N	BB-18N-1	4		0	0	0	0	0
		-2	4		0.496	1.26	50	160 000	110 000
		-3	4		0.797	2.02	80	257 000	176 000
	BB-19N	BB-19N-1	8		0	0	0	0	0
		-2	8		0.484	1.23	50	156 000	108 000
		-3	8		0.775	1.97	80	250 000	172 000
	BB-20N	BB-20N-1	8		0	0	0	0	0
		-2	8		Pin Hole Failure - Straining				
		-3	8	950 (783)					

Table 14 (concl)

Material condition	Straining blank No.	Test specimen No.	Aging treatment: Time (hr)	Aging treatment: Temperature °F (°K)	Midpoint deflection: in.	Midpoint deflection: cm	Outer fiber stress: % of tensile yield	Outer fiber stress: /Psi	Outer fiber stress: N/cm²
Condition A	N/A	XX-1	N/A	N/A	0	0	0	0	0
		-2			0.081	0.203	50	28 500	19 700
		-3			0.129	0.327	80	45 500	32 100
		-4			0	0	0	0	0
		-5			0.081	0.203	50	28 500	19 700
		-6			0.129	0.327	80	45 500	32 100
SRH 950	N/A	S9-1			0	0	0	0	0
		-2			0.291	0.738	50	102 000	70 400
		-3			0.465	1.18	80	163 000	112 000
		-4			0	0	0	0	0
		-5			0.291	0.738	50	102 000	70 400
		-6			0.465	1.18	80	163 000	112 000
SRH 1050	N/A	S1-1			0	0	0	0	0
		-2			0.276	0.700	50	97 000	67 000
		-3			0.439	1.12	80	154 000	106 000
		-4			0	0	0	0	0
		-5			0.276	0.700	50	97 000	67 000
		-6	N/A	N/A	0.439	1.12	80	154 000	106 000
Level A-A strained 10% at room temperature	AA-1R	AA-1R-1	1	900 (756)	0	0	0	0	0
		-2	1		0.217	0.550	50	70 000	48 300
		-3	1		0.347	0.880	80	112 000	72 200
	AA-2R	AA-2R-1	1		0	0	0	0	0
		-2	1		0.217	0.550	50	70 000	48 300
		-3	1		0.347	0.880	80	112 000	72 200
Level BB strained 15% at room temperature	BB-1R	BB-1R-1	1		0	0	0	0	0
		-2	1		0.298	0.756	50	96 000	66 200
		-3	1		0.474	1.20	80	153 000	105 000
	BB-2R	BB-2R-1	1		0	0	0	0	0
		-2	1		0.298	0.756	50	96 000	66 200
		-3	1	900 (756)	0.474	1.20	80	153 000	105 000

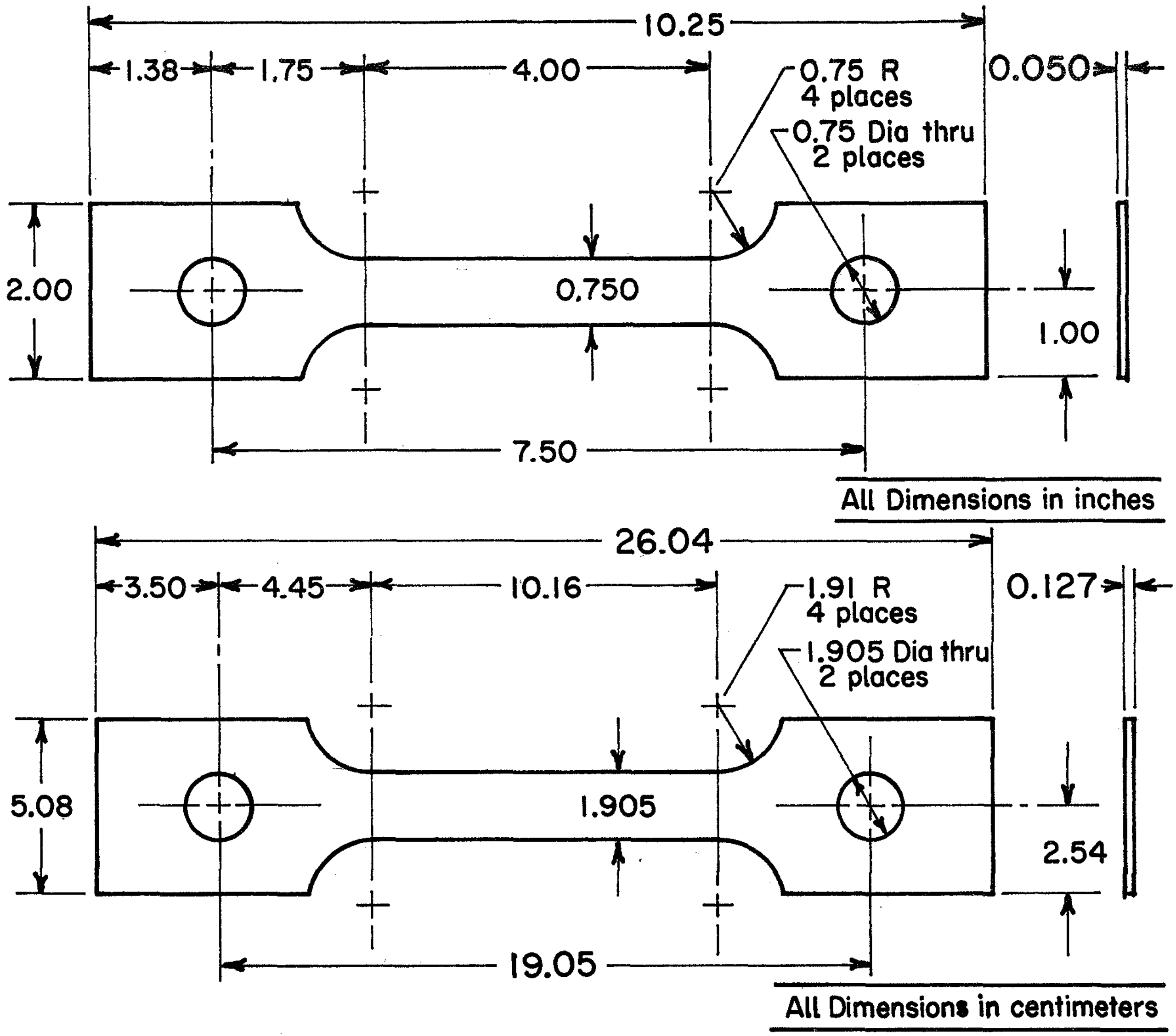


Figure 31 Configuration of the Straining Blank for the Stress Corrosion Specimens

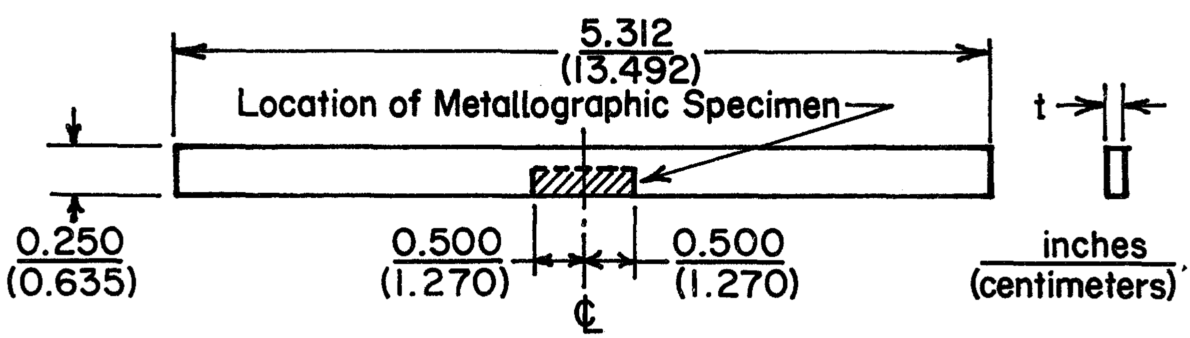
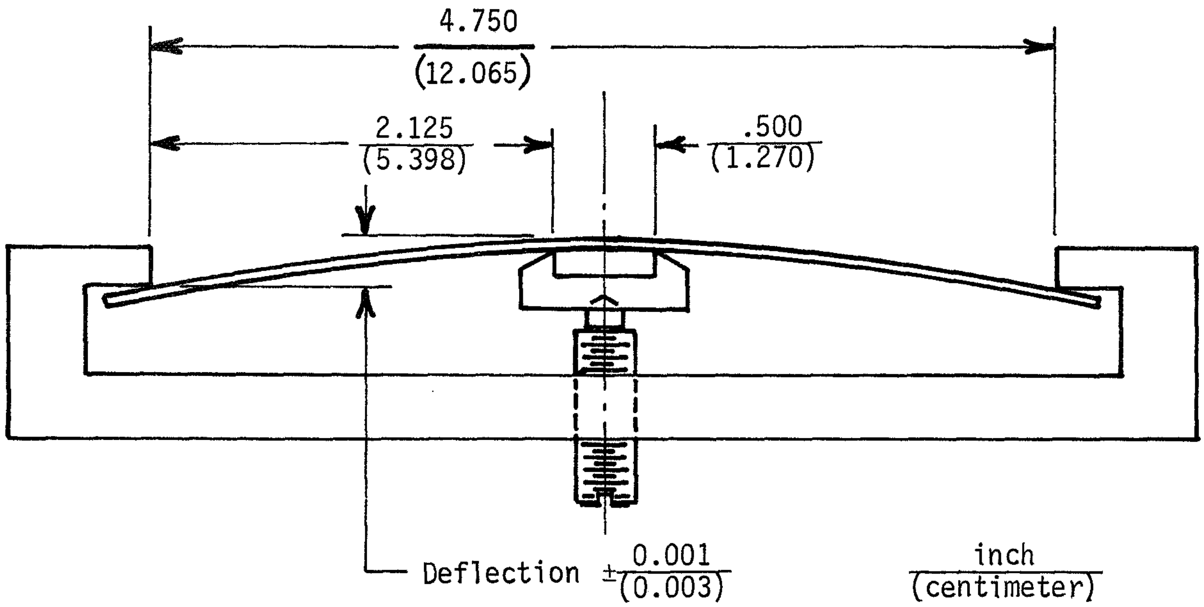


Figure 32 Configuration of Stress Corrosion Specimens



$$\text{*Deflection (max)} = \frac{\sigma}{3Et}\left(3/4\ \ell^2 - a^2\right)$$

Where:

σ = Outer fiber stress.

t = Thickness.

a = Distance from load point to support = 2.125 inches (5.398 cm).

E = Modulus of Elasticity = 29 x 10^6 psi (20 x 10^6 N/cm^2)

ℓ = Length between supports = 4.750 inches (12.065 cm).

* Reference: *New Departure Handbook, Vol II.* Seventh Edition.

Stress Corrosion Specimen Assembled in Fixture

Figure 33 The Method and Fixture Design Used to Apply Load to Stress Corrosion Specimens

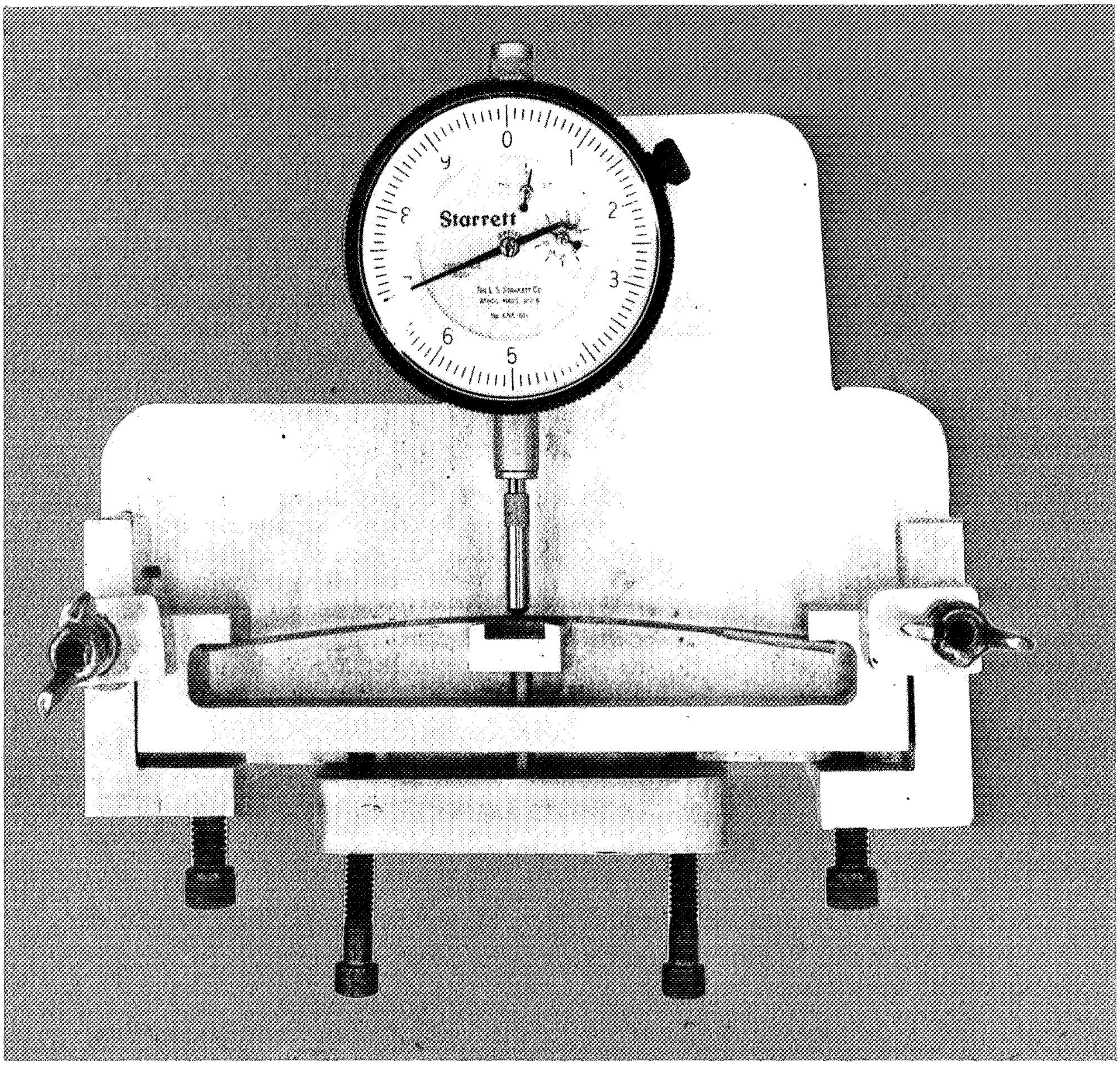


Figure 34 The Device and Method Used to Deflect the Stress Corrosion Specimens

2. Before a specimen was installed into a loading fixture, Mylar tape was applied to both ends of the specimen, and to the load points on the fixture and loading block. This was done to prevent dissimilar metal contact. After a specimen had been properly deflected, a butyl rubber maskent was applied to all surfaces of the fixture, set screw, and loading block, including those locations where the specimen contacted the loading block and the fixture. All unnecessary maskent was subsequently removed from the specimen, after which the specimen was cleaned with MEK and wiped dry.

The fixtured specimens were suspended from the specimen loading rack of the alternate immersion machine with nylon cord.

The alternate immersion machine (Fig. 35) consisted of a frame to which were mounted two butyl rubber lined tanks containing the NaCl solution; a rack from which the specimens were suspended; a pneumatic cylinder to actuate the rack; and an electric timer actuated 4-way cylinder valve. The timer was adjusted so that for 10 minutes of each hour the cylinder was held in the downstroke position, and the specimens were completely submerged in the solution. For the remainder of each hour the cylinder was in the retracted position, holding the specimens suspended above the solution.

The solution was made of reagent grade NaCl salt and deionized water. The specific gravity of the solution was adjusted to 1.023. The specific gravity was tested daily, and additionally, whenever water was added to maintain the proper level in the tanks. All specimens were removed from test after 523 hours. Each specimen was cleaned, examined, and observations were recorded. Sections were removed from selected specimens, as indicated in Figure 32, mounted in bakelite, ground, polished, etched, and examined at magnifications to 500X on a Balfont optical metallograph.

HIGH ENERGY RATE STRAINING TESTS

Purpose: This series of tests was conducted to develop data by which to compare the room temperature tensile properties developed by PH 14-8 Mo through cryostraining and room temperature straining in:

1. Uniaxial tension at a strain rate of 0.050 in./in./min (0.050 cm/cm/min) (Task VI).
2. Roll straining (Task VI).
3. Uniaxial tension at a strain rate of 1.5 in./in./min (1.5 cm/cm/min) (Task VII).
4. Tension when strained by a high energy rate (explosive) method.

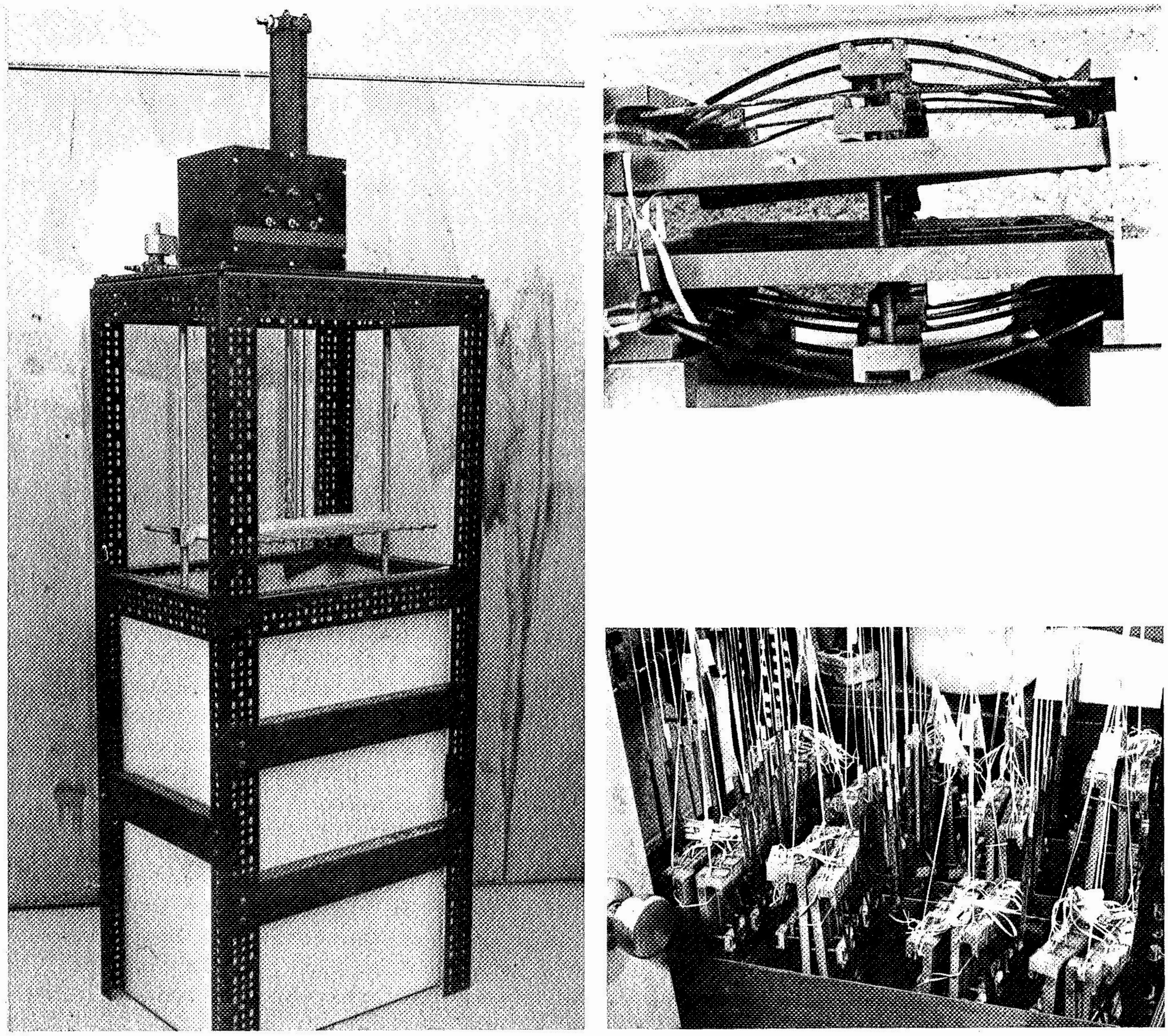


Figure 35 The Alternate Immersion Machine Specimens and Setups Used in the Stress Corrosion Tests

Approach: Pieces of the PH 14-8 Mo sheet were explosively formed into a die having a rectangular, flat bottomed cavity. The dimensions of the cavity were 4 in. (10.16 cm) wide, 6 in. (15.24 cm) long, and 1.38 in. (3.51 cm) deep. Samples of PH 14-8 Mo were explosively formed in the die at both room temperature and at -320°F (78°K). Tensile specimens of the type shown in Figure 1 were then made from the strained material. These were aged one hour at 900°F (756°K) and tested to failure at room temperature.

Procedures: Room temperature straining: The straining blanks used in the room temperature high energy rate straining tests were 8.5 in. (21.6 cm) x 12 in. (30.48 cm) x t. The standard grid pattern was applied to one surface of each blank.

The sequence of operations for forming the PH 14-8 Mo sheet at room temperature was:

1. The blank was placed in position over the die cavity, with the gridded side of the blank facing the bottom of the die cavity.
2. A rectangular holding plate, with a rectangular opening having the same peripheral dimensions as the die cavity, was placed on the blank and bolted to the die, as shown in Figure 36. Each holddown bolt was torqued to 500 in.-lb (56.6 joules).
3. A 325 grain (0.020 kg), hemispherically shaped charge of A3 explosive (93% RDX, 7% wax) was positioned over the geometric center of the blank. Cardboard supports were used to hold the charge in position at the established standoff distance, 4.5 in. (11.4 cm) above the surface of the blank (Figure 36).
4. The die, blank, and charge assembly was then lowered into the forming pool, the die cavity was evacuated, and the charge was detonated. The assembly was then removed from the pool, inspected, and the bolts were checked and retightened if necessary. Another 325 grain (0.020 kg) charge was then installed at the same standoff distance as the first. Then, after the assembly had been submerged in the pool and the die cavity evacuated, the charge was detonated.

As shown in Figure 37 the two-shot forming sequence was necessary to strain the material properly. Even so, cracking did occur at the corners. However, the stock from which the tensile specimens were made (the material in contact with the flat bottom of the die cavity) did strain uniformly in the long [6 in. (15.24 cm)] direction.

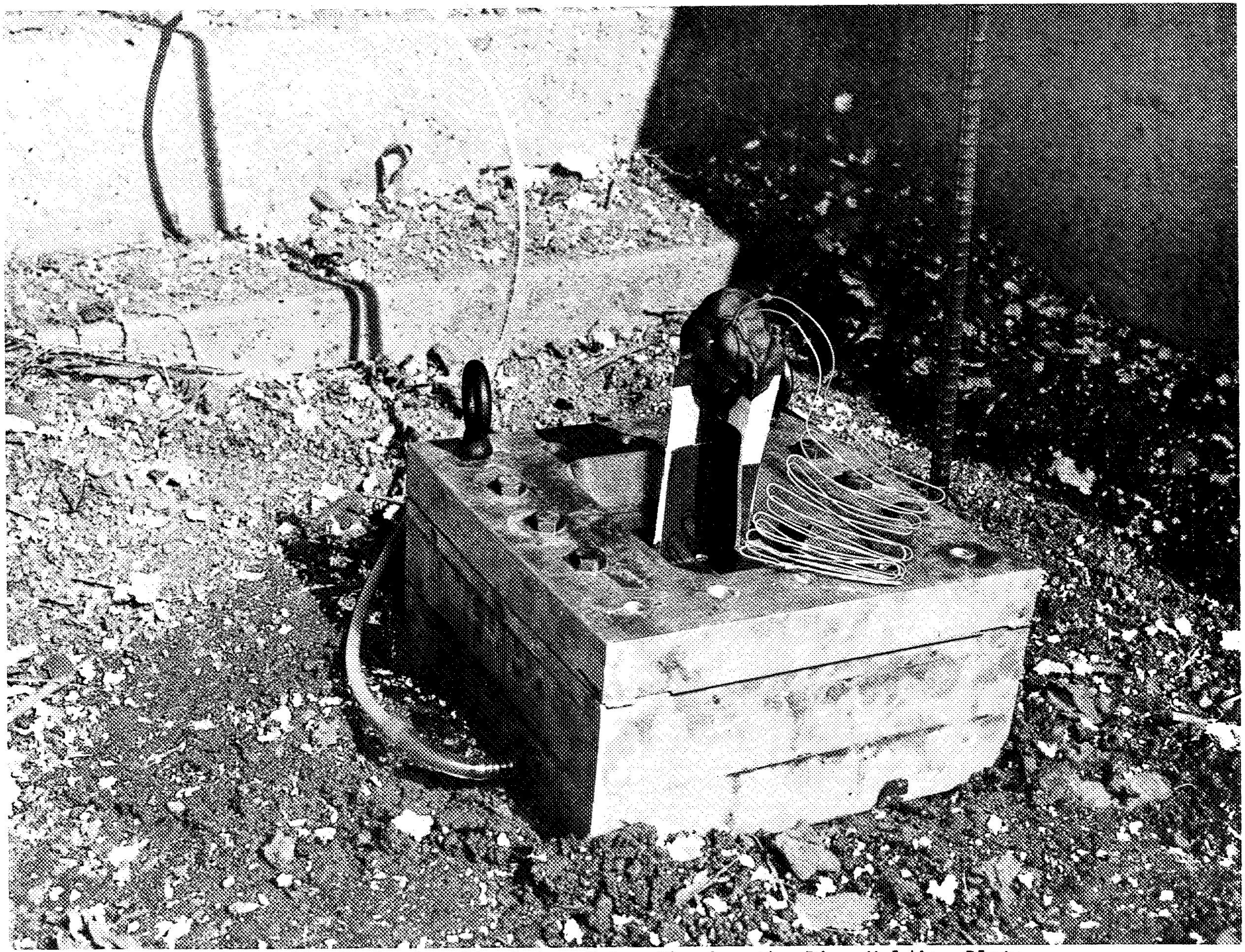


Figure 36 Explosive Straining Setup Showing the Die, Holding Plate, and Positioning of Charge

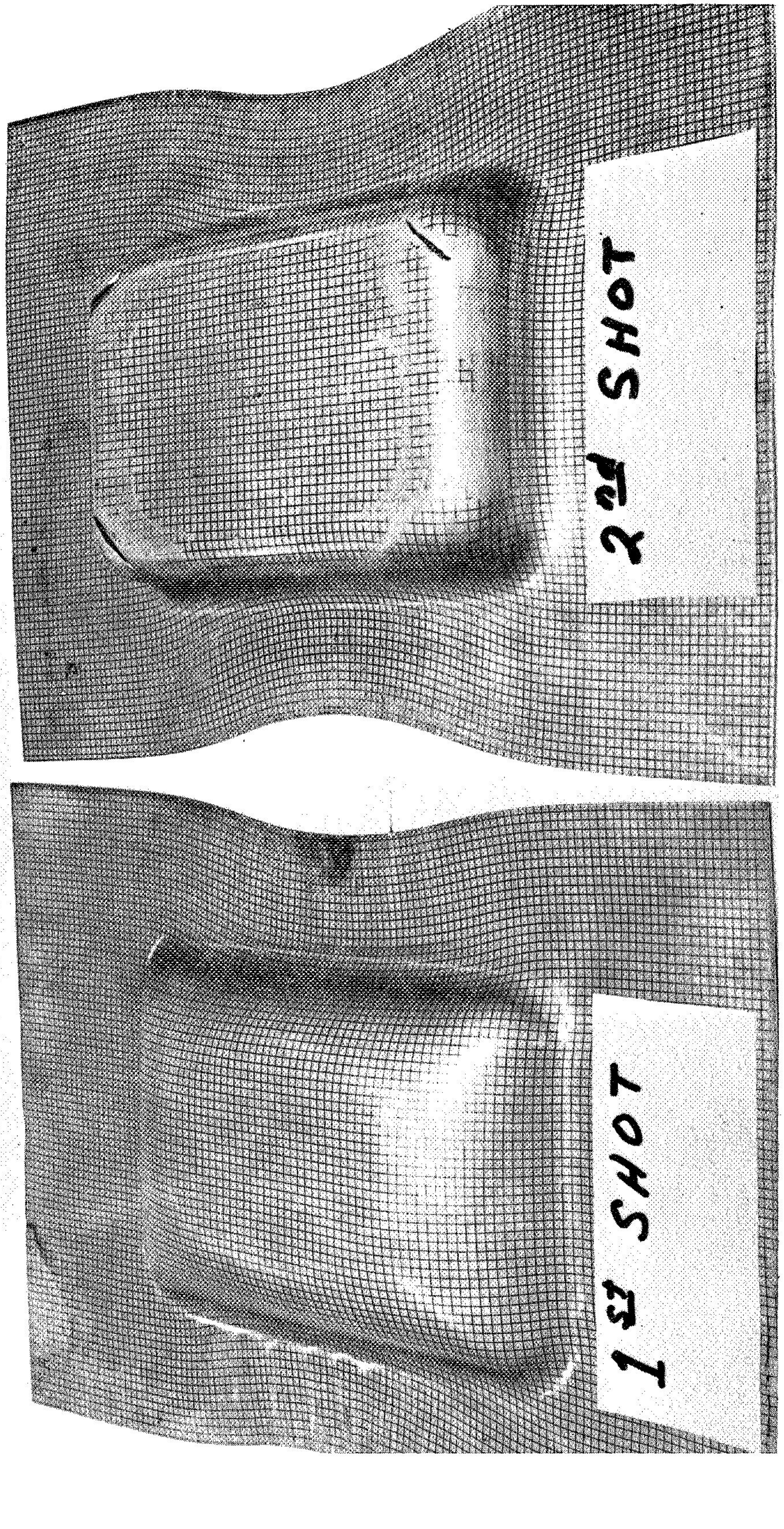


Figure 37 Explosively Strained Blanks after the First and Second Shots

The same die and holddown plate used in the room temperature straining operations were used to strain the PH 14-8 Mo sheet at -320°F (78°K). However, it was necessary to use a straining blank 12 inches (30.5 cm) square to get the material to draw properly. It was also necessary to increase the torque on the holddown bolts to 100 ft-lb (136 joules) to prevent excessive buckling of the flange material. And, to get reliable detonation of the blasting caps and explosive charges, it was necessary to insulate them from the LN_2 in which they were immersed. Since the insulation decreased the efficiency of the charge, it was necessary to use larger charges for both shots. The size of the charge for first shots were increased to 1100 grains (0.066 kg) of A3 explosive, and for second shots a 900 grain (0.054 kg) charge was used. A 4.5 in. (11.4 cm) standoff distance was used for both shots.

