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ALCOA

DEVELOPMENT OF A HIGH STRENGTH ALUMINUM ALLOY, READILY WELDABLE IN PLATE THICKNESSES, AND SUITABLE FOR APPLICATIONS AT -423 F

FINAL REPORT

CONTRACT NO. NAS 8-5452

GEORGE C MARSHALL SPACE FLIGHT CENTER

Alcoa Research Laboratories

DEVELOPMENT OF A HIGH STRENGTH ALUMINUM ALLOY, READILY WELDABLE IN PLATE THICKNESSES, AND SUITABLE FOR APPLICATION AT -423 F (-253 C)

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by

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FOREWORD

This report was prepared by the Aluminum Company of America under Contract Number NAS 8-5452 entitled "Development of a High Strength Aluminum Alloy, Readily Weldable in Plate Thicknesses, and Suitable for Application at -423 F (-253 C)" for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the MATERIALS DIVISION, Propulsion and Vehicle Engineering Laboratory, of the George C. Marshall Space Flight Center with Mr. James H. Hess acting as Project Manager.

Mr. H. Y. Hunsicker was the Alcoa Project Coordinator, Mr. R. H. Brown, Project Advisor, and Dr. W. A. Anderson, Project Supervisor. The authors would like to acknowledge the following Alcoa Research Laboratories personnel for major contributions to the research activities: Dr. W. G. Fricke, Jr., assisted in the literature search and conducted research programs on plate and filler alloys; Dr. H. C. Stumpf conducted x-ray diffraction studies on X2021 parent plate and weldments; Mr. W. D. Vernam evaluated the effect of thermal treatments on the stress-corrosion of X7007; Mr. J. W. Coursen determined the mechanical properties of plant fabricated X2021-T81 and X7007-T6E136 sheet and plate; Mr. D. L. Robinson conducted electron microscopic examinations of metal structures.

SYNOPSIS

This report summarizes the results of a research program to develop a high-strength, weldable aluminum alloy suitable for applications at temperatures to -423 F. Work on this program was initiated with a literature search which indicated that the contract objectives could probably best be met by an alloy of the Al-Cu, Al-Mg or Al-Zn-Mg type. Research on these alloy systems showed that an Al-Cu alloy containing Cd and Sn (ultimately designated X2021) and an Al-Zn-Mg alloy (ultimately designated X7007) merited further development.

The effects of composition and thermal treatment on the strength, notch-toughness, corrosion resistance and weld properties of X2021 and X7007 were determined. Using the optimum composition and thermal treatment, sheet and plate were fabricated commercially for use in determining detailed mechanical and physical properties, weld properties and corrosion resistance of these alloys.

The nominal composition of X2021 is 6.3% Cu, .15% Cd, .05% Sn, .30% Mn, .18% Zr, .10% V and .06% Ti. Cadmium and tin promote the formation of an intense concentration of fine Al-Cu θ' transition precipitate platelets which produce high strengths. The remaining elements act as grain refiners. Strengths of this alloy are significantly reduced by cold work resulting from flattening operations which precede artificial aging. Strengths can be partially restored by employing a short aging treatment before flattening (called a pre-age). The thermal treatment to produce the T81 temper employs a pre-aging treatment before flattening and final aging. Estimated typical tensile properties of X2021-T81 are 73 ksi tensile strength, 63 ksi yield strength and 9% elongation. The notch-toughness of X2021 at room temperature is lower than that of some other aluminum alloys of similar strength. However, the notch-toughness does not decrease with decreasing testing temperatures, and at -423 F the notch-toughness is better than that of most other alloys of similar strength. The resistance to stress-corrosion cracking of X2021-T81 is very good. Alloy X2021 welded with 2319 filler alloy has excellent weldability, weld tensile strengths slightly higher than 2219, and acceptable weld ductility at room temperature and cryogenic temperatures. In the as-welded condition, weldments are susceptible to stress-corrosion cracking when stressed to 75% of the yield strength or more. Additional work is needed to determine the threshold stress. The post-weld aged condition has good resistance to stress-corrosion cracking. In summary, alloy X2021 appears to be a significant improvement in high-strength, weldable aluminum alloys.

The nominal composition of X7007 is 6.5% Zn, 1.8% Mg, .20% Mn, .12% Cr, .12% Zr, .10% Cu and .04% Ti. Strengthening is by zone formation and the precipitation of $MgZn_2$. Other elements are present to aid weldability, improve cryogenic notch-toughness and increase resistance to stress corrosion. Estimated typical properties of X7007-T6E136 are 73 ksi tensile strength, 67 ksi yield strength and 12% elongation. X7007 provides an excellent combination of strength and notch-toughness at room temperature. The notch-toughness decreases significantly with decreasing testing temperature but still meets the contract goal at -423 F. Alloy X7007 has good stress-corrosion resistance in the long transverse and longitudinal directions, but is susceptible to stress-corrosion cracking in the short-transverse direction at stress levels as low as 25% of the yield strength. X7007 can be commercially welded with 5356 filler alloy, but will require somewhat more care than 2219 or X2021. Weld tensile strengths are among the highest observed for aluminum weldments with strengths approaching 60 ksi. Weld ductility is acceptable at room temperature and cryogenic temperatures. Weldments of X7007 are susceptible to stress-corrosion cracking when stressed to 30 ksi; additional work is needed to determine the threshold stress. In view of the excellent mechanical properties and high weld strengths of X7007, additional research should be performed to solve problems in stress-corrosion cracking.

INTRODUCTION

Future space exploration will require more-powerful boosters than are available on present space vehicles. To minimize the size and cost of such boosters, metals with higher strength-weight ratios are needed. Aluminum alloy 2219 is used in the current Saturn V, S-IC booster stage, and has a tensile strength of 66-68 ksi, a yield strength of 50-56 ksi, and a weld tensile strength of approximately 40 ksi. The present report summarizes research on the development of a tough, weldable aluminum alloy with higher strengths than 2219. This research was performed under Contract NAS 8-5452.

The following properties and characteristics were tentatively established as goals in the development of the new alloy:

1. Tensile properties at room temperature:
   a. Tensile strength - 75 ksi, minimum
   b. Yield strength - 65 ksi, minimum
   c. Elongation - 10% in 2 inches, minimum
2. Tensile properties at -423 F not inferior to those specified at room temperature
3. Notched/unnotched tensile ratio (K_t = 10) at:
   a. Room temperature - 1.0 minimum
   b. At -423 F - 0.9 minimum
4. Weldability by conventional TIG or MIG techniques equivalent to those of 5456 or 2219
5. Good ductility and fracture toughness at temperatures down to -423 F in both as-welded condition and after post-weld aging

6. Weld joint efficiencies of 80% minimum at room temperature

7. Notched/unnotched tensile ratio (K_t = 10) in the as-welded condition - 0.85 minimum at -423 F

8. Maximum resistance to corrosion and stress-corrosion cracking.

The first section of this report describes the results of survey programs designed to determine what compositions and thermal treatments could fulfill the contract objectives. A literature survey of published information initiated the work and resulted in the selection of three promising alloy series: the Al-Cu, the Al-Mg and the Al-Zn-Mg series. Preliminary tests on 30 compositions and advanced evaluations of ten promising compositions resulted in the selection of two alloys which fulfilled many of the contract goals and were considered to merit further development.

The initial survey program was followed by further development work on these two alloys. Compositions and fabrication practices were surveyed to determine the optimum composition and heat treating practice, and to establish composition and property ranges. Mechanical, physical and corrosion properties were determined for plant-fabricated sheet and plate of each alloy. Filler alloys were evaluated for each alloy and mechanical and corrosion properties of weldments were determined.

The final section of this report summarizes the properties of the new alloys, compares these alloys with other commercial, weldable aluminum alloys, and considers how well the contract objectives have been fulfilled.

SURVEY PROGRAMS

LITERATURE SURVEY

In the literature search which initiated the project, published information on the properties and characteristics of various aluminum alloys showed that the existing high-strength alloys did not provide the desired combination of strength, notch-toughness and weldability. None of the readily weldable alloys developed the required strengths, whereas those alloys capable of meeting the strength requirements did not possess adequate weldability and generally did not satisfy the -423 F notch-toughness requirement.

The available information concerning the effects of composition, fabrication and heat treatment on the properties of the different types of alloys was examined to ascertain the most promising avenues for further development. It was concluded that alloys of the Al-Zn-Mg type with additions of Cr, Mn and Zr offered promise and that Al-Cu type alloys with appropriate supplementary alloying additions also had possibilities of meeting the program objectives. The Al-Mg alloys were considered to have less potential for improvement, but were believed to merit some experimental work. The possibility of increasing the strength of $Al-Mg_2Si$ alloys to the desired range was considered so remote that no development effort on them was recommended. No completely new alloy systems that would produce likely candidates for this program were revealed by the survey.

2000 SERIES ALLOYS

In the Al-Cu system, the experimental alloys investigated were modifications of 2219. Although 2219 does not develop as high strengths as 2014, it has the important advantage, for the present purposes, of superior weldability. It was hoped that the strength of 2219 could be increased by the addition of Mg, Si, Cd or Sn without sacrificing weldability.

During the preliminary survey of alloys in this system, seven compositions were prepared as .064 inch sheet. The compositions are listed in Table I and their properties are given in Table II. It should be noted that notched specimens had a sharper radius than that used in subsequent tests; therefore, the data are not strictly comparable.

The highest strengths were obtained with the alloys containing Cd and Sn. The notched/unnotched tensile ratio tended to decrease with increasing strength and was only slightly lower at -320 F than at room temperature. As illustrated in Table II, the strengths of the alloys with Cd or Sn decreased when the metal was cold worked (stretched) before aging. This effect was greater for the alloy with Cd, only. A short artificial aging treatment (pre-aging) before stretching partially restored the strengths.

Four alloys with Cd, Sn, Cd and Sn, or Mg additions showed some promise of reaching the strength goals. Therefore, additional aging studies were conducted to determine the optimum pre-aging and final aging practices, with emphasis on maximizing strengths.

Advanced tests were conducted on 0.525 and 1.0 inch plate of these most promising compositions. Compositions are given in Table I and tensile and notch-tensile properties in Table III. The notched/unnotched tensile ratios were higher than observed for sheet due to a difference in specimen design. The addition of a small amount of Mg, Cd, or Sn to 2219 did not increase strengths to the desired level and were thus eliminated from active consideration.

The addition of both Cd and Sn to 2219 resulted in strengths which met the contract requirements, but only when pre-aged before stretching. The elongation of the alloy approached the desired value of 10% in a 2 inch gage length. The notched/unnotched tensile ratio also was close to the room temperature goal, exceeded the -423 F goal and showed only slight variation with testing temperature.

Results of stress-corrosion tests on 0.525 inch and 1.0 inch plate of these alloys are shown in Tables IVa and b. Failures occurred in all four alloys at high stress levels; however, the 1.0 inch plate of the alloy with Cd and Sn had superior resistance to stress-corrosion cracking, with failure occurring only after an extended time in the accelerated corrosion test. This plate also had a high solution potential, indicating more extensive precipitation of Cu from solid solution.

Weld cracking tests were conducted using an inverted-T joint* and 2319 or parent metal strips as filler alloy. Very

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* Test described by J. D. Dowd, WELDING J. (October 1952).

little cracking was obtained, indicating good commercial weldability.

Weld properties were determined for three of the experimental alloys using 0.525 inch plate. Both MIG and TIG weldments were prepared without difficulty and radiographic examination showed sound welds. Weld properties for MIG weldments are presented in Table V. Values for TIG weldments were below those for the MIG process. In the as-welded condition the alloy with Mg had the highest weld strengths; however, after post-weld aging all alloys had similar weld strengths. Weld efficiencies were 60% for the as-welded condition and 65% for the post-weld aged condition. This is below the desired goal of 80%; however, the weld strengths of the alloys were slightly higher than those of 2219 welded with 2319. Notch-toughness of the weldments was good at both room temperature and -320 F.

The resistance to stress-corrosion cracking of these weldments was also good, with the only failures occurring in the as-welded condition after extended exposures in the accelerated corrosion test.

In summary, the survey of Al-Cu alloys showed that a modification of 2219 with Cd and Sn could meet the strength requirements. This alloy also had good notch-toughness, good weldability, and there was evidence that acceptable stress-corrosion resistance could be developed. The one property significantly below the contract goal was weld tensile strength.

This alloy, therefore, was selected for further development and was first designated M825, then later registered with the Aluminum Association as X2021.

5000 SERIES ALLOYS

Commercial 5000 series alloys, having Mg as their major alloying addition, do not age harden, but are employed in the annealed or the strain-hardened conditions. In general, they have good weldability, ductility, and resistance to corrosion. Their principal shortcoming as far as the present goals are concerned is relatively low strength. An increase of about 20 ksi in tensile and yield strength above that of existing commercial alloys would be needed to meet the contract goals.

Although the prospect of improving the strength of the 5000 series alloys by this amount was not encouraging, several approaches were tried. These were (1) increasing the Mg concentration, (2) adding Zn to provide age hardening, and (3) combining strain hardening with selected thermal treatments.

Four compositions were selected for a preliminary trial. These varied from 7 to 8.5% Mg and 0 to 2% Zn. Exact analyses are given in Table I. These alloys in the hot rolled H321 temper had tensile strengths varying from 58-64 ksi and yield strengths from 37-42 ksi. Since the strengths are significantly below the minimum strength goals, several of the alloys were cold worked various amounts in order to obtain higher properties. The following data (Table VI) are typical of the results.

TABLE VI

TENSILE PROPERTIES OF 5000 SERIES ALLOYS†

RT* Period	Stabilized 2 hr/250 F	Room Temperature TS ksi	YS ksi	% El. in 2"	NTS/TS	-320 F NTS/TS
		7.25% Mg Alloy - 75% Reduction				
0	No	85.6	72.8	5.0		
61	No	82.0	66.8	7.5	.75	.60
38	Yes	76.6	60.0	11.5	.80	.67
		8.5% Mg, 2.0% Zn Alloy - 45% Reduction				
0	No	87.6	71.0	7.5		
61	No	85.1	64.8	13.0	.88	.65
38	Yes	86.3	70.6	11.5	.88	.68

* Days at room temperature before testing or stabilizing.

† Transverse properties - 0.064 inch sheet - K_t = 10.

The 7.25% Mg alloy required approximately 75% cold work to achieve the desired strength level, whereas the Al-Mg-Zn alloy needed only 45%. Both alloys tended to lose strength by age softening if permitted to stand at room temperature after rolling. However, when the 8.5% Mg-2.0% Zn alloy was given a low temperature recovery or stabilizing treatment (2 hours at 250 F) the accompanying age hardening offset the loss by age softening.

In the case of the Al-Mg-Zn alloy, it was possible to attain the desired strengths of the contract. But, since the amount of cold rolling necessary was considered commercially impractical, no further experimentation was performed.

7000 SERIES ALLOYS

The commercial 7000 series alloys include the highest strength aluminum alloys. The strongest of these contain appreciable Cu, which decreases weldability and notch-toughness below the levels desired for this contract. Commercial Cu-free alloys, on the other hand, have good weldability and notch-toughness, but low strengths.

The literature survey indicated that the desired strengths could be achieved with Cu-free Al-Zn-Mg alloys if the Zn and Mg levels were increased. This system was selected for investigation with the realization that the high solute alloys might be susceptible to stress-corrosion cracking.

Twenty experimental Al-Zn-Mg alloys were evaluated (Table I). After solution heat treatment, the sheet was quenched in boiling water to simulate the lower quenching rate of plate. It was then stretched and aged by three practices: (a) an isothermal aging treatment of 48 hours at 250 F, (b) a two-step aging treatment of 8 hours at 225 F + 16 hours at 300 F, or (c) a treatment of 6 hours at 225 F + 8 hours at 350 F.

The effect of the aging treatment on the yield strength and notched/unnotched tensile ratio of various Al-Zn-Mg alloys at room temperature and -320 F is shown in Figure 1. The notch-toughness of the alloys at room temperature was generally very good but was much poorer at -320 F. As anticipated, notch-toughness decreased with increasing yield strength. The notch-toughness was approximately the same with aging treatments (a) and (b), but significantly lower for aging practice (c), which was an overaging treatment for the alloys.

The effects of Zn and Mg concentration on the room temperature yield strength and the -320 F notched/unnotched tensile ratios are shown in Figures 2 and 3 for several aging treatments. The dashed lines show compositions with equal yield strengths. The isothermal aging treatment used in obtaining the data in Figure 2 provided higher strengths than the step-aging treatment of Figure 3. The dark solid lines show compositions with equal notched/unnotched tensile ratios. The light solid line running from lower left to upper right shows compositions having the most favorable combination of yield strength and notch-toughness. For isothermally aged material, an alloy in the vicinity of 6% Zn and 2% Mg met the desired yield strength of 65 ksi and provided the optimum cryogenic notch-toughness.

Further investigations were conducted on three plant fabricated alloys with compositions near the desirable 6% Zn-2% Mg composition. The compositions are shown in Table I and identified as alloys M790, M791 and M793. In addition to Zn and Mg, these alloys contained small additions of Mn, Cr and Cu. Alloys M791 and M793 also contained a small amount of Zr to improve weldability. A fourth alloy, M792, with 9% Zn was included to determine if underaging or overaging a higher strength alloy would produce a desirable combination of strength and notch-toughness.

Tensile and notch-tensile properties of naturally aged (W temper) and artificially aged plate of M790, M791 and M793 are shown in Table VII. The artificially aged tempers provided a better combination of strength and cryogenic notch-toughness than the W temper.

To determine the effect of aging treatment on the strength and cryogenic notch-toughness, alloys M790 and M792 were isothermally aged at 250 F to produce underaged, fully aged and overaged conditions (Figure 4). All aging conditions appeared to provide similar combinations of notch-toughness and yield strength, although there was an indication that at slightly beyond peak strengths there was a drop in notch-toughness.

Alloy M792 was evaluated in an underaged condition to determine if a high solute alloy in such a temper would provide better notch-toughness at cryogenic temperatures than a lower solute alloy aged to full strength. Although the range of overlapping strengths was small, the results indicated the underaged M792 had slightly lower notch-toughness than M790 aged to the same strength (Figure 5).

The effect of artificial aging treatment on the room temperature yield strength and the -320 F notched/unnotched tensile ratio of M790, M791, and M793 plate is shown in Figure 6. The order of superiority is from M790 to M793.

The notch-toughness appeared to be dependent on both the Zr and the Mg content.

Tensile and notch-tensile tests were conducted at room temperature to -423 F on 1.0 inch plate of alloys M791 and M793. Isothermal aging treatments expected to give properties consistent with the contract goals were studied (Table VIII and Figure 7). The strengths increased uniformly with decreasing testing temperatures, while elongations decreased only slightly. The notched/unnotched tensile ratios decreased with decreasing testing temperatures, as is characteristic of the 7000 series alloys. Only alloy M793 approached the room temperature yield strength and the -423 F notch-toughness goals.

Stress-corrosion tests on 3 inch plate of M790, M791, M792 and M793 showed that stress-corrosion cracking was more probable in the short-transverse direction than in the long-transverse direction (Tables IXa and b). Alloys M791 and M793 with Zr had higher resistance to stress-corrosion cracking than alloys M790 and M792 without Zr. Alloy M792 with 9% Zn had the lowest resistance. Hot water quenching and step-aging provided higher resistance to stress corrosion than cold water quenching and isothermal aging. Although M791 and M793 showed the best corrosion resistance, failures were still obtained in the short-transverse direction at stresses to 50% of the yield strength.

Weld cracking tests were conducted on several experimental filler alloys. Filler alloys containing Zr showed low amounts of weld cracking and would be expected to be commercially weldable, although not as weldable as the 2219/2319 combination.

Weldments of 0.5 inch plate of M791 and M793 were prepared without difficulty by both the MIG and TIG welding processes using M822 filler alloy. The tensile properties of the M793 weldments (Table X) were slightly lower than those of the M791 weldments. Tensile strengths of the MIG weldments approached the contract goal of 60 ksi (80% of the parent metal tensile strength goal of 75 ksi). The TIG weldments showed lower tensile strengths. Failure of full section specimens occurred in the heat-affected zone of the parent metal. The notched/unnotched tensile ratios of these weldments at -320 F were below the -423 F goal of .85.

Stress-corrosion tests were conducted on M791 and M793 welded specimens loaded in bending to a fiber stress of 75% of the yield strength. Stress-corrosion results for M793 are shown in Table XI. Specimens of M791 weldments failed more rapidly. Post-weld aging had no significant effect on stress-corrosion. For TIG weldments, the face side failed less rapidly than the root side (last side welded), probably due to the heating it received during the subsequent root pass. All specimens failed within one year.

The location of the stress-corrosion cracks is illustrated in Figure 8. The stress-corrosion cracks followed the edge of the weld bead except for short deviations into the recrystallized grain region of the parent metal.

In summary, the survey of Al-Zn-Mg alloys indicated that a composition of about 6% Zn and 2% Mg could most nearly meet the contract strength and notch-toughness requirements. More extensive tests showed that alloy M793 (6.51% Zn, 1.64% Mg, .12% Cu and .10% Zr) could meet the room temperature yield strength and the -423 F notch-toughness goals. Alloy M793 had better stress-corrosion resistance than other alloys with higher Mg, but was still susceptible to stress-corrosion cracking in the short-transverse direction. M793 showed acceptable weldability and had weld strengths approaching the contract goals; however, the weldments had low cryogenic notch-toughness and were susceptible to stress-corrosion cracking.

Since M793 fulfilled many of the contract goals, a modification of M793 was selected for further development. The modified alloy had the Mg concentration increased to 1.8% to provide slightly higher strengths. This modified alloy was initially designated M826. After further evaluation and development, it was registered with the Aluminum Association as X7007 alloy.

ALLOY X2021

Studies on X2021 were conducted in the following areas:

Variations in major alloying elements
Quench sensitivity
Trace elements
Alloy modification
Fabrication practices

As outlined previously, X2021 develops its highest strengths when solution heat treated, cold water quenched and aged without flattening or working. Working between quenching and aging reduces both tensile and yield strengths significantly. Investigation has shown that this loss in strength can be reduced if a short aging treatment (pre-aging) is used before flattening or working. In the development of X2021, heat treating practices incorporating a pre-aging treatment after quenching and before flattening and final aging were identified by the T8E31 temper. More recently, this temper has been registered with the Aluminum Association as the T81 and will be so designated throughout the remainder of this report. X2021 products that are not cold worked between quenching and aging will be identified by the T62 temper.

VARIATIONS OF MAJOR ALLOYING ELEMENTS

The effects of variations in the Cd, Sn, Cu and Mn contents of X2021 were studied to determine the optimum level for these elements. Composition variations included .06-.19% Cd, .02-.08% Sn, 5.7-6.7% Cu and .01-.65% Mn. Detailed chemical analyses are reported in Table XII. Based on these studies, the tentative composition limits shown in Table XIII were established.

The effects of the above composition variations on the tensile properties of X2021 were determined using 0.064 inch sheet. Since changes in composition may affect the rate of aging, properties were measured after several aging times in order to establish maximum strengths.

The effects of Cd and Sn on the yield strength of X2021 are shown in Figures 9 and 10. Within tentative composition limits, there was no variation in the strength of X2021 in a T62 type temper that could be directly associated with Cd and Sn contents. Outside these limits, the yield strength decreased at low Cd and Sn contents.

In the case of the T81 type temper, the yield strength decreased continuously with decreasing Cd and Sn concentrations (Figure 10).

The mechanism whereby Cd and Sn modify precipitation to produce higher strengths in X2021 was elucidated by electron microscopy. 2219 (X2021 without Cd and Sn) when aged without cold work showed only zone hardening and had low strengths (Figure 11). Cold working 2219 10% before aging formed θ' precipitate in a Widmanstatten pattern (Figure 12) which produced higher strengths. Cd and Sn provide a more uniform distribution of small θ' precipitate (Figure 13), which must be responsible for the still higher strengths of X2021.

The effect of Cd and Sn on the notch-toughness of X2021 is shown in Table XIV and Figure 14. Alloys of the first group were tested as 0.525 inch plate in the T81 temper. Alloys of the second group were tested as 1.0 inch plate which was also used for short-transverse stress-corrosion tests. This plate was prepared in the T62 temper since equipment for stretching 1.0 inch plate was not available. The results of the tests show that the notch-toughness of X2021 at -320 F was about the same as at room temperature and tended to improve with decreasing Cd and Sn levels, possibly as the result of the lower strength of such alloys. The results indicate that X2021 of nominal composition should develop a notched/unnotched tensile ratio near 1.0 at room temperature and 0.9 at -423 F.

The effects of 5.7 to 6.7% Cu on the properties of X2021 plate are also shown in Table XIV. The results suggest that strength is lowered slightly at low Cu contents, although this does not agree with data on sheet. The notch-toughness of the plate tended to increase with decreasing Cu, probably because of the low strength of the 5.7% Cu alloy.

Aging studies on the alloys with .01 to .65% Mn indicated that the nominal concentration of .30% Mn provided optimum strengths. The effects of Mn on notch-toughness (Table XIV) are probably related to differences in yield strength.

The effects of composition variations on the resistance to stress-corrosion of X2021 are shown in Tables XVa and b. Resistance to stress-corrosion cracking in the long-transverse direction was excellent with failures occurring only in low Cd and Sn or low Mn alloys. A greater incidence of failures was encountered in the short-transverse direction. There was an indication that the resistance to stress-corrosion cracking of the alloys decreased with decreasing Cd and Sn concentration.

QUENCH SENSITIVITY OF X2021

Unpublished data at the Alcoa Research Laboratories have indicated that Zr increases the quench sensitivity (i.e., the strength loss resulting from slow quenching rates) of Al-Cu-Cd alloys. Investigations, therefore, were conducted to check this observation and also to determine the effect of V, Ti, Cd, Sn and Mn on the quench sensitivity of X2021. The results showed that V, Ti, Cd, Sn and Mn have little or no effect on the quench sensitivity of X2021, but verified the observation that Zr increases the quench sensitivity. This is illustrated in Figure 15, which also compares these alloys to 2014 and 2219.

Electron micrographs showing the effects of Zr on the structure of X2021 are reproduced in Figures 16 and 17. The alloy with Zr contains a greater number of dispersoid particles and has a slightly coarser precipitate in the slowly quenched condition. This suggests that the lower strengths may be due to precipitate coarsening.

Weld cracking studies were conducted to determine the effect of eliminating Zr from X2021 on weldability. The effects of other elements, such as V and Ti, were also checked. No conclusive results were obtained from these studies.

MINOR IMPURITIES

Unpublished Alcoa research on an alloy containing Sn (X27S) has shown that small amounts of Mg tend to decrease tensile properties. The effects of Mg and trace amounts of Ca, Zn and abnormally high concentrations of the impurities Fe and Si were, therefore, studied in X2021.

Only Mg was found to affect the tensile properties of X2021. Figure 18 shows that as the Mg concentration increased, the rate of aging decreased and peak strength tended to decrease. From these results it would appear that control of Mg to .020% or less would be desirable.

It has been theorized that Mg combines with Cd and Sn and prevents them from refining the precipitate structure. Aging data do not support this, however, since .044 or .079% Mg retards aging much more than the complete elimination of Cd and Sn. In addition, x-ray diffraction studies have detected no phases containing Mg.

Electron microscopic examinations of samples containing .044 and .079% Mg (Figures 19 and 20) showed a duplex precipitate structure consisting of coarse and fine θ' precipitate, whereas X2021 had a uniform precipitate size (Figure 21). Also, the alloys with trace amounts of Mg had a region along the grain boundary devoid of large θ' precipitates, as illustrated in Figure 19. The mechanism whereby Mg affects the precipitate structure is not understood, but is an interesting problem for further investigation.

ALLOY MODIFICATIONS

An attempt was made to increase the strengths of X2021 by adding 0.3 and 0.6% Li. Hardness tests on sheet indicated 0.3% Li lowered strengths but that 0.6% Li increased strengths. Tensile and notch-tensile tests showed that 0.6% Li increased strengths substantially but lowered the elongation and the notched/ unnotched tensile ratios at room temperature and -320 F. Because of the low notch-toughness, further evaluation of the Li-containing alloy was stopped.

The substitution of Cr for Zr in X2021 decreased the yield strength about 5 ksi. The notch-toughness was similar to that of other alloys with lower yield strength. Chromium appeared to have the same effect on quench sensitivity as Zr. The substitution of Cr for Zr had no effect on the stress-corrosion cracking of X2021.

HEAT TREATING PRACTICES

Heat Treating Temperature

The solidus temperature of X2021 varies with the Cd and Sn contents, as shown below:

Composition Cd	Sn		Solidus Temperature - F
.06	.02		1006
.15	.05	(nominal)	998
.20	.08		997

To prevent melting of alloys within the composition limits of X2021, the heat treating temperature has been set at 990 F.

The effect of solution heat treating temperature on the tensile properties of X2021-T81 is shown in Table XVI. Decreasing the solution heat treating temperature from 990 to 970 F reduced peak yield strengths about 3 ksi. Solution heat treating times of 2 to 4 hours are recommended for X2021 plate and 1 hour for sheet.

Quenching

The effect of quenching rate on the tensile properties of X2021 was discussed previously. A fast, cold water quench is desirable. At slow quenching rates, such as obtained with plate 2.0 inches thick or greater, the strengths decrease and the rate of aging decreases. The effects of quenching rate are illustrated in Figure 22 for sheet quenched in cold water and boiling water.

Pre-Aging

As shown in Table XVII, stretching before artificial aging reduces the strengths of X2021. Tests have shown that a short aging treatment (pre-aging) before stretching for flatness or stress relieval can partially offset this loss in strength. Various pre-aging treatments were studied to find one that would not raise the strength of the quenched material to such a level that it could not be flattened properly, yet would minimize the loss in strength that would normally result from the sequence of stretching and full artificial aging. Results are shown in Table XVIII. Lowest strengths were obtained for the 8 hour at 250 F pre-age, while highest strengths were obtained for the 2 hour at 300 F pre-age. In the case of the cold water quenched material, the 2 hour treatment at 300 F produced a higher yield strength than would be desirable for stretching or leveling. Therefore, the 1 hour at 300 F pre-age was selected as a standard treatment.

Stretching

Table XVII shows that the strengths of the pre-aged temper decreased with increasing amounts of stretching. Therefore, the amount of stretching for the T81 temper has been specified as the minimum amount needed for flattening with a maximum of 1.5%.

In order to determine the effects of stretching and pre-aging on the microstructure of X2021-T81, transmission electron microscopic examinations were conducted on the following samples:

Sample	Pre-Age	Stretch	Age
A1	None	None	None
A4	None	None	16 hr/325 F
B2	None	1.5%	None
B4	None	1.5%	16 hr/325 F
C1	1 hr/300 F	None	None
C2	1 hr/300 F	1.5%	None
C4	1 hr/300 F	1.5%	16 hr/325 F

Results are shown in Figures 23-26. In the as-quenched condition, the structure was characterized by dispersoid and a few quenched-in dislocations. Stretching produced a marked increase in the number of dislocations (Figure 24) and pre-aging appeared to align these dislocations (Figure 25). Such differences in microstructure before final aging, however, had little effect on the microstructure after aging. Figure 26 shows a microstructure typical of all samples aged 16 hours at 325 F.

X-ray diffraction studies have been successful in determining the effect of cold work on the microstructure of X2021. Figure 27 shows that cold work decreases the half-height width of the θ' (101) diffraction peak, thus suggesting that cold work increases the θ' precipitate thickness.

Final Aging

The effects of aging time and temperature are shown in Figure 28. Aging temperatures from 300-350 F result in similar peak yield strengths, but the time to attain such strengths varies with quench rate and aging temperatures. When the quenching rate is low, as in thick plate, the aging time to peak yield strength increases.

In selecting an aging treatment for X2021, the primary criteria were high strength and a high level of stress-corrosion resistance. Preliminary evaluations of X2021 indicated that the resistance to stress-corrosion improved as the aging time increased; consequently, a program was conducted to determine the amount of aging necessary to insure good stress-corrosion resistance. Aging times of 4 to 96 hours at 325 F were studied. To determine the effect of aging temperature on stress corrosion, specimens were aged at 300, 325 and 350 F. Solution potential measurements were used to indicate the amount of Cu in solid solution and were found to closely correlate with stress-corrosion resistance. Therefore, solution potential measurements were used throughout the stress-corrosion programs for X2021.

The results of the stress-corrosion tests are given in Table XIX. Specimens exposed by alternate immersion in a 3 1/2% NaCl solution were removed from test after 88 days because of the known severity of this corrosion test for Al-Cu alloys. Results showed that resistance to stress-corrosion cracking increased with increasing aging time at 325 F and increasing solution potentials. Metallographic examination of a corrosion specimen aged 4 hours at 325 F showed intergranular cracks indicative of stress-corrosion cracking. With increased aging time, the number of such cracks diminished until, for the specimen aged 48 or 96 hours at 325 F, no such cracks were observed. Figure 29 shows that a high degree of resistance to stress-corrosion cracking is achieved when the solution potential is about -820 mv. It is significant that high strengths generally coincide with high resistance to stress-corrosion cracking. The resistance to stress-corrosion cracking also increased with increasing aging temperature.

Microscopic examinations were made of these samples to determine the structural changes responsible for the improved stress-corrosion resistance. Optical microscopic examination did not reveal any significant microstructural differences. Transmission electron microscopy showed that the density of θ' precipitates increased as the aging time at 325 F increased (Figures 30 and 31). According to Brown and co-workers*, grain boundaries are anodic to grain bodies after short aging periods. As artificial aging proceeds, the solution potential of the grain matrix increases and approaches the potential of the grain boundary. This equalization of potentials reduces intergranular corrosion and stress-corrosion cracking.

In selecting an aging treatment for the initial plant fabrication of X2021-T81 plate, a treatment of 10 hours at 325 F was chosen, based on sheet data (Figure 22). Stress-corrosion tests on three items of 1.0 inch plate and one item of 2.370 inch plate (Tables XXa and b) showed that this aging treatment was insufficient, since the 2.370 inch plate developed short-transverse, stress-corrosion cracks in all three test environments. Additional aging treatments of 6 hours at 325 F or 24 hours at 300 F significantly improved the resistance to stress-corrosion and also increased the yield strength.

In later plant trials of X2021-T81, the aging time was lengthened to 16 hours at 325 F. Tables XXa and b show stress-corrosion data on 1.0 inch and 2.0 inch plate. No stress-corrosion failures have occurred, although test times are still short. In addition to these tests, plant-fabricated

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*This theory is reviewed in the METALS HANDBOOK, Vol. I, p 918.

X2021 was aged 16 hours at 325 F in the laboratory. This material had a low solution potential and failed by stress-corrosion cracking. Additional aging reduced stress-corrosion cracking significantly.

In summary, an aging treatment of 16 hours at 325 F should be satisfactory for sheet and light gage plate. For rolled plate 1.0 inch thick or greater, where the slow quenching rate retards aging, the recommended aging time has been increased to 24 hours at 325 F.

Natural Aging

Natural aging curves are shown in Figure 32 for X2021 in the as-quenched, and the pre-aged and stretched conditions. Both conditions showed only slight increases in strength for room temperature aging periods up to one year, although the pre-aged and stretched condition had initial strengths about 10 ksi higher than that of the as-quenched condition. Tests have shown that a room temperature interval between heat treating steps has little effect on properties (Table XXI).

Based on the results of the above studies, the heat treating practice for the T81 temper of X2021 is as follows:

1. Solution heat treatment:

   1 hour at 990 F for sheet
   2-4 hours at 990 F for plate
   (maximum furnace temperature of 995 F)

2. Quench - rapid cold water quench

3. Pre-age - 1 hour at 300 F

4. Stretch - minimum to flatten; maximum of 1.5%
5. Final age:

   16 hours at 325 F for sheet and light gage plate
   24 hours at 325 F for plate 1 inch thick or greater

The practice for the T62 temper is similar except for the absence of pre-aging and stretching.

STRUCTURE AND PROPERTIES OF PLANT FABRICATED X2021

The results of examinations and tests on plant fabricated X2021 sheet and plate are reviewed in this section. The specific properties and characteristics reported are as follows:

Microstructure
Engineering properties
Physical properties
Resistance to stress-corrosion cracking.

Microstructure of X2021-T81

Micrographs of 1.000 inch plate and 0.064 inch sheet of X2021-T81 are shown in Figure 33. The plate obviously has somewhat more elongated grains and a coarser grain size than the sheet. Measurements on the sheet gave approximately 15,000 grains per mm^3. The large constituents in the microstructure are the light colored $CuAl_2$ phase and the dark colored Al_7Cu_2Fe phase.

Transmission electron micrographs of the midplane structure of the 1.000 inch plate are shown in Figure 34. The matrix contains dispersoids of various sizes and shapes, and fine θ' precipitate in a Widmanstatten pattern. The grain boundaries contain isolated particles of constituent that probably precipitated during the quench. Similar structures are observed near the surface of plate and also for sheet, although the grain boundary precipitates are smaller for sheet.

Engineering Properties

Since initial determinations of the mechanical properties and fracture characteristics of X2021 were limited to tests on a few lots of experimentally produced material, six gages of plant fabricated X2021-T81 were evaluated to obtain additional information. The thicknesses of the X2021 sheet and plate are listed in Table XXII, and the compositions are listed in Table XII. Tensile, compressive, shear, bearing, bend and fatigue properties, hardness, notch-toughness, tear resistance and fracture-toughness were determined at room temperature. Tensile and notch-tensile properties and tear resistance of a few lots were determined at temperatures to -452 F.

Descriptions of the tests conducted and complete reporting of the results are described in Appendix I entitled "Mechanical Properties and Fracture Characteristics of X2021-T81 and X7007-T6E136 Sheet and Plate," by J. W. Coursen. The results are only summarized in this section with average properties quoted where possible.

Tensile properties for X2021-T81 sheet and plate at room and cryogenic temperatures are given in Table XXII. Average tensile, compressive, shear, bearing properties and hardness values of five gages of sheet and plate at room temperature are reported in Table XXIII. Tensile strengths and tensile yield strnegths are slightly below the goals of 75 ksi and 65 ksi and average elongations are below the goal of 10%. Tensile and compressive stress-strain curves for specimens from 1.000 inch plate are shown in Appendix I. Average elastic moduli obtained were 10.7 x 10^6 psi tensile modulus and 10.9 x 10^6 psi compressive modulus.

Although the number of lots of X2021 sheet and plate that have been produced is wholly inadequate to establish minimum guaranteed tensile properties on the statistical experience basis that is normally applied for aluminum alloy products, an estimate of the possible minimum values has been made based upon the relationship observed between typical and guaranteed minimum properties of 2219-T81 and T87. Tentative minimum values registered with the Aluminum Association are shown in Table XXIV.

TABLE XXIV

TENTATIVE LONG-TRANSVERSE MINIMUM TENSILE PROPERTIES
FOR X2021-T81 AND T62 SHEET AND PLATE

	X2021-T81		
Thickness Range Inches	TS ksi	YS ksi	% El. in 2"
0.040-0.249	67.0	57.0	6
0.250-0.499	67.0	57.0	5
0.500-1.000	67.0	57.0	3
1.001-2.000	65.0	55.0	3

	X2021-T62		
Thickness Range Inches	TS ksi	YS ksi	% El. in 2"
0.040-0.249	69.0	59.0	6
0.250-0.499	69.0	59.0	5
0.500-1.000	69.0	59.0	3
1.001-2.000	67.0	57.0	3

It is hoped that these values are somewhat conservative and that, as statistical data become available, somewhat higher values can be guaranteed.

Results of minimum 180 degree bend tests on X2021-T81 sheet and plate with the axis of bend either normal (N) to or parallel (P) with the rolling direction are shown below:

Thickness Inches	Minimum 180° Bend Radius	
	N	P
.064	4t	4 1/2t
.125	4t	6t
.250	4t	6 1/2t
.500	8t	8t

Fatigue properties were determined using sheet-type flexural fatigue specimens from 0.064 inch sheet, axial-stress fatigue specimens from 0.125 inch sheet, and smooth and notched rotating-beam and axial-stress specimens from 1.000 inch plate. The average fatigue limits at 5 x 10^8 cycles are summarized below:

Type of Specimens	Fatigue Limit, ksi Smooth	Notched (K_t >12)
Sheet - Flexure	19	--
Rotating-Beam	17	5.5
Axial-Stress, Sheet	27	--
Axial-Stress, Plate	26	8.0

The fatigue strengths are similar to those of 2219-T8X products.

The effect of testing temperature on the tensile and notch-tensile (K_t = 10) properties of X2021-T81 are shown in Table XXII. Tests were conducted at -452 F rather than at -423 F, as specified in the contract, since -452 F testing capabilities were available, even though it was realized that the -452 F test was more severe. Notch-tensile tests on specimens with notch intensity factors (K_t) other than 10 were also determined and are given in Appendix I. The change in tensile and notch-tensile properties with testing temperature is shown in Figure 35. Tensile and yield strengths increased uniformly with decreasing temperature; the elongation of sheet did not change significantly but the elongation of plate increased with decreasing temperature. The notch-toughness showed no consistent change with decreasing testing temperatures but was not lower at cryogenic temperatures than it was at room temperature. The notch-toughness of sheet was lower than that of plate due to a difference in specimen design.

Tear tests were also conducted. Unit propagation energy, a measure of the energy needed to propagate a crack, is used as a measure of tear resistance. Average tear properties at room temperature are shown in Table XXV and the effects of testing temperature on tear properties are shown in Table XXVI. The unit propagation energy is higher at cryogenic temperatures than room temperature.

Plane-strain stress intensity factors (K_{Ic}) and strain-energy release rates (G_{Ic}) were determined using center-notched tension specimens from .250 inch plate and notched bend specimens from 0.500 and 1.000 inch plate. The values of K_{Ic} and G_{Ic} were based upon the loads at a 5 percent secant offset, corresponding to a crack growth of about 2 percent. Reasonable estimates of K_{Ic} and G_{Ic} are as follows:

Direction	K_{Ic} psi $\sqrt{in.}$	G_{Ic} in.-lb./in.^{2}
L	29,000	80
T	23,000	50

Physical Properties

Typical physical properties of X2021 are presented in Table XXVII

Resistance to Stress-Corrosion

The stress-corrosion data for plant fabricated X2021 (Tables XXa and b) were discussed previously in the section on aging treatments for X2021. The long-transverse direction of plate has shown excellent resistance to stress-corrosion cracking with no failures of specimens stressed to 75% of the yield strength.

Numerous short-transverse specimens have failed by stress-corrosion cracking, but these failures have been limited to plate 2.000 or 2.370 inches thick which was insufficiently aged (as indicated by the low solution potentials). Additional aging greatly improved the stress-corrosion resistance of these items.

Several recent lots of plant fabricated plate have shown no stress-corrosion failures, although the test time is somewhat short. It is anticipated that the present recommended aging practice of 24 hours at 325 F should produce excellent resistance to stress-corrosion cracking in thick plate.

PROPERTIES OF X2021 WELDMENTS

Since alloy X2021 is similar to alloy 2219, filler alloy 2319 was employed for X2021. High quality welds were produced and all evidence indicates that the X2021/2319 parent metal / filler alloy combination provides excellent weldability. It should be noted that toxic CdO fumes are generated during the welding of X2021. Good ventilation should be used to protect the welding operator from excessive exposure to these fumes.

Tensile properties of MIG and TIG weldments of X2021 plate using full section specimens (weld bead reinforcement left intact) are shown in Table XXVIII. The weld efficiencies for the as-welded and post-weld aged conditions are about

60%. Failure generally occurred at the edge of the weld bead in the weld metal.

Reduced section tensile and notch-tensile properties (using round specimens) were also determined for several of these weldments (Table XXIX). The notch was placed in the center of the weld bead. Tensile strengths were similar to those of full-section specimens, but yield strengths and elongations differed because of a difference in gage length. Although the notched/unnotched tensile ratios decreased slightly with decreasing testing temperature, the notch-toughness of these weldments was good and would be expected to meet the contract goal of 0.85 at -423 F. To determine if other areas of the weldments might be more notch sensitive than the weld bead, notches were placed at the edge of the weld and in the heat-affected zone. These areas also appeared to have good notch-toughness.

The effect of parent metal temper on the tensile properties of X2021 weldments was determined for the following sheet conditions:

W - (as-quenched)
WE5 - (pre-aged and stretched)
T81

Figure 36 shows the effect of post-weld aging. Parent metal temper of X2021 appears to have only a slight effect on the weld tensile properties.

Stress-Corrosion Resistance of Weldments

Stress-corrosion tests have been conducted on three different X2021/2319 weldments. These were MIG welded 0.500 inch plate and MIG and TIG welded 1.000 inch plate. Four-point loaded beam specimens were used. The MIG weldments were tested first using short specimens (Assemblies A and B of Figure 37). The TIG weldments were tested later using a longer center span to achieve a more uniform stress distribution across the weld (Assembly D of Figure 37).

The method of loading the stress-corrosion specimens varied for the three weldments. The 0.500 inch specimens were stressed to 75% Y.S. (based on a 10 inch gage length), considering them to be homogeneous elastic beams. It was realized, however, that the deformation was not entirely elastic, since plastic deformation occurs in the heat-affected zone, starting at a stress of about 50% of the Y.S. of the weldment. Therefore, the MIG welded 1.000 inch plate specimens were loaded using a more accurate method. First, a calibration tensile test was run to obtain the relation between tensile stress and localized strain in an area immediately adjacent to the weld bead (as measured by a foil-type electrical resistance strain gage). Then, the stress-corrosion specimens were loaded in bending to a localized strain corresponding to a stress of 75% Y.S.

The same procedure was attempted for the TIG welded 1.0 inch specimens, but warpage of the specimens prevented calibration of the localized strains. Therefore, these specimens were loaded to a stress of 30 ksi in the unaffected parent metal.

The stresses used for these tests were purposely set at a high level so that any tendencies towards stress-corrosion cracking could be detected. Residual welding stresses can also be significant (9-16 ksi) in weldments of thick plate*; however, no attempt was made to control or measure such residual stresses.

The results of stress-corrosion tests (Table XXX) were similar for all three of the X2021/2319 weldments. In the case of specimens exposed to an industrial atmosphere (New Kensington, Pa.), only one specimen has failed by stress-corrosion cracking with exposure times up to 3 years. The resistance to stress-corrosion cracking of specimens exposed to an accelerated salt solution test (alternate immersion in a 3 1/2% NaCl solution) varied with the condition of the weld. The post-weld aged condition was generally quite resistant to stress-corrosion cracking, lasting from six months to one year without failure.

All as-welded specimens cracked after extended times (greater than 100 days) of exposure to the accelerated salt solution test. Extensive corrosion also occurred. Macrographs

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*Evaluation of Various Techniques for Stress-Corrosion Testing Welded Aluminum Alloys. M. B. Shumaker, et al. Paper prepared for the Stress-Corrosion Testing Symposium at the ASTM 69th Annual Meeting, June 28, 1966.

of TIG welded 1.0 inch thick specimens illustrate the nature of the stress-corrosion cracks (Figure 38).

The effect of parent metal temper on the stress-corrosion resistance of X2021 was studied using weldments of parent metal in the W, WE5 and T81 tempers, as described above. Specimens in the as-welded and post-weld aged (4, 16 and 48 hours at 325 F) conditions were tested in a 3 1/2% salt solution by alternate immersion. After 84 days in test, the only failure was for the W temper weldment in the as-welded condition. Additional work is needed to determine if weldments of W temper X2021 are truly more susceptible to stress-corrosion cracking.

Solution potential surveys* of the weldments are shown in Figure 39. The as-welded condition has a low potential in the heat-affected zone near the weld bead and is susceptible to stress-corrosion cracking, similar to parent plate with a low solution potential. The post-weld aged condition has higher solution potentials and improved stress-corrosion performance.

General Corrosion of Weldments

General corrosion after one year in 3.5% NaCl (alternate immersion) is illustrated in Figure 40. Both the as-welded and post-weld aged conditions showed localized areas of severe corrosion. In the as-welded condition, there was a band 1/16 to 3/8 inch from the edge of the weld bead

*The solution potential measurements were made on masked-off strips 1/32 inch wide and parallel to the edge of the weld bead.

with random deep pitting. This pitting was more severe on the root side. The post-weld aged condition had a band of uniform moderate pitting 3/8 to 9/16 inch from the edge of the weld bead. These locations of localized corrosion correspond with the peaks of the potentials gradients shown in Figure 39.

Al-Cu-Mg Experimental Filler Alloys

The weld strengths of X2021/2319 weldments are below the contract goals. Since tensile failure generally occurs through the weld metal, higher strength filler alloys were investigated. Weldments made with Al-Cu-Mg type filler alloys were found to provide as-welded tensile strengths about 10% higher than the X2021/2319 weldments, but notch-tensile tests indicated the weldments were more notch sensitive (Table XXXI). Metallographic and x-ray examination suggested that different types and increased amounts of phases present in the inter-dendritic network of the weld bead was responsible for the lower notch-toughness of the Al-Cu-Mg experimental filler alloys.

To understand the mechanical and corrosion properties of weldments, a thorough understanding of the physical metallurgy of the heat-affected zones in welds is important. A program providing such understanding was conducted on a TIG weld in X2021-T81 plate and reported in an Addendum to Progress Report 33. X-ray diffraction was used for identification of phases and measurement of the amount of copper in or out of solution. X-ray results were correlated with structure observed by optical and electron microscopy and hardness and solution potential measurements.

ALLOY X7007

VARIATIONS IN MAJOR ALLOYING ELEMENTS

A detailed study of the effects of variations in the chemistry of X7007 was made in order to establish the optimum composition and tentative composition limits. Variations included .03 to .23% Cu, .07 to .17% Zr, 1.52% Mg and 6.05% Zn to 2.21% Mg and 6.85% Zn, and .25% Cr (with .011 or .24% Mn). The chemical analyses of these alloys are shown in Table XXXII.

Tensile and notch-tensile properties of the alloys are shown in Table XXXIII. Strengths increased slightly with Cu and Zr concentrations up to the nominal level, decreased 3-5 ksi with high Cr, but were primarily affected by Zn and Mg concentration. To achieve the strength goals of the contract, Zn and Mg concentrations of at least nominal level for X7007 were required.

The notch-toughness of these alloys was excellent at room temperature but at cryogenic testing temperatures was lower and dependent on composition. The effects of composition on -320 F notch-toughness are illustrated in Figure 41. Curves showing the relation between -320 F notched/unnotched tensile ratio and room temperature yield strength for previous alloys M790, M791 and M793 are included for comparison. The results suggest that Cu in combination with Zr produced optimum notch toughness. Electron microscopic fractographic analysis indicated that the higher Cu concentrations decreased the amount of intergranular fracture during tests at cryogenic temperatures. This probably was the reason for the improved notch-toughness. The notched/unnotched tensile ratio varied greatly with Mg and Zn concentrations, but the differences appeared to be attributable to the differences in strength.

Results of stress-corrosion tests on 1.000 inch plate are presented in Table XXXIV. No variation showed significantly improved resistance to stress-corrosion cracking, although high Cr provided a slight improvement in accelerated tests.

The results of weld cracking tests using parent metal as filler alloy are presented in Table XXXV. The results of these tests showed that X7007 has a high susceptibility to weld cracking and, therefore, requires a filler alloy with low weld cracking tendencies.

The above results show that no variation in the concentrations of the major alloying elements in X7007 provided an overall improvement in properties. Increasing the Cu level improved some properties (cryogenic notch-toughness and stress-corrosion resistance in the New Kensington atmosphere) but decreased other properties (weldability and stress-corrosion resistance in a salt water environment). Since the other variations also did not provide significant improvements in the properties, the tentative composition limits shown in Table XIII were continued.

ALLOY MODIFICATIONS OF X7007

Small additions of elements not included in the makeup of X7007 were made in an attempt to improve the properties and characteristics of X7007, especially the resistance to stress-corrosion cracking. The elements studied were Ag, Ca, Li, Ta and Nb. The addition of Ag was studied since it had been reported* to permit aging at higher temperatures which provided improved resistance to stress-corrosion cracking. Initial tests indicated .31% Ag improved the resistance to stress-corrosion cracking so alloys with .20% and .41% Ag were studied to verify the effect and to determine the effect of Ag concentration.

The addition of Ca to Al-Mg-Zn alloys with more Mg than Zn had been reported** to increase resistance to stress-corrosion cracking by producing a more uniform precipitate structure. The addition of .30% Ca to X7007 was studied to see if similar improvements would result for Al-Zn-Mg alloys with more Zn than Mg. Lithium was studied because it has appreciable solid solubility and because its effects in Al-Zn-Mg alloys were not well documented. Small concentrations of dispersoid-forming elements Ta and Nb were studied since other dispersoid-forming elements such as Cr and Mn appear to affect precipitation and resistance to stress-corrosion

* I. J. Polmear, J. INST. METALS, 89, 193-202, 1961.

**U. S. Patent 2,261,210.

cracking in some compositions. Complete chemical analyses of these alloys are listed in Table XXXII.

Tensile and notch-tensile properties of these alloy modifications of X7007 are given in Table XXXVI. Data for the first group of alloys, tested as sheet, showed that Ag increased the strength of X7007 and decreased the -320 F notched/unnotched tensile ratio only slightly. Lithium did not affect strengths, while Ca lowered strengths slightly, but both elements significantly reduced the -320 F notch-toughness.

The alloys with Ag in the second group, tested as plate, showed lower strength than X7007, contrary to the results for sheet. This is thought to indicate that the alloys with Ag are more quench sensitive than X7007. These tests confirm the observation that Ag does not affect notch-toughness. Tantalum and Nb do not affect strengths but Nb does decrease cryogenic notch-toughness.

The results of stress-corrosion tests on the alloy modifications of X7007 with Ag are shown in Table XXXVIIa and b. For tests in salt water (Figure 42), the alloys with Ag tend to fail more rapidly than X7007, but probably do not have a lower threshold stress for stress-corrosion cracking. The data for the alloys with Ag are somewhat questionable, however, because of the pitting that occurred. These alloys are presently being tested in the Point Judith, R.I., atmosphere to determine the resistance to stress-corrosion cracking in a natural seacoast environment.

Figure 43 shows that the X7007 with Ag has improved resistance to stress-corrosion cracking in the New Kensington industrial atmosphere. All specimens of X7007 failed within 330 days when stressed to 50% of the yield strength, while less than half of the specimens of the alloys with Ag failed within 350 days when stressed to 75% of the yield strength.

The results of stress-corrosion tests on the alloys with Li, Ca, Ta and Nb are shown in Table XXXVIII. The alloy with Li had higher strengths and somewhat poorer stress-corrosion resistance than X7007, while the alloy with Ca had lower strengths and similar stress-corrosion resistance. The alloys with Ta and Nb had strengths and stress-corrosion resistance similar to that of X7007.

The results of weld cracking tests on the last group of alloys, using parent metal as filler metal, are shown in Table XXXIX. Silver appeared to decrease the amount of weld cracking slightly, while Ta and Nb decreased the amount of weld cracking slightly more.

To summarize the effect of alloy modifications, the addition of Ag to X7007 improved the resistance to stress-corrosion cracking in an industrial atmosphere without decreasing strength, notch-toughness or weldability, and so therefore will be continued to be studied. The addition of Ta improved the weldability of X7007 without adversely affecting other properties; nevertheless, evaluation of this alloy was discontinued because of the availability of filler alloys with low weld-cracking characteristics. The tests of modifications with Ca and Li were terminated due to low notch-toughness.

AGING STUDIES

The natural aging of X7007 alloy is shown in Table XL and Figure 44. This alloy shows a large increase in tensile and yield strengths with natural aging at room temperature.

Results of a preliminary program on the effect of aging treatment on the tensile and notch-tensile properties of X7007 are shown in Table XLI. In Figure 45, the -320 F notched/unnotched tensile ratios are plotted against room temperature yield strength and agree well with previous data for alloys M791 and M793.

Figure 46 shows the tensile and notch-tensile properties of X7007 plotted against testing temperature for several aging treatments. The aging treatment of 16 hours at 275 F appeared to provide the best combination of properties. This included yield strengths that met the contract goal, a notched/unnotched tensile ratio at -423 F which closely approached the contract goal of 0.90, and gave higher cryogenic ductility than aging treatments providing similar strengths. This treatment was selected for further evaluation and was designated the T6E136 temper.

The results of stress-corrosion tests on the above items of 1.000 inch plate of X7007 are shown in Table XLII. Only a slight variation in resistance to stress-corrosion cracking was observed with the different aging treatments; the resistance to stress-corrosion cracking improved slightly as the strength decreased. Stress-corrosion cracking occurred in the short-transverse direction of plate aged by all practices.

From the above results, it was evident that the T6E136 temper could provide acceptable strength and notch-toughness, but that a considerable improvement in resistance to stress-corrosion cracking for the short-transverse direction would be desirable. Therefore, an extensive program was undertaken in an effort to improve the resistance to stress-corrosion cracking by alteration of the thermal treatment.

INVESTIGATION OF TREATMENTS TO IMPROVE RESISTANCE TO STRESS CORROSION

Several variables in thermal treatments were studied to determine their effects on the stress-corrosion susceptibility of X7007. The variables included the effects of ingot preheating, solution heat treating temperatures and artificial aging and quench aging practices. Other investigations of 7XXX type alloys had shown that such variations in thermal practice produced changes in dispersoid particles, M-phase precipitate distribution and size, and the width of denuded areas at the grain boundaries. It was reasoned that such structural changes might influence the stress-corrosion behavior of X7007 by changing the intragranular electrochemical potential. The purpose of these investigations was to relate thermal treatment to obvious structural changes and any improvement in the stress-corrosion characteristics.

The results of stress-corrosion tests are shown in Tables XLIII-XLVI. Table XLIII shows that ingot preheating temperature and solution heat treating temperature variations had no significant influence on the stress-corrosion performance of X7007. The performance of material produced by normal practices of ingot preheating and solution heat treating at 860 F was as good as or better than that of material produced by other practices. Solution heat treating below the solvus temperature (approximately 750 F) adversely affected the strengths, probably due to precipitation of T-phase and M-phase (Table XLIV). Similar losses in strengths occurred by slow cooling from a solution temperature of 860 to 650 F prior to quenching.

The wide selection of artificial aging practices produced yield strengths ranging from 57 to 71 ksi (Table XLV). The lower range of strengths were produced by overaging. Step-aging treatments generally provided lower strengths than the recommended aging treatment of 16 hours at 275 F. These lower strengths were not associated with any improvement in the stress-corrosion performance.

Interrupted quenching or quench aging improved the resistance to stress-corrosion cracking for certain treatments, but with a considerable loss in strength (Table XLVI). The procedure which produced the best resistance to corrosion consisted of solution heat treating at 860 F, quenching to 400 F and soaking for a period of 60 minutes followed by a normal artificial aging practice. This material exhibited a yield strength of 31 ksi and no stress-corrosion failures within a 300 day exposure period.

Representative electron micrographs showing the variety of microstructures obtained by the diverse practices employed in these investigations are shown in Figures 47-50. X7007 in a fully aged condition has small zone and precipitate particle sizes accompanied by narrow, zone-free areas at grain boundaries as seen in Figure 47. Such a structure is typical of that of X7007-T6E136. Precipitate growth typical of overaged material was produced by aging at 350 F (Figure 48). Both of these items had relatively high strengths and were susceptible to stress-corrosion cracking. The large precipitates and zone-free areas obtained by quench aging are shown in Figures 49 and 50. Figure 50 illustrates the extreme modification in microstructure needed to provide good stress-corrosion resistance in the present tests.

The above work has shown no thermal treatment could provide resistance to stress-corrosion cracking significantly better than that of the T6E136 treatment, except for quench-aging treatments which drastically reduced the strengths. Therefore, the T6E136 treatment was used as a standard product temper in determining the typical properties and characteristics of X7007.

STRUCTURE AND PROPERTIES OF PLANT FABRICATED X7007

Microstructure

The optical microstructures of X7007-T6E136 sheet and plate are shown in Figures 51 and 52. X-ray analysis showed that the 0.064 inch sheet was partially recrystallized, while the 1.000 inch plate was unrecrystallized. The recrystallized grains of the sheet were elongated in the rolling direction. The constituent particles are $Al_{12}(Fe,Mn)_3Si$ and $(Fe,Mn)Al_6$.

Electron microscopic examinations were also conducted on the 0.064 inch sheet and 1.000 inch plate. Figure 53 shows the microstructure of X7007 1.000 inch plate on a plane perpendicular to the surface. The subgrains appear to be slightly elongated and contain dislocation tangles, although only a few subgrains are oriented correctly to show the dislocations. Figure 54 shows the microstructure at a higher magnification. The large dark particles in Figure 54 are dispersoid particles, probably E phase ($Al_{12}Mg_2Cr$), M-phase ($MgZn_2$ type) and Mg_2Si phase. The small and uniformly distributed spots throughout the matrix are probably zones.

Engineering Properties

To obtain more information on the engineering properties and fracture characteristics of X7007, six gages of plant fabricated X7007-T6E136 sheet and plate were evaluated. The compositions of these items are given in Table XXXII. Tensile, compressive, shear, bearing, bend and fatigue properties, hardness, notch-toughness, tear resistance and fracture-toughness were determined at room temperature. Tensile and notch-tensile properties and tear resistance of a few lots were determined at temperatures to -452 F. The results of these tests will only be summarized in this section. Descriptions of the tests conducted and complete reporting of the test results are given in Appendix I.

Average tensile, compressive, shear, bearing properties and hardness values are given in Table XLVII. The average tensile yield strength and elongation met the contract goals of 65 ksi and 10%, but the tensile strength was slightly below the 75 ksi goal. Tensile and compressive stress-strain curves for specimens from 1.000 inch plate are shown in Appendix I. Average elastic moduli obtained were 10.4×10^6 psi tensile modulus and 10.6×10^6 psi compressive modulus.

In repeated 90 degree bend tests on 0.064 inch sheet, the number of completed bends was 10 for tests with the axis of the bend normal to the rolling direction and 4 for tests with axis of bend parallel to the rolling direction. The minimum 180 degree bend radius for material with thicknesses up to 1.000 inch was approximately 2.5 times the thickness (2.5t).

Fatigue tests were conducted using sheet-type flexural specimens from 0.064 inch sheet, smooth axial-stress fatigue specimens from 0.125 inch sheet, and smooth and notched rotating-beam and axial-stress specimens from 1.000 inch plate. The average fatigue limits at 5×10^8 cycles are summarized below:

Type of Specimen	Fatigue Limit, ksi Smooth	Notched K_t <12
Sheet - Flexure	18	--
Rotating - Beam	22	5.5
Axial - Stress, Sheet	27	--
Axial - Stress, Plate	33	8.0

These fatigue strengths are similar to those of 7075-T6 products.

The effects of testing temperature on the tensile and notch-tensile (K_t = 10) properties of X7007-T6E136 sheet and plate are shown in Table XLVIII. Resutls of notch-tensile tests on specimens with notch-intensity factors (K_t) other than 10 are given in Appendix I. Figure 55 shows that the strengths increased with decreasing testing temperatures, although between -320 and -423 F the sheet did not increase in strength as much as the plate. The elongations did not change significantly with temperature. The notch-toughness was lower for the sheet than for the plate due to a difference in specimen design. The notch-toughness was excellent at room temperature but decreased with decreasing testing temperature. Nevertheless, the notched/ unnotched tensile ratio for round specimens was 0.9 at -423 F.

Tear tests were conducted to determine the fracture characteristics of X7007-T6E136. Unit propagation energy, a measure of the energy needed to propagate a crack, is used as a measure of tear resistance. Average room temperature tear properties of sheet and plate are shown in Table XLIX. X7007 exhibits one of the best combinations of strength and tear resistance of all alloys examined. Table L shows that the tear resistance decreases significantly with decreasing testing temperature.

Plane-strain stress-intensity factors (K_{Ic}) and strain-energy release rates (G_{Ic}) were determined with center-notched tension specimens from 0.250 inch plate and notched bend specimens from 0.500 and 1.000 inch plate. The values of K_{Ic} and G_{Ic} were based upon the loads at a 5 percent secant offset, corresponding to a crack growth of about 2 percent. Reasonable estimates of K_{Ic} and G_{Ic} are as follows:

Direction	K_{Ic} psi $\sqrt{in.}$	G_{Ic} in.-lb/in.^{2}
L	45,000	200
T	37,500	135

Physical Properties

The physical properties of X7007 are shown in Table LI.

Resistance to Stress-Corrosion

Tests have shown that the resistance to stress-corrosion of X7007-T6E136 is excellent in the long transverse direction of sheet and plate. In the short-transverse direction of plate, stress-corrosion cracking may occur, as illustrated in Tables XXXVII, XLII and LII or Figure 56 for 1 inch thick plate.

For tests in a 3 1/2% NaCl salt solution by alternate immersion, failures occurred at 75%, 50% and 25% of the yield strength. The threshold stress for stress-corrosion cracking in this environment is below 16 ksi. A similar threshold stress would be expected for a natural seacoast environment, but with times to failure significantly longer. For tests in the New Kensington industrial atmosphere, specimens stressed to 75% or 50% of the yield strength failed fairly rapidly, but specimens stressed to 25% of the yield strength have not failed within exposure times to 730 days. Longer test times are needed before a threshold stress can be determined for the New Kensington atmosphere.

Because of stress-corrosion cracking in the short-transverse direction of X7007-T6E136 plate, structures using this alloy must be designed so as to eliminate exposed transverse sections that may be subjected to sustained short-transverse direction tensile stresses.

PROPERTIES OF X7007 WELDMENTS

The initial filler alloy evaluated for X7007 was an Al-Zn-Mg filler alloy with high Zn, M822. After considerable evaluation of this filler alloy*, it became apparent that M822 would provide very desirable weld strengths, but that weld cracking would probably be a problem in restrained joints and also that M822 weldments were noticeably susceptible to stress-corrosion cracking. Because of these problems with M822 filler alloy, two high Mg filler alloys (5356 and X5180) were evaluated. In the following section, the properties of weldments prepared using these three filler alloys are reviewed.

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*These data were summarized in the Third Annual Report of this contract, dated April 4, 1967.

Results of weld cracking tests (Table LIII) showed that filler alloys 5356 and X5180 are significantly less susceptible to weld cracking than filler alloy M822.

TABLE LIII

RESULTS OF WELD CRACKING TESTS ON X7007

Filler Alloy	Nominal Composition					Inches of Cracking*
	Mg	Zn	Mn	Ti	Zr	
M822	2.25	6	.3	.12	.18	16
5356	5	-	.1	.1	-	3
X5180	4	2	.5	.1	.15	3

*Discontinuous test - J. Dowd, WELDING JOURNAL, 31, October 1952.

The tests indicate that X7007 should be commercially weldable using 5356 or X5180, although the weldability would be slightly lower than that of 2219 or X2021 welded with 2319. Some weld cracking might occur if the weld bead were excessively diluted by parent metal.

All three filler alloys provided weld tensile strengths (Table LIV) which met the contract goal of ≥60 ksi (80% of the parent metal tensile strength goal of ≥75 ksi). Results of limited tests showed that the as-welded tensile strength of a weldment made with 5356 filler increased with time after testing. The elongations of these weldments were good, although the elongation was small numerically due to the 10 inch gage length used.

Results of notch-tensile tests on M793 alloy (which is within the composition range for X7007) welded with M822 filler alloy were reported earlier in Table X. Filler alloy M822 provided good notch-toughness at room temperature, but at -320 F the notched/unnotched tensile ratio was below that of the -423 F goal of 0.85.

Notch-tensile tests of X7007 welded with 5356 showed excellent notch-toughness at room temperature and cryogenic temperatures (Table LV). The reduced section unnotched tensile strengths were significantly below the full section tensile strengths of Table LIV; this showed the importance of weld bead reinforcement on full section tensile properties. The elongation decreased with post-weld aging and decreasing testing temperature. Notch-tensile tests were limited to 5356 filler alloy since it is currently recommended for X7007.

The results of stress-corrosion tests on X7007 weldments using three types of specimens are shown in Table LVI. These data supported the previous observations on M822 weldments that the root side of the weldment (last side welded) was generally more susceptible to stress-corrosion cracking than the face side. The data also verified the previous indication that removing the weld bead reinforcement only slightly extended the time to failure.

Filler alloys 5356 and X5180 showed significantly better resistance to stress-corrosion cracking than M822. Filler alloy 5356 appeared slightly better than X5180.

Post-weld aging did not seem to have a significant effect on stress-corrosion cracking. Weldments made with 5356 appeared to have good resistance to stress-corrosion cracking in salt water but were susceptible to cracking in the New Kensington, Pa., industrial atmosphere.

As a result of these investigations of weldments, filler alloy 5356 is currently recommended for X7007 since it provides tensile properties similar to those obtained with the other filler alloys studied, it offers good notch-toughness at ambient and cryogenic temperatures, it appears to produce slightly better resistance to stress-corrosion cracking than the other filler alloys studied, and because it is commercially available.

SUMMARY AND COMPARISON OF ALLOYS X2021 AND X7007

The estimated average tensile and notch-tensile properties of X2021-T81 and X7007-T6E136 are summarized in Table LVII and compared with the contract objectives. Also listed in Table LVII are the properties of existing weldable alloys, some of which have been used in space vehicle applications. These alloys include the nonheat-treatable alloy 5456 which was used in the S-IB booster stage of the Saturn 1, and the heat-treatable alloys 2219 and 2014 which are used in the S-IC and S-II stages of the Saturn 5. Another is the weldable Al-Zn-Mg alloy 7039.

The room temperature tensile and yield strengths of the alloys are graphically compared in Figure 57. The tensile strengths of X2021 and X7007 are similar and are slightly below the contract goal of 75 ksi. The yield strength of X7007 is slightly above the goal of 65 ksi, while the yield strength of X2021 is slightly below the goal. Both X2021 and X7007 provide improved strengths over the existing weldable alloys. Alloy X2021 has lower elongation at room temperature than the other alloys.

Notched/unnotched tensile ratios at room temperature and -423 F are plotted in Figure 58. The room temperature notch-toughness of alloy X2021-T81 is lower than that of the other alloys, although it still meets the room temperature notch-toughness goal; however, the notch-toughness remains constant with decreasing testing temperature so that at -423 F it is higher than those of the other alloys. In contrast, the notch-toughness of X7007-T6E136 is excellent at room temperature but decreases with decreasing temperatures so that at -423 F it is lower than those of the 2XXX series alloys. It still meets the -423 F goal, though.

The stress-corrosion resistance of X2021-T81 approaches that of 2219, which is excellent and shows no failures when stressed to 75% of the yield strength. The resistance to stress-corrosion cracking of X7007-T6E136 is of a lower order, being similar to that of 7039. When tested in the long-transverse direction, such alloys have low susceptibility to stress-corrosion cracking. In the short-transverse direction, however, the alloys are quite susceptible. The threshold stress for stress-corrosion cracking of X7007-T6E136 appears to be of the order of 25% of the yield strength for the New Kensington industrial atmosphere. The threshold stress is less than 16 ksi for the accelerated test consisting of alternate immersion in 3 1/2% NaCl.

The X2021/2319 parent metal/filler alloy combination provides weldability similar to that of the 2219/2319 combination and better than that of 2014/2319. The X7007/5356 combination has weldability similar to that of the 7039/5356 combination; that is, it is commercially weldable, but will require somewhat more care than the 2219/2319 or X2021/2319 combinations.

The tensile strengths of 0.5 inch thick welded plate are compared in Figure 59. The X2021/2319 weldments provide tensile strengths slightly lower than the 2014/2319 weldments but slightly higher than the 2219/2319 weldments. These strengths are well below the contract objective of 60 ksi (80% of the parent metal tensile strength goal of 75 ksi). Weldments of X7007/5356 have tensile strengths which closely approach the contract goal and which are among the highest observed for aluminum. The tensile strengths of X7007/5356 weldments are slightly higher than those of 7039/5356 weldments.

Limited stress-corrosion tests on X2021/2319 weldments show that the post-weld aged condition is resistant to stress-corrosion cracking, but that the as-welded condition is susceptible. It is difficult to appraise the relative stress corrosion of X2021/2319 weldments from these results, however, since high stress levels were used in these tests to uncover any tendencies towards stress-corrosion cracking. Presently, it appears that the stress-corrosion resistance of X2021/2319 weldments approaches that of 2219/2319 weldments and is superior to that of 2014/2319 weldments. It should be noted that 2014/2319 weldments have been employed commercially with very few problems. X7007/5356 weldments are susceptible to stress-corrosion cracking in the New Kensington atmosphere when exposed at high stress levels.

The preceding comparisons have shown that alloy X2021 is an improvement in high-strength weldable alloys. This can be most easily shown by a direct comparison with 2219-T851 and 2014-T651. Alloy X2021-T81 provides higher parent metal strengths and slightly higher weld strengths when welded with 2319 than 2219-T851, while maintaining the good stress-corrosion resistance and weldability of 2219. Alloy X2021-T81 has about the same strength as 2014-T651, superior stress-corrosion resistance and superior weldability. The weld strengths of 2014 appear to be slightly higher than those of X2021.

Alloy X7007 has an excellent combination of properties but is susceptible to stress-corrosion cracking in the short-transverse direction and in weldments. For this reason X7007 cannot be recommended for use without limitations on design and application to avoid short-transverse direction stresses. The capability of high parent metal strengths and high weld strengths, however, justifies further work to solve these stress-corrosion problems.

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TABLE I

COMPOSITIONS OF ALLOYS USED IN SURVEY PROGRAMS

	Cast No.	Cu	Fe	Si	Mn	Mg	Zn	Cr	Zr	V	Ti	Cd	Sn	Ni
2000 Series Alloys Preliminary Survey	291076	6.53	.20	.12	.31	.00	.00	.00	.17	.10	.08	.00	.00	.00
	291077	6.32	.19	.11	.31	.31	.01	.00	.18	.10	.08	.00	.00	.01
	291079	6.25	.19	.30	.31	.31	.01	.00	.17	.10	.08	.00	.00	.01
	291080	6.43	.20	.12	.32	.00	.00	.00	.16	.10	.07	.20	.00	.01
	291081	6.26	.19	.11	.32	.00	.00	.00	.17	.10	.07	.18	.05	.01
	291082	6.33	.19	.29	.32	.00	.00	.00	.17	.11	.09	.20	.00	.01
Advanced Evaluation	291597	6.16	.17	.07	.29	.31	.00	.00	.17	.11	.06	.00	.00	.01
	291715	6.21	.18	.07	.29	.00	.00	.00	.17	.11	.06	.17	.00	.00
	291716	6.24	.18	.07	.28	.00	.00	.00	.17	.11	.06	.14	.05	.00
	291816	6.02	.16	.07	.28	.00	.01	.00	.17	.10	.07	--	.04	.00
5000 Series Alloys Preliminary Survey	291138	.10	.12	.06	.30	7.22	.00	.10	.00		.03			.00
	291139	.11	.12	.06	.32	8.55	.00	.10	.00		.03			.00
	291140	.11	.12	.07	.31	8.64	2.05	.10	.00		.03			.00
	291141	.11	.14	.07	.30	8.45	2.02	.08	.11		.03			.01
7000 Series Alloys Preliminary Survey	291104	.02	.19	.06	.21	1.29	7.40	.16			.03			.00
	291105	.02	.19	.06	.22	1.24	8.95	.16			.03			.00
	291106	.02	.19	.06	.21	1.76	5.60	.15			.03			.00
	291107	.02	.19	.06	.21	1.80	7.30	.16			.03			.00
	291108	.02	.20	.07	.22	1.78	9.05	.16			.02			.00
	291109	.02	.19	.06	.20	2.29	4.34	.15			.03			.00
	291110	.02	.19	.07	.21	2.29	5.54	.15			.03			.00
	291111	.02	.19	.07	.21	2.20	7.35	.16			.03			.00
	291112	.02	.19	.07	.22	2.26	8.90	.16			.03			.00
	291113	.02	.19	.07	.20	2.76	4.12	.15			.03			.00
	291114	.02	.17	.07	.21	2.78	5.48	.15	.00		.03			.00
	291115	.02	.18	.07	.22	2.75	6.96	.16	.00		.03			.00
	291116	.02	.17	.07	.21	3.16	5.60	.15	.00		.03			.00
	291117	.01	.18	.07	.22	1.24	7.00	.16	.14		.03			.00
	291118	.02	.18	.07	.21	2.32	4.34	.15	.14		.03			.01
	291119	.02	.18	.07	.21	2.28	5.60	.15	.12		.03			.00
	291120	.02	.18	.07	.22	2.31	7.16	.16	.12		.03			.00
	291342	.26	.13	.06	.20	2.28	4.20	.11	.15		.03			.01
	291343	.28	.13	.07	.21	2.33	5.49	.13	.15		.03			.01
	291344	.28	.13	.07	.25	2.23	7.13	.14	.15		.03			.01
Advanced Evaluation (Davenport)	M790	.11	.16	.15	.20	2.65	6.18	.12	.00		.01			.00
	M791	.12	.16	.09	.21	2.22	6.20	.13	.10		.01			.00
	M792	.09	.21	.09	.21	2.65	9.14	.12	.00		.02			.00
	M793	.12	.18	.09	.20	1.64	6.51	.13	.10		.01			.00

TABLE II

TENSILE PROPERTIES OF 2000 SERIES ALLOYS
(0.064 inch sheet)

Alloy	Cast No.	Pre-age	Stretch %	Aging Time at Temp Hr/°F	Room Temperature TS ksi	Room Temperature YS ksi	Room Temperature % El. in 2"	Room Temperature NTS/TS	-320 F NTS/TS
2219	291076	No	1 1/2	18/350	67.8	52.0	9.5	.80	.78
2219 + .31 Mg	291077	No	1 1/2	8/350	67.2	53.0	11.2	.85	.79
		No	6	12/325	70.3	60.9	9.5	.88	.76
2219 + .31 Mg + .30 Si	291079	No	1 1/2	8/350	67.4	57.1	9.5	.84	.77
		No	6	12/325	69.9	61.9	9.5	.77	.73
2219 + .20 Cd	291080	No	No	18/350	75.8	66.2	8.5	.58	.59
		No	1 1/2	18/320	68.2	51.5	12.5	.74	.75
		1 hr at 320 F	1 1/2	18/320	74.7	62.2	11.5	.67	.71
2219 + .20 Cd + .29 Si	291081	No	No	18/350	75.3	65.4	10.5	.74	.65
2219 + .18 Cd + .05 Sn	291082	No	No	18/350	75.0	65.8	8.0	.62	.62
		No	1 1/2	18/320	71.8	61.1	9.8	.66	.61
		1 hr at 320 F	1 1/2	18/320	76.3	67.9	7.5	.63	.50
2219 + .04 Sn*	291816	No	1 1/2	16/325	72.6	59.8	10.4		

* Properties for 0.525 inch plate.

1) Long transverse properties - $K_t \geq 17$.

TABLE III

TENSILE PROPERTIES OF 2000 SERIES ALLOYS
(0.525 inch plate)

				Aging	Room Temperature				Notch-Tensile Ratio			
Cast No.	Lot No.	Pre-age	Stretch %	Time at Temp Hr/°F	TS ksi	YS ksi	% El. in 1.4"	% R of A	RT	-112 F	-320 F	-423 F
2219 + Mg												
291597	291817	No	1 1/2	16/325	68.6	52.1	16.8	30	1.21	--	1.15	--
291597	291820	No	1 1/2	96/300	69.2	53.2	16.4	28	1.22	--	1.14	--
2219 + Cd												
291715	291818	1 hr at 325 F	1 1/2	16/325	73.8	60.8	11.4	18	1.13	1.17	1.08	1.00
291715	291829	4 hr at 300 F	1 1/2	16/325	71.4	56.2	12.5	20	1.14	--	1.10	--
2219 + Cd + Sn												
291716	291819	No	1 1/2	8/325	73.0	61.3	10.0	14	1.03	1.12	1.08	1.00
291716	291905	1 1/2 hr at 300 F	1 1/2	8/325	75.4	66.0	9.0	12	.98	1.09	1.06	1.03
2219 + Sn												
291816	292066	No	No	16/325	72.6	59.8	10.4	15	1.07	--	1.05	--
291816	292067	2 hr at 300 F	1 1/2	10/325	72.6	59.6	11.0	17	1.10	--	1.08	--

1) Solution heat treated at 995 F; cold water quenched and aged as indicated.

2) Long transverse properties - Notched round specimens - K_t = 10.

TABLE IVa

RESULTS OF STRESS-CORROSION TESTS ON 2000 SERIES ALLOYS

				Long Transverse 1/8" Diameter Tensile Bars Stressed to 75% of the Yield Strength						
				3 1/2% NaCl - Alternate Immersion			New Kensington Atmosphere			Pt. Judith Atm.
		Plate Thick	Soln† Pot.	Days to Failure	% Loss in TS*		Days to Failure	% Loss in TS*		Days to Failure
Cast No.	Lot No.	Inches	mv	or Days OK	Stressed	Unstressed	or Days OK	Stressed	Unstressed	or Days OK
2219 + Mg										
291597	291817	0.525	-750	80,90, R106	34	20	R365	5	2	OK1030
291597	291820	0.525	-759	5,84,92, R106	28	19	R365	5	2	402, OK1030
2219 + Cd										
291715	291818	0.525	-769	31,80,80,87,106, R106	30	22	276, R365	2	4	OK1030
291715	291829	0.525	-763	5,15,80,84, R106	32	22	R365	2	1	343, OK1030
291715	292313	1.000	-774	2,2,2,3,3,3	--	28	39,145,165	--	6	14,38,38
2219 + Cd + Sn										
291716	291819	0.525	-774	30,30, R106	35	20	R365	4	2	157,157, OK1030
291716	291905	0.525	-764	7,7,8,8,9,9	--	21	144,210,224	--	3	119,119,119
291716	292314	1.000	-806	34, R106	25	19	R365	3	3	R365
2219 + Sn										
291816	292066	0.525	-748	3,3,3,5,5,6	--	21	447, OK975	--	--	105,105,105
291816	292067	0.525	-753	3,3,3,3,3,3	--	20	209,943, OK975	--	--	3,5,6
291816	292315	1.000	--	2,2,3,3,3,3	--	24	117,123,242	--	2	14,14,14

† Potential, 0.1 N calomel scale, $NaCl-H_2O_2$ electrolyte.

* Percent loss in tensile strength after 106 or 365 days exposure, as indicated.

1) Heat treatment for 0.525 inch plate described in Table III. One-inch plate solution heat treated at 995 F, cold water quenched, and aged 16 hr at 325 F.

2) R indicates specimen removed intact after indicated time; OK indicates specimen intact and still in test after indicated time.

3) Sextuplet stressed specimens for 3.5% NaCl test, otherwise triplicate stressed and duplicate unstressed specimens exposed.

TABLE IVb

RESULTS OF STRESS CORROSION TESTS FOR X2021-T6 TYPE ALLOY PLATE

	Composition - %				Soln		Short Transverse C-rings Stressed as Indicated		
					Pot.		3 1/2% NaCl-A.I.	New Kensington	Pt. Judith
Lot No.	Cu	Mg	Cd	Sn	mv	Stress Level	Days to Failure or Days OK	Days to Failure or Days OK	Days to Failure or Days OK
292313	6.21	--	.17	--	-774	75	4, 7, 7	53, 88, 88	243, 243, 349
						50	7, 7, 10	536, OK975	243, OK870
						25	R180	OK975	--
292314	6.24	--	.14	.05	-806	75	171, 171, 173	OK975	OK870
						50	R180	OK975	OK870
						25	R180	OK975	OK870
292315	6.02	--	--	.04	--	75	10, 10, 19	OK975	OK870
						50	173, R180	OK975	OK870
						25	R180	OK975	OK870

NOTES: 1) Fabricating Procedure in preceding Table IVa.

2) R specimen removed intact after indicated time.
OK specimen intact and still in test after indicated time.

3) Tests in triplicate.

TABLE V

TYPICAL WELD PROPERTIES OF 2000 SERIES ALLOYS

MIG Welded 0.525" Plate - 2319 Filler Metal

	Condition of Weld	Bend Properties: Angle of Bend*	Bend Properties: Location/ of Failure	Full-Section Properties: TS ksi	Full-Section Properties: YS ksi	Full-Section Properties: % El. in 10"	Full-Section Properties: Location/ of Failure
2219 + Mg (291817)	As-Welded	30	A	45.0	42.1	1.0	A and B
	Aged**	19	A	47.0	44.5	0.9	A and B
2219 + Cd (291818)	As-Welded	30	A	43.0	37.8	0.8	B
	Aged	10	A	45.5	--	0.7	B
2219 + Cd + Sn (291819)	As-Welded	30	A	42.4	37.6	1.1	A and B
	Aged	9	A	47.4	44.9	0.8	A and B

Reduced-Section Properties***

	Condition of Weld	Room Temperature: TS ksi	Room Temperature: YS ksi	Room Temperature: % El. in 1.4"	Room Temperature: NTS/TS	-320°F: NTS/TS	Location/ of Failure
2219 + Mg	As-Welded	44.5	26.5	4.3	1.09	.96	A
	Aged	46.9	32.8	3.3	1.07	.96	A and B
2219 + Cd	As-Welded	40.2	21.4	5.4	1.04	.85	A and B
	Aged	47.2	31.6	3.1	1.09	.95	A and B
2219 + Cd + Sn	As-Welded	39.4	19.1	6.0	1.00	.87	A and B
	Aged	46.8	29.4	2.9	1.03	.93	A and B

*Root bend specimen (3.125" bend radius - 8 1/3t).
**Post-Weld Aged 16 hours at 325°F.
***Round specimens - K_t = 10.
/Location of Failure A - through weld
B - through edge of weld.

TABLE VII

EFFECT OF AGING TREATMENT ON THE STRENGTH AND NOTCH-TOUGHNESS OF M790, M791 AND M793

Aging Treatment	Room Temperature				-320°F			
Time at Temp. Hr/°F	TS ksi	YS ksi	% El. in 4D	NTS/TS	TS ksi	YS ksi	% El. in 4D	NTS/TS
M790								
48/250	77.0	71.2	10.5	1.21	96.3	86.8	5.0	.73
*6 mo/70	77.6	57.4	13.2	1.12	89.9	72.2	8.0	.72
8/225 + 16/300	69.2	61.0	12.0	1.27	90.2	73.9	11.0	.85
4/250	77.2	65.8	12.8	1.21	95.0	79.4	8.8	.80
M791								
48/225	77.8	68.4	11.5	1.25	96.7	82.1	9.5	.84
*6 mo/70	76.2	58.0	12.1	1.19	93.0	70.2	12.0	.83
8/225 + 16/300	69.0	60.8	13.2	1.36	90.4	74.9	11.5	1.05
16/225	73.6	60.9	12.2	1.26	91.4	73.7	10.5	1.00
M793								
24/225	73.6	63.4	11.5	1.31	91.8	77.0	11.0	1.10
*6 mo/70	73.2	56.4	11.4	1.24	91.2	70.2	12.8	.96
8/225 + 16/300	63.8	56.3	13.8	1.41	85.2	69.4	13.7	1.15

* Greater than 6 months aging (W temper).

1. The naturally aged material was 0.5" plate, while the other material was 1.0" plate.

2. Long transverse properties - Notched round specimens - K_t = 10.

TABLE VIII

TENSILE AND NOTCH TENSILE PROPERTIES OF M791 AND M793 PLATE

		Aging Treatment		Room Temperature				Notch-Tensile Ratio			
S. No.	Alloy	Time-Hr	Temp-°F	TS ksi	YS ksi	% El. in 2"	% R of A	RT	-112°F	-320°F	-423°F
291704-I	M791	16	225	73.6	60.9	12.2	16	1.26	1.15	1.00	.83
291706-A	M793	4	300	70.4	64.0	12.5	26	1.37	--	1.10	.97
291706-J	M793	24	225	73.6	63.4	11.5	15	1.31	--	1.10	.98
291706-K	M793	48	225	74.8	66.9	11.0	16.5	1.32	--	.99	.89

1. Long transverse direction of 1.0" plate - Notched round specimens - $K_t = 10$.

TABLE IXa

RESULTS OF TENSILE AND STRESS-CORROSION TESTS FOR Al-Zn-Mg ALLOYS

			Tensile Properties			Long Transverse 1/8 Inch Diameter Tensile Bars, Stressed to 75% of the Yield Strength								
						3 1/2% NaCl - Alternate Immersion			New Kensington Atmosphere			Point Judith Atmosphere		
						Days to Failure or Days OK	% Loss in TS*		Days to Failure or Days OK	% Loss in TS*		Days to Failure or Days OK	% Loss in TS*	
Alloy	S. No.	Thick in.	TS ksi	YS ksi	% El. in 2"		Stressed	Unstressed		Stressed	Unstressed		Stressed	Unstressed
						Solution Heat Treated and Hot Water Quenched at Plant; Aged 8 hr at 225 F + 16 hr at 300 F at ARL								
M792	291572	3.0	72.6	64.7	8.0	180, R180	17,28	6	119,119,132	--	2	161,444,444	--	12
M790	291570	3.0	68.4	59.8	8.5	R180	16	3	235, R365	8	0	R455	17	13
M791	291571	3.0	69.5	61.4	8.0	R180	1	4	R365	0	0	R455	8	10
M793	291573	3.0	67.5	61.4	10.0	R180	1	2	R365	2	1	R455	8	7
						Solution Heat Treated, Cold Water Quenched and Aged 48 hr at 250 F at ARL								
M792	292310	3.0	91.2	87.6	4.0	5,5,10	--	6	6,6,6	--	4			
M790	292308	3.0	78.7	74.1	6.5	48,48,87	--	4	22,27,40	--	0	225,284,388	--	--
M791	292309	3.0	78.2	73.2	6.5	76,164,180	--	3	R365	5	0	388, R388	6,14	5
M793	292311	3.0	74.2	69.1	7.0	R180	8	4	R365	0	1	R388	5	4

* Percent loss in tensile strength after 180, 365, 388 or 455 days exposure, as indicated.

1) Triplicate stressed and duplicate unstressed specimens.

2) R - Removed from test intact after indicated time.
OK - Intact and still in test after indicated time.

TABLE IXb

RESULTS OF STRESS CORROSION TESTS FOR Al-Zn-Mg ALLOYS

				Short Transverse 1/8 Inch Diameter Tensile Bars, Stressed as Indicated								
				3 1/2% NaCl - Alternate Immersion			New Kensington Atmosphere			Point Judith Atmosphere		
			Stress	Days to Failure	% Loss in TS†		Days to Failure	% Loss in TS†		Days to Failure	% Loss in TS †	
Alloy	S. No.	Thick in.	Level % YS	or Days OK	Stressed	Unstressed	or Days OK	Stressed	Unstressed	or Days OK	Stressed	Unstressed
Solution Heat Treated and Hot Water Quenched at Plant; Aged 8 hr at 225 F + 16 hr at 300 F at ARL												
M792	291572	3.0	75	31,63,180	--	52	55,63,63	--	20	57,57,57	--	67
			50	83,180,180	--	52	82,82,82	--	20	161,161,161	--	67
			25	180, R180	89	52	109,119,125	--	20	161,199,445	--	67
M790	291570	3.0	75	131,151, R180	82	18	90,99,99	--	--	62,161,161	--	--
			50	178, R180	22,34	18	109,112,125	--	--	161,161, R445	--	--
			25	R180	29	18	159,206,233	--	3	R445	62	36
M791	291571	3.0	75	134,151, R180	24	6	109,112,119	--	--	161,191,445	--	--
			50	R180	10	6	125,125,125	--	--	445, R445	16,32	16
			25	R180	10	6	197, R365	3	3	R445	13	16
M793	291573	3.0	75	151,180,180	--	8	119,120,146	--	--	161,161, R445	--	--
			50	R180	21	8	159,166, R365	1	--	445, R445	12,21	14
			25	R180	19	8	R365	1	--	R445	11	14
Solution Heat Treated, Cold Water Quenched and Aged 48 hr at 250 F at ARL												
M792	292310	3.0	75	1,1,1	--	6	**	--	22	**	--	--
			50	1,1,2	--	6	**	--	22	**	--	--
			25	3,7,10	--	6	6,6,8	--	22	38,225,225	--	--
M790	292308	3.0	75	3,5,5	--	4	**	--	4	**	--	--
			50	11,18,21	--	4	6,6,6	--	4	**	--	--
			25	87,146,146	--	4	6,11,22	--	4	38,225,225	--	--
M791	292309	3.0	75	5,7,7	--	3	6,6*	--	2	**	--	--
			50	18,18,18	--	3	6,6,6	--	2	38,225,225	--	--
			25	164,180,180	--	3	11,27,47	--	2	388,388,388	--	--
M793	292311	3.0	75	13,14,14	--	4	6,6,6	--	4	**	--	--
			50	22,40, R180	--	4	8,22,22	--	4	38,280*	--	--
			25	R180	42	4	57,214,302	--	4	388,388,388	--	--

† Percent loss in tensile strength after 180, 365 or 445 days exposure.

* Either single or duplicate specimens exposed.

** All specimens failed before exposure.

1) Triplicate stressed and duplicate unstressed specimens exposed.

2) R - Removed from test intact after indicated time.
OK - Intact and still in test after indicated time.

TABLE X

TENSILE PROPERTIES OF M793 0.5 INCH PLATE WELDED WITH M822 FILLER ALLOY

Designation	Welding Method	Weld* Condition	Bend Test** Angle of Bend	Full Section Tensile Properties TS ksi	YS ksi	% El. in 10"
292059-A1	MIG	AW	180	58.0	50.8	3.2
-A2	MIG	PWA	180	57.7	50.8	5.8
292059-B1	TIG	AW	180	52.8	45.4	2.5
-B2	TIG	PWA	180	56.8	50.4	4.5

			Reduced Section Tensile Properties (Round Specimens)							
			Room Temperature				-320 F			
Designation	Welding Method	Weld* Condition	TS ksi	YS ksi	% El. in 1.4"	NTS/TS	TS ksi	YS ksi	% El. in 1.25"	NTS/TS
292059-A1	MIG	AW	54.8	41.5	9.0	1.22	63.4	51.2	3.2	.74
-A2	MIG	PWA	57.7	50.4	7.1	1.34	76.4	60.2	6.8	.66
292059-A1	TIG	AW	53.0	41.5	8.6	1.39	64.4	51.7	3.6	.80
-A2	TIG	PWA	51.9	51.0	6.4	1.76	74.7	59.6	4.0	.73

** Root bend specimens (3.125" bend radius - 8 1/3 t).

* AW - As-welded; naturally aged over two months.
PWA - Post-weld aged 8 hr at 225 F + 16 hr at 300 F.

1) Plant fabricated M793; aged 8 hr at 225 F + 16 hr at 300 F.

2) M822 composition: .01 Cu, .17 Fe, .06 Si, .34 Mn, 2.25 Mg, 5.91 Zn, .01 Cr, .14 Zr, .10 Ti and .02 Ni.

3) Specimens transverse to weld bead and rolling direction. Notched round specimens - K_t = 10. Notch centered in this weld bead.

TABLE XI

STRESS-CORROSION RESULTS ON M793 0.5 INCH PLATE WELDED WITH M822 FILLER ALLOY

				Days to Failure			
				3 1/2% NaCl - Alt. Imm.		New Kensington Atm.	
S. No.	Welding Method	Weld† Condition	YS* ksi	Face in†† Tension	Root in†† Tension	Face in†† Tension	Root in†† Tension
292059-A1	MIG	AW	50.8	174	165	19	122
292059-A2	MIG	PWA	50.8	26	51	39	39
292059-B1	TIG	AW	45.4	206	11	329	19
292059-B2	TIG	PWA	50.4	165	33	70	49

* 0.2% offset in 10" gage length.

† AW - As-welded; naturally aged several months;
PWA - Post-weld aged 8 hr at 225 F + 16 hr at 300 F.

†† Root side last side welded; face side opposite side.

1) Plant fabricated M793; aged 8 hr at 225 F + 16 hr at 300 F.

2) Single assemblies (Type A, Figure 37) stressed to 75% YS*.

TABLE XII

CHEMICAL COMPOSITION OF X2021 TYPE ALLOYS

Description	Cast No.	Cu	Fe	Si	Mn	Mg	Zn	Cr	Zr	V	Ti	Cd	Sn	Ni	Other
X2021 Variations	292602	5.70	.17	.10	.33	.00	.00	.00	.12	.08	.06	.17	.06	.01	
	292603	6.25	.18	.09	.32	.00	.00	.00	.12	.09	.06	.16	.06	.01	
	292604	6.70	.18	.10	.33	.00	.00	.00	.12	.07	.05	.16	.06	.01	
	292605	6.20	.18	.10	.29	.00	.00	.00	.12	.10	.05	.10	.02	.01	
	292606	6.42	.18	.10	.33	.00	.00	.00	.12	.09	.05	.10	.08	.01	
	292607	6.35	.18	.09	.31	.00	.00	.00	.12	.09	.05	.19	.02	.01	
	292608	6.33	.17	.10	.34	.00	.00	.00	.12	.08	.05	.19	.08	.01	
	294849	6.54	.14	.08	.31	.00	.01	.01	.17	.10	.05	.17	.06	.00	
	294850	6.47	.14	.08	.31	.00	.01	.01	.18	.10	.05	.11	.06	.00	
	294851	6.57	.14	.08	.32	.00	.01	.01	.19	.10	.05	.06	.06	.00	
	294852	6.42	.14	.08	.32	.00	.01	.01	.19	.10	.06	.17	.02	.00	
	294853	6.39	.14	.08	.32	.00	.01	.01	.18	.10	.05	.11	.02	.00	
	294854	6.50	.14	.08	.32	.00	.01	.01	.19	.10	.06	.06	.02	.00	
	294855	6.51	.13	.08	.01	.00	.01	.01	.18	.10	.05	.17	.06	.00	
	294856	6.37	.14	.09	.65	.00	.01	.01	.18	.10	.06	.17	.06	.00	
Quench Sensitivity	291599	6.27	.18	.07	.28	.00	.00	.00	.00	.01	.06	.15	.05	.00	
	326714	6.28	.14	.07	.31	.00	.01	.01	.00	.08	.05	.14	.05	.00	
	326715	6.41	.14	.07	.29	.00	.01	.00	.20	.01	.05	.14	.04	.01	
	294857	6.42	.13	.08	.32	.00	.01	.01	.07	.10	.05	.16	.06	.00	
	294849	6.54	.14	.08	.31	.00	.01	.01	.17	.10	.05	.17	.06	.00	
	326716	6.41	.15	.07	.31	.00	.01	.00	.00	.01	.12	.14	.04	.00	
	326717	6.26	.14	.07	.29	.00	.01	.01	.00	.09	.11	.14	.05	.00	
	294859	6.42	.15	.07	.31	.00	.01	.00	--	.09	.06	.16	.05	.00	.02 Nb
	294860	6.44	.14	.08	.32	.00	.01	.01	.01	.09	.05	.17	.06	.00	.10 Mo
	294861	6.40	.14	.08	.31	.00	.01	.01	.01	.10	.05	.16	.06	.00	.08 Ta
Minor Impurities	326459	6.46	.13	.09	.33	.00	.02	.01	.19	.09	.06	.16	.05	.00	
	326460	6.38	.13	.09	.32	.04	.01	.01	.19	.09	.06	.17	.05	.00	
	326461	6.37	.13	.09	.33	.07	.02	.01	.19	.09	.06	.17	.05	.00	
	326462	6.35	.12	.09	.33	.00	.11	.01	.19	.09	.06	.17	.05	.00	
	326463	6.06	.12	.08	.32	.00	.01	.01	.19	.09	.06	.15	.05	.00	.05 Ca
	326466	5.60	.43	.08	.30	.00	.01	.01	.17	.08	.05	.13	.05	.00	
	326467	6.18	.12	.28	.32	.00	.02	.01	.19	.09	.06	.15	.05	.00	
Alloy Modifications	292538	6.15	.15	.09	.27	.00	.02	.00	.14	.10	.06	.13	.06	--	.29 Li
	292539	6.15	.16	.10	.27	.00	.02	.01	.14	.09	.06	.14	.05	--	.61 Li
	295858	6.51	.14	.08	.31	.00	.01	.15	.01	.01	.09	.05	.17	.06	.00
Plant Fabricated	326889, 327102, 342719	6.08	.11	.07	.25	.001	.03	.00	.13	.08	.05	.14	.03	.01	
	326888	6.19	.14	.05	.31	.006	.03	.00	.13	.08	.06	.14	.05	.01	
	342352	6.21	.12	.07	.26	.002	.02	.00	.14	.08	.06	.14	.04	.01	
	326402	6.20	.14	.06	.32	.01	.02	.00	.13	.09	.06	.13	.05	.01	
	292489-95	6.49	.15	.09	.34	.01	.02	.00	.13	.08	.05	.14	.06	.00	
	326410, 327021, 327022	6.19	.19	.08	.31	--	--	--	.18	.08	.07	.15	.07	--	

TABLE XIII

NOMINAL COMPOSITIONS AND TENTATIVE LIMITS FOR ALUMINUM ALLOYS X2021 AND X7007

Alloy No.	X2021 Nominal	X2021 Min.	X2021 Max.	X7007 Nominal	X7007 Min.	X7007 Max.
Si	-	-	0.20	- {Si + Fe		0.40}
Fe	-	-	0.30	-		
Cu	6.3	5.8	6.8	0.10	-	0.25
Mn	0.3	0.20	0.40	0.2	-	0.40
Mg	-	-	0.02	1.8	1.4	2.2
Cr	-	-	-	0.12	0.05	0.25
Zn	-	-	0.10	6.5	6.0	7.0
Ti	0.06	0.02	0.10	0.04	0.01	0.06
Zr	0.18	0.10	0.25	0.12	0.05	0.25
V	0.10	0.05	0.15	-	-	-
Cd	0.15	0.05	0.20	-	-	-
Sn	0.05	0.03	0.08	-	-	-
Others, each	-	-	0.05	-	-	0.05
Others, total	-	-	0.15	-	-	0.15

TABLE XIV

EFFECT OF COMPOSITION VARIATIONS ON THE NOTCH-TOUGHNESS OF X2021 PLATE

		Composition						Room Temperature Tests				-320 F Tests			
Cast No.	Lot No.	Cu	Mn	Cd	Sn	Thickness inches	Temper* Type	TS ksi	YS ksi	% El. in 4D	NTS/TS	TS ksi	YS ksi	% El. in 4D	NTS/TS
--	292602-2	5.70	.33	.17	.06	.525	T81	71.2	61.4	9.3	1.09	88.1	73.6	11.5	1.06
--	292603-2	6.25	.32	.16	.06	.525	T81	73.0	64.6	9.0	1.00	90.9	77.7	10.0	.98
--	292604-2	6.70	.33	.16	.06	.525	T81	72.8	64.2	8.8	.95	89.9	76.9	10.5	.95
--	292605-2	6.20	.29	.10	.02	.525	T81	71.4	62.5	9.1	1.10	88.8	74.4	11.2	1.06
--	292606-2	6.42	.33	.10	.08	.525	T81	71.6	61.7	8.6	1.03	89.0	74.1	9.8	1.05
--	292607-2	6.35	.31	.19	.02	.525	T81	71.5	61.2	9.3	1.07	88.1	73.1	11.5	1.06
--	292608-2	6.33	.34	.19	.08	.525	T81	72.2	63.2	8.6	.98	90.0	75.4	8.5	.97
294849	326320	6.54	.31	.17	.06	1.000	T62	72.1	63.8	5.0	.91	88.6	75.9	6.8	.93
294851	326321	6.57	.32	.06	.06	1.000	T62	70.7	60.4	7.5	1.02	87.4	72.6	10.8	.99
294852	326322	6.42	.32	.17	.02	1.000	T62	74.0	65.0	7.0	.99	90.6	76.7	8.8	.96
294854	326323	6.50	.32	.06	.02	1.000	T62	71.2	59.8	7.5	1.07	86.3	69.3	10.8	1.07
294855	326324	6.51	.01	.17	.06	1.000	T62	70.8	62.0	6.5	.94	87.0	73.1	9.5	.96
294856	326325	6.37	.65	.17	.06	1.000	T62	71.0	59.1	7.8	1.02	87.2	69.8	10.8	.99

* T81 temper items solution heat treated 1 hr at 985 F, cold water quenched, pre-aged 1 hr at 300 F, stretched 1 1/2% and aged 12 hr at 325 F.

T62 temper items solution heat treated 3 hr (total furnace time) at 990 F, cold water quenched and aged 16 hr at 325 F.

TABLE XVa

THE EFFECTS OF COMPOSITION ON THE RESISTANCE TO CORROSION OF X2021 PLATE

Cast No.	Composition Cu	Mn	Cd	Sn	Plate Thick in.	Temper Type	Long Transverse Tensile Properties TS ksi	YS ksi	% El. in 2"	Soln* Pot. mv	Long Transverse 1/8" Diameter Tensile Bars Stressed to 75% of the Yield Strength: 3 1/2% NaCl - Alternate Immersion, Days to Failure or Days OK	% Loss in TS** Stressed	Unstressed	New Kensington Atm. Days to Failure or Days OK	Point Judith Atm. Days to Failure or Days OK
292602	5.70	.33	.17	.06	.525	T81	71.2	61.4	9.3	-800	R180	17	20	OK 735	OK 705
292603	6.25	.32	.16	.06	..525	T81	73.0	64.6	9.0	-800	R180	23	26	OK 735	OK 705
292604	6.70	.33	.16	.06	.525	T81	72.8	64.2	8.8	-796	R180	23	29	OK 735	OK 705
292605	6.20	.29	.10	.02	.525	T81	71.4	62.5	9.1	-794	R180	18	23	OK 735	OK 705
292606	6.42	.33	.10	.08	.525	T81	71.6	61.7	8.6	-794	R180	21	23	OK 735	OK 705
292607	6.35	.31	.19	.02	.525	T81	71.5	61.2	9.3	-787	R180	20	27	OK 735	OK 705
292608	6.33	.34	.20	.08	.525	T81	72.2	63.2	8.6	-808	R180	20	27	OK 735	OK 705
294849	6.54	.31	.17	.06	1.000	T62	72.1	63.8	5.0	-806	R84	25	14	OK 200	--
294851	6.57	.32	.06	.06	1.000	T62	70.7	60.4	7.5	-796	R84	25	16	OK 200	--
294852	6.42	.32	.17	.02	1.000	T62	74.0	65.0	7.0	-803	R84	26	25	OK 200	--
294854	6.50	.32	.05	.02	1.000	T62	71.2	59.8	7.5	-770	11,40,84	--	14	OK 200	--
294855	6.51	.01	.17	.06	1.000	T62	70.8	62.0	6.5	-817	18,40,R84	33	22	OK 200	--
294856	6.37	.65	.17	.06	1.000	T62	71.0	59.0	7.8	-800	R84	19	13	OK 200	--

* Potential, 0.1N calomel scale, $NaCl-H_2O_2$ electrolyte.

** Percent loss in tensile strength after 84 or 180 days exposure.

1) All items solution heat treated at 985 to 990 F and cold water quenched.
Items 292602-608 pre-aged 1 hr at 300 F, stretched 1.5% and aged 12 hr at 325 F.
Items 294849-56 aged 16 hr at 325 F.

2) Duplicate unstressed and triplicate stressed specimens exposed.

3) R - Removed from test intact after indicated time.
OK - Intact and still in test after indicated time.

TABLE XVb

THE EFFECTS OF COMPOSITION ON THE RESISTANCE TO STRESS-CORROSION CRACKING OF ONE INCH THICK X2021-T62 PLATE

Cast No.	Solution Potential mv	Short-Transverse C-rings - Days to Failure or Days OK					
		3 1/2% NaCl Solution - Alternate Immersion			New Kensington Atmosphere		
		75% YS	50% YS	25% YS	75% YS	50% YS	25% YS
294849	-806	R84	R84	R84	OK 200	OK 200	OK 200
294851	-796	R84†	R84	R84	OK 200	OK 200	OK 200
294852	-803	84*,84*,84*	R84	R84	OK 200	OK 200	OK 200
294854	-770	8,10,10	10,24,24	R84	OK 200	OK 200	OK 200
294855	-817	84*,84*,R84	R84	R84	OK 200	OK 200	OK 200
294856	-800	84*,84*,84*	84*,84*,84*	R84	OK 200	OK 200	OK 200

* Stress-corrosion cracking discovered after removal from test and nitric acid cleaning.

† Metallographic examination showed stress-corrosion cracks.

1) See preceding table for description of material.
2) Triplicate specimens exposed.
3) R - removed from test intact after indicated time.
   OK - intact and still in test after indicated time.

TABLE XVI

EFFECT OF SOLUTION HEAT TREATING TEMPERATURE ON TENSILE PROPERTIES OF X2021-T81

S. No.	SHT Temp	Pre-aged and Stretched	Aging Time at 325 F in Hours							
			1	2	4	8	16	24	48	72
			Tensile Strength - ksi							
295149 -6	990 F	60.7	66.0	69.4	73.1	75.2	75.4	75.3	74.0	73.3
-2	980	60.9	65.6	67.9	70.5	72.6	73.1	72.6	71.9	71.3
-3	970	56.8	64.4	66.3	69.5	71.3	71.7	71.4	70.9	69.8
			Yield Strength - ksi							
-6	990	37.3	47.5	53.0	62.0	66.7	66.7	66.5	64.3	62.9
-2	980	39.0	46.8	52.2	59.7	64.3	65.2	64.6	63.2	62.5
-3	970	34.0	45.0	50.0	58.3	62.7	63.6	62.8	61.8	60.2
			Elongation % in 2 inches							
-6	990	20.0	18.5	16.0	13.5	10.0	8.5	9.0	9.0	9.5
-2	980	20.0	19.0	15.5	13.5	10.5	10.0	10.0	10.0	10.0
-3	970	20.0	19.5	17.0	13.0	11.0	11.0	11.0	10.0	10.0

1. Solution heat treated at the indicated temperature, cold water quenched, pre-aged immediately 1 hour at 300 F, stretched 1 1/2% and aged immediately as indicated.

2. Single transverse specimens - 0.125 inch sheet - YS = 0.2% Offset.

TABLE XVII

EFFECT OF PERCENT REDUCTION AFTER QUENCHING ON THE STRENGTH OF X2021 ALLOY

Pre-age	Cold Work or Stretch	T.S. ksi	Y.S. ksi	% El. in 2"
no	no	76.5	69.3	9.0
no	Minimum stretch to flatten	75.4	66.5	9.5
no	1 1/2% Stretch	72.9	61.9	9.0
no	5% - Cold rolling and stretching	72.0	60.9	9.5
no	10% - Cold rolling and stretching	71.3	60.2	9.0
1 hr/300°F	1 1/2% Stretch	73.6	63.9	9.0
1 hr/300°F	5% - Cold rolling and stretching	73.5	63.3	9.5
1 hr/300°F	10% - Cold rolling and stretching	72.7	62.8	8.5

1. Transverse tests - 0.064 inch thick sheet.

2. All material solution heat treated 30 minutes at 995 F, cold water quenched, pre-aged and cold worked as shown above, then aged to peak strength at 325 F.

TABLE XVIII

EFFECT OF PRE-AGING TREATMENTS ON TENSILE PROPERTIES OF X2021-T81

S. No.	Quench Water Temp.	Pre-aging Treatment Hr at °F	Pre-aged and Stretched	Aging Time at 325 F in Hours							
				1	2	4	8	16	24	48	72
				Tensile Strength - ksi							
295149 -4	Cold	8/250	59.4	65.0	66.7	70.4	72.8	74.2	74.0	73.0	72.3
-6	Cold	1/300	60.7	66.6	69.4	73.1	75.2	75.4	75.3	74.0	73.3
-8	Cold	2/300	68.5	70.7	73.2	75.4	76.5	76.7	76.0	74.8	73.5
-5	212 F	8/250	60.9	60.2	61.3	62.9	64.9	66.4	67.7	67.6	67.2
-7	212 F	1/300	58.9	60.3	61.2	62.9	64.9	67.2	68.6	67.5	67.6
-9	212 F	2/300	61.0	61.0	61.9	63.0	64.9	67.8	68.7	66.8	66.8
				Yield Strength - ksi							
295149 -4	Cold	8/250	35.4	42.0	45.8	54.8	61.2	64.2	63.7	61.7	60.5
-6	Cold	1/300	37.3	47.5	53.0	62.0	66.7	66.7	66.5	64.3	62.9
-8	Cold	2/300	50.0	54.9	60.0	65.9	68.0	68.9	67.5	65.5	63.2
-5	212 F	8/250	38.2	35.2	36.9	40.0	44.8	51.4	53.4	53.2	52.8
-7	212 F	1/300	34.2	34.3	36.2	39.2	44.8	53.0	55.5	53.9	53.7
-9	212 F	2/300	36.3	35.3	36.7	40.3	45.7	54.5	56.0	53.2	52.9
				Elongation - % in 2"							
295149 -4	Cold	8/250	21.0	21.0	19.0	15.5	12.0	9.5	10.0	9.0	9.5
-6	Cold	1/300	20.0	18.5	16.0	13.5	10.0	8.5	9.0	9.0	9.5
-8	Cold	2/300	15.0	15.5	14.0	9.5	10.5	10.0	8.0	9.0	9.5
-5	212 F	8/250	16.5	20.0	19.0	17.0	15.5	10.0	10.0	8.5	8.5
-7	212 F	1/300	21.5	22.0	18.5	17.5	17.5	12.0	11.5	9.0	9.5
-9	212 F	2/300	19.5	20.5	20.5	18.5	15.5	11.0	10.0	9.0	9.0

1. Solution heat treated at 990 F for 2 hours, quenched and pre-aged immediately as indicated above, stretched 1 1/2% and aged immediately as indicated above.

2. Single transverse specimens - YS = 0.2% offset - 0.125 inch sheet.

TABLE XIX

EFFECT OF AGING TIME AND TEMPERATURE ON STRESS CORROSION OF X2021-T62

S. No.	Aging Treatment	Transverse Properties T.S. ksi	Y.S. ksi	% El. in 2"	Lattice Parameter Å	Solution Potential -mv	Days to Failure† Alternate Immersion in 3 1/2% NaCl	New Kensington Atmosphere
294776-1	48 hr / 300 F	73.4	64.7	6.8	4.0460	813	26, 26, 26, 26	92, 92, 101, 125
294776-4	4 hr / 325 F	68.6	56.2	8.8	4.0420	778	3, 3, 3, 3	62, 62, 62, 62
294776-5	8 hr / 325 F	70.8	60.4	8.2	--	797	26, 26, 26, 26	45, 62, 62, 76
294776-6	16 hr / 325 F	72.4	63.4	6.2	4.0460	809	26, 88*, 88*, 88*	97, 97, 127, 164
294776-7	24 hr / 325 F	72.9	64.4	5.8	4.0460	813	55, 88*, 88*, 88*	115, 115, 125, 326
294776-8	48 hr / 325 F	73.2	65.0	5.0	--	821	R 88††	**
294776-9	96 hr / 325 F	71.4	62.8	5.0	4.0488	823	R 88††	**
294776-12	8 hr / 350 F	73.6	65.6	6.2	4.0467	812	R 88††	**

† Quadruple short-transverse c-ring specimens (axis normal to rolling direction) stressed to 75% Y.S.

* Cracks discovered when cleaned after removal from test.

†† Removed from test; no cracks apparent after cleaning.

** Specimens have been in test 510 days without cracking.

1. All material solution heat treated 3 hr (total time) at 990 F, cold water quenched, and aged immediately, as indicated above.
2. Solution potential: 0.1 N Calomel scale, NaCl - H_2O_2 solution.
3. Composition: see analysis for 294513.

TABLE XXa

STRESS-CORROSION RESISTANCE OF PLANT FABRICATED X2021 PLATE

S. No.	Temper Type	Thick in.	Pre-age Time at Temp Hr/°F	Stretch %	Aging Treatment At Plant Time at Temp Hr/°F	Aging Treatment At Lab Time at Temp Hr/°F	Long Transverse Tensile Properties TS ksi	YS ksi	% El. in 2"	Solution* Potential mv
292495	T62	1.000	--	--	10/325	--	73.6	65.7	5.5	-804
292490	T81	1.000	1/300	1.5	10/325	--	75.9	66.8	5.0	-802
292491	T81	1.000	1/300	3.0	10/325	--	75.6	65.9	6.0	-802
327102	T81	1.000	1/300	1.5	16/325	--	74.2	65.6	4.5	-814
326410	T81	2.000	1/300	1.5	16/325	--	72.4	60.9	5.5	-809
327021	T81	2.000	1/300	1.5	--	16/325	71.3	60.4	5.2	-786
327022	T81	2.000	1/300	1.5	--	48/325	73.2	61.8	6.0	-812
292489	T81	2.370	1/300	1.5	10/325	--	70.6	60.8	4.8	-801
292489-1	T81	2.370	1/300	1.5	10/325	24/300	68.6	63.2	2.2	-817
292489-2	T81	2.370	1/300	1.5	10/325	6/325	72.8	63.2	7.0	-807

Long Transverse Tensile Bars Stressed to 75% of the Yield Strength

S. No.	Solution* Potential mv	3 1/2% NaCl - Alternate Immersion: Days to Failure or Days OK	% Loss in TS** Stressed	% Loss in TS** Unstressed	New Kensington Atmosphere: Days to Failure or Days OK	Point Judith Atmosphere: Days to Failure or Days OK	% Loss in TS** Stressed	% Loss in TS** Unstressed
292495	-804	R119	20	22	OK 850	--	--	--
292490	-802	77†,105†,105†	--	23	OK 940	R365	15	9
292491	-802	R119	21	13	OK 850	--	--	--
327102	-814	OK 80	--	--	OK 77	OK 40	--	--
326410	-809	R84	30	26	OK 81	---	--	--
327021	-786	R84	34	29	OK 81	--	--	--
327022	-812	R84	26	25	OK 81	--	--	--
292489	-801	R138	19	17	OK 940	--	--	--
292489-1	-817	180, R180	26,44	19	OK 605	--	--	--
292489-2	-807	R180	30	17	OK 605	--	--	--

* Potential 0.1 N calomel scale, NaCl - H_2O_2 electrolyte.

** Percent loss in tensile strength after 119, 138, 180 or 365 days exposure.

† Metallographic examination indicated failure may have been mechanical in nature.

1) All items solution heat treated at 990 F and cold water quenched.
2) Duplicate unstressed and triplicate stressed specimens exposed.
3) R - removed from test intact after indicated time.
   OK - intact and still in test after indicated time.

TABLE XXb

STRESS-CORROSION RESISTANCE OF PLANT FABRICATED X2021 PLATE

					Short-Transverse Specimens Stressed as Indicated††						
					3 1/2% NaCl - Alternate Immersion			New Kensington Atm.	Point Judith Atmosphere		
S. No.	Temper Type	Thick in.	Solution Potential mv	Stress Level % YS	Days to Failure or Days OK	% Loss in TS† Stressed	% Loss in TS† Unstressed	Days to Failure or Days OK	Days to Failure or Days OK	% Loss in TS† Stressed	% Loss in TS† Unstressed
292495	T6	1.000	-804	75,50 or 25	R93	--	--	OK 850	--	--	--
292490	T81	1.000	-802	75	130*,130*,130*	--	--	OK 910	--	--	--
				50	130*,R134	--	--	OK 910	--	--	--
				25	R134	--	--	OK 910	--	--	--
292491	T81	1.000	-802	75,50 or 25	R93	--	--	OK 850	--	--	--
327102	T81	1.000	-814	75,50 or 25	OK 80	--	--	OK 77	OK 40	--	--
326410	T81	2.000	-809	75,50 or 25	R84	29	34	OK 81	--	--	--
327021	T81	2.000	-786	75	4,4,4	--	29	80,OK 81	--	--	--
				50	8,14,24	--	29	OK 81	--	--	--
				25	OK 83	32	29	OK 81	--	--	--
327022	T81	2.000	-812	75	49, R84	26,42	28	OK 81	--	--	--
				50 or 25	R84	30	28	OK 81	--	--	--
292489	T81	2.370	-801	75	5,5,5	--	--	47,121,326	210,210,284	--	--
				50	22,138**,138**	--	--	33, OK940	R426	27	14
				25	R138	23	21	OK 940	R426	19	14
292489-1	T81	2.370	-817	75	54,59,67	--	--	OK 605	--	--	--
				50	180, R180	35	24	OK 605	--	--	--
				25	R180	23	24	OK 605	--	--	--
292489-2	T81	2.370	-807	75	12,44,49	--	--	OK 605	--	--	--
				50	105,180,R180	62	19	OK 605	--	--	--
				25	R180	23	19	OK 605	--	--	--

†† C-rings for 1.000 inch plate and .125 inch tensile bars for thicker plate.
† Percent loss in tensile strength after 84, 138, 180 or 426 days exposure.

* Metallographic examination indicates failure may be mechanical in nature.

** Crack discovered in shoulder after removal from test.

1) Fabricating procedures and tensile properties given in preceding table.
2) Duplicate unstressed and triplicate stressed specimens exposed.
3) R - removed from test intact after indicated time.
OK - intact and still in test after indicated time.

TABLE XXI

EFFECT OF ROOM TEMPERATURE INTERVALS ON TENSILE PROPERTIES OF X2021

S - No.	Room Temperature Interval		Aging Time	Transverse Properties		
	Before Pre-age	Before Age	at 325 F	TS ksi	YS ksi	% El. in 2"
326556-A	None	None	None	57.9	32.8	22.5
			4 hr	69.1	53.2	13.5
			8 hr	73.8	62.7	11.0
			16 hr	73.7	62.9	10.5
			24 hr	73.6	62.5	10.0
326556-B	1 wk	None	None	60.4	35.2	24.0
			4 hr	71.7	58.4	13.0
			8 hr	74.3	64.0	10.0
			16 hr	74.1	63.7	9.5
			24 hr	73.8	63.1	9.5
326556-C	1 wk	1 wk	None	60.2	35.8	21.0
			4 hr	71.2	56.7	13.5
			8 hr	74.4	64.0	10.5
			16 hr	74.2	63.5	8.5
			24 hr	73.9	63.2	9.0
326556-D	1 wk	2 wk	None	60.5	35.8	22.5
			4 hr	72.8	59.4	13.0
			8 hr	73.6	62.2	11.0
			16 hr	74.6	64.4	10.5
			24 hr	74.3	63.8	9.5
326556-E	2 wk	None	None	57.4	32.1	22.5
			4 hr	70.2	54.5	15.5
			8 hr	73.9	63.1	10.0
			16 hr	73.8	63.0	9.5
			24 hr	73.6	62.6	9.5

1. Solution heat treated 2 hr at 990 F, cold water quenched and then pre-aged 1 hr at 300 F, stretched 1 1/2% and aged with room temperature intervals between steps, as indicated above.

2. Sheet .125 inch thick - YS = 0.2% Offset.

TABLE XXII

TENSILE AND NOTCH-TENSILE PROPERTIES OF PLANT FABRICATED X2021-T81

Thick In.	S. No.	Testing Temp °F	Longitudinal TS ksi	Longitudinal YS ksi	Longitudinal % El. in 4D or 2"	Longitudinal NTS ksi	Longitudinal NTS/TS	Long Transverse TS ksi	Long Transverse YS ksi	Long Transverse % El. in 4D or 2"	Long Transverse NTS ksi	Long Transverse NTS/TS
.064	326889	RT	73.4	66.0	7.2	--	--	74.4	64.3	9.0	--	--
		-112	79.7	70.3	8.8	--	--	80.5	69.4	8.5	--	--
		-320	91.4	80.0	10.5	--	--	92.0	77.6	10.8	--	--
.125	326888	RT	72.8	63.4	10.2	62.1	0.85	73.4	62.4	9.5	57.4	0.78
		-112	79.1	69.3	10.0	71.6	0.91	79.6	65.8	9.5	71.6	0.90
		-320	90.8	75.7	10.8	72.4	0.80	92.2	73.5	10.0	71.1	0.77
		-452	97.0	82.8	9.0	88.0	0.91	101.0	82.0	9.8	84.8	0.84
.250	342352	RT	72.9	65.8	11.8	--	--	74.0	65.6	9.5	--	--
.500	342719	RT	73.7	64.7	10.5	--	--	74.1	63.6	7.0	--	--
1.000	327102	RT	74.4	66.6	8.5	87.4	1.18	73.7	64.7	5.0	77.0	1.04
		-112	79.4	69.5	9.5	100.6	1.27	81.0	70.6	6.2	87.4	1.08
		-320	90.2	78.9	11.0	111.0	1.23	91.6	77.2	7.2	93.2	1.02
		-452	101.6	86.1	12.5	122.0	1.20	102.9	86.4	8.8	115.6	1.12
2.500	326402	RT	72.1	62.7	7.0	--	--	68.9	61.6	3.8	--	--
Average*		RT	73.4	65.3	9.5†	--	--	73.9	64.1	6.0†	--	--

* Does not include data for 2.500 inch plate.

† Elongation in 4D for round specimens from plate.

TABLE XXIII

AVERAGE† MECHANICAL PROPERTIES OF PLANT FABRICATED X2021-T81 SHEET AND PLATE

Direction	Tensile Data TS ksi	Tensile Data TYS ksi	Tensile Data % El. in 4D	Compressive Data CYS ksi	Compressive Data CYS/TYS	Shear Data Direction†† and Plane of Loading	Shear Data SS ksi	Shear Data SS/TS	Hardness Brinell	Hardness Rockwell
Longitudinal	73.4	65.3	8.6	66.2	1.03	YZ-Y	47.3	--	139	B83
						YZ-Z	44.8	0.60		
Long Transverse	73.9	64.1	6.0	68.2	1.06	XZ-X	44.9	--		
						XZ-Z	42.7	0.58		

Direction	Bearing Strength* e/D** = 1.5 BS ksi	Bearing Strength* e/D** = 1.5 BS/TS	Bearing Strength* e/D = 2.0 BS ksi	Bearing Strength* e/D = 2.0 BS/TS	Bearing Strength* e/D = 1.5 BYS ksi	Bearing Strength* e/D = 1.5 BYS/YS	Bearing Strength* e/D = 2.0 BYS ksi	Bearing Strength* e/D = 2.0 BYS/YS
Longitudinal	112.4	1.52	145.5	1.97	96.6	1.50	114.8	1.79
Long Transverse	114.4	1.55	145.3	1.97	98.3	1.53	115.2	1.80

† Average properties of five gages of sheet and plate.

* Data for flatwise specimens.

†† First letters describe plane of shear and last letter describes direction of loading: X - longitudinal; Y - long transverse; Z - short transverse.

** e/D - ratio of edge distance to pin diameter.

TABLE XXV

AVERAGE TEAR PROPERTIES OF X2021-T81 SHEET AND PLATE

Direction	Tear Strength ksi	Unit Propagation Energy in.-lb/in.^{2}
Longitudinal	61.3	230
Long-Transverse	46.6	80
Short-Transverse*	45.2	90

* Data for one lot

TABLE XXVI

EFFECT OF TESTING TEMPERATURE ON TEAR PROPERTIES* OF 0.064 INCH X2021-T81 SHEET

Testing Temp. °F	Tear Strength ksi	Unit Propagation Energy in.-lb/in.^{2}
RT	48.7	85
-112	58.6	180
-320	64.8	155

* Long-transverse direction

TABLE XXVII

TYPICAL PHYSICAL PROPERTIES OF X2021

Specific Gravity	2.83
Density, lb/in.^{3}	0.103
Melting Range, °F	997 - 1195
Electrical Conductivity at 20°C, % IACS:	
0 Temper	44
W Temper*	30
T81 Temper	32
Thermal Conductivity at 25°C, CGS Units:	
0 Temper	0.41
W Temper*	0.29
T81 Temper	0.30
Average Coefficient of Thermal Expansion (T81 Temper)	
68°F - 212°F	12.6×10^{-6}/°F
68°F - 302°F	12.9×10^{-6}/°F

* Pre-aged 1 hour at 300°F and stretched a maximum of 1.5%.

TABLE XXVIII

SUMMARY OF TENSILE PROPERTIES OF X2021 WELDED PLATE

Full Section Properties - 2319 Filler

S. No.	Gage Thickness Inches	Welding Method	As-Welded*			Post-Weld Aged**		
			T.S. ksi	Y.S. ksi	% El. in 10"	T.S. ksi	Y.S. ksi	% El. in 10"
291819	0.525	MIG	42.4	37.6	1.1	47.4	44.9	0.8
318497†	0.5	MIG	41.4	37.8	0.8	43.0	††	0.5
292666†	1.0	MIG	42.8	36.2	1.2	46.9	46.4	0.8
291819	0.525	TIG	42.8	33.2	1.4	48.3	45.5	0.6
292666†	1.0	TIG	43.2	38.5	1.1	43.5	††	0.7
AVERAGE			42.3	36.7	1.1	45.8	45.6	0.7

* Tested after several weeks of room temperature aging.

** Post-weld aged 14 - 16 hours at 325°F.

† Parent plate plant fabricated. Items not marked laboratory fabricated.

†† Failed before 0.2% offset in 10".

1. All parent plate was in the T81 temper.
2. YS - 0.2% Offset in 10". Welded parallel to rolling direction. Transverse properties.

TABLE XXIX

TENSILE AND NOTCH-TENSILE PROPERTIES OF X2021 WELDED PLATE

Round Reduced-Section Specimens--2319 Filler Alloy

S. No.	Gage Thickness Inches	Welding Method	Post-Weld Aging	Room Temperature Tests					-320°F Tests
				TS ksi	YS†† ksi	% El. in 4D	% R of A	NTS**/TS	NTS**/TS
291819	0.525	MIG	None*	39.4	19.1	6.0	16	1.00	.87
			16 hr/325°F	46.8	29.4	2.9	10	1.03	.93
318497†	0.5	MIG	None*	40.2	21.9	7.0	17	--	.90
292666-A†	1.0	MIG	None*	38.3	24.2	3.4	12	1.09	1.01
			16 hr/325°F	42.1	28.6	3.0	10	1.10	1.02
292666-B†	1.0	TIG	None*	42.5	24.1	4.8	17	1.05	.94
			16 hr/325°F	46.9	31.9	4.0	12	1.00	.94

† Parent plate plant fabricated. Other item laboratory fabricated.

* Naturally aged several weeks.

†† YS = 0.2% Offset in 4D (2" or less).

** Notch centered in the weld bead.

1. Transverse specimens - Notched round specimens, K_t = 10.

TABLE XXX

RESULTS OF STRESS-CORROSION TESTS ON X2021-T81 PLATE WELDED WITH 2319 FILLER ALLOY

							3 1/2% NaCl - Alternate Immersion			New Kensington Atmosphere		
Sample Designation	Plate Thick. in.	Weld Method	Weld++ Condition	Specimen/ Design	Side Stressed* in Tension	Stress Level ksi	Specimen Numbers	Days to Failure or Days OK	Crack// Location	Specimen Numbers	Days to Failure or Days OK	Crack// Location
291819-A1	.525	MIG	AW	A	F	28.2+	S11 & S12	R180**	1/4 in.	S15 & S16	OK 1179	--
	.525	MIG	AW	A	R	28.2+	S13 & S14	R180**	0	S17 & S18	OK 1179	--
291819-A2	.525	MIG	PWA	A	F	33.6+	S11 & S12	R180	--	S15 & S16	OK 1179	--
	.525	MIG	PWA	A	R	33.6+	S13 & S14	R180	--	S17 & S18	OK 1179	--
292666-A1	1.000	MIG	AW	B	F	30.0	S11 & S12	R208**	1/8 in.	S15 & S18	OK 479	--
	1.000	MIG	AW	B	F	30.0	S13 & S14	R208**	1/8	S16 & S17	F 367	1/8 in.
292666-A2	1.000	MIG	PWA	B	F	35.4+	S11 & S12	R180 (assembly seemed unloaded)		S15 & S16	OK 937	--
	1.000	MIG	PWA	B	F	35.4+	S13 & S14	F22		S17 & S18	OK 937	--
292666-B1	1.000	TIG	AW	D	R	30.0	S11 & S12	F117	1/4 in.	S13 & S14	OK 682	--
	1.000	TIG	AW	D	F	30.0	S15 & S16	R365**	0	S17 & S18	OK 682	--
292666-B2	1.000	TIG	PWA	D	R	30.0	S11 & S12	R365	--	S13 & S14	OK 682	--
	1.000	TIG	PWA	D	F	30.0	S15 & S16	R365	--	S17 & S18	OK 682	--

** Stress-corrosion cracks discovered after removal from test and cleaning.

+ 75% of the yield strength based on a 10 inch gage length.