Immersion of the die in LN_2 was impractical and unnecessary. The method used is shown in Figures 38 and 39. An expendable styrofoam cylinder was attached to the die to form an open-top container above the PH 14-8 Mo blank. LN_2 was fed into the container from a shielded pressurized dewar until the explosive charge was submerged in LN_2. The flow of LN_2 was maintained until rapid boiloff stopped. The LN_2 supply hose was then removed and the charge was detonated.

Specimens of the type shown in Figure 1 were made from the strained blanks. These were aged for one hour at 900°F (756°K) and then tensile tested to failure at room temperature.

COMPRESSION TESTS

Purpose: This series of tests was conducted to determine how the room temperature compressive yield strength of the PH 14-8 Mo annealed sheet material was affected when the material was prestrained in uniform uniaxial tension at -320°F (78°K) or at room temperature.

Approach: The test schedule for the Task VIII compression test series is shown in Table 15. One hundred twenty-eight straining blanks of the type shown in Figure 40 were strained, 64 at room temperature and 64 at -320°F (78°K). After being strained, 40 of the blanks were made into tensile specimens of type shown in Figure 1. The remaining blanks were made into compression specimens of the type shown in Figure 41. Two compression specimens were made from the gage section of each of these strained blanks. Corresponding tensile and compression specimens were aged together according to the schedule (Table 15), except when, as noted in Table 15, tensile data from the Task VI Parent Metal Test series were used for comparison. After aging, the specimens were tested at room temperature. The tensile tests were conducted in accordance with the provisions and requirements of ASTM-E8-69. The compression tests were conducted in accordance with the provisions and requirements of ASTM-E9-69. A Montgomery-Templin compression fixture, subpress and a Wiedemann Machine Co. compressometer, Model PC-5M were used to conduct the compression tests.

In addition to testing the strained specimens, tensile and compression specimens, made from the PH 14-8 Mo sheet that had been heat treated to the SRH 950 and SRH 1050 conditions were tested as indicated in Table 15.

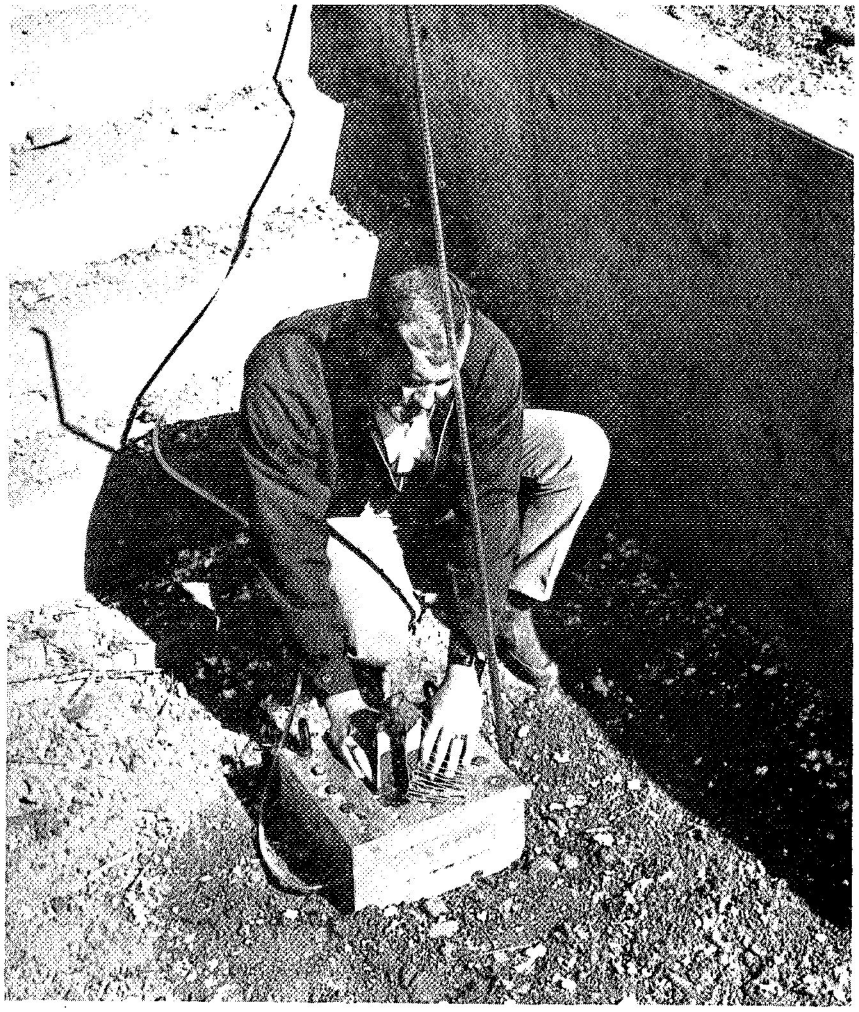


Figure 38 Setting Up the Die and Charge for Explosive Straining Shot at -320°F (78°K)

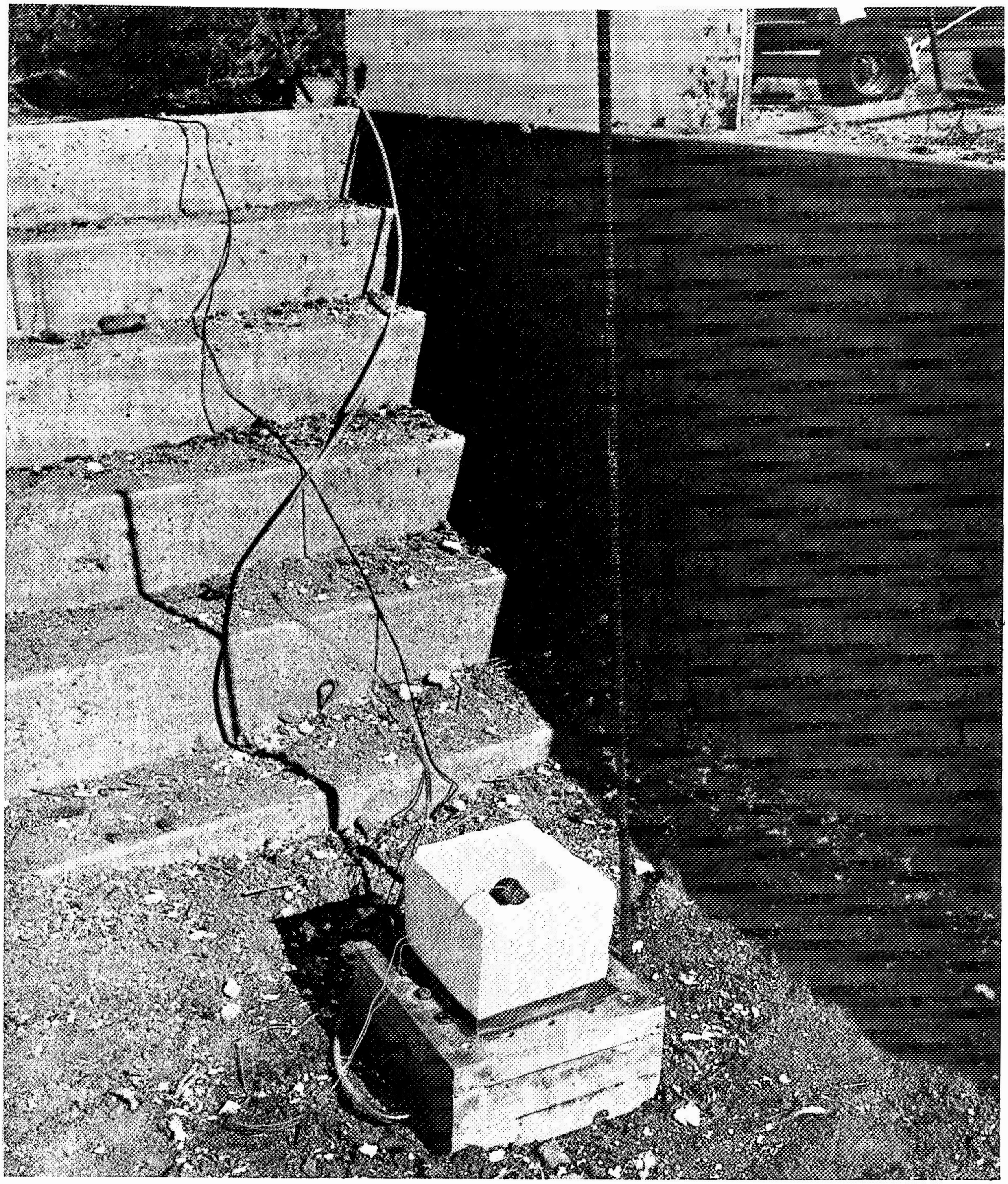


Figure 39 Showing the Styrofoam Container in Position

Table 15. Test Schedule, Task VIII Compression Tests

Straining			Aging			Number of Specimens Tested			
Temperature		Level	Temperature		Time	Compression		Tension	
°F	°K	%	°F	°K	hr	Long	Trans	Long	Trans
RT	RT	8	900	756	1	4	4	*	*
RT	RT	8	900	756	8	4	4	2	2
RT	RT	8	Unaged		---	4	4	*	*
RT	RT	15	900	756	1	4	4	*	*
RT	RT	15	900	756	8	4	4	2	2
RT	RT	15	Unaged		---	4	4	*	*
RT	RT	8	950	783	1	4	4	2	2
RT	RT	8	950	783	8	4	4	2	2
RT	RT	15	950	783	1	4	4	2	2
RT	RT	15	950	783	8	4	4	2	2
-320	78	8	900	756	1	4	4	*	*
-320	78	8	900	756	8	4	4	2	2
-320	78	8	Unaged		---	4	4	*	*
-320	78	15	900	756	1	4	4	*	*
-320	78	15	900	756	8	4	4	2	2
-320	78	15	Unaged		---	4	4	*	*
-320	78	8	950	783	1	4	4	2	2
-320	78	8	950	783	8	4	4	2	2
-320	78	15	950	783	1	4	4	2	2
-320	78	15	950	783	8	4	4	2	2
SRH 950			N/A	N/A	N/A	4	4	2	2
SRH 1050			N/A	N/A	N/A	4	4	2	2

* Data from Task VI Parent Metal Test Series to be used for comparison.

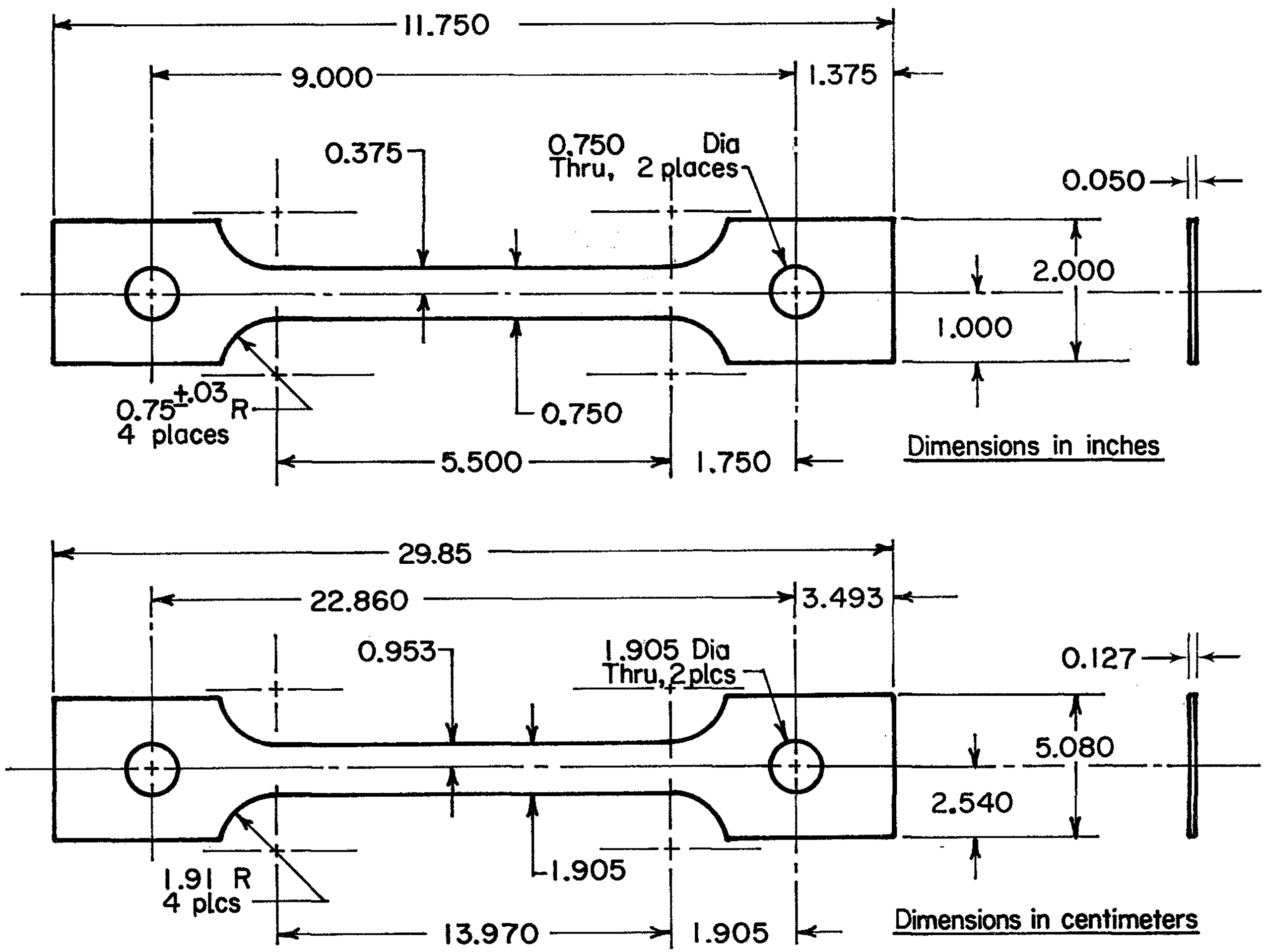


Figure 40 Configuration of the Straining Blanks from Which Compression Specimens Were Made

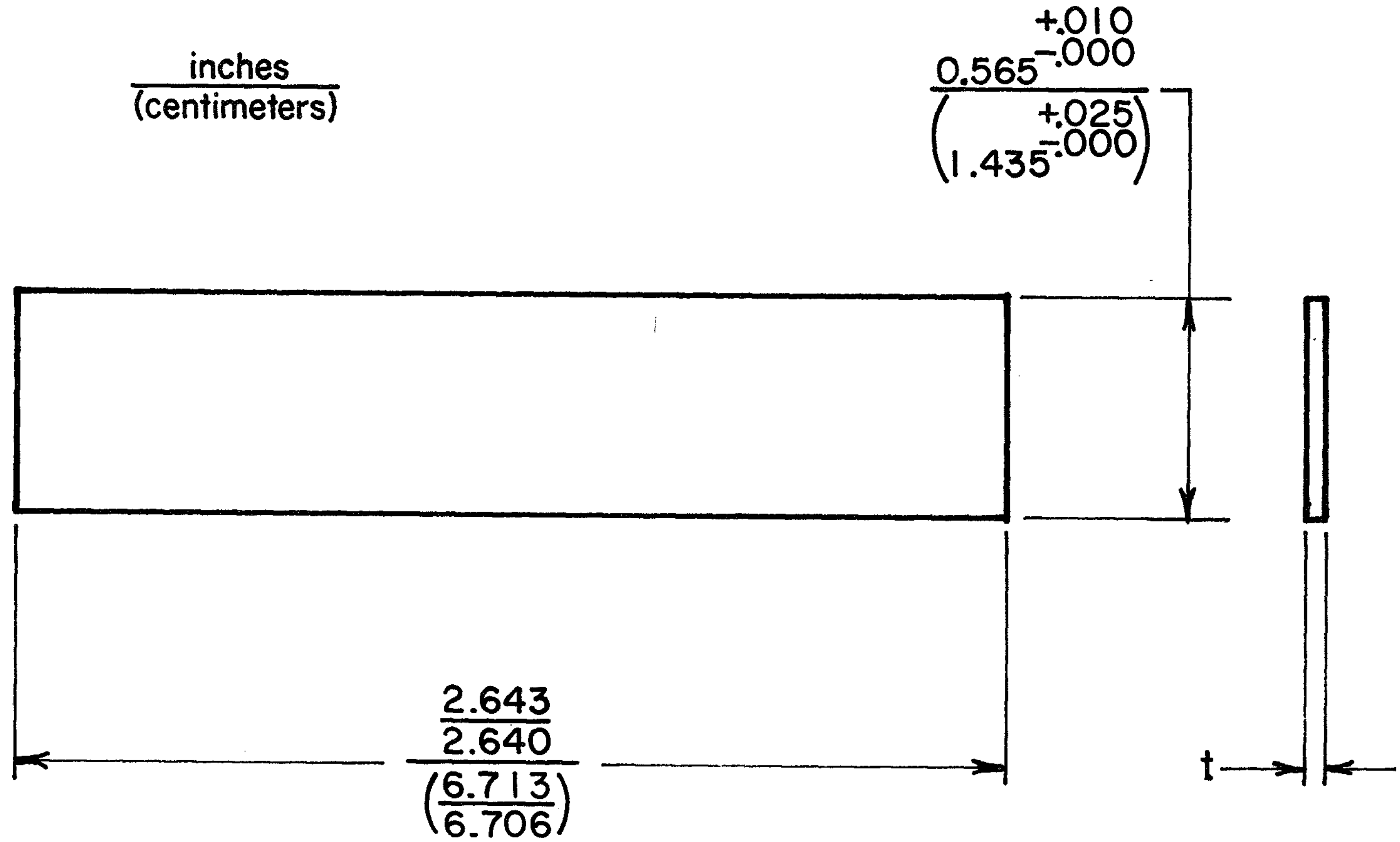


Figure 41 Configuration of the Compression Specimens

V. RESULTS AND DISCUSSION

TASK VI - SELECTION OF A PROMISING ALLOY

Synopsis

Task VI was conducted to develop data by which to compare the three alloys tested with respect to changes in room temperature tensile properties induced by straining at -320° (78°K). The prime objective of the task was to determine through comparative evaluation of the test results, the alloy that should be tested in Tasks VII and VIII. PH 14-8 Mo was chosen for that purpose.

Actually Task VI test results indicated that all three alloys were worthy candidates for continued cryostraining tests. However, based on overall performance, PH 14-8 Mo offered slight advantages over each of the other alloys. From the results of the parent metal test series it was learned that PH 14-8 Mo developed slightly higher tensile strengths for equal prestrains than 17-7 PH. Also, while developing somewhat lower strengths than PH 15-7 Mo for equal prestrains, PH 14-8 Mo did not exhibit the tendency for premature brittle fracture during tensile testing as did PH 15-7 Mo. Additionally, the weldment test results indicated that, as-welded, PH 14-8 Mo has a higher uniform strain capability than PH 15-7 Mo at -320°F (78°K). And, while 17-7 PH and PH 14-8 Mo have equal uniform strain capability, as-welded at -320°F (78°K), the 17-7 PH specimens prestrained at -320°F (78°K) tended to fail prematurely during tensile test. PH 14-8 Mo did not demonstrate the same tendency.

Based on overall performance, PH 14-8 Mo was chosen for testing in Tasks VII and VIII.

Parent Metal Tests

Results: Uniform strain capability (USC) values:

Each alloy had been procured in sheet form, 0.050 in. (0.127 cm) thick, Condition A. Twelve specimens of the type shown in Figure 18 were made from each alloy, six longitudinal, and six long transverse. Three of the longitudinal and three of the long transverse specimens of each alloy were tensile tested to failure at room temperature. The remaining specimens of each alloy were similarly tested at -320°F (78°K). The properties obtained from these tests were: ultimate tensile strength, total elongation (Figure 4) in 2 inches (5.08 cm), and uniform elongation (Figure 4) in 1 inch (2.54 cm). The uniform elongations for each set of three specimens representative of an alloy, grain direction, and test temperature, were averaged.

These average elongation values were designated as uniform strain capability (USC) values. The USC values established for each alloy are listed in Table 16.

Table 16 - USC Values, Task VI, Parent Metal Tests

Alloy	*Grain direction	Temp °F (°K)	Uniform strain capability
PH 14-8 Mo	L	RT	25.0
PH 14-8 Mo	T	RT	25.0
PH 14-8 Mo	L	-320 (78)	20.0
PH 14-8 Mo	T	-320 (78)	21.0
PH 15-7 Mo	L	RT	36.0
PH 15-7 Mo	T	RT	36.0
PH 15-7 Mo	L	-320 (78)	22.0
PH 15-7 Mo	T	-320 (78)	22.0
17-7 PH	L	RT	48.0
17-7 PH	T	RT	48.0
17-7 PH	L	-320 (78)	25.0
17-7 PH	T	-320 (78)	20.0

*L = Longitudinal; T = Long Transverse.

Strain Levels

The USC values were used to compute the strain levels for each alloy, as described in Table 6. The strain levels established in this manner for each alloy are listed in Table 17.

Table 17 - Strain Levels, Task VI, Parent Metal Tests

Alloy	Straining temperature	Strain levels, %							
		A		B		C		D	
		L	T	L	T	L	T	L	T
PH 14-8 Mo	Room temp, and -320°F (78°K)	8.0	8.5	12.0	12.5	15.0	16.0	18.0	19.0
PH 15-7 Mo	Room temp and -320°F (78°K)	9.0	9.0	13.0	13.0	16.5	16.5	20.0	20.0
17-7 PH	Room temp and -320°F (78°K)	10.0	8.0	15.0	12.0	19.0	15.0	22.0	18.0

Room Temperature Tensile Tests of Prestrained Specimens

Room temperature tensile tests were conducted on specimens of each alloy that were prepared and conditioned as indicated in Table 7. The results of these tests are summarized in Figures 42 through 62 and are compiled in Tables 32 thru 34 of the appendix.

Discussion: The parent metal series results confirmed that both PH 15-7 Mo and 17-7 PH, like PH 14-8 Mo, developed significantly higher room temperature tensile strengths when strained at -320°F (78°K) than they did when strained an equal amount at room temperature.

Figures 42 through 50 show the longitudinal and transverse room temperature tensile properties of the three alloys after having been strained at room temperature or -320°F (78°K) and then aged one hour at 900°F (756°K). Two significant facts are evidenced in these plots: first, straining at -320°F (78°K) is a much more effective means of strengthening each of the alloys than is room temperature straining; second, the room temperature tensile properties developed by each alloy are nearly the same in the longitudinal and long transverse directions. None of the alloys is shown to be significantly anisotropic. All three alloys developed essentially equivalent room temperature tensile properties.