++ AW - naturally aged several months
PWA - post-weld aged 16 hr at 325 F.

/ Stress-corrosion test assemblies as shown in Figure 37.

* R - root side, last side welded
F - face side, opposite from root side.

// Distance of crack from edge of weld bead.

1) R - Removed from test intact after indicated time
OK - intact and still in test after indicated time.

TABLE XXXI

NOTCH-TENSILE PROPERTIES OF X2021-T81 WELDED WITH Al-Cu-Mg FILLER ALLOYS

			Unnotched Specimens - Weld Bead Intact				Notched Specimens - Weld Bead Intact		
S. No.	Filler Alloy	Test Temp.	TS ksi	YS ksi	% El. in 2"	Location* of Failure	NTS† ksi	NTS†† / TS	Location* of Failure
327087	2319	RT	35.2	28.9	1.8	B	42.8	1.22	B & D
		-320 F	47.3	36.1	1.8	B	55.4	1.17	B
327088	292561	RT	39.9	29.2	2.5	B	37.0	.93	D
		-320 F	49.2	36.4	1.8	B	38.0		
							39.5		
							48.3	.98	D
327089	292562	RT	41.6	30.2	2.5	B	37.6	.90	D
		-320 F	50.2	36.1	1.2	B	41.0		
							42.1		
							45.1	.90	D
342152	292564	RT	40.8	31.0	2.0	B	43.9	1.08	D
		-320 F	50.0	37.7	1.0	B	51.5	1.03	D

Composition of Filler Alloys - %

S. No.	Cu	Fe	Si	Mn	Mg	Zn	Zr	V	Ti	Ni	
2319	6.30	--	--	.30	--	--	.15	.10	.15	--	(Nominal)
292561	6.29	.16	.10	.75	1.68	.03	.16	.09	.15	2.05	
292562	6.25	.16	.10	.72	1.56	2.80	.14	.08	.13	1.98	
292564	7.96	.16	.10	.72	1.60	.03	.16	.08	.13	.01	

* Location of Failure: A - through weld bead; B - edge of weld bead; D - through notch.

† Notched in the center of the weld bead.

†† Calculated using highest NTS if all NTS values are listed

1) 0.125 inch sheet - TIG welded, one pass, .125 inch diameter filler wire.

2) Triplicate specimens for -320 F notched tests; duplicate specimens for other tests.

TABLE XXXII

CHEMICAL COMPOSITION OF X7007 TYPE ALLOYS

Description	Cast No.	Cu	Fe	Si	Mn	Mg	Zn	Cr	Zr	Ti	Ni	Other
X7007 Variations	292609	.03	.11	.07	.21	1.83	6.38	.13	.12	.04	.01	
	292610	.12	.11	.07	.24	1.84	6.39	.15	.12	.03	.01	
	292611	.23	.10	.07	.19	1.80	6.25	.19	.13	.04	.01	
	292612	.12	.09	.08	.23	1.85	6.43	.21	.07	.03	.01	
	292613	.12	.09	.07	.24	1.84	6.45	.17	.17	.04	.01	
	292614	.12	.09	.07	.22	1.52	6.05	.21	.13	.04	.01	
	292615	.13	.08	.08	.22	2.21	6.85	.17	.13	.04	.01	
	294862	.12	.15	.07	.24	1.78	6.40	.12	.11	.04	.00	
	294865	.11	.14	.08	.01	1.78	6.45	.25	.11	.04	.00	
	294866	.11	.17	.08	.24	1.78	6.44	.26	.11	.04	.00	
X7007 Modifications	292540	.15	.10	.09	.22	1.76	6.28	.14	.13	.05	--	
	292541	.13	.11	.09	.24	1.75	6.39	.15	.13	.05	--	.25 Li
	292542	.12	.09	.07	.21	1.83	6.28	.12	.13	.05	--	.31 Ag
	292543	.12	.10	.07	.21	1.87	6.36	.18	.12	.05	--	.30 Ca
	294863	.12	.15	.08	.24	1.79	6.47	.12	.11	.04	.00	.20 Ag
	294864	.11	.15	.07	.24	1.79	6.45	.12	.11	.04	.00	.41 Ag
	294867	.11	.17	.07	.24	1.75	6.33	.12	.11	.04	.00	.04 Ta
	294868	.13	.17	.06	.22	1.90	6.44	.13	.12	.04	.00	.02 Nb
Plant Fabricated	327105, 08	.06	.11	.05	.21	1.76	6.55	.11	.10	.03	--	
	326786, 88, 90	.14	.19	.08	.20	1.77	6.18	.20	.10	.05	--	
	295582	.14	.14	.06	.21	1.51	6.83	.10	.10	.03	--	
	292459, 688	.14	.16	.10	.23	2.03	6.62	.12	.11	.04	.01	
	293542	.12	.17	.11	.22	1.84	6.61	.12	.11	.03	.00	
	326782	.10	.18	.08	.22	1.76	6.36	.18	.11	.04	.00	

TABLE XXXIII

TENSILE AND NOTCH-TENSILE PROPERTIES OF X7007 VARIATIONS

S. No.	Composition Variations						Room Temperature Tests					-320 F Tests
	Cu	Mn	Mg	Zn	Cr	Zr	TS ksi	YS ksi	% El. in 4D	% R of A	NTS/TS	NTS*/TS
292609	.03	.21	1.83	6.38	.13	.12	75.5	68.1	13.2	22	1.31	.75
292610	.12	.24	1.84	6.39	.15	.12	77.0	70.1	13.2	22	1.30	.81
292611	.23	.19	1.80	6.25	.19	.13	77.4	70.0	13.2	20	1.29	.86
292612	.12	.23	1.85	6.43	.21	.07	75.4	67.3	12.5	18	1.30	.84
292613	.12	.24	1.84	6.45	.17	.17	76.9	69.8	12.9	18	1.26	.80
292614	.12	.22	1.52	6.05	.21	.13	69.8	62.0	14.3	27	1.39	1.06
292615	.13	.22	2.21	6.85	.17	.13	82.7	75.9	11.4	18	1.18	.65
294862	.12	.24	1.78	6.40	.12	.11	76.2	71.1	12.0	18	1.36	.93
294865	.11	.01	1.78	6.45	.25	.11	72.9	65.9	10.8	17	1.35	.97
294866	.11	.24	1.78	6.44	.25	.11	75.4	67.8	12.5	20	1.33	.90

* Calculated using the highest notch-tensile strength.

1) Items 292609-15, 0.525 inch plate; items 294862, 65 and 66, 1.000 inch plate.

2) All items solution heat treated at 860 F, hot water quenched, and aged after 3-4 days at room temperature. Items 292609-15 aged 48 hr at 225 F. Items 294862, 65 and 66 aged 16 hr at 275 F.

3) Transverse specimens for items 292609-15; longitudinal specimens for items 294862, 65 and 66.

4) YS - 0.2% offset; round notched specimens, K_t = 10.

TABLE XXXIV

RESULTS OF STRESS-CORROSION TESTS ON COMPOSITION VARIATIONS OF X7007

S. No.	Composition Variations Cu	Mn	Mg	Zn	Cr	Zr	Long Transverse Tensile Properties TS ksi	YS ksi	% El. in 2"	Stress Level % YS	Short-Transverse C-rings: 3 1/2% NaCl - A.I. Days to Failure or Days OK	New Kensington Atm. Days to Failure or Days OK
292609	.03	.21	1.83	6.38	.13	.12	77.0	68.9	9.0	75	21,42, R88	35,37,42
										50	R88	162,162,192
										25	R88	265,303,303
292610	.12	.24	1.84	6.39	.15	.12	77.9	70.4	10.0	75	21, R88	192,206,206
		(nominal composition)								50	R88	240,240,245
										25	R88	OK 987
292611	.23	.19	1.80	6.25	.19	.13	78.3	70.3	9.0	75	9,14,17	216,240,258
										50	16,17,R88	352,405,535
										25	R88	OK 987
292612	.12	.23	1.85	6.43	.21	.07	76.4	67.0	10.0	75	17,23, R88	206,216,238
										50	R88	253,253,258
										25	R88	OK 987
292613	.12	.24	1.84	6.45	.17	.17	78.4	69.1	11.0	75	14,14,17	35,56,99
										50	R88	190,213,220
										25	R88	624,701,713
292614	.12	.22	1.52	6.05	.21	.13	70.9	61.7	11.5	75	21,21, R88	184,190,216
										50	R88	226,289,293
										25	R88	OK 987
292615	.13	.22	2.21	6.85	.17	.13	82.8	70.6	10.0	75	23,38,88	56,129,141
										50	R88	216,216,240
										25	R88	OK 987
294862-C	.12	.24	1.78	6.40	.12	.11	76.2	71.1	12.0	75	20,20,27	130,177,199
		(nominal composition)								50	27,58,64	248,248,248
										25	66,70,70	OK 285
294865	.11	.01	1.78	6.45	.25	.11	72.9	65.9	10.8	75	30,48,70	192,238,259
										50	70,70,106	252,259,285
										25	R180	280, OK 285
294866	.11	.24	1.78	6.44	.25	.11	75.4	67.8	12.5	75	32,42,48	238,238,248
										50	48,63,64	273,280,280
										25	R180	OK 285

1) Solution heat treated at 860 F, hot water quenched and aged after four days as follows: items 292609-15, 48 hr at 225 F; items 294862, 65 and 66, 16 hr at 275 F.

2) Triplicate c-rings exposed.

3) For items 292609-15, long transverse tensile bars stressed to 75% YS were removed intact after 109 days in alternate immersion and showed losses in strength due to corrosion similar to unstressed bars. Long-transverse bars exposed to New Kensington atmosphere are still in test after 1008 days exposure.

4) R - removed from test intact after indicated time.
OK - intact and still in test after indicated time.

TABLE XXXV

WELD CRACKING EVALUATION OF X7007 TYPE ALLOYS
(Welded with Parent Metal Filler Alloy)

S. No.	Composition Variations						Inches of Weld Cracking	
	Cu	Mn	Mg	Zn	Cr	Zr	Continuous Test	Distontinuous Test
292609	.03	.21	1.83	6.38	.13	.12	13 1/4	18 1/4
292610	.12	.24	1.84	6.39	.15	.12	14	18
		(nominal composition)						
292611	.23	.19	1.80	6.25	.19	.13	16 1/2	18
292612	.12	.23	1.85	6.43	.21	.07	17 3/4	--
292613	.12	.24	1.84	6.45	.17	.17	16 3/4	--
292614	.12	.22	1.52	6.05	.21	.13	15 1/2	--
292615	.13	.22	2.21	6.85	.17	.13	17 3/4	--
294862	.12	.24	1.78	6.40	.12	.11	14	17
		(nominal composition)						
294865	.11	.01	1.78	6.45	.25	.11	11 1/2	17 1/2
294866	.11	.24	1.78	6.44	.25	.11	11	17 1/2

1) Used Alcoa T-joint weld cracking test as described by J. D. Dowd, WELDING J. (October 1952).

TABLE XXXVI

TENSILE AND NOTCH-TENSILE PROPERTIES OF COMPOSITION MODIFICATIONS OF X7007

			Room Temperature Tests				-320 F Tests
S. No.	Alloy Modification	Thick in.	TS ksi	YS ksi	% El. in 2"	NTS*/TS	NTS*/TS
292540	X7007	.064	75.8	70.8	12.8	1.06	.75
292541	X7007 + .25 Li	.064	75.8	70.6	11.2	1.00	.60
292542	X7007 + .31 Ag	.064	79.0	74.0	11.5	1.05	.70
292543	X7007 + .30 Ca	.064	72.1	68.2	13.5	0.92	.66
294862	X7007	1.000	76.2	71.1	12.0	1.36	.93
294863	X7007 + .20 Ag	1.000	74.6	68.4	11.5	1.36	.95
294864	X7007 + .41 Ag	1.000	74.2	67.1	12.5	1.35	.92
294867	X7007 + .04 Ta	1.000	76.2	70.4	12.0	1.36	.93
294868	X7007 + .02 Nb	1.000	76.2	70.8	13.2	1.35	.84

* Calculated using highest notch-tensile strength of triplicate tests.

1) All items solution heat treated at 860 F. Sheet items stretched 1 1/2% and after 3 days at room temperature aged for 72 hr at 225 F (168 hr for item 292541). Plate items quenched in hot water and aged after 4 days for 16 hr at 275 F.

2) Transverse specimens for sheet - longitudinal specimens for plate.

3) YS - 0.2% Offset - notched specimens, K_t = 10.

TABLE XXXVIIa

EFFECT OF SILVER ON THE STRESS CORROSION RESISTANCE OF X7007

S. No.	Silver Conc.	Aging Treatment	Long Trans. Properties TS ksi	Long Trans. Properties YS ksi	Long Trans. Properties % EL. in 2"	Stress Level % Y.S.	3 1/2% NaCl Solution - Alternate Immersion: Long Trans. Tensile Bars, Days to Failure or Days OK	Long Trans. Tensile Bars, % Loss in T.S. * Stressed	Long Trans. Tensile Bars, % Loss in T.S. * Unstressed	S. Trans. C-rings, Days to Failure or Days OK	New Ken Atm.: S. Trans. C-rings, Days to Failure or Days OK
292540-A	.00	48 hrs/225°F	74.7	67.1	12.2	75 50 25	R180	5	4	17, 17, 17 17, 20, 32 R180	12, 12, 19 29, 41, 325 OK 725
294862-A	.00	48 hrs/225°F	74.0	66.1	10.0	75 50 25	R180	8	10	17, 21, 26 47, 49, 122 R180	25, 25, 34 39, 321, 321 OK 351
294863-A	.20	48 hrs/225°F	74.3	64.4	9.0	75 50 25	R180	9, 9, 26	8	12, 17, 18 17, 21, 27 R180	330, 347, OK 351 OK 351 OK 351
292542-A	.31	48 hrs/225°F	75.8	67.1	10.0	75 50 25	140+, 158+	--	9	14, 17, 21 R180 R180	68, 238, 371 OK 725 OK 725
294864-A	.41	48 hrs/225°F	72.7	63.2	11.5	75 50 25	143+, R180	11, 24	8	10, 17, 17 21, 37, 49 28, R180	OK 351 OK 351 OK 351
292540-B	.00	12 hrs/300°F	70.2	64.7	13.0	75 50 25	R180	1	2	25, 29, 29 43, 59, 71 R180	19, 19, 19 51, 51, 68 OK 725
292542-B	.31	12 hrs/300°F	70.4	64.6	12.5	75 50 25	R180	9	7	28, 32, 45 R180 R180	OK 725 OK 725 OK 725

* Percent loss in tensile strength after indicated days exposure

+ Metallographic examination indicated mechanical failure

1. All material solution heat treated at 860°F, hot water quenched, and aged as indicated after 4 days
2. Duplicate unstressed and triplicate stressed specimens exposed
3. R-removed from test intact after indicated time; OK-intact and still in test after indicated time

TABLE XXXVIIb

EFFECT OF SILVER ON THE STRESS CORROSION RESISTANCE OF X7007

S. No.	Silver Conc.	Aging Treatment	Long Trans. Properties TS ksi	Long Trans. Properties YS ksi	Long Trans. Properties % EL. in 2"	Stress Level % Y.S.	3 1/2% NaCl Solution - Alternate Immersion: Long Trans. Tensile Bars Days to Failure or Days OK	3 1/2% NaCl Solution - Alternate Immersion: Long Trans. Tensile Bars % Loss in T.S. * Stressed	3 1/2% NaCl Solution - Alternate Immersion: Long Trans. Tensile Bars % Loss in T.S. * Unstressed	3 1/2% NaCl Solution - Alternate Immersion: S. Trans. C-rings Days to Failure or Days OK	New Ken Atm. S. Trans. C-rings Days to Failure or Days OK
292540-C	.00	16 hrs/275°F	74.0	68.8	13.0	75 50 25	OK 155	--	--	27, 39, 52 67, 67, 89 R180	137, 178, 178 255, 255, 257 OK 287
294862-B	.00	16 hrs/275°F	73.0	66.9	11.5	75 50 25	R180	3	4	21, 27, 43 43, 49, 168 R180	18, 27, 27 34, 321, 330 OK 351
294862-C	.00	16 hrs/275°F	76.2	71.1	12.0	75 50 25	--	--	--	20, 20, 27 27, 58, 64 66, 70, 70	130, 177, 199 248, 248, 248 OK 280
294863-B	.20	16 hrs/275°F	72.2	65.6	11.0	75 50 25	R180	6	6	20, 21, 21 27, 27, 27 21, 49, R180	OK 351 OK 351 OK 351
294863-C	.20	16 hrs/275°F	74.6	68.4	11.5	75 50 25	--	--	--	17, 17, 20 20, 20, 38 70, 70, 70	OK 280 OK 280 OK 280
292542-C	.31	16 hrs/275°F	74.6	68.8	11.8	75 50 25	OK 155	--	--	22, 24, 24 39, 39, 47 47, 52, 52	OK 287 OK 287 OK 287
294864-B	.41	16 hrs/275°F	67.3	58.9	11.5	75 50 25	R180	7	5	21, 21, 21 21, 26, 50 43, R180	OK 351 OK 351 OK 351
294864-C	.41	16 hrs/275°F	74.2	67.1	12.5	75 50 25	---	--	--	17, 17, 17 17, 17, 20 17, 55, 55	152, OK 280 OK 280 OK 280

* Percent loss in tensile strength after indicated days exposure

1. See preceding table for notes.

TABLE XXXVIII

RESULTS OF STRESS-CORROSION TESTS ON X7007 MODIFICATIONS

		Long Transverse Tensile Properties			Short-Transverse C-rings					
					3 1/2% NaCl - Alternate Immersion Days to Failure or Days OK			New Kensington Atmosphere Days to Failure or Days OK		
S. No.	X7007 Modification	TS ksi	YS ksi	% El. in 2"	75% YS	50% YS	25% YS	75% YS	50% YS	25% YS
292540-C	Nominal	74.0	68.8	13.0	27,39,52	67,67,89	R180	137,178,178	255,255,257	OK 283
292541	.25 Li	76.5	71.4	9.8	10,15,15	52,55,67	R180*	19,19,19	35,63,112	257,264,278
292543	.30 Ca	70.0	66.0	6.0	35,39,47	61,67,67	R180*	28,49,63	229,237,255	OK 283
294862-C	Nominal	76.2	71.1	12.0	20,20,27	27,58,64	66,70,70	130,177,199	248,248,248	OK 276
294867	.04 Ta	76.2	70.4	12.0	20,29,29	30,38,65	5†,13†,70	124,124,177	231,241,241	OK 276
294868	.02 Nb	76.2	70.8	13.2	9,30,38	106,106,106	R180*	140,171,196	243,243,243	OK 276

† No reason for these rapid failures was apparent.

* Metallographic examination after removal from test revealed stress-corrosion cracks.

1) One-inch plate solution heat treated at 860 F for 3 hr (total furnace time), quenched in hot water, and aged 16 hr at 275 F after four days.

2) Triplicate stressed, short transverse C-rings exposed.

3) R - removed from test intact after indicated time;
OK - intact and still in test after indicated time.

TABLE XXXIX

WELD CRACKING EVALUATION OF X7007 MODIFICATIONS
(Welded with Parent Metal Filler Alloy)

S. No.	Alloy Description	Inches of Weld Cracking	
		Continuous Test	Discontinuous Test
294862	X7007	14	17
294863	X7007 + .20 Ag	13	17 1/2
294864	X7007 + .41 Ag	7	17 1/2
294867	X7007 + .03 Ta	5 1/2	18
294868	X7007 + .02 Nb	2 1/2	17 1/2

1) Used the Alcoa T-joint weld cracking test as described by J. D. Dowd, WELDING J (October 1952).

TABLE XL

NATURAL AGING OF 0.064 INCH X7007-W SHEET

Aging Time at Room Temperature	Transverse Tensile Properties TS ksi	YS ksi	% El. in 2"
10 min	44.0	28.3	21.8
1 hr	47.2	32.2	19.8
2 hr	50.5	35.0	20.5
5 hr	54.4	37.4	20.5
1 day	59.8	41.6	20.0
3 days	63.2	44.4	20.0
1 wk	65.4	46.0	20.5
2 wk	67.3	47.2	19.8
1 mo	68.6	49.2	18.0
3 mo	71.5	52.2	18.5
6 mo	73.8	54.4	18.0
1 yr	74.8	56.2	18.2

1) Solution heat treated 2 hours at 860 F, boiling water quenched and tested after indicated natural aging interval.

TABLE XLI

EFFECT OF AGING PRACTICE ON TENSILE AND NOTCH-TENSILE PROPERTIES OF X7007 1.0 INCH PLATE

S. No.	Thermal Treatment	Testing Temperature	Long Transverse Tensile Properties				
			TS ksi	YS* ksi	% El. in 2"	% R of A	NTS/TS
292459	8 hr/225 F + 16 hr/300 F	RT	67.5	59.4	13.8	32	1.32
		-112 F	73.4	61.9	12.0	21	1.24
		-320 F	86.2	69.0	12.7	18	1.12
292688	48 hr/225 F	RT	79.5	72.2	12.2	16	1.31
		-112 F	82.8	78.2	3.8	6	1.16
		-320 F	92.3	86.8	2.2	3	.95
		-423 F	102.5	95.4	2.8	2	.88
293542-A	48 hr/225 F	RT	77.9	71.1	6.8	8	1.28
		-320 F	90.2	85.6	2.2	2	.84
293542-B	48 hr/225 F + 16 hr/275 F	RT	73.4	67.6	10.2	18	1.33
		-112 F	80.6	73.4	5.0	8	1.17
		-320 F	89.0	82.1	2.8	6	.89
		-423 F	99.4	88.5	4.0	5	.97
293542-C	48 hr/225 F + 6 hr/300 F	RT	71.4	65.6	10.0	18	1.34
		-320 F	87.4	79.7	3.0	6	1.00
293542-D	16 hr/275 F	RT	72.8	66.8	12.2	24	1.31
		-112 F	81.2	70.6	8.8	12	1.17
		-320 F	91.4	81.3	4.5	6	.93
		-423 F	105.0	87.8	6.0	5	.88

* Result of single test at -112 F and -320 F.

1) 292459 - solution heat treated, hot water quenched and aged at plant.
   292688 - solution heat treated, hot water quenched and aged at ARL.
   293542 - solution heat treated and hot water quenched at plant; aged at ARL.

2) YS - 0.2% offset - Round notched specimens, K_t = 10.

TABLE XLII

EFFECT OF AGING TREATMENT ON THE RESISTANCE TO STRESS-CORROSION CRACKING OF X7007 1.000 INCH PLATE

						Long Transverse 1/8 Inch Diameter Tensile Bars				Short Transverse C-Rings	
	Age	Tensile Properties			Stress	3 1/2% NaCl - Alternate Immersion			New Kensington Atm.	3 1/2% NaCl-A.I.	New Kensington Atm.
S. No.	Time at Temp Hr/°F	TS ksi	YS ksi	% El. in 2"	Level % YS	Days to Failure or Days OK	% Loss in TS* Stressed	% Loss in TS* Unstressed	Days to Failure or Days OK	Days to Failure or Days OK	Days to Failure or Days OK
292459	8/225 + 16/300	67.5	59.4	13.8	75	R 138	2	1	OK 940	109,109, R 134	39,39,231
					50	--	--	--	--	R 134	312,437,437
					25	--	--	--	--	R 134	OK 1067
292688	48/225	79.5	72.2	12.2	75	R 84	2	2	OK 880	11,11,11	71,225,225
					50	--	--	--	--	17,31,31	237,245,255
					25	--	--	--	--	R 84	588,588, OK 1028
293542A	48/225	77.9	71.1	6.8	75	R 180	11	8	OK 635	15,15,15	43,43,43
					50	--	--	--	--	15,28,28	67,88,90
					25	--	--	--	--	R 90	426,440,440
293542B	48/225 + 16/275	73.4	67.6	10.2	75	R 180	7	7	OK 635	2,3,3	53,57,57
					50	--	--	--	--	38,46,52	82,123, R730
					25	--	--	--	--	R 90	R 730
293542C	48/225 + 6/300	71.4	65.6	10.0	75	R 180	6	6	OK 635	28,35,35	75,77,77
					50	--	--	--	--	52,65,75	145,440,442
					25	--	--	--	--	R 90	R 730
293542D (TE136 temper)	16/275	72.8	66.8	12.2	75	R 180	6	7	OK 635	28,28,28	50,50,50
					50	--	--	--	--	65,70,72	82,152,172
					25	--	--	--	--	R 90	R 730

* Percent loss in tensile strength after 84, 138 or 180 days exposure.

1) 292688 - solution heat treated, hot water quenched and aged at ARL.
   292459 - solution heat treated, hot water quenched and aged at Davenport plant.
   293542 - solution heat treated, hot water quenched and stretched at Davenport plant; aged at ARL.

2) Triplicate stressed and duplicate unstressed specimens exposed.

3) R - removed from test intact after indicated time.
   OK - intact and still in test after indicated time.

TABLE XLIII

EFFECTS OF INGOT PREHEAT AND SOLUTION TEMPERATURE ON THE PROPERTIES AND RESISTANCE TO STRESS-CORROSION CRACKING OF X7007 1.000 INCH PLATE

	Ingot Preheat Temp - F	Solution Heat Treat Temp - F	TS ksi	YS ksi	% El. in 2"	Alternate Immersion in 3 1/2% NaCl, Days to Failure or Days OK: Stressed 75% YS	Alternate Immersion in 3 1/2% NaCl, Days to Failure or Days OK: Stressed 50% YS	New Kensington Atmosphere, Days to Failure or Days OK: Stressed 75% YS	New Kensington Atmosphere, Days to Failure or Days OK: Stressed 50% YS
X7007 (.12 Cr)	750	750	72	66	13.0	29,29,32	82,91,91	32,32,32	97,134,197
	750	860	74	69	12.2	14,32,36	91,85,85	32,32,32	258,260,267
	860	750	73	67	12.5	30,30,35	62,62,128	46,73,153	223,235,235
	860	860	76	71	12.0	20,20,27	27,58,64	130,177,199	248,248,248
	960	750	73	67	12.5	11,14,20	64,77,91	32,46,55	123,267,272
	960	860	74,	69	12.0	11,11,11	32,46,64	27,32,39	46,237,239
X7007 (.26 Cr)	750	750	70	63	12.5	16,21,32	35,91,91	55,71,71	223,223,260
	750	860	73	66	11.8	21,21,21	67,85,91	46,46,71	267,277,277
	860	750	71	64	12.5	30,30,35	42,92,180	235,235,244	253,260,279
	860	860	75	68	12.5	32,42,48	48,63,64	238,238,248	273,280,280
	960	750	71	64	12.5	35,36,36	85,85,91	211,214,279	214,279,283
	960	860	74	67	12.2	16,26,29	85,85,91	41,46,50	277,277,283

1) One inch thick plate solution heat treated 3 hours, 160 F water quenched, room aged 4 days prior to artificial aging of 16 hours at 275 F.

2) Long transverse 1/2 inch diameter tensile bars; C-ring type specimens stressed in the short transverse direction for corrosion evaluation.

3) Triplicate specimens exposed at each stress level to each environment.

4) YS = 0.2% Offset

Chemical Composition

	Cu	Fe	Si	Mn	Mg	Zn	Cr	Ti	Zr
X7007	.12	.15	.07	.24	1.78	6.40	.12	.04	.11
High Cr X7007	.11	.17	.08	.24	1.78	6.44	.26	.04	.11

TABLE XLIV

EFFECT OF SOLUTION TEMPERATURE ON THE PROPERTIES AND STRESS CORROSION OF X7007 ONE INCH THICK PLATE

S-326337-1

Solution Heat Treatment (1)	TS ksi	YS ksi	% El. in 2"	Alternate Immersion in 3 1/2% NaCl — Days to Failure or Days OK — Stressed 75% YS	Alternate Immersion in 3 1/2% NaCl — Days to Failure or Days OK — Stressed 50% YS	New Kensington Atmosphere — Days to Failure or Days OK — Stressed 75% YS	New Kensington Atmosphere — Days to Failure or Days OK — Stressed 50% YS
3 hr at 700 F	71	66	13.2	20,20,20	29,34,34	44,44,46	113,113,135
3 hr at 750 F	74	69	12.5	14,18,20	28,28,29	25,25,28	102,113,113
3 hr at 860 F	76	70	12.5	14,14,14	23,31,32	25,25,44	86,113,156
3 hr at 960 F	76	71	12.0	14,14,17	28,31,31	25,25,77	77,86,135
3 hr at 860 F, furnace cool to 750 F	74	69	13.5	14,14,20	28,29,31	25,28,58	77,113,113
3 hr at 860 F, furnace cool to 700 F	74	69	14.0	14,14,18	28,28,31	25,25,44	135,154,165
3 hr at 860 F furnace cool to 650 F	62	55	13.0	32,32,46	32,34,46	123,156,156	168,182,221

1) X7007 plant fabricated plate room temperature aged 18 months prior to re-solution heat treatments, S-293542. All samples quenched in 160 F water, room temperature aged 4 days and artificially aged 16 hours at 275 F.

2) Duplicate long transverse 1/2 inch diameter tensile specimens; C-ring type specimens stressed in the short transverse direction for corrosion evaluation.

3) Triplicate specimens exposed at each stress level to each environment.

TABLE XLV

EFFECT OF ARTIFICIAL AGING TREATMENT ON THE STRESS-CORROSION RESISTANCE OF X7007

(Short Transverse C-rings from 1.0 Inch Thick Plate)

Item No.	Artificial Aging Treatments: Step 1 Time	Step 1 Temp-F	Step 2 Time-Hr	Step 2 Temp-F	Step 3 Time-Hr	Step 3 Temp-F	Long Transverse Properties: TS ksi	YS ksi	% El. in 2"	Alternate Immersion in 3 1/2% NaCl, Days to Failure or Days OK: Stressed 75% YS	Stressed 50% YS	New Kensington Atmosphere, Days to Failure or Days OK: Stressed 75% YS	Stressed 50% YS
0	18 mo	RT	--	--	--	--	74	58	8.5	10,10,11	10,14,46	226,226,231	233,256,265
1	16 hr	275	--	--	--	--	72	66	12.0	27,28,53	27,38,47	221,224,226	256,261,268
2	3 wk	250	--	--	--	--	66	60	14.5	47,91,95	69,74,127	184,217,217	224,226,228
3	8 hr	225	16	300	--	--	70	65	14.0	38,38,47	47,47,47	135,165,184	205,217,224
4	8 hr	225	2	325	--	--	70	65	14.2	25,38,47	47,53,74	140,133,184	217,221,221
5	8 hr	225	4	325	--	--	68	62	13.8	47,47,53	48,74,74	88,133,135	28,224,224
6	8 hr	225	8	325	--	--	65	58	13.8	74,91,95	127,127, R184	184,224,224	231,240,256
7	8 hr	225	1	350	--	--	66	60	14.8	46,46,60	74,86,89	184,184,205	231,231,235
8	8 hr	225	2	350	--	--	64	58	15.8	86,90,105	86,90,105	205,212,224	226,226,235
9	48 hr	225	2	325	--	--	71	66	13.5	22,32,33	47,47,47	88,88,140	205,212,212
10	48 hr	225	8	325	--	--	64	58	14.5	74,95,105	112,157, R184	184,191,191	226,228,231
11	4 hr	300	8	225	--	--	75	70	13.0	15,15,24	28,31,46	28,28,28	154,154,168
12	4 hr	300	48	225	--	--	75	71	13.0	15,25,25	15,28,47	28,28,67	38,135,161
13	2 hr	325	8	225	--	--	71	67	13.5	15,15,28	47,48,48	28,28,65	154,205,205
14	2 hr	325	48	225	--	--	72	67	14.2	15,15,28	48,60,74	65,65,65	113,168,184
15	4 hr	325	8	225	--	--	70	64	14.0	47,60,74	74,74,89	113,113,135	217,217,217
16	4 hr	325	48	225	--	--	70	65	14.5	74,74,74	74,90,90	154,154,179	205,228,228
17	48 hr	175	48	225	8	325	64	57	14.2	95,112,122	74,157,164	212,221,221	231,233,235
18	8 hr	225	16	300	48	225	72	67	13.8	46,47,48	47,74,89	156,165,182	221,221,224
19	8 hr	225	2	325	48	225	72	68	13.2	25,25,46	47,74,74	65,65,84	184,205,212
20	8 hr	225	8	325	48	225	66	60	14.0	74,90,90	86,164, R184	182,189,189	221,228,231
21	8 hr	225	2	325	---	--	71	66	13.8	15,25,46	47,47,74	84,154,165	212,217,217
22	8 hr	225	8	325	--	--	65	58	14.8	95,105,105	158,182, R184	205,212,217	231,231,231
23	8 hr	225	2	325	48	225	72	68	13.0	25,46,46	46,74,74	113,113,150	212,224,224
24	8 hr	225	8	325	48	225	65	59	15.2	47,74,95	143,158,182	205,205,214	226,231,235
25	2 hr	325	48	225	--	--	70	65	12.0	25,27,30	86,105,109	107,113,135	193,205,205

1) 1.0 inch plant fabricated X7007-W plate used. Item 0, as-received. Item 1, as-received plus 16 hours at 275 F. All other items re-heat treated 3 hours at 860 F, warm water quenched and aged after a 4 day room temperature interval, except for items 17, 21, 22, 23, 24, and 25 had no room temperature interval. See S. No. 293542 for composition (Table XXXII).

2) Triplicate specimens exposed at each stress level to each environment.

3) R-removed from test intact after indicated time.

TABLE XLVI

EFFECTS OF INTERRUPTED QUENCHING (QUENCH AGE) ON THE STRENGTHS AND STRESS-CORROSION RESISTANCE OF X7007 PLATE

(S-326411)

Min/ F in Bath	TS ksi	YS ksi	% El. in 2"	Elec. Cond. % IACS	Alternate Immersion in 3 1/2% NaCl — Days to Failure or Days OK: Stressed 75% YS	Alternate Immersion in 3 1/2% NaCl — Days to Failure or Days OK: Stressed 50% YS	New Kensington Atmosphere — Days to Failure or Days OK: Stressed 75% YS	New Kensington Atmosphere — Days to Failure or Days OK: Stressed 50% YS
20/300	71.4	65.1	11.5	37.5	38,54,54	65,65,65	154,180,192	201,224,245
60/300	70.0	63.7	11.5	38.3	38,38,38	38,38,49	173,192,192	203,220,229
20/350	68.4	60.3	11.5	38.2	54,76,76	76,76,76	201,201,203	255,278,280
60/350	63.9	54.3	13.5	38.9	65,76,76	76,124,176	201,220,241	229,241,245
20/400	51.1	37.2	15.8	40.6	65, OK 300	OK 300	OK 300	OK 300
60/400	45.6	30.7	17.0	41.4	OK 300	OK 300	OK 300	OK 300

1) One inch thick plate solution heat treated 3 hours at 860 F, quenched in Wood's metal bath and held indicated time at temperature, then quenched in water at room temperature, held 4 days at room temperature and aged 16 hours at 275 F. See S. No. 293542 for composition (Table XXXII).

2) C-ring type specimens stressed in the short-transverse direction for corrosion evaluation.

3) Triplicate specimens exposed at each stress level to each environment.

4) OK - intact and still in test after indicated time.

TABLE XLVII

AVERAGE† MECHANICAL PROPERTIES OF PLANT FABRICATED X7007-T6E136 SHEET AND PLATE

Direction	Tensile Data TS ksi	Tensile Data TYS ksi	Tensile Data % El. in 4D or 2"	Compressive Data CYS ksi	Compressive Data CYS/TYS	Shear Data Direction†† and Plane of Loading	Shear Data SS ksi	Shear Data SS/TS	Hardness Brinell	Hardness Rockwell
Longitudinal	73.0	68.6	12.0	67.7	1.01	YZ-Y	44.4	--	136	B82
						YZ-Z	42.3	0.59		
Long Transverse	72.1	67.0	12.0	70.7	1.06	XZ-X	44.2			
						XZ-Z	41.4	0.58		
Short Transverse	74.0	65.8	7.5	73.4	1.07	XY-X	40.5	0.56		

Direction	Bearing Strength* e/D** = 1.5 BS ksi	Bearing Strength* e/D** = 1.5 BS/TS	Bearing Strength* e/D = 2.0 BS ksi	Bearing Strength* e/D = 2.0 BS/TS	Bearing Yield Strength* e/D = 1.5 BYS ksi	Bearing Yield Strength* e/D = 1.5 BYS/TYS	Bearing Yield Strength* e/D = 2.0 BYS ksi	Bearing Yield Strength* e/D = 2.0 BYS/TYS
Longitudinal	109.0	1.51	140.9	1.96	93.3	1.40	110.0	1.64
Long Transverse	110.0	1.53	142.1	1.97	93.1	1.39	112.2	1.68

† Average properties of six gages of sheet and plate.

* Data for flatwise specimens.

†† First letters describe plane of shear and last letter describes direction of loading: X - longitudinal; Y - long transverse; Z - short transverse.

** e/D - ratio of edge distance to pin diameter.

TABLE XLVIII

TENSILE AND NOTCH-TENSILE PROPERTIES OF PLANT FABRICATED X7007-T6E136 SHEET AND PLATE

			Longitudinal					Long Transverse				
Thick Inches	S. No.	Testing Temperature	TS ksi	YS ksi	% El. in 2"*	NTS ksi	NTS/TS	TS ksi	YS ksi	% El. in 2"*	NTS ksi	NTS/TS
.064	327105	RT	70.2	68.4	8.8	--	--	74.0	70.5	9.2	--	--
		-112 F	77.8	71.8	7.8	--	--	81.6	76.7	9.2	--	--
		-320 F	87.6	79.9	10.8	--	--	94.6	85.5	5.5	--	--
.125	326790	RT	73.7	68.5	10.8	77.4	1.05	70.8	65.6	12.0	76.6	1.08
		-112 F	83.0	76.4	9.5	83.2	1.00	79.6	72.6	11.0	81.6	1.03
		-320 F	99.0	84.5	11.5	77.8	0.79	93.0	81.2	12.5	73.6	0.79
		-452 F	96.9	83.8	8.5	83.5	0.88	95.2	82.2	10.2	77.2	0.81
.250	326788	RT	73.2	66.8	12.0	--	--	70.6	64.1	12.2	--	--
.500	326786	RT	72.0	65.2	14.0	--	--	70.8	64.2	13.0	--	--
1.000	327108	RT	77.0	73.1	13.0	107.0	1.39	73.8	68.8	13.0	104.8	1.42
		-112 F	87.5	81.3	11.2	106.4	1.22	82.3	74.4	10.8	93.2	1.13
		-320 F	101.4	89.3	12.8	109.8	1.08	95.2	84.5	11.2	88.2	0.93
		-452 F	116.1	98.1	14.2	118.6	1.02	107.1	91.8	11.5	104.6	0.98
2.500	295582	RT	70.9	69.8	13.5	--	--	72.6	68.5	12.8	--	--
Averages		RT	73.0	68.6	13.5	--	--	72.1	67.0	12.9	--	--

*Elongation in 4D for round specimens from plate .500" and over.

TABLE XLIX

AVERAGE TEAR PROPERTIES OF X7007-T6E136 SHEET AND PLATE

Direction	Tear Strength ksi	Unit Propagation Energy in.-lb/in.^{2}
Longitudinal	92.9	730
Long-Transverse	90.8	430
Short-Transverse	63.8	135

TABLE L

EFFECT OF TESTING TEMPERATURE ON TEAR PROPERTIES*
OF 0.064 INCH X7007-T6E136 SHEET

Testing Temp. °F	Tear Strength ksi	Unit Propagation Energy in.-lb/in.^{2}
RT	95.6	575
-112	79.2	270
-320	62.5	150

*Long-transverse properties

TABLE LI

PHYSICAL PROPERTIES OF X7007

Specific Gravity	2.80
Density, lb/in.^{3}	0.101
Melting Range, °F	1080-1190
Electrical Conductivity at 20°C, % IACS:	
W Temper	32
T6E136 Temper	38
Thermal Conductivity at 25°C, CGS Units:	
W Temper	0.30
T6E136 Temper	0.36
Average Coefficient of Thermal Expansion (T6E136 Temper)	
68°F - 122°F	12.5×10^{-6}
68°F - 212°F	13.1×10^{-6}
68°F - 266°F	13.2×10^{-6}

TABLE LII

RESULTS OF STRESS-CORROSION TESTS ON PLANT FABRICATED
X7007-T6E136 1.000 INCH PLATE

	Long-Transverse Tensile Properties					Short Transverse C-rings	
					Stress	3 1/2% NaCl-Alt. Imm.	New Kensington Atm.
S. No.	TS ksi	YS ksi	% El. in 2"	% R of A	Level % YS	Days to Failure or Days OK	Days to Failure or Days OK
326782	69.6	62.9	13.0	28	75	52,58,68	121,121,128
					50	68,73,101	OK 175
					25	108,108,108	OK 175
327108	73.7	69.1	15.0	37	75	12,19,19	39,39,39
					50	34,46,49	57,48,57
					25	73,88, OK 119	OK 116

1) Triplicate stressed specimens exposed.

2) OK - Intact and still in test after indicated time.

3) Long-transverse tensile bars stressed to 75% of yield strength have been in test 116, 119 or 175 days without any failures.

TABLE LIV

TENSILE PROPERTIES OF WELDED X7007-T6E136 0.500 INCH PLATE

S. No.	Filler Alloy	Post-Weld Aging Treatment	Full Section Tensile Properties TS ksi	YS ksi	% El. in 10"	Location* of Failure
326604	M822	98 days at 70 F	59.4	53.0	1.3	B
		8 hr at 225 F + 16 hr at 300 F	61.4	57.8	1.7	B
295233	5356	133 days at 70 F	58.4	49.0	1.4	B
		8 hr at 225 F + 16 hr at 300 F	61.2	56.2	2.5	B
342711	5356	40 days at 70 F	54.7	44.0	1.6	B
		90 days at 70 F	59.2	42.4	1.8	A
		8 hr at 225 F + 16 hr at 300 F	56.8	52.3	1.3	A & B
295231	X5180	133 days at 70 F	59.2	51.5	1.1	B
		8 hr at 225 F + 16 hr at 300 F	60.8	56.4	2.8	C

* A - through weld bead; B - edge of weld bead; C - through parent metal.

1) Welding procedure: MIG manual, three face passes and one root pass.

2) Transverse specimens - YS - 0.2% Offset in 10 inch gage length.

TABLE LV

NOTCH-TENSILE PROPERTIES OF X7007-T6E136 0.5 INCH PLATE
WELDED WITH 5356 FILLER ALLOY

			Reduced Section Tensile Properties (Round Specimens)						
			Unnotched					Notched*	
S - No.	Post-Weld Aging Treatment	Testing Temperature	TS ksi	YS ksi	El.† %	% R of A	Location** of Failure	NTS ksi	NTS/TS
342711-1	40 days at RT	RT	46.3	25.6	8.6	32	A & B	49.8	1.08
		-320 F	54.4	31.6	3.4	11	A	55.0	1.01
342711-2	8 hr at 225 F + 16 hr at 300 F	RT	47.4	31.8	5.6	28	A	56.4	1.19
		-320 F	60.0	38.0	2.6	10	A	59.0	.98

* Notched in center of weld bead ($K_t = 10$). Failed through notch.

† Elongation in 1.4 and 1.25 inch for RT and -320 F tests, respectively.

** A - through weld bead; B - at edge of weld bead.

1) Welding procedure: MIG manual, three face passes and one root pass.

2) Transverse specimens.

TABLE LVI

RESULTS OF STRESS-CORROSION TESTS ON WELDED X7007-T6E136 0.500 INCH PLATE

S. No.	Filler Alloy	Post-Weld Aging Treatment	Specimen* Type	3 1/2% NaCl - Alt. Imm. F/N†	3 1/2% NaCl - Alt. Imm. Days to Failure or Days OK	New Kensington Atm. F/N†	New Kensington Atm. Days to Failure or Days OK
326604-1	M822	Natural Aging**	Root	1/1	44	1/1	79
326604-1	M822	Natural Aging**	Root (red.)	1/1	26	1/1	138
326604-1	M822	Natural Aging**	Face	1/1	108	1/1	138
326604-2	M822	8 hr at 225 F + 16 hr at 300 F	Root	1/1	131	1/1	79
295233-1	5356	Natural Aging**	Root	0/1	OK 345	1/1	273
295233-1	5356	Natural Aging**	Root (red.)	0/1	OK 345	0/1	OK 345
295233-1	5356	Natural Aging**	Face	0/1	OK 345	0/1	OK 345
295233-2	5356	8 hr at 225 F + 16 hr at 300 F	Root	0/1	OK 345	1/1	325
295231-1	X5180	Natural Aging**	Root	0/2	OK 345	2/2	55, 302
295231-1	X5180	Natural Aging**	Root (red.)	0/2	OK 345	0/2	OK 345
295231-1	X5180	Natural Aging**	Face	1/1	256	1/1	332
295231-2	X5180	8 hr at 225 F + 16 hr at 300 F	Root	0/2	OK 345	2/2	71, 244

* Root - root side of specimen (last side welded) stressed in tension.
Root (red.) - weld bead machined flush with plate surface.
Face - face side os specimen (opposite root side) stressed in tension.

† Ratio of number of specimens failed to number exposed.

** Naturally aged several months before exposing.

1) Welding procedure: MIG manual, three face passes and one root pass.

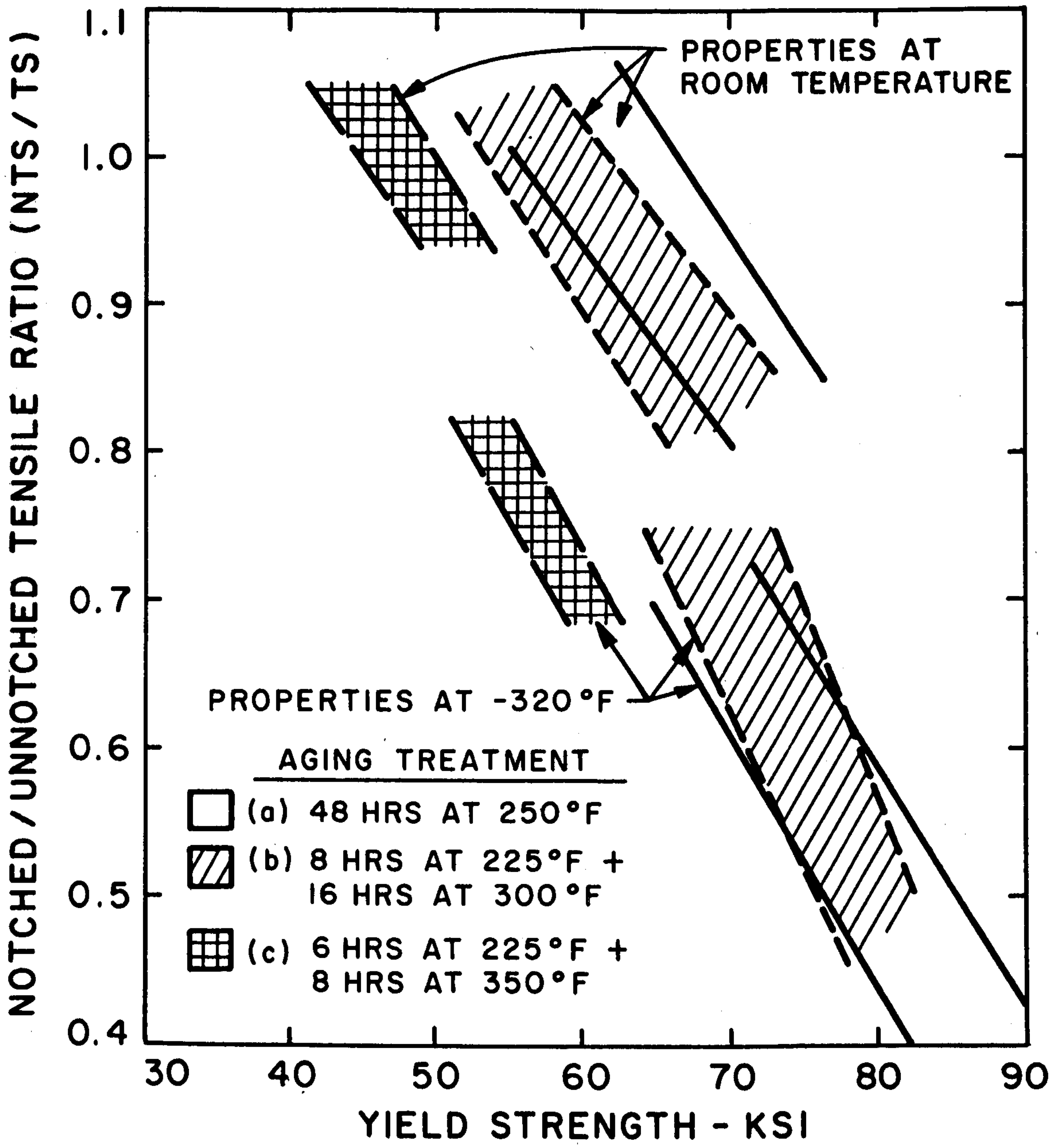
2) Specimens stressed in bending to a fiber stress of 30 ksi, Assembly C, Figure 37.

TABLE LVII

COMPARISON OF TENSILE PROPERTIES OF EXPERIMENTAL AND COMMERCIAL HIGH STRENGTH, WELDABLE ALLOYS

Property	Testing Temperature	2219-T851	2014-T651	X2021-T81	5456-H343	7039-T6351	X7007-T6E136	Contract Goals
TS, ksi	RT	66	70	73	56	67	73	75
	-112 F	71	74	79	59	73	81	--
	-320 F	83	84	89	73	86	91	--
	-423 F	99	100	101	81	99	104	--
YS, ksi	RT	50	63	63	43	57	67	65
	-112 F	54	68	68	45	63	71	--
	-320 F	61	74	75	51	70	81	--
	-423 F	68	81	82	54	77	88	--
Elongation, %	RT	12	13	9	8	12	12	10
	-112 F	13	13	9	9	12	12	--
	-320 F	15	14	9	11	12	10	--
	-423 F	18	12	9	7	12	10	--
Notched/Unnotched Tensile Ratio*	RT	1.17	1.15	1.00	--	1.28	1.31	1.00
	-112 F	1.08	--	1.06	--	1.09	1.15	--
	-320 F	1.06	0.98	1.02	--	0.94	0.95	--
	-423 F	0.99	0.96	1.00	--	0.89	0.90	0.90

*Round notched specimens - K_t = 10.



XFKI5

FIGURE 1 - EFFECT OF AGING TREATMENT ON THE NOTCH-SENSITIVITY OF THE 7000 SERIES ALLOYS. (.064 INCH SHEET-EDGE NOTCHED SPECIMENS, K_t = 10)

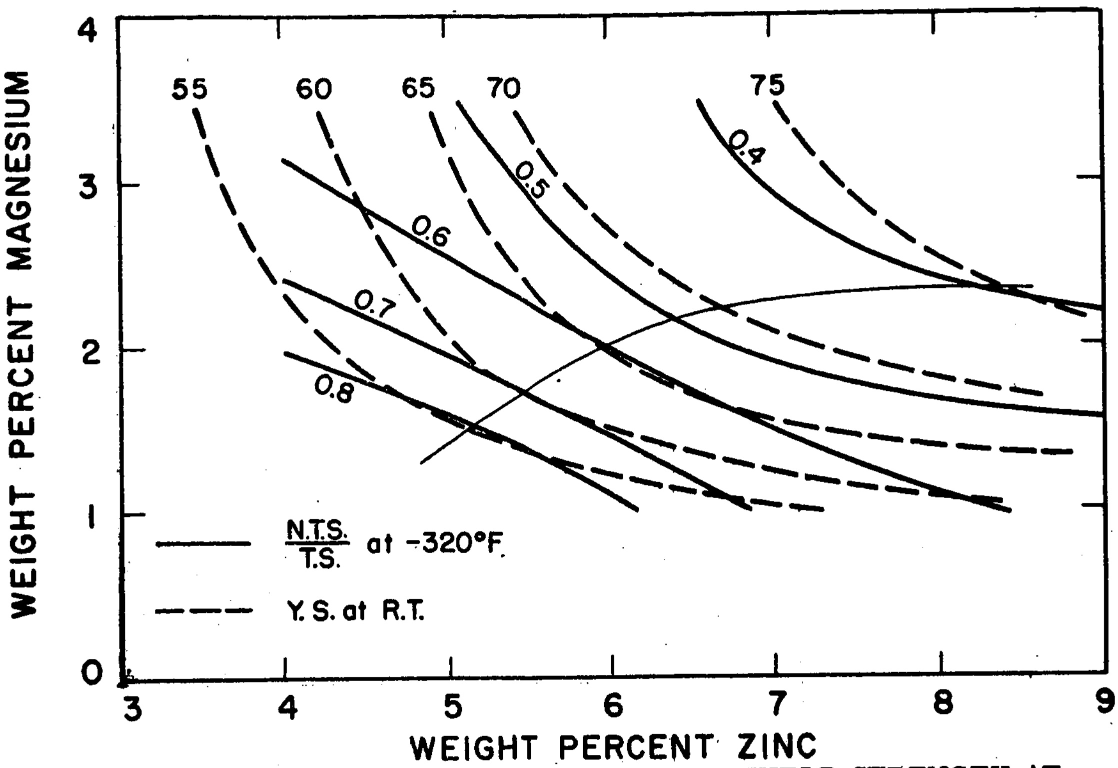
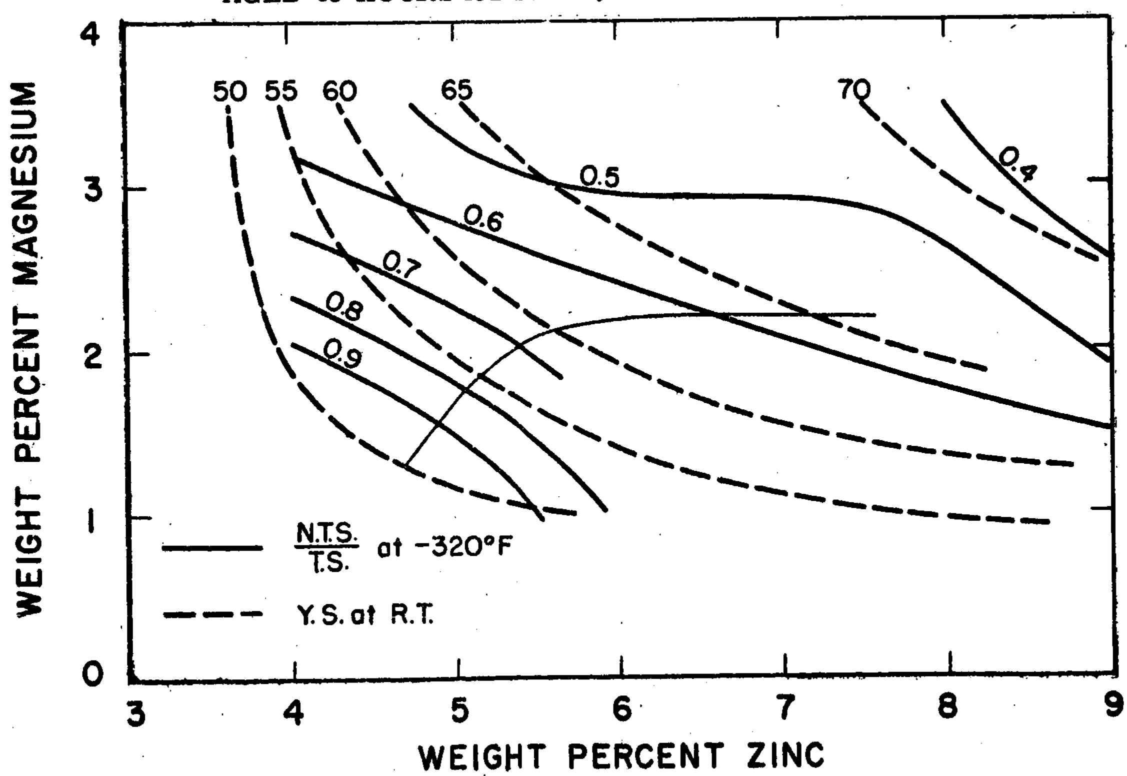
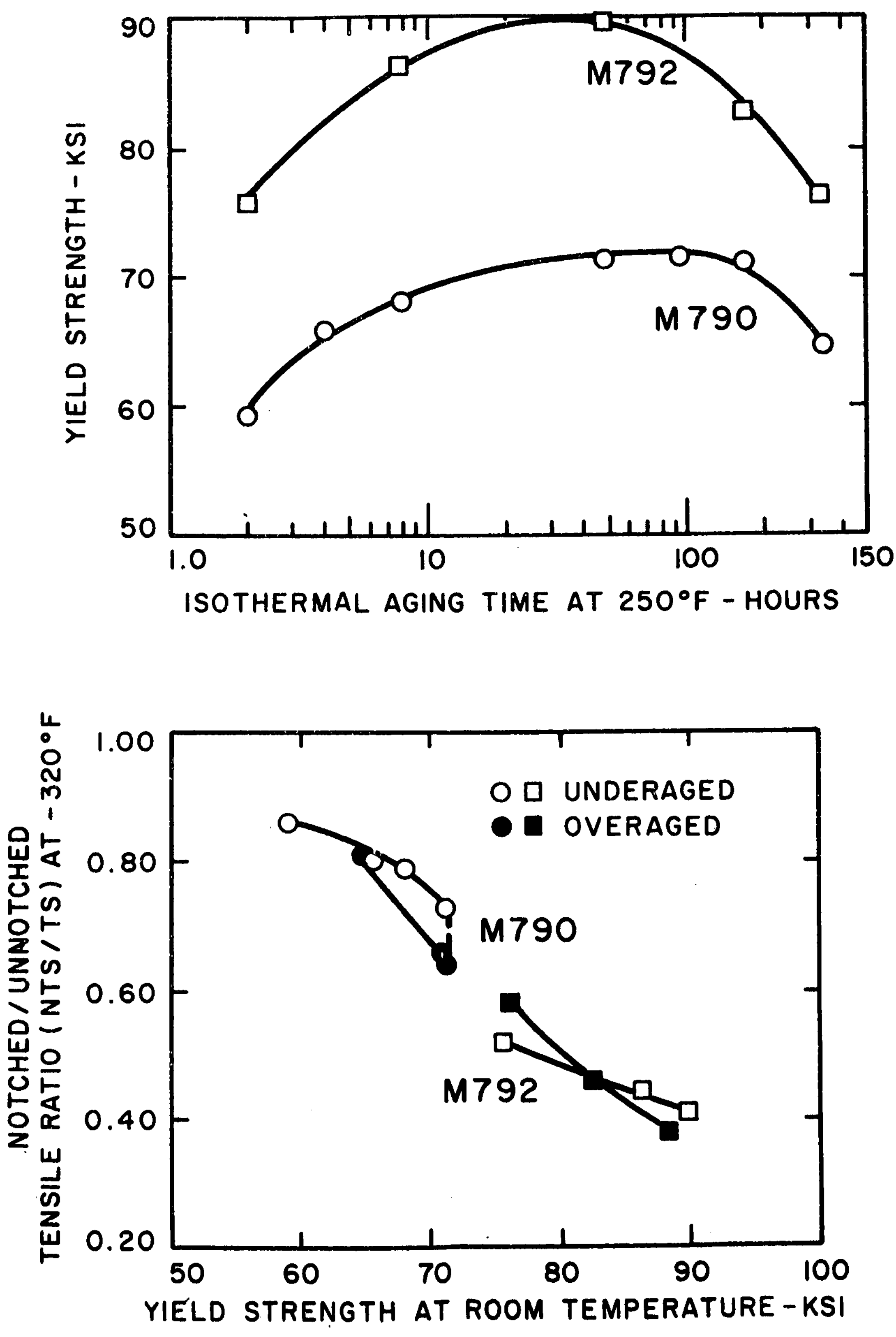


FIGURE 2 - EFFECT OF COMPOSITION ON THE YIELD STRENGTH AT ROOM TEMPERATURE AND THE NOTCHED/UNNOTCHED TENSILE RATIO AT - 320°F FOR THE 7000 SERIES ALLOYS AGED 48 HOURS AT 250°F.