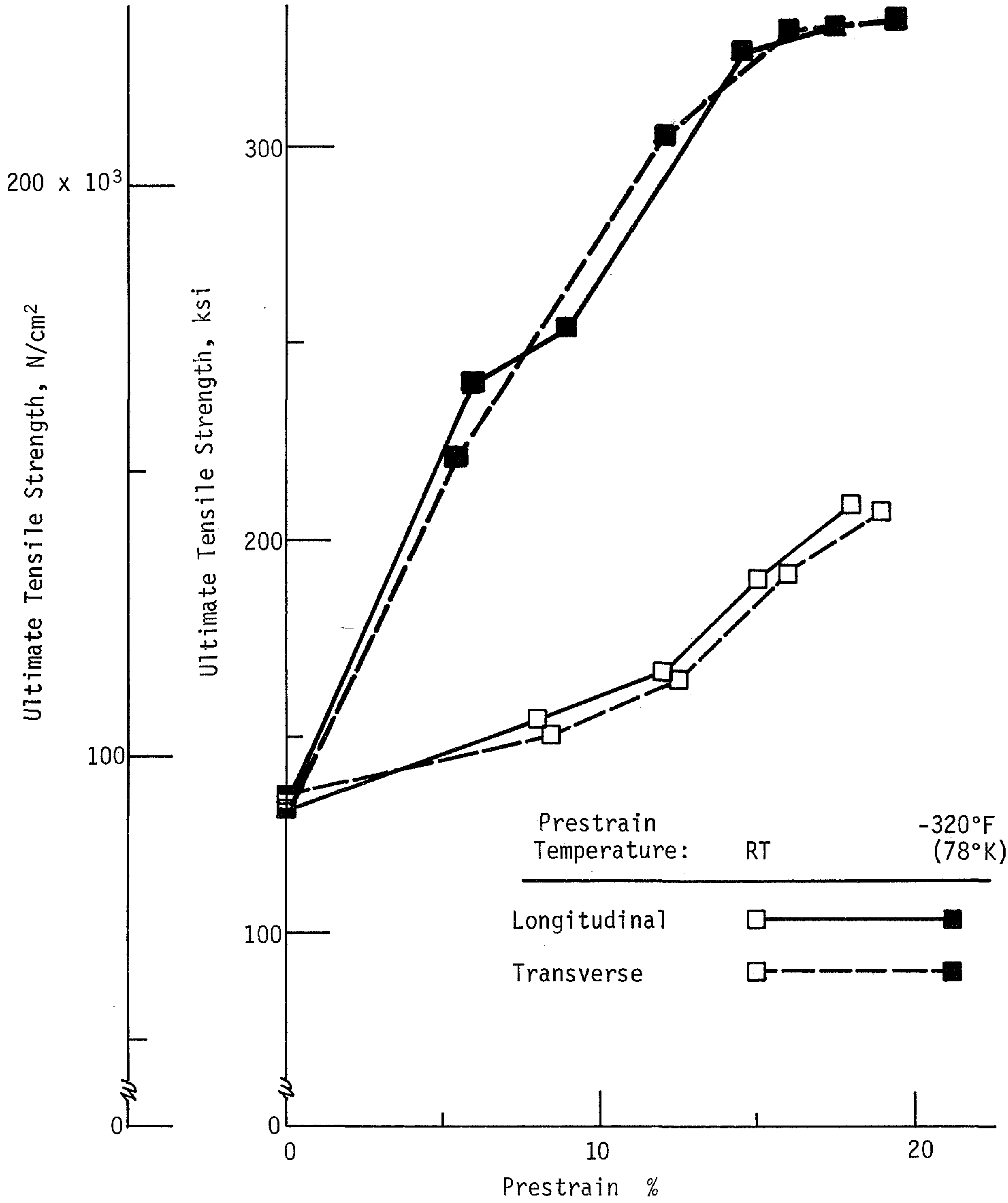


Figure 42 Room Temperature Ultimate Tensile Strengths, Prestrained PH 14-8 Mo, Aged One Hour at 900°F (756°K)

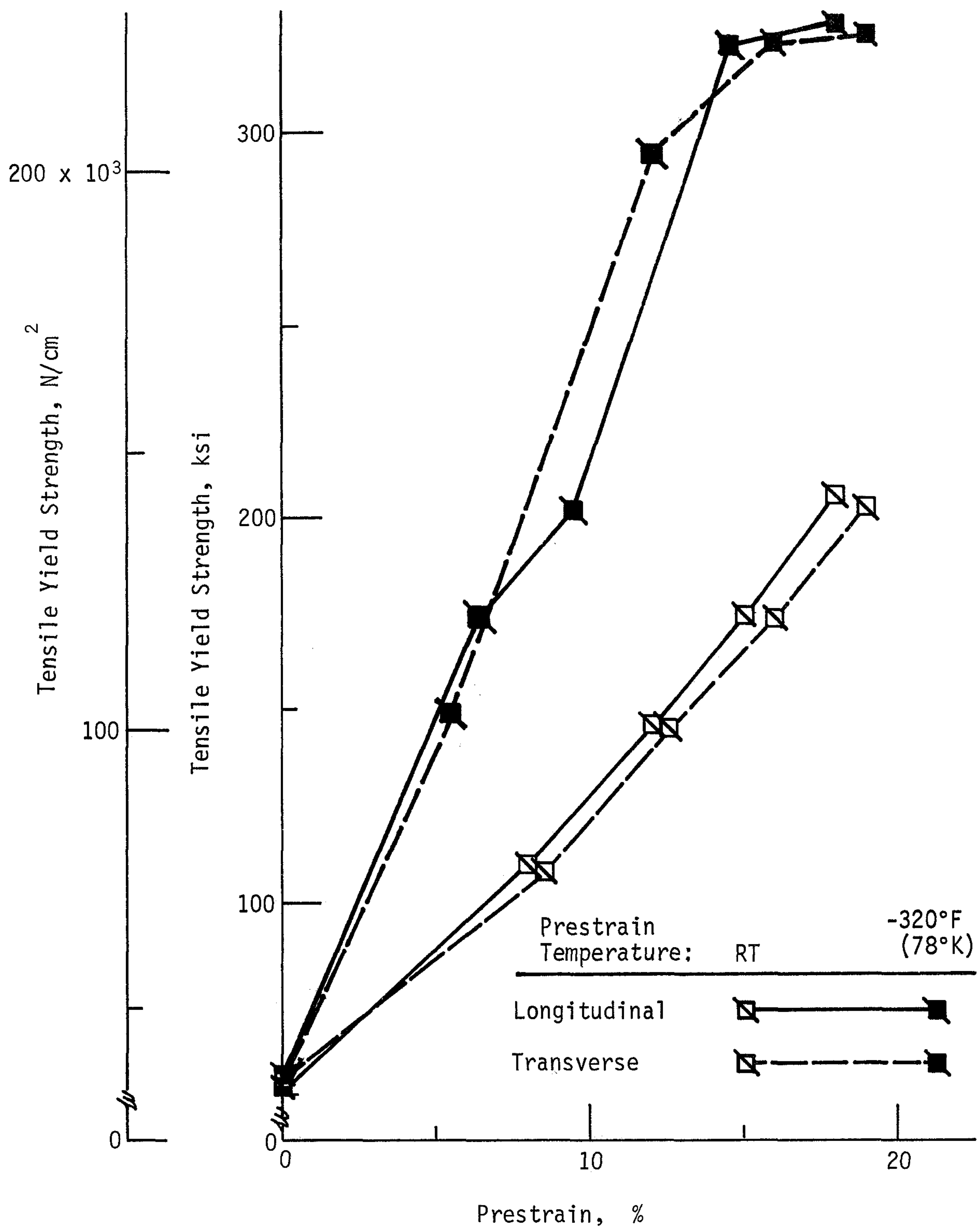


Figure 43 Room Temperature Tensile Yield Strength of Prestrained PH 14-8 Mo Aged One Hour at 900°F (756°K)

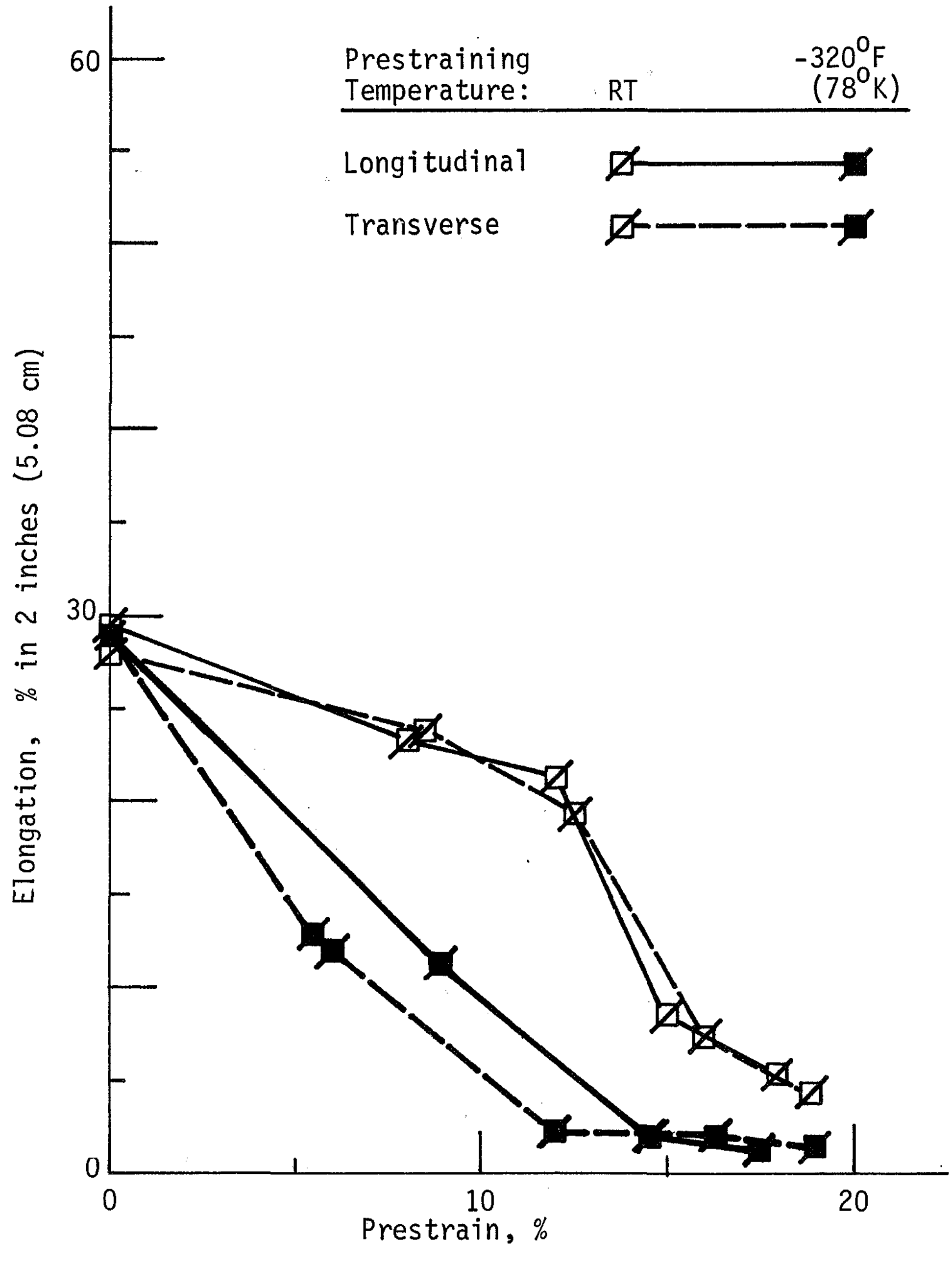


Figure 44 Room Temperature Elongations of Prestrained PH 14-8 Mo, Aged One Hour at 900°F (756°K)

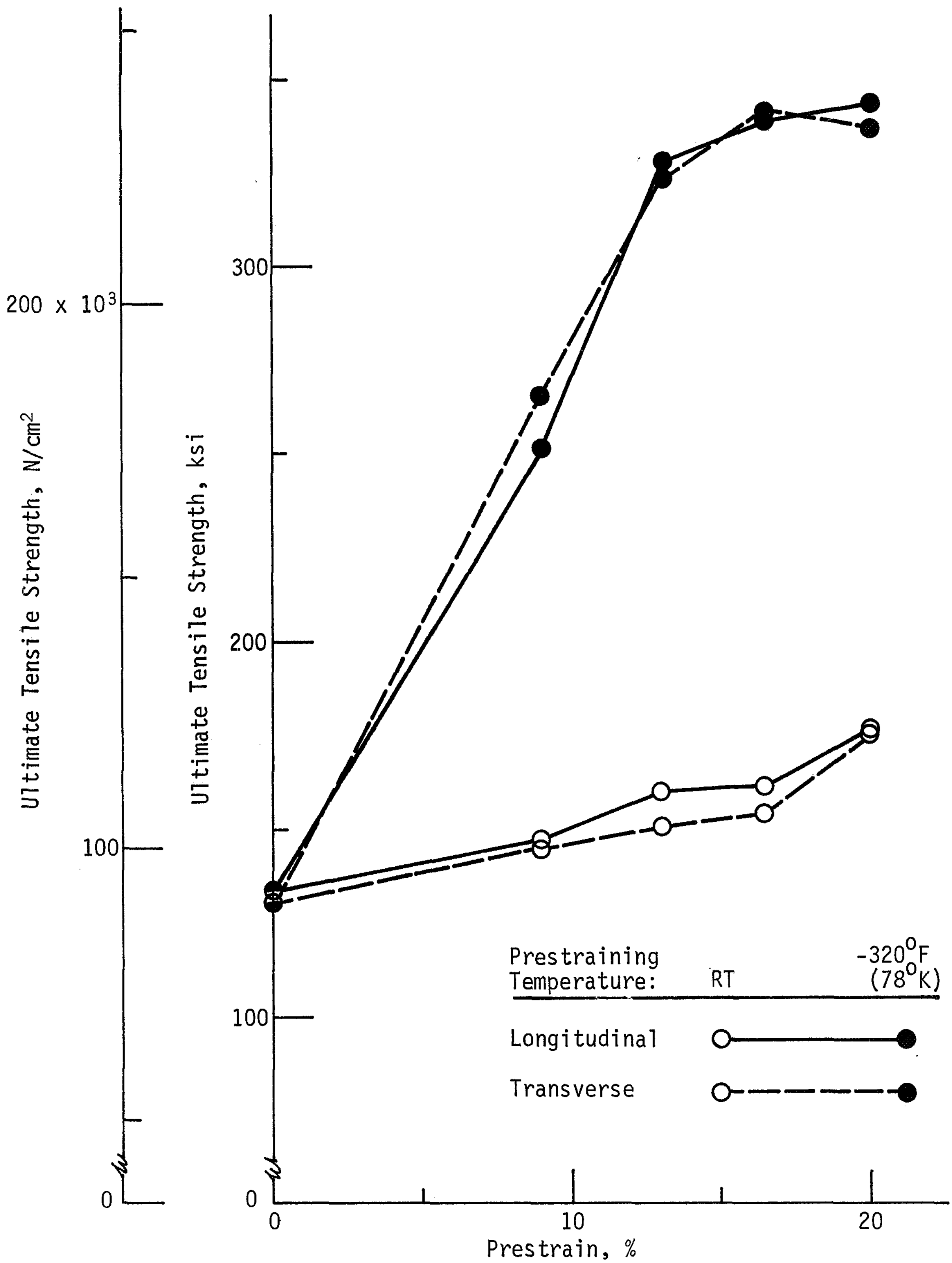


Figure 45 Room Temperature Ultimate Tensile Strengths of Prestrained PH 15-7 Mo, Aged One Hour at 900°F (756°K)

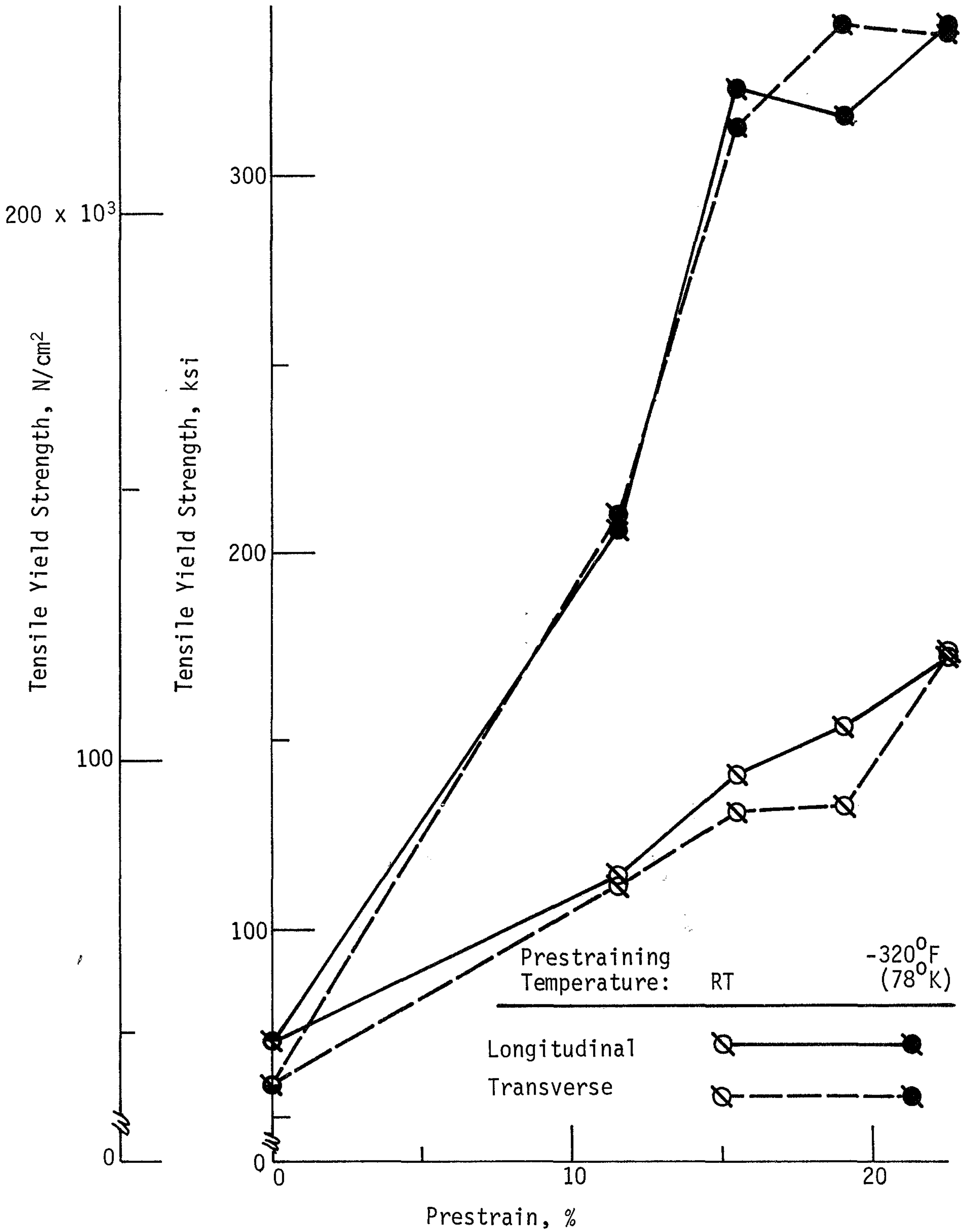


Figure 46 Room Temperature Tensile Yield Strengths of Prestrained PH 15-7 Mo, Aged One Hour at 900°F (756°K)

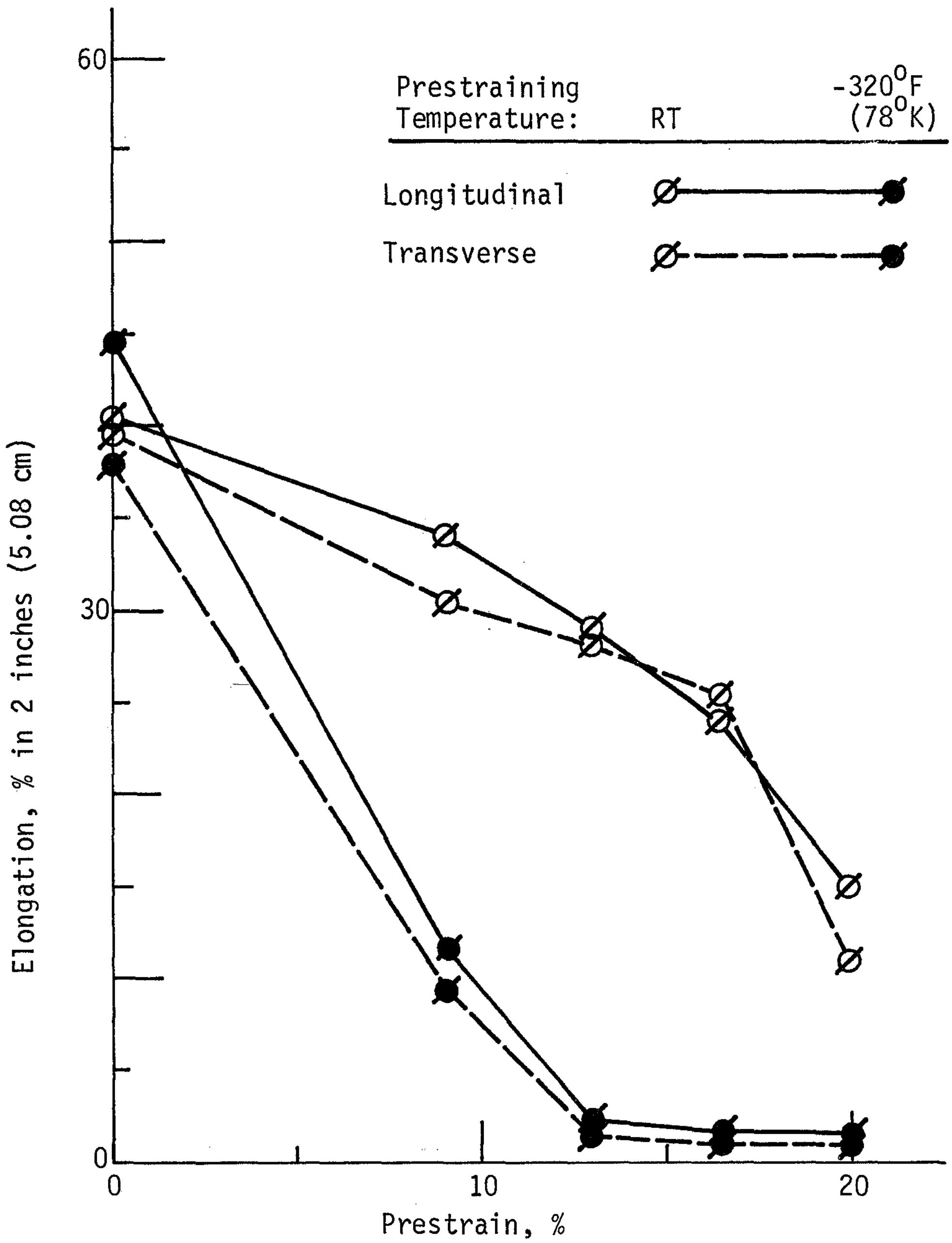


Figure 47 Room Temperature Elongations of Prestrained PH 15-7 Mo, Aged One Hour at 900°F (756°K)

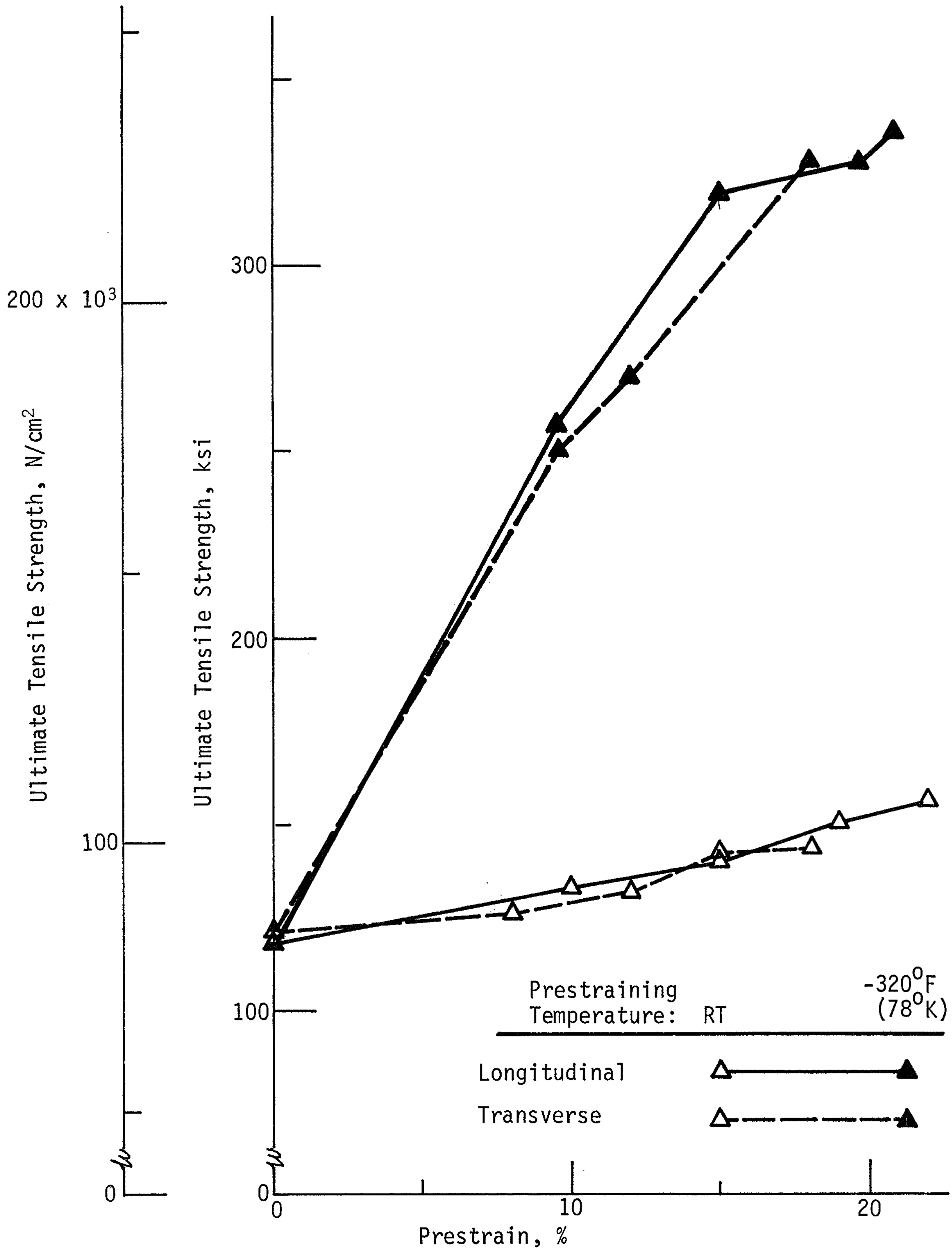


Figure 48 Room Temperature Ultimate Tensile Strengths of Prestrained 17-7 PH, Aged One Hour at 900°F (756°K)

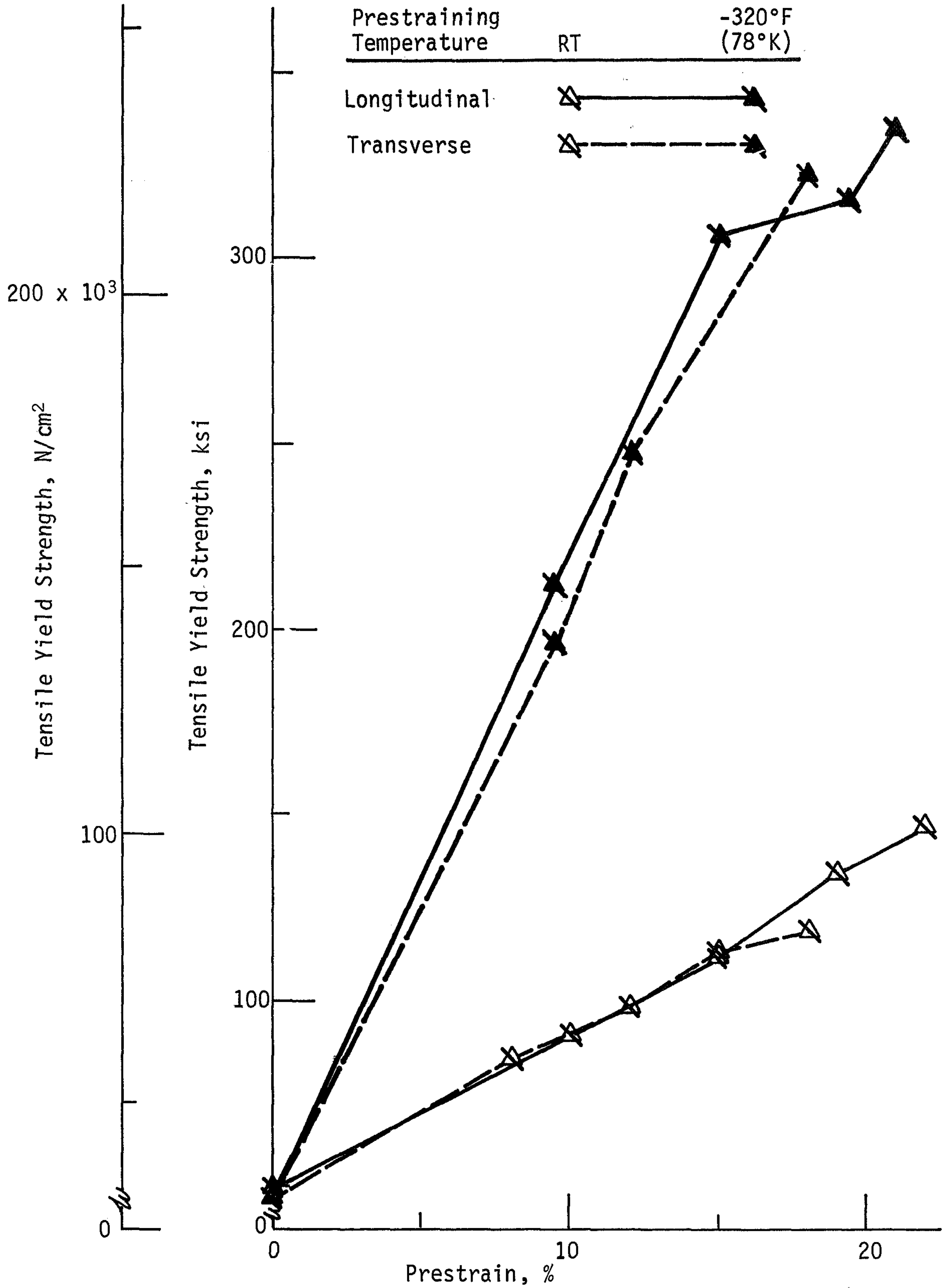


Figure 49 Room Temperature Tensile Yield Strengths of Prestrained 17-7 PH, Aged One Hour at 900°F (756°K)

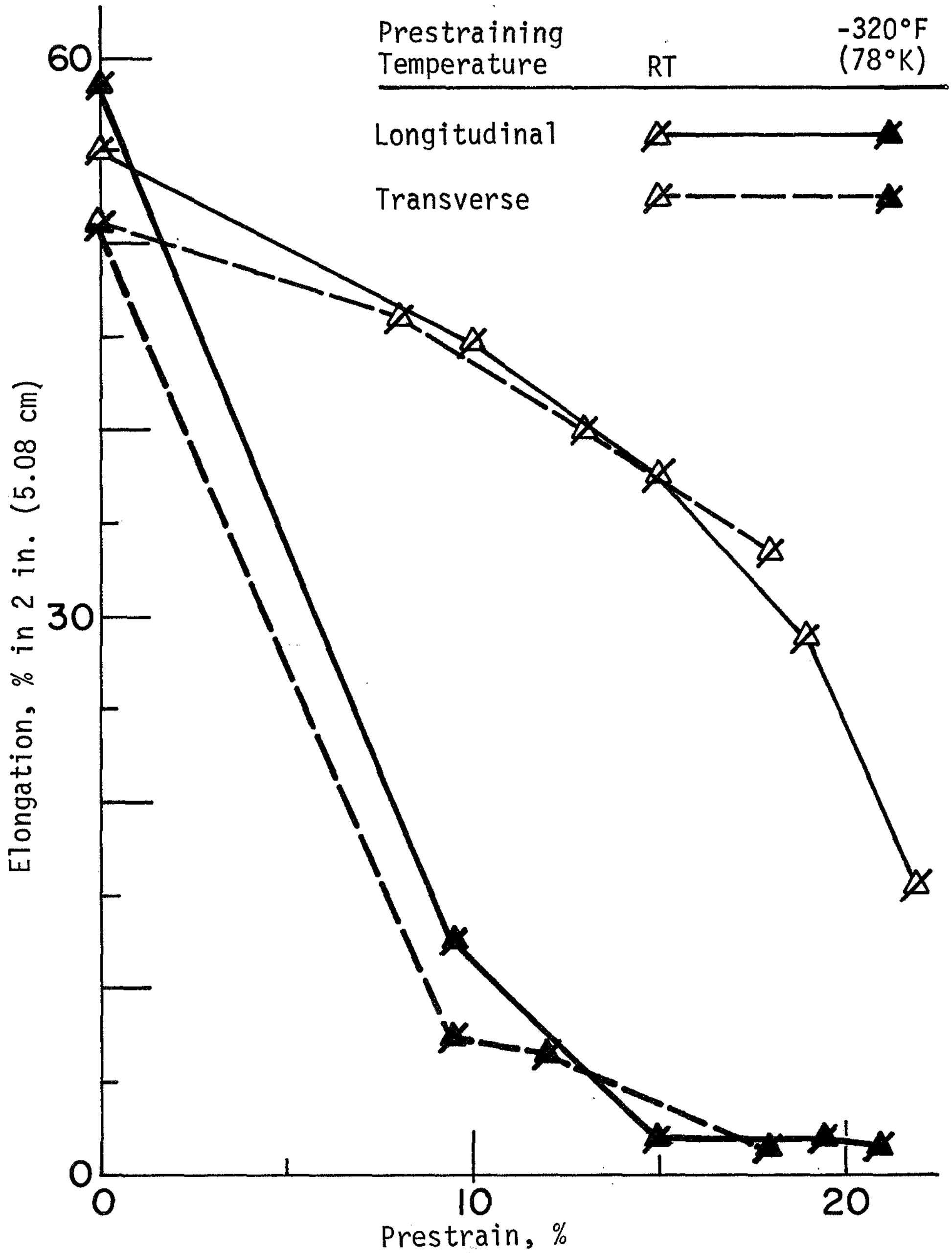


Figure 50 Room Temperature Elongations of Prestrained 17-7 PH, Aged One Hour at 900°F (756°K).

Figures 51 through 56 provide a comparison of the room temperature tensile properties, both longitudinal and transverse, of each alloy after straining at -320°F (78°K), and after straining at -320°F (78°K) and aging one-hour at 900°F (756°K). The significant strengthening of each alloy that is achieved by the simple aging treatment is clearly indicated in these figures. However, the aging treatment also serves to temper the strain-transformed martensite, as noted previously in Chapter III. The tempering effect of the aging treatment toughens each of the alloys. This effect is indicated by comparing the results of the tensile tests of as-strained, and strained and aged specimens of each alloy, Tables 32 thru 34. As noted in the Tables, some as-strained specimens of each alloy, generally the more highly strained specimens, fractured before a stress equal to the 0.2% offset yield strength was reached. Specimens of PH 15-7 Mo were more susceptible, with 13 specimens, three strained only to level B, failing in this manner. Three specimens of 17-7 PH, all strained to the C or D levels failed in this manner. Only two PH 14-8 Mo specimens failed in this way, both transverse and prestrained to level D at -320°F (78°K). By comparison, this type of brittle fracture was not observed in any aged PH 14-8 Mo or 17-7 PH specimens, regardless of strain level. However, while aging did eliminate the tendency for such failure in the PH 15-7 Mo specimens strained to levels A and B, four aged specimens that had been strained to the C or D levels at -320°F (78°K) did fracture at a stress lower than 0.2% offset yield strength. Therefore, the results indicate that the aging treatment tempered and toughened the prestrained specimens of each alloy.

The room temperature tensile properties in both the longitudinal and long transverse directions developed by the three alloys through straining at -320°F (78°K) and aging at 900°F (756°K) for one-hour are compared in Figures 57 through 62. All of the alloys developed strengths above 300 000 psi (207 000 N/cm^2) in both grain directions. However, elongations were correspondingly reduced to 2.0% or less.

Although PH 15-7 Mo was shown to develop somewhat higher strengths for equal strains than either PH 14-8 Mo or 17-7 PH, PH 14-8 Mo was chosen for testing in Task VII rather than PH 15-7 Mo because of the indicated tendency of the PH 15-7 Mo specimens for brittle fracture even after aging. PH 14-8 Mo was chosen over 17-7 PH because for equal strains PH 14-8 Mo developed slightly higher strengths.

Weldment Tests

Results: One weld panel (Figure 21) was prepared from representative stock of each alloy. The panels were penetrant inspected, X-ray inspected, and visually inspected. Except for a small amount of localized porosity in the PH 15-7 Mo panel, none of the inspections disclosed any significant or rejectable sized defects. Even the porosity in the PH 15-7 Mo panel was no problem. The porosity was confined to a 4-inch (10.2-cm) length of weld at one edge of the panel (the start location). Therefore, it was possible to discard the unsound portion of the panel and still obtain the necessary specimens from the remainder of the panel.

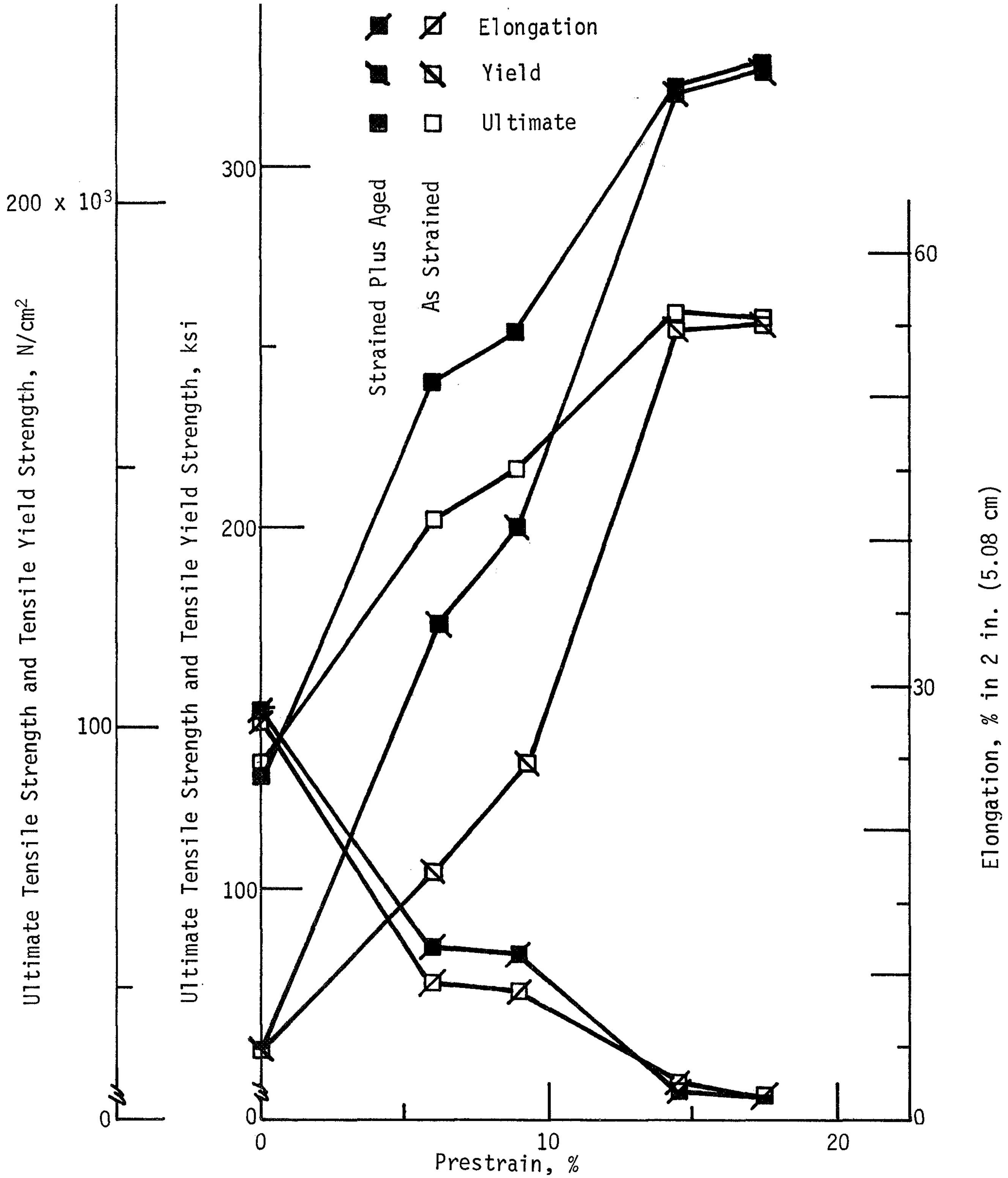


Figure 51 Room Temperature Longitudinal Tensile Properties of PH 14-8 Mo Prestrained at -320°F (78°K), As-Prestrained vs Prestrained and Aged One Hour at 900°F (756°K).

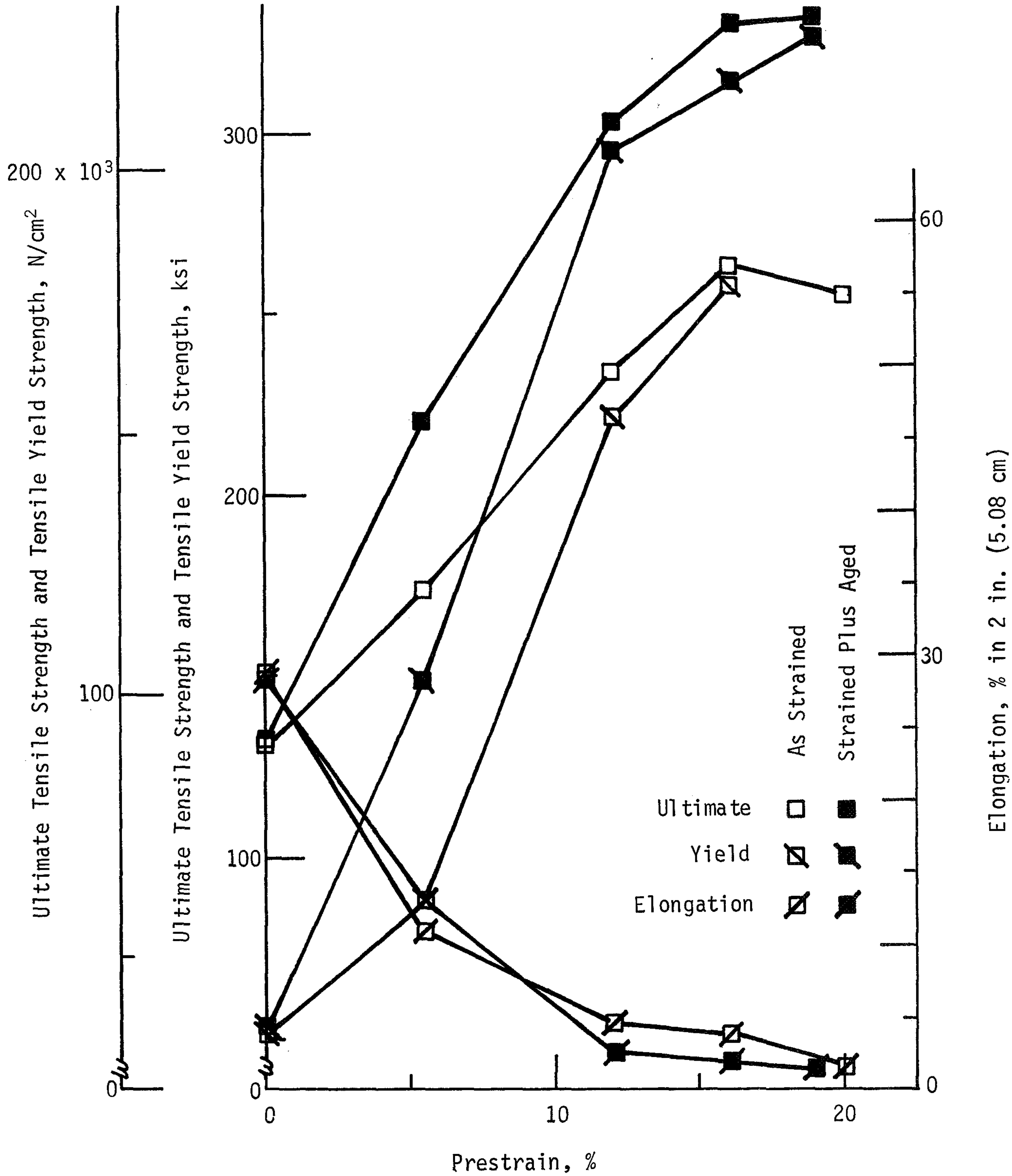


Figure 52 Room Temperature Transverse Tensile Properties of PH 14-8 Mo Prestrained at -320°F (78°K), As-Prestrained vs Prestrained and Aged One Hour at 900°F (756°K).

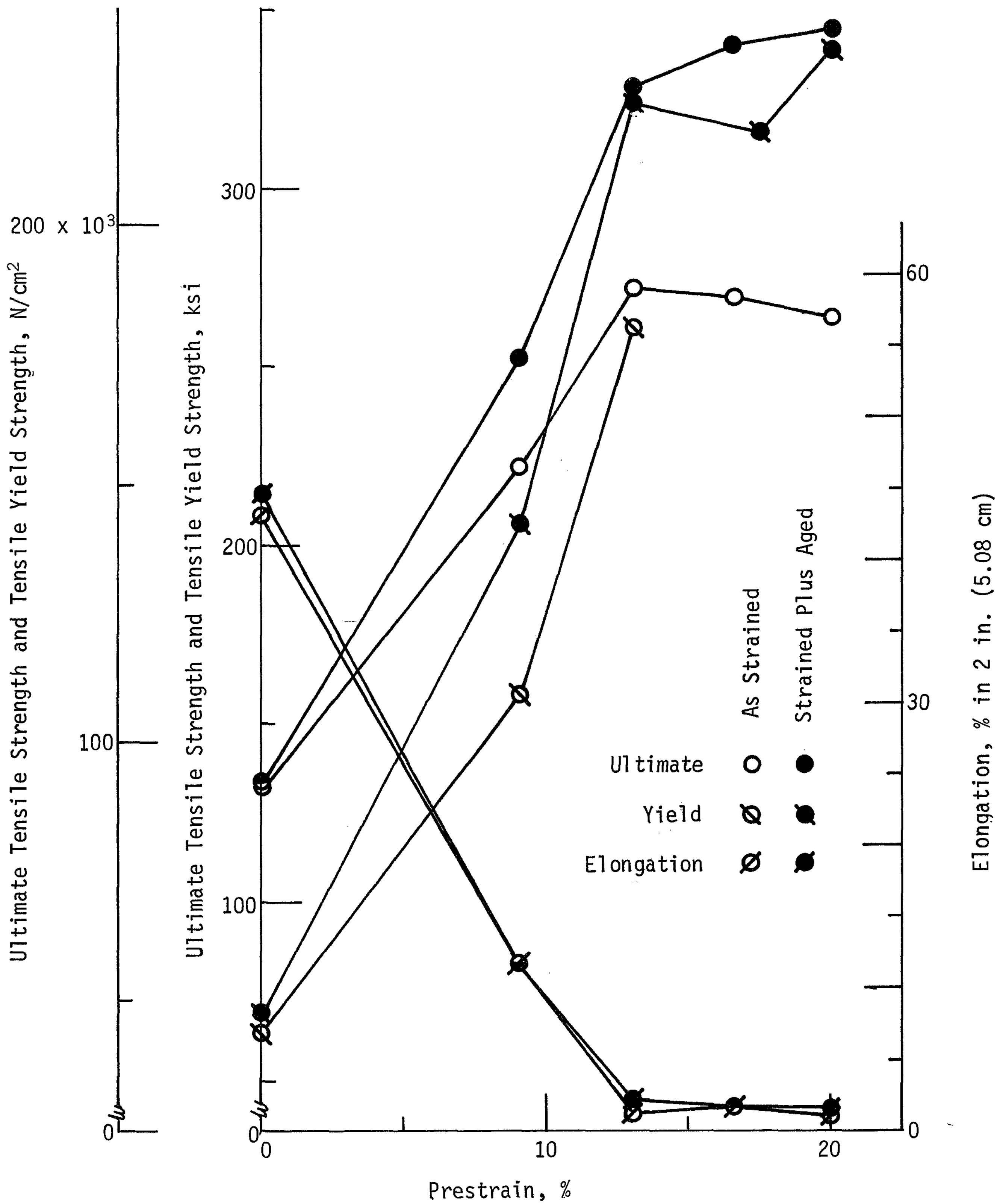


Figure 53 Room Temperature Longitudinal Tensile Properties of PH 15-7 Mo Prestrained at -320°F (78°K), As-Prestrained vs Prestrained and Aged One Hour at 900°F (756°K).

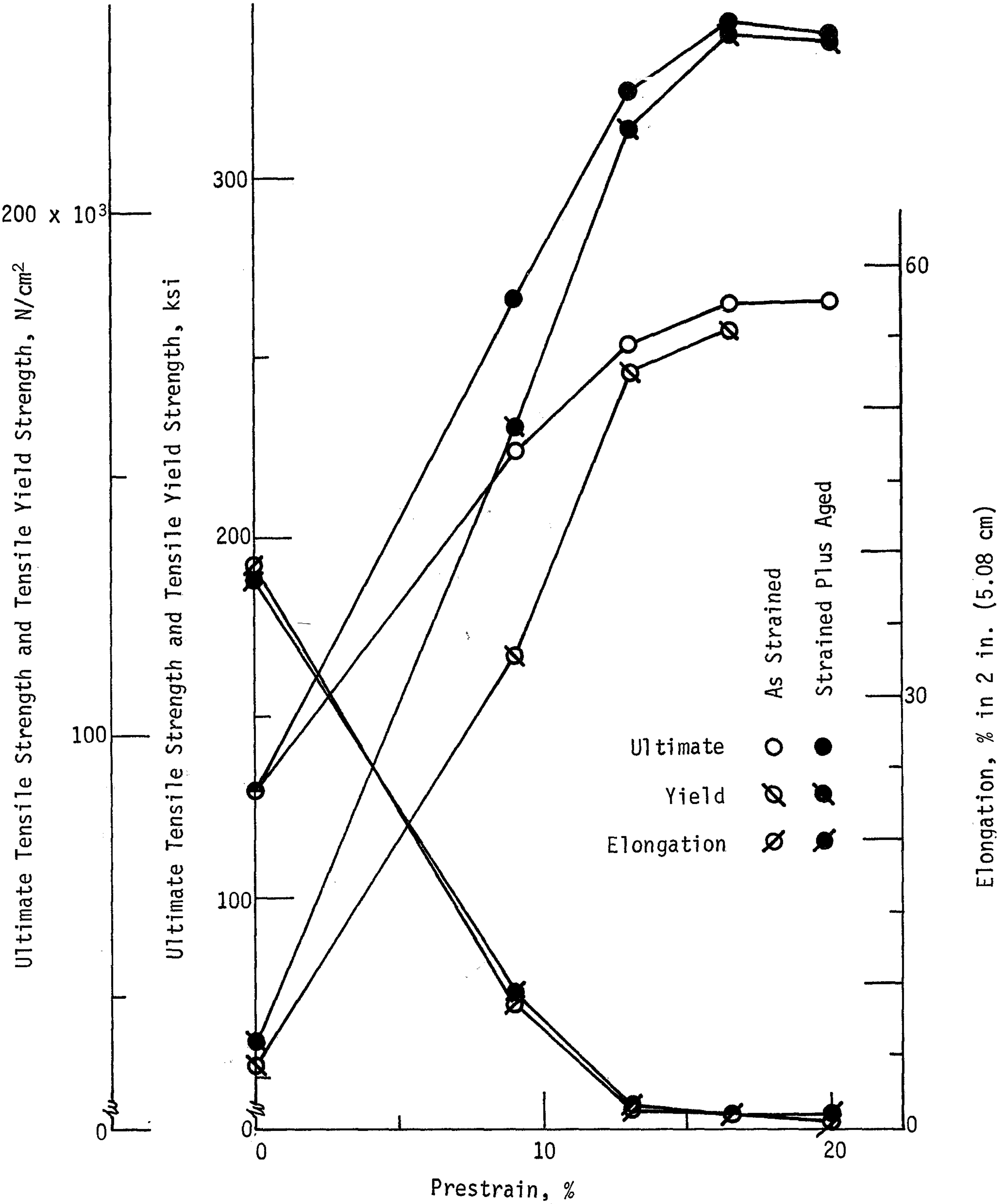


Figure 54 Room Temperature Transverse Tensile Properties of PH 15-7 Mo Prestrained at -320°F (78°K), As-Prestrained vs Prestrained and Aged One Hour at 900°F (756°K).

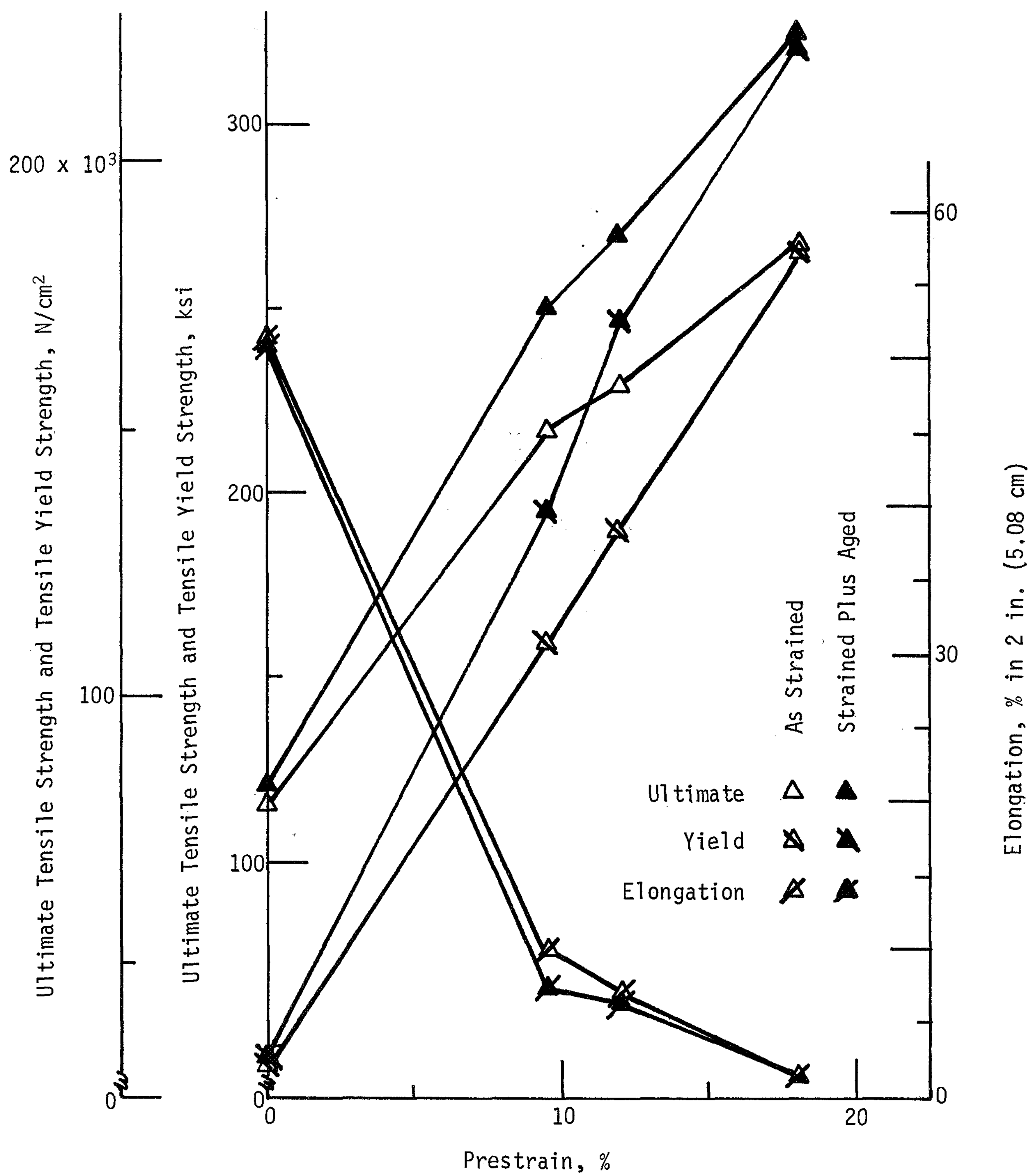


Figure 55 Room Temperature Longitudinal Tensile Properties of 17-7 PH Prestrained at -320°F (78°K), As-Prestrained vs Prestrained and Aged One Hour at 900°F (756°K).

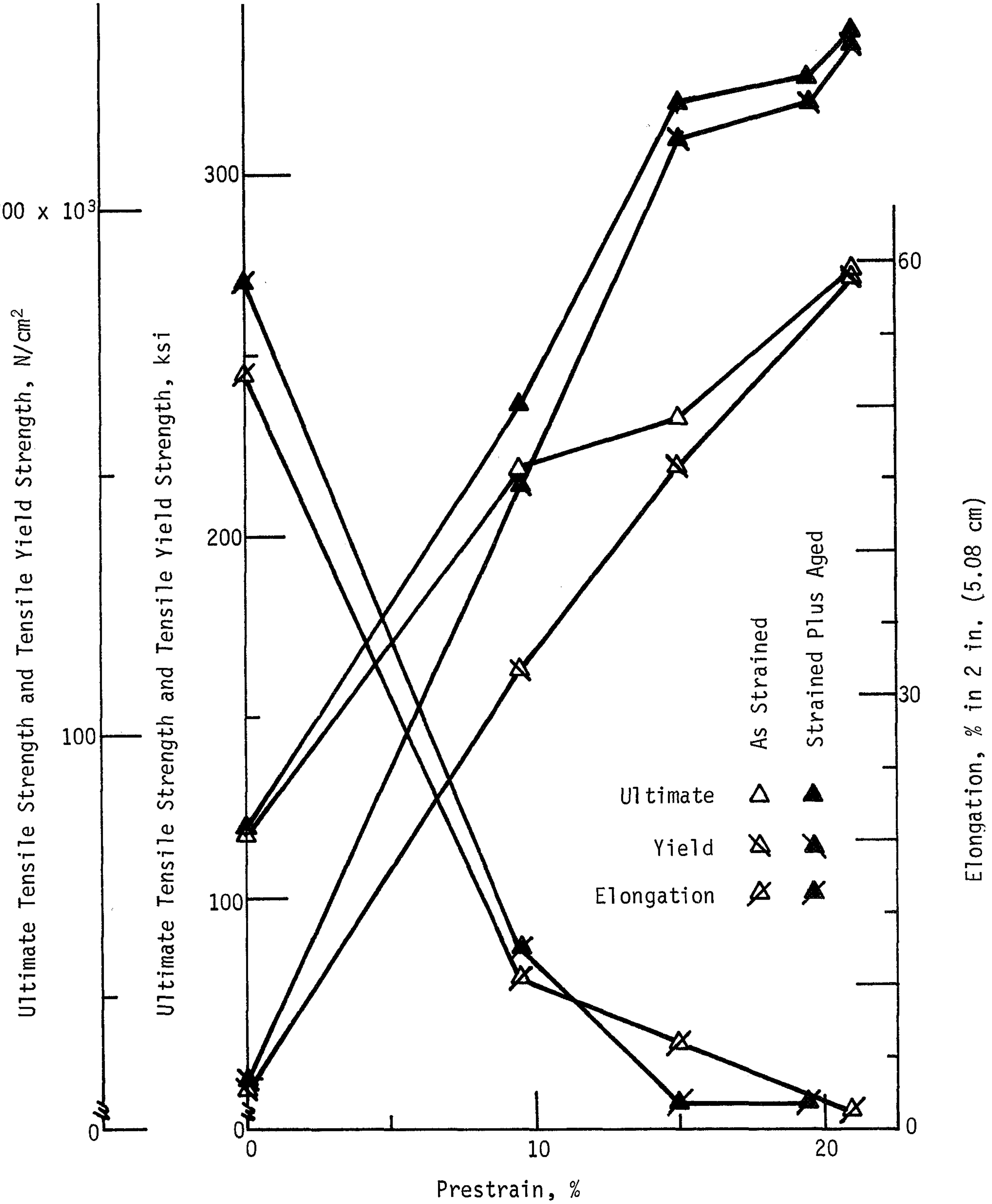


Figure 56 Room Temperature Transverse Tensile Properties of 17-7 PH Prestrained at -320°F (78°K), As-Prestrained vs Prestrained and Aged One Hour at 900°F (756°K).