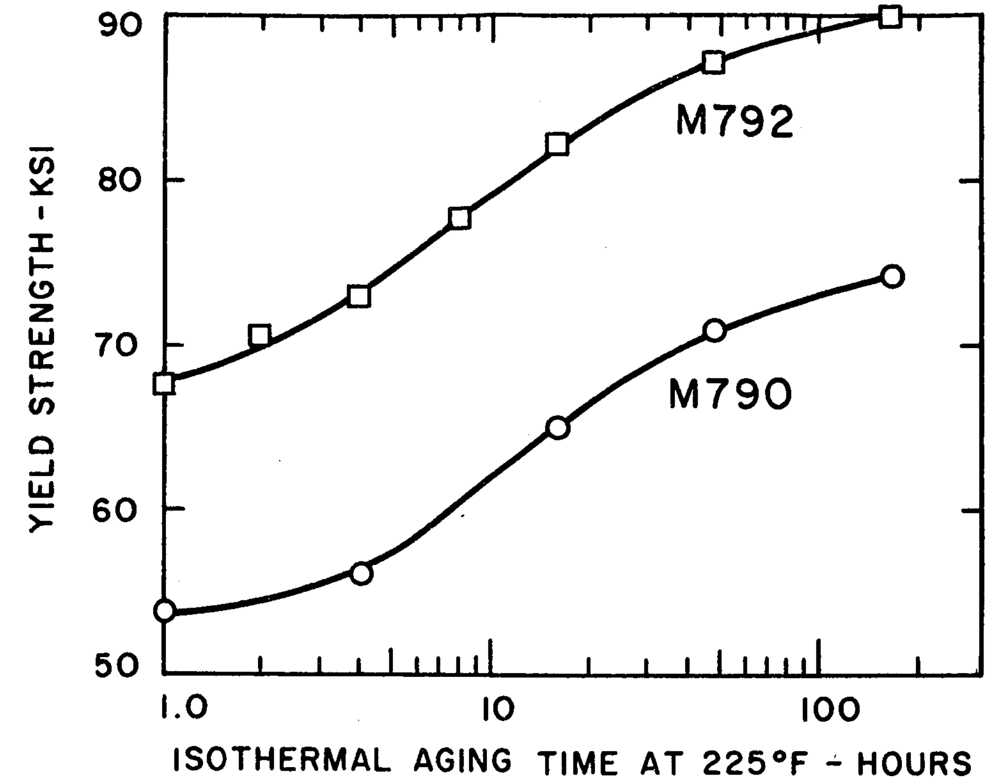
XFKI6

FIGURE 3 - EFFECT OF COMPOSITION ON THE YIELD STRENGTH AT ROOM TEMPERATURE AND THE NOTCHED/UNNOTCHED TENSILE RATIO AT -320°F FOR THE 7000 SERIES ALLOYS AGED 8 HOURS AT 225°F + 16 HOURS AT 300°F (.064 INCH SHEET-EDGE NOTCHED SPECIMENS, K_t = 10)



XFK17

FIGURE 4 - EFFECT OF AGING AT 250°F ON THE YIELD STRENGTH AND NOTCH-TOUGHNESS OF M790 AND M792. (1.000 INCH PLATE-NOTCHED ROUND SPECIMENS, K_t = 10)



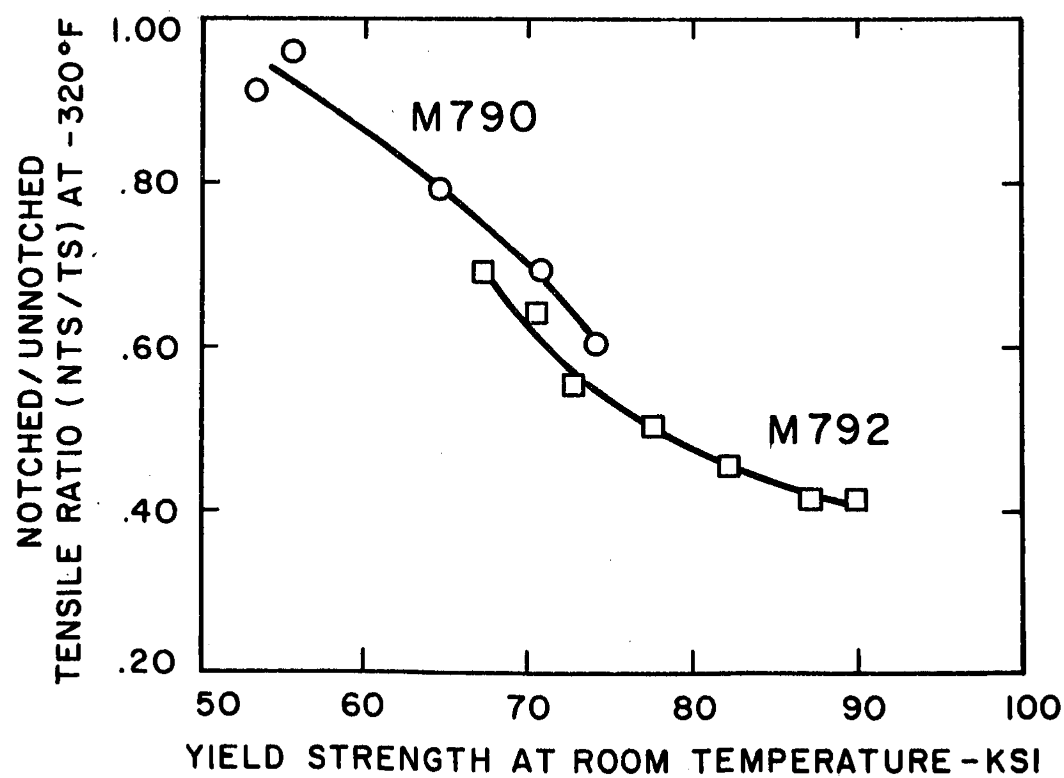
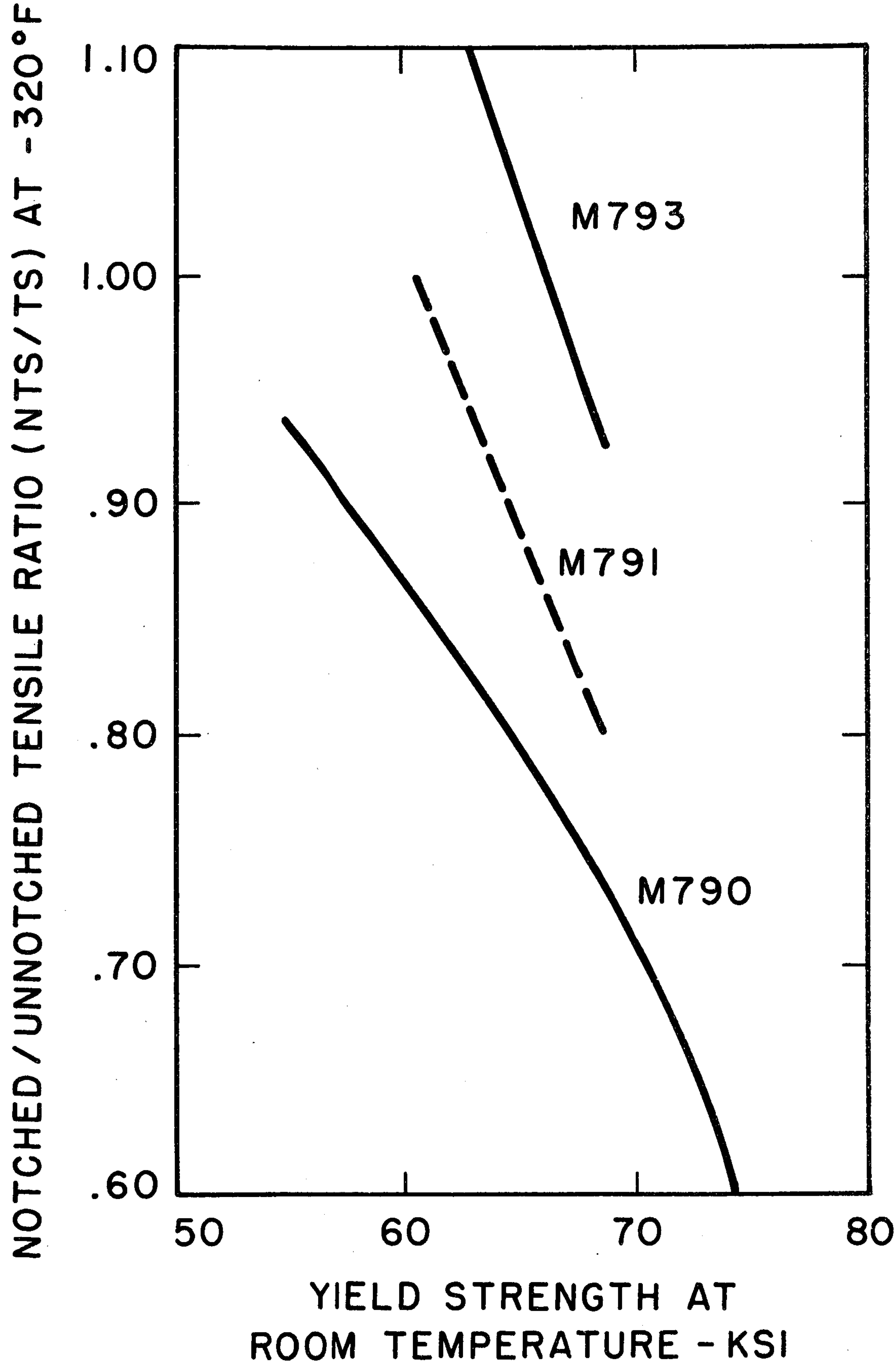


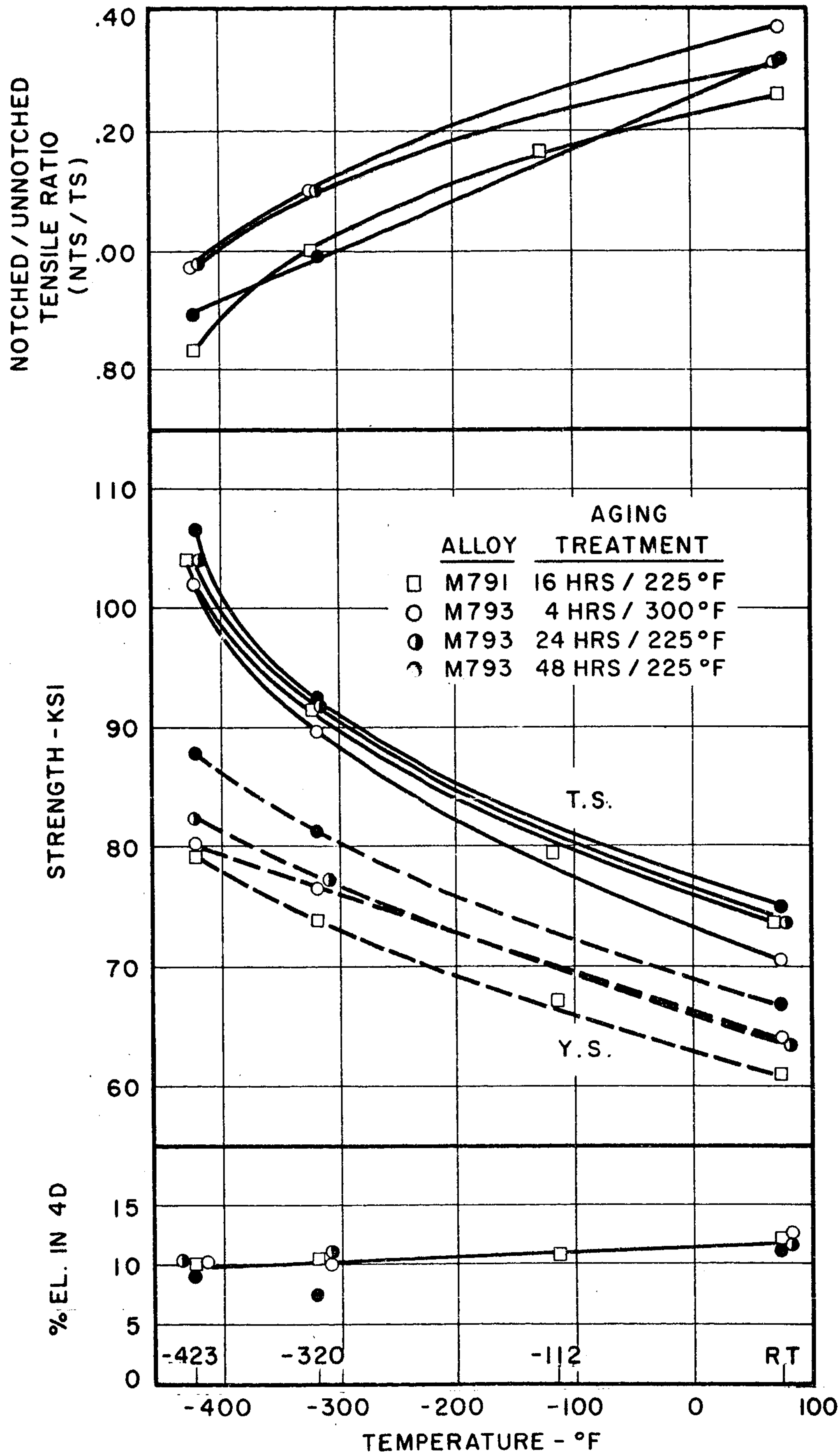
FIGURE 5 - EFFECT OF AGING AT 225°F ON THE YIELD STRENGTH AND NOTCH TOUGHNESS OF M790 AND M792. (1.000 INCH PLATE-NOTCHED ROUND SPECIMENS, $K_t = 10$)

XFK18



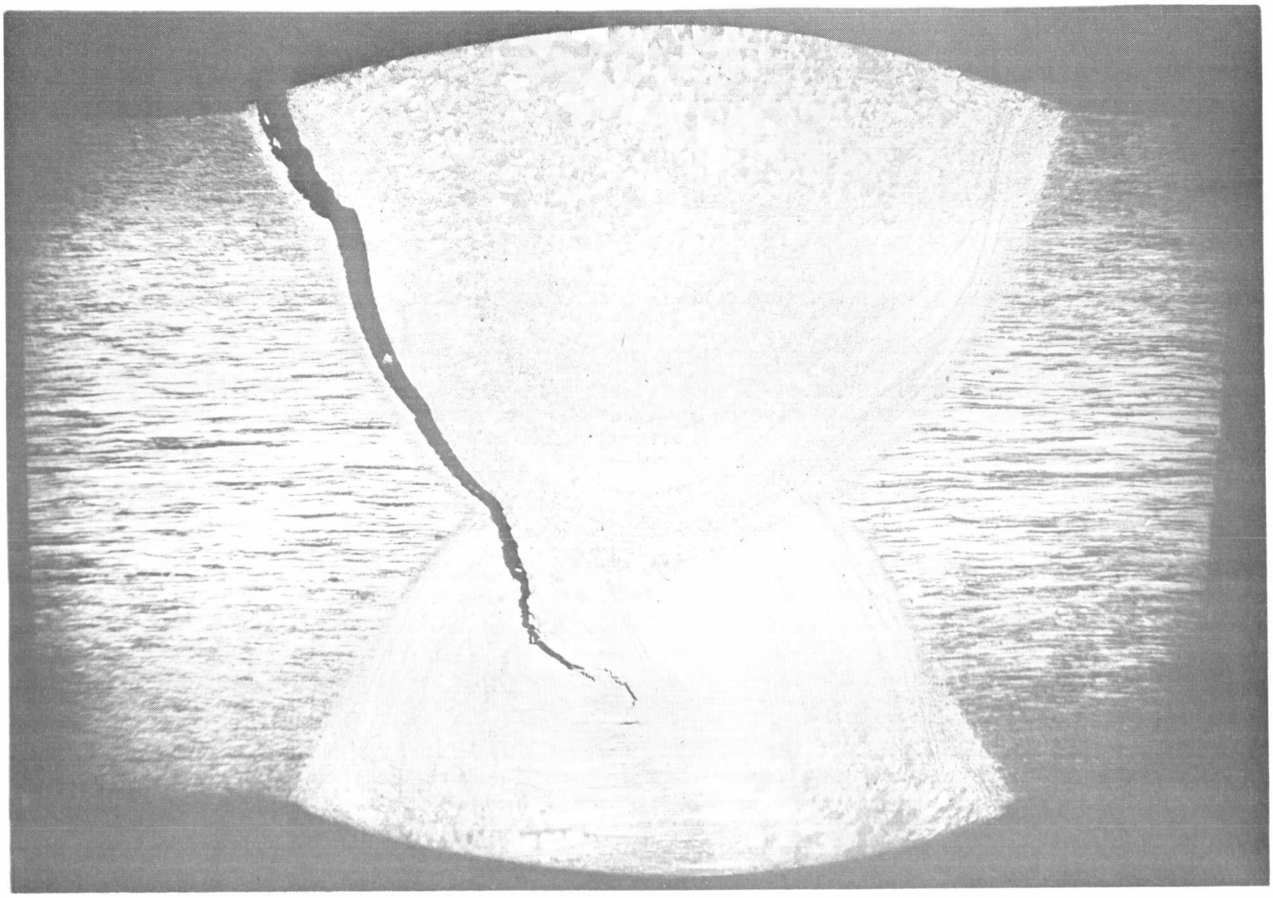
XFK19

FIGURE 6 - EFFECT OF AGING TREATMENT ON THE NOTCH-TOUGHNESS OF M790, M791 and M793 ALLOYS. (1.000 INCH PLATE-NOTCHED ROUND SPECIMENS, K_t = 10)

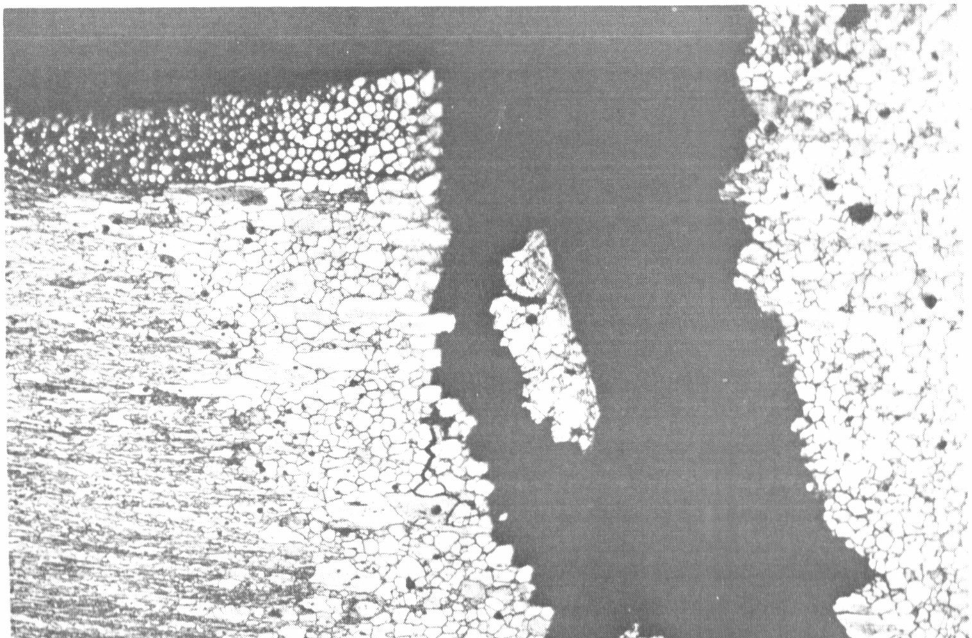


XFK20

FIGURE 7 - THE EFFECT OF TESTING TEMPERATURE ON THE MECHANICAL PROPERTIES OF M791 AND M793. (1.000 INCH PLATE-NOTCHED ROUND SPECIMENS, K_t = 10)



S. NO. 292059-B1-S16 Keller's Etch 7 1/2X



144868AJ
144869AJ

S. NO. 292-59-B1-S16 Keller's Etch 100X

FIGURE 8 - MICROGRAPHS SHOWING TYPICAL STRESS-CORROSION CRACK OF WELDED 0.5 INCH PLATE OF M793 ALLOY.

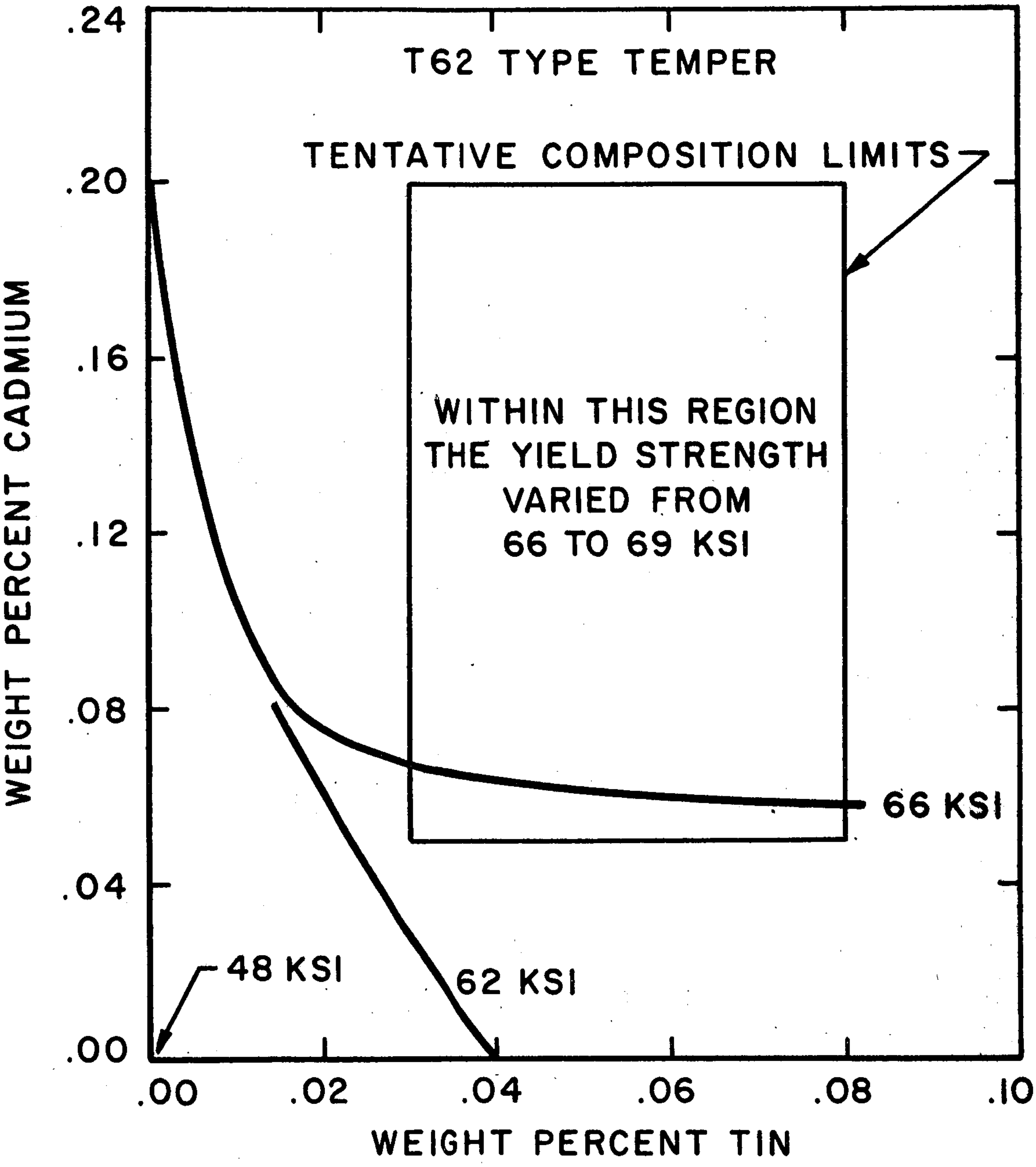


FIGURE 9 - VARIATION OF YIELD STRENGTH WITH Cd AND Sn CONCENTRATIONS FOR THE T62 TYPE TEMPER. (.064 INCH SHEET)

XFK21

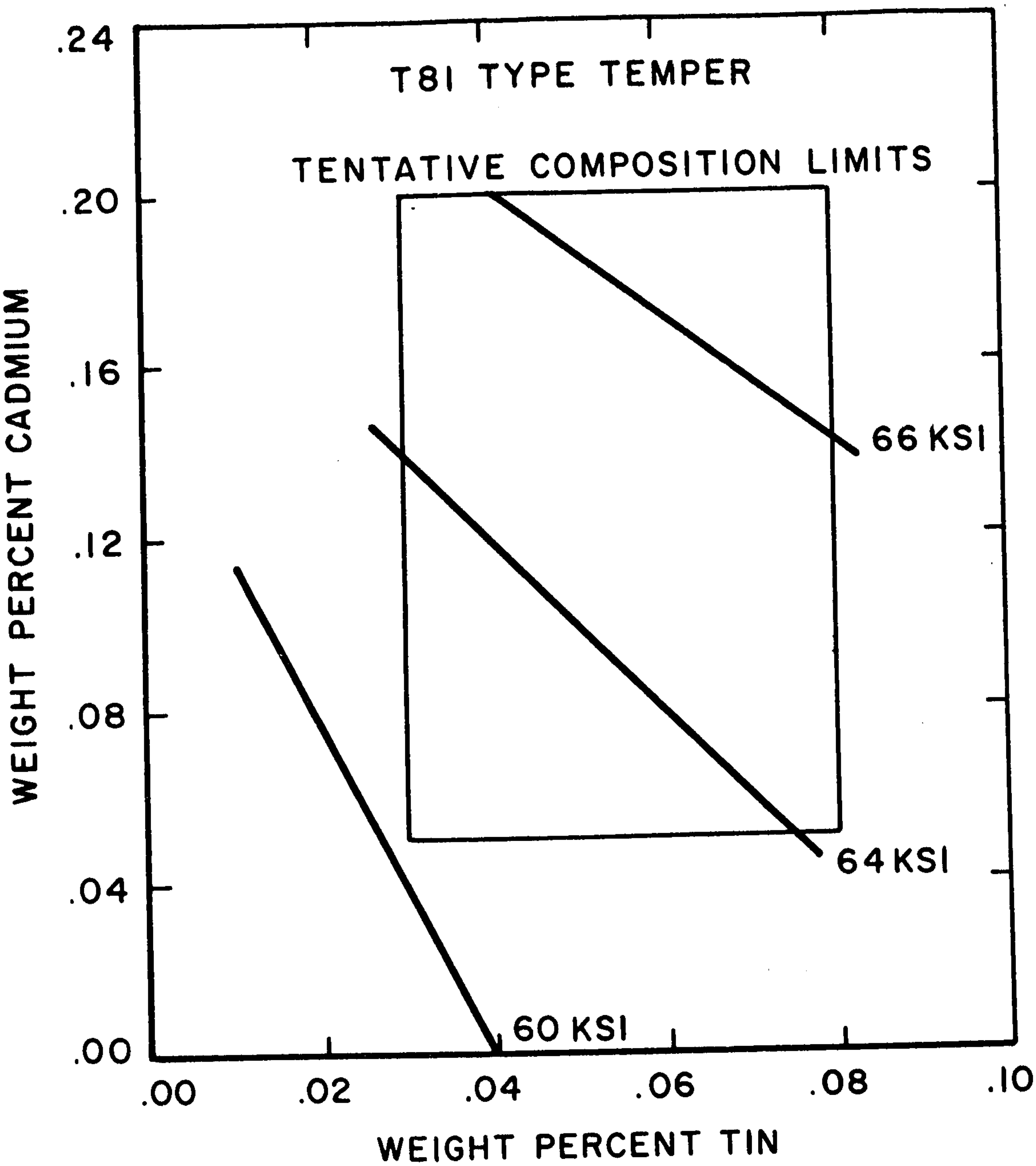
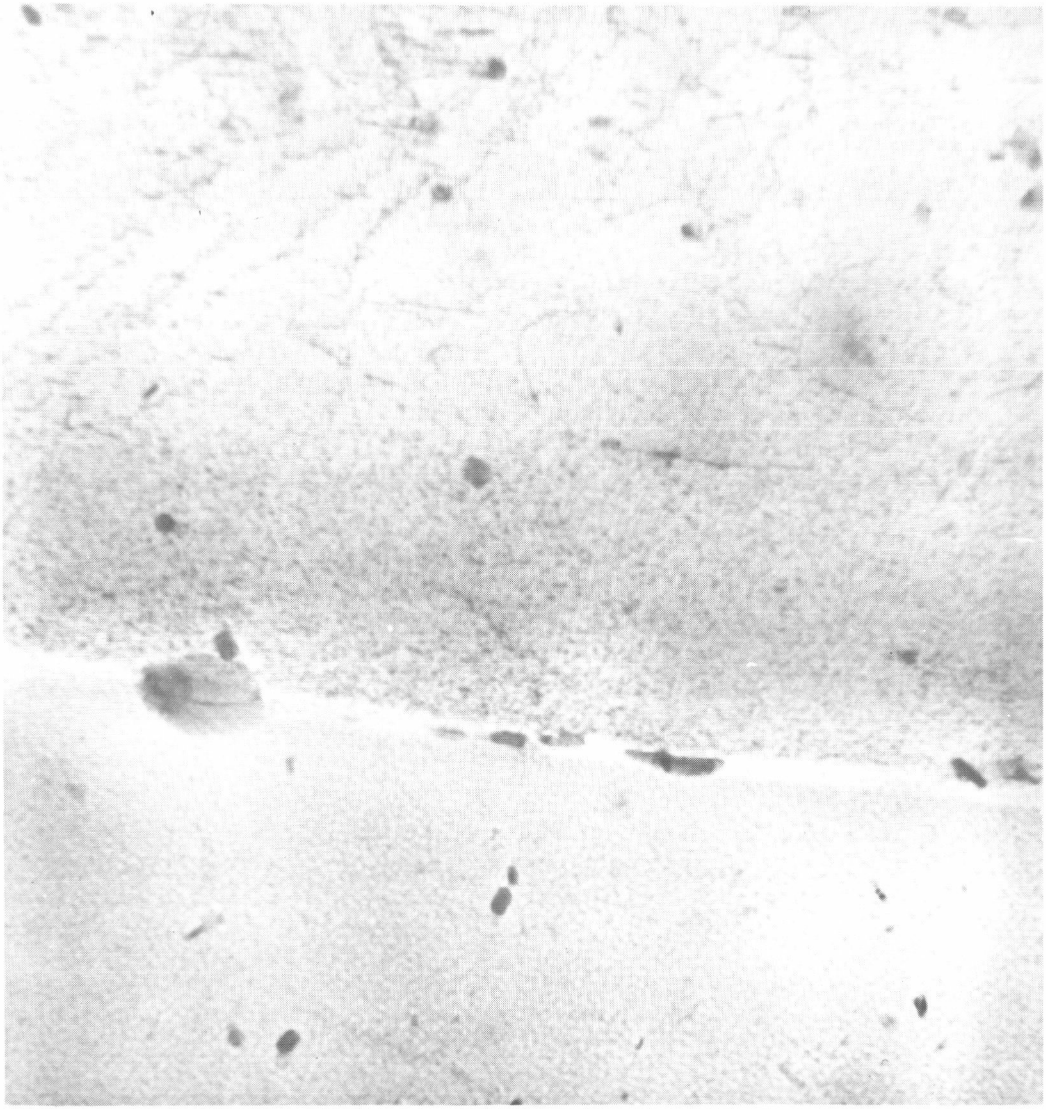


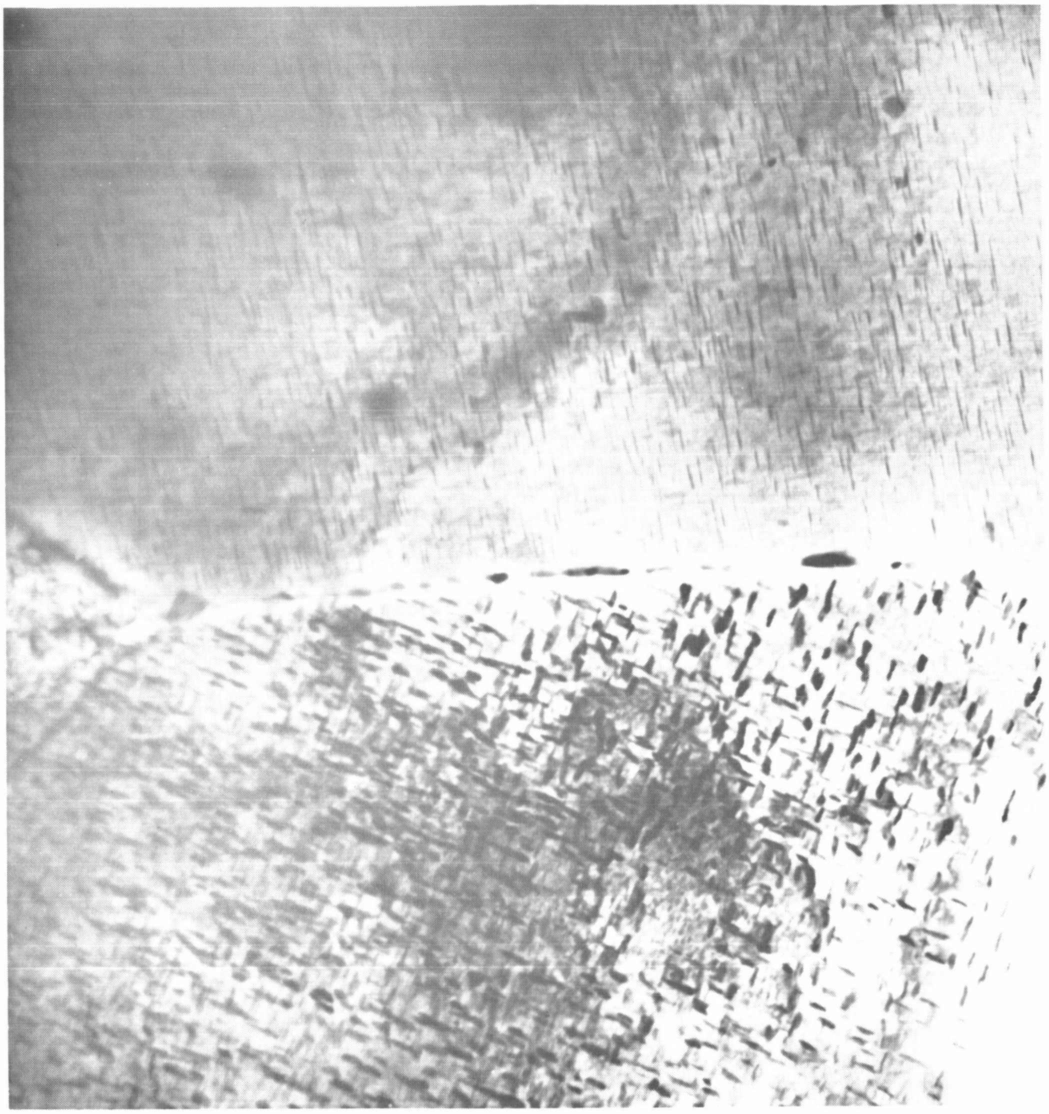
FIGURE 10 - VARIATION OF YIELD STRENGTH WITH Cd AND Sn CONCENTRATION FOR THE T81 TYPE TEMPER. (.064 INCH SHEET)

XFK22



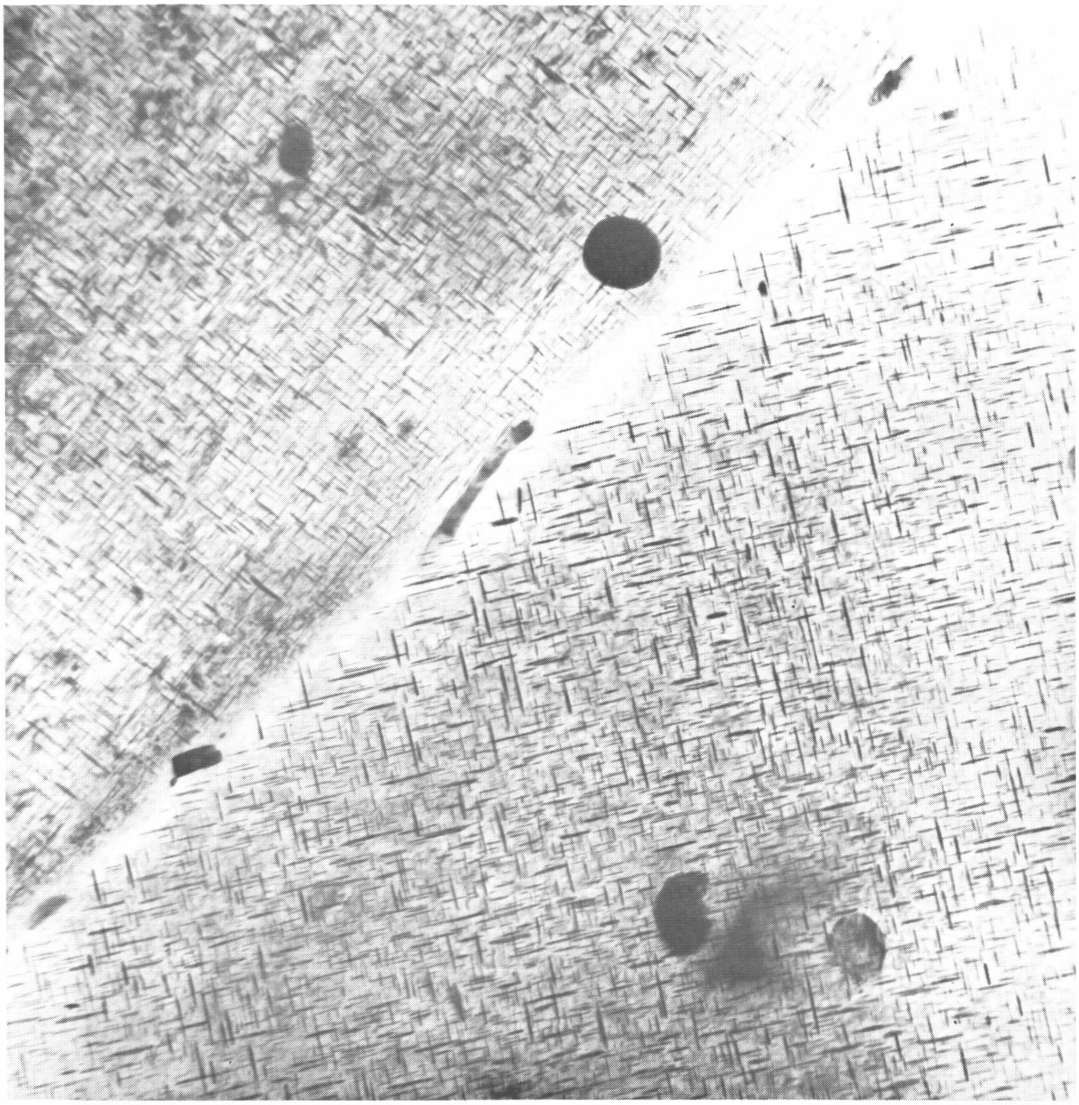
50,000X

FIGURE 11 - TRANSMISSION ELECTRON MICROGRAPH OF 2219 WHICH WAS SOLUTION HEAT TREATED, QUENCHED AND AGED. (YS = 51 ksi).



50,000X

FIGURE 12 - TRANSMISSION ELECTRON MICROGRAPH OF 2219 WHICH WAS SOLUTION HEAT TREATED, QUENCHED, STRETCHED 10% AND AGED. (YS = 57 ksi)



50,000X

FIGURE 13 - TRANSMISSION ELECTRON MICROGRAPH OF X2021 WHICH WAS SOLUTION HEAT TREATED, QUENCHED AND AGED. (YS = 67 ksi).

PFI266J

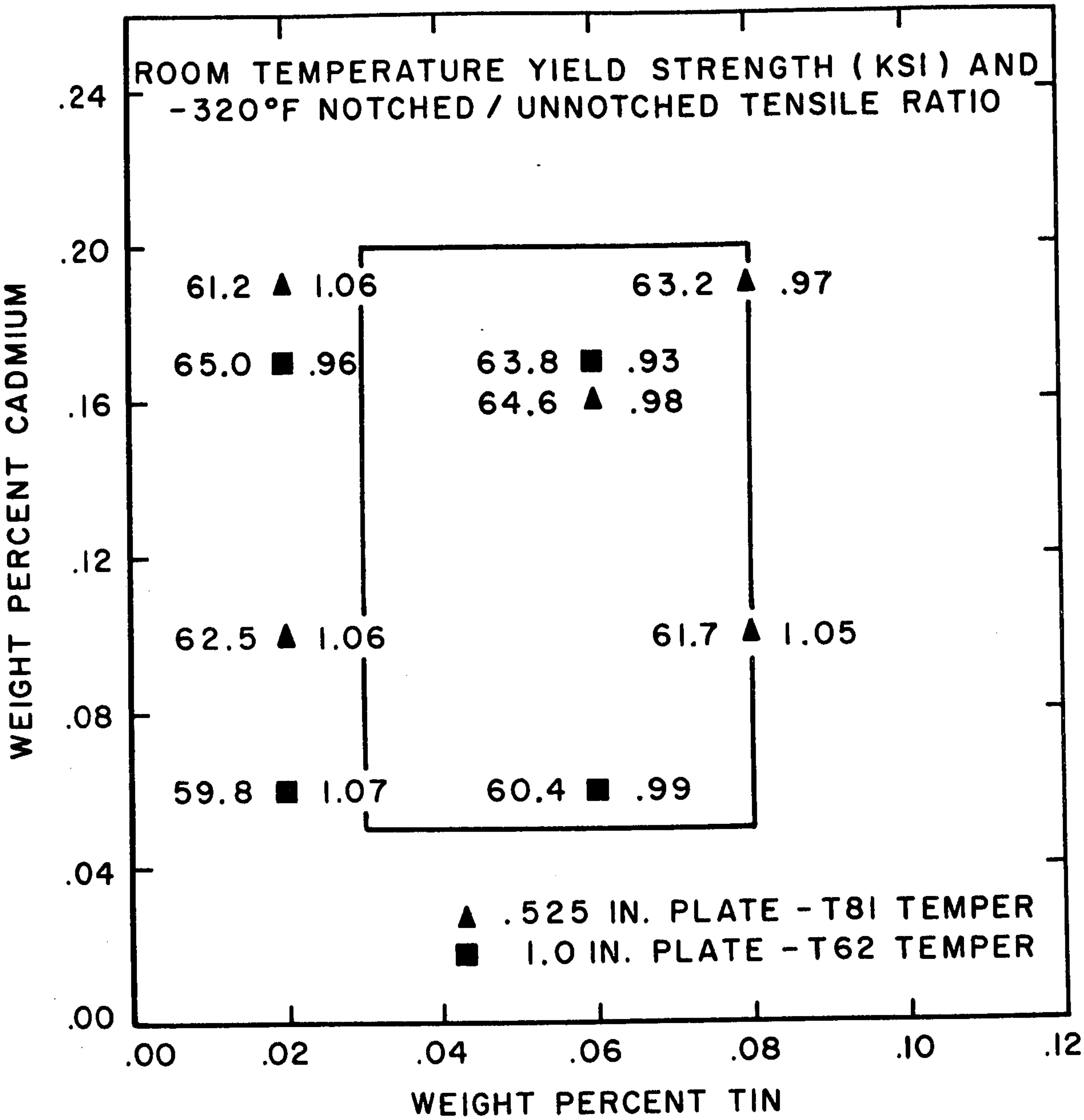


FIGURE 14 - EFFECT OF Cd AND Sn CONCENTRATION ON THE ROOM TEMPERATURE YIELD STRENGTH AND -320°F NOTCH-TOUGHNESS OF X2021.

XFK23

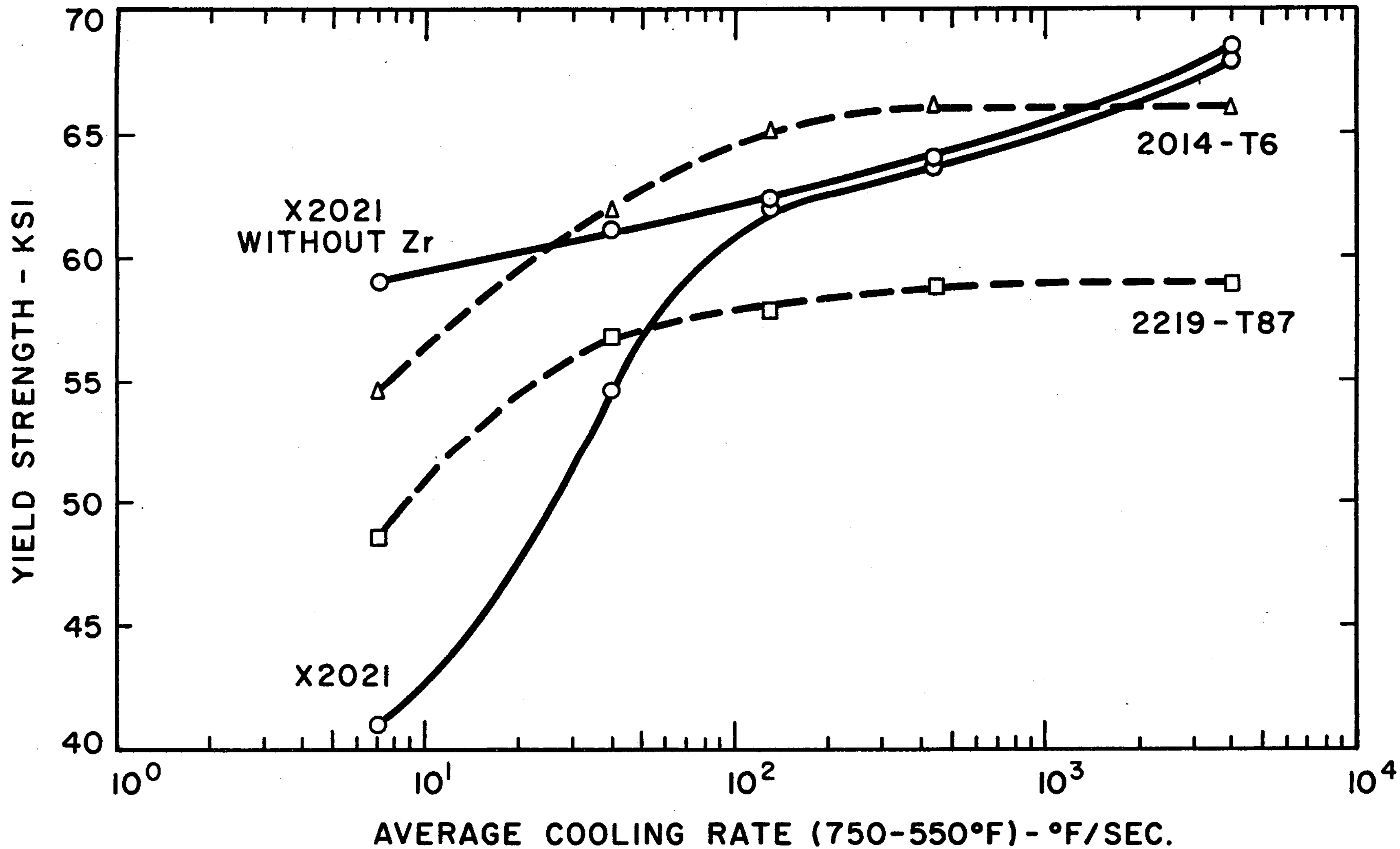
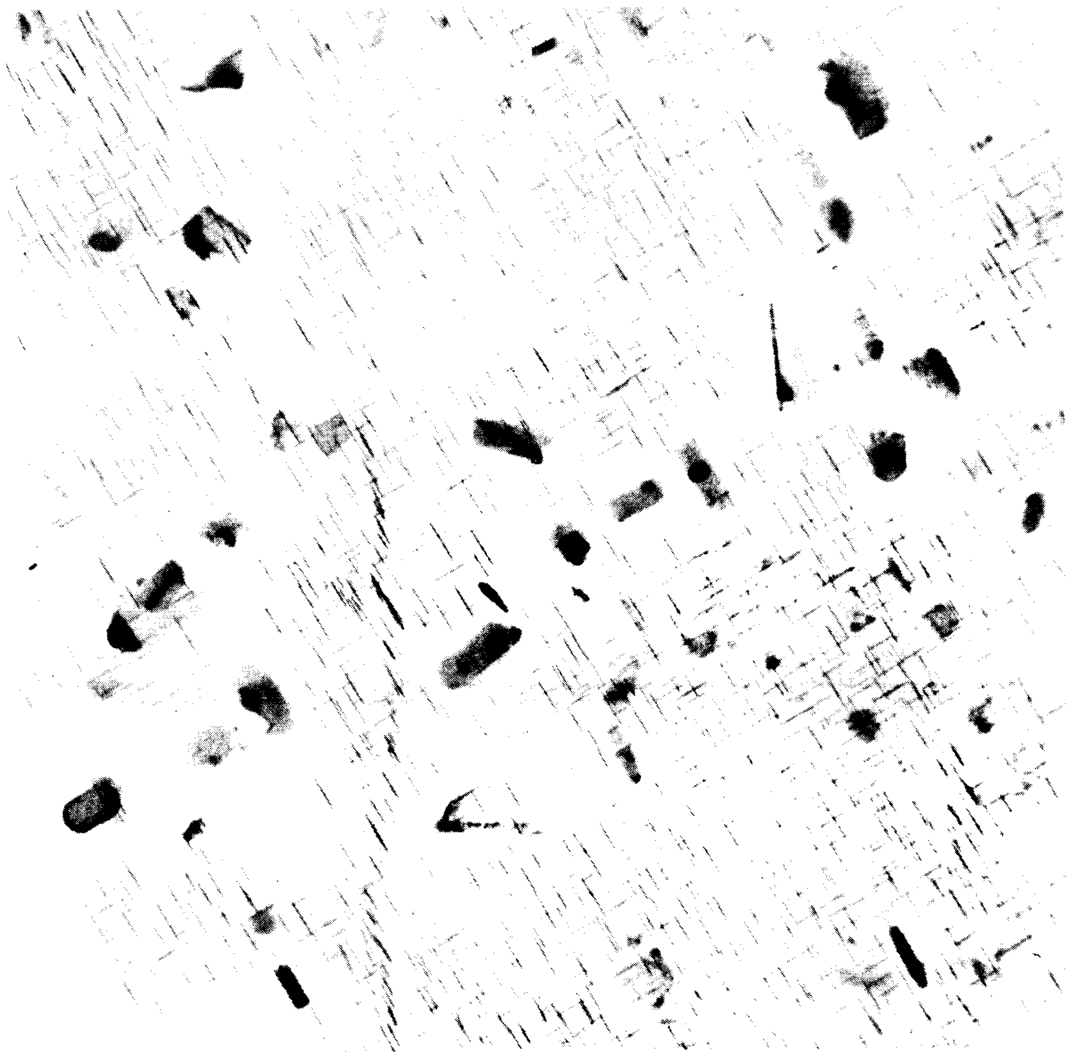


FIGURE 15 - EFFECT OF QUENCH RATE ON THE YIELD STRENGTH OF X2021, X2021 WITHOUT Zr, AND TWO OTHER Al-Cu ALLOYS. (.064 INCH SHEET)

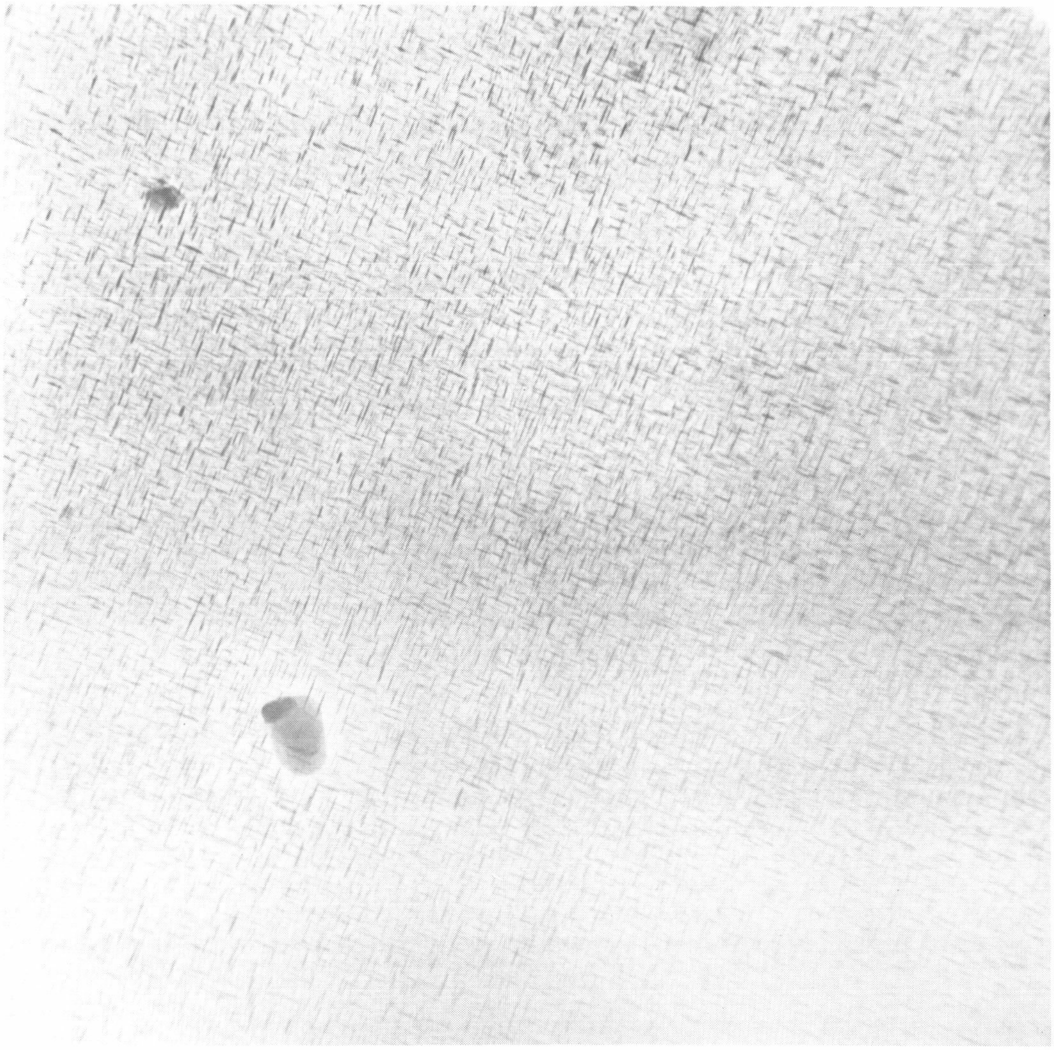
XFK24



S. NO. 327023-B-T3 50,000X

FIGURE 16 - TRANSMISSION ELECTRON MICROGRAPH OF X2021 SAMPLE WHICH WAS BOILING WATER QUENCHED AND AGED 24 HOURS AT 325°F.

EM889J



S. NO. 327024-B-T3 50,000X

FIGURE 17 - TRANSMISSION ELECTRON MICROGRAPH OF X2021 TYPE ALLOY WITH THE Zr AND V REMOVED. SAMPLE WAS BOILING WATER QUENCHED AND AGED 24 HOURS AT 325°F.

EM907J

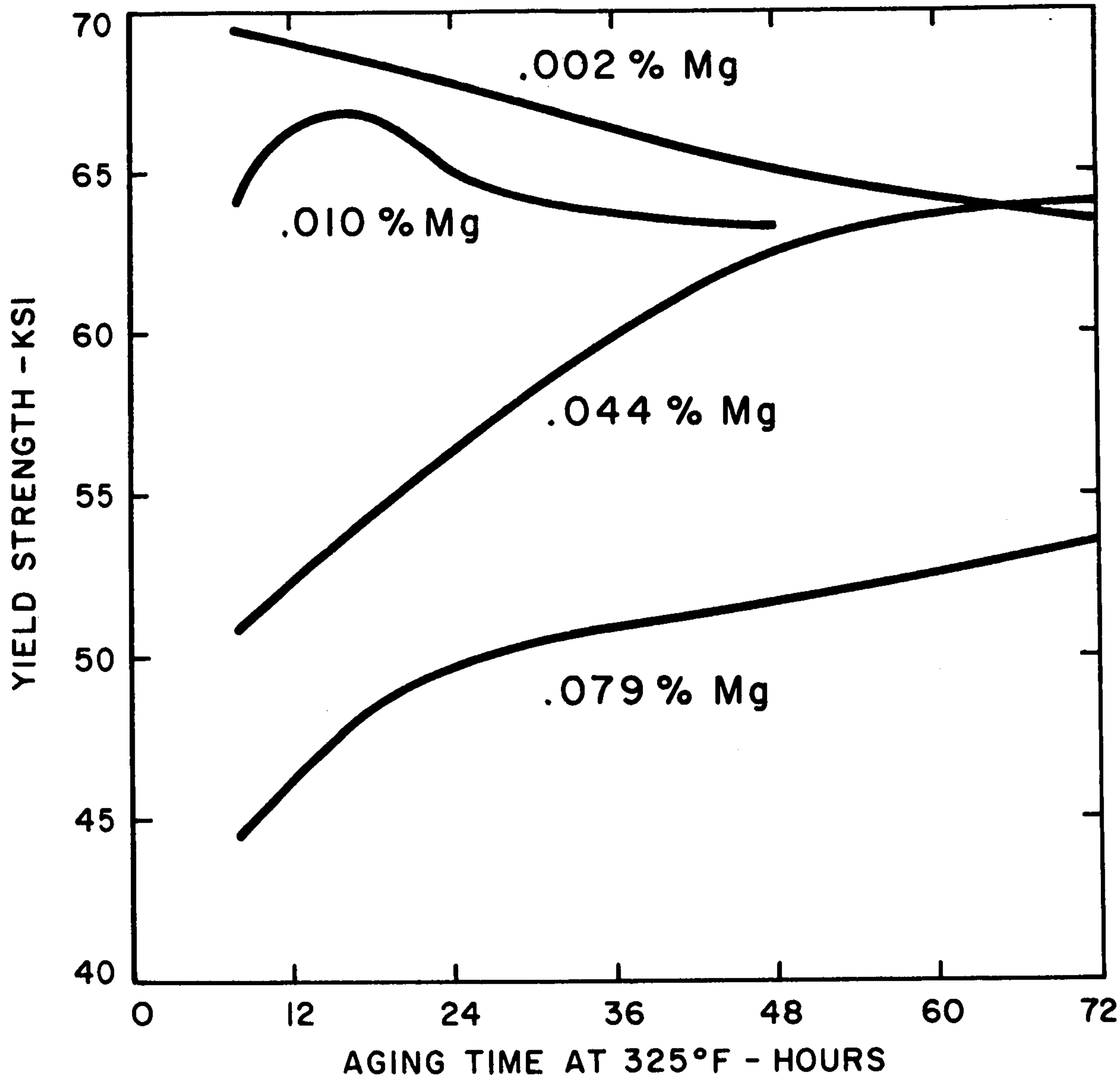
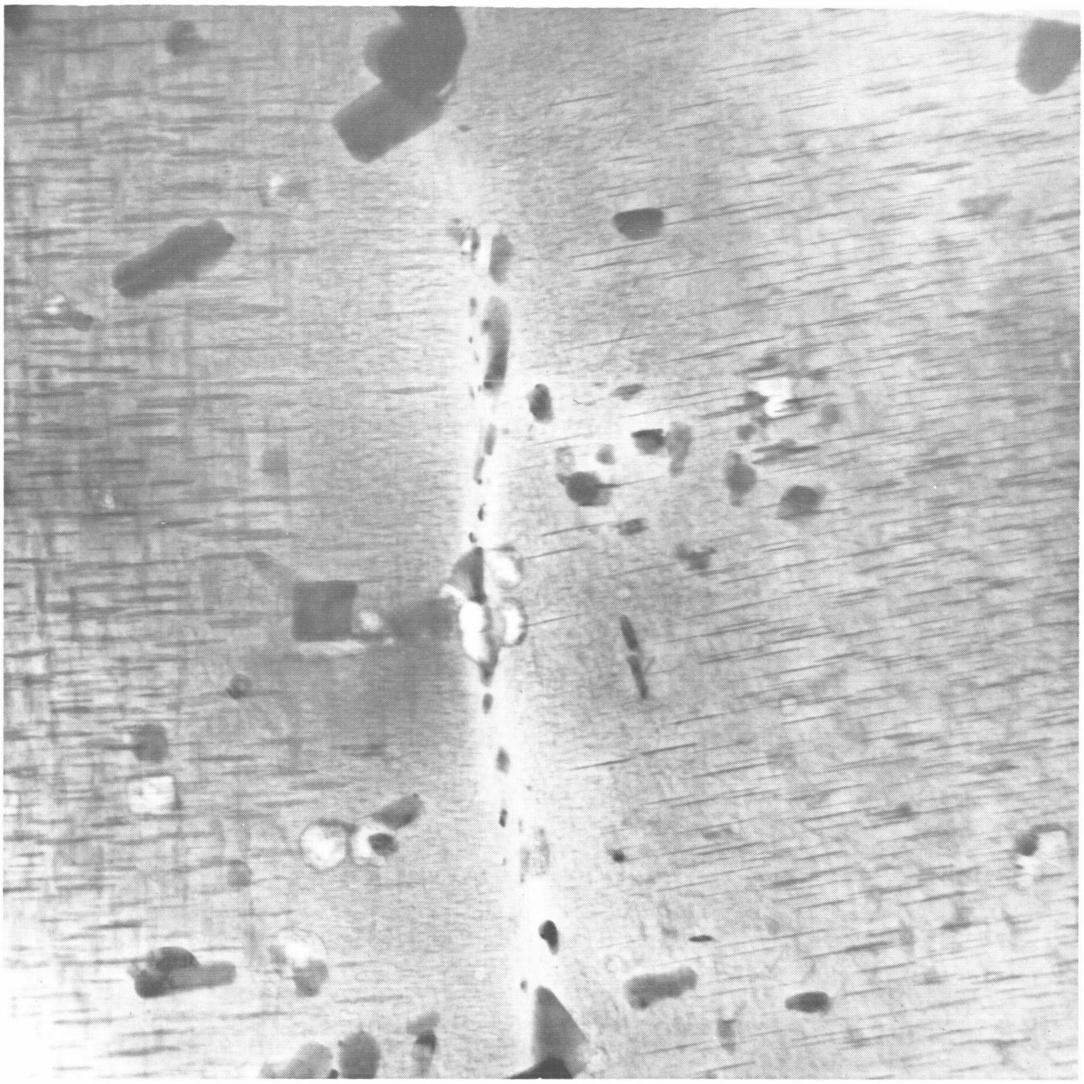


FIGURE 18 - EFFECT OF Mg CONCENTRATION ON THE TENSILE PROPERTIES OF X2021 (T62 TYPE TEMPER - .064 INCH SHEET).

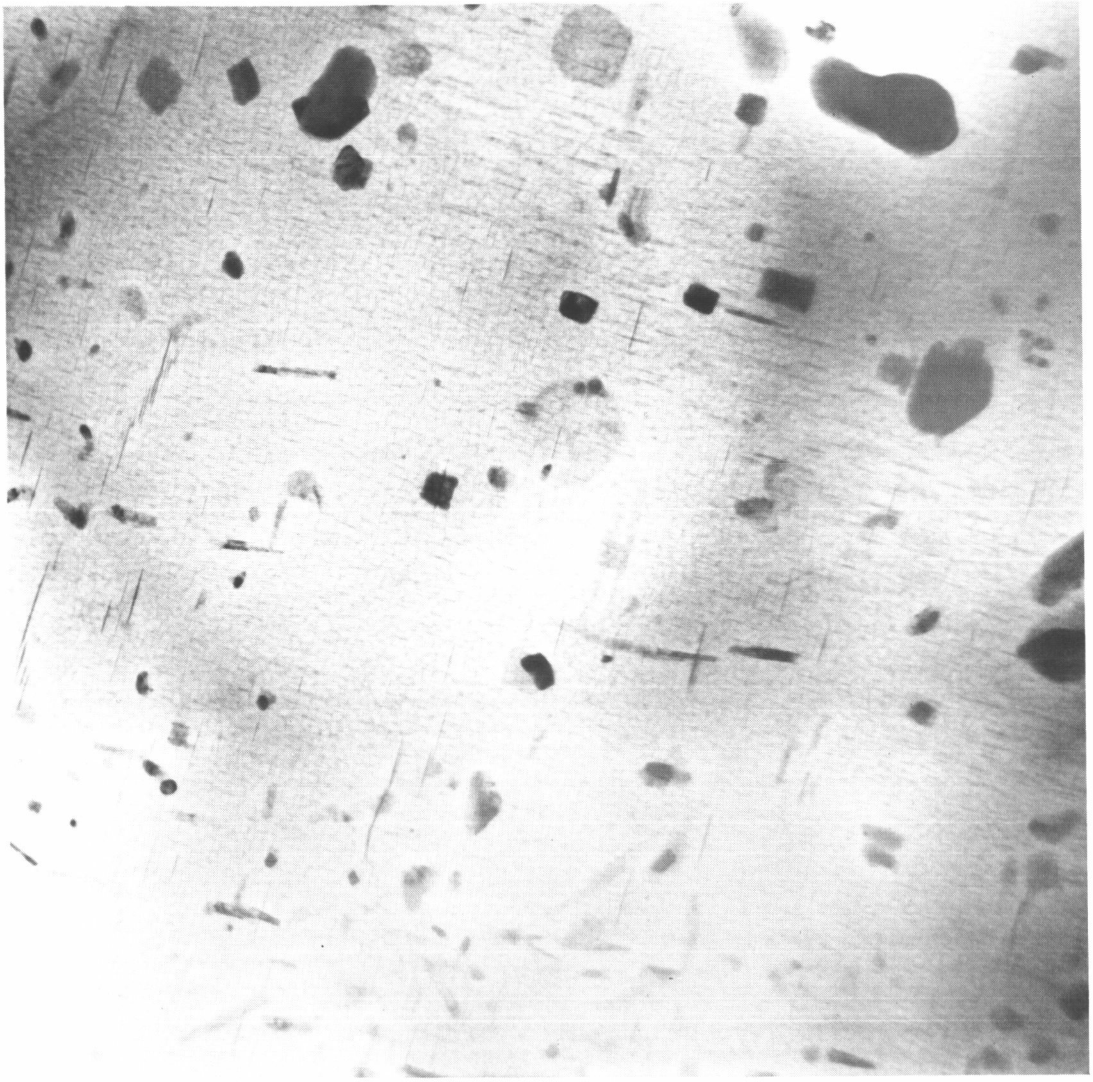
XFK25



S. NO. 326460A 50,000X

FIGURE 19 - TRANSMISSION ELECTRON MICROGRAPH OF X2021 ALLOY WITH .044% Mg. SAMPLE WAS COLD WATER QUENCHED AND AGED 48 HOURS AT 325 F.

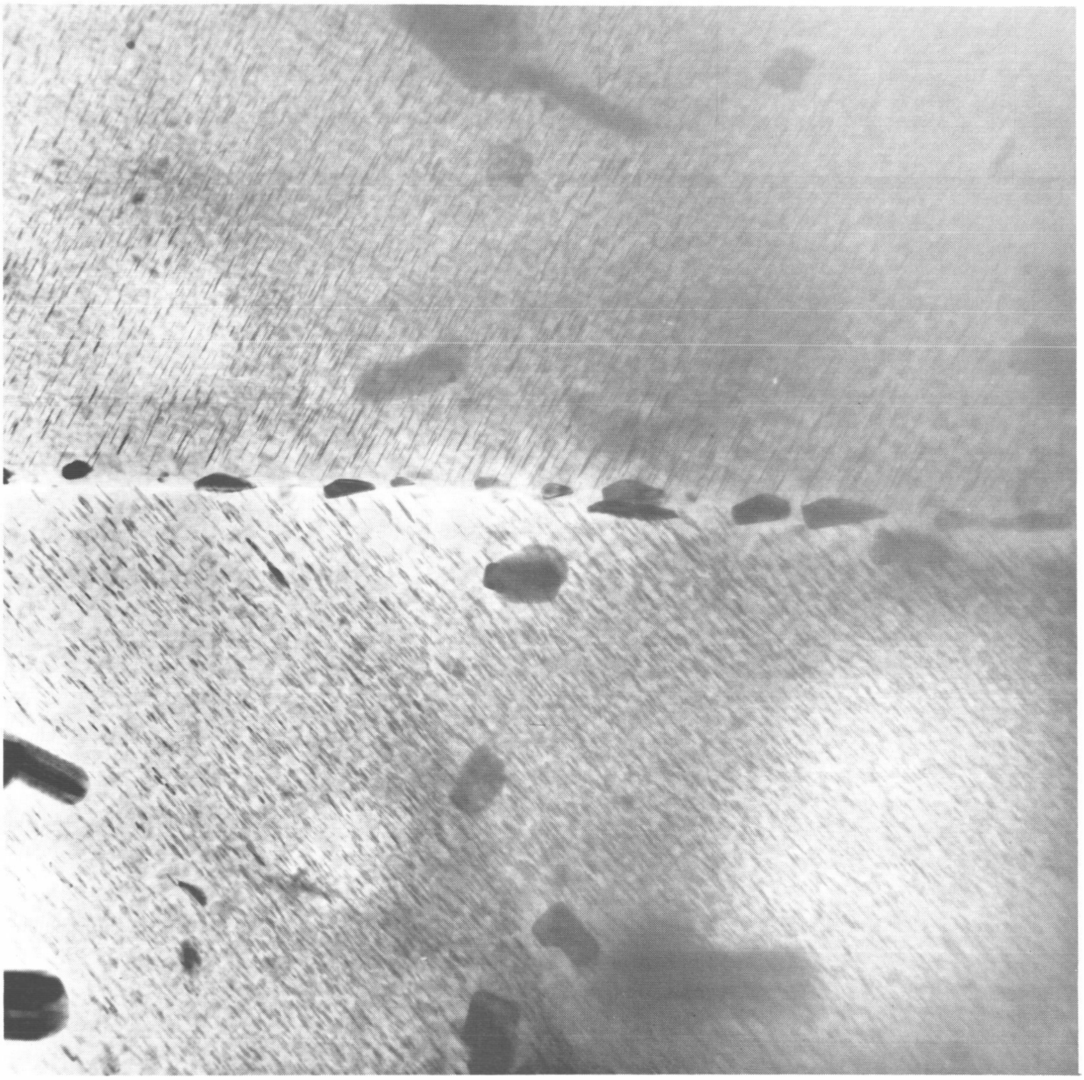
EM1005J



S. NO. 326461A 50,000X

FIGURE 20 - TRANSMISSION ELECTRON MICROGRAPH OF X2021 ALLOY WITH .079% Mg. SAMPLE WAS COLD WATER QUENCHED AND AGED 48 HOURS AT 325 F.

EM1008J



S. NO. 326459A 50,000X

FIGURE 21 - TRANSMISSION ELECTRON MICROGRAPH OF X2021 ALLOY WITH .002% Mg. SAMPLE WAS COLD WATER QUENCHED AND AGED 48 HOURS AT 325 F.

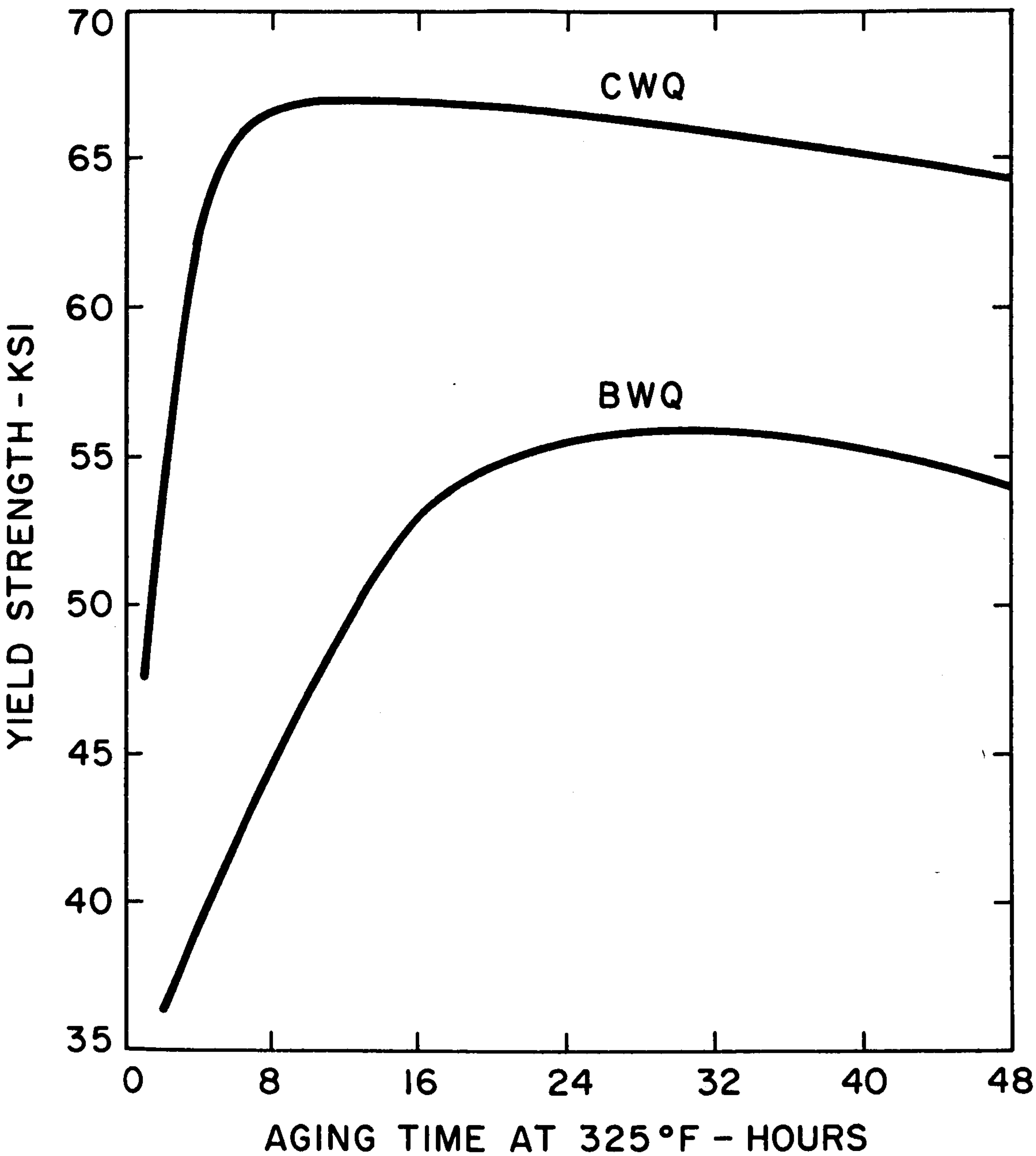
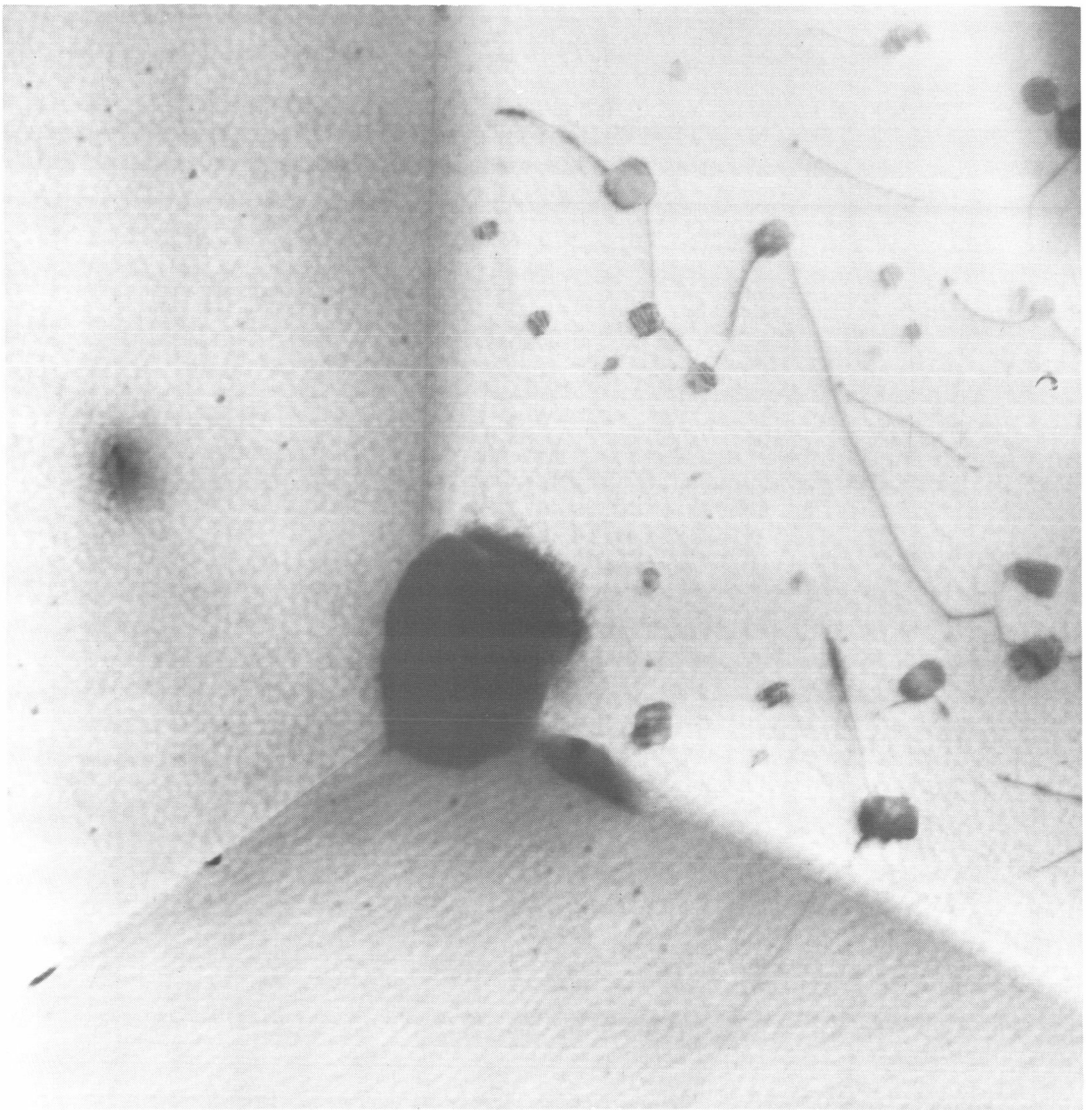


FIGURE 22 - EFFECT OF QUENCHING RATE ON THE 325 F AGING CURVE OF X2021 -T81 (0.125 INCH SHEET).

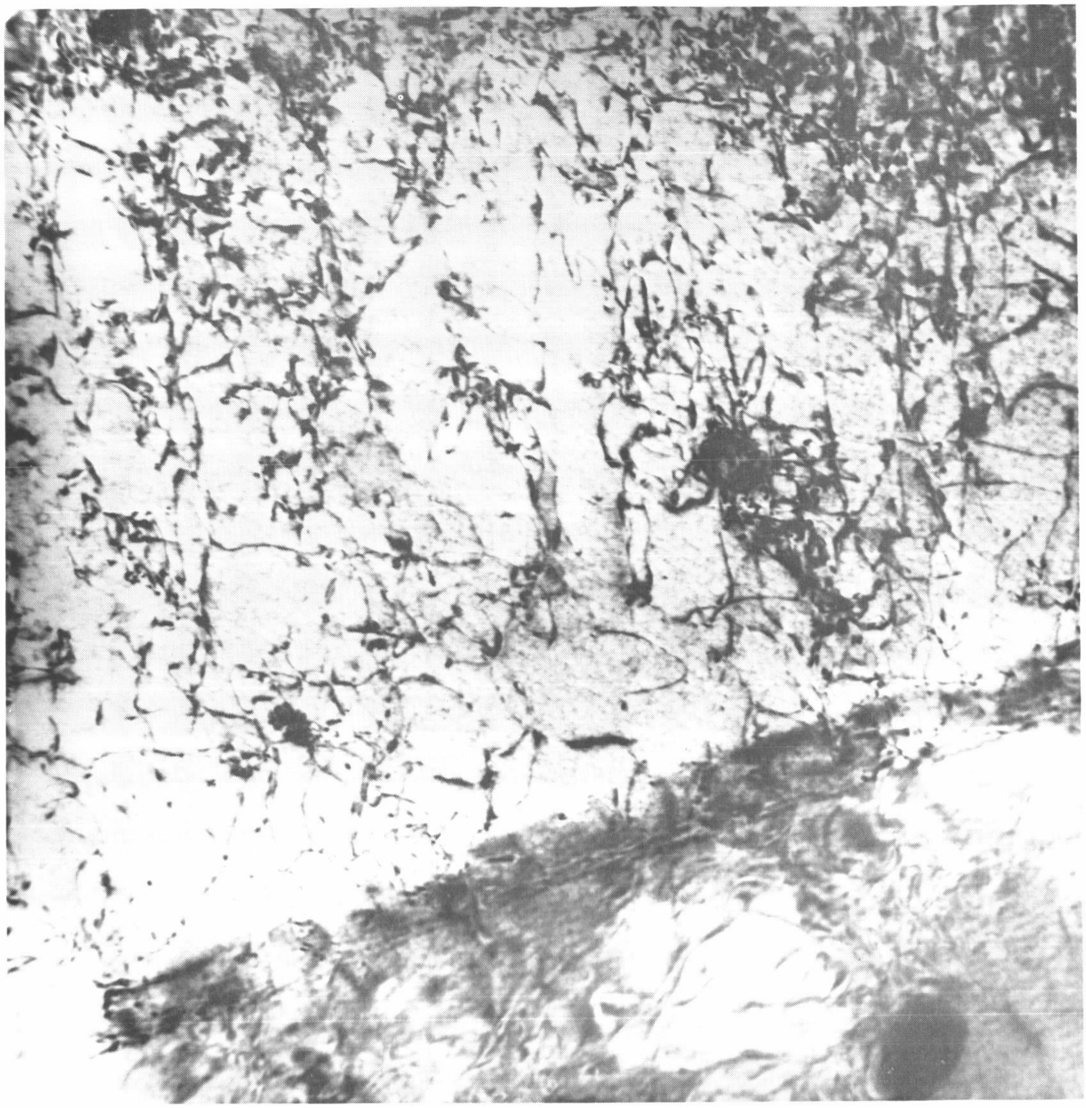
XFK26



S. NO. 343038-A1 50,000X

FIGURE 23 - TRANSMISSION ELECTRON MICROGRAPH OF X2021 COLD WATER QUENCHED.

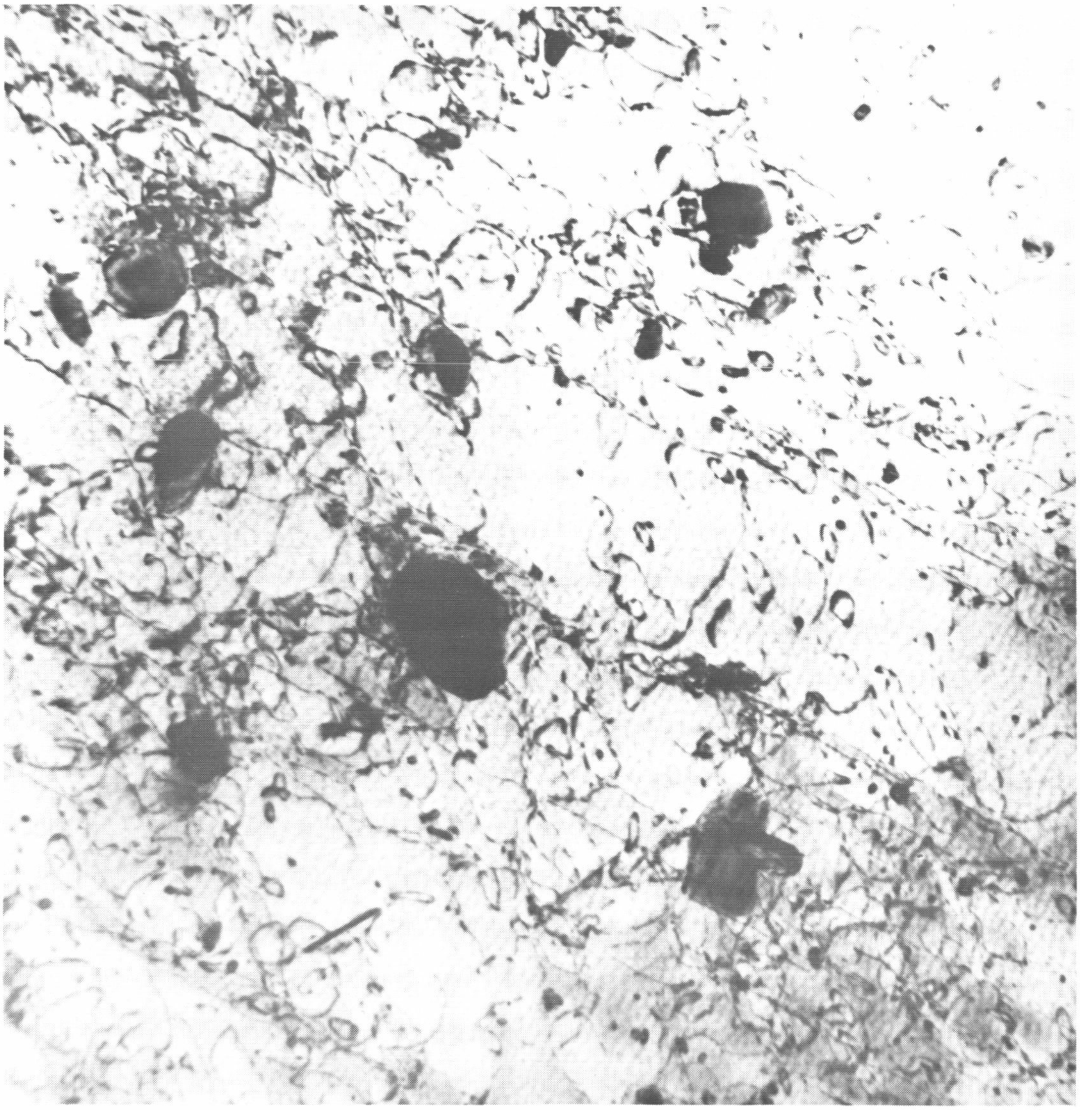
EM1055J



S. NO. 343038-B2 50,000X

FIGURE 24 - TRANSMISSION ELECTRON MICROGRAPH OF X2021 COLD WATER QUENCHED AND STRETCHED 1.5%.

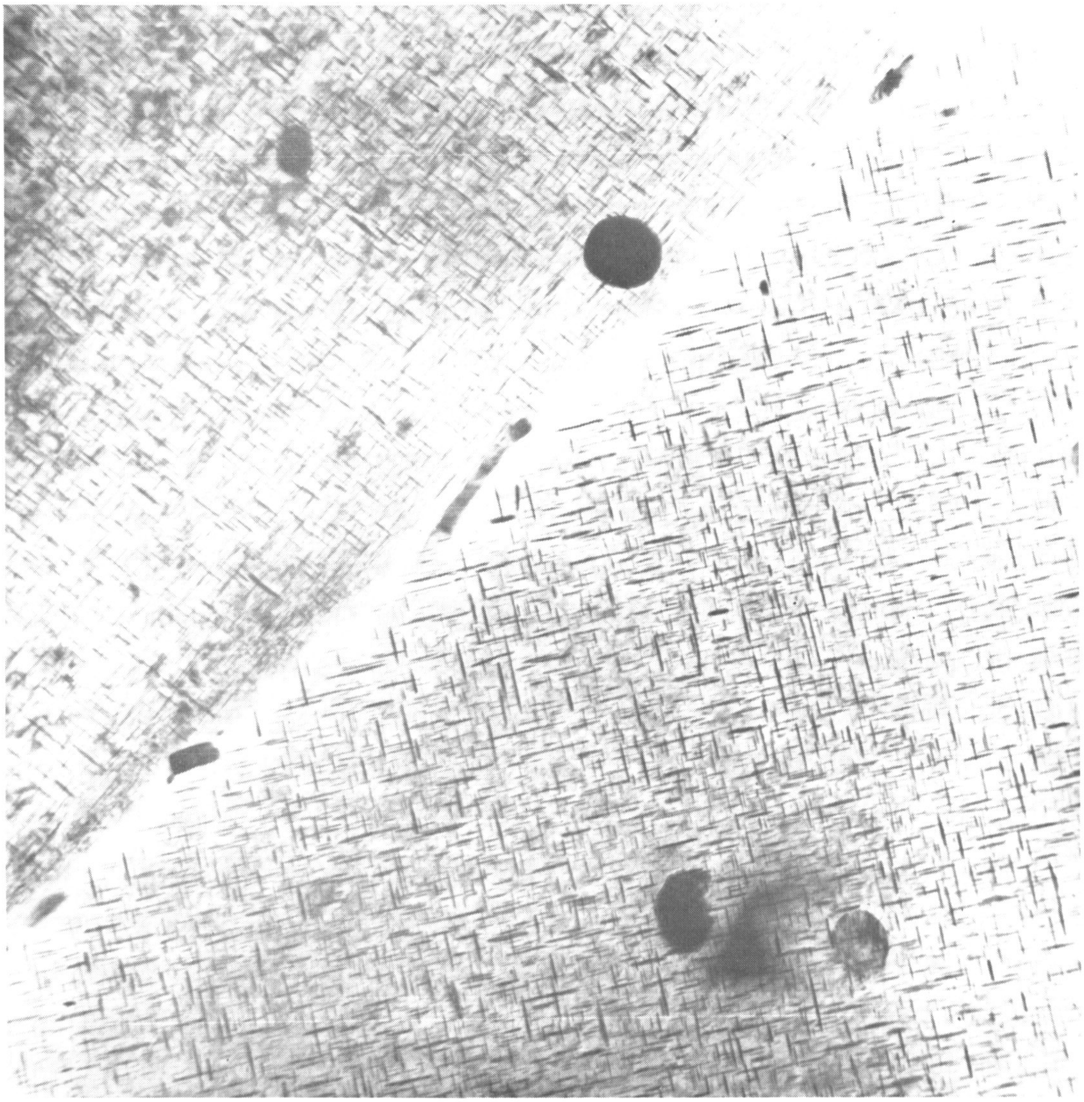
EM1060J



S. NO. 343038-C2 50,000X

FIGURE 25 - TRANSMISSION ELECTRON MICROGRAPH OF X2021 COLD WATER QUENCHED, PRE-AGED 1 HOUR AT 300 F AND STRETCHED 1.5%.

EM1068J



S. NO. 343038-C4 50,000X

FIGURE 26 - TRANSMISSION ELECTRON MICROGRAPH OF X2021 COLD WATER QUENCHED, PRE-AGED 1 HOUR AT 300 F, STRETCHED 1.5% AND AGED 16 HOURS AT 300 F.

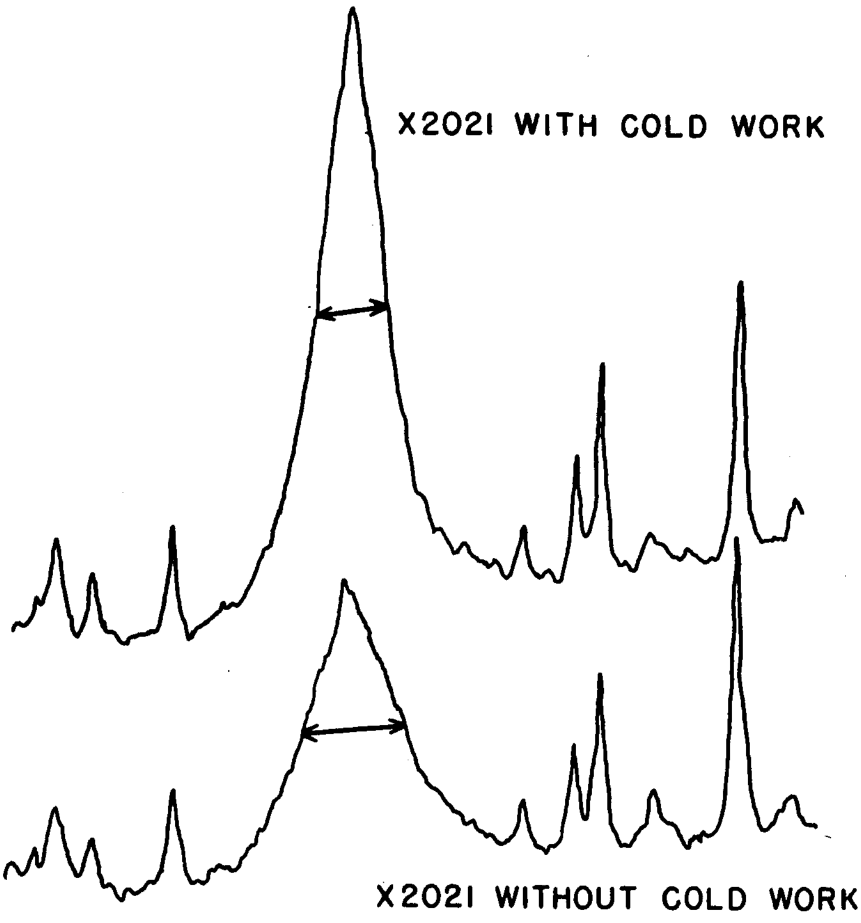


FIGURE 27 - DENSITOMETER TRACES OF X-RAY DIFFRACTION PATTERNS SHOWING THE EFFECT OF COLD WORK ON THE HALF-HEIGHT WIDTH OF THE θ' (101) DIFFRACTION PEAK.

XFK27

XFK28

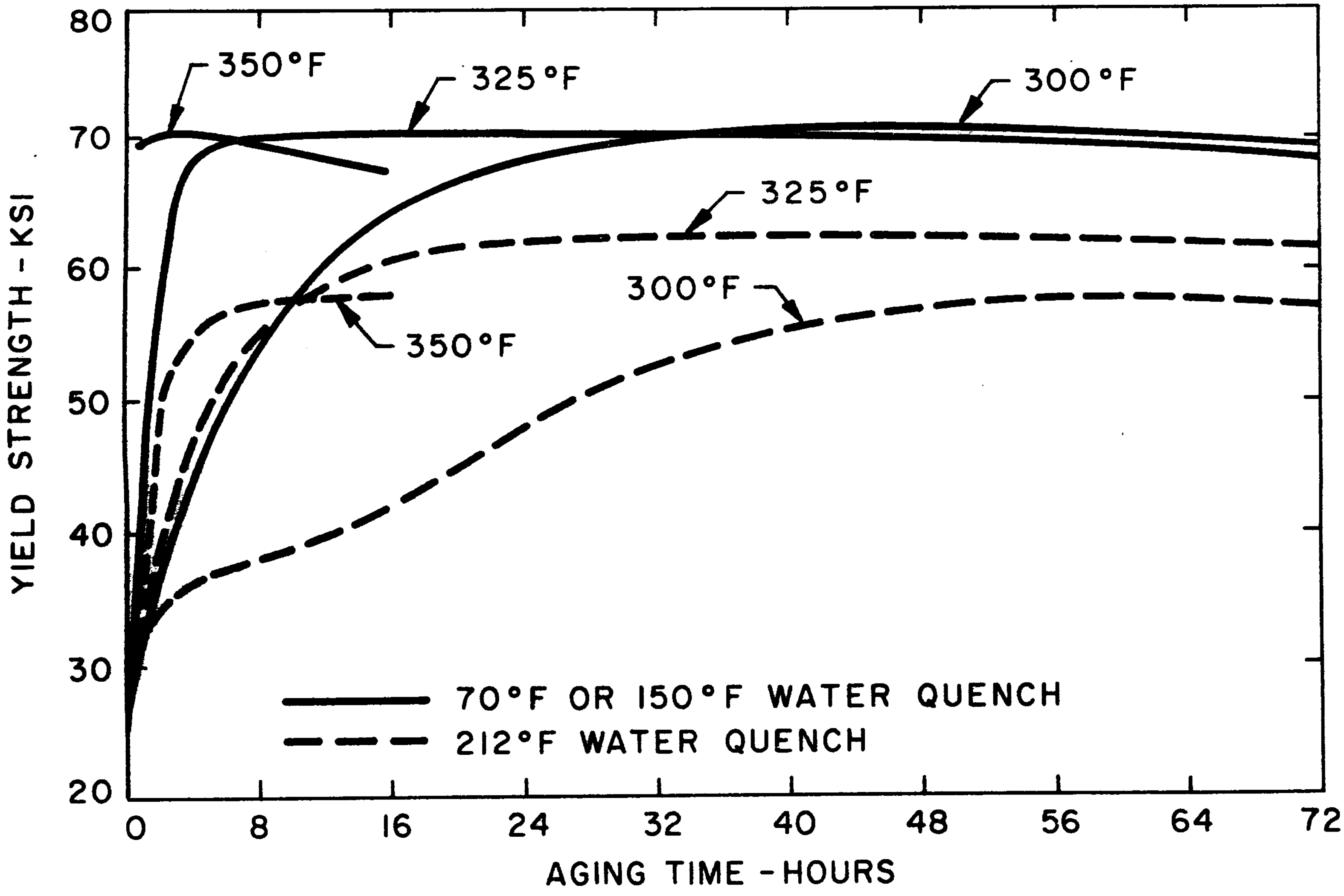


FIGURE 28 - EFFECT OF AGING TEMPERATURE AND QUENCHING RATE ON THE AGING CURVE OF X2021-T62 (0.125 INCH SHEET).

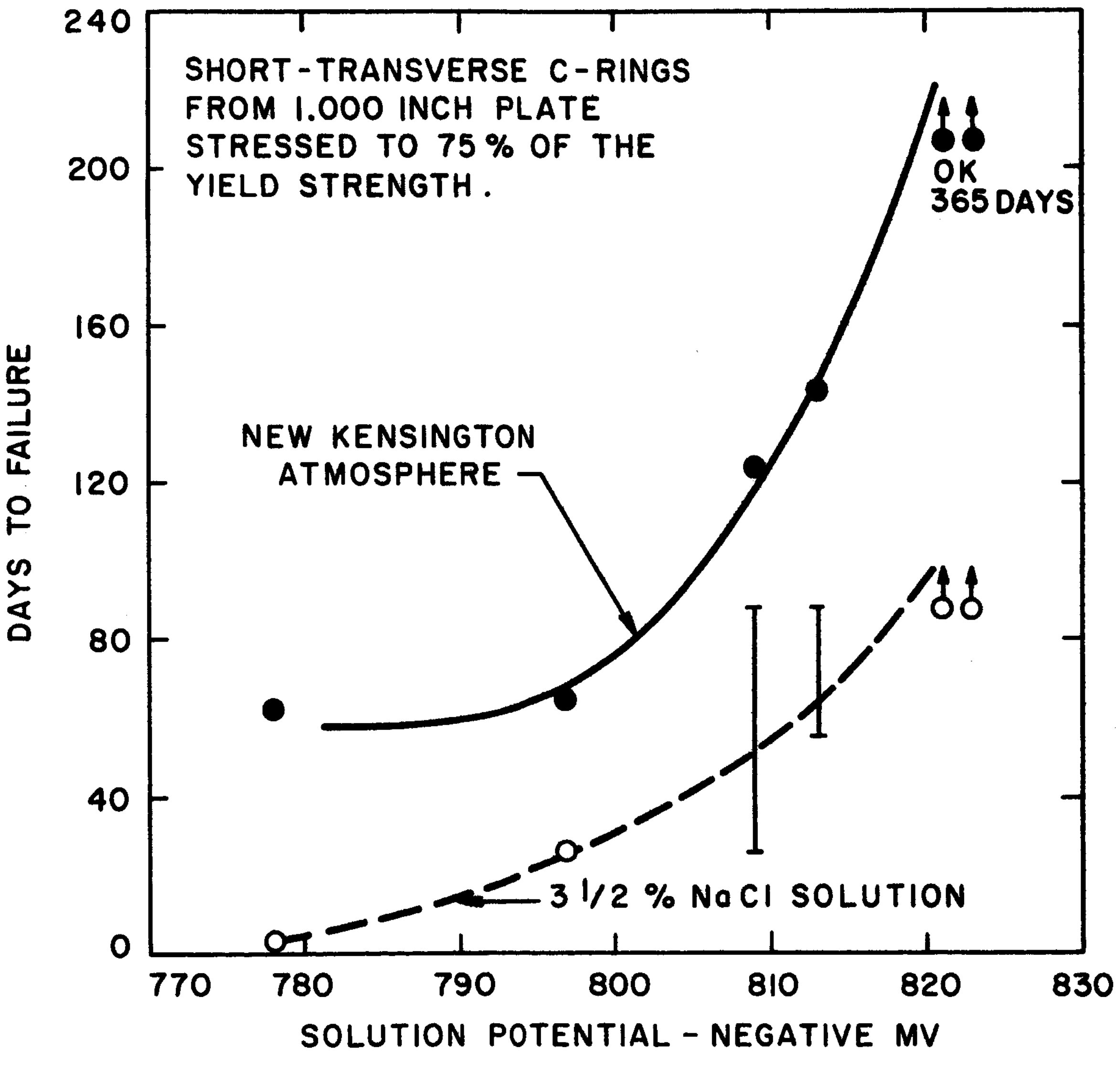


FIGURE 29 - RELATION BETWEEN SOLUTION POTENTIAL AND STRESS CORROSION RESISTANCE OF X2021. SAMPLES AGED 4 TO 96 HOURS AT 325 F.

XFK29

S. NO. 294776-4 50,000X

FIGURE 30 - TRANSMISSION ELECTRON MICROGRAPH OF X2021 PLATE AGED 4 HOURS AT 325°F.

EM717J

S. NO. 294776-9 50,000X

FIGURE 31 - TRANSMISSION ELECTRON MICROGRAPH OF X2021 PLATE AGED 96 HOURS AT 325°F.

EM727J

XFK30

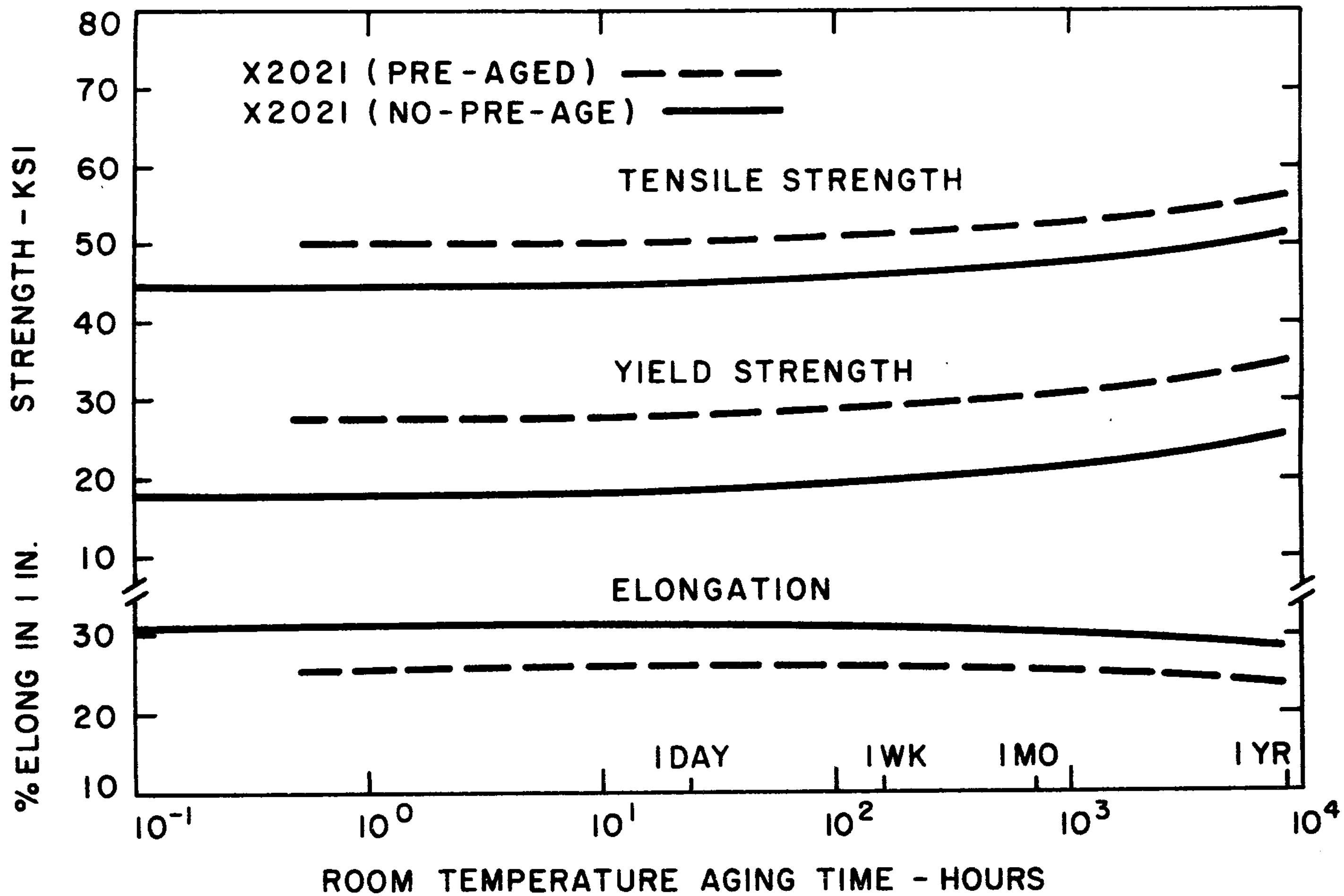
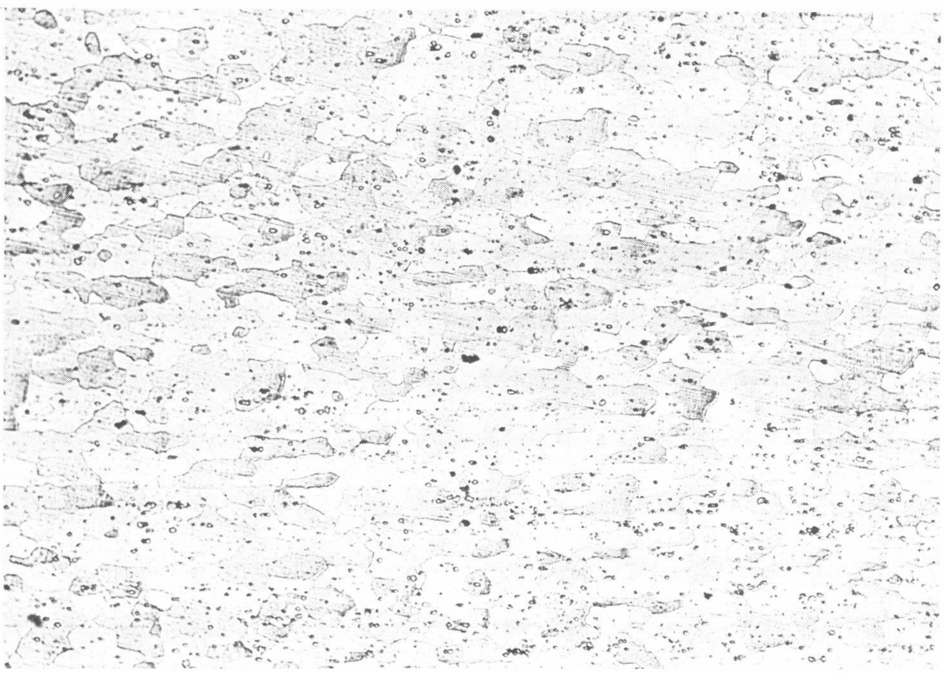


FIGURE 32 - ROOM TEMPERATURE AGING OF X2021 0.500 INCH PLATE.

1.000 IN. PLATE (S. NO. 327102)



0.064 IN. SHEET (S. NO. 326889)

163611A,13AJ

FIGURE 33 - MICROSTRUCTURE OF X2021-T81 SHEET AND PLATE. (LONGITUDINAL SECTION - 100X MAG. - KELLER'S ETCH).

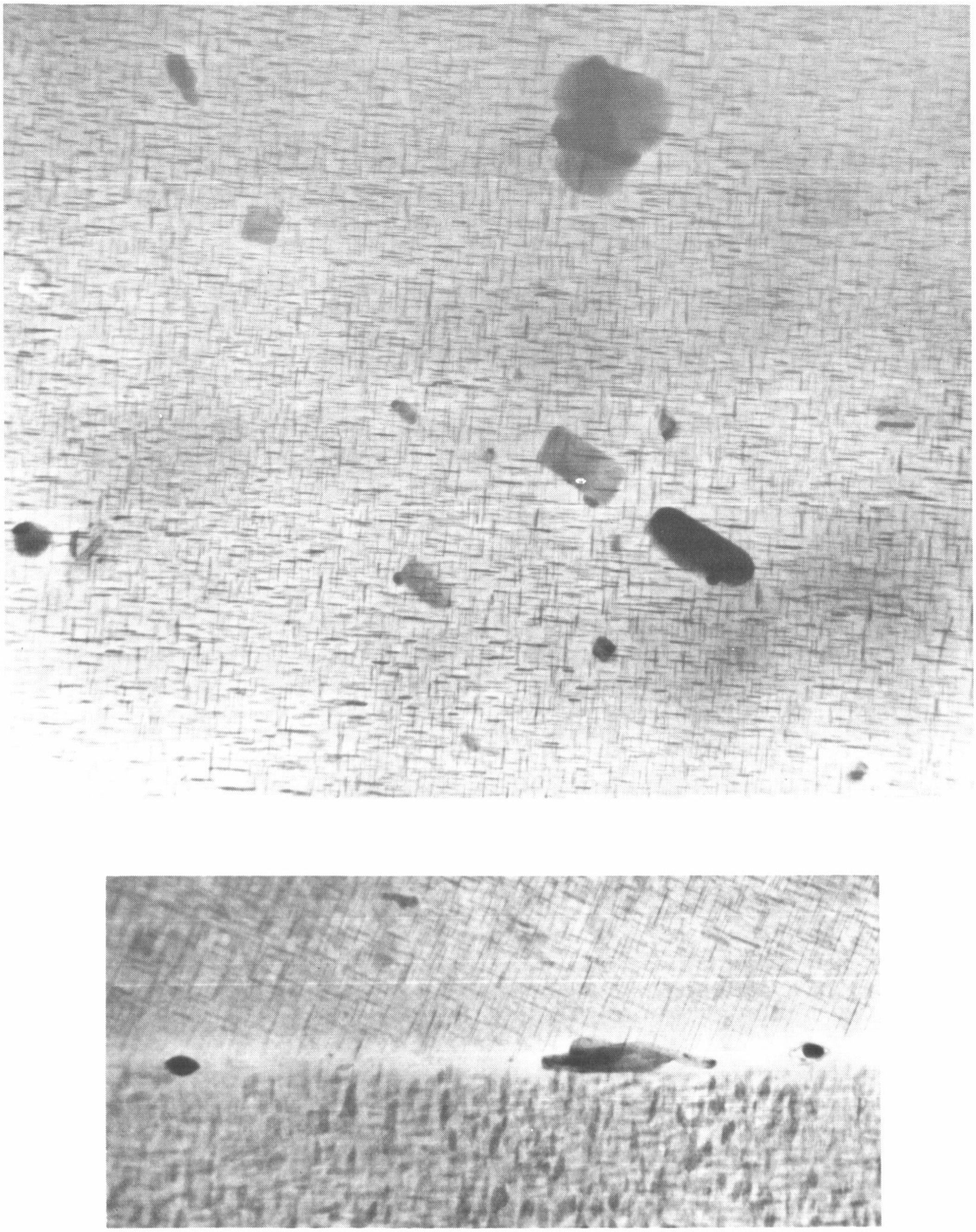


FIGURE 34 - TRANSMISSION ELECTRON MICROGRAPHS OF CENTER OF 1.000 IN. PLATE OF X2021-T81 (S. NO. 327102 - 50,000X).

EM939,941J

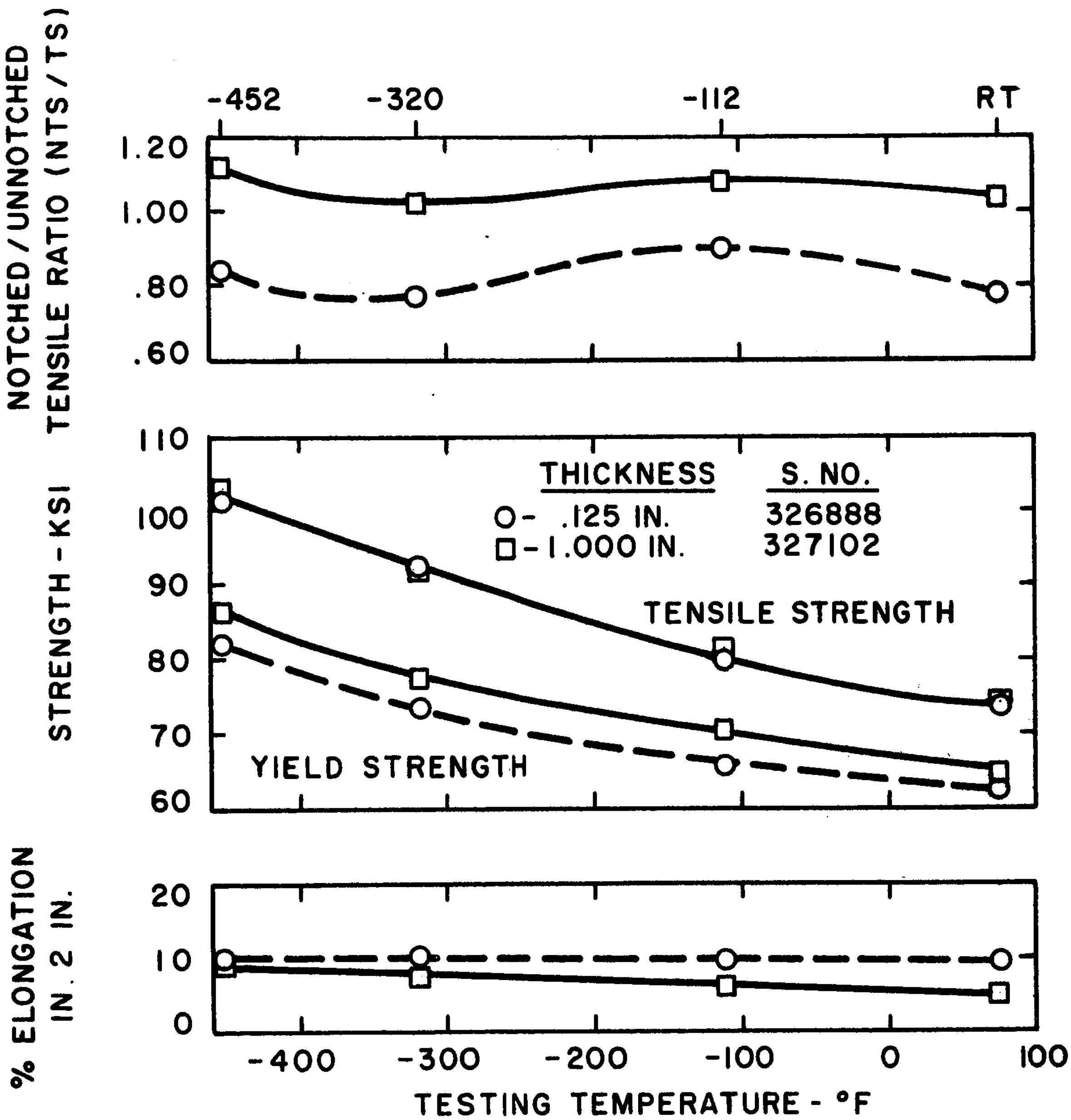


FIGURE 35 - TENSILE AND NOTCH-TENSILE PROPERTIES OF PLANT FABRICATED X2021-T81 SHEET AND PLATE. (EDGE NOTCHED SPECIMENS FOR SHEET-NOTCHED ROUND SPECIMENS FOR PLATE, $K_t = 10$)

XFK31

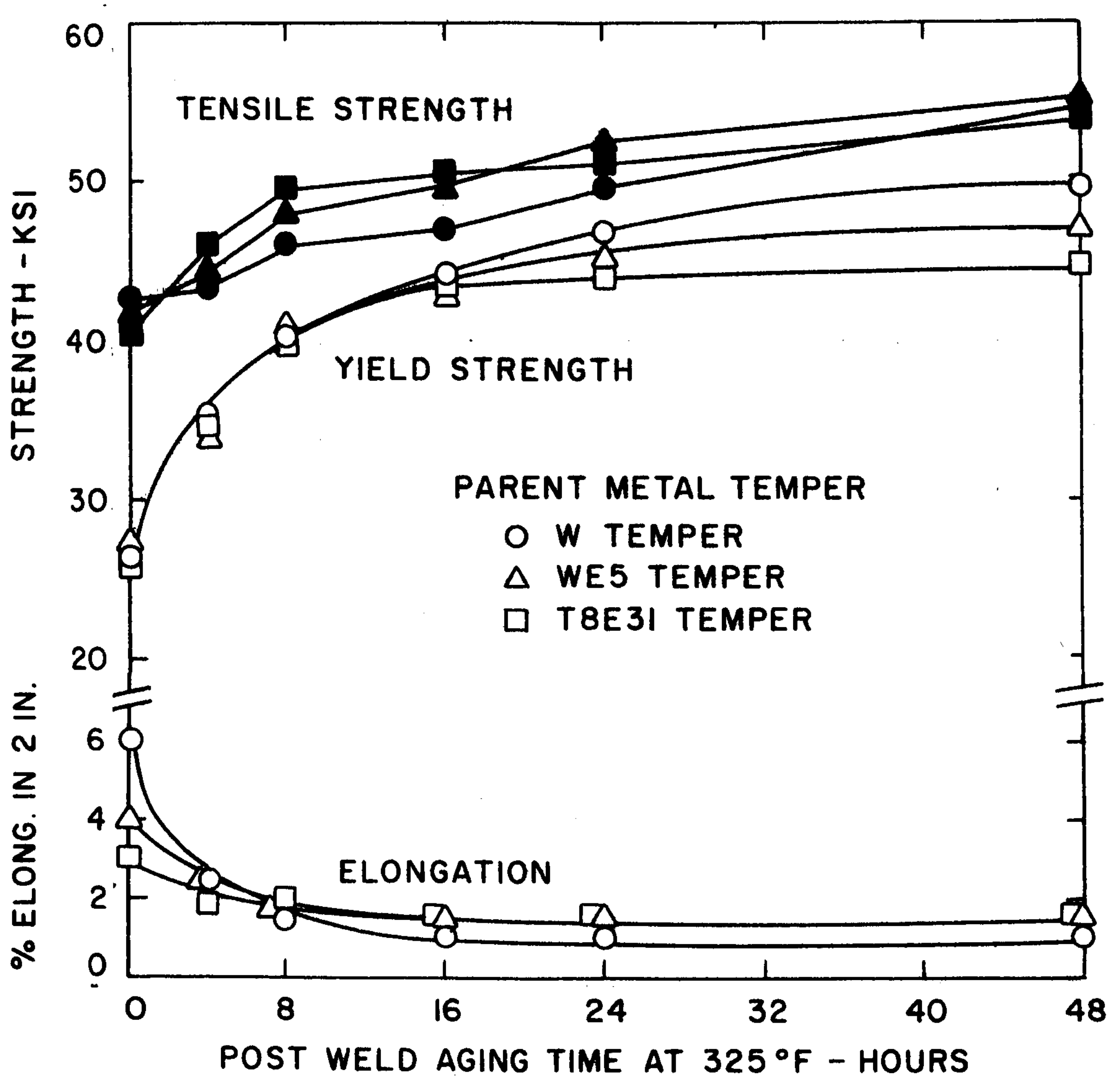
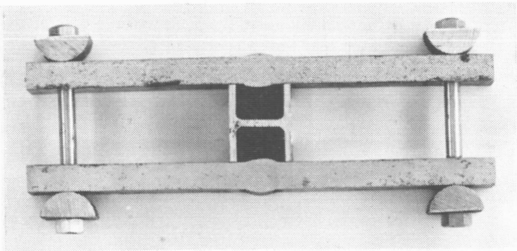


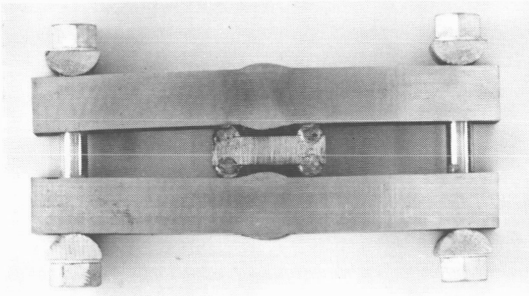
FIGURE 36 - EFFECT OF PARENT METAL TEMPER AND POST-WELD AGING TIME ON THE WELD PROPERTIES OF X2021.

XFK32

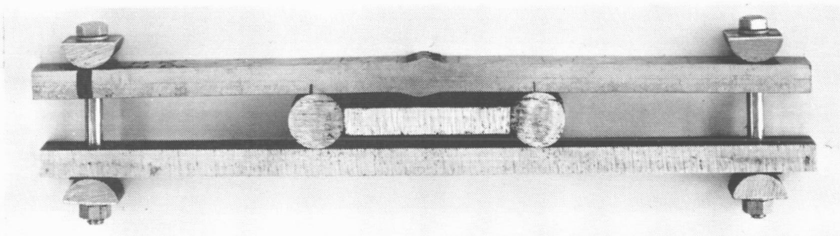
A



B



C



D

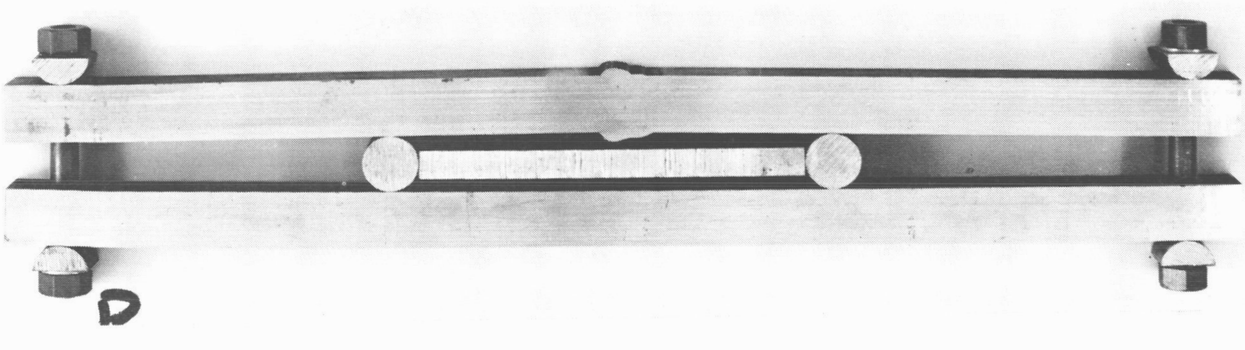
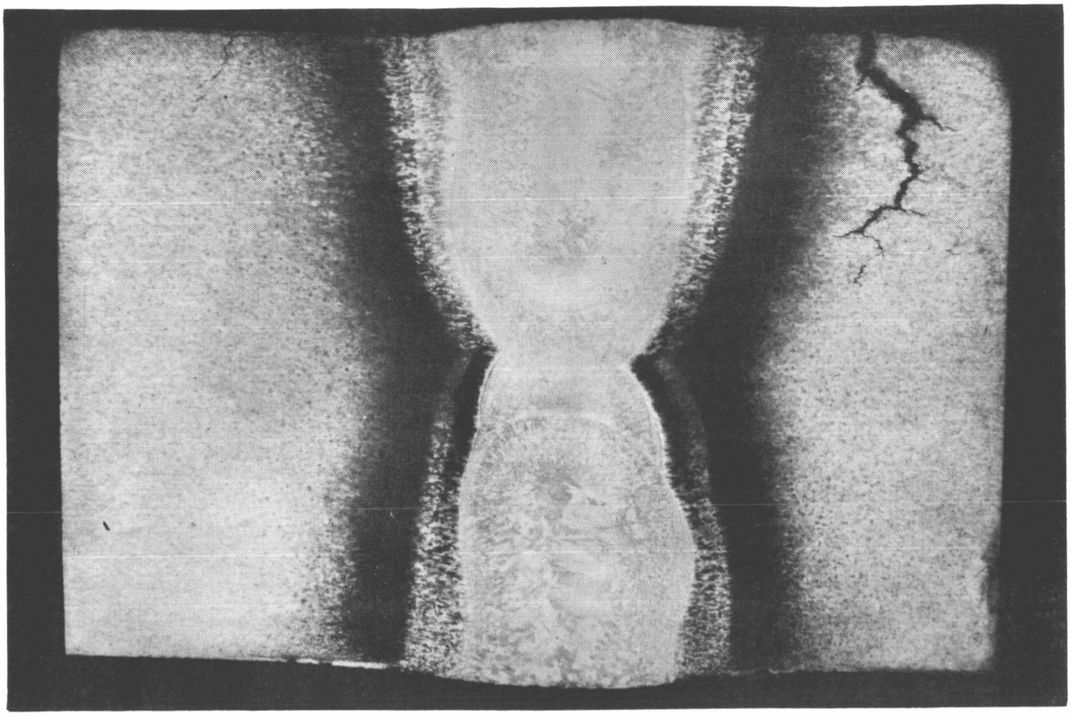
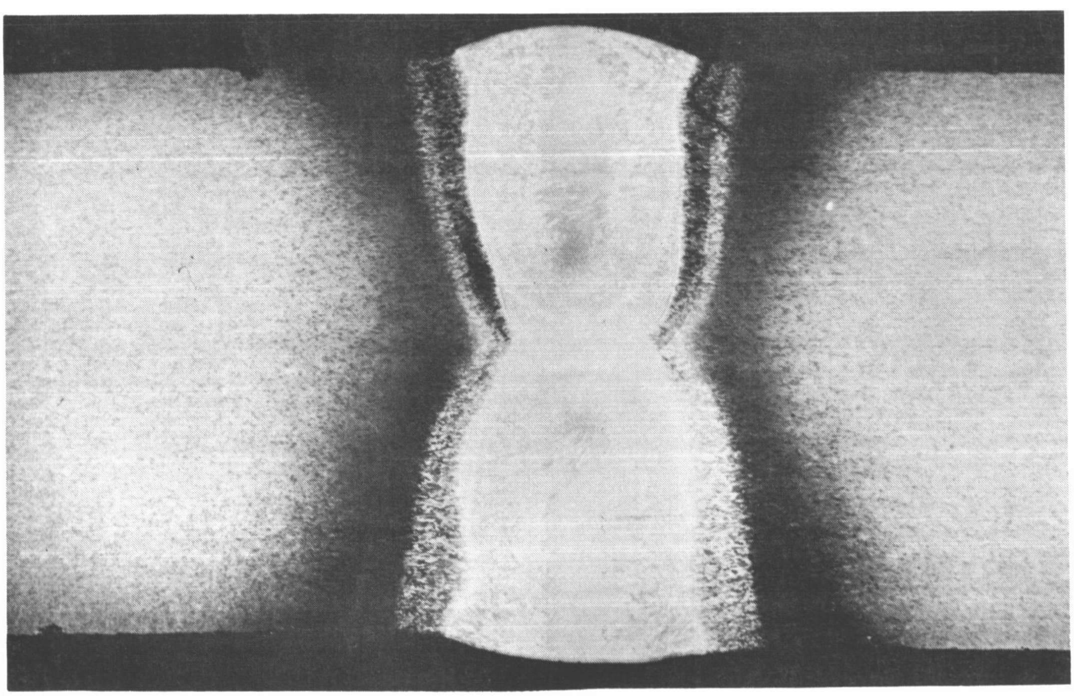


FIGURE 37 - ASSEMBLIES FOR STRESS CORROSION TESTING OF WELDS.



S. NO. 292666-B1-S12 Root Side in Tension



S. NO. 292666-B1-S15 Face Side in Tension

161305AJ
160517AJ

FIGURE 38 - STRESS CORROSION CRACKING OF TIG WELDED 1.0 INCH PLATE OF X2021-T81. LOCATION OF CRACK IS DEPENDENT ON THE SIDE OF THE WELDMENT STRESSED IN TENSION. (Keller's Etch - 3X Mag.)

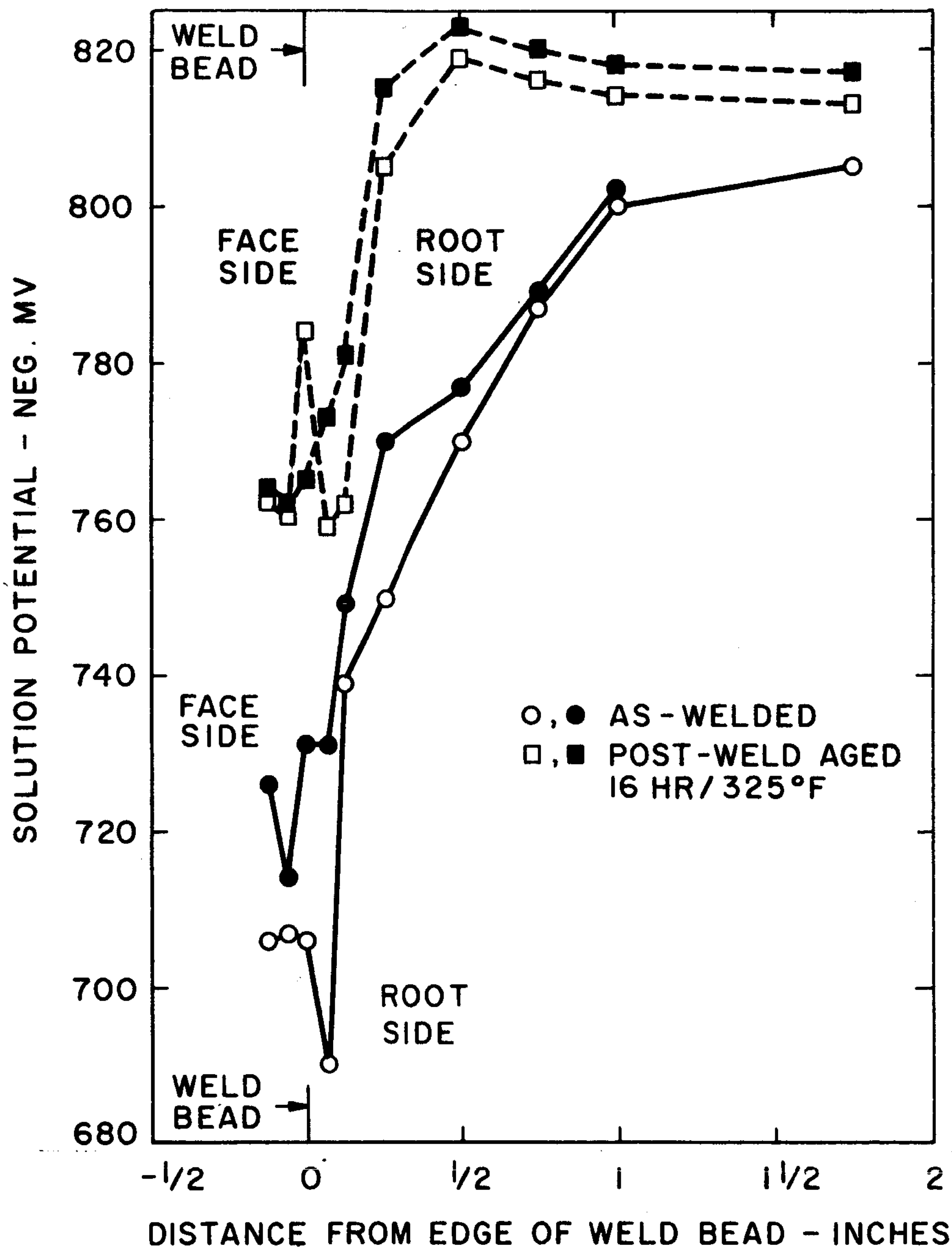
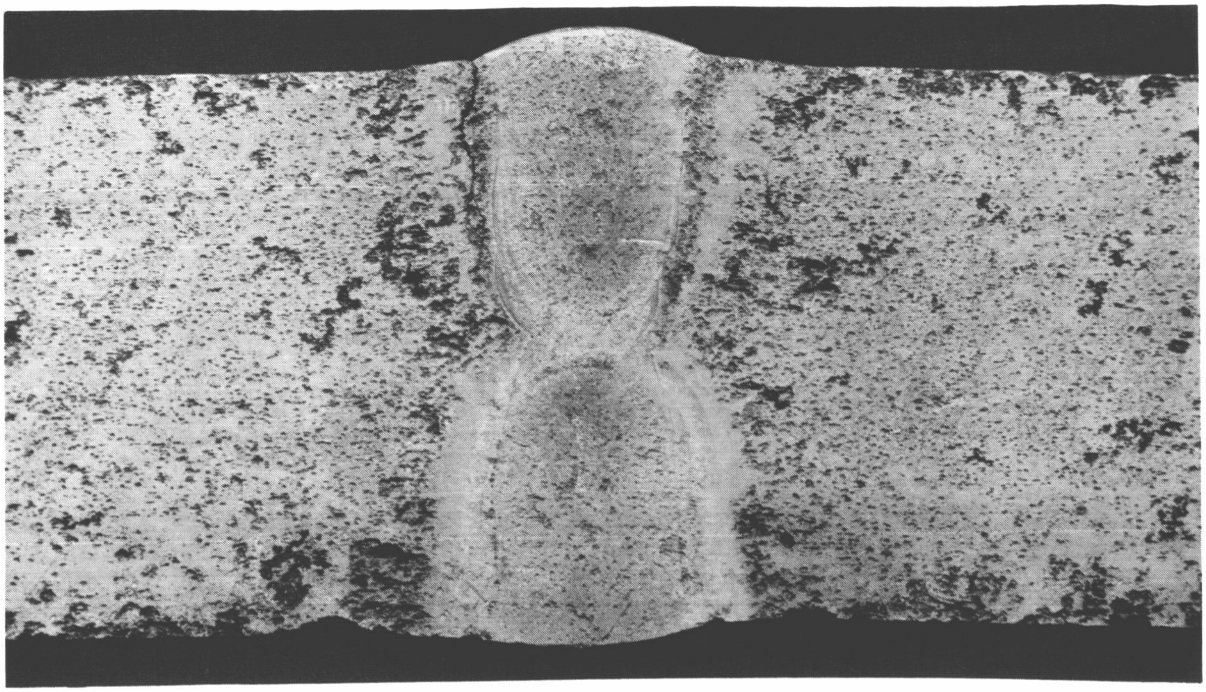
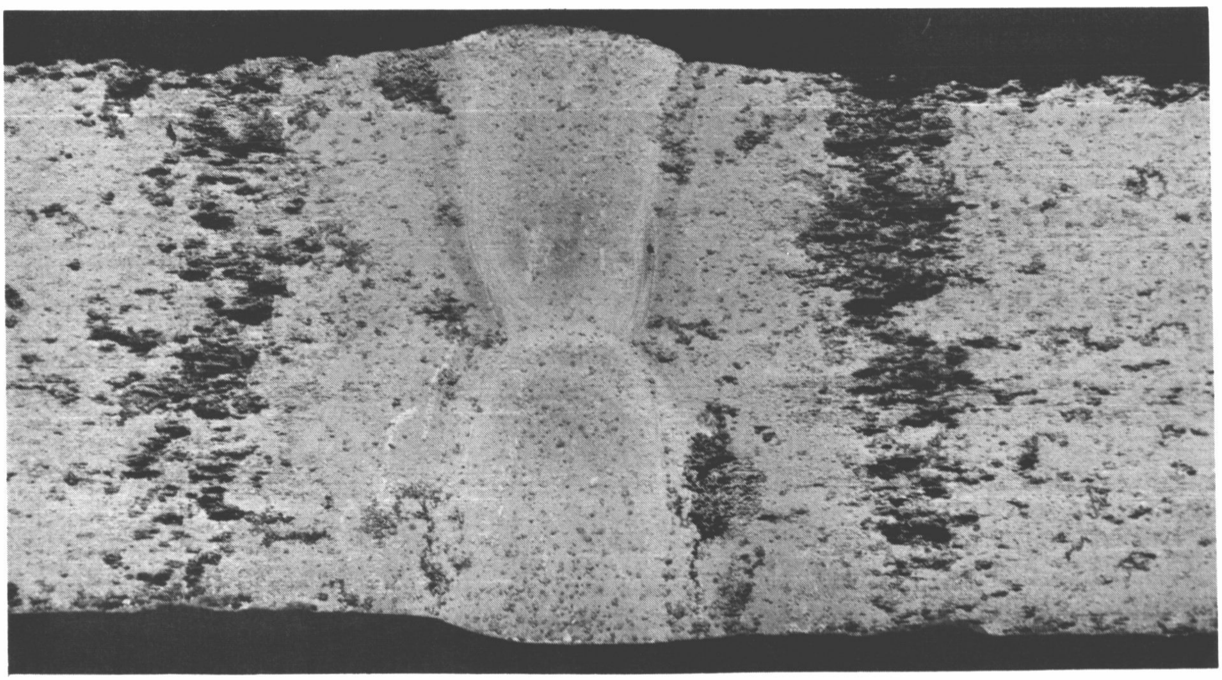


FIGURE 39 - SOLUTION POTENTIAL SURVEYS OF TIG WELDED 1.0 INCH PLATE OF X2021-T81.