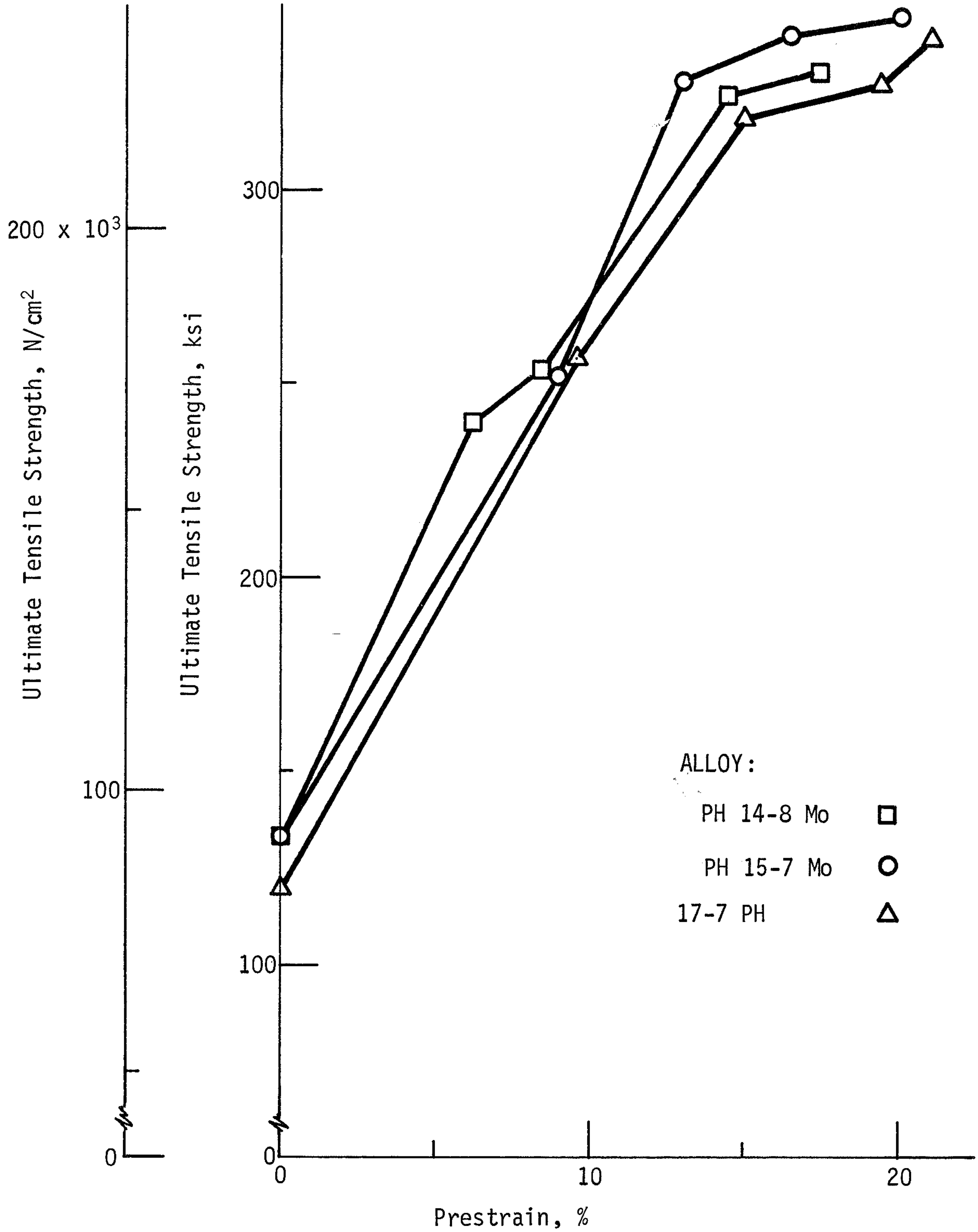


Figure 57 Room Temperature Longitudinal Ultimate Tensile Strengths of Three Alloys Prestrained at -320°F (78°K) and Aged One Hour at 900°F (756°K).

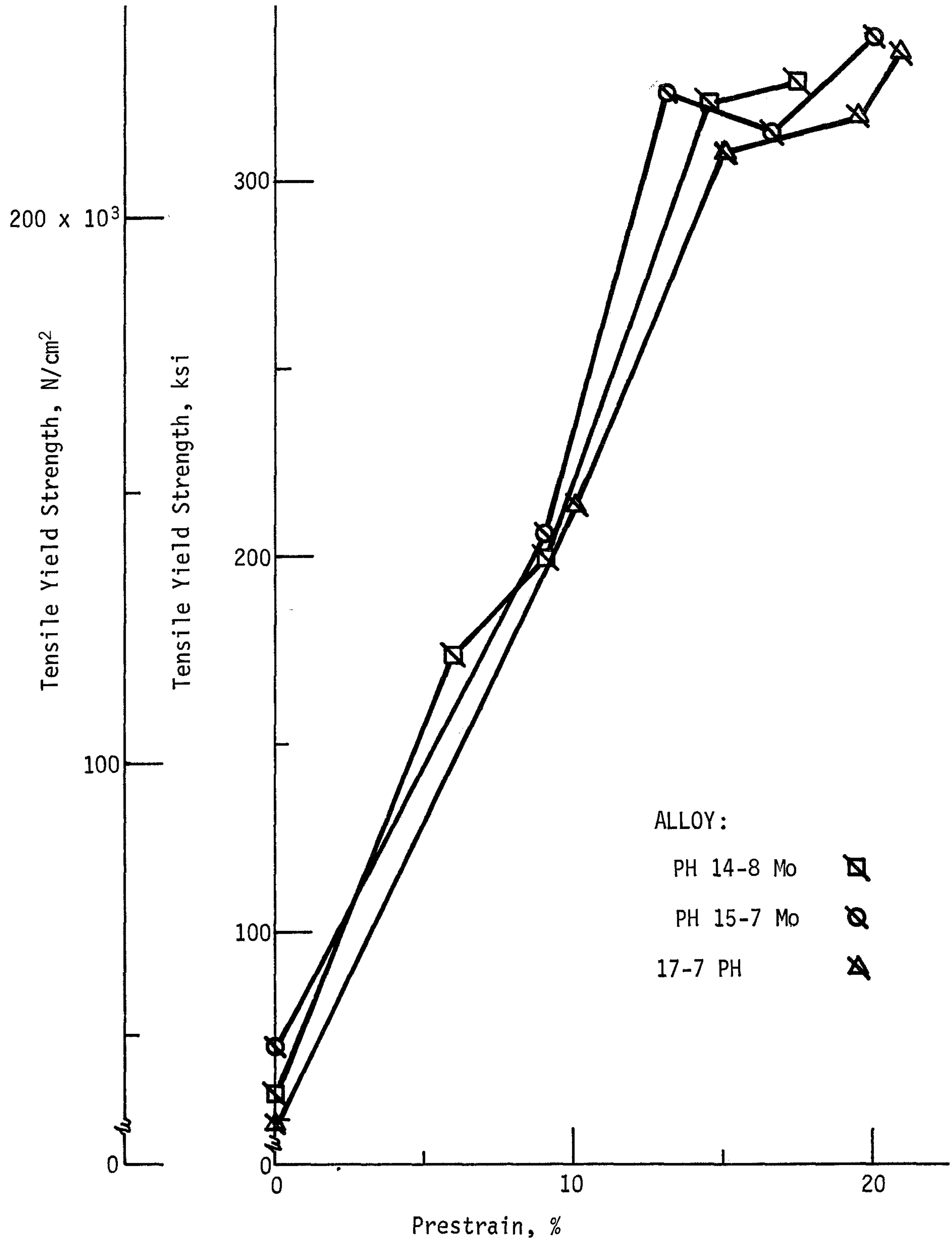


Figure 58 Room Temperature Longitudinal Tensile Yield Strengths of Three Alloys Prestrained at -320°F (78°K) and Aged One Hour at 900°F (756°K).

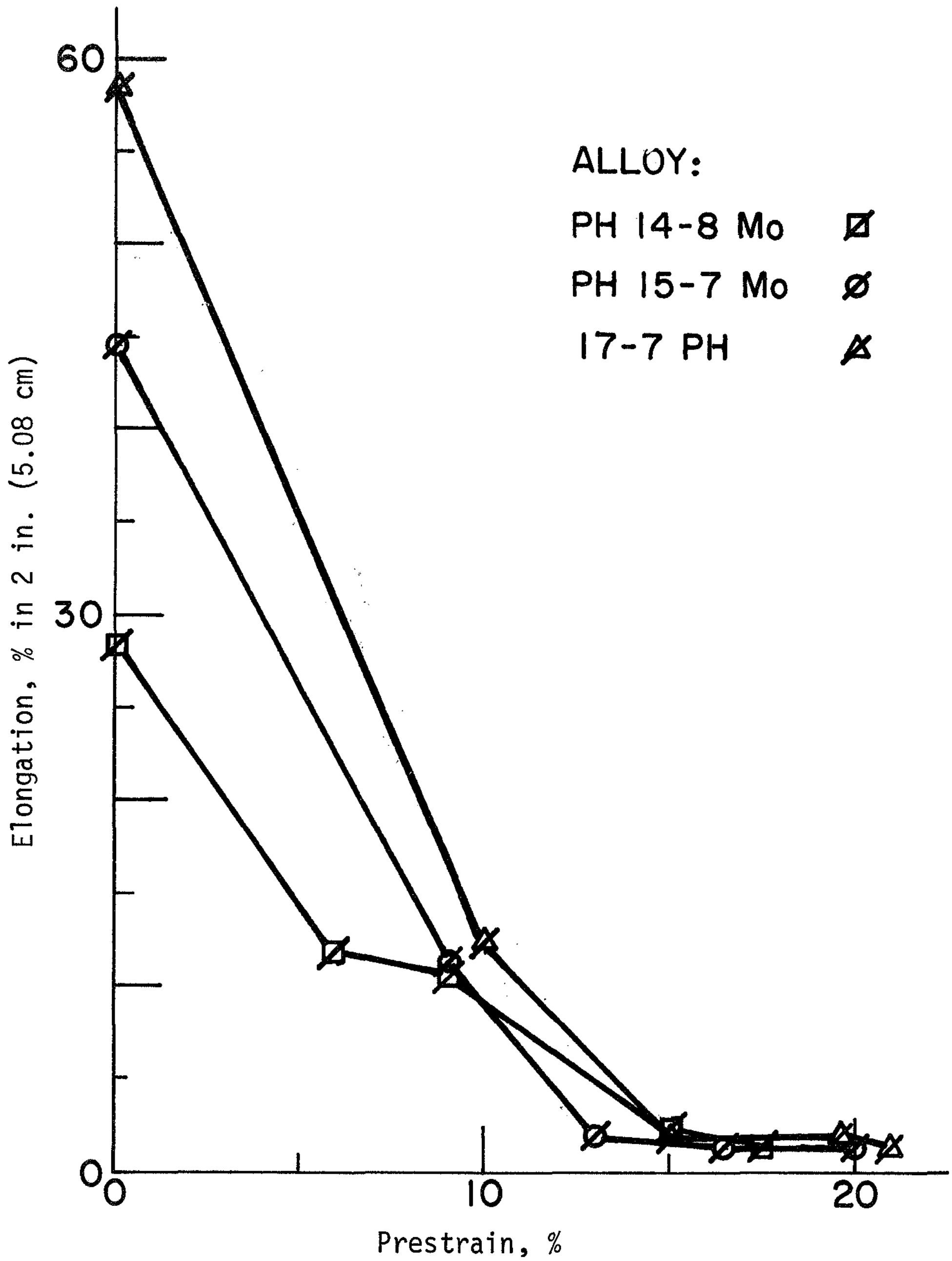


Figure 59 Room Temperature Longitudinal Elongations of Three Alloys Prestrained at -320°F (78°K) and Aged One Hour at 900°F (756°K).

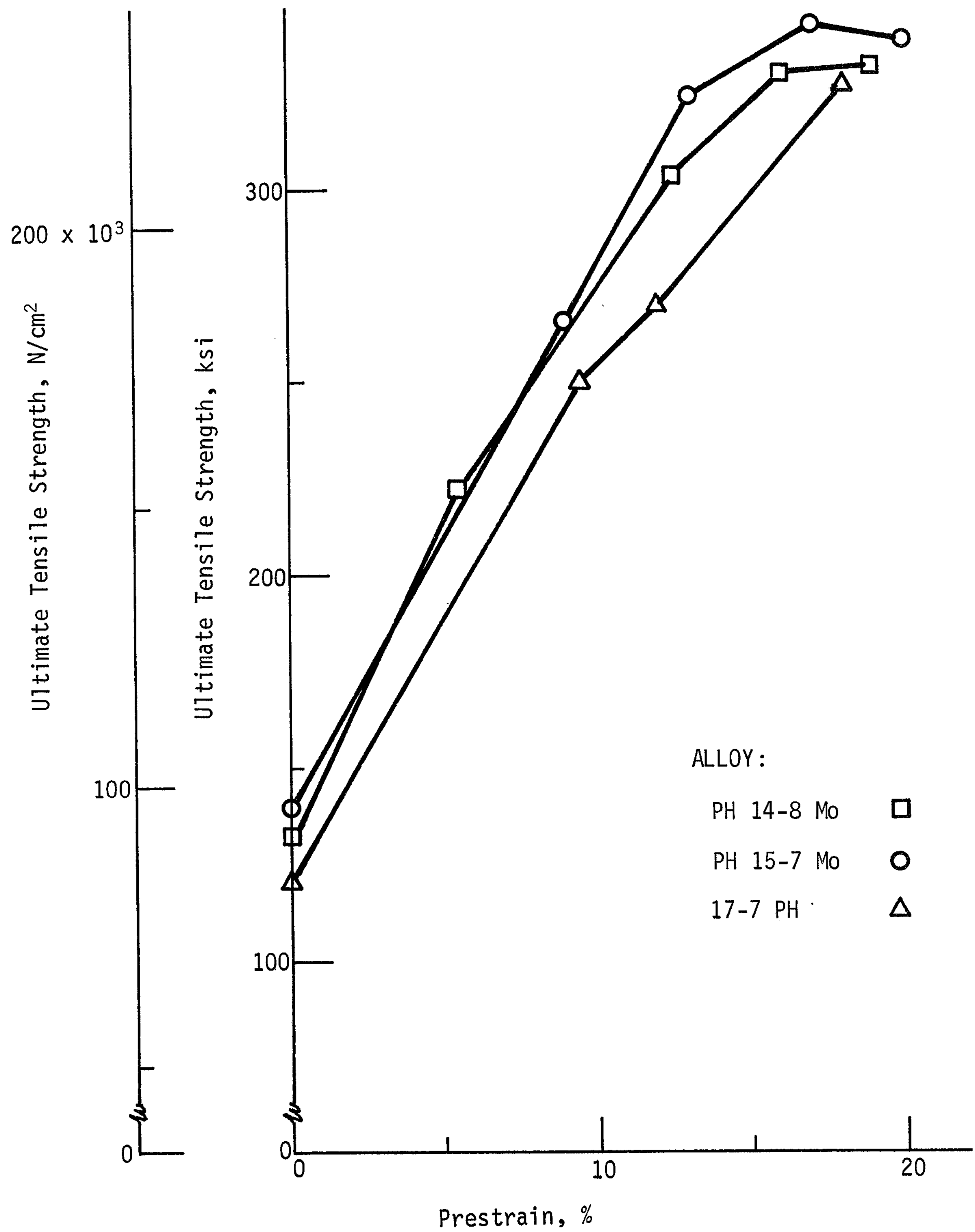


Figure 60 Room Temperature Transverse Ultimate Tensile Strengths of Three Alloys Prestrained at -320°F (78°K) and Aged One Hour at 900°F (756°K).

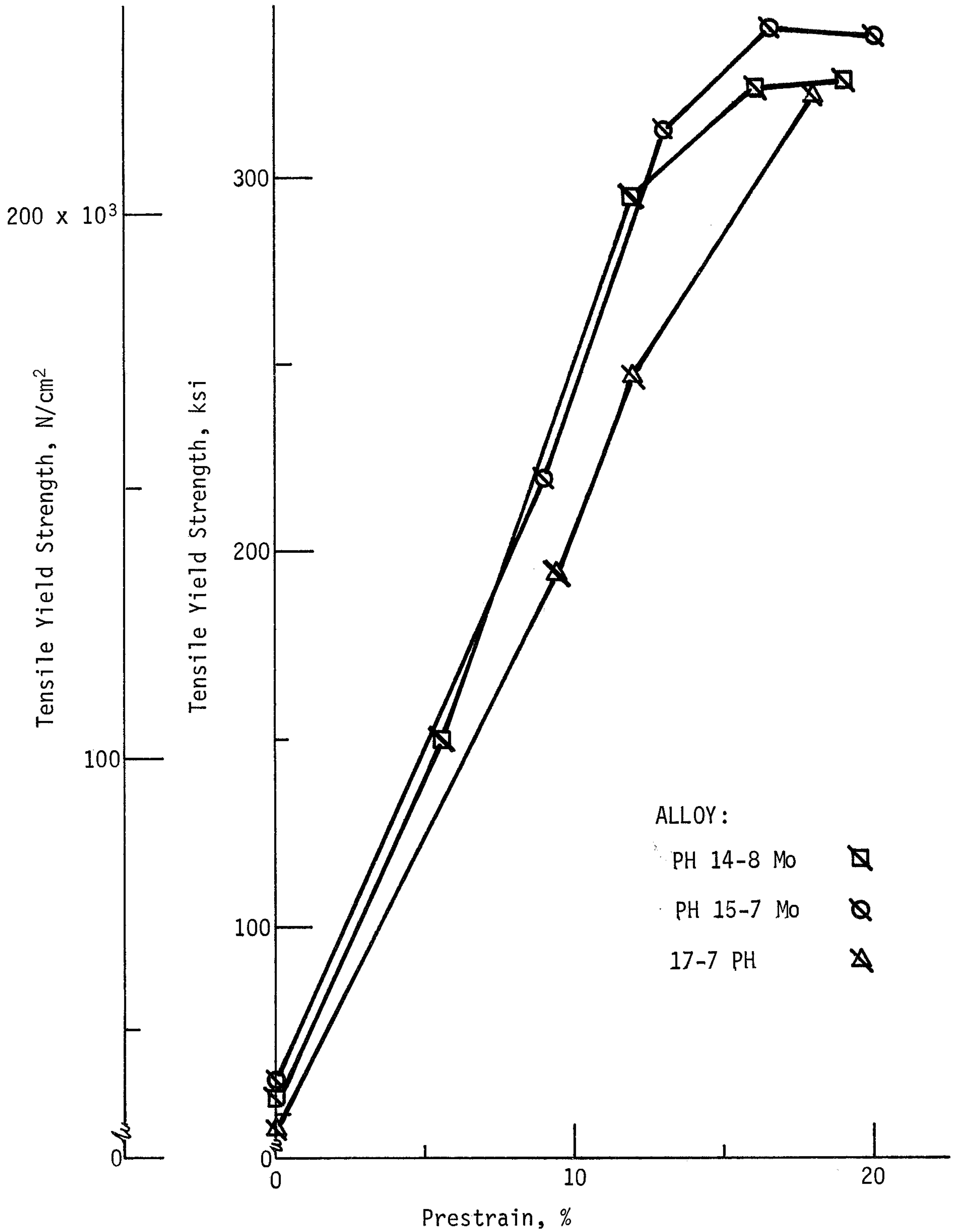


Figure 61 Room Temperature Transverse Yield Strengths of Three Alloys Prestrained at -320°F (78°K) and Aged One Hour at 900°F (756°K).

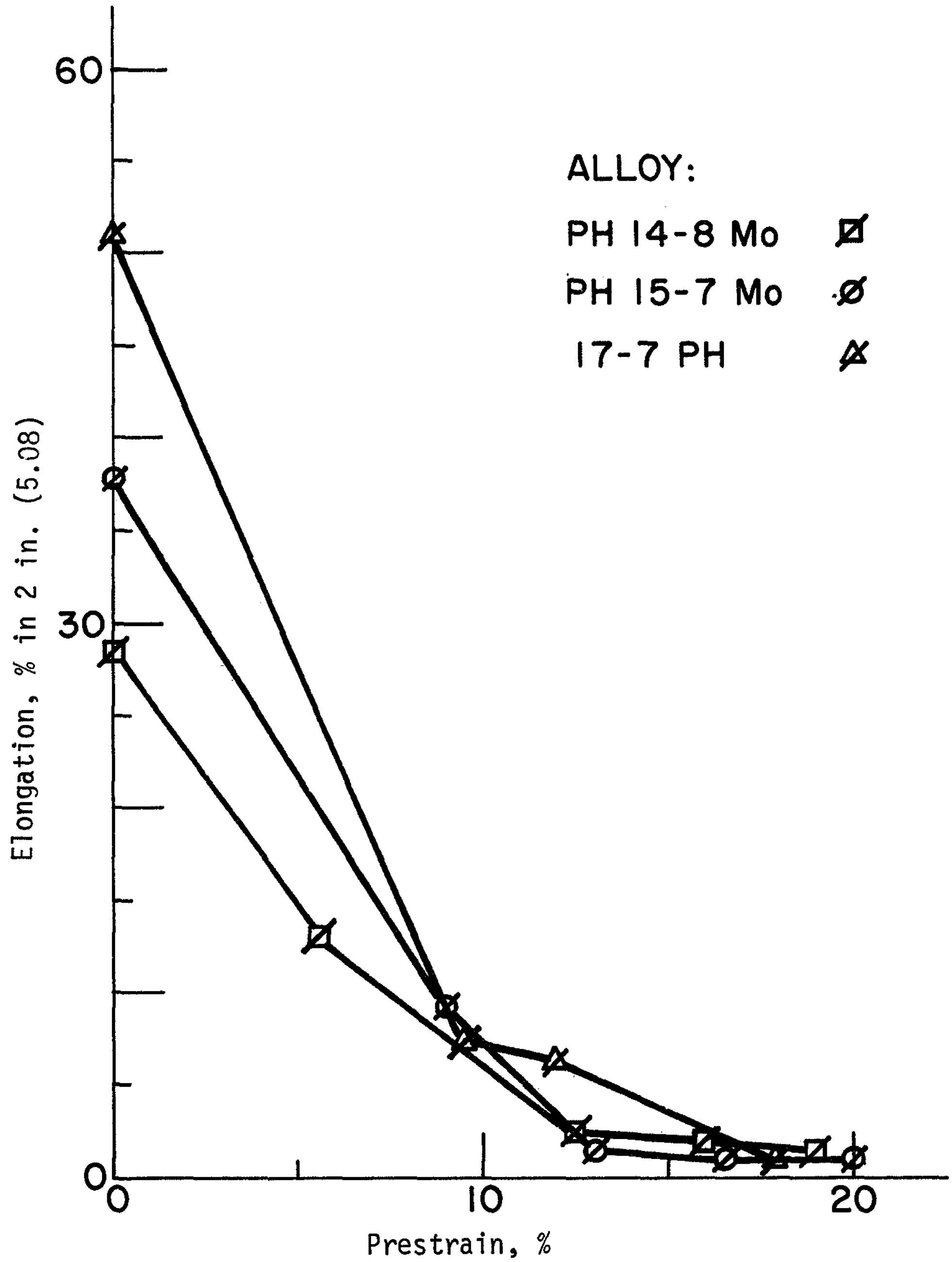


Fig. 62 Room Temperature Transverse Elongations of Three Alloys Prestrained at -320°F (78°K) and Aged One Hour at 900°F (756°K).

As indicated in the weldment test schedule, Table 8, three welded specimens of each alloy were tested to failure at room temperature and three at -320°F (78°K). The results of these tests are listed in Table 18. The uniform elongations measured on the specimens tested at -320°F (78°K) were used to establish the USC value for the weldments of each alloy, these in turn were used to calculate the Level E target strain values listed in Table 19.

Table 18 Test Results, Tensile Tests of Weldments at Room Temperature and -320°F (78°K)

Alloy	Specimen No.	Test temp		Ultimate tensile strength		Total elongation % in 2 in. (5.08 cm)
		°F	°K	psi	N/cm²	
PH 14-8 Mo	12LWT-1	RT	RT	133 900	92 300	--
	-3	RT	RT	132 300	91 200	24.5
	-5	RT	RT	133 100	91 800	25.0
	-2	-320	78	292 800	201 900	21.0
	-4	-320	78	274 300	189 100	14.5
	-6	-320	78	292 800	201 900	21.5
PH 15-7 Mo	22LWT-1	RT	RT	134 400	92 700	36.0
	-3	RT	RT	134 400	92 700	34.5
	-5	RT	RT	132 500	91 400	35.0
	-2	-320	78	202 400	139 600	10.0
	-4	-320	78	234 300	161 500	11.0
	-6	-320	78	220 800	152 200	10.0
17-7 PH	32LWT-1	RT	RT	120 000	82 700	41.0
	-3	RT	RT	120 800	83 300	40.5
	-5	RT	RT	122 400	84 400	42.5
	-2	-320	78	232 800	160 500	14.5
	-4	-320	78	244 000	168 200	17.0
	-6	-320	78	236 800	163 300	15.5

Table 19 USC and Strain Level Values, Task VI, Weldment Tests

Alloy	USC (%) Minimum uniform elongation at -320°F (78°K), % in 1 inch (2.54 cm)	Strain level E (%) [60% of USC at -320°F (78°K)]
PH 14-8 Mo	14.0	8.0
PH 15-7 Mo	9.0	5.0
17-7 PH	14.0	8.0

Other specimens prepared from the weld panels were conditioned and tested as specified in Table 8. The results of these tests are listed in Tables 20 through 22.

Discussion: The weldment tests were conducted to develop data by which to compare the uniform strain capability, at -320°F (78°K), of the three alloys in the as-welded condition. Also, to determine how the room temperature tensile properties of each alloy are affected when:

a) Strained at room temperature and then aged one hour at 900°F (756°K),

b) Strained at -320°F (78°K) and then aged one hour at 900°F (756°K).

PH 14-8 Mo and 17-7 PH, as-welded, had equal uniform strain capability at -320°F (78°K); 14%. The corresponding uniform strain capability for PH 15-7 Mo is 9%.