XFK33



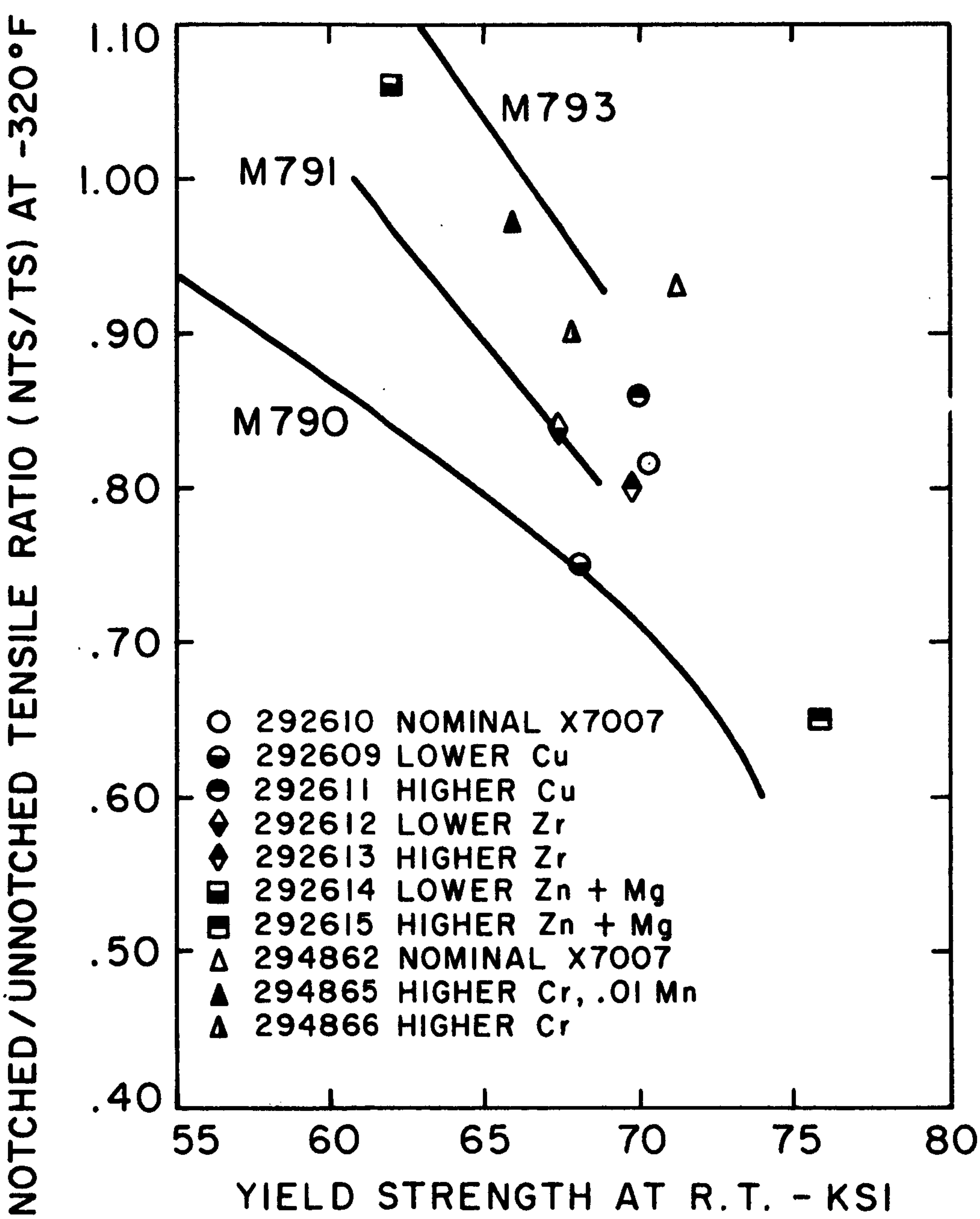
S. NO. 292666-B1-S15 As-Welded



S. NO. 292666-B2-S11 Post-Weld Aged 16 Hours at 325F

160515 AJ
160516 AJ

FIGURE 40 - CORROSION OF TIG WELDED 1.0 INCH PLATE OF X2021 AFTER EXPOSURE TO 3 1/2% NaCl SOLUTION BY ALTERNATE IMMERSION FOR ONE YEAR. (CLEANED IN NITRIC ACID AFTER EXPOSURE - 3X MAG.)



XFK34

FIGURE 41 - COMPARISON OF DATA FOR X7007 WITH PREVIOUS RESULTS ON M790, M791 AND M793 ALLOYS. (ITEMS 292610-615 WERE 0.525 INCH PLATE AGED 48 HOURS AT 225°F; ITEMS 294862, 865 AND 866 WERE 1.000 INCH PLATE AGED 16 HOURS AT 275°F - NOTCHED ROUND SPECIMENS, $K_t = 10$.)

XFK35

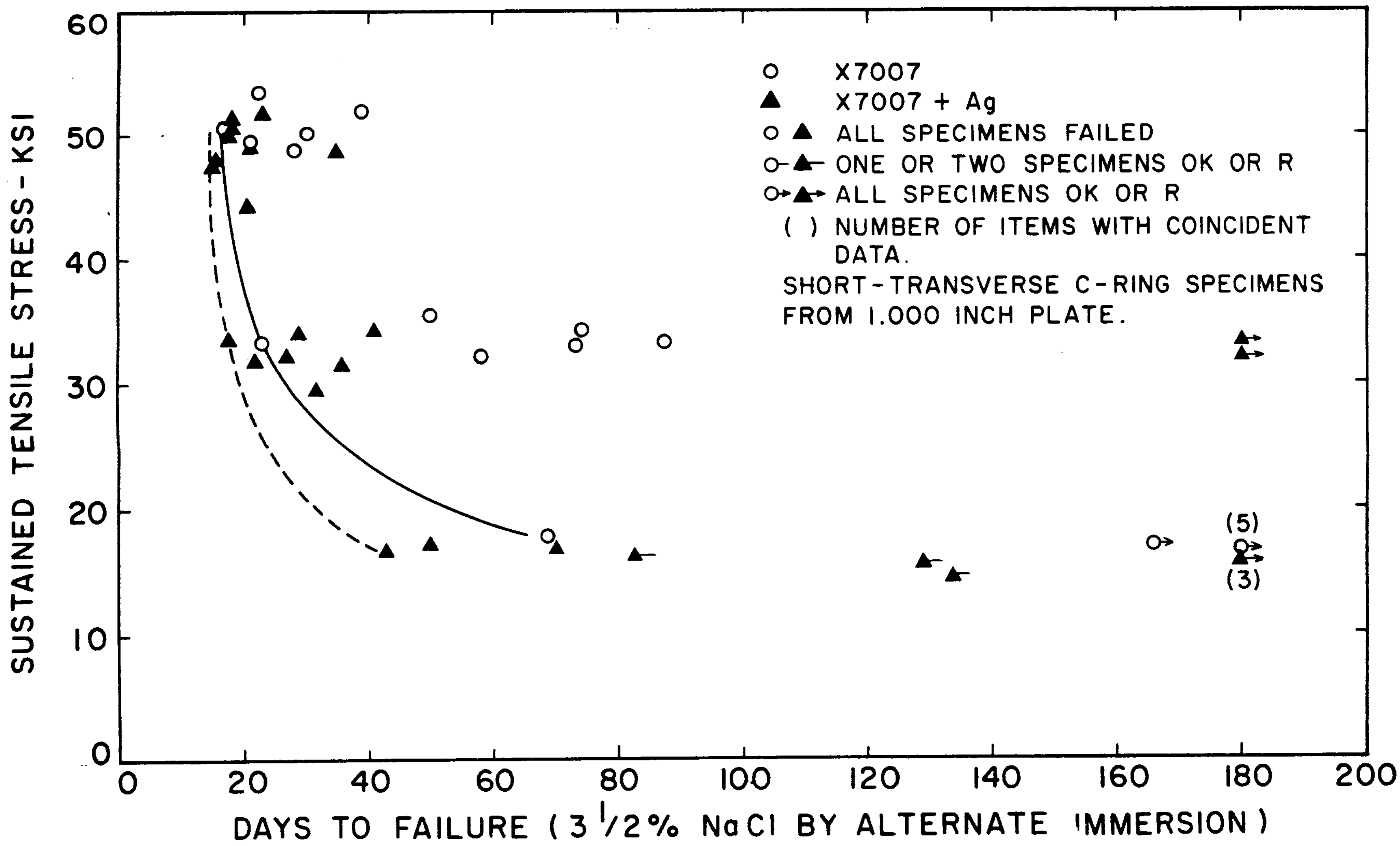


FIGURE 42 - STRESS-CORROSION RESISTANCE OF X7007 ALLOY AND X7007 + Ag ALLOY MODIFICATIONS.

XFK36

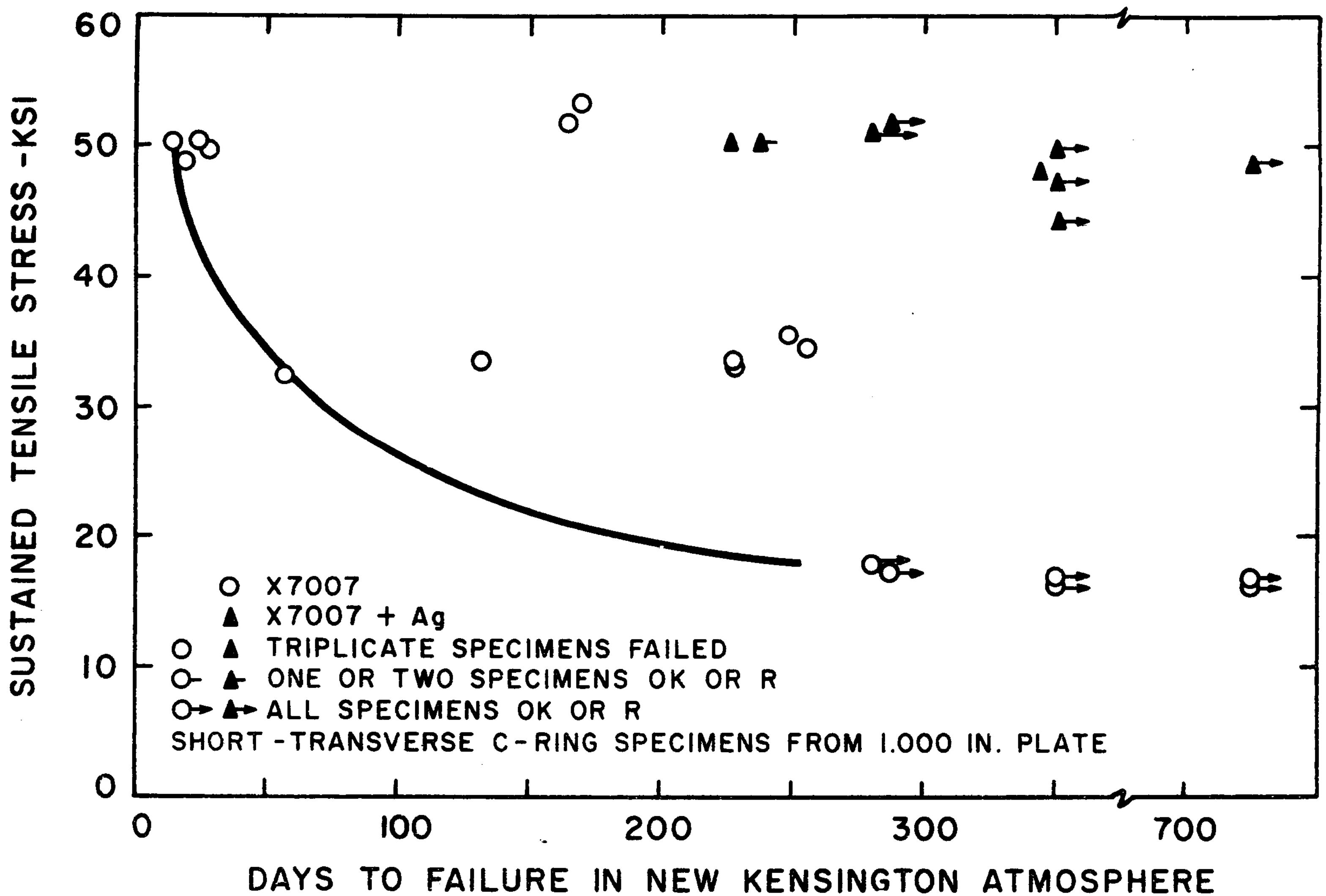


FIGURE 43 - STRESS CORROSION RESISTANCE OF X7007 ALLOY AND X7007 + Ag ALLOY MODIFICATIONS.

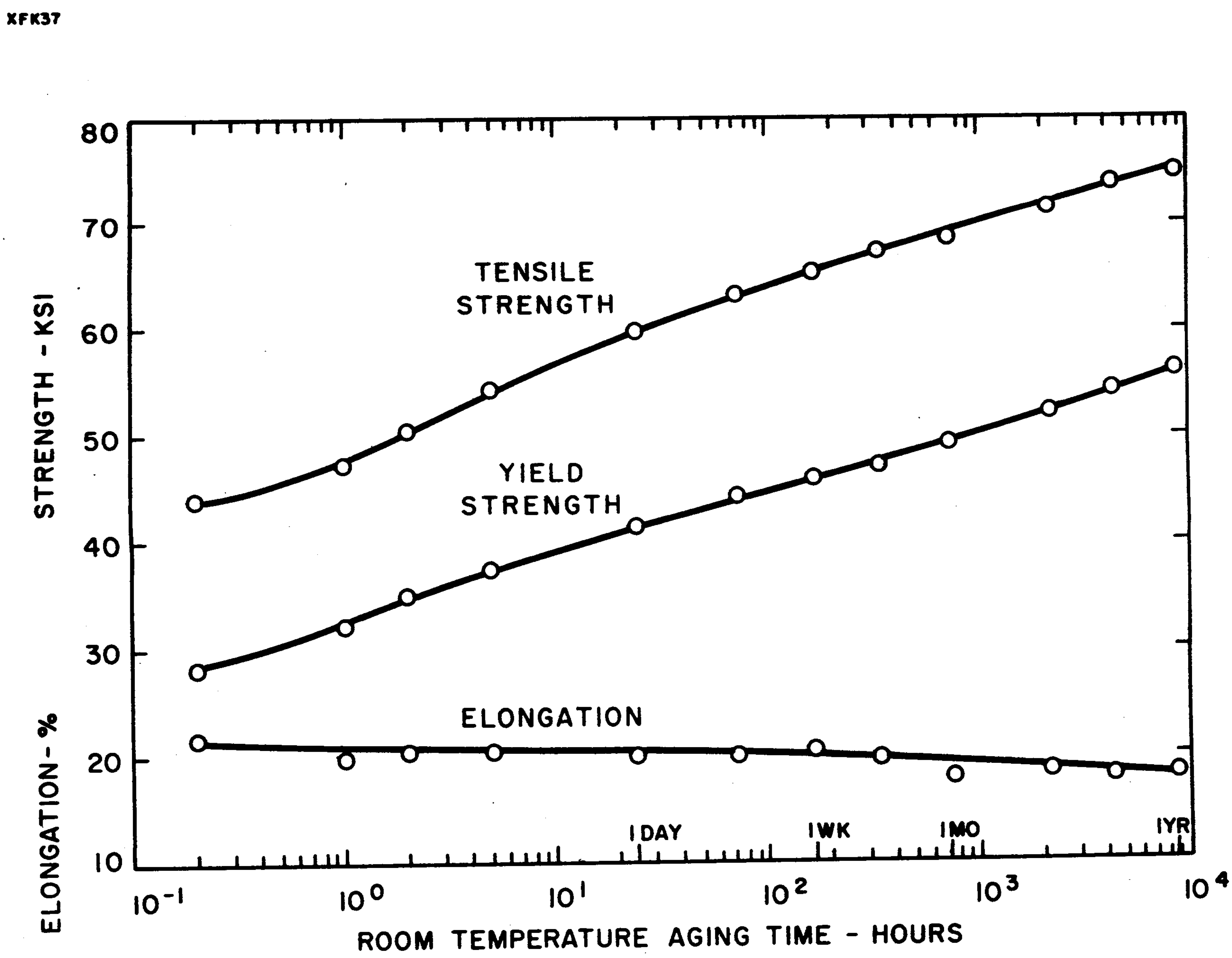


FIGURE 44 - ROOM TEMPERATURE AGING OF X7007 0.064 INCH SHEET.

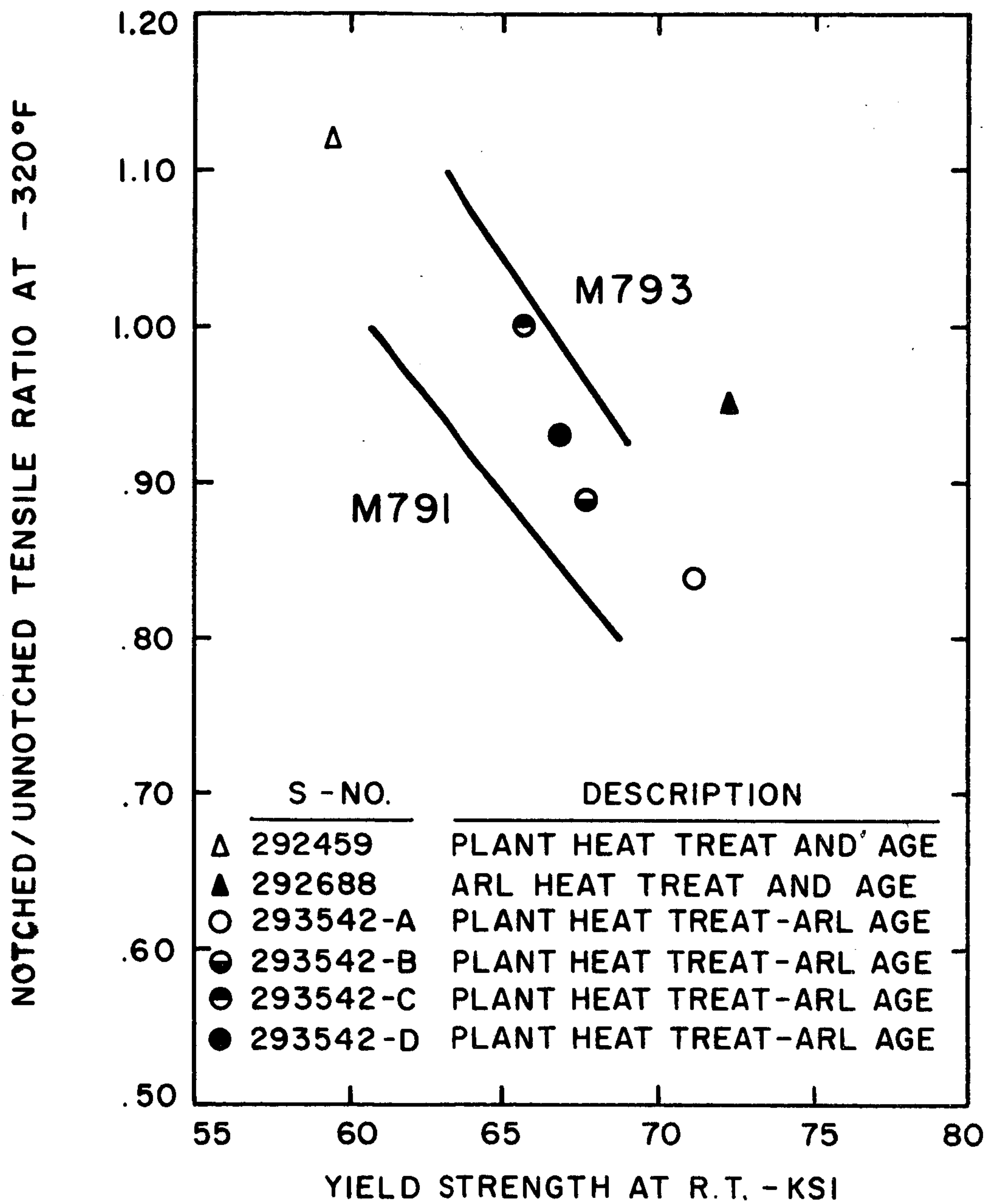


FIGURE 45 - NOTCH-TENSILE DATA FOR X7007 COMPARED WITH PREVIOUS DATA FOR M791 AND M793. (PLANT FABRICATED 1.0 INCH PLATE - NOTCHED ROUND SPECIMENS, $K_t = 10$.)

XFK38

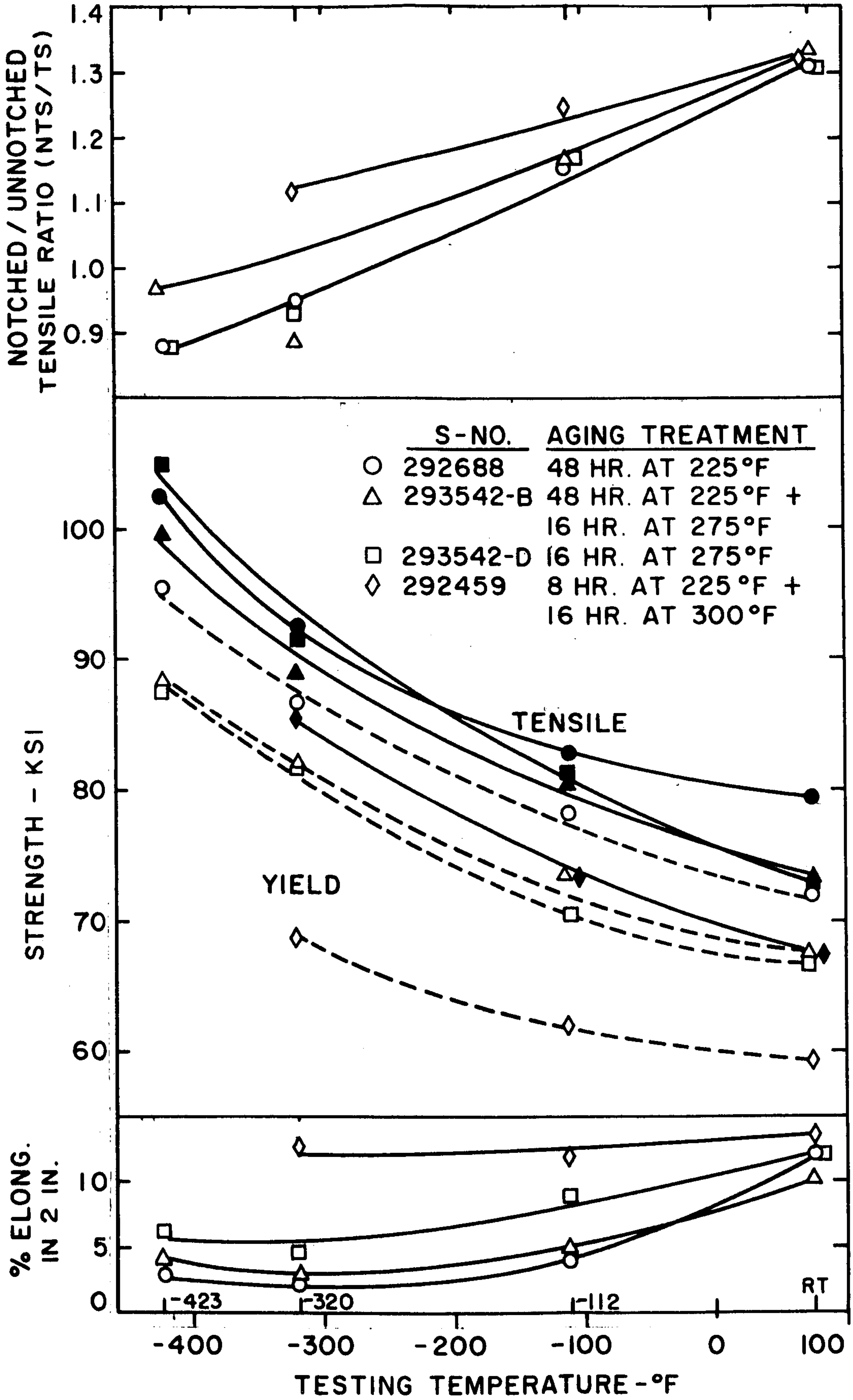
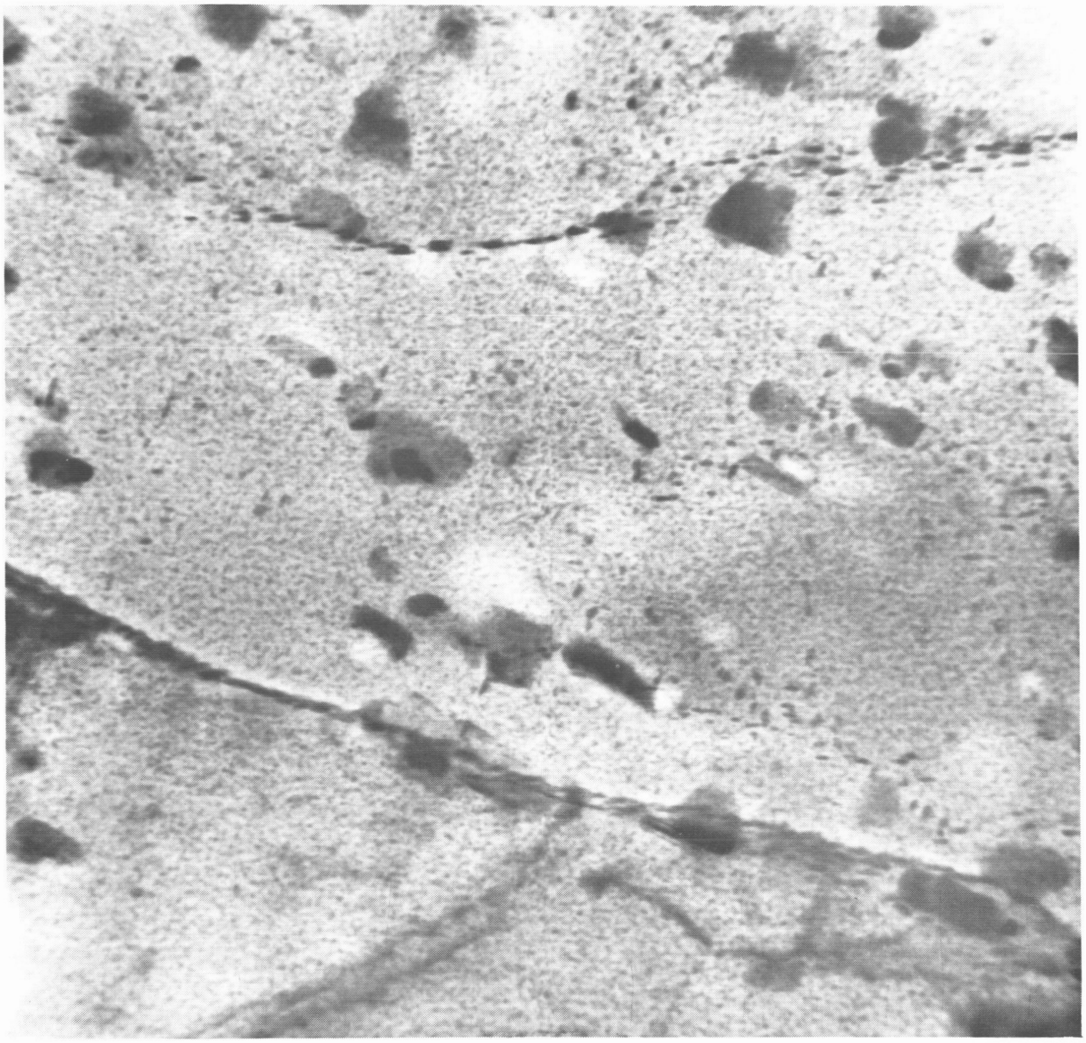


FIGURE 46 - TENSILE AND NOTCH-TENSILE PROPERTIES OF 1.0 INCH PLANT FABRICATED PLATE OF X7007. (NOTCHED ROUND SPECIMENS, $K_t = 10.$)

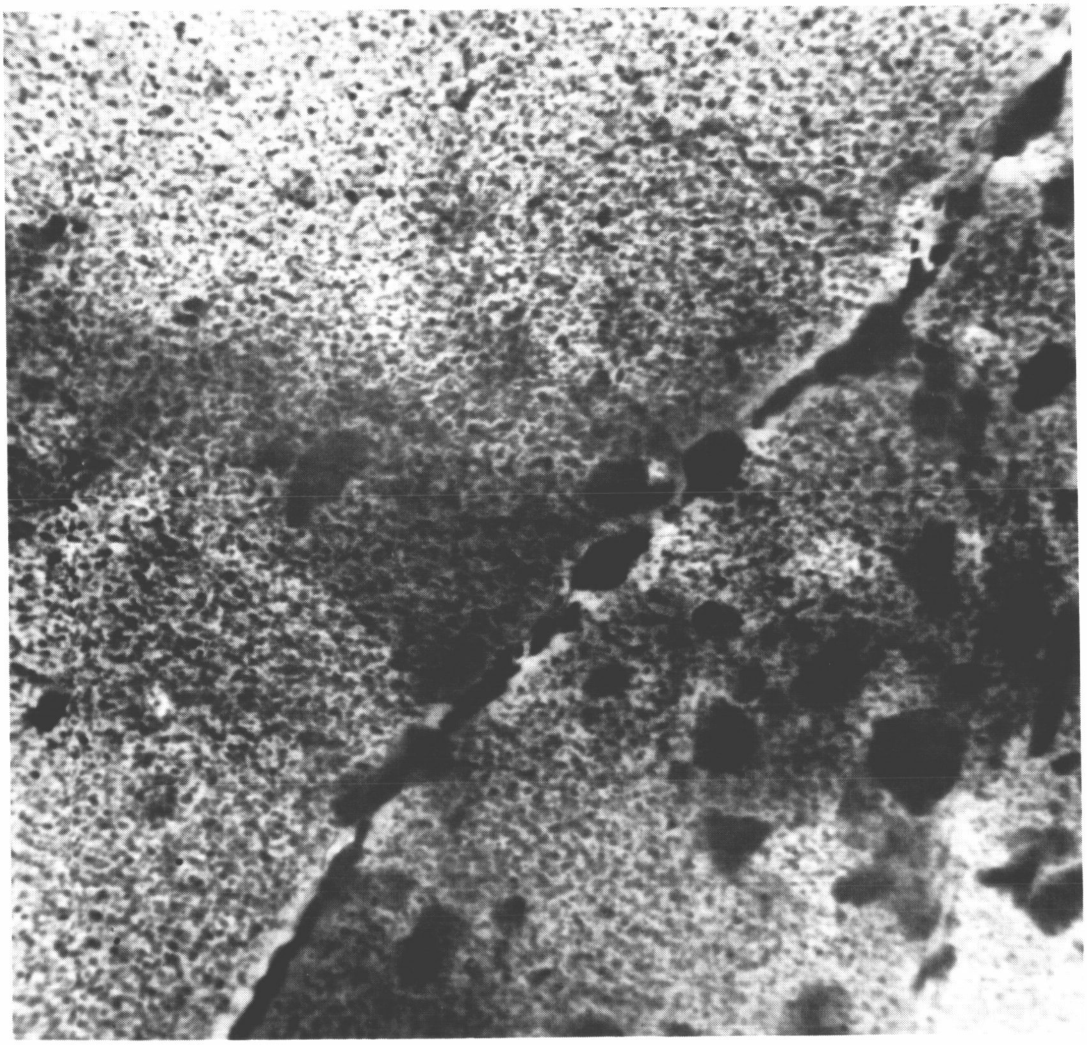
XFK39



S. NO. 326302-4 100,000X

FIGURE 47 - TRANSMISSION ELECTRON MICROGRAPH OF X7007 PLATE IN A FULLY AGED CONDITION. (YS = 65 ksi).

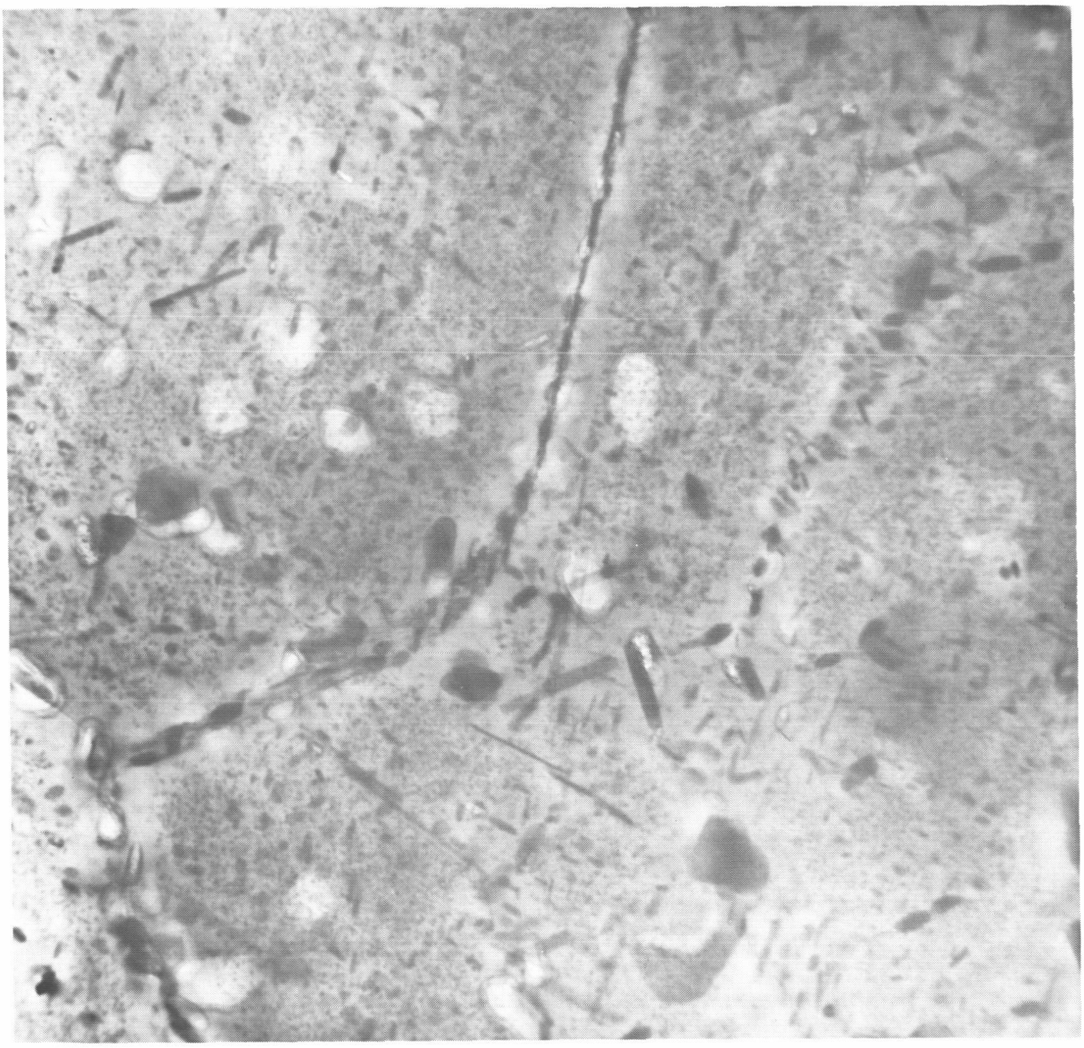
EM968J



S. NO. 326302-8 100,000X

FIGURE 48 - TRANSMISSION ELECTRON MICROGRAPH OF X7007 PLATE IN AN OVERAGED CONDITION. (YS = 58 ksi).

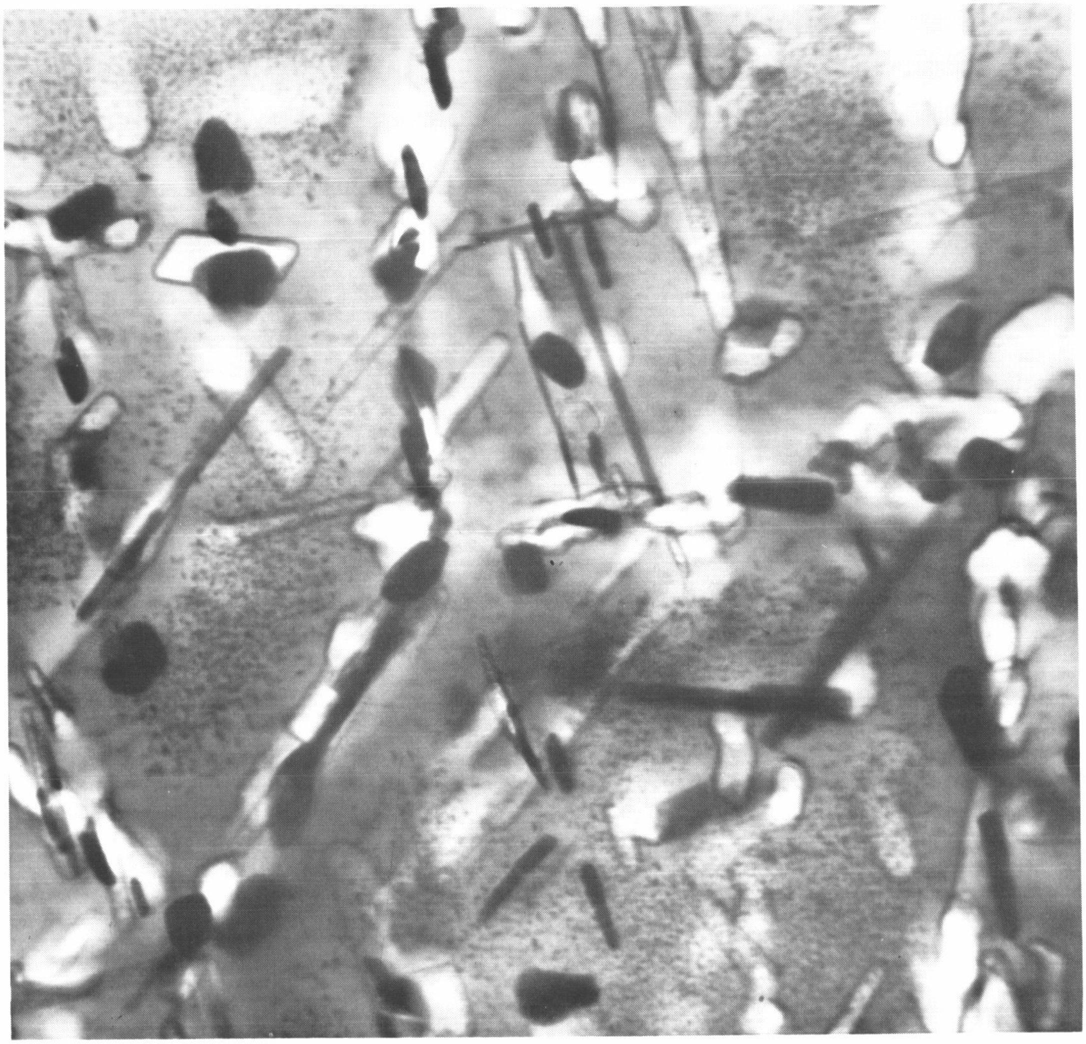
EM971J



S. NO. 326411-22 100,000X

FIGURE 49 - TRANSMISSION ELECTRON MICROGRAPH OF X7007 PLATE QUENCH-AGED 60 MINUTES AT 350 F BEFORE FINAL AGING. (YS = 54 ksi).

EM983J



S. NO. 326411-20 100,000X

FIGURE 50 - TRANSMISSION ELECTRON MICROGRAPH OF X7007 PLATE QUENCH-AGED 60 MINUTES AT 400 F BEFORE FINAL AGING. (YS = 31 ksi).

EM980J

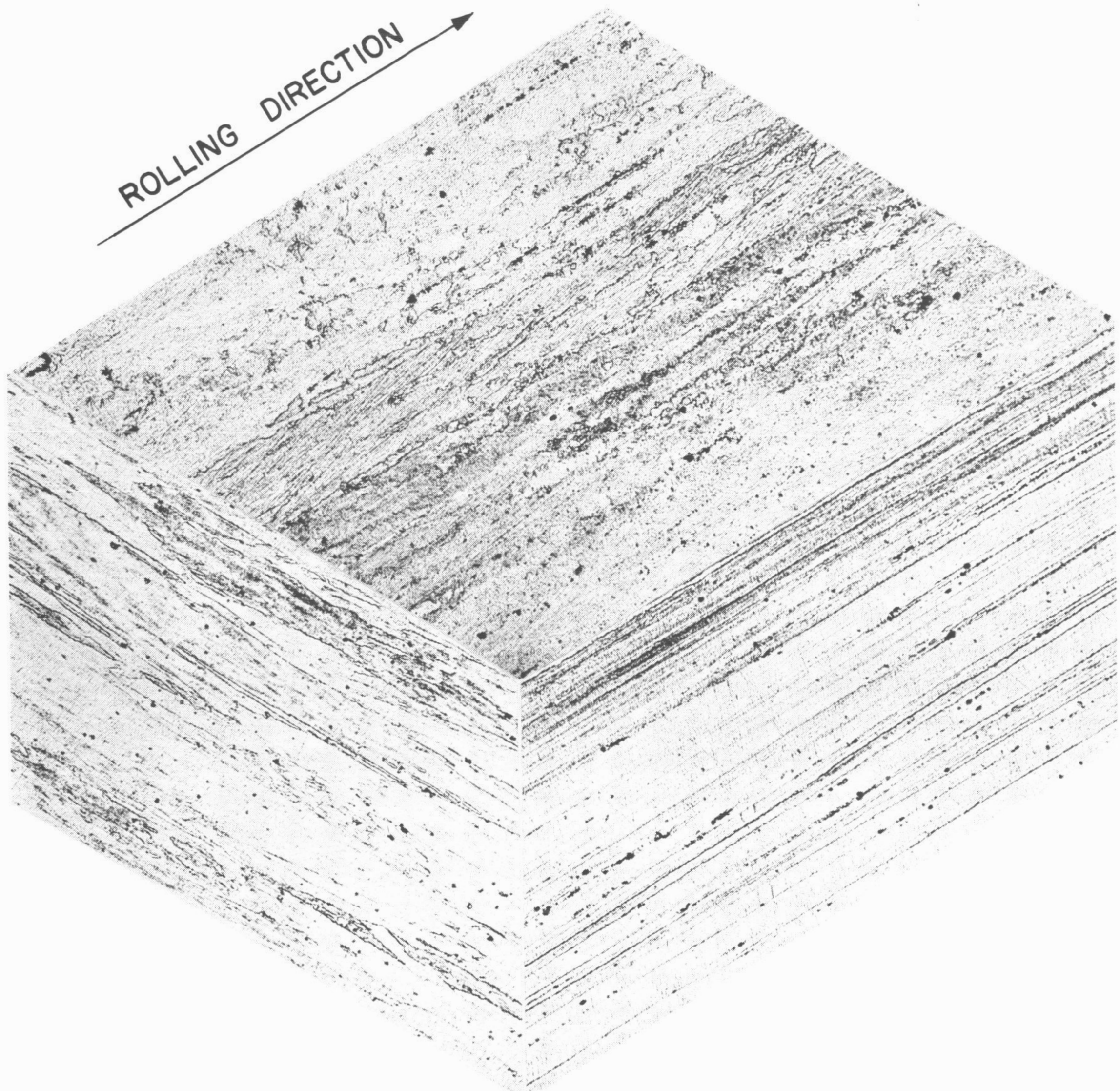


FIGURE 52 TYPICAL MICROSTRUCTURE OF X7007-T6E136 1.000 IN. PLATE (S. NO. 327108 - 100X MAG. - KELLER'S ETCH).

162124A, 25A, 26AJ

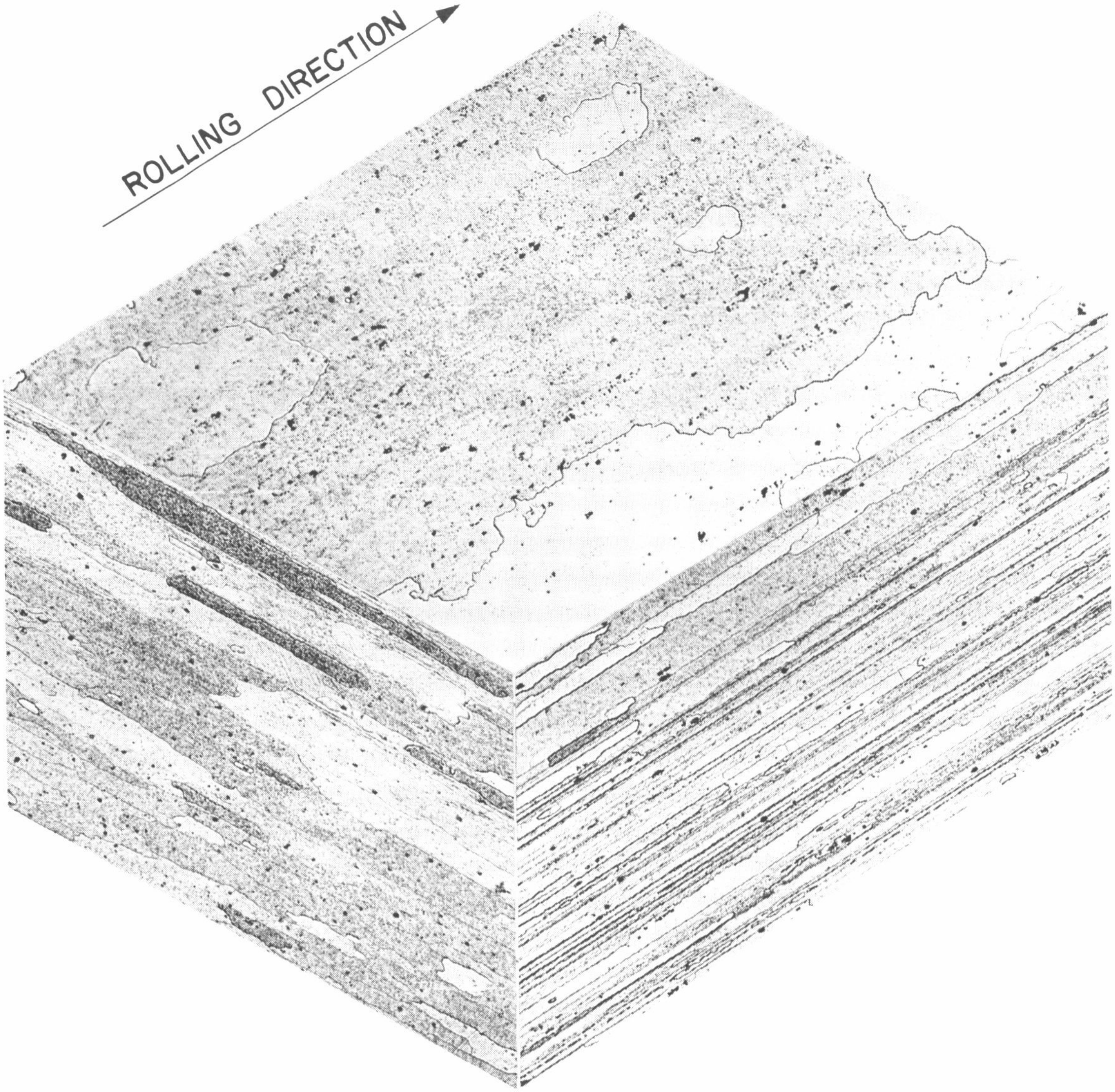


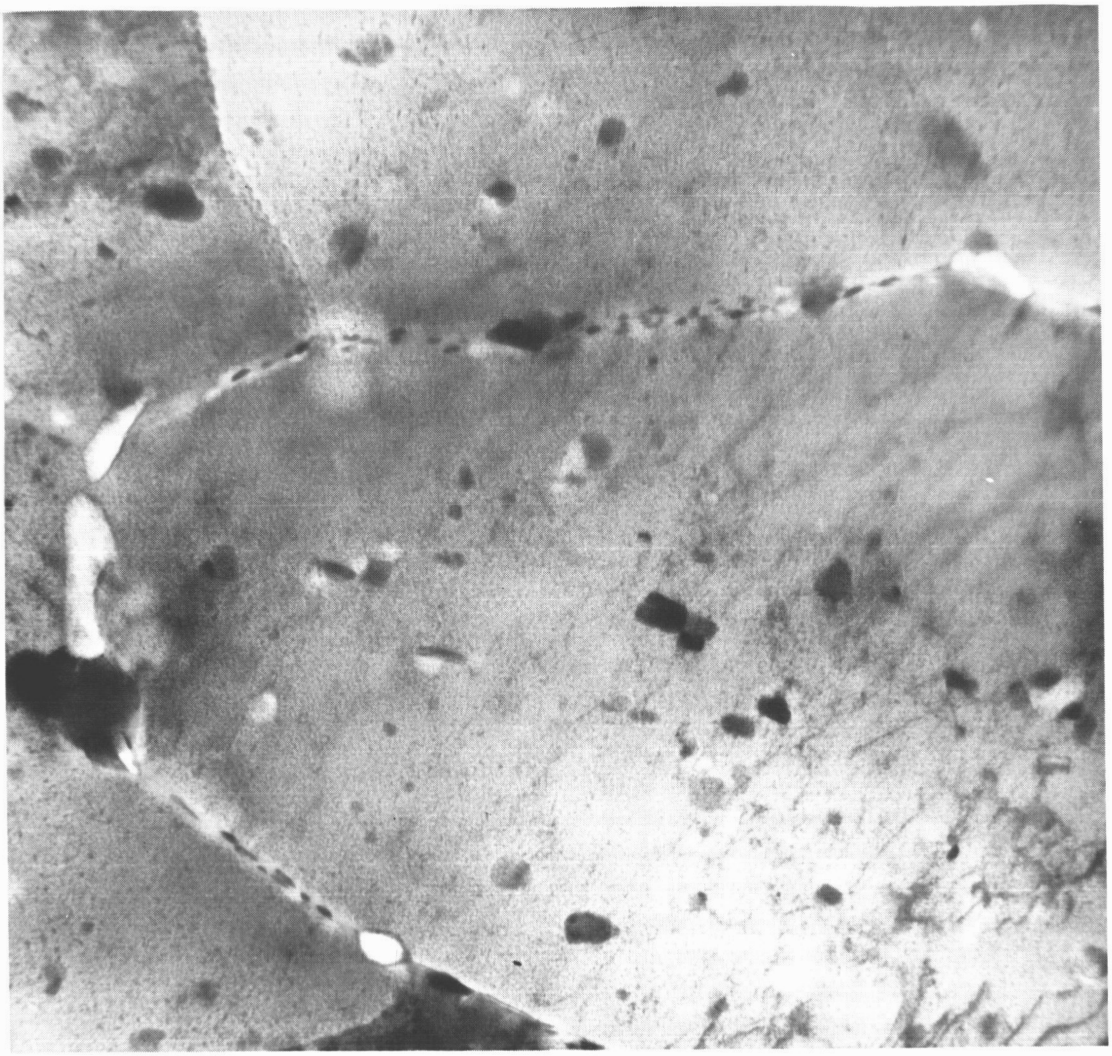
FIGURE 51 - TYPICAL MICROSTRUCTURE OF X7007-T6E136 0.064 IN. SHEET (S. NO. 327105 - 100X MAG. - KELLER'S ETCH).

162726A, 27A, 28AJ

S. NO. 327108P 20,000X

FIGURE 53 - TRANSMISSION ELECTRON MICROGRAPH SHOWING MICROSTRUCTURE OF X7007-T6E136 1.000 IN. PLATE. SPECIMEN WAS FROM PLANE PERPENDICULAR TO SURFACE LOCATED NEAR MID-THICKNESS.

EM959J



S. NO. 327108P 50,000X

FIGURE 54 - TRANSMISSION ELECTRON MICROGRAPH SHOWING MICROSTRUCTURE OF X7007-T6E136 1.000 IN. PLATE. SPECIMEN WAS FROM PLANE PERPENDICULAR TO SURFACE LOCATED NEAR MID-THICKNESS.

EM960J

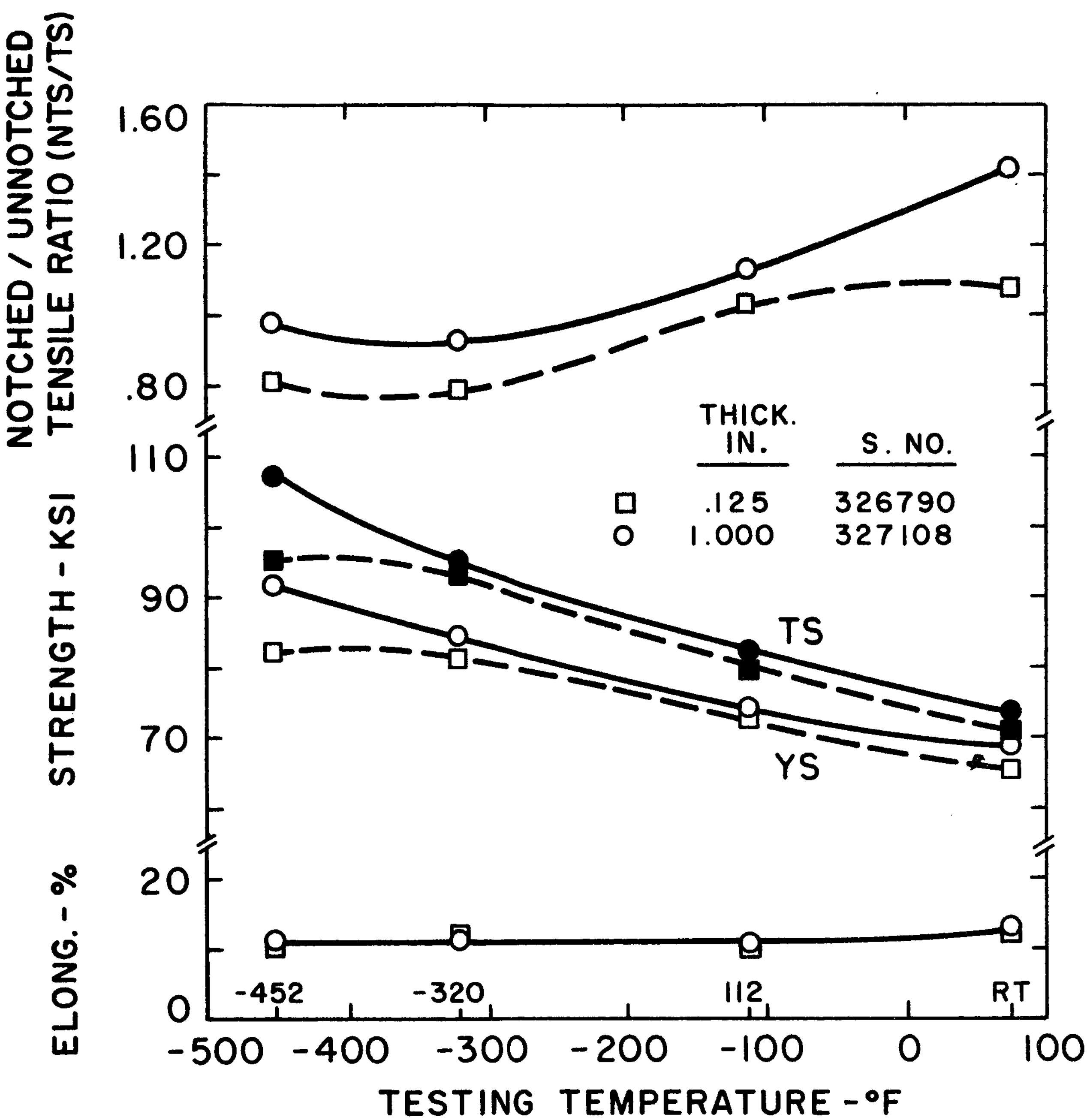


FIGURE 55 - TENSILE AND NOTCH-TENSILE PROPERTIES OF PLANT FABRICATED X7007-T6E136 SHEET AND PLATE (EDGE NOTCHED SHEET SPECIMENS FOR SHEET-NOTCHED ROUND SPECIMENS FOR PLATE, $K_t = 10$).

XFK40

XFK41

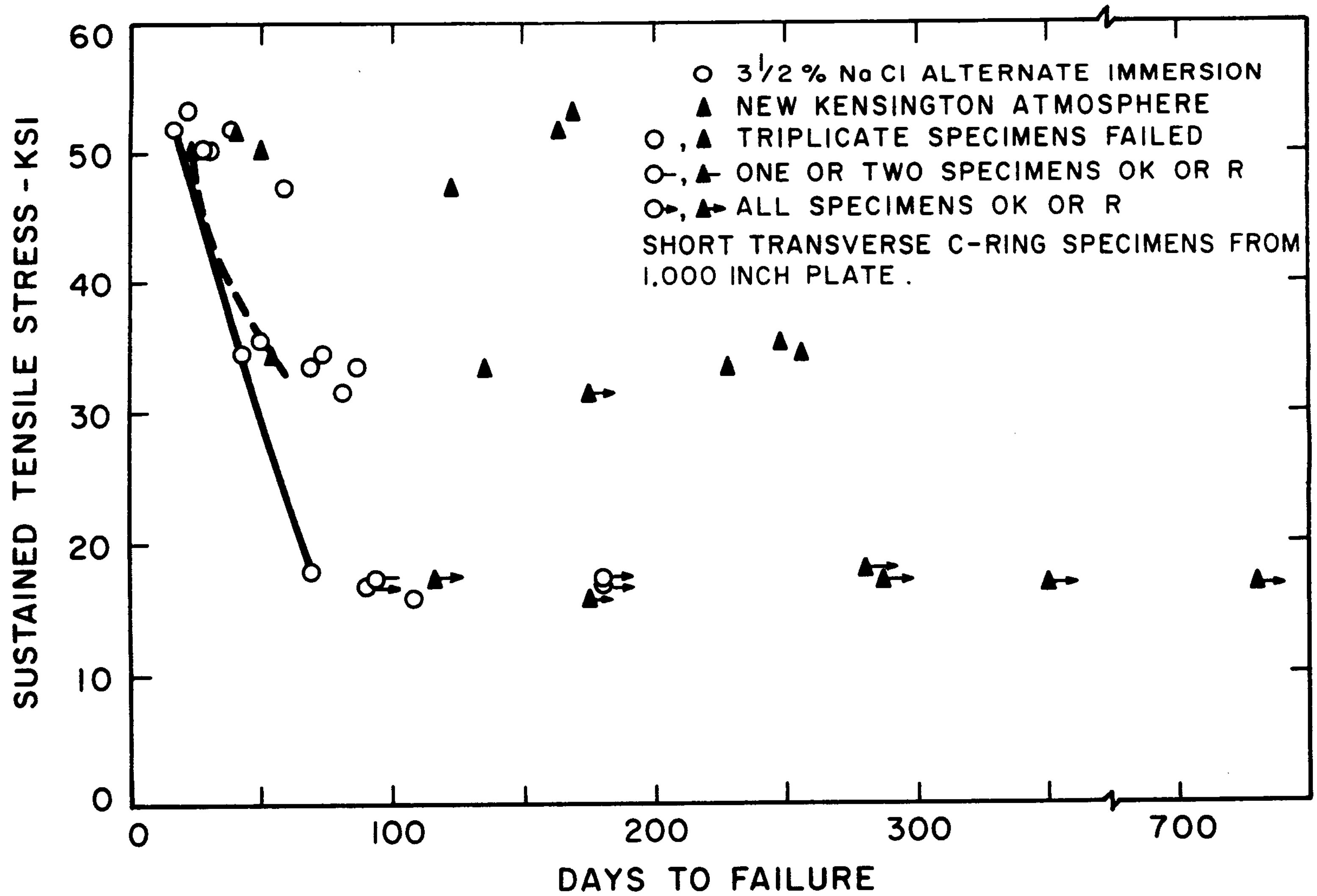


FIGURE 56 - RESISTANCE TO STRESS CORROSION CRACKING OF 1.000 INCH PLATE OF X7007-T6E136 (POINTS PLOTTED ARE AVERAGE OF TRIPLICATE TESTS).

XFI-15

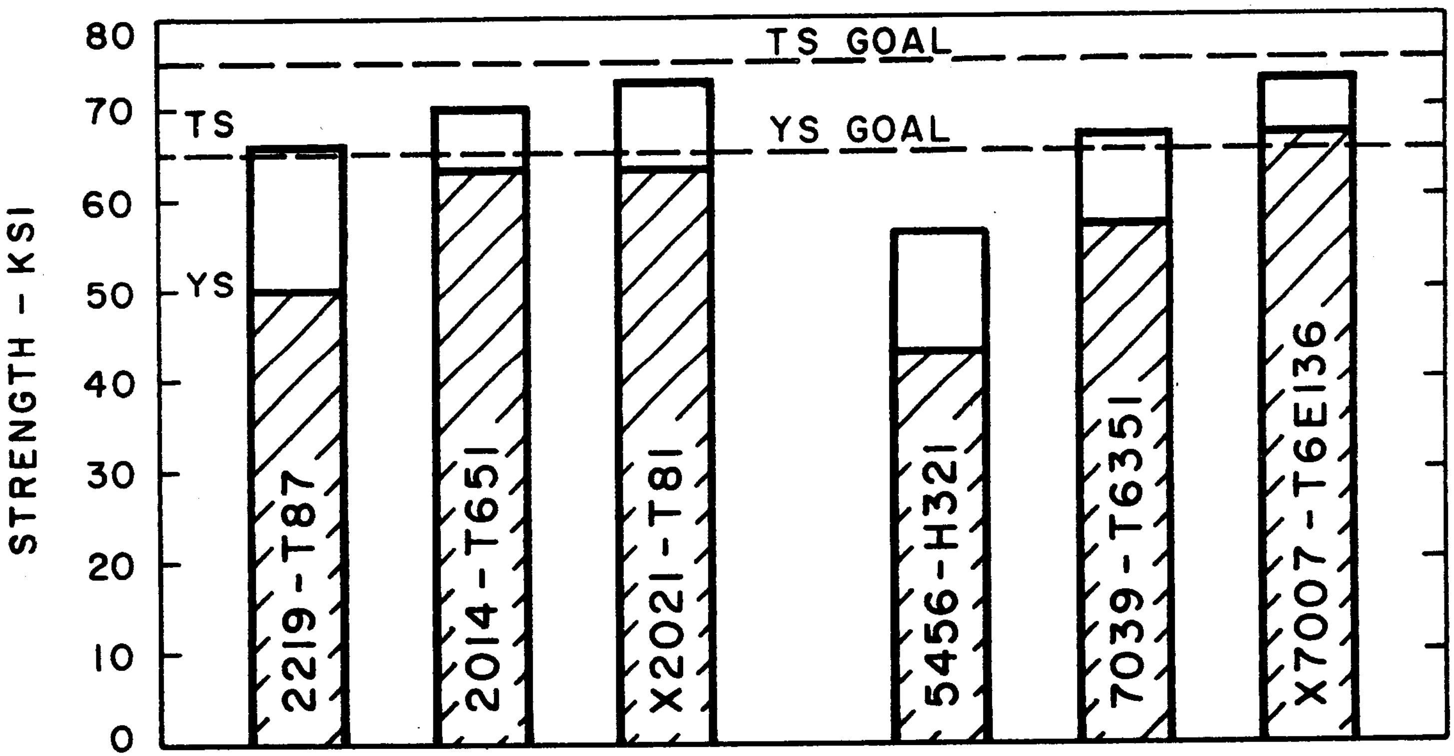
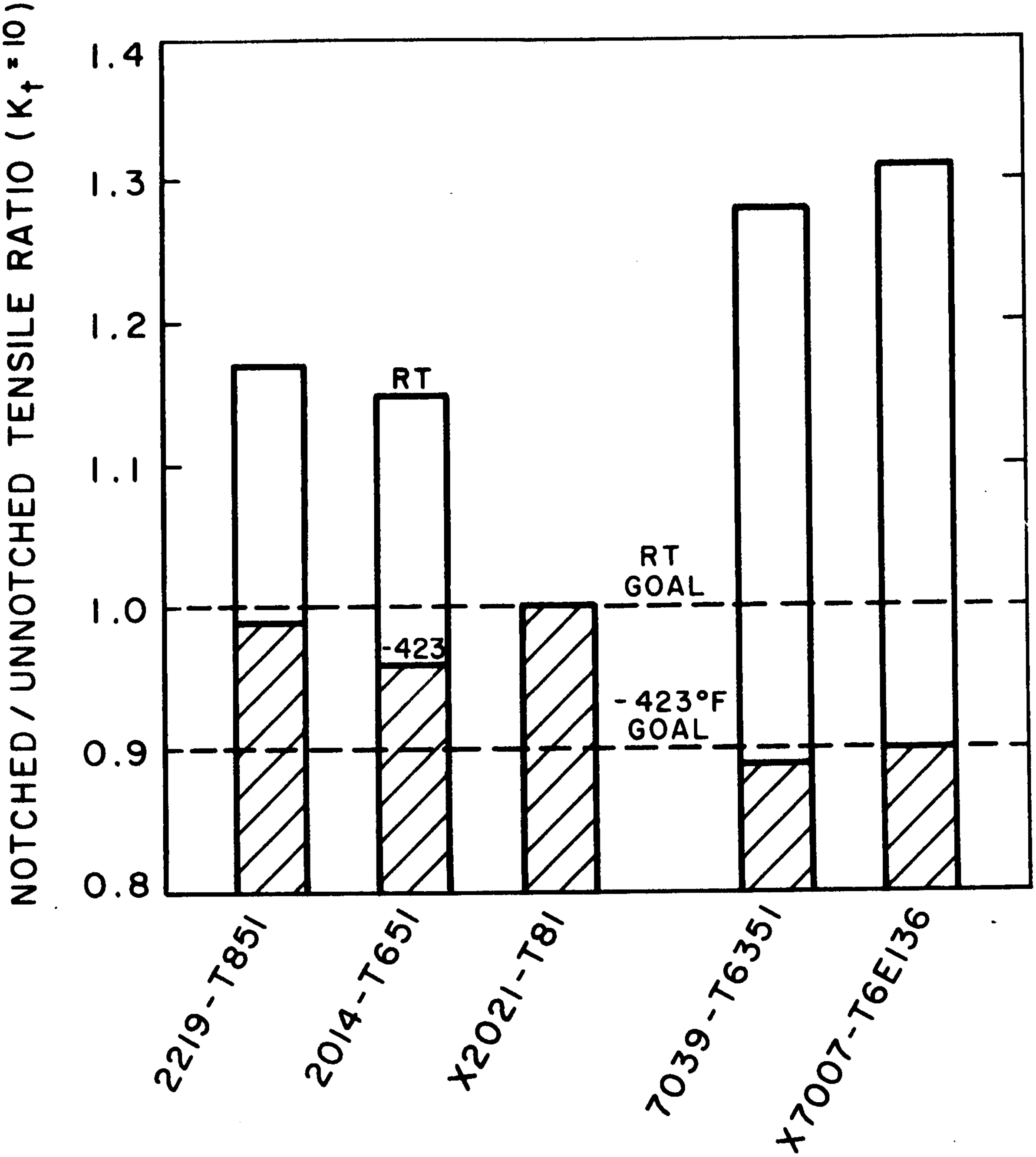


FIGURE 57 - COMPARISON OF TENSILE AND YIELD STRENGTH OF X2021-T81 AND X7007-T6E136 WITH COMMERCIAL HIGH STRENGTH, WELDABLE ALLOYS.



XFK42

FIGURE 58 - COMPARISON OF NOTCHED/UNNOTCHED TENSILE RATIOS AT ROOM TEMPERATURE AND -423 F.

XFI-16

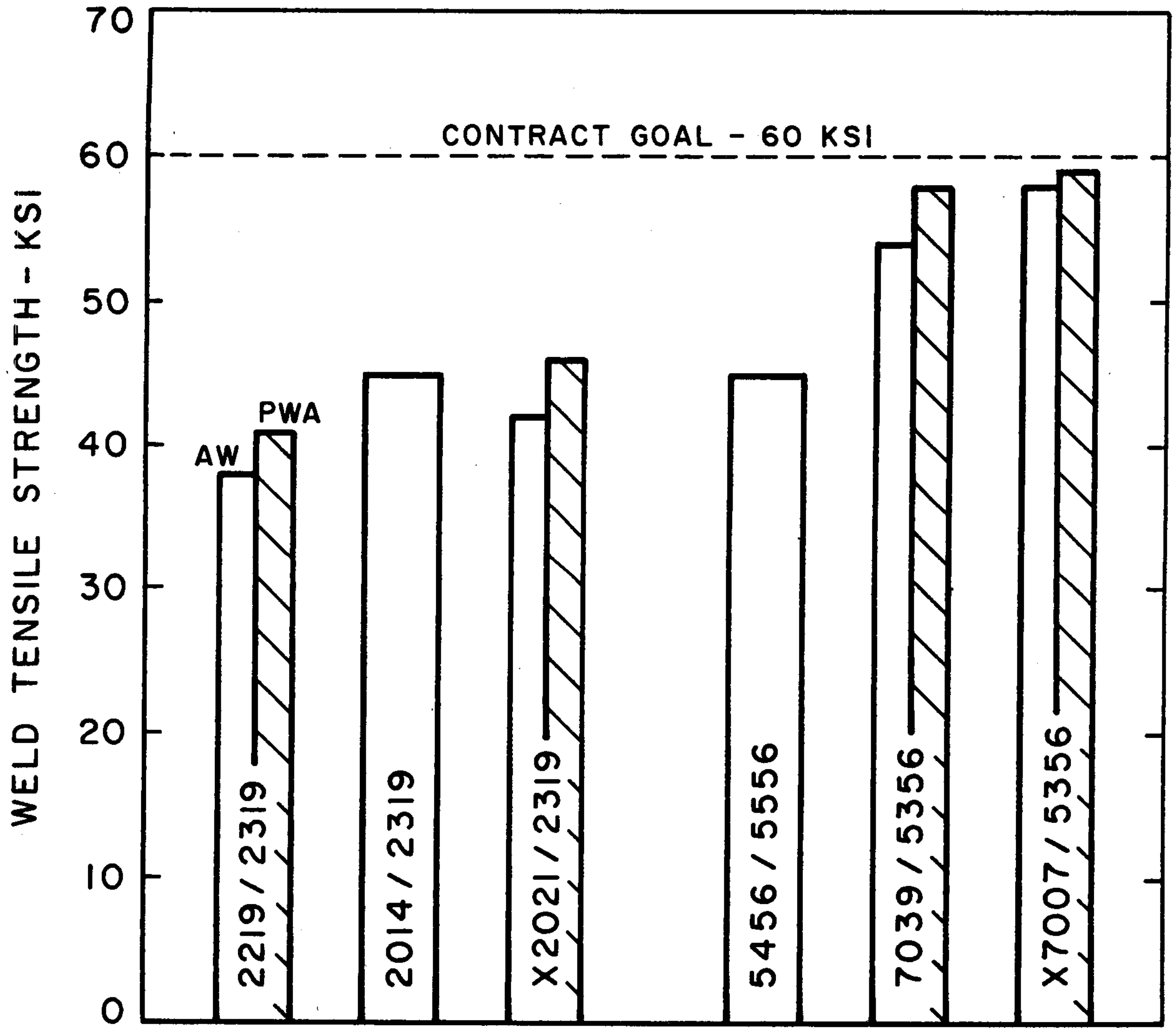


FIGURE 59 - COMPARISON OF TENSILE STRENGTHS OF WELDED PLATE ABOUT .500 INCH THICK.

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APPENDIX I

MECHANICAL PROPERTIES AND FRACTURE CHARACTERISTICS OF X2021-T81 AND X7007-T6E136 SHEET AND PLATE

by

J. W. Coursen

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INTRODUCTION AND OBJECT

Alloys X2021-T81 and X7007-T6E136 were developed under government contract No. NAS 8-5452 with the objective of obtaining a high strength aluminum alloy which is readily weldable in plate thicknesses and suitable for application at -423 F. Both alloys essentially satisfy these goals; and because they possess such a desirable combination of properties, considerable interest in these alloys has developed.

The mechanical properties and fracture characteristics of a few lots of sheet and plate were determined previously with material from experimental production. This investigation was conducted as part of an extension of the above contract in order to obtain a more comprehensive background of information concerning the properties of several thicknesses of sheet and plate from commercial production. The tensile, compressive, shear, bearing, bend and fatigue properties, hardness, electrical conductivity, notch-toughness, tear resistance and fracture toughness were determined at room temperature and the tensile properties, notch-toughness and tear resistance of a few lots were determined at temperatures down to -452 F.

The properties of these alloys are compared with each other and with those of some other high strength aluminum alloys.

MATERIAL

The samples of X2021-T81 and X7007-T6E136 sheet and plate tested in this investigation were produced commercially at the Davenport Works of Aluminum Company of America. They are identified as follows:

Thickness inches	Sample No. X2021-T81	Sample No. X7007-T6E136
1/16	326889	327105
1/8	326888	326790
1/4	342352	326788
1/2	342719	326786
1	327102	327108
2 1/2	326402	295582

The chemical compositions, based on an analysis of one lot from each cast of metal, are shown in Table I. The compositions were close to the nominal values and well within the tentative limits established for these alloys. The fabricating procedures are shown in Table II.

PROCEDURE

In most instances, duplicate specimens were taken in the longitudinal and long-transverse directions for each type of test conducted in this investigation. Short-transverse specimens were taken from the 2 1/2 inch thick plate only. The specimens were taken from the center of samples 1.0 inch or less in thickness. Longitudinal and long-transverse specimens from 2 1/2 inch thick plate were taken midway between the surface and the center. In general, the specimens from samples 1/4 inch or less in thickness were sheet-type and those from samples 1/2 inch or more in thickness were round.

Tensile tests were conducted at room temperature; and for one sample of sheet and plate of each alloy, tensile tests were conducted at -112, -320 and -452 F. The tests were made essentially in accordance with ASTM Methods E8. At -112 and -320 F, strain-transfer devices were used in conjunction with strain followers to obtain autographic load-strain diagrams. At -452 F, autographic curves of load versus head movement were obtained. Yield strengths were determined at 0.2 percent offset.

Compressive tests were conducted in accordance with ASTM Methods E9. Sheet-type specimens were supported with a Montgomery-Templin jig and loads were applied through a sub-press. Yield strengths were determined at 0.2 percent offset.

Tensile and compressive elastic moduli of both alloys were determined with specimens taken from the 1 inch plate. The tests were conducted and the data analysed in accordance with ASTM Method E111. Tensile strains were measured over an 8 inch gage length with an Amsler-Martens mirror-type extensometer. Compressive strains were measured over a 2 inch gage length with a Tuckerman optical strain gage.

Stress-strain curves defining the yield strength were developed from data obtained with these instruments operating on 2 inch gage lengths. The tensile stress-strain curve was extended to completion with strains measured with a dial indicator.

The blanking-shear strengths of the 1/16 inch sheet were determined from the loads required to punch a 2 3/4 inch circle from the sheet, with a hardened steel punch and die having a clearance of about 12 percent of the sheet thickness. The double-shear strengths of thicker samples were determined with round specimens and an Amsler tool in which the specimens are sheared on two planes 1.0 inch apart. In these latter tests, loads were applied parallel and normal to the surface of the sample, for longitudinal and long-transverse specimens. For short-transverse specimens, loads were applied in the longitudinal direction.

Bearing specimens were tested with edge distances of 1.5 and 2 times the pin diameter in accordance with ASTM Method E238. For the samples of plate 1.0 and 2 1/2 inch thick, bearing specimens were taken flatwise and edgewise with respect to the surface of the sample. The specimens and test fixtures were cleaned ultrasonically in Toson Fluid prior to testing. Bearing yield strengths were determined from autographic load-deformation diagrams at 2.0 percent offset.

Brinell hardness numbers were determined with a 500 kg, 10 mm load-ball combination. Rockwell hardness values were determined on the B scale.

Repeated reversed-bend tests, in which specimens are bent 90 degrees over a 1/4 inch radius, were conducted for the samples of 1/16 inch sheet. The minimum radii for 180-degree bends were determined for samples up to 1.0 inch in thickness.

Sheet-type flexural fatigue specimens, illustrated at the top of Figure 5, were taken from the samples of 1/16 inch sheet, and smooth and notched rotating-beam fatigue specimens, shown in Figure 6, were taken from the 1.0 inch plate. Smooth axial-stress fatigue specimens were taken from the 1/8 inch sheet, and smooth and notched axial-stress specimens were taken from the 1.0 inch plate; the axial-stress specimens are illustrated in Figures 7 and 8. All axial-stress fatigue tests were conducted with a stress ratio $(\frac{\text{minimum stress}}{\text{maximum stress}})$ of 0.0.

Electrical conductivities were determined with a Magnatest FM-103 conductivity meter in accordance with ASTM Method B342 and by the potential-drop method in accordance with ASTM Method B193.

Notch-tensile tests were conducted at room temperature; and for one sample of sheet and plate of each alloy, tests were conducted at -112, -320 and -452 F. The designs of the notch-tensile specimens taken from different samples are shown in the following figures.

Sample Thickness inches	Specimens
1/16	Figure 9
1/8	Figures 9 and 10
1/4	Figure 11
1	Figures 12 and 13

The ratio of notch-tensile strength to tensile yield strength (notch-yield ratio) was used as the primary criterion of notch toughness.

Tear tests of each sample (except 1/2 inch thick plate) were conducted at room temperature; and tests of the 1/16 inch sheet were conducted at -112 and -320 F. The design of the tear specimens is shown in Figure 14. Specimens from the 1/16 inch sheet were full thickness, and those from the other samples were machined to 0.100 inch thickness. The energies required to initiate and propagate cracks in the specimens were determined from the area under the appropriate portions of autographic load-deformation curves of the type shown in Figure 14. The ratio of tear strength (maximum direct and bending stress) to the tensile yield strength was used as a measure of notch toughness, and the unit propagation energy was used as a measure of tear resistance.

Center-notched fracture-toughness specimens of the design shown in Figure 15 were taken from the samples of 1/4 inch plate. Fatigue cracks were developed at each end of the notch using maximum stresses (R = 0.0) equal to or less than 15 percent of the yield strength. The critical crack lengths associated with a free-running crack were determined from compliance measurements and calibration curves of the type shown in Figure 14 of Reference 1. Stress-intensity factors (K_c and K_{Ic}) and strain-energy release rates (G_c and G_{Ic}) were calculated with the following equations[2, 3].

$$(EG_c)^{1/2} = K_c = \sigma_c \left[W \tan \left(\frac{\pi a_c}{W}\right)\right]^{1/2}$$

$$(EG_{Ic})^{1/2} = K_{Ic} = \frac{Pa^{1/2}}{tW} \left[1.77+0.227\left(\frac{2a}{W}\right)-0.510\left(\frac{2a}{W}\right)^2+2.7\left(\frac{2a}{W}\right)^3\right]$$

where P = load at 5% secant offset (essentially equivalent to plane strain instability in absence of "pop-in"),

σ_c = gross-section stress at onset of unstable crack growth, psi

W = width of specimen, inches

t = thickness of specimen, inches

2a = original crack length (after fatigue cracking), inches

$2a_c$ = crack length at onset of unstable crack growth, inches

E = elastic modulus, psi

Notch-bend fracture-toughness specimens, of the type shown in Figure 16, were taken from the samples of 1/2 and 1 inch plate. The specimens were fatigue cracked and tested essentially in accordance with current ASTM recommendations.(4) Values of K_{Ic} and G_{Ic} were calculated with the equation:(3)

$$(EG_{Ic})^{1/2}=K_{Ic}=\frac{6Pa^{1/2}}{tW}\left[1.93-3.07\left(\frac{a}{W}\right)+14.53\left(\frac{a}{W}\right)^2-25.11\left(\frac{a}{W}\right)^3+25.80\left(\frac{a}{W}\right)^4\right]$$

where the terms are as defined above.

RESULTS

The results of tensile, compressive, shear, bearing and hardness tests are shown in Tables III and IV, and the ratios between some of these properties are given in Table V. The tensile properties at the center and midway locations in the 2 1/2 inch plate are compared in Table VI. Tensile and compressive moduli of elasticity, the results of bend tests, and the electrical conductivities are shown in small tables within the text of this report. Tensile and compressive stress-strain curves are shown in Figures 1 to 4 and fatigue strengths are shown in Figures 5 to 8. The notch-tensile properties at room and subzero temperatures are shown in Table VII and tear test data is shown in Table VIII. Critical stress-intensity factors and other fracture-toughness data are shown in Tables IX and X.

DISCUSSION

MECHANICAL PROPERTIES

Except for one sample of each alloy, the properties of various samples of each alloy (see Tables III and IV) are reasonably uniform. The properties of the 2 1/2 inch thick X2021-T81 plate were 2 to 12 percent lower than the average values for thinner samples. Since the slower cooling rate experienced by samples of this thickness is likely to affect the properties of this alloy, it seemed reasonable to exclude the data for this sample from the calculations for average properties. The longitudinal tensile properties and the compressive yield strengths of the 1 inch thick X7007-T6E136 plate are significantly higher than those of most of the other samples; however, in this case, there is no evident reason for excluding the properties of this sample from the average values.

The average tensile properties of both alloys are shown below:

	Direction	Tensile Strength psi	Yield Strength psi	Elongation in 4D %
X2021-T81*	L	73 400	65 300	9.5
	T	73 900	64 100	6.0
X7007-T6E136	L	73 000	68 600	13.5
	T	72 100	67 000	12.9

* Does not include data for 2 1/2 inch thick plate

Tensile and compressive stress-strain curves for the 1.0 inch thick plate of each alloy are shown in Figures 1 to 4. The average values of elastic moduli obtained in tests of these samples are as follows:

	Direction	Tensile Modulus 10^6 psi	Compressive Modulus 10^6 psi
X2021-T81	L	10.6	10.9
	T	10.8	11.0
X7007-T6E136	L	10.4	10.6
	T	10.4	10.7

The relations among some of the mechanical properties are shown in Table V. For both alloys, the longitudinal compressive yield strengths are about equal to the longitudinal tensile yield strengths, and the long-transverse compressive yield strengths are about 6 percent higher than the long-transverse tensile yield strengths. Longitudinal and long-transverse shear strengths are approximately 60 percent of the transverse tensile strengths. Average ratios of bearing properties to tensile properties are as follows (flatwise specimens):

	Bearing Strength / Tensile Strength		Bearing Yield Strength / Tensile Yield Strength	
	e/D=1.5	e/D=2.0	e/D=1.5	e/D=2.0
X2021-T81	1.50	1.95	1.50	1.80
X7007-T6E136	1.50	1.95	1.40	1.65

The bearing properties of edgewise specimens are lower than those of flatwise specimens by the following percentages:

	Bearing Strength e/D=1.5	Bearing Strength e/D=2.0	Bearing Yield Strength e/D=1.5	Bearing Yield Strength e/D=2.0
X2021-T81	17	14	7	4
X7007-T6E136	11	8	6	2

The short-transverse tensile yield strengths and shear strengths of the 2 1/2 inch thick plate of both alloys are lower than the corresponding long-transverse properties.

The tensile properties at the t/4 and t/2 locations in the 2 1/2 inch thick plate, shown in Table VI, indicate that there may be considerable variation in properties through the thickness of thick plate of both alloys. The strengths at the center of the X2021-T81 plate are 2 to 5 percent lower than those at the t/4 location. On the other hand, the strengths at the center of the X7007-T6E136 plate are 5 to 10 percent higher than those at the t/4 location.

In repeated 90 degree bend tests of the 1/16 inch sheet over a 1/4 inch radius, the X2021-T81 sheet would not complete one full bend before fracturing, but the X7007-T6E136 sheet completed 10 or 4 bends (axis of bend normal, N, to or parallel, P, with the rolling direction) before fracturing. The superior bend characteristics of X7007-T6E136 compared with those of X2021-T81 are further demonstrated by the results of minimum 180 degree cold-bend tests shown below:

Thickness inches	Minimum 180 Degree Bend Radius X2021-T81 N	X2021-T81 P	X7007-T6E136 N	X7007-T6E136 P
1/16	4t	4 1/2t	1 1/2t	2 1/2t
1/8	4t	6t	3t	2 1/2t
1/4	4t	6 1/2t	3t	2 1/2t
1/2	8t	8t	2t	3t
1	--	--	2 1/2t	3t

The electrical conductivities of several of the samples determined with a Magnatest FM-103 conductivity meter and by the potential-drop method are as follows:

Thickness inches	Electrical Conductivity, % IACS			
	X2021-T81		X7007-T6E136	
	Magnatest Meter	Potential-Drop	Magnatest Meter	Potential-Drop
1/16	31.6	31.5	37.4	38.0
1/8	32.2	--	38.7	--
1/4	30.8	30.8	38.7	38.7
1/2	--	--	37.9	--
1	31.6	32.2	36.7	36.1
Average	31.5	31.5	37.9	37.6

The fatigue strengths in various types of fatigue tests are shown in Figures 5 to 8. There seems to be little difference between the fatigue strengths of longitudinal and transverse specimens of each alloy. The flexural and axial-stress fatigue strengths of sheet of both alloys are about equal, but the fatigue strengths of smooth specimens from the 1.0 inch thick X7007-T6E136 plate were significantly higher than those of the X2021-T81 plate. The fact that the static strengths of the 1.0 inch thick X7007-T6E136 were relatively high might account for the higher fatigue strengths of this particular sample. A summary of average fatigue limits at 5×10^8 cylces is shown below.

Type of Test	Stress Ratio (Max./Min.)	Fatigue Limit, 1000 psi			
		X2021-T81		X7007-T6E136	
		Smooth	Notched $K_t > 12$	Smooth	Notched $K_t > 12$
Sheet-Flexure	-1.0	19	--	18	--
Rotating-Beam	-1.0	17	5.5	22	5.5
Axial-Stress, Sheet	0.0	27	--	27	--
Axial-Stress, Plate	0.0	26	8.0	33	8.0

FRACTURE CHARACTERISTICS

The tensile, notch-tensile and tear properties of these alloys at room and subzero temperatures are shown in Tables VII and VIII, and some of these values have been plotted as a function of temperature in Figure 17.

The tensile and yield strengths of both alloys increase with decreasing temperature and are approximately 40 and 30 percent, respectively, higher at -452 F than at room temperature. In most instances, the elongations did not change significantly with temperature.

Several designs of notch-tensile specimens were used to evaluate the notch toughness of these alloys. The results of these tests differ depending upon the notch geometry; nevertheless, the pattern of behavior exhibited by each alloy for a given type of specimen is the same. For instance, transverse notch-yield ratios are generally somewhat less than longitudinal ratios and the variations with temperature are similar.

The notch-yield ratios for two types of specimens ($K_t \geq 16$) are shown in Figure 17. The notch toughness of X2021-T81 is almost constant with temperature. The notch toughness of X7007-T6E136 is considerably higher than that of X2021-T81 at room temperature, but it decreases significantly at subzero temperatures and is less than that of X2021-T81 at -320 and -452 F.

The average tear properties of X7007-T6E136 are also higher than those of X2021-T81 at room temperature. Average room-temperature unit propagation energies are

	Direction	Unit Propagation Energy, in.-lb/in.^{2}
X2021-T81	L	230
	LT	80
	ST	90
X7007-T6E136	L	730
	LT	430
	ST	135

The tear data for 1/16 inch thick sheet, also shown in Figure 17, indicate that the tear resistance of X7007-T6E136 decreases with temperature so that the values for the two alloys are about equal at -320 F.

Plane-strain stress-intensity factors (K_{Ic}), strain-energy release rates (G_{Ic}) and other fracture toughness data developed with center-notched tension and notched bend specimens are shown in Tables IX and X, respectively. Since no obvious pop-in instabilities were observed, the values of K_{Ic} and G_{Ic} were all based upon the loads at a 5 percent secant offset, corresponding to a crack growth of about 2 percent.[4]

One important criterion generally used to determine the validity of fracture toughness data, that is, to require that the thickness of the specimen must be equal to or greater than 50 times the plastic zone size i.e., $t = 2.5\left[\frac{K_{Ic}}{YS^2}\right]^2$, indicates that the validity of the plane-strain data obtained from some of these tests is questionable. Nevertheless, the K_{Ic} and G_{Ic} values for center-notched and notched-bend specimens are generally in good agreement and the majority of the values appear to be valid.

One notable exception is that the values obtained for longitudinal notched-bend specimens from the 1.0 inch thick X2021-T81 plate are considerably higher than the longitudinal values obtained in tests of the other samples. The fatigue cracks in the longitudinal specimens from this sample did not progress on a single plane, and there was evidence of numerous shear lips on the fracture surfaces. The values of K_{Ic} and G_{Ic} determined in these tests may not be valid, but the behavior of this particular sample indicates that it is relatively tough in the longitudinal direction. Supporting evidence for this anomaly are the high longitudinal tear properties of this particular sample.

Considering all the data, the values shown below seem to be reasonable estimates of typical values of K_{Ic} and G_{Ic}:

	Direction	K_{Ic} psi $\sqrt{in.}$	G_{Ic} in.-lb/in.^{2}
X2021-T81	L	29 000	80
	T	23 000	50
X7007-T6E136	L	45 000	200
	T	37 500	135

The only valid values of K_c and G_c (i.e., obtained in tests where rapid crack propagation took place at essentially elastic stresses) were obtained with long-transverse center-notched specimens of the 1/4 inch thick X2021-T81. These values were 36,000 psi $\sqrt{inch}$ and 120 in.-lb/in.^{2}.

COMPARISON WITH OTHER ALLOYS

The long-transverse tensile and tensile yield strengths of X2021-T81 and X7007-T6E136 are compared with typical long-transverse values for some other high-strength aluminum alloys in Figure 18. At both room temperature and -320 F, the strengths of these alloys are about equal to or greater than those of 2014-T6 2219-T87 and 7075-T73. They are lower than those of 7075-T6.

The fatigue strengths of X2021-T81 and X7007-T6E136 are generally in fair agreement with those of 2219-T8XX and 7075-T6 products, respectively, as shown in Figures 5 to 8.

Although the strengths of these alloys are in the same range, the fracture characteristics are considerably different. At room temperautre, the fracture characteristics of aluminum alloys can be grouped according to alloy series; and for each series, the fracture characteristics vary roughly as a function of tensile yield strength.[1] In general, the room-temperature fracture characteristics of alloys in the 7000 series are somewhat higher than those of alloys in the 2000 series for a given level of yield strength. This is illustrated in Figures 19 and 20 where the room-temperature notch-yield ratios of plate (specimen in Figure 11) and unit propagation energies of sheet of these two alloys are compared with those of some other alloys in the 2000 and 7000 series. In both figures, the data points for X2021-T81 fall slightly below the trend line for other alloys in the 2000 series, whereas the data points for X7007-T6E136 lie above those for other alloys in the 7000 series. In fact, at room temperature, X7007-T6E136 seems to offer one of the best combinations of strength and fracture characteristics of the aluminum alloys tested to date.

A more specific comparison of the notch toughness of plate of several alloys at room temperature and -320 F is shown in Figure 21. The notch-yield ratios of X2021-T81 are less than those of 2219-T87, about equal to those of 2014-T651, and greater than those of 7075-T651 and T7351 at -320 F. The notch yield ratios of X7007-T6E136 are greater than those of any of these alloys at room temperature, but less than those of the 2000 series alloys at subzero temperatures.

The unit propagation energies of sheet and plate, shown in Figure 22, rate these alloys in about the same order at room temperature except that the unit progagation energy of X2021-T81 is quite low in the long-transverse direction. At -320 F, the unit propagation energies of sheet of both X2021-T81 and X7007-T6E136 are less than those of 2014-T6 and 2219-T87 sheet but greater than those of 7075-T6 and T73 sheet.

SUMMARY AND CONCLUSIONS

Based on tests of six lots of each alloy, the following summary statements and conclusions concerning the mechanical properties and fracture characteristics of X2021-T81 and X7007-T6E136 sheet and plate seem warranted:

1. The average long-transverse tensile properties of these samples at room temperature are as follows:

	Tensile Strength psi	Yield Strength psi	Elongation in 4D %
X2021-T81*	73 900	64 100	6.0
X7007-T6E136	72 100	67 000	12.9

These strengths are equal to or greater than the typical values for 2014-T6, 2219-T87 and 7075-T73.

2. At -452 F, the tensile and tensile yield strengths of both alloys are approximately 40 and 30 percent, respectively, higher than the room-temperature strengths. Elongations do not change significantly with temperature.

3. Average tensile and compressive moduli of elasticity are as follows:

	Tensile Modulus 10^6 psi	Compressive Modulus 10^6 psi
X2021-T81	10.7	11 11.0
X7007-T6E136	10.4	10.6

Tensile and compressive stress-strain curves are shown in Figures 1 to 4.

4. Compressive yield strengths are generally equal to or greater than the long-transverse tensile yield strengths.

5. Longitudinal and long-transverse shear strengths are approximately 60 percent of the long-transverse tensile strengths. Short-transverse shear strengths are somewhat lower.

6. Average ratios of bearing properties to tensile properties (flatwise specimens) are as follows:

---

* Does not include properties of 2 1/2 inch plate.

	Bearing Strength / Tensile Strength		Bearing Yield Strength / Tensile Yield Strength	
	e/D=1.5	e/D=2.0	e/D=1.5	e/D=2.0
X2021-T81	1.50	1.95	1.50	1.80
X7007-T6E136	1.50	1.95	1.40	1.65

7. The bend characteristics of X7007-T6E136 are considerably better than those of X2021-T81 (see tabulation on page 10).

8. The electrical conductivities of X2021-T81 and X7007-T6E136 are approximately 32 and 38 percent IACS, respectively.

9. The fatigue strengths of X2021-T81 and X7007-T6E136 are usually in fair agreement with those of 2219-T8XX and 7075-T6 products, respectively. The axial-stress fatigue limits at 5×10^8 cycles (R = 0.0) are as follows:

	Fatigue Limits, ksi			
	X2021-T81		X7007-T6E136	
	Smooth	Notched	Smooth	Notched
Sheet	27	--	27	--
Plate	26	8.0	33	8.0

10. At room temperature, alloy X7007-T6E136 seems to offer one of the best combinations of strength and fracture characteristics of the aluminum alloys tested to date. The room-temperature fracture characteristics of X2021-T81 are relatively low but about in line with the data for other alloys in the 2000 series. Average values of unit propagation energy (UPE) and plane-strain stress-intensity factor (K_{Ic}) for the two alloys are as follows:

	UPE, in.-lb/in.^{2}		K_{Ic}, psi $\sqrt{in.}$	
	L	T	L	T
X2021-T81	230	80	29 000	23 000
X7007-T6E136	730	430	45 000	37 500

11. The fracture characteristics of X7007-T6E136 decrease considerably at subzero temperatures, but the fracture characteristics of X2021-T81 do not change significantly with temperature.

12. At subzero temperatures the fracture characteristics of X7007-T6E136 are higher than those of 7075-T6 and T73. The fracture characteristics of X2021-T81 are about equal to those of 2014-T651 and equal to or greater than those of X7007-T6E136 at temperatures of -320 F and lower.

REFERENCES

1. J. G. Kaufman and Marshall Holt, "Fracture Characteristics of Aluminum Alloys," Alcoa Research Laboratories, Technical Paper No. 18, 1967.

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3. W. F. Brown and John E. Srawley, "Plane-Strain Crack Toughness Testing of High-Strength Metallic Materials," American Society for Testing and Materials, Special Technical Publication No. 410, December 1966.

4. "Recommended Practice for the Determination of Plane-Strain Fracture Toughness," American Society for Testing and Materials, Drafted Method, May 1967.

TABLE I

CHEMICAL COMPOSITIONS OF SOME SAMPLES OF X2021-T81 AND X7007-T6E136 SHEET AND PLATE

Alloy and Temper	Thickness, in.	Sample Number	Element, %											
			Cu	Fe	Si	Mn	Mg	Zn	Cr	Zr	V	Ti	Cd	Sn
X2021-T8E31	1/16 1/2 1	326889 342719 327102	6.08	0.11	0.07	0.25	0.001	0.03	0	0.13	0.08	0.05	0.14	0.03
	1/8	326888	6.19	0.14	0.05	0.31	0.006	0.03	0	0.13	0.08	0.06	0.14	0.05
	1/4	342352	6.21	0.12	0.07	0.26	0.002	0.02	0	0.14	0.08	0.06	0.14	0.04
	2-1/2	326402	6.20	0.14	0.06	0.32	0.01	0.02	0	0.13	0.09	0.06	0.13	0.05
	Nominal		6.30	--	--	0.30	--	--	---	0.18	0.10	0.06	0.15	0.05
	Tentative Limits		5.8-6.8	0.30	0.20	0.20-0.40	0.02	0.10	---	0.10-0.25	0.05-0.15	0.02-0.10	0.05-0.20	0.03-0.08
X7007-T6E136	1/16 1	327105 327108	0.06	0.11	0.05	0.21	1.76	6.55	0.11	0.10	--	0.03	--	--
	1/8 1/4 1/2	326790 326788 326786	0.14	0.19	0.08	0.20	1.77	6.18	0.20	0.10	--	0.05	--	--
	2-1/2	295582	0.14	0.14	0.06	0.21	1.51	6.83	0.10	0.10	--	0.03	--	--
	Nominal		0.10	--	--	0.20	1.80	6.50	0.12	0.12	--	0.04	--	--
	Tentative Limits		0.25	0.40 Si + Fe		0.40	1.4-2.2	6.0-7.0	0.05-0.25	0.05-0.25	--	0.01-0.06	--	--

TABLE II

FABRICATING PROCEDURES FOR X2021-T81 AND X7007-T6E136 SHEET AND PLATE

Alloy and Temper	Heat Treating Temperature, °F	Quench	Pre-Aging	Stretch	Aging
X2021-T8E31	990	Cold Water	1 hr. at 300 F	1.0% max.	16 hrs. at 325 F
X7007-T6E136	860	Controlled Moderate Rate	--	1.5-3.0%	16 hrs. at 275 F

TABLE III

MECHANICAL PROPERTIES OF SOME X2021-T81 SHEET AND PLATE
(M.T. No. 013167-A)

Thickness, in.	Sample Number	Direction of Specimens	Tensile Strength, psi	Tensile Yield Strength, psi	Elongation in 2 in. or 4D, %	Compressive Yield Strength, psi	Shear Data: Direction and Plane of Loading*	Shear Data: Shear Strength, psi	Bearing Strength, psi e/D=1.5	Bearing Strength, psi e/D=2.0	Bearing Yield Strength, psi e/D=1.5	Bearing Yield Strength, psi e/D=2.0	Hardness Brinell	Hardness Rockwell
1/16	326889	L	73 400	66 000	7.2	66 000	**	43 700**	118 700	151 400	98 500	116 000	137	B83
		LT	74 400	64 300	9.0	69 000	**	43 700**	118 300	151 600	98 200	116 100		
1/8	326888	L	72 800	63 400	10.2	64 000	--	--	112 600	145 400	94 300	113 300	137	B83
		LT	73 400	62 400	9.5	67 600	--	--	113 400	144 600	95 500	111 800		
1/4	342352	L	72 900	65 800	11.8	69 400	YZ-Y YZ-Z	47 100 44 800	112 400	144 800	97 400	116 400	143	B84
		LT	74 000	65 600	9.5	68 200	XZ-X XZ-Z	44 800 43 600	114 600	144 200	100 600	120 400		
1/2	342719	L	73 700	64 700	10.5	65 500	YZ-Y YZ-Z	47 300 44 700	109 400	145 000	96 000	113 500	146	B86
		LT	74 100	63 600	7.0	68 400	XZ-X XZ-Z	45 100 42 800	113 400	144 900	98 000	111 400		
1	327102	L	74 400	66 600	8.5	66 200	YZ-Y YZ-Z	47 400 44 800	109 000 85 400†	140 800 120 900†	96 600 --- #	114 800 110 500†	134	B79
		LT	73 700	64 700	5.0	68 000	XZ-X XZ-Z	44 700 41 600	112 200 91 000†	141 100 126 900†	99 200 --- #	116 500 112 100†		
2-1/2	326402	L	72 100	62 700	7.0	62 500	YZ-Y YZ-Z	44 700 42 400	99 200 85 600†	133 200 117 400†	93 600 85 000†	109 300 104 000†	---	---
		LT	68 900	61 600	3.8	63 800	XZ-X XZ-Z	43 900 41 400	103 000 90 000†	134 100 122 400†	91 400 86 800†	109 400 104 600†		
		ST	68 800	59 900	4.0	61 000	XY-X	35 400	---	---	---	---		
Averages‡		L	73 400	65 300	9.5‡‡	66 200	YZ-Y YZ-Z	47 300 44 800	112 400 85 400†	145 500 120 900†	96 600 --- #	114 800 110 500†	139	B83
		LT	73 900	64 100	6.0‡‡	68 200	XZ-X XZ-Z	44 900 42 700	114 400 91 000†	145 300 126 900†	98 300 --- #	115 200 112 100†		

* First two letters describe the plane of shear and the last letter describes the direction of loading:
X - longitudinal, Y - long transverse, Z - short transverse.

** Blanking shear values.

† Edgewise specimens. All others were flatwise.

\# Did not reach 2.0 per cent offset.

‡ Does not include data for 2-1/2 in. thick plate.

‡‡ Average elongation in 4D.

TABLE IV

MECHANICAL PROPERTIES OF SOME X7007-T6E136 SHEET AND PLATE
(M.T. No. 013167-A)

Thickness, in.	Sample Number	Direction of Specimens	Tensile Strength, psi	Tensile Yield Strength, psi	Elongation in 2 in. or 4D, %	Compressive Yield Strength, psi	Shear Data: Direction and Plane of Loading*	Shear Data: Shear Strength, psi	Bearing Strength, psi: e/D=1.5	Bearing Strength, psi: e/D=2.0	Bearing Yield Strength, psi: e/D=1.5	Bearing Yield Strength, psi: e/D=2.0	Hardness: Brinell	Hardness: Rockwell
1/16	327105	L	70 200	68 400	8.8	67 600	---**	43 800**	111 200	145 800	94 600	113 600	140	B85
		LT	74 000	70 500	9.2	74 900	---**	43 800**	114 500	149 000	96 100	116 100		
1/8	326790	L	73 700	68 500	10.8	68 800	---	---	106 600	138 000	90 500	106 800	132	B82
		LT	70 800	65 600	12.0	69 500	---	---	108 200	139 800	89 900	108 700		
1/4	326788	L	73 200	66 800	12.0	66 600	YZ-Y YZ-Z	44 300 41 700	106 400	137 300	89 600	108 400	135	B80
		LT	70 600	64 100	12.2	67 600	XZ-X XZ-Z	43 800 40 100	107 200	137 200	91 400	110 500		
1/2	326786	L	72 000	65 200	14.0	63 200	YZ-Y YZ-Z	42 200 39 200	105 400	136 400	90 000	106 000	134	B79
		LT	70 800	64 200	13.0	66 500	XZ-X XZ-Z	41 700 38 800	105 100	136 400	87 800	108 200		
1	327108	L	77 000	73 100	13.0	72 500	YZ-Y YZ-Z	44 300 42 200	109 900 95 800†	141 600 128 900†	95 300 90 600†	111 200 111 800†	138	B83
		LT	73 800	68 800	13.0	73 600	XZ-X XZ-Z	44 300 41 500	109 600 99 500†	142 700 131 100†	92 500 90 000†	113 000 111 000†		
2-1/2	295582	L	70 900	69 800	13.5	67 600	YZ-Y YZ-Z	46 700 46 100	114 400 101 200†	146 300 135 000†	100 000 93 600†	114 300 111 800†	---	---
		LT	72 600	68 500	12.8	72 200	XZ-X XZ-Z	47 100 45 000	115 500 102 400†	147 600 134 200†	100 800 93 000†	116 500 112 900†		
		ST	74 000	65 800	7.5	73 400	XY-X	40 500	--	--	--	--		
Averages		L	73 000	68 600	13.5‡	67 700	YZ-Y YZ-Z	44 400 42 300	109 000 98 500†	140 900 132 000†	93 300 92 100†	110 000 111 800†	136	B82
		LT	72 100	67 000	12.9‡	70 700	XZ-X XZ-Z	44 200 41 400	110 000 101 000†	142 100 132 600†	93 100 91 500†	112 200 112 000†		
		ST	74 000	65 800	7.5‡	73 400	XY-X	40 500	--	--	--	--		

* First two letters describe the plane of shear and the last letter describes the direction of loading:
X - longitudinal, Y - long transverse, Z - short transverse.

** Blanking shear values.

† Edgewise specimens. All others were flatwise.

‡ Average elongation in 4D.

TABLE V

RELATIONSHIPS AMONG THE PROPERTIES OF SOME
X2021-T81 AND X7007-T6E136 SHEET AND PLATE
(M.T. No. 013167-A)

Thickness, in.	Sample Number	LONGITUDINAL/LONG TRANSVERSE								LONG TRANSVERSE/LONG TRANSVERSE						SHORT TRANSVERSE/LONG TRANSVERSE			
		TS/TS	TYS/TYS	CYS/TYS	SS*/TS	BS/TS# e/D=1.5	BS/TS# e/D=2.0	BYS/TYS# e/D=1.5	BYS/TYS# e/D=2.0	CYS/TYS	SS*/TS	BS/TS# e/D=1.5	BS/TS# e/D=2.0	BYS/TYS# e/D=1.5	BYS/TYS# e/D=2.0	TS/TS	TYS/TYS	CYS/TYS	SS†/TS
									X2021-T81										
1/16	326889	0.99	1.03	1.03	0.59	1.60	2.03	1.53	1.80	1.07	0.59	1.59	2.04	1.53	1.81	--	--	--	--
1/8	326888	0.99	1.02	1.03	--	1.53	1.98	1.51	1.82	1.08	--	1.54	1.97	1.53	1.79	--	--	--	--
1/4	342352	0.99	1.00	1.06	0.61	1.52	1.96	1.48	1.77	1.04	0.59	1.55	1.95	1.53	1.84	--	--	--	--
1/2	342719	0.99	1.02	1.03	0.60	1.48	1.96	1.51	1.78	1.08	0.58	1.53	1.96	1.54	1.75	--	--	--	--
1	327102	1.01	1.03	1.02	0.61	1.48	1.91	1.49	1.77	1.05	0.56	1.52	1.91	1.53	1.80	--	--	--	--
2-1/2	326402	1.05	1.02	1.01	0.62	1.44	1.93	1.52	1.77	1.04	0.60	1.49	1.95	1.48	1.78	1.00	0.97	0.99	0.51
Averages‡		0.99	1.02	1.03	0.60	1.52	1.97	1.50	1.79	1.06	0.58	1.55	1.97	1.53	1.80	--	--	--	--
									X7007-T6E136										
1/16	327105	0.95	0.97	0.96	0.59	1.50	1.97	1.34	1.61	1.06	0.59	1.55	2.01	1.36	1.65	--	--	--	--
1/8	326790	1.04	1.04	1.05	--	1.51	1.95	1.38	1.63	1.06	--	1.53	1.97	1.37	1.66	--	--	--	--
1/4	326788	1.04	1.04	1.04	0.59	1.51	1.94	1.40	1.69	1.05	0.57	1.52	1.94	1.43	1.72	--	--	--	--
1/2	326786	1.02	1.02	0.98	0.55	1.49	1.93	1.40	1.65	1.04	0.55	1.48	1.93	1.37	1.69	--	--	--	--
1	327108	1.05	1.06	1.05	0.57	1.49	1.92	1.39	1.62	1.07	0.56	1.49	1.93	1.34	1.64	--	--	--	--
2-1/2	295582	0.98	1.02	0.99	0.63	1.58	2.02	1.46	1.67	1.05	0.62	1.59	2.03	1.47	1.70	1.02	0.96	1.07	0.56
Averages		1.01	1.02	1.01	0.59	1.51	1.96	1.40	1.64	1.06	0.58	1.53	1.97	1.39	1.68	1.02	0.96	1.07	0.56

* Shear load applied in the short transverse (Z) direction.
\# Flatwise specimens.
† Shear load applied in the longitudinal (X) direction.
‡ Does not include ratios for 2-1/2 in. plate.

TABLE VI

TENSILE PROPERTIES AT THE t/4 AND t/2 LOCATIONS
IN 2-1/2-IN. X2021-T81 AND X7007-T6E136 PLATE

(M.T. No. 013167-A)

Alloy and Temper	Sample Number	Direction of Specimens	Location of Specimens *	Tensile Strength, psi	Yield Strength, psi	Elongation in 4D, %
X2021-T8E31	326402	L	t/4	72 100	62 700	7.0
			t/2	69 000	59 600	8.5
		T	t/4	68 900	61 000	3.8
			t/2	67 600	58 000	5.0
X7007-T6E136	295582	L	t/4	70 900	69 800	13.5
			t/2	77 800	75 300	10.5
		T	t/4	72 600	68 500	12.8
			t/2	76 200	72 400	10.5

* t/4 - midway between center of thickness and surface of plate

t/2 - center of thickness of plate

TABLE VII

TENSILE AND NOTCH-TENSILE PROPERTIES OF SOME X2021-T81 AND X7007-T6E136 SHEET AND PLATE AT ROOM AND SUBZERO TEMPERATURES

(M.T. No. 013167-A)

Thick-ness, in.	Sample Number	Temper-ature, °F	LONGITUDINAL: Tensile Strength, psi	LONGITUDINAL: Yield Strength, psi	LONGITUDINAL: Elong. in 2 in. or 4D, %	LONGITUDINAL, for K_t = 16*: Notch-Tensile Strength, psi	LONGITUDINAL, for K_t = 16*: Notch-Strength Ratio NTS/TS	LONGITUDINAL, for K_t = 16*: Notch-Yield Ratio NTS/TYS	LONGITUDINAL, for K_t = 10*: Notch-Tensile Strength, psi	LONGITUDINAL, for K_t = 10*: Notch-Strength Ratio NTS/TS	LONGITUDINAL, for K_t = 10*: Notch-Yield Ratio NTS/TYS	LONG-TRANSVERSE: Tensile Strength, psi	LONG-TRANSVERSE: Yield Strength, psi	LONG-TRANSVERSE: Elong. in 2 in. or 4D, %	LONG-TRANSVERSE, for K_t = 16*: Notch-Tensile Strength, psi	LONG-TRANSVERSE, for K_t = 16*: Notch-Strength Ratio NTS/TS	LONG-TRANSVERSE, for K_t = 16*: Notch-Yield Ratio NTS/TYS	LONG-TRANSVERSE, for K_t = 10*: Notch-Tensile Strength, psi	LONG-TRANSVERSE, for K_t = 10*: Notch-Strength Ratio NTS/TS	LONG-TRANSVERSE, for K_t = 10*: Notch-Yield Ratio NTS/TYS
X2021-T81																				
1/16	326889	RT	73 400	66 000	7.2	50 700	0.69	0.77	--	--	--	74 400	64 300	9.0	48 000	0.65	0.75	--	--	--
		-112	79 700	70 300	8.8	--	--	--	--	--	--	80 500	69 400	8.5	--	--	--	--	--	--
		-320	91 400	80 000	10.5	--	--	--	--	--	--	92 000	77 600	10.8	--	--	--	--	--	--
1/8	326888	RT	72 800	63 400	10.2	53 000	0.73	0.84	62 100	0.85	0.98	73 400	62 400	9.5	48 000	0.65	0.77	57 400	0.78	0.92
		-112	79 100	69 300	10.0	62 400	0.79	0.90	71 600	0.91	1.03	79 600	65 800	9.5	58 000	0.73	0.88	71 600	0.90	1.09
		-320	90 800	75 700	10.8	69 600	0.77	0.92	72 400	0.80	0.96	92 200	73 500	10.0	60 900	0.66	0.83	71 100	0.77	0.97
		-452	97 000	82 800	9.0	74 500	0.77	0.90	88 000	0.91	1.06	101 000	82 000	9.8	70 600	0.70	0.86	84 800	0.84	1.03
1/4	342352	RT	72 900	65 800	11.8	35 600	0.49	0.54	--	--	--	74 000	65 600	9.5	27 700	0.37	0.42	--	--	--
1	327102	RT	74 400	66 600	8.5	84 600	1.14	1.27	87 400	1.18	1.31	73 700	64 700	5.0	72 400	0.98	1.12	77 000	1.04	1.19
		-112	79 400	69 500	9.5	95 800	1.21	1.38	100 600	1.27	1.45	81 000	70 600	6.2	85 700	1.06	1.21	87 400	1.08	1.34
		-320	90 200	78 900	11.0	106 100	1.18	1.34	111 000	1.23	1.41	91 600	77 200	7.2	92 000	1.00	1.19	93 200	1.02	1.21
		-452	101 600	86 100	12.5	116 400	1.15	1.35	122 000	1.20	1.42	102 900	86 400	8.8	103 600	1.01	1.20	115 600	1.12	1.34
Averages		RT†	73 400	65 400	--	--	--	--	--	--	--	73 900	64 200	--	--	--	--	--	--	--
		-112	79 400	69 700	--	--	--	--	--	--	--	80 300	68 600	--	--	--	--	--	--	--
		-320	90 800	78 200	--	--	--	--	--	--	--	91 900	76 100	--	--	--	--	--	--	--
		-452	99 300	84 400	--	--	--	--	--	--	--	102 000	84 200	--	--	--	--	--	--	--
X7007-T6E136																				
1/16	327105	RT	70 200	68 400	8.8	72 400	1.03	1.06	--	--	--	74 000	70 500	9.2	75 000	1.01	1.06	--	--	--
		-112	77 800	71 800	7.8	--	--	--	--	--	--	81 600	76 700	9.2	--	--	--	--	--	--
		-320	87 600	79 900	10.8	--	--	--	--	--	--	94 600	85 500	5.5	--	--	--	--	--	--
1/8	326790	RT	73 700	68 500	10.8	73 200	0.99	1.07	77 400	1.05	1.13	70 800	65 600	12.0	72 400	1.02	1.10	76 600	1.08	1.17
		-112	83 000	76 400	9.5	75 000	0.90	0.98	83 200	1.00	1.09	79 600	72 600	11.0	72 800	0.91	1.00	81 600	1.03	1.12
		-320	99 000	84 500	11.5	61 100	0.62	0.72	77 800	0.79	0.92	93 000	81 200	12.5	51 600	0.55	0.64	73 600	0.79	0.91
		-452	96 900	83 800	8.5	66 800	0.71	0.80	83 500	0.88	1.00	95 200	82 200	10.2	57 900	0.61	0.70	77 200	0.81	0.94
1/4	326788	RT	73 200	66 800	12.0	65 600	0.90	0.98	--	--	--	70 600	64 100	12.2	60 000	0.85	0.93	--	--	--
1	327108	RT	77 000	73 100	13.0	107 400	1.40	1.47	107 000	1.39	1.46	73 800	68 800	13.0	100 600	1.36	1.46	104 800	1.42	1.52
		-112	87 500	81 300	11.2	104 000	1.19	1.28	106 400	1.22	1.31	82 300	74 400	10.8	86 900	1.06	1.16	93 200	1.13	1.25
		-320	101 400	89 300	12.8	95 200	0.94	1.07	109 800	1.08	1.23	95 200	84 500	11.2	81 600	0.86	0.96	88 200	0.93	1.04
		-452	116 100	98 100	14.2	94 000	0.81	0.96	118 600	1.02	1.21	107 100	91 800	11.5	85 400	0.80	0.93	104 600	0.98	1.14
Averages		RT†	73 000	68 600	--	--	--	--	--	--	--	72 100	67 000	--	--	--	--	--	--	--
		-112	82 800	76 500	--	--	--	--	--	--	--	81 200	74 600	--	--	--	--	--	--	--
		-320	96 000	84 600	--	--	--	--	--	--	--	94 300	83 700	--	--	--	--	--	--	--
		-452	106 500	91 000	--	--	--	--	--	--	--	101 200	87 000	--	--	--	--	--	--	--

* The designs of the various notch-tensile specimens are shown in Figs. 9 to 13.

† Average room-temperature properties from Tables III and IV.

TABLE VIII

TEAR PROPERTIES OF SOME X2021-T81 AND X7007-T6E136 SHEET AND PLATE
(M.T. No. 013167-A)

Thickness, in.	Sample Number	Temperature, °F	Longitudinal: Tear Strength, psi	Longitudinal: Tear Strength / Yield Strength	Longitudinal: Unit Propagation Energy, in.-lb/in.²	Long-Transverse: Tear Strength, psi	Long-Transverse: Tear Strength / Yield Strength	Long-Transverse: Unit Propagation Energy, in.-lb/in.²	Short-Transverse: Tear Strength, psi	Short-Transverse: Tear Strength / Yield Strength	Short-Transverse: Unit Propagation Energy, in.-lb/in.²
X2021-T81											
1/16	326889	RT	51 000	0.77	100	48 700	0.76	85	--	--	--
		-112	61 500	0.87	175	58 600	0.84	180	--	--	--
		-320	69 800	0.87	185	64 800	0.84	155	--	--	--
1/8	326888	RT	58 000	0.91	280†	49 700	0.80	105	--	--	--
1/4	342352	RT	59 600	0.91	145	45 400	0.69	65	--	--	--
1	327102	RT	72 800	1.09	375†	41 600	0.64	60	--	--	--
2-1/2	326402	RT	64 900	1.03	245	47 600	0.77	95	45 200	0.76	90
	Averages	RT	61 300	0.94	230	46 600	0.73	80	45 200	0.76	90
X7007-T6E136											
1/16	327105	RT	94 100	1.38	985	95 600	1.36	575	--	--	--
		-112	86 600	1.21	445	79 200	1.03	270	--	--	--
		-320	73 400	0.92	250	62 500	0.73	150	--	--	--
1/8	326790	RT	92 300	1.35	730	91 000	1.39	530	--	--	--
1/4	326788	RT	90 200	1.35	600	89 600	1.40	395	--	--	--
1	327108	RT	94 400	1.29	515	90 600	1.32	315#	--	--	--
2-1/2	295582	RT	93 400	1.34	830	87 200	1.28	340	63 800	0.97	135#
	Averages	RT	92 900	1.34	730	90 800	1.35	430	63 800	0.97	135

† Diagonal fractures.

Rapid fracture.

TABLE IX

PLANE-STRAIN FRACTURE TOUGHNESS DATA DETERMINED WITH CENTER-NOTCHED SPECIMENS#
FROM 1/4-IN. THICK X2021-T81 AND X7007-T6E136 SHEET

(M.T. No. 013167-A)

Sample Number	Direction of Specimens	Specimen Number	Tensile Yield Strength, σ_{ys} psi	Crack Length, a in.	At 5% Secant Offset				Net-Section Fracture Strength, psi	NSFS/TYS
					Gross Stress, σ psi	Stress-Intensity Factor* K_{Ic} $psi\sqrt{in.}$	Strain-Energy Release Rate* G_{Ic} in.-lb/in.^{2}	$t^{\dagger}$ $\left(\frac{K_{Ic}}{\sigma_{YS}}\right)^2$		
					X2021-T81					
342352	L	1	65 800	0.790	14 000	24 500	56	1.80	35 000	0.52
		2	65 800	0.760	16 300	27 600	72	1.41	36 600	0.56
		3	65 800	0.770	14 500	24 800	58	1.76	35 500	0.54
		Avg.				25 600	62			0.54
	T	1	65 600	0.785	12 300	21 200	42	2.38	15 500	0.24
		2	65 600	0.790	12 900	22 500	47	2.12	16 700	0.25
		3	65 600	0.750	14 900	25 100	58	1.71	18 300	0.28
		Avg.				22 900	49			0.26
					X7007-T6E136					
326788	L	1	66 800	0.770	26 600	46 200	207	0.514	64 000	0.96
		2	66 800	0.780	25 400	44 500	193	0.554	63 500	0.95
		3	66 800	0.770	26 100	45 400	200	0.533	63 200	0.95
		Avg.				45 400	200			0.95
	T	1	64 100	0.760	24 100	41 400	167	0.590	60 000	0.94
		2	64 100	0.790	22 800	40 200	157	0.626	59 700	0.93
		3	64 100	0.795	17 500	30 800	92	1.065	60 100	0.94
		Avg.				37 500	139			0.94

\# Specimen design shown in Fig. 15.

* Plane-strain conditions; see equations page 6

† Critical plane-strain values K_{Ic} and G_{Ic} are considered valid if this ratio is greater than 2.5.

TABLE X

PLANE-STRAIN FRACTURE-TOUGHNESS DATA
DETERMINED WITH NOTCH-BEND SPECIMENS* FROM SOME SAMPLES OF
X2021-T81 AND X7007-T6E136 PLATE

(M.T. No. 013167-A)

Thickness, in.	Sample Number	Direction of Specimens	Specimen Number	Tensile Yield Strength, σ_{ys} psi	Crack Length, a in.	At 5% Secant Offset: Max. Bend Stress, psi	At 5% Secant Offset: Stress Intensity Factor** K_{Ic}, psi $\sqrt{in.}$	At 5% Secant Offset: Strain-Energy Release Rate** G_{Ic}, in-lb/in^2	$\left(\frac{K_{Ic}}{\sigma_{YS}}\right)^2$ †
					X2021-T81				
1/2	342719	L	1	64 700	0.540	143 000	32 200	98	2.02
			2	64 700	0.550	146 400	32 500	101	1.97
			3	64 700	0.480	116 700	27 000	69	2.87
			Avg.				30 600	89	
		T	1	63 600	0.560	105 000	22 500	47	3.99
			2	63 600	0.500	94 600	21 300	43	4.44
			3	63 600	0.500	95 600	21 600	44	4.34
			Avg.				21 800	45	
1	327102	L	1	66 400	0.954	110 000	35 800#	120#	3.52
			2	66 400	0.947	109 000	35 600#	118#	3.57
			3	66 400	0.924	131 200	43 700#	179#	2.36
			Avg.				38 400#	139#	
		T	1	65 200	1.106	79 100	23 900	54	7.62
					X7007-T6E316				
1/2	326786	L	1	65 200	0.594	193 200	42 500	173	1.16
			2	65 200	0.576	164 400	36 100	125	1.61
			3	65 200	0.598	189 800	41 400	164	1.23
			Avg.				40 000	154	
		T	1	64 200	0.598	175 900	37 900	138	1.41
			2	64 200	0.625	186 900	39 000	147	1.33
			3	64 200	0.613	167 600	35 100	119	1.64
			Avg.				37 300	135	
1	327108	L	1	73 000	1.102	143 200	44 400	189	2.75
			2	73 000	1.054	143 900	45 600	200	2.61
			3	73 000	1.234	161 000	46 600	209	2.49
			Avg.				45 500	199	
		T	1	69 100	1.070	126 800	39 600	151	3.09
			2	69 100	1.054	116 400	36 500	128	3.65
			3	69 100	1.059	115 800	36 200	126	3.70
			Avg.				37 400	135	

* Specimen design shown in Fig. 16.

** Plane-strain condition, see equations on page 7

† Critical plane-strain values K_{Ic} and G_{Ic} are considered valid if this ratio is greater than 2-1/2.

\# Fatigue cracks did not propagate on a single plane.

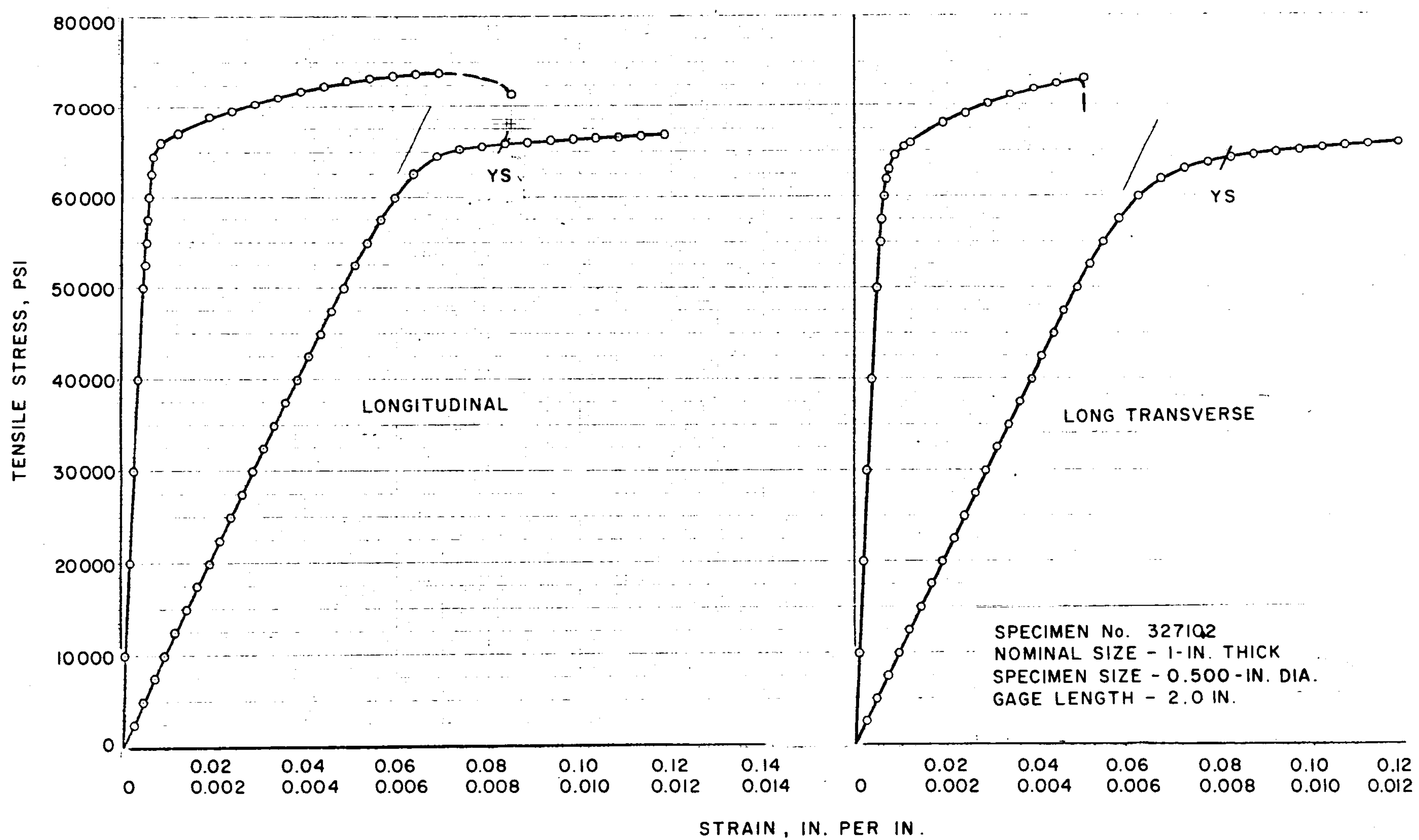


FIGURE 1 - TENSILE STRESS-STRAIN CURVES FOR X2021-T81 PLATE.

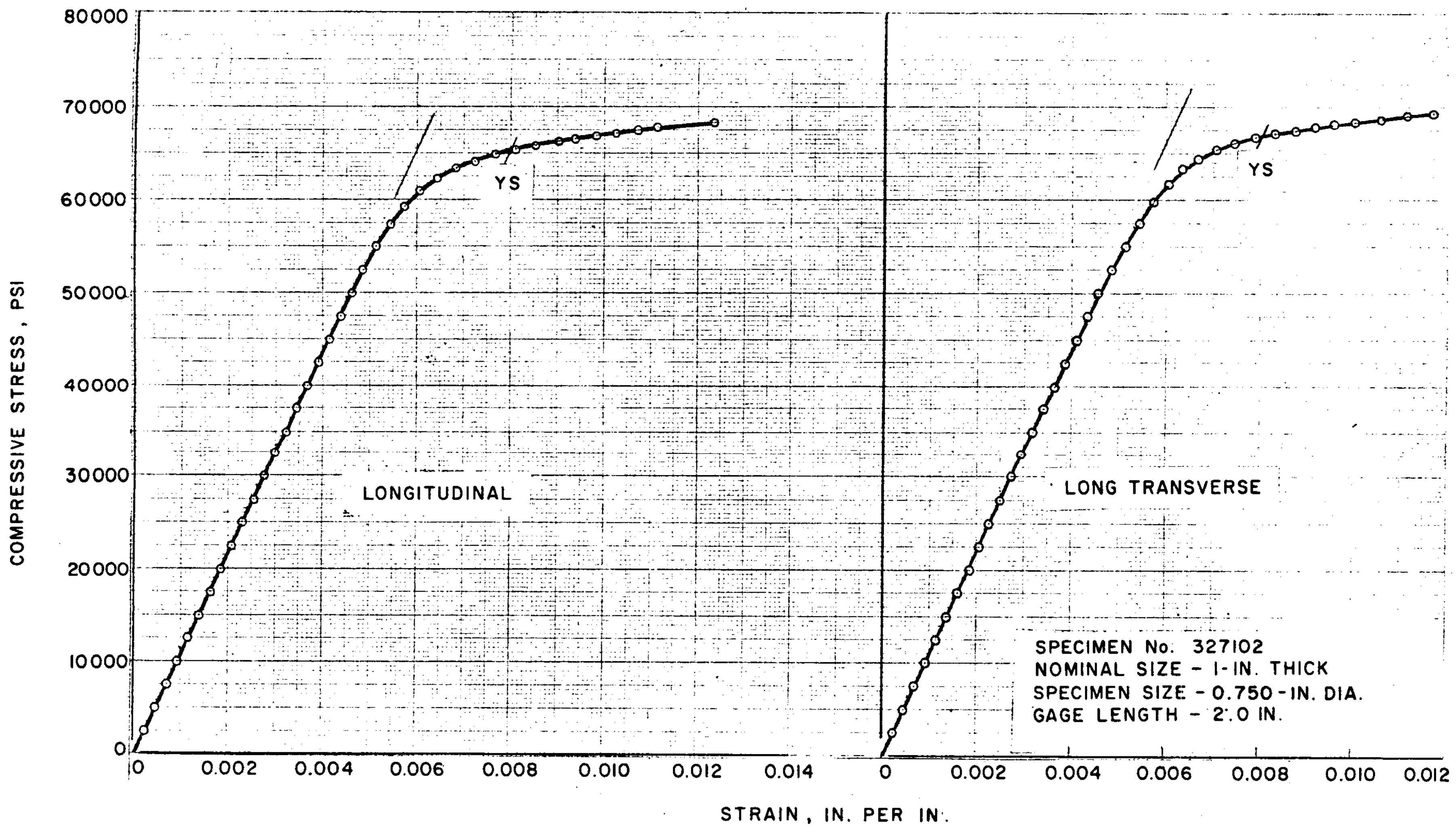


FIGURE 2 - COMPRESSIVE STRESS-STRAIN CURVES FOR X2021-T81 PLATE.