The PH 14-8 Mo specimens were inadvertently strained lesser amounts at both room temperature and -320°F (78°K) than were the 17-7 PH specimens. However, the room temperature tensile strengths of the prestrained and aged PH 14-8 Mo specimens were found to be greater than the strengths of comparably conditioned 17-7 PH specimens. Also, the as-welded 17-7 PH specimens strained at -320°F (78°K) and then aged tended to fail at a stress level less than that equivalent to the 0.2% offset yield strength.

Compared on the basis of the results of the weldment tests, PH 14-8 Mo was judged the better of the three alloys.

Higher Strain Rate Tests

Results: As indicated in the higher strain rate test schedule, Table 9, three specimens of each alloy were tensile tested to failure at room temperature and three at -320°F (78°K). These were tested at a strain rate of 1.5 in./in./min (1.5 cm/cm/min). The uniform elongations measured on the specimens tested at -320°F (78°K) were used to establish a high strain rate minimum USC for each alloy. The USC values were then used to calculate two strain levels for each alloy, levels X and Y, which were 50% and 75%, respectively, of an alloy's USC at -320°F (78°K). The results of these tests are listed in Table 23.

Room temperature tensile tests were conducted on other specimens of each alloy that had been conditioned as specified in Table 9. The results of these tests are given in Table 24.

Discussion: In Table 25 the tensile properties developed by the three alloys through straining at room temperature and -320°F (78°K) and aging one hour at 900°F (756°K) are compared for standard and high strain rates. No significant advantage with respect to total strengthening capability is indicated for either strain rate.

Table 20 Weld Test Results: PH 14-8 Mo

Specimen number	Strain data			Measured prestrain,	Room temperature tensile properties				
					Ultimate strength		Yield strength, 0.2% offset		Elongation % in 2 in. (5.08 cm)
	Temp, °F	Level	Target,		psi	N/cm^2	psi	N/cm^2	
*12LWS - 1	RT	E	8.0	10.0	161 800	111 600	126 500	87 200	20.5
- 3	RT	E	8.0	10.0	161 800	111 600	127 100	87 600	20.0
- 5	RT	E	8.0	10.0	161 800	111 600	135 300	93 300	20.0
*12LWS - 2	-320	E	8.0	7.5	261 100	180 000	237 700	163 900	4.5
- 4	-320	E	8.0	7.5	255 400	176 100	217 100	149 700	4.0
- 6	-320	E	8.0	7.5	256 100	176 600	213 900	147 500	4.5

*All specimens aged 1 hour at 900°F (756°K).

Table 21 Weld Test Results: PH 15-7 Mo

Specimen Number	Strain data			Measured prestrain, %	Room temperature tensile properties				
					Ultimate strength		Yield strength, 0.2% offset		Elongation % in 2 in. (5.08 cm)
	Temp., °F	Level	Target, %		psi	N/cm^2	psi	N/cm^2	
*22LWS - 1	RT	E	5.0	5.0	138 800	95 700	-	-	57.5
- 3	RT	E	5.0	5.0	141 700	97 700	101 100	69 700	32.0
- 5	RT	E	5.0	5.0	143 300	98 800	104 200	71 800	36.5
*22LWS - 2	-320	E	5.0	5.0	155 100	106 900	94 600	65 200	6.0
- 4	-320	E	5.0	5.0	154 100	106 300	91 900	63 400	7.0
- 6	-320	E	5.0	5.0	154 100	106 300	91 900	63 400	6.0

*All specimens aged 1 hour at 900°F (756°K).

Table 22 Weld Test Results: 17-7 PH

Specimen number	Strain data: Temp, °F	Strain data: Level	Strain data: Target, %	Measured prestrain, %	Room temperature tensile properties: Ultimate strength, psi	Ultimate strength, N/cm²	Yield strength, 0.2% offset, psi	Yield strength, 0.2% offset, N/cm²	Elongation % in 2 in. (5.08 cm)
32LWS - 1	RT	E	8.0	11.0	132 700	91 500	102 400	70 600	37.5
- 3	RT	E	8.0	11.0	135 200	93 200	105 800	72 900	34.0
- 5	RT	E	8.0	11.0	140 600	96 900	109 400	75 400	32.0
32LWS - 2†	-320	E	8.0	9.0	-	-	-	-	-
- 4§	-320	E	8.0	9.0	211 200	145 600	-	-	1.5
- 6§	-320	E	8.0	9.0	202 700	139 800	-	-	1.5

*All specimens aged 1 hour at 900°F (756°K).
†Failed out of gage
§Failed before 0.2% offset.

Table 23 High Strain Rate Tensile Tests

Specimen No.	Strain rate: in./in./min	Strain rate: cm/cm/min	Test temp °F	Test temp °K	Ultimate tensile strength, psi	Ultimate tensile strength, N/cm²	Elongation: Total % in 2 in. (5.08 cm)	Elongation: Uniform % in 1 in. (2.54 cm)	USC at -320°F (78°K)
(PH 14-8 Mo)									
11LRH-1	1.50	1.50	RT	RT	121 600	83 800	31.0	26.0	
-2	1.50	1.50	RT	RT	122 400	84 400	30.0	26.0	
-3	1.50	1.50	RT	RT	123 200	84 500	30.0	25.0	
11LNH-1	1.50	1.50	-320	78	283 200	195 300	19.0	18.0	
-2	1.50	1.50	-320	78	290 400	200 200	20.5	19.5	18.0
-3	1.50	1.50	-320	78	291 200	200 800	21.0	19.5	
(PH 15-7 Mo)									
21LRH-1	1.50	1.50	RT	RT	114 600	79 000	36.0	30.0	
-2	1.50	1.50	RT	RT	115 400	79 600	35.0	32.0	
-3	1.50	1.50	RT	RT	114 600	79 000	36.0	34.0	
21LNH-1	1.50	1.50	-320	78	293 700	202 500	20.5	18.5	
-2	1.50	1.50	-320	78	293 300	202 200	21.7	20.0	18.0
-3	1.50	1.50	-320	78	(Failed out of gage)				
(17-7 PH)									
31LRH-1	1.50	1.50	RT	RT	107 200	73 900	48.0	42.0	
-2	1.50	1.50	RT	RT	105 600	72 800	45.0	37.0	
-3	1.50	1.50	RT	RT	106 400	73 400	46.0	38.0	
31LNH-1	1.50	1.50	-320	78	(Failed out of gage)		---	---	
-2	1.50	1.50	-320	78	276 000	190 300	24.0	20.5	20.0
-3	1.50	1.50	-320	78	280 000	193 000	25.0	23.0	

Table 24 Task VI High Strain Rate Test Results

Alloy	Strain level	Prestrain temp °F	Prestrain temp °K	Prestrain (%) Target	Prestrain (%) Actual	Room temperature tensile properties[a]: Ultimate tensile strength, psi	Ultimate tensile strength, N/cm²	Tensile yield strength (0.2% offset), psi	Tensile yield strength, N/cm²	Elongation % in 2 in. (5.08 cm)
PH 14-8 Mo	X[b]	RT	RT	9.0	8.0	144 800	99 800	89 700	61 800	18.0
	Y[c]	RT	RT	13.0	13.0	145 800	100 500	104 600	72 100	16.0
	X: aged[c,e]	RT	RT	9.0	8.5	147 800	101 900	109 400	75 400	23.0
	Y: aged[c,e]	RT	RT	13.0	13.0	160 700	110 800	140 400	96 800	19.5
	X	-320	78	9.0	9.0	214 300	147 800	165 500	114 100	8.0
	Y	-320	78	13.0	13.0	234 600	161 800	217 700	150 100	7.0
	X: aged[e]	-320	78	9.0	9.0	275 400	189 900	259 600	179 000	4.5
	Y: aged[e]	-320	78	13.0	13.0	314 900	217 100	305 200	210 400	2.0
PH 15-7 Mo	X	RT	RT	9.0	8.5	142 400	98 200	94 400	65 100	30.0
	Y	RT	RT	13.0	12.0	140 600	96 900	95 700	66 000	26.5
	X: aged[e]	RT	RT	9.0	9.0	145 500	100 300	110 200	76 000	35.0
	Y: aged[e]	RT	RT	13.0	12.0	151 000	104 100	127 700	88 000	28.5
	X[d]	-320	78	9.0	9.5	232 700	160 400	218 400	150 600	6.5
	Y[c]	-320	78	13.0	14.0	229 000	157 900	185 000	127 600	7.0
	X: aged[d,e]	-320	78	9.0	10.0	291 700	201 100	278 600	192 100	4.5
	Y: aged[b,e]	-320	78	13.0	12.0	293 800	202 600	279 400	192 600	5.5
17-7 PH	X	RT	RT	10.0	9.0	121 800	84 000	75 300	51 900	33.5
	Y	RT	RT	15.0	14.0	133 600	92 100	96 800	66 700	33.5
	X: aged[e]	RT	RT	10.0	10.0	129 200	89 100	92 800	64 000	39.0
	Y: aged[e]	RT	RT	15.0	14.5	134 500	92 700	109 100	75 200	38.5
	X	-320	78	10.0	11.0	220 600	152 100	183 600	126 200	7.5
	Y	-320	78	15.0	15.0	238 800	164 700	228 000	157 200	5.5
	X: aged[e]	-320	78	10.0	10.5	260 800	179 800	228 500	157 600	9.0
	Y: aged[c,e]	-320	78	15.0	14.5	300 700	207 300	290 600	200 400	2.5

[a]Average of three tests unless noted.

[b]One test.

[c]Average of four tests.

[d]Average of four tests.

[e]Aged 1 hour at 900°F (756°K), air cooled.

Table 25 Comparison of Properties Developed by Standard and High Strain Rates, All Specimens Aged 1 Hour at 900°F (756°K) after Straining

Alloy	Prestrain temp °F	Prestrain temp °K	Actual strain, %	Strain rate in./in./min	Strain rate cm/cm/min	Room temperature tensile properties: Ultimate, psi	Ultimate, N/cm²	Yield, psi	Yield, N/cm²	Elongation % in 2 in. (5.08 cm)
PH 14-8 Mo	RT	RT	8.0	0.050	0.050	154 400	106 500	109 900	75 800	23.5
	RT	RT	12.0	0.050	0.050	162 800	112 300	145 800	100 500	21.5
	RT	RT	9.0	1.5	1.5	147 800	101 900	109 400	75 400	23.0
	RT	RT	13.0	1.5	1.5	160 700	110 800	140 400	96 800	19.5
	-320	78	9.0	0.050	0.050	253 700	174 900	200 100	138 000	11.5
	-320	78	14.5	0.050	0.050	324 100	223 500	321 700	221 800	2.0
	-320	78	9.0	1.5	1.5	275 400	189 900	259 600	179 000	4.5
	-320	78	13.0	1.5	1.5	314 900	217 100	305 200	210 400	2.0
PH 15-7 Mo	RT	RT	9.0	0.050	0.050	147 100	101 400	114 700	79 100	34.0
	RT	RT	13.0	0.050	0.050	160 200	110 500	141 100	97 300	29.0
	RT	RT	9.0	1.5	1.5	145 500	100 300	110 200	76 000	35.0
	RT	RT	12.0	1.5	1.5	151 000	104 100	127 700	88 000	28.5
	-320	78	7.0	0.050	0.050	252 200	172 900	206 300	142 200	11.5
	-320	78	13.0	0.050	0.050	328 300	226 400	323 600	223 100	2.0
	-320	78	9.5	1.5	1.5	291 700	201 100	278 600	192 100	4.5
	-320	78	14.0	1.5	1.5	293 800	202 600	279 400	192 600	5.5
17-7 PH	RT	RT	10.0	0.050	0.050	131 400	90 600	90 000	62 100	44.5
	RT	RT	15.0	0.050	0.050	138 800	95 700	111 200	76 700	37.5
	RT	RT	10.0	1.5	1.5	129 200	89 100	92 800	64 000	39.0
	RT	RT	14.5	1.5	1.5	134 500	92 700	109 100	75 200	38.5
	-320	78	9.5	0.050	0.050	256 100	176 600	214 600	148 000	12.5
	-320	78	15.0	0.050	0.050	319 000	220 000	308 600	212 800	2.0
	-320	78	10.5	1.5	1.5	260 800	179 800	228 500	157 600	9.0
	-320	78	14.5	1.5	1.5	300 700	207 300	290 600	200 400	2.5

Roll Straining Tests

Results: Specimens of each alloy were rolled at room temperature and others at -320°F (78°K). Tensile test bars of the type shown in Figure 1 were made from the rolled materials. For each alloy, three tensile specimens made from room temperature rolled stock and three tensile specimens made from -320°F (78°K) rolled stock, were tested to failure at room temperature in the as-rolled condition. Like quantities of similarly conditioned specimens of each alloy were aged at 900°F (756°K) for one hour and then tested to failure at room temperature. The results of these tests are listed in Table 26.

As shown in Table 26, PH 15-7 Mo developed higher room temperature tensile strengths through cryorolling or cryorolling and aging than either PH 14-8 Mo or 17-7 PH. The difference is most marked in the yield strengths; PH 15-7 Mo developed a yield strength of 309 500 psi (213 400 N/cm^2), a value approximately 9% greater than yield strengths developed by PH 14-8 Mo and 17-7 PH. However, PH 14-8 Mo developed higher strengths, as-rolled or rolled and aged, when the rolling was done at room temperature.

The rolling tests confirmed that cryoworking, regardless of whether by cryostraining in uniaxial tensile or by cryorolling, is an effective means of strengthening each of the alloys tested.

Table 26 Test Results, Task VI Roll-Strain Tests

Alloy	Rolling temp °F	Final condition	Room temperature tensile properties[a]				
			Ultimate tensile strength		Tensile yield strength, 0.2% offset		Elongation, % in 2 in. (5.08 cm)
			psi	N/cm^2	psi	N/cm^2	
PH 14-8 Mo	Room temp	As rolled,[b]	155 000	106 900	122 100	84 200	21.0
		Rolled[b]+aged[b,c]	156 800	108 100	139 100	95 900	22.0
	-320	As rolled[b]	256 500	176 800	204 400	140 900	2.0
		Rolled+aged[b,c]	307 500	212 000	283 000	195 100	2.0
PH 15-7 Mo	Room temp	As rolled[b]	146 100	100 700	103 400	71 300	21.5
		Rolled+aged[b,c]	165 100	113 800	116 200	80 100	26.5
	-320	As rolled[b]	261 400	180 200	235 900	162 700	2.0
		Rolled+aged[b,c]	318 800	219 800	309 500	213 400	2.0
17-7 PH	Room temp	As rolled[b]	130 000	89 600	85 300	58 800	27.5
		Rolled+aged[b,c]	140 500	96 900	106 300	73 300	33.0
	-320	As rolled[b]	251 600	173 500	208 000	143 400	2.5
		Rolled+aged[b,c]	303 500	209 300	283 600	195 500	2.5

[a]Average of three tests.

[b]Material thickness reduced from 0.050 in. (0.127 cm) to 0.043 in. (0.109 cm).

[c]Aged 1 hour at 900°F (756 °K).

TASK VI - CONCLUSION

PH 14-8 Mo was chosen for testing in Tasks VII and VIII. It was chosen primarily because, as previously discussed, it produced better results than the other alloys during the weld test series. Also, the results of the parent metal test series indicated that it developed slightly higher strengths for equal strains than 17-7 PH, and, although developing lower strengths than PH 15-7 Mo, PH 14-8 Mo demonstrated superior toughness than that alloy both after and before aging. Actually all three alloys showed good response to cryostraining and none offered marked advantage over the others. But, PH 14-8 Mo was shown to be slightly better than each of the others in some respects, therefore it was chosen for further testing.

TASK VII - THERMAL RESPONSE TESTS

Results: The Task VII test results are listed in Table 35 of Appendix A. Constant temperature aging curves developed from these data are shown in Figures 63 through 65.

Discussion: These tests were conducted in accordance with the test schedule, Table 12, to determine how various time-temperature aging cycles affect the room temperature tensile properties developed by cryostrained PH 14-8 Mo.

Aging the cryostrained PH 14-8 Mo for 0.5 hour at 1100°F (866°K) produced comparatively poor room temperature tensile properties (Table 35), regardless of the strain level.

Aging the cryostrained PH 14-8 Mo at 1000°F (811°K) also produced comparatively poor results, as indicated in Figures 63, 64 and 65. The data indicate that aging at 1100°F (866°K) or 1000°F (811°K) results in overaging cryostrained PH 14-8 Mo material, even if aging time is limited to 0.5 hour. The room temperature tensile strengths developed by aging cryostrained PH 14-8 Mo at these temperatures are low compared to the strengths developed by equivalently cryostrained material aged at lower temperatures. Also, while the tensile strengths developed through aging the cryostrained material at 1000°F (811°K) and 1100°F (866°K) are relatively low, elongations of the aged material do not improve correspondingly.

As indicated in Figures 63, 64, and 65 aging cryostrained PH 14-8 Mo at 800°F (700°K), 900°F (756°K), or 950°F (783°K) will produce essentially equal tensile properties for a given cryostrained condition, provided aging time is appropriately adjusted for temperature. Regardless of aging temperature, strengths increase with increasing time at temperature until the maximum values per cryostrain condition are reached, then increasing time at temperature produces lower strengths. By contrast, however, corresponding elongation values remain relatively constant, showing no improvement with increased aging time.

Aging, as noted in Chapter III, serves a dual purpose of strengthening and also tempering the martensitic structure of transformed PH 14-8 Mo. The tempering effect, or more accurately the lack of tempering, was noted in testing the 16% cryostrained specimens after aging 0.5 and 1 hour at 800°F (700°K). All four of these specimens fractured before 0.2% offset (0.004 inch [0.010 cm]) strain was reached. This brittle behavior suggests that the short aging periods at the 800°F (700°K) temperature did not provide for adequate tempering of the highly strained material.

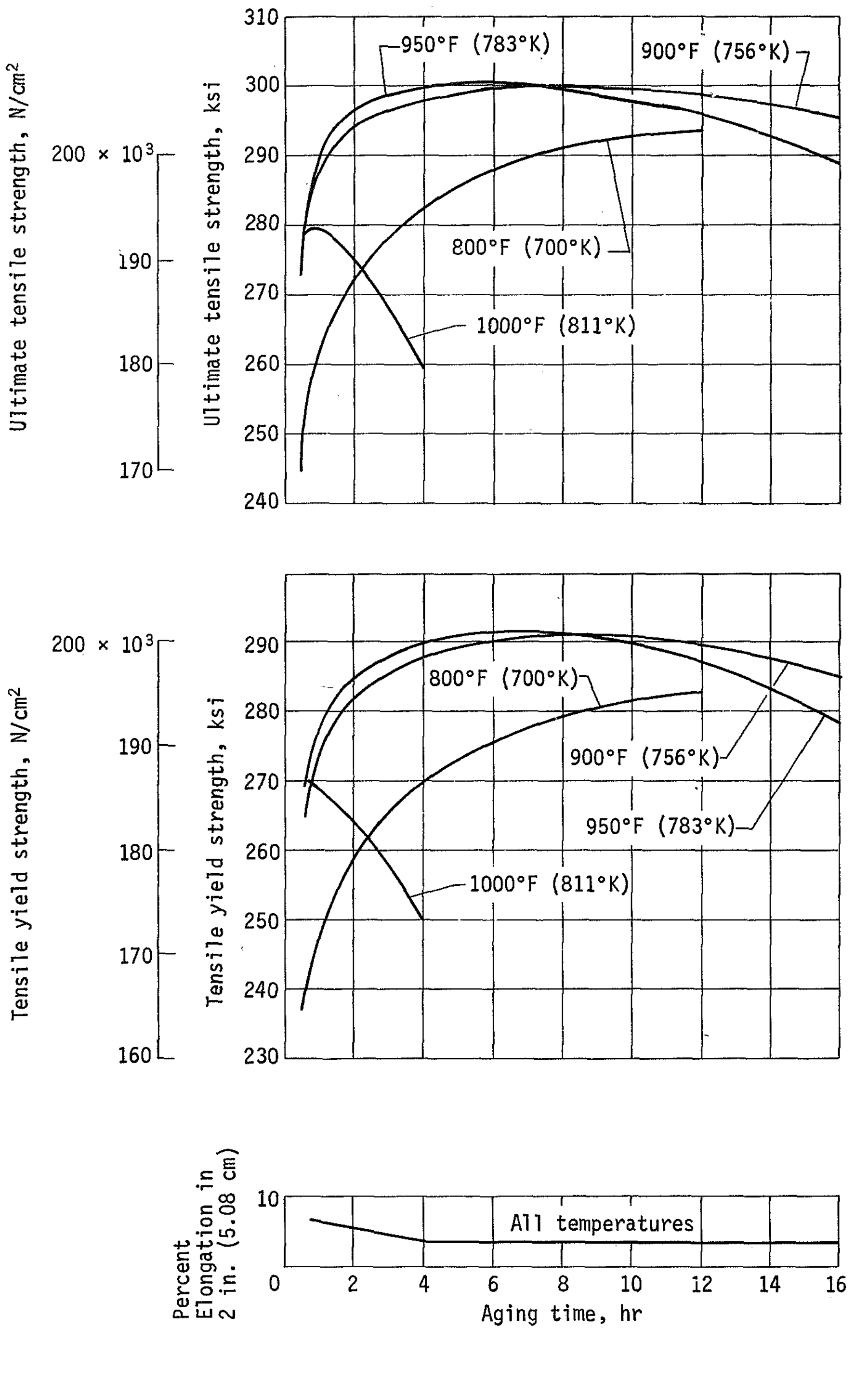


Figure 63 Constant Temperature Aging Curves, PH 14-8 Mo Strained 10% at -320°F (78°K)

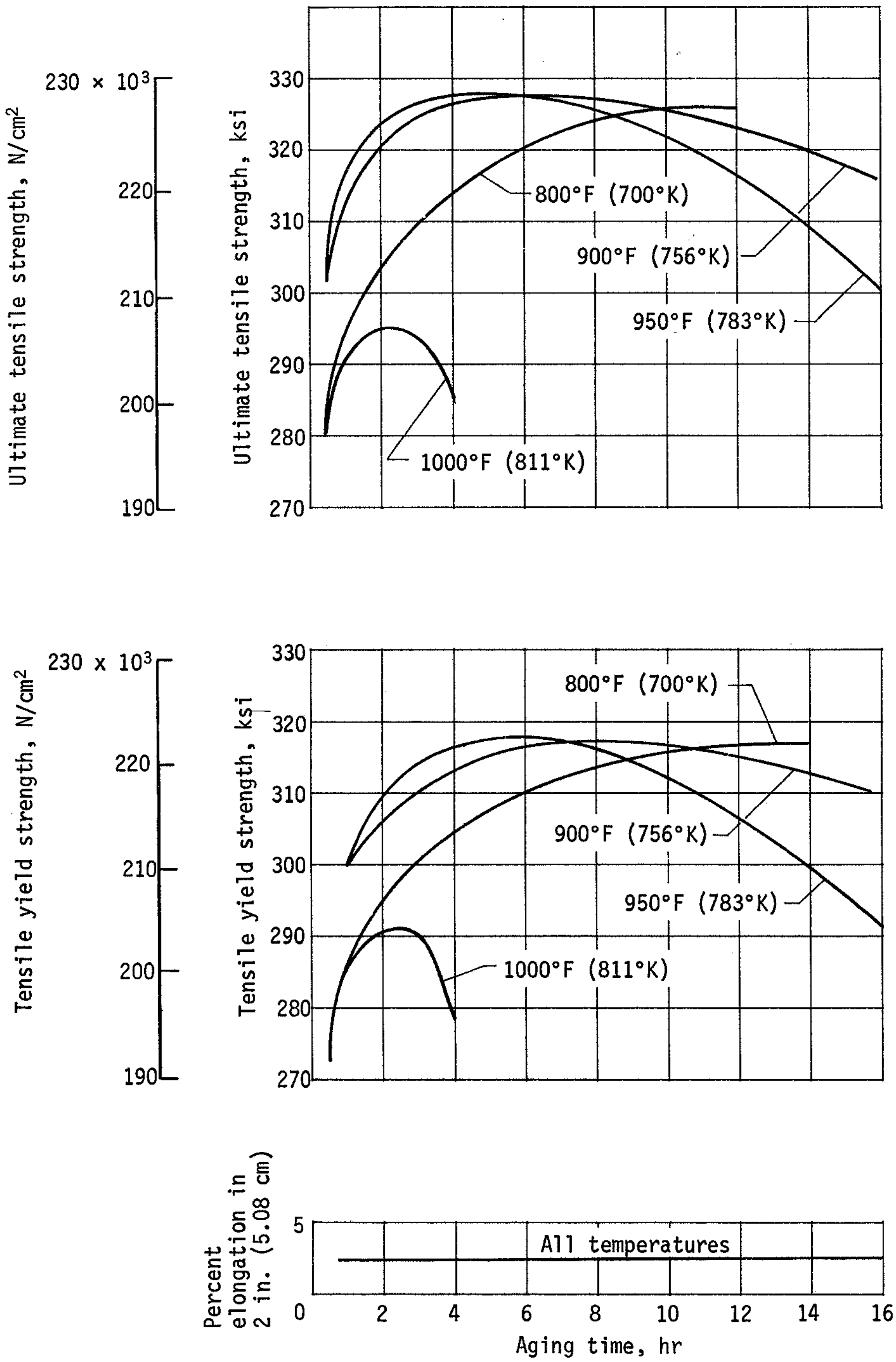


Figure 64 Constant Temperature Aging Curves, PH 14-8 Mo Strained 13% at -320°F (78°K)

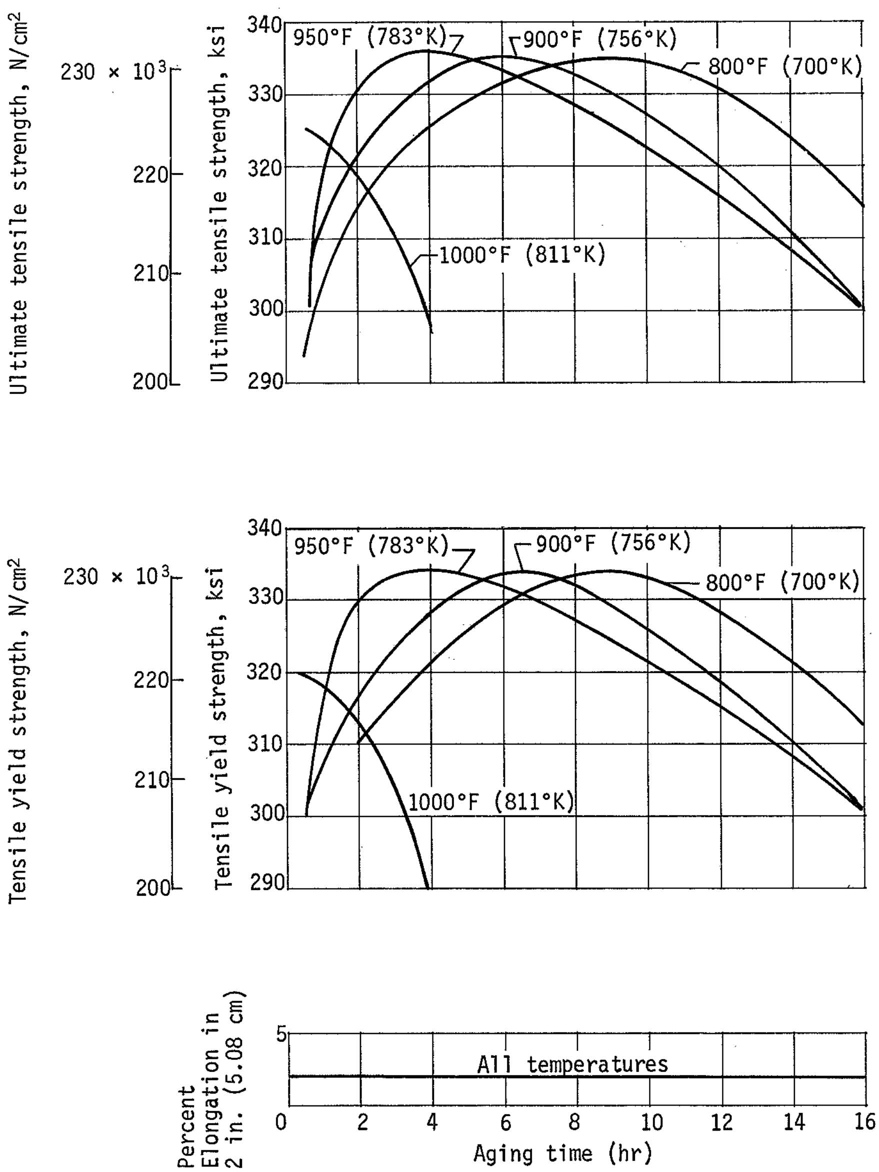


Figure 65 Constant Temperature Aging Curves, PH 14-8 Mo Strained 16% at -320°F (78°K)

The secondary purpose of Task VII was to choose ten temperature-time aging cycles for use in the Task VIII stress corrosion and toughness test series. The aging cycles indicated in the following tabulation were selected for that purpose.

Time (hr)	Temperature		
	800°F (700°K)	900°F (756°K)	950°F (783°K)
1	X	X	X
2		X	
4	X	X	X
8	X	X	X

TASK VIII - TOUGHNESS, STRESS CORROSION, HIGH ENERGY RATE STRAINING, AND COMPRESSION TESTS

Toughness Tests

Results: Results of the edge-notched and center-cracked specimen tests are listed in Table 27. Figure 66 is a plot of the notched-unnotched strength ratios for both types of specimens vs aging time at the three aging temperatures.

Discussion: The data plotted in Figure 66 indicate that cryostrained PH 14-8 Mo aged at 950°F (783°K) develops better notched-unnotched strength ratios than aging at 900°F (756°K) or at 800°F (700°K).

In Task VII it was found that essentially equal room temperature tensile properties can be developed in cryostrained PH 14-8 Mo (for a given strain level) by aging at any of the three temperatures, if aging time is appropriately adjusted. Considering this with respect to the trend indicated in Figure 66, 800°F (700°K) is shown to be the least desirable aging temperature, since, by comparison with aging at 900°F (756°K) or 950°F (783°K), aging at 800°F (700°K) offers no improvement in tensile properties and relatively lower toughness. Similarly, aging at 900°F (756°K) is shown to be somewhat less effective than aging at 950°F (783°K) with respect to relative toughness developed at a given strength level.

Stress Corrosion Tests

Results: Specimens of PH 14-8 Mo prepared as indicated in Table 14 were exposed to a 3.5% aqueous NaCℓ solution on an alternating cycle of 10 minutes immersed in the solution, 50 minutes out of solution. The test was terminated at the completion of 523 cycles. None of the specimens developed stress corrosion cracks.

Table 28 is a compilation of test results. As is indicated, specimens of the normally heat treated PH 14-8 Mo, those in conditions SRH 950 or SRH 1050, were more affected by the salt solution than the specimens of cryostrained material or specimens tested in the room temperature strained or annealed conditions.

Table 27 Task VIII Notched Tensile Test Results [PH 14-8 Mo Prestrained at -320°F (78°K)]

Target Prestrain, %	Aging			Unnotched[a]					Edge notched[b]			Center notched[b]			Ratios	
	Temp		Time hr	Prestrain, actual, %	Ultimate strength		Yield strength		Prestrain, actual, %	Ultimate strength		Prestrain, actual, %	Net stress		EN/UN	CN/UN
	°F	°K			psi	N/cm²	psi	N/cm²		psi	N/cm²		psi	N/cm²		
10.0	900	756	1	11.0	308 700	212 800	300 000	206 900	10.0	278 000	191 800	9.5	197 900	136 500	.90	.65
10.0	900	756	2	11.0	300 900	207 500	283 500	195 500	--	c		10.0	193 500	133 500	--	.65
10.0	900	756	4	10.5	299 100	206 200	281 700	194 200	9.5	269 100	185 500	10.0	196 200	135 400[a]	.90	.66
10.0	900	756	8	10.5	306 100	211 100	297 000	204 800	10.0	288 000	198 800	10.5	206 200	142 500[a]	.95	.68
10.0	800	700	1	11.0	287 800	198 400	282 600	194 900	9.5	264 600	183 000	10.0	165 000	113 900[a]	.92	.57
10.0	800	700	4	11.0	297 400	205 100	286 100	197 300	10.0	253 000	174 600	--	c	--	.85	--
10.0	800	700	8	10.0	278 300	191 900	d	--	10.0	248 700	173 100	9.5	167 300	115 500	.90	.60
10.0	950	783	1	11.0	300 000	206 900	289 100	199 300	10.0	295 500[a]	203 500[a]	10.0	206 800	142 700	.99	.69
10.0	950	783	4	9.5	295 700	203 900	277 400	191 300	10.5	285 000	193 000	10.0	214 000	147 800[a]	.97	.72
10.0	950	783	8	10.0	282 600	194 900	269 100	185 500	10.0	300 000	207 000	10.0	209 000	144 100[a]	1.06	.74
15.0	900	756	1	17.0	321 700	221 800	317 400	218 800	14.5	249 600	192 100	--	c	--	.78	--
15.0	900	756	2	15.0	328 700	226 600	325 700	224 600	15.0	255 800	176 400	15.0	172 500	119 000[a]	.78	.53
15.0	900	756	4	15.0	327 800	226 000	321 700	221 800	15.0	274 500	189 400	--	c	--	.84	--
15.0	900	756	8	15.0	323 500	223 100	322 200	222 200	15.0	285 400	197 000	14.5	185 800	128 100	.88	.58
15.0	800	700	1	15.0	318 300	219 500	315 700	217 700	15.0	233 600	161 500[a]	15.5	132 200	91 400[a]	.74	.43
15.0	800	700	4	15.0	325 200	224 200	321 300	221 500	14.5	227 000	156 800	15.0	137 200	94 700	.70	.42
15.0	800	700	8	15.0	334 000	230 300	326 600	222 500	14.5	246 800	170 000	15.0	140 300	98 800	.74	.42
15.0	950	783	1	14.5	318 300	219 500	313 000	215 800	15.0	275 000	189 900	--	c	--	.87	--
15.0	950	783	4	14.0	309 600	213 500	304 300	209 800	15.5	296 000	204 100	15.0	194 000	133 900[a]	.96	.63
15.0	950	783	8	14.0	291 300	200 900	283 500	195 500	15.5	305 000	210 300	15.0	268 800	144 000	1.05	.72

[a]One test.
[b]Average of two tests unless noted.
[c]Specimens lost in preparation.
[d]No curve obtained.

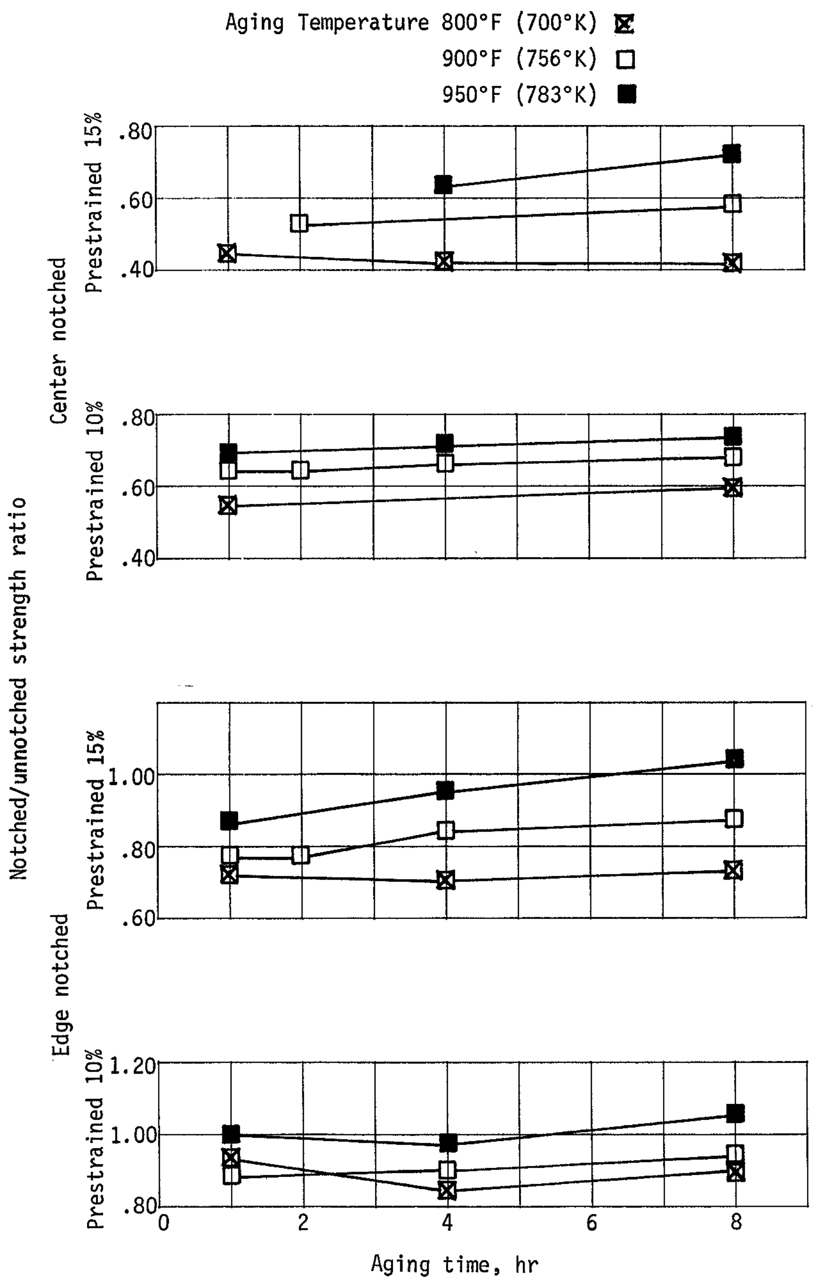


Figure 66 Notched/Unnotched Ratios, PH 14-8 Mo Prestrained at -320°F (78°K) and Aged as Indicated

Table 28 Test Results, Task VIII Stress Corrosion Tests

Specimen number (Ref. Table 14)	Specimen condition after 523 alternate immersion cycles, 10 minutes immersed in 3.5% NaCℓ solution, 50 minutes out					
	No visible change	Very light uniform rust	Light uniform rust	Moderate uniform rust	Heavy uniform rust	Sectioned for metallographic examination
AA-1N-1	X					
-2	X					
-3		X				X
AA-2N-1	X					
-2	X					
-3		X				X
AA-3N-1		X				
-2		X				
-3			X			X
AA-4N-1		X				
-2		X				
-3			X			
AA-5N-1		X				
-2		X				
-3			X			
AA-6N-1		X				
-2		X				
-3			X			X
AA-7N-1		X				
-2		X				
-3			X			
AA-8N-1		X				
-2		X				
-3			X			X
AA-9N-1		X				
-2		X				
-3			X			X
AA-10N-1		X				
-2		X				
-3			X			X
AA-11N-1		X				
-2			X			
-3			X			X
AA-12N-1			X			
-2			X			
-3			X			X

Table 28 Test Results, Task VIII Stress Corrosion Tests - Continued

Specimen number (Ref. Table 14)	Specimen condition after 523 alternate immersion cycles, 10 minutes immersed in 3.5% NaCℓ solution, 50 minutes out					
	No visible change	Very light uniform rust	Light uniform rust	Moderate uniform rust	Heavy uniform rust	Section for metallographic examination
AA-13N-1			X			
-2			X			
-3			X			X
AA-14N-1			X			
-2			X			
-3			X			X
AA-15N-1			X			
-2			X			
-3			X			
AA-16N-1			X			
-2			X			
-3			X			X
AA-17N-1			X			
-2			X			
-3			X			
AA-18N-1			X			
-2			X			
-3			X			X
AA-19N-1			X			
-2			X			
-3			X			
AA-20N-1			X			
-2			X			
-3			X			X
BB-1N-1	X					
-2	X					
-3		X				X
BB-2N-1	X					
-2	X					
-3		X				
BB-3N-1		X				
-2		X				
-3		X				X
BB-4N-1		X				
-2		X				
-3		X				

Table 28 Test Results, Task VIII Stress Corrosion Tests - Continued

Specimen number (Ref. Table 14)	Specimen condition after 523 alternate immersion cycles, 10 minutes immersed in 3.5% NaCℓ solution, 50 minutes out					
	No visible change	Very light uniform rust	Light uniform rust	Moderate uniform rust	Heavy uniform rust	Section for metallographic examination
BB-5N-1		X				
-2		X				
-3			X			X
BB-6N-1		X				
-2		X				
-3			X			
BB-7N-1		X				
-2		X				
-3			X			X
BB-8N-1		X				
-2		X				
-3			X			
BB-9N-1			X			
-2			X			
-3			X			X
BB-10N-1			X			
-2			X			
-3			X			
BB-11N-1			X			
-2			X			
-3			X			X
BB-12N-1			X			
-2			X			
-3			X			
BB-13N-1			X			
-2			X			
-3			X			X
BB-14N-1			X			
-2			X			
-3			X			
BB-15N-1			X			
-2			X			
-3			X			X
BB-16N-1			X			
-2			X			
-3			X			

Table 28 Test Results, Task VIII Stress Corrosion Tests - Continued

Specimen number (Ref. Table 14) *	Specimen condition after 523 alternate immersion cycles, 10 minutes immersed in 3.5% NaCℓ solution, 50 minutes out					
	No visible change	Very light uniform rust	Light uniform rust	Moderate uniform rust	Heavy uniform rust	Section for metallographic examination
BB-17N-1			X			
-2			X			
-3			X			X
BB-18N-1			X			
-2			X			
-3			X			
BB-19N-1			X			
-2			X			
-3			X			X
BB-20N	Blank damaged in processing					
XX-1						
XX-2		X				
XX-3		X				
XX-4		X				
XX-5		X				
XX-6		X				X
S9-1					X	
S9-2					X	
S9-3					X	
S9-4					X	
S9-5					X	
S9-6					X	X
S1-1				X		
S1-2					X	
S1-3					X	
S1-4				X		
S1-5					X	
S1-6					X	X
AA-1R-1	X					
-2	X					
-3	X					X
AA-2R-1	X					
-2	X					
-3	X					
BB-1R-1	X					
-2	X					
-3	X					X

Table 28 Test Results, Task VIII Stress Corrosion Tests - Concluded

Specimen number (Ref. Table 14)	Specimen condition after 523 alternate immersion cycles, 10 minutes immersed in 3.5% NaCℓ solution, 50 minutes out					
	No visible change	Very light uniform rust	Light uniform rust	Moderate uniform rust	Heavy uniform rust	Section for metallographic examination
BB-2R-1		X				
-2		X				
-3		X				

Discussion: The results indicate that PH 14-8 Mo in the annealed, cryostrained and aged, or room temperature strained and aged conditions is more resistant to corrosion by the 3.5% NaCℓ solution than PH 14-8 Mo in either the SRH 950 or SRH 1050 conditions.

Figures 67, 68, and 69 are photomicrographs of sections through the most highly stressed portions of specimens S1-6, S9-6 and BB-19N-3 (Ref. Table 14). BB-19N-3 was representative of rusted cryostrained specimens, S1-6 and S9-6 were specimens of SRH 1050 and SRH 950 conditioned PH 14-8 Mo, respectively. All three had been stressed to 80% of their tensile yield strength when exposed to the salt solution. Figures 68 and 69 show intergranular corrosion of both the SRH 1050 and SRH 950 specimens, while there is no evidence of such attack of the cryostrained material shown in Figure 67. Of the specimens examined metallographically only the SRH 1050 and SRH 950 specimens showed evidence of intergranular attack.

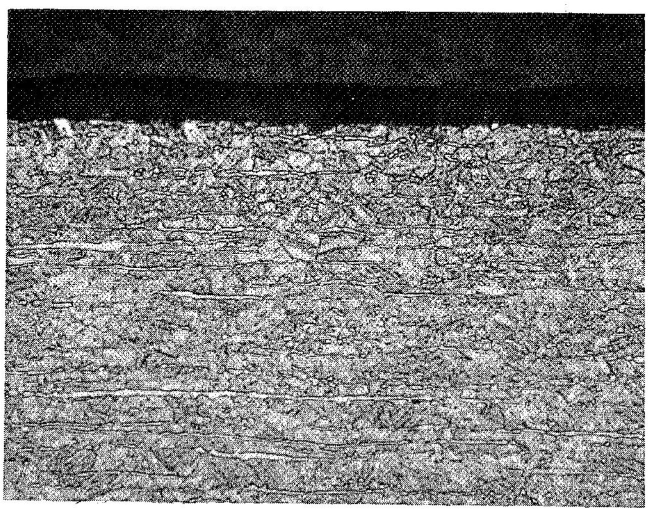


Figure 67.
Photomicrograph of a Section through the Highly Stressed Region of Specimen BB-19N-3.
(500 X)

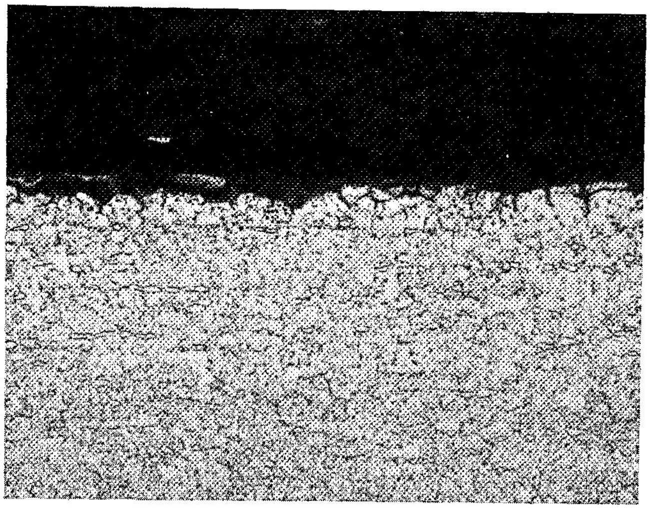


Figure 68.
Photomicrograph of a Section through the Highly Stressed Region of Specimen S1-6 Showing Intergranular Attack.
(500X)

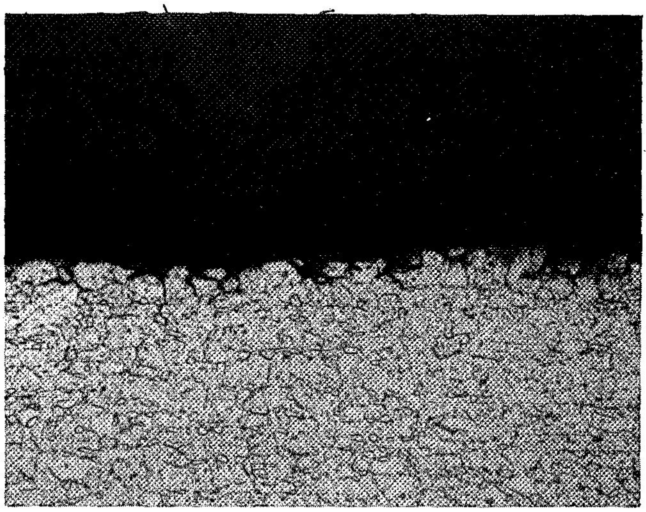


Figure 69.
Photomicrograph of a Section through the Highly Stressed Region of Specimen S9-6 Showing Intergranular Attack.
(500X)

High Energy Rate Straining Tests

Results: The high energy rate straining test results are listed in Tables 29 and 30. Table 31 is a compilation of the room temperature tensile properties developed by the PH 14-8 Mo sheet material through various methods of cryo-working followed by aging one hour at 900°F (756°K). The values listed are taken from tables 25, 26 and 30.

Discussion: The data in Table 31 indicate that higher strain rates do offer some advantage with respect to the amount of strengthening achieved per unit of strain. PH 14-8 when strained 6.0% by the explosive (high energy rate) method developed almost the identical room temperature tensile properties it developed when strained 9.0% at a rate of 1.5 in./in./minute in uniaxial tension. Also, when strained 9.0% in uniaxial tension at a strain rate of 0.050 in./in./minute the yield strength developed by the PH 14-8 Mo was about 25%

less than its yield strength after being strained 9.0% at 1.5 in./in./minute. Then, a comparison of the properties developed by the material strained 3.0% by the high energy rate method and the material strained in uniaxial tension at a rate of 0.050 in./in./minute show a 7.0% higher yield strength for the high energy rate strained material, and equivalent elongations. The data indicate that cryostraining at higher strain rates results in the development of higher room temperature tensile strengths per unit of strain compared with the effects produced by straining at lower rates. However, elongation degrades in correspondence with improvement in strength, regardless of the strain rate. Thus, while the rate of strengthening apparently increases as strain rate increases, the data indicate that the same total effect can be achieved regardless of strain rate by merely adjusting the total amount of strain to correspond with the strain rate used and the strengthening desired.

Table 29 Room Temperature Tensile Properties of PH 14-8 Mo Prestrained at Room Temperature by a High Energy Rate (Explosive) Method and Aged One Hour at 900°F (756°K)

Grain[a] direction	Prestrain %	Room temperature tensile properties				
		Ultimate strength		Yield strength, 0.2% offset		Elongation, % in 2 in. (5.08 cm)
		psi	N/cm^2	psi	N/cm^2	
L	9.0	141 800	97 800	131 800	90 900	18.5
L	9.5	147 300	101 600	126 100	86 900	18.5
L	9.0	140 900	97 200	122 700	84 600	17.5
L	9.5	150 900	104 000	124 100	85 600	19.5
L	10.0	144 500	99 600	118 200	81 500	20.5
L	10.5	139 100	95 900	127 300	87 800	21.0
L	10.5	147 300	101 600	139 100	95 900	20.5
L	9.0	140 900	97 200	---	---	23.0
Avg		144 100	99 400	127 000	87 600	20.0
T	9.0	140 000	96 500	---	---	18.0
T	9.0	143 600	99 000	---	---	18.5
T	9.0	135 200	93 200	112 800	77 800	18.5
T	9.0	140 000	96 500	99 100	68 300	18.0
T	9.5	139 100	95 900	133 900	92 300	17.5
T	9.5	147 300	101 600	144 600	99 700	16.5
Avg		140 900	97 100	122 600	84 500	18.0
T	13.0	266 100	183 500	260 400	179 500	5.5

[a]Relative to mill rolling, L = Longitudinal, T = Long transverse.

Table 30 Room Temperature Tensile Properties of PH 14-8 Mo Prestrained at -320°F (78°K) by a High Energy Rate (Explosive) Method and Aged One Hour at 900°F (756°K)

Grain[a] direction	Prestrain %	Room temperature tensile properties				
		Ultimate strength		Yield strength, 0.2% offset		Elongation, % in 2 in. (5.08 cm)
		psi	N/cm^2	psi	N/cm^2	
L	3.0	239 100	164 900	216 500	149 300	11.0
L	3.0	241 700	166 700	215 200	148 400	11.0
Avg		240 400	165 800	215 600	148 700	11.0
L	7.0	279 100	192 400	268 300	185 000	4.5
L	6.0	280 900	193 700	269 600	185 900	3.5
L	6.0	267 000	184 100	243 500	167 900	5.5
L	6.0	279 100	192 400	258 700	178 400	3.5
Avg		276 500	190 600	260 000	179 300	4.25
T	5.0	225 800	155 700	182 500	125 800	10.0
T	5.0	225 000	155 100	183 300	126 500	10.5
T	5.0	229 200	158 000	191 700	132 100	9.5
T	5.0	240 800	166 000	212 500	146 500	6.0
T	5.0	225 200	155 300	199 100	137 300	5.5
T	5.0	228 000	157 200	203 200	140 100	9.0
T	5.0	242 600	167 300	223 900	154 400	4.5
Avg		230 900	159 200	199 500	137 500	8.0

[a]Relative to mill rolling, L = Longitudinal, T = Long transverse.

Table 31 Room Temperature Tensile Properties of PH 14-8 Mo Cryoworked by Various Methods

Method of cryoworking at -320°F (78°K)	Actual prestrain, %	Strain rate		Room temperature tensile properties				
				Ultimate		Yield		Elongation % in 2 in. (5.08 cm)
		in./in./min	cm/cm/min	psi	N/cm²	psi	N/cm²	
Uniaxial tension	9.0	0.050	0.050	253 700	174 900	200 100	138 000	11.5
	14.5	0.050	0.050	324 100	223 500	321 700	221 800	2.0
	9.0	1.5	1.5	275 400	189 900	259 600	179 000	4.5
	13.0	1.5	1.5	314 900	217 100	305 200	210 400	2.0
Roll strained	(b)	N/A	N/A	307 500	212 000	283 000	195 100	2.0
High energy rate	3.0	N/A	N/A	240 400	165 800	215 600	148 700	11.0
	6.0	N/A	N/A	276 500	190 600	260 000	179 300	4.5

[a]Longitudinal properties after cryoworking and aging one hour at 900°F (756°K).

[b]Material thickness reduced from 0.050 in. (0.127 cm) to 0.043 in. (0.109 cm).

Compression Tests

Results: Table 32 is a compilation of the results of the compression test series of tests.

Discussion: For strained and aged PH 14-8 Mo, whether strained at -320°F (78°K) or at room temperature, and for PH 14-8 Mo in the SRH 950 and SRH 1050 conditions, compression and tensile yield strengths are essentially equal. However, the Bauschinger effect (ref 15) is manifest in the reduced compression yield strength of the strained and unaged PH 14-8 Mo material. However, the data indicate that aging, even for short periods at 800°F, provides sufficient stress relief that the Bauschinger effect is not a problem with strained and aged PH 14-8 Mo.

Table 32 Task VIII Compression Test Series Results

Strain			Aging			Grain dir.[a]	Compression tests			Tensile tests					
Temp.		Target	Temp.		Time		Actual prestrain	Yield strength		Actual prestrain	Ultimate strength		Yield strength		Elongation % in 2 in. (5.08 cm)
°F	°K	%	°F	°K	hr		%	psi	N/cm²	%	psi	N/cm²	psi	N/cm²	
-320	78	8	900	756	1	L	8.5	235 200	162 200	6.0	239 200	164 900	174 000	120 000	12.0 X
-320	78	8	900	756	8	L	8.0	238 900	164 700	8.0	256 900	177 200	224 500	154 700	9.0
-320	78	8	950	783	1	L	8.0	241 500	166 500	8.0	257 000	177 200	219 000	151 000	9.5
-320	78	8	950	783	8	L	8.0	233 100	160 500	8.0	253 500	174 800	221 800	153 000	9.0
-320	78	15	900	756	1	L	15.5	283 000	195 100	15.0	324 100	233 500	321 700	221 800	2.0 X
-320	78	15	900	756	8	L	13.5	281 500	194 100	15.0	326 000	225 000	318 600	219 700	2.0
-320	78	15	950	783	1	L	15.0	277 800	191 500	15.0	303 100	209 000	301 100	207 700	2.0
-320	78	15	950	783	8	L	15.0	299 800	206 800	12.0	291 300	200 900	279 800	192 900	2.5
-320	78	8	900	756	1	T	7.5	222 300	153 700	9.0	253 700	174 900	200 100	138 000	11.5 X
-320	78	8	900	756	8	T	8.0	235 800	162 000	8.0	252 100	174 100	198 800	137 000	10.0
-320	78	8	950	783	1	T	7.5	207 500	151 200	8.0	250 000	172 600	204 500	140 900	9.0
-320	78	8	950	783	8	T	8.0	218 400	144 300	8.0	258 200	178 000	219 800	151 500	10.0
-320	78	15	900	756	1	T	15.5	*		16.0	330 500	227 900	324 400	223 700	2.0 X
-320	78	15	900	756	8	T	15.0	307 800	212 000	15.5	309 600	213 400	308 100	212 400	2.0
-320	78	15	950	783	1	T	13.5	292 700	195 000	15.5	303 100	209 000	300 500	207 200	2.0
-320	78	15	950	783	8	T	15.0	300 400	207 100	15.0	315 900	217 800	311 900	215 000	2.0
RT	RT	8	900	756	1	L	8.0	87 400	60 300	7.5	154 400	106 500	107 500	74 200	20.0 X
RT	RT	8	900	756	8	L	8.0	105 600	72 800	8.0	148 300	102 200	107 600	74 200	24.5
RT	RT	8	950	783	1	L	8.0	88 900	61 300	8.0	147 800	101 900	108 300	74 900	24.0
RT	RT	8	950	783	8	L	8.0	100 900	69 600	8.0	148 700	102 500	107 400	74 100	22.5
RT	RT	15	900	756	1	L	14.5	113 400	74 300	15.0	189 300	130 500	174 600	120 400	8.5 X
RT	RT	15	900	756	8	L	15.0	113 400	74 300	15.0	171 700	118 400	159 800	110 200	17.5
RT	RT	15	950	783	1	L	15.5	122 200	84 300	15.0	168 300	116 000	163 300	112 600	13.5
RT	RT	15	950	783	8	L	15.0	120 000	82 700	14.5	177 400	121 300	168 500	116 000	12.5

[X]Data from Task VI Testing, Ref Table 33.

[a]L = Longitudinal, T = Transverse.

* No curve obtained

Table 32 Task VIII Compression Test Series Results - concluded

Strain			Aging				Compression tests			Tensile tests					
Temp.		Target %	Temp.		Time	Grain dir.[a]	Actual prestrain %	Yield strength		Actual prestrain %	Ultimate strength		Yield strength		Elongation % in 2 in. (5.08 cm)
°F	°K		°F	°K	hr			psi	N/cm^2		psi	N/cm^2	psi	N/cm^2	
RT	RT	8	900	756	1	T	8.0	83 800	57 800	8.5	149 900	103 400	109 400	75 400	24.0 X
RT	RT	8	900	756	8	T	8.0	91 800	63 200	8.0	146 100	100 700	105 200	72 500	22.5
RT	RT	8	950	783	1	T	8.0	98 100	67 600	8.0	144 000	99 300	106 300	72 800	23.0
RT	RT	8	950	783	8	T	8.0	101 600	70 100	8.0	142 600	98 300	104 300	71 900	23.0
RT	RT	15	900	756	1	T	15.0	114 900	79 200	16.0	191 200	131 800	174 800	120 500	7.5 X
RT	RT	15	900	756	8	T	15.0	122 200	84 300	15.0	179 100	123 500	162 500	112 100	8.0
RT	RT	15	950	783	1	T	15.0	128 900	88 900	15.0	167 000	115 000	159 200	109 700	11.0
RT	RT	15	950	783	8	T	15.0	120 400	83 000	15.0	174 300	120 100	158 700	109 400	12.5
-320	78	8	---	---	---	L	8.0	95 400	66 400	6.0	202 600	139 700	104 500	72 100	9.5 X
-320	78	15	---	---	---	L	15.0	163 400	112 700	14.5	259 400	178 900	255 600	176 200	2.5 X
-320	78	8	---	---	---	T	8.0	98 200	67 700	5.5	173 000	119 300	88 000	60 700	11.0 X
-320	78	15	---	---	---	T	15.5	164 500	111 100	16.0	262 600	181 100	258 400	178 200	4.0 X
RT	RT	8	---	---	---	L	8.0	63 400	43 700	7.5	140 700	97 000	103 500	71 400	20.0 X
RT	RT	15	---	---	---	L	15.0	96 400	66 400	15.0	148 500	102 400	145 400	100 200	16.5 X
RT	RT	8	---	---	---	T	8.0	64 800	44 700	8.5	140 600	97 000	104 500	72 100	20.0 X
RT	RT	15	---	---	---	T	15.0	93 800	64 700	16.0	149 600	103 100	147 700	101 800	15.5 X
SRH			950			L		232 300	160 200		234 800	161 900	224 000	154 400	4.0
SRH			950			T		241 500	164 000		242 400	167 000	230 100	158 600	5.0
SRH			1050			L		221 000	152 400		220 100	151 700	215 900	148 200	8.0
SRH			1050			T		---	---		223 200	160 000	222 000	151 600	5.0

[X]Data from Task VI Testing, Ref Table 33.

[a]L = Longitudinal, T = Transverse.

VI. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The general conclusion that can be drawn from the results of this program is that PH 14-8 Mo can be cryostrained and aged to strengths above those achieved by industry standard treatments. Also, at some strengths above the normal level, the cryostrained and aged PH 14-8 Mo will retain sufficient toughness and corrosion resistance to be considered a useful structural material.

Specific conclusions drawn from the results of this study are:

1) PH 14-8 Mo, PH 15-7 Mo, and 17-7 PH, can be cryostrained and aged to strengths above 300 000 psi (206 900 N/cm^2).

2) The strengths developed by the three alloys through cryostraining are not significantly affected by the rate of straining.

3) Cryostrained PH 14-8 Mo can be aged to the same maximum strength for a given strain level at temperatures between 800°F (700°K) and 950°F (783°K) provided the aging time is adjusted according to aging temperature. Aging time decreases as aging temperature increases.

4) The toughness of cryostrained PH 14-8 Mo, for a strength level, improves with increasing aging temperature. Therefore, the recommended aging temperature is 950°F (783°K).

5) Aging cryostrained PH 14-8 Mo at 1000°F (811°K) or 1050°F (866°K) results in overaging.

6) The compression yield strength of cryostrained (tension) and unaged PH 14-8 Mo is markedly reduced due to the Bauschinger effect.

7) Aging cryostrained PH 14-8 Mo provides sufficient stress relief so that degradation of the compression yield strength from the Bauschinger effect is eliminated.

8) PH 14-8 Mo SRH 950 and PH 14-8 Mo SRH 1050 are less resistant to corrosion by 3.5% NaCℓ solution than PH 14-8 Mo in the annealed, cryostrained and aged, or room temperature strained and aged conditions.

9) PH 14-8 Mo cryostrained at -320°F (78°K) and aged 4 hr at 950°F (783°K) develops an ultimate tensile strength 20% higher than PH 14-8 Mo condition SRH 950, while for the same conditions the notched to unnotched strength ratios are essentially equivalent (Ref 10 and Table 27).

10) PH 14-8 Mo cryostrained 10% at -320°F (78°K) and aged 4 hr at 950°F (783°K) (Table 27) has an ultimate tensile strength to density ratio of 1.03×10^6 inches (2.62×10^6 cm), while the equivalent value for PH 14-8 Mo condition SRH 950 is 0.88×10^6 inches (2.24×10^6 cm).

Recommendations

The data compiled so far indicate that cryostrained and aged PH 14-8 Mo is a potentially useful structural material. But, before a final determination can be made other data must be obtained. For that purpose the following recommendations for additional study are made.

1) Determine the resistance of cryostrained and aged PH 14-8 Mo to corrosion by salt air, industrial environment, and appropriate propellants and pressurants, commonly used in aerospace vehicles, as well as solvents, and media used in cleaning and fabrication processes.

2) Study the effects of cryostraining and aging on the fatigue properties of PH 14-8 Mo.

3) Determine the properties of cryostrained and aged PH 14-8 Mo at cryogenic and elevated temperatures.

4) Determine K_{Ic}, K_c and K_{TH} (in appropriate media and environments) for cryostrained and aged PH 14-8 Mo.

APPENDIX

TEST RESULTS FOR TASKS VI AND VII

(For Task VIII refer to Tables 27, 28, 29, 30, and 32; for Tasks II, III, and IV refer to Reference 8.)

Table 33 Test Results, Task VI Parent Metal Tests, PH 14-8 Mo

Strain level[b,c]	Target strain %	Room temperature tensile properties[a]													
		Prestrained at room temperature						Prestrained at -320°F (78°K)							
		Actual strain %	Ultimate strength		Yield strength 0.2% offset		Elongation % in 2 in. (5.08 cm)	Actual strain %	Ultimate strength		Yield strength 0.2% offset		Elongation % in 2 in. (5.08 cm)		
			psi	N/cm²	psi	N/cm²			psi	N/cm²	psi	N/cm²			
0%(L)	0	0	132 600	91 400	56 600[d]	39 000	28.5	0	135 100	93 200	56 400	38 900	28.0		
A (L)	8.0	7.5	140 700	97 000	103 500	71 400	20.0	6.0	202 600	139 700	104 500	72 100	9.5		
B (L)	12.0	11.5	143 800	99 200	132 300	91 200	17.5	9.0	216 800	149 500	135 000	93 100	9.0		
C (L)	15.0	15.0	148 500	102 400	145 400	100 200	16.5	14.5	259 400[d]	178 900	255 600[e]	176 200	2.5		
D (L)	18.0	18.5	160 200	110 500	154 400	106 500	10.5	17.5	257 300	177 400	256 900	177 100	1.5		
0%(L) A	0	0	131 500	90 700	52 800	36 400	29.5	0	131 000	90 300	56 400	38 900	28.5		
A (L) A	8.0	7.5	154 400	106 500	107 500	74 200	23.5	6.0	239 200	164 900	174 000	120 000	12.0		
B (L) A	12.0	11.5	162 800	112 300	145 800	100 500	21.5	9.0	253 700	174 900	200 100	138 000	11.5		
C (L) A	15.0	15.0	189 300	130 500	174 600[d]	120 400	8.5	14.5	324 100	223 500	321 700[d]	221 800	2.0		
D (L) A	18.0	18.5	209 400	144 400	206 100	142 100	5.5	17.5	330 700	228 000	327 900[d]	226 100	1.5		
0%(T)	0	0	132 700	91 500	52 400	36 100	29.0	0	132 800	91 600	51 900	35 800	29.0		
A (T)	8.5	8.5	140 600	97 000	104 500	72 100	20.0	5.5	173 000	119 300	88 000	60 700	11.0		
B (T)	12.5	12.0	142 400	98 100	132 000[d]	91 000	17.0	12.0	233 700	161 100	221 600[d]	152 800	4.5		
C (T)	16.0	16.0	149 600	103 100	147 700[d]	101 800	15.5	16.0	262 600	181 100	258 400	178 200	4.0		
D (T)	19.0	19.5	158 500	109 300	157 100	108 300	10.5	20.0	256 100[g]	176 600	---[f]	---	1.5		
0%(T) A	0	0	134 200	92 500	52 400	36 100	28.0	0	132 200	91 200	53 800	37 100	28.5		
A (T) A	8.5	8.5	149 900	103 400	109 400	75 400	24.0	5.5	221 000	152 400	149 500	103 100	13.0		
B (T) A	12.5	12.0	164 100	113 100	145 800	100 500	19.5	12.0	303 400	209 200	295 700	203 900	2.5		
C (T) A	16.0	16.0	191 200	131 800	174 800	120 500	7.5	16.0	330 500	227 900	324 400[d]	223 700	2.0		
D (T) A	19.0	19.5	207 300	142 900	203 500[d]	140 300	4.5	19.0	332 300	229 100	326 300[d]	225 000	1.5		

[a]Average of three tests unless noted.

[b](L) = longitudinal, (T) = transverse, relative to mill rolling.

[c]A = aged 1 hour at 900°F (756°K).

[d]2 tests.

[e]One test.

[f]Specimens failed before 0.2% offset strain.

[g]One specimen.

Table 34 Test Results, Task VI Parent Metal Tests, PH 15-7 Mo

Strain level[b,c]	Target strain %	Room temperature tensile properties[a]														
		Prestrained at room temperature							Prestrained at -320°F (78°K)							
		Actual strain %	Ultimate strength		Yield strength 0.2% offset		Elongation % in 2 in. (5.08 cm)		Actual strain %	Ultimate strength		Yield strength 0.2% offset		Elongation % in 2 in. (5.08 cm)		
			psi	N/cm²	psi	N/cm²				psi	N/cm²	psi	N/cm²			
0%(L)	0	0	129 800	89 500	64 500	44 500	39.0		0	132 100	91 100	64 400	44 400	43.0		
A%(L)	9.0	9.0	140 500	96 900	100 100	69 000	27.5		7.0	221 100	152 400	158 400	109 200	11.5		
B%(L)	13.0	13.0	147 000	101 400	121 800	84 000	26.5		13.0	273 200	188 400	261 300[d]	180 200	1.0		
C%(L)	16.5	16.5	149 900	103 400	130 700	90 100	21.0		16.5	268 900	185 400	---[g]	---	1.5		
D%(L)	20.0	20.0	155 100	106 900	143 900	99 200	20.0		18.5	263 900	181 600	---[g]	---	1.0		
0%(L) A	0	0	133 300	91 900	69 200	47 700	40.5		0	133 600	92 100	69 000	47 500	44.5		
A%(L) A	9.0	9.0	147 100	101 400	114 700	79 100	34.0		7.0	252 200	172 900	206 300	142 200	11.5		
B%(L) A	13.0	13.0	160 200	110 500	141 100	97 300	29.0		13.0	328 300	226 400	323 600	223 100	3.0		
C%(L) A	16.5	16.5	161 300	111 200	153 500	105 800	24.0		16.5	339 900	234 400	314 700[f]	216 800	1.5		
D%(L) A	20.0	20.0	177 300	122 200	172 700	119 700	15.0		20.0	344 500[e]	237 500	339 600[e]	234 200	1.5		
0%(T)	0	0	129 400	89 200	54 700	37 700	38.5		0	129 200	89 100	54 400	37 500	39.0		
A%(T)	9.0	9.0	139 300	96 000	103 100	71 100	27.0		8.0	224 000	154 400	163 500	112 700	8.5		
B%(T)	13.0	13.0	139 600	96 300	118 400	163 700	26.5		13.0	253 500	174 800	246 200[f]	169 800	1.5		
C%(T)	16.5	16.5	141 900	97 800	123 000	84 800	20.0		16.5	264 400	182 300	258 300[d]	178 100	1.0		
D%(T)	20.0	20.0	146 700	101 100	143 400	98 900	15.0		20.0	264 700	182 500	---[g]	---	0.5		
0%(T) A	0	0	129 800	89 500	60 400	41 600	39.5		0	129 300	89 200	58 900	41 200	38.0		
A%(T) A	9.0	9.0	145 100	100 000	113 300	78 100	30.5		8.0	266 100	183 500	230 000	158 600	9.5		
B%(T) A	13.0	13.0	150 400	103 700	131 900	90 900	28.0		13.0	323 900	223 300	313 200	216 000	1.5		
C%(T) A	16.5	16.5	154 600	106 600	132 100	91 100	25.5		16.5	343 300	236 700	340 100	234 500	1.0		
D%(T) A	20.0	20.0	177 300	122 200	173 600	119 700	11.0		20.0	338 500	233 400	338 000[d]	233 100	1.0		

[a]Average of three tests unless noted.

[b](L) = longitudinal, (T) = transverse, relative to mill rolling.

[c]A = aged 1 hr at 900°F (756°K).

[d]One test, 2 specimens failed before 0.2% offset strain.

[e]2 tests.

[f]2 tests, one specimen failed before 0.2% offset.

[g]Specimens failed before 0.2% offset strain.

Table 35 Test Results, Task VI Parent Metal Tests, 17-7 PH

Strain level[b,c]	Target strain %	Room temperature tensile properties[a]													
		Prestrained at room temperature						Prestrained at -320°F (78°K)							
		Actual strain %	Ultimate strength		Yield strength 0.2% offset		Elongation % in 2 in. (5.08 cm)	Actual strain %	Ultimate strength		Yield strength 0.2% offset		Elongation % in 2 in. (5.08 cm)
			psi	N/cm²	psi	N/cm²			psi	N/cm²	psi	N/cm²	
0%(L)	0	0	119 000	82 100	48 000	33 100	52.5	0	117 200	80 800	47 300	32 600	52.0
A (L)	10.0	10.0	126 600	87 300	84 300	58 100	41.5	9.5	219 100	151 100	163 300	112 600	10.5
B (L)	15.0	15.0	127 400	87 800	94 600	65 200	35.5	15.0	232 500	160 300	219 900	151 600	6.0
C (L)	19.0	19.0	142 000	97 900	114 000	78 600	28.5	19.5	---[d]	---	---	---	
D (L)	22.0	22.0	141 300	97 400	124 200	85 600	23.5	21.0	273 600	188 600	271 900	187 500	1.5
0%(L) A	0	0	117 700	81 200	48 200	33 200	55.0	0	119 400	82 300	49 200	33 900	58.5
A (L) A	10.0	10.0	131 400	90 600	90 000	62 100	44.5	9.5	256 100	176 600	214 600	148 000	12.5
B (L) A	15.0	15.0	138 800	95 700	111 200	76 700	37.5	15.0	319 000	220 000	308 600	212 800	2.0
C (L) A	19.0	19.0	150 400	103 700	134 600	92 800	29.0	19.5[e]	327 000	225 500	317 900	219 200	2.0
D (L) A	22.0	22.0	156 600	108 000	146 500	101 000	15.5	21.0	339 000	233 700	336 500	232 000	1.5
0%(T)	0	0	118 100	81 400	43 800	30 200	50.5	0	115 600	79 700	43 600	30 100	51.5
A (T)	8.0	8.0	121 900	84 100	78 200	53 900	42.5	9.5	216 800	149 500	158 700	109 400	10.0
B (T)	12.0	12.0	127 900	88 200	87 500	60 300	34.5	12.0	228 700	157 700	189 500	130 700	7.0
C (T)	15.0	15.0	135 600	93 500	100 400	69 200	31.0	18.0	Combined with D level				
D (T)	18.0	18.0	133 200	91 800	107 500	74 100	27.0	18.0	267 200	184 300	266 600	184 000	1.5
0%(T) A	0	0	121 100	83 500	46 600	32 100	51.0	0	120 400	83 000	46 500	32 100	51.0
A (T) A	8.0	8.0	125 900	86 800	84 200	58 100	46.0	9.5	250 400	172 700	195 000	134 500	7.5
B (T) A	12.0	12.0	131 500	90 700	97 400	67 200	40.0	12.0	270 200	186 300	247 200	170 400	6.5
C (T) A	15.0	15.0	141 900	97 800	113 500	78 300	37.5	18.0	Combined with D level				
D (T) A	18.0	18.0	143 000	98 600	117 600	81 100	33.5	18.0	326 600	225 800	322 100	221 400	1.5

[a]Average of three tests.

[b](L) = Longitudinal, (T) = Transverse, with respect to mill rolling.

[c]A = Aged 1 hour at 900°F (756°K).

[d]No specimens tested.

[e]Average six tests.

Table 36 Test Results, Task VII

Prestrain		Heat treatment			Room temperature tensile properties[a]				
Target %	Actual %	Temp °F	Temp °K	Time, hr	Ultimate strength psi	Ultimate strength N/cm²	Yield strength psi	Yield strength N/cm²	Elongation, % in 2 in. (5.08 cm)
(P level)[b]									
10.0	10.0	800	700	0.5	245 800	169 500	238 000	164 100	7.5
10.0	10.0	800	700	1.0	265 800	179 800	248 000	171 000	9.0
10.0	10.0	800	700	2.0	277 600	191 400	252 500	174 100	8.0
10.0	10.0	800	700	4.0	281 000	193 700	267 300	184 300	6.5
10.0	9.0	800	700	6.0	292 000	201 300	267 500	191 300	5.5
10.0	9.0	800	700	8.0	288 000	198 600	267 000	184 100	3.5
10.0	9.0	800	700	12.0	280 000	193 100	271 800	187 000	3.0
10.0	10.0	900	756	0.5	280 400	193 300	264 600	182 400	8.5
10.0	10.0	900	756	1.0	283 800	195 700	265 800	183 300	6.0
10.0	9.0	900	756	2.0	286 700	197 700	272 100	187 600	5.0
10.0	9.0	900	756	4.0	289 800	199 800	273 900	188 900	4.5
10.0	10.0	900	756	4.5	296 000	204 100	281 500	194 100	5.0
10.0	10.0	900	756	5.0	300 000	206 900	287 500	198 200	5.5
10.0	10.0	900	756	5.5	299 000	206 200	289 400	199 500	5.0
10.0	10.0	900	756	6.0	299 500	206 500	285 200	196 600	5.0
10.0	10.0	900	756	8.0	294 000	202 700	276 800	190 900	4.0
10.0	10.0	900	756	16.0	295 000	203 400	285 000	196 500	3.0
10.0	10.0	950	783	0.5	272 500	187 900	264 500	182 400	5.5
10.0	10.0	950	783	1.0	292 500	201 700	279 800	192 900	7.0
10.0	10.0	950	783	2.0	293 500	202 400	280 500	193 400	4.5
10.0	9.0	950	783	4.0	287 000	197 900	275 000	189 600	3.5
10.0	9.0	950	783	6.0	278 000	191 700	266 800	184 000	3.5
10.0	10.0	950	783	8.0	288 000	198 600	271 000	186 900	3.0
10.0	10.0	1000	811	0.5	277 500	191 300	270 500	186 500	6.5
10.0	10.0	1000	811	1.0	279 200	192 500	269 900	186 100	3.5
10.0	10.0	1000	811	2.0	275 000	189 600	264 600	182 400	3.0
10.0	10.0	1000	811	4.0	257 000	177 200	250 700	172 900	4.0
10.0	10.0	1100	866	0.5	249 100	171 800	244 800	168 900	4.0

[a]Average of two or more tests.

[b]Prestrained at -320°F (78°K).

[c]Prestrained at room temperature.

Table 36 Test Results, Task VII - Continued

Prestrain		Heat treatment			Room temperature tensile properties[a]				
Target %	Actual %	Temp °F	Temp °K	Time, hr	Ultimate strength psi	Ultimate strength N/cm²	Yield strength psi	Yield strength N/cm²	Elongation, % in 2 in. (5.08 cm)
(Q level)[b]									
13.0	12.0	800	700	0.5	281 200	193 900	273 900	188 900	2.0
13.0	14.0	800	700	1.0	302 500	208 600	299 400	206 400	2.5
13.0	13.0	800	700	2.0	305 500	210 600	303 800	209 500	2.5
13.0	12.0	800	700	4.0	294 300	202 900	292 000	201 300	2.0
13.0	12.0	800	700	6.0	307 500	212 000	304 000	209 600	2.0
13.0	13.0	800	700	8.0	325 000	224 100	317 500	218 900	2.5
13.0	14.0	800	700	12.0	330 200	227 700	321 000	221 300	2.0
13.0	13.0	900	756	0.5	305 900	210 900	300 500	207 200	2.5
13.0	14.0	900	756	1.0	318 300	219 500	312 300	215 300	2.5
13.0	12.0	900	756	2.0	307 700	212 200	300 700	207 300	2.0
13.0	12.0	900	756	4.0	312 500	215 500	307 900	212 300	3.0
13.0	11.5	900	756	4.5	307 500	212 000	303 100	209 000	2.5
13.0	13.0	900	756	5.0	327 700	225 900	313 800	216 400	2.5
13.0	12.0	900	756	5.5	318 500	219 600	316 300	218 100	3.0
13.0	12.0	900	756	6.0	320 500	221 000	317 500	218 900	3.0
13.0	12.0	900	756	8.0	316 000	217 900	308 800	212 900	2.5
13.0	13.0	900	756	16.0	316 000	217 900	310 500	214 100	2.5
13.0	13.0	950	783	0.5	302 800	208 800	300 000	207 200	2.5
13.0	13.0	950	783	1.0	313 500	216 200	308 800	212 900	2.5
13.0	12.0	950	783	2.0	308 300	212 600	304 800	210 200	3.0
13.0	12.0	950	783	4.0	312 700	215 600	308 500	212 700	3.0
13.0	12.0	950	783	6.0	299 000	206 200	292 000	201 300	2.5
13.0	13.0	950	783	8.0	311 600	145 900	306 300	211 200	2.5
13.0	13.0	950	783	16.0	300 000	206 900	288 400	198 900	2.5
13.0	13.0	1000	811	0.5	280 000	193 100	278 300	191 900	2.5
13.0	13.0	1000	811	1.0	293 000	202 000	289 000	192 400	2.5
13.0	14.0	1000	811	2.0	297 500	205 100	291 800	201 200	2.5
13.0	13.0	1000	811	4.0	282 500	194 800	275 700	190 100	3.0
13.0	13.0	1100	866	0.5	251 000	173 100	242 500	167 200	2.5

[a] Average of two or more tests.

[b] Prestrained at -320°F (78°K)

[c] Prestrained at room temperature.

Table 36 Test Results, Task VII - Continued

Prestrain		Heat treatment			Room temperature tensile properties[a]				
Target	Actual	Temp		Time	Ultimate strength		Yield strength		Elongation, % in 2 in. (5.08 cm)
%	%	°F	°K	hr	psi	N/cm²	psi	N/cm²	
(N level)[b]									
16.0	16.0	800	700	0.5	293 500	202 400	a	a	1.5
16.0	15.0	800	700	1.0	298 600	205 900	a	a	2.0
16.0	16.0	800	700	2.0	316 900	218 500	312 700	215 600	2.0
16.0	16.0	800	700	4.0	320 600	221 100	318 400	219 500	2.0
16.0	16.0	800	700	6.0	328 200	226 300	326 500	225 100	2.0
16.0	17.5	800	700	8.0	340 600	234 800	339 100	233 800	2.0
16.0	15.0	800	700	12.0	323 400	223 000	321 300	221 500	2.0
16.0	17.5	800	700	16.0	329 400	227 000	316 100	218 000	2.0
16.0	17.0	900	756	0.5	315 500	217 500	313 900	216 400	2.0
16.0	15.0	900	756	1.0	309 100	213 100	306 700	211 100	2.5
16.0	17.5	900	756	2.0	335 600	231 400	332 800	229 500	2.5
16.0	15.5	900	756	4.0	329 300	227 100	323 900	223 300	3.0
16.0	15.5	900	756	4.5	329 500	227 200	327 800	226 000	2.0
16.0	17.0	900	756	5.0	342 800	236 400	341 000	235 100	2.0
16.0	16.0	900	756	5.5	336 200	231 800	332 700	229 400	2.5
16.0	16.0	900	756	6.0	331 500	228 600	332 700	229 400	2.0
16.0	15.0	900	756	8.0	320 000	220 600	315 400	217 500	2.5
16.0	16.0	900	756	16.0	293 000	205 500	291 500	201 000	2.5
16.0	16.0	950	783	0.5	302 800	208 800	300 700	207 300	2.0
16.0	17.0	950	783	1.0	330 500	227 900	326 500	225 100	2.0
16.0	16.5	950	783	2.0	333 900	230 200	330 600	227 900	2.0
16.0	15.0	950	783	4.0	327 800	226 000	321 200	221 500	2.5
16.0	15.0	950	783	6.0	330 800	228 100	327 100	225 500	2.5
16.0	15.0	950	783	8.0	320 900	221 300	313 700	216 300	2.5
16.0	16.0	950	783	16.0	307 400	212 600	303 200	209 100	2.5
16.0	16.0	1000	811	0.5	326 700	225 300	321 000	221 300	2.5
16.0	16.0	1000	811	1.0	317 100	218 600	309 000	213 100	2.5
16.0	15.5	1000	811	2.0	311 700	214 900	307 500	212 000	2.5
16.0	16.0	1000	811	4.0	297 800	205 300	287 000	197 900	2.5
16.0	16.0	1100	866	0.5	255 500	176 200	253 700	174 900	2.5

[a]Average of two or more tests.

[b]Prestrained at -320°F (78°K).

[c]Prestrained at room temperature.

Table 36 Test Results, Task VII - Concluded

Prestrain		Heat treatment			Room temperature tensile properties[a]				
Target %	Actual %	Temp		Time, hr	Ultimate strength		Yield strength		Elongation, % in 2 in. (5.08 cm)
		°F	°K		psi	N/cm^2	psi	N/cm^2	
(NR level)[c]									
16.0	17.0	900	756	1.0	199 500	135 600	194 500	134 100	6.0
16.0	16.0	900	756	7.0	201 000	138 600	191 800	132 200	6.0
16.0	16.0	950	783	1.0	195 000	134 500	189 300	130 500	5.5
16.0	15.5	950	783	7.0	201 000	138 600	192 000	132 400	5.5
16.0	16.5	1000	811	1.0	204 500	141 000	195 500	134 800	6.5
16.0	16.0	1000	811	7.0	189 500	130 700	189 000	130 300	6.0
16.0	16.0	1050	839	1.0	186 000	128 200	177 700	122 500	6.0
16.0	16.0	1050	839	7.0	166 000	114 500	153 800	106 000	11.0

[a]Average of two or more tests.
[b]Prestrained at -320°F (78°K).
[c]Prestrained at room temperature.

APPENDIX

Table 37 Conversions

To convert from	To	Multiply by
inch	meter	0.0254
inch	centimeter	2.54
pound force, lb_f (avoirdupois)	Newton	4.4482216152605
grain	kilogram	0.00006479891
$lb_f/inch^2$ (psi)	Newton/meter^2	6894.7472
$lb_f/inch^2$ (psi)	Newton/cm^2	0.68947572
foot lb_f	joule	1.3558179
Fahrenheit (temperature)	Kelvin	$K = (5/9)\ (F + 459.67)$
$lb_m/inch^3$	gm/cc	27.679905

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