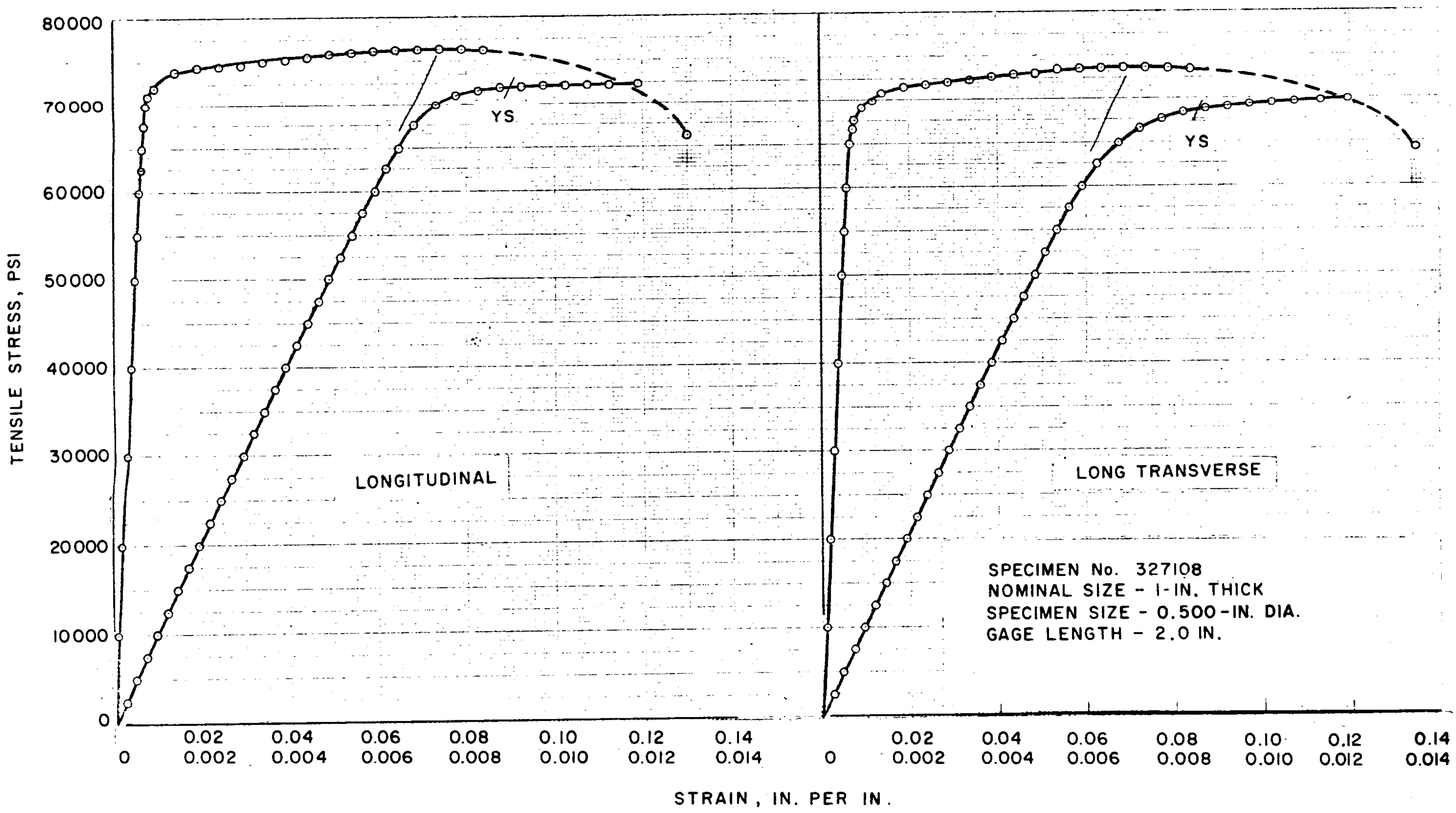


FIGURE 3 - TENSILE STRESS-STRAIN CURVES FOR X7007-T6E136 PLATE

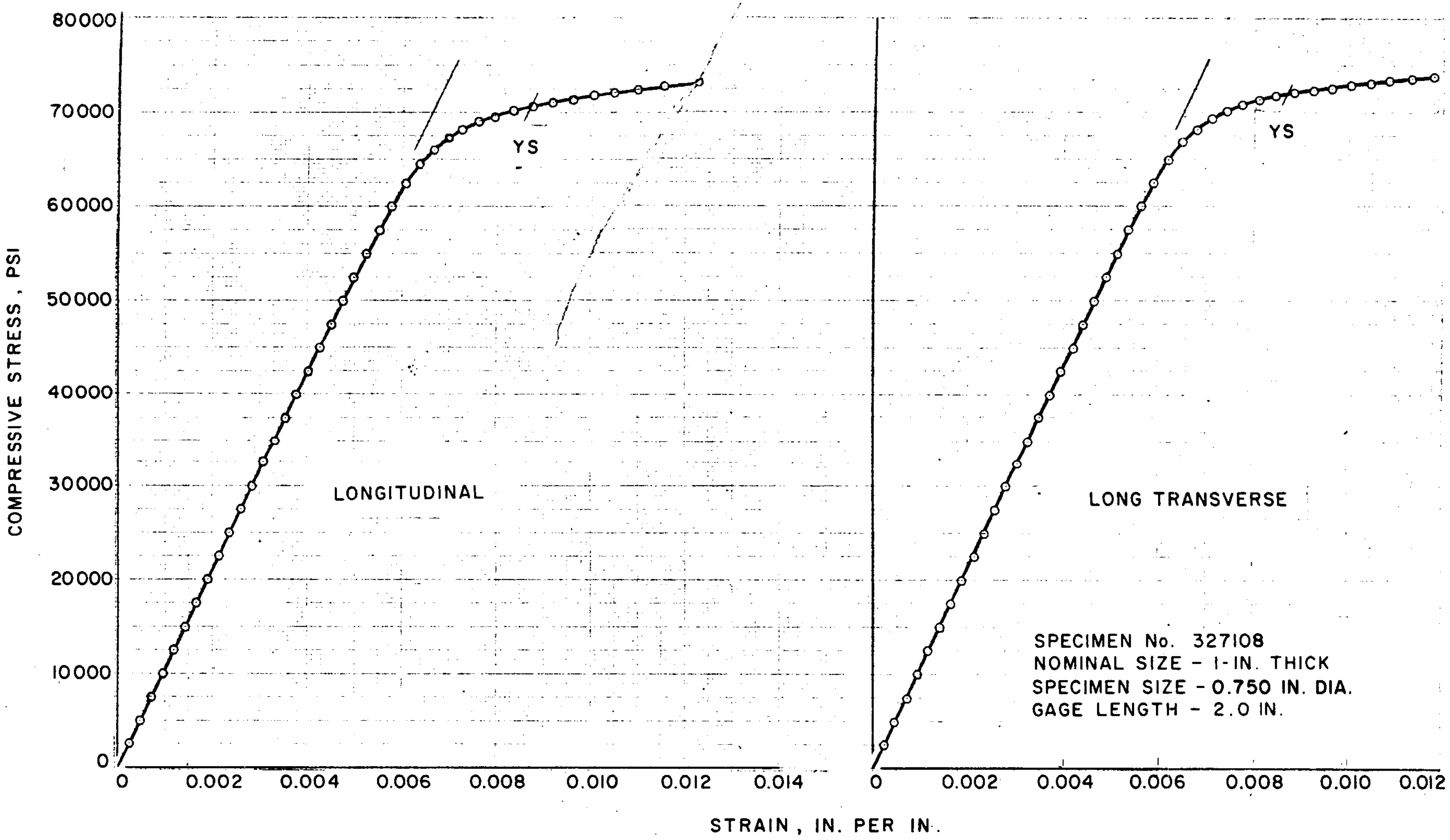


FIGURE 4 - COMPRESSIVE STRESS-STRAIN CURVES FOR X7007-T6E136 PLATE.

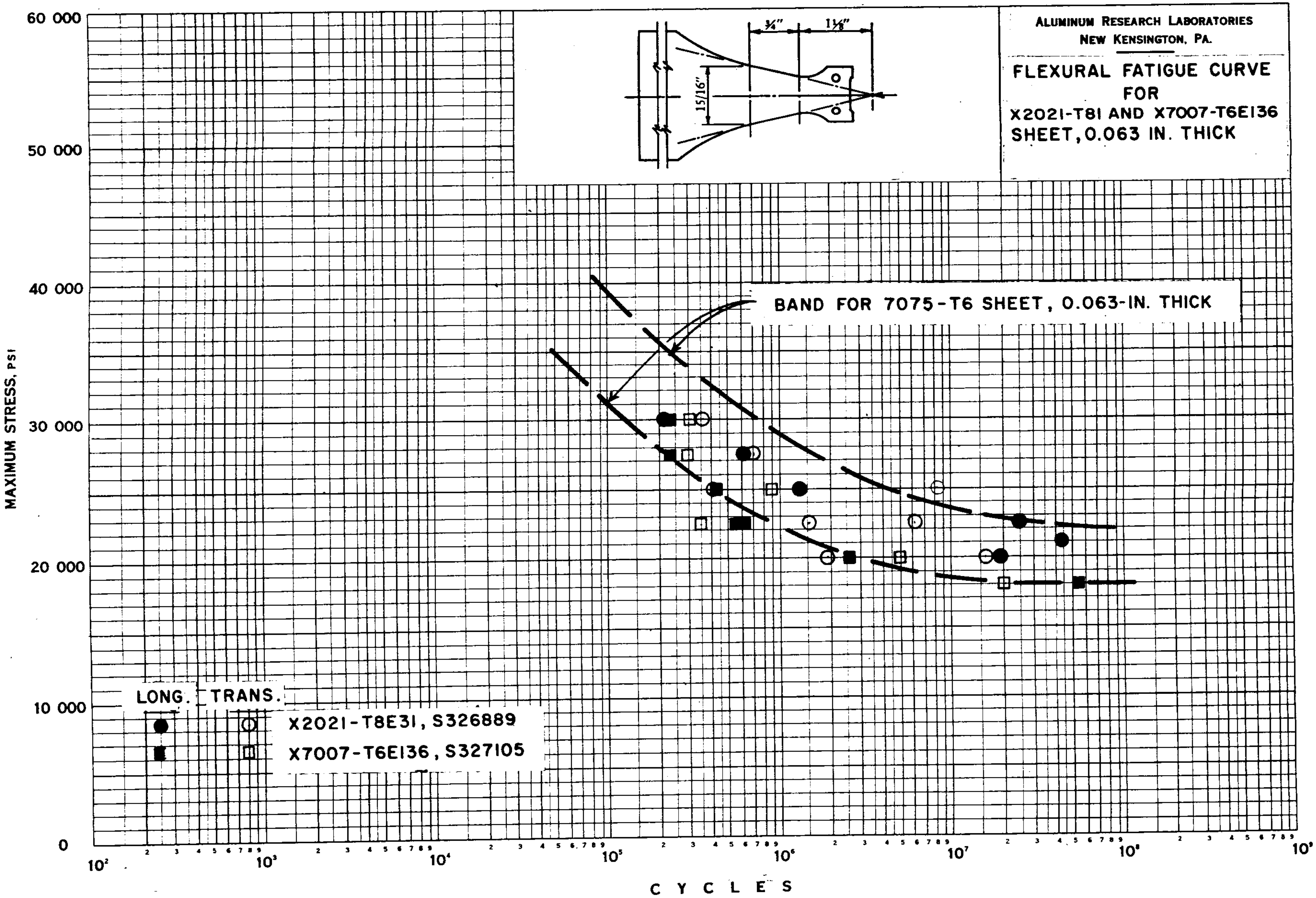


FIGURE 5 - FLEXURAL FATIGUE CURVES FOR X2021-T81 AND X7007-T6E136 0.063 INCH SHEET.

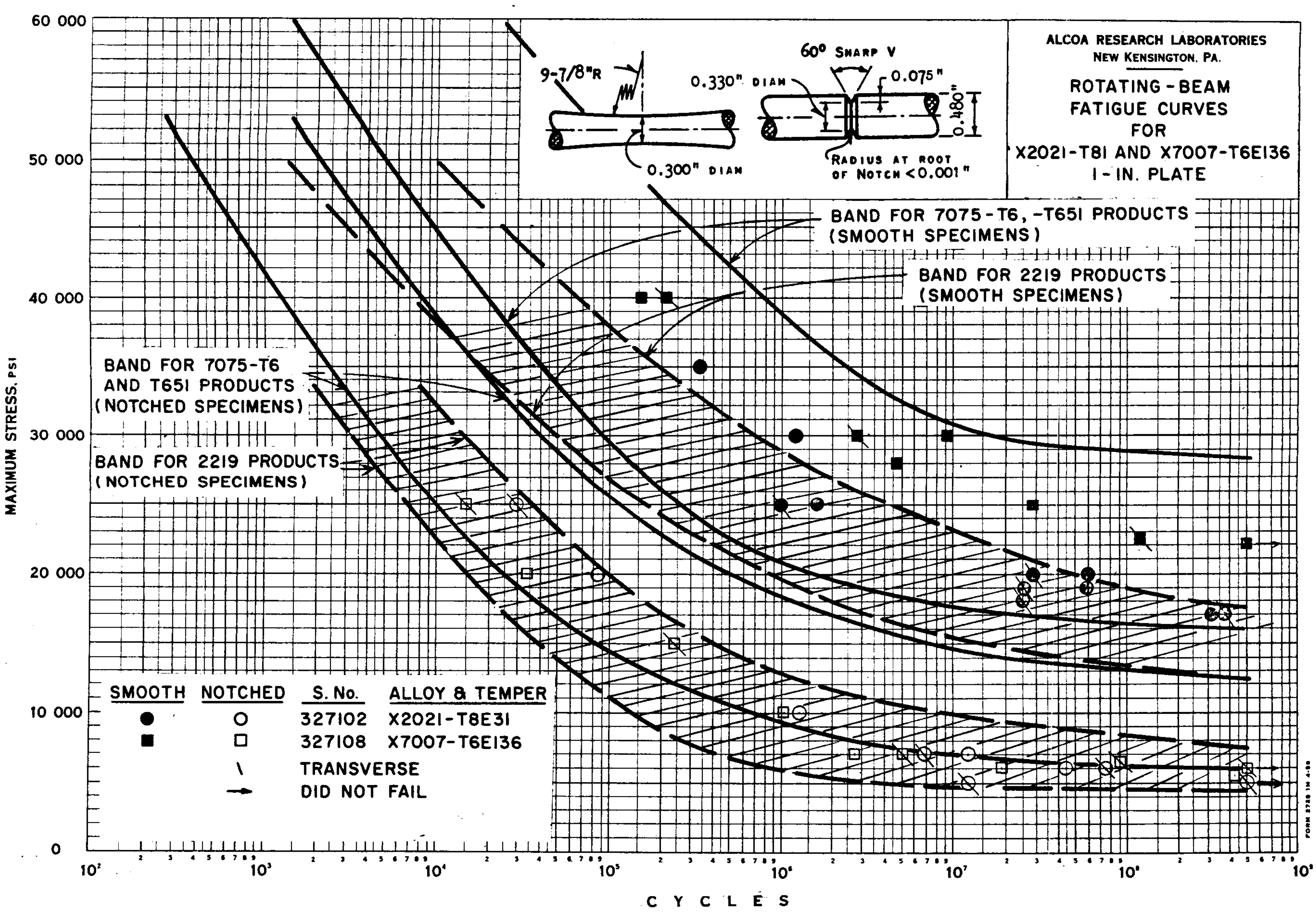


FIGURE 6 - ROTATING-BEAM FATIGUE CURVES FOR X2021-T81 AND X7007-T6E136 1.000 INCH PLATE.

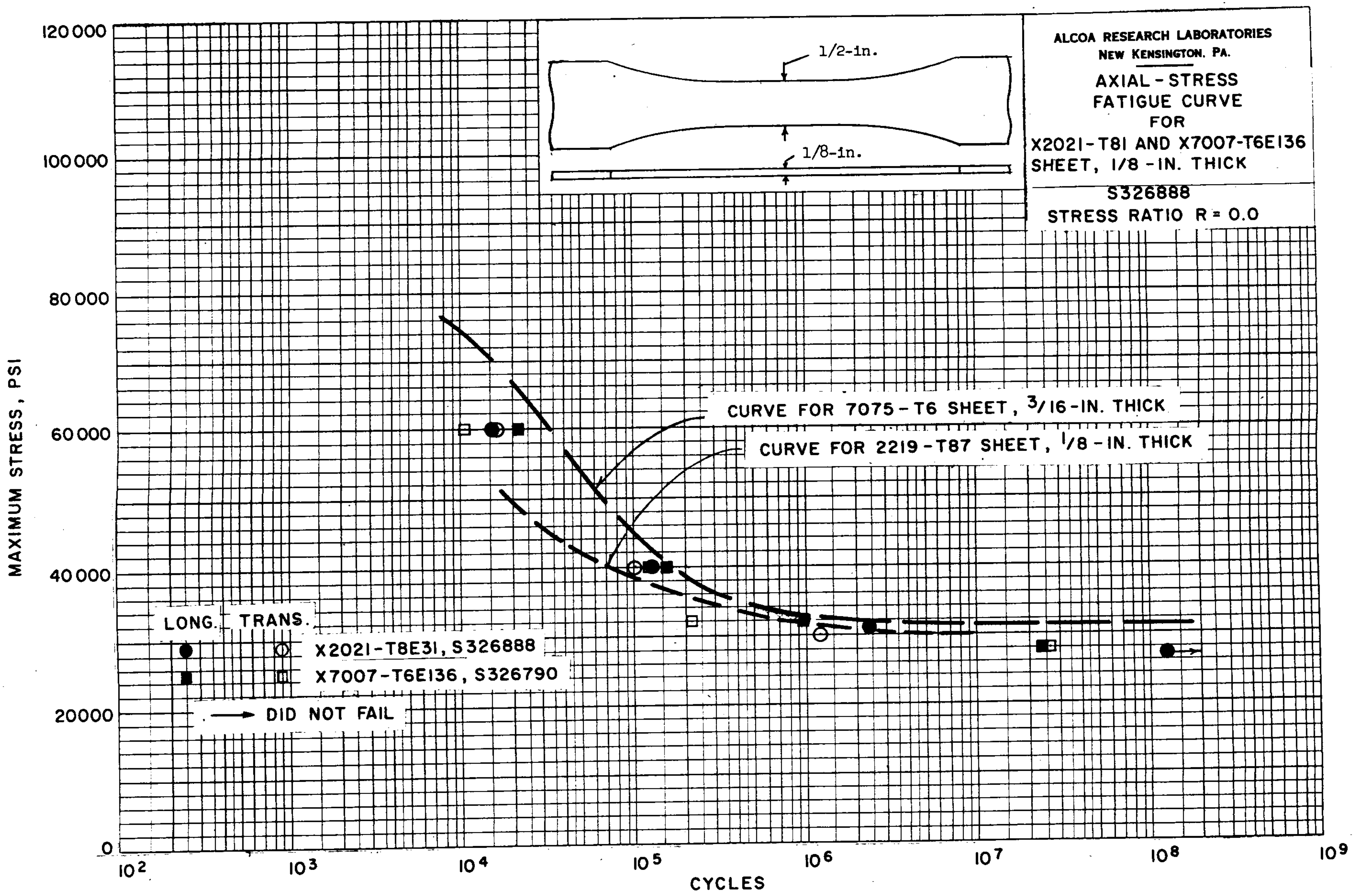


FIGURE 7 - AXIAL-STRESS FATIGUE CURVES FOR X2021-T81 AND X7007-T6E136 0.125 INCH SHEET.

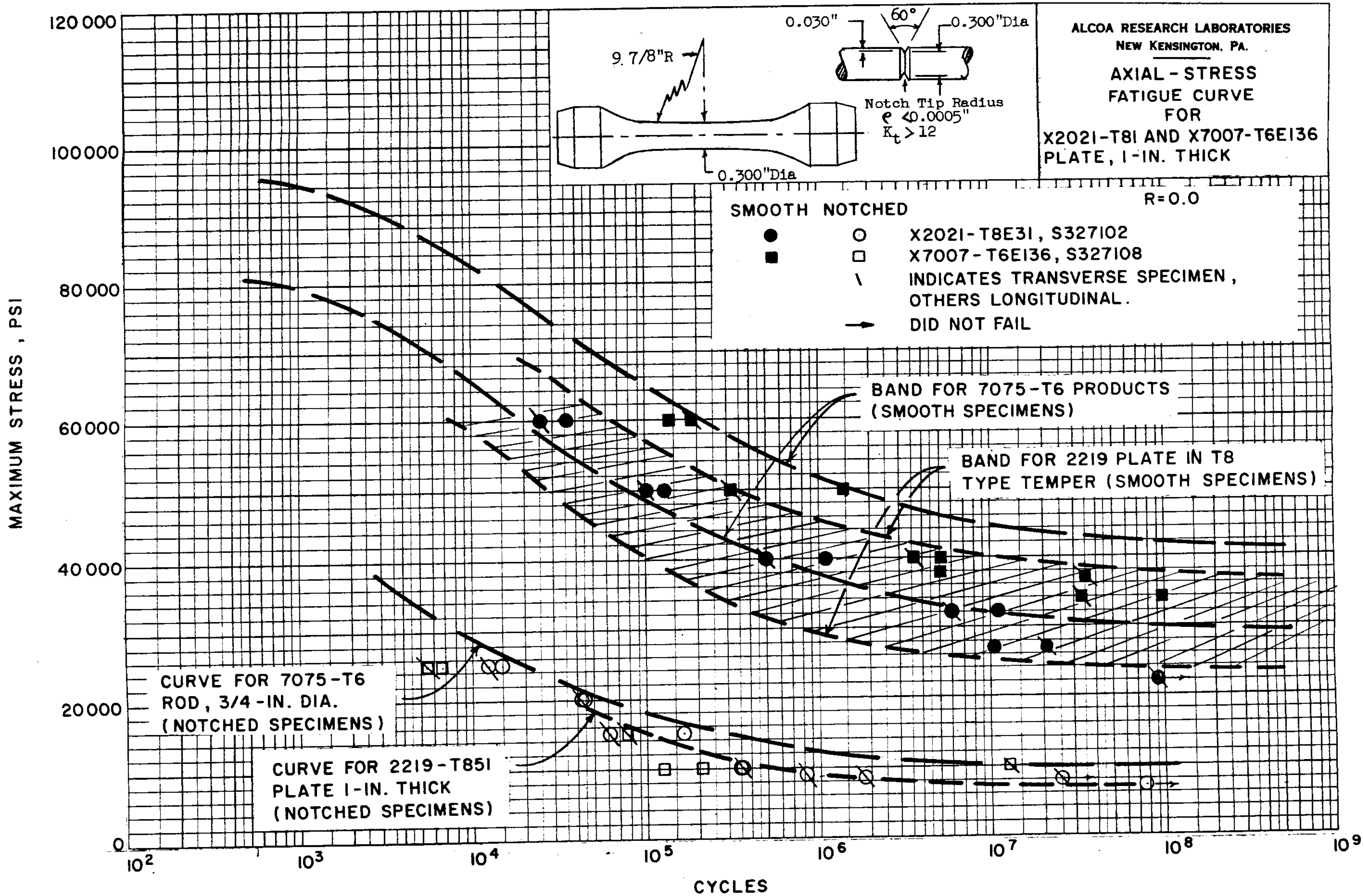


FIGURE 8 - AXIAL-STRESS FATIGUE CURVES FOR X2021-T81 AND X7007-T6E136 1.000 INCH PLATE.

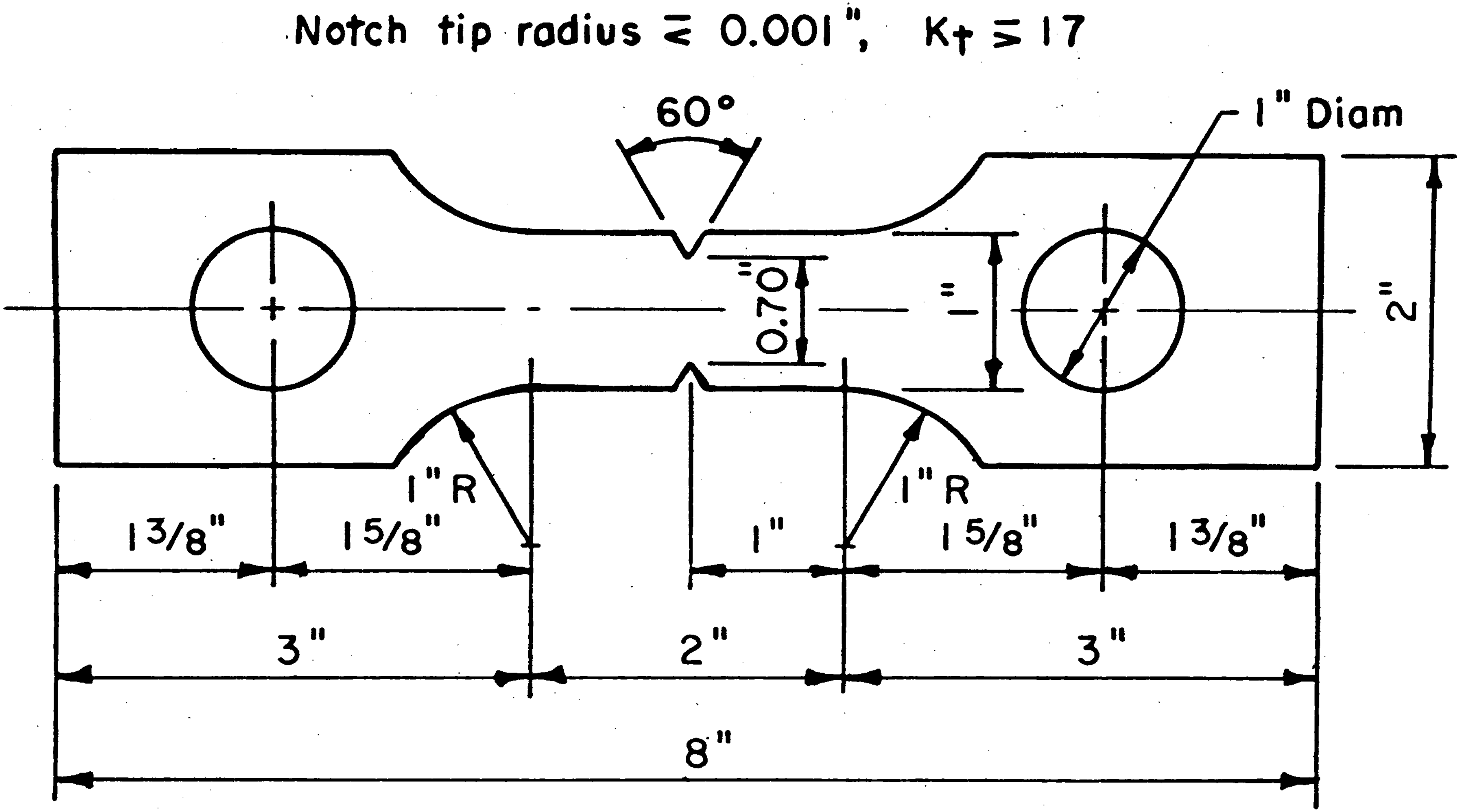


FIGURE 9 - EDGE-NOTCHED SPECIMEN TAKEN FROM SAMPLES OF 1/16 AND 1/8-INCH THICK SHEET. ($K_t \gtrsim 17$)

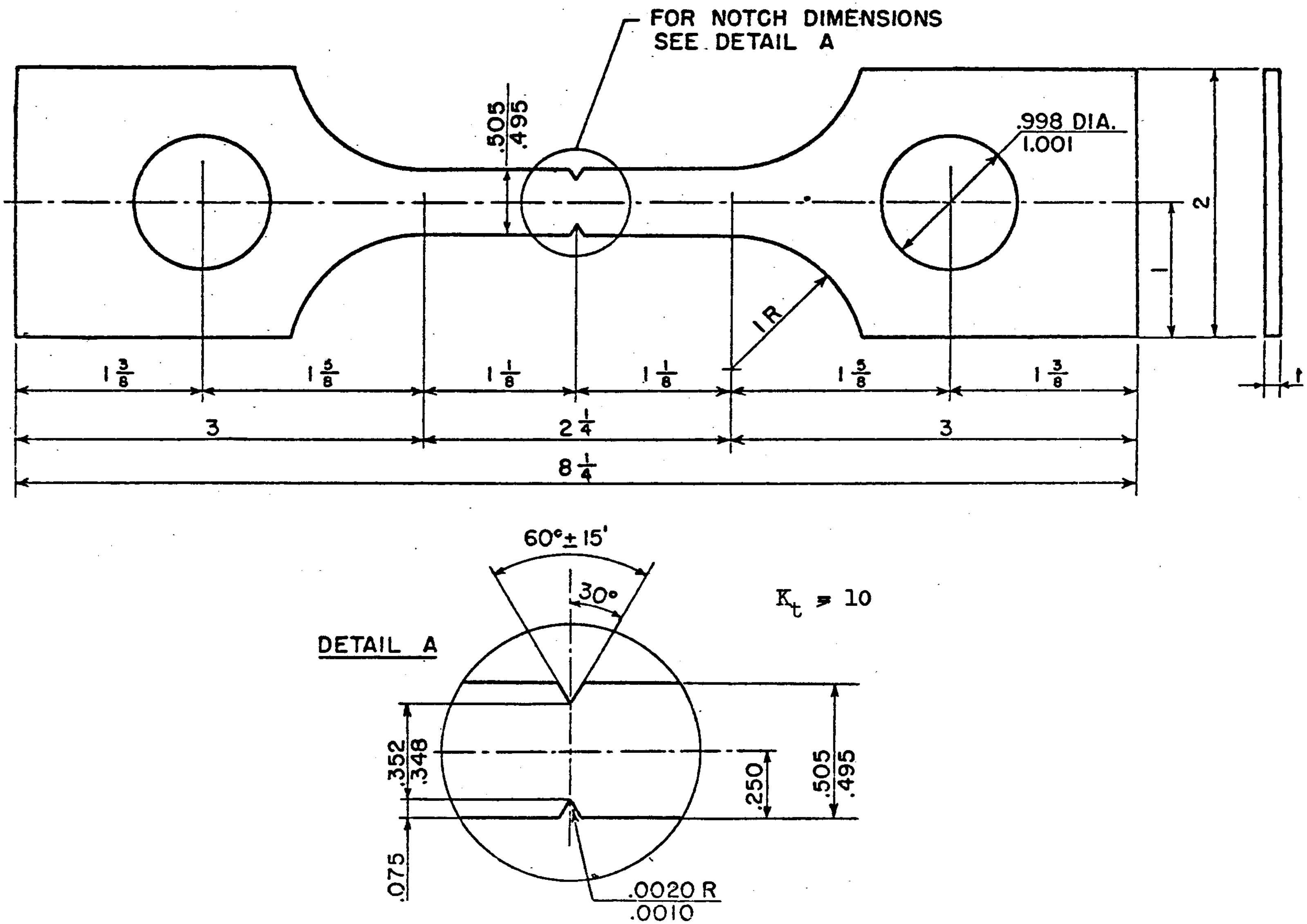


FIGURE 10 - EDGE-NOTCHED SPECIMEN TAKEN FROM 1/8-INCH THICK SHEET. ($K_t \leq 10$)

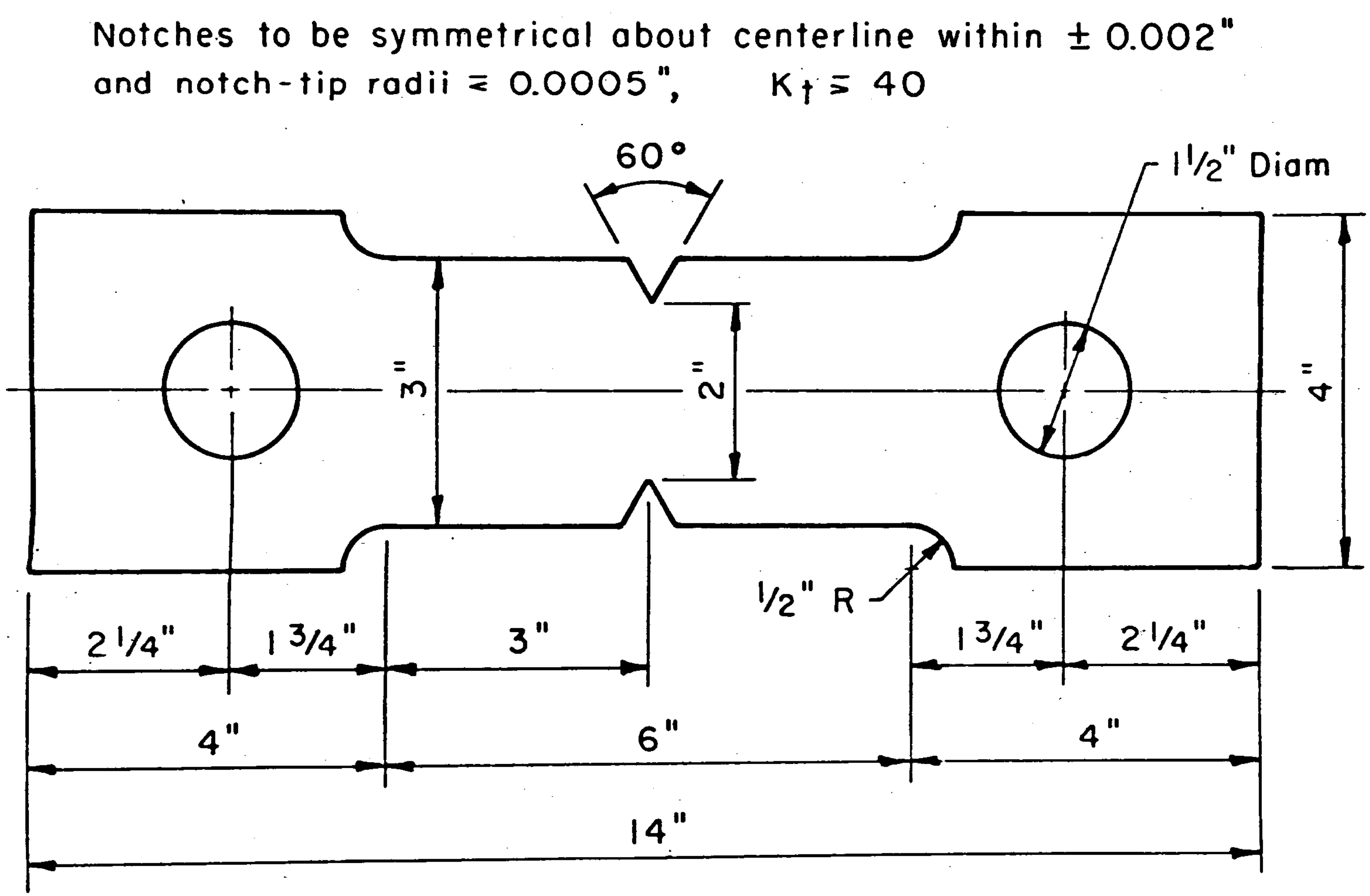


FIGURE 11 - EDGE-NOTCHED SPECIMEN TAKEN FROM 1/4-INCH PLATE. ($K_t \geq 40$)

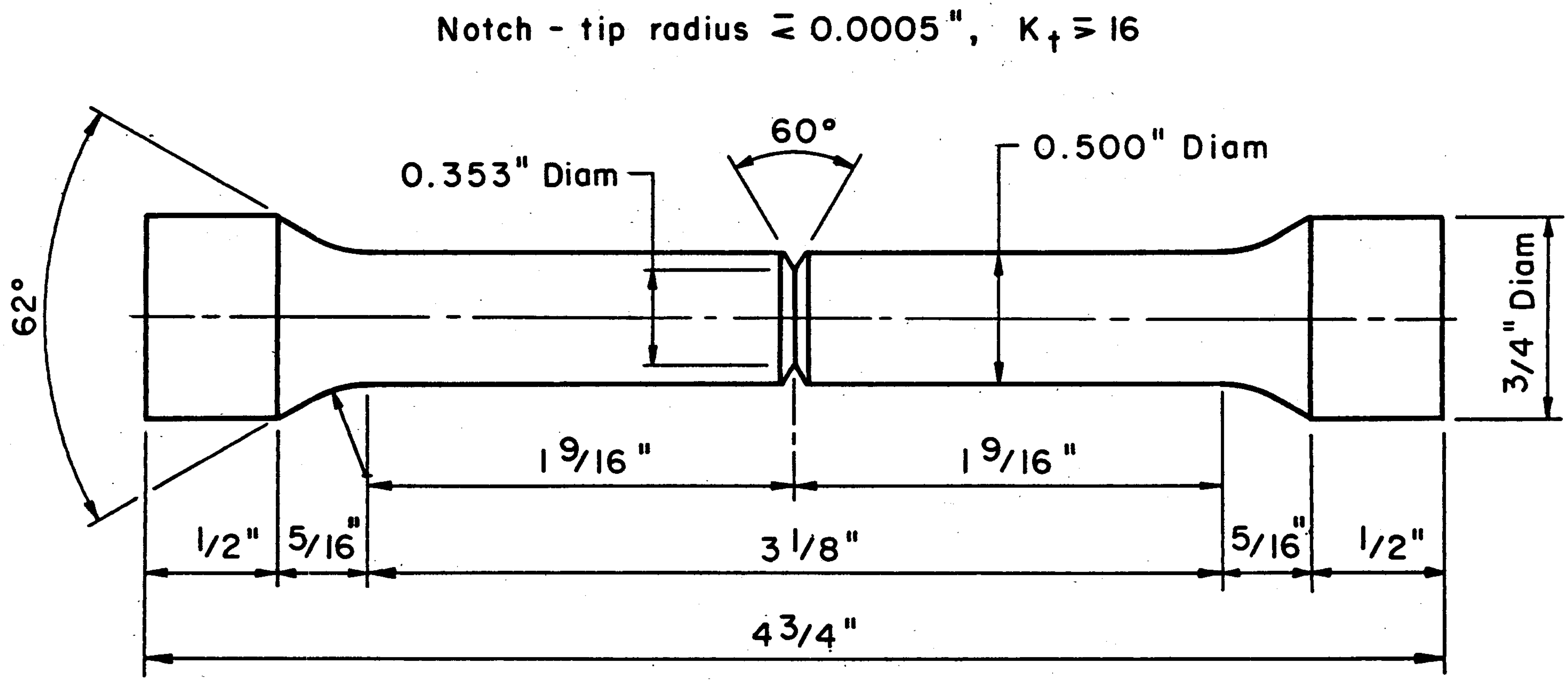
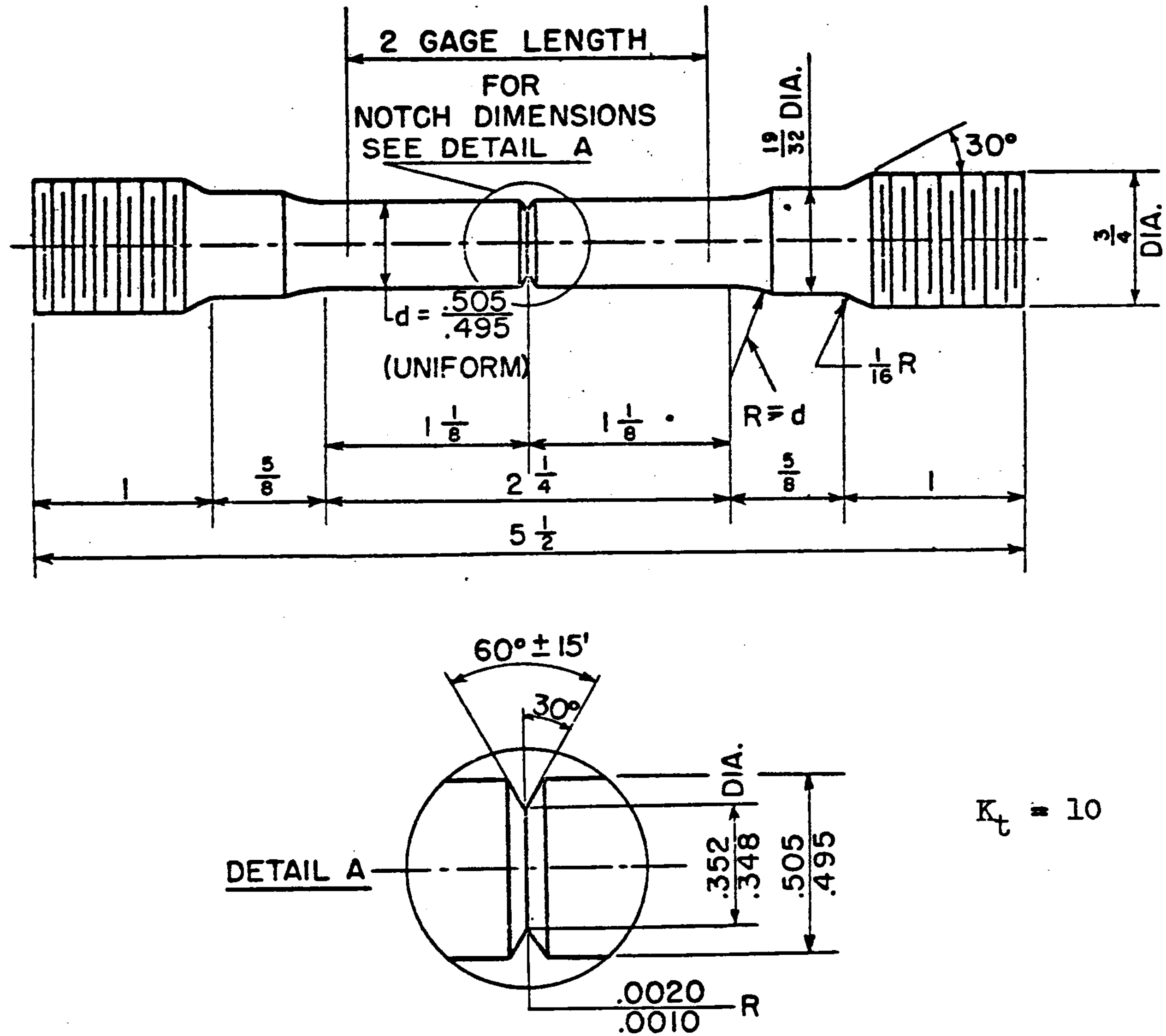


FIGURE 12 - NOTCHED ROUND SPECIMEN TAKEN FROM 1-INCH THICK PLATE. ($K_t \gtrsim 16$)



$K_t = 10$

FIGURE 13 - NOTCHED ROUND SPECIMEN TAKEN FROM 1.000 INCH THICK PLATE. ($K_t = 10$)

$$\text{Tear strength, psi} = \frac{P}{A} + \frac{MC}{I} = \frac{P}{bt} + \frac{3P}{bt} = \frac{4P}{bt}$$

$$\text{Unit propagation energy, in.-lb per sq in.} = \frac{\text{energy to propagate a crack}}{bt}$$

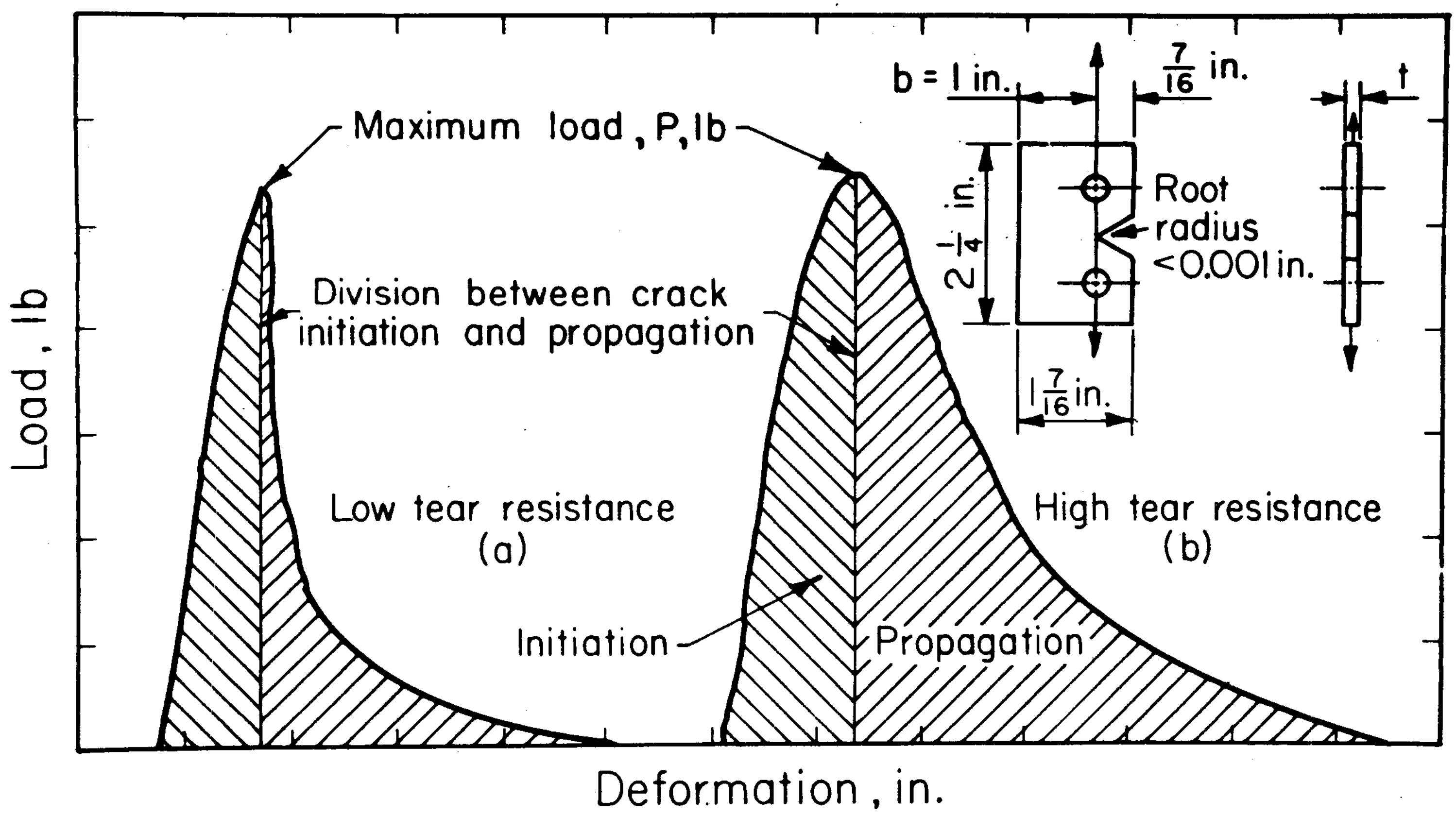


FIGURE 14 - TEAR-TEST SPECIMEN AND REPRESENTATIVE TEAR-TEST CURVES.

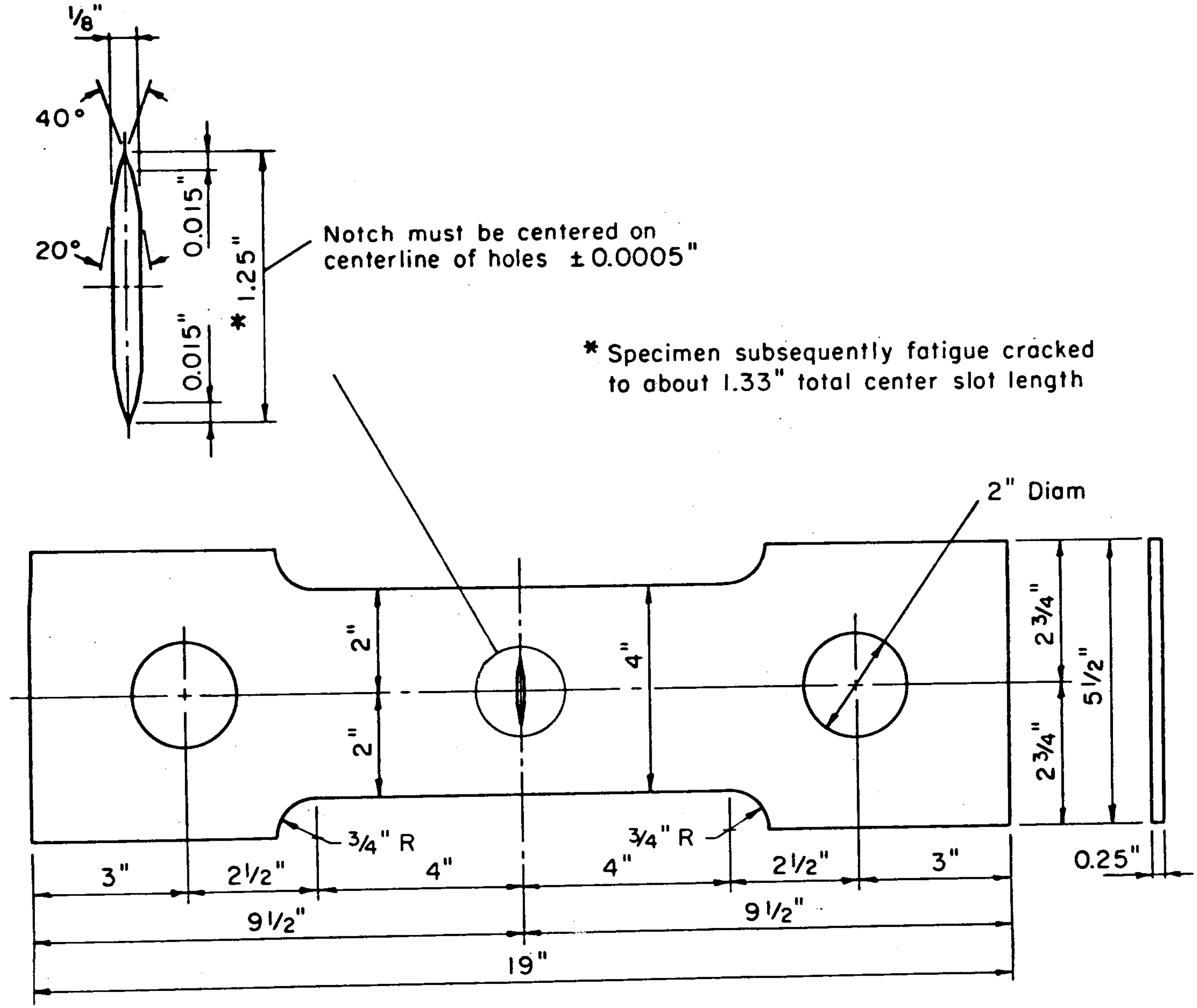
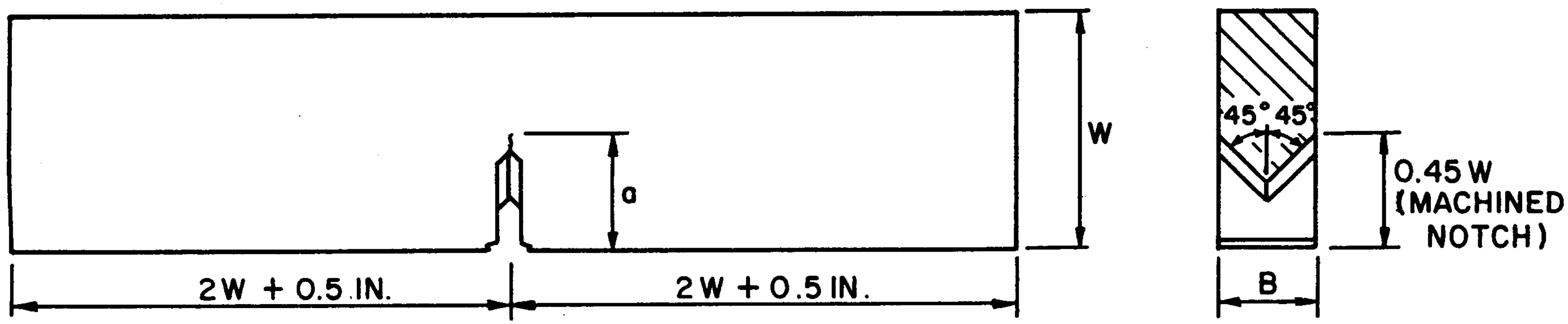


FIGURE 15 - CENTER-NOTCHED FRACTURE-TOUGHNESS SPECIMEN.



TYPE	THICKNESS, B, IN.	WIDTH, W, IN.	LENGTH, IN.	CRACK LENGTH, a,* IN.
1	1/2	1	5	1/2
3	1	2	9	1

* INCLUDING AT LEAST 0.050 IN. OF FATIGUE CRACK.

FIGURE 16 - FATIGUE-CRACKED NOTCHED-BEND FRACTURE-TOUGHNESS SPECIMEN.

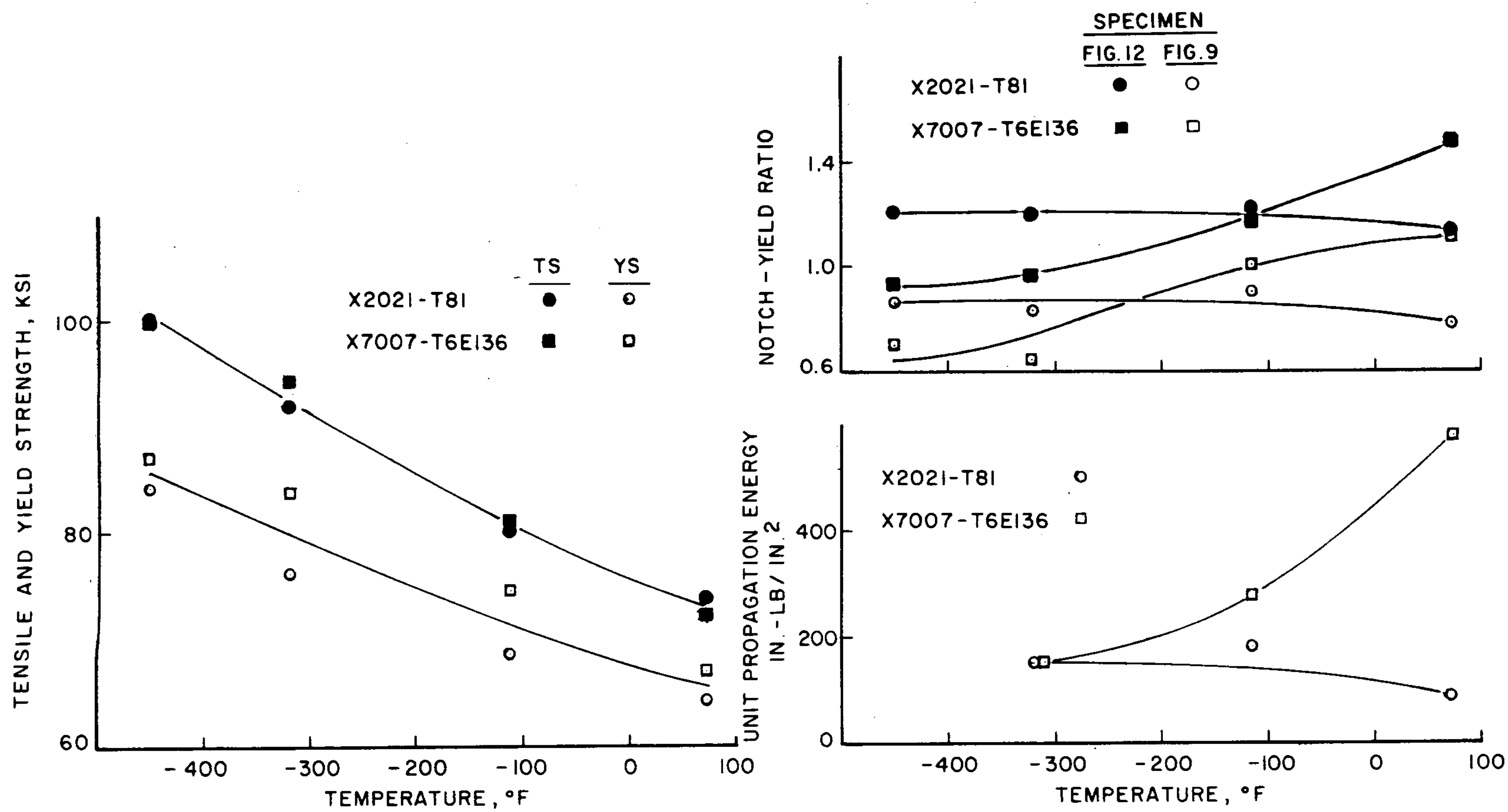


FIGURE 17 - LONG-TRANSVERSE STRENGTHS AND FRACTURE CHARACTERISTICS OF X2021-T81 AND X7007-T6E136 SHEET AND PLATE AT VARIOUS TEMPERATURES.

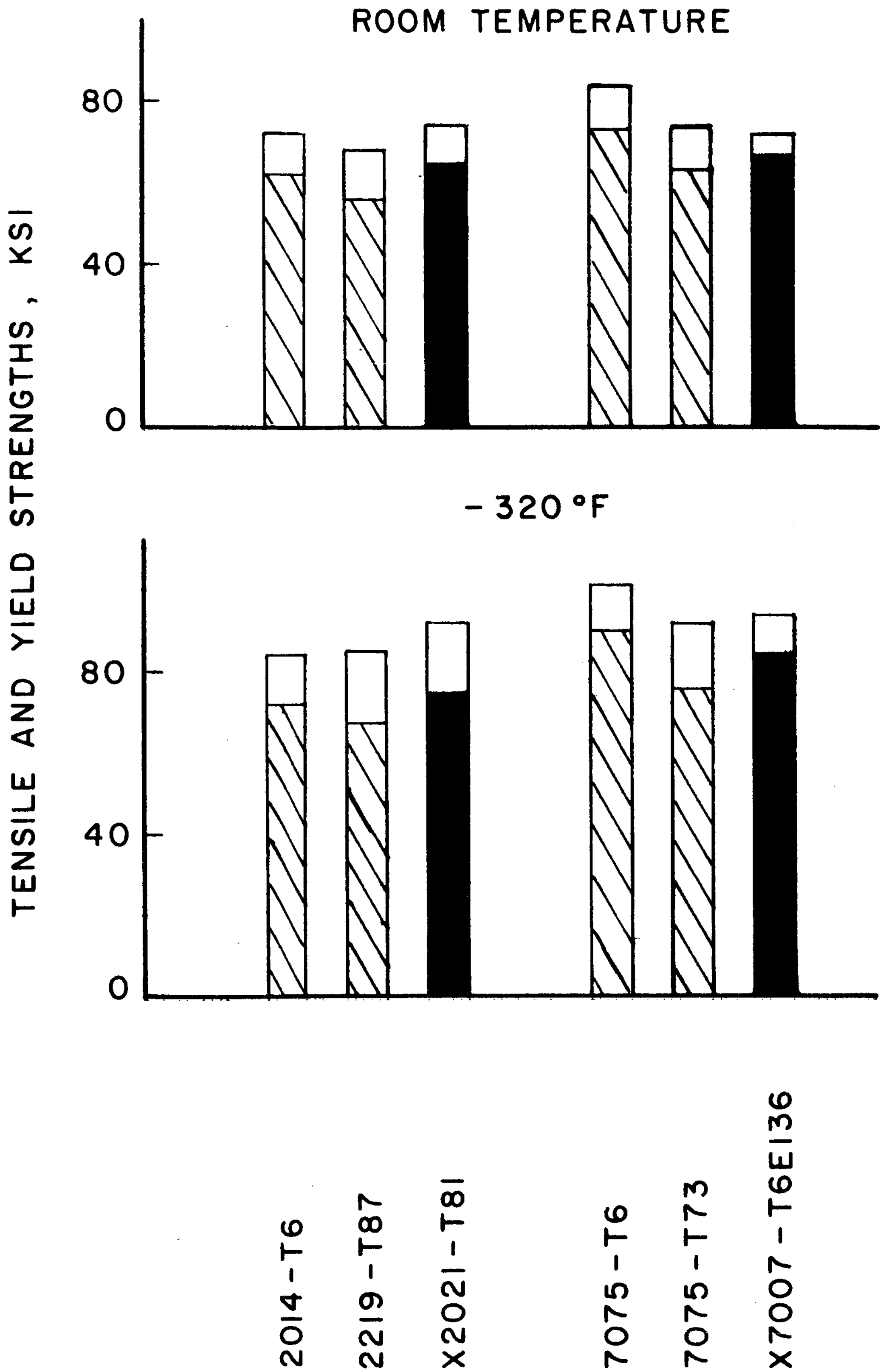


FIGURE 18 - LONG TRANSVERSE TENSILE AND YIELD STRENGTHS OF SOME HIGH STRENGTH ALUMINUM ALLOYS AT ROOM TEMPERATURE AND -320 F

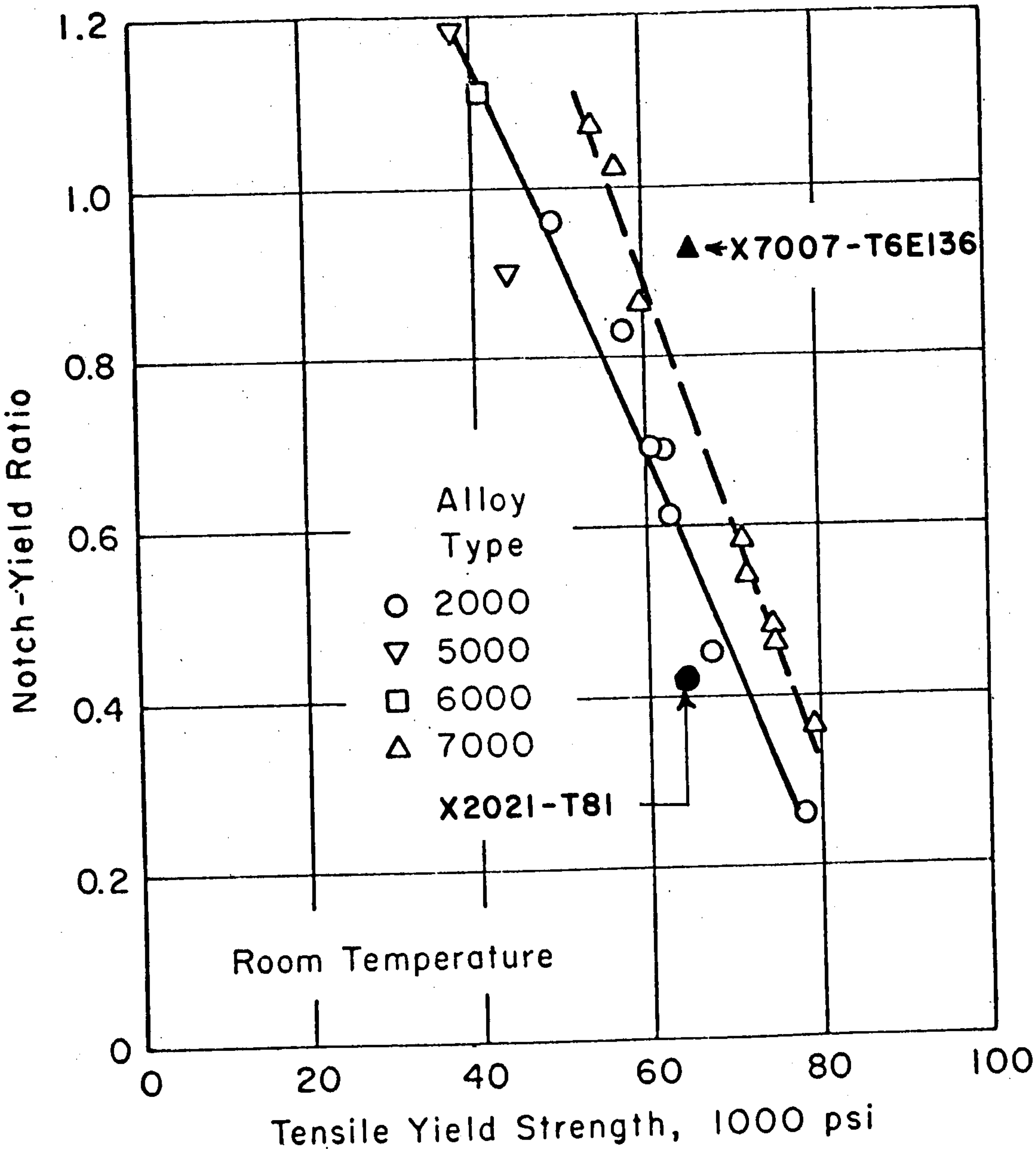


FIGURE 19 - NOTCH-YIELD RATIO (EDGE-NOTCHED SPECIMEN, FIGURE 11) VS TENSILE YIELD STRENGTH FOR 0.250-INCH PLATE - TRANSVERSE DIRECTION.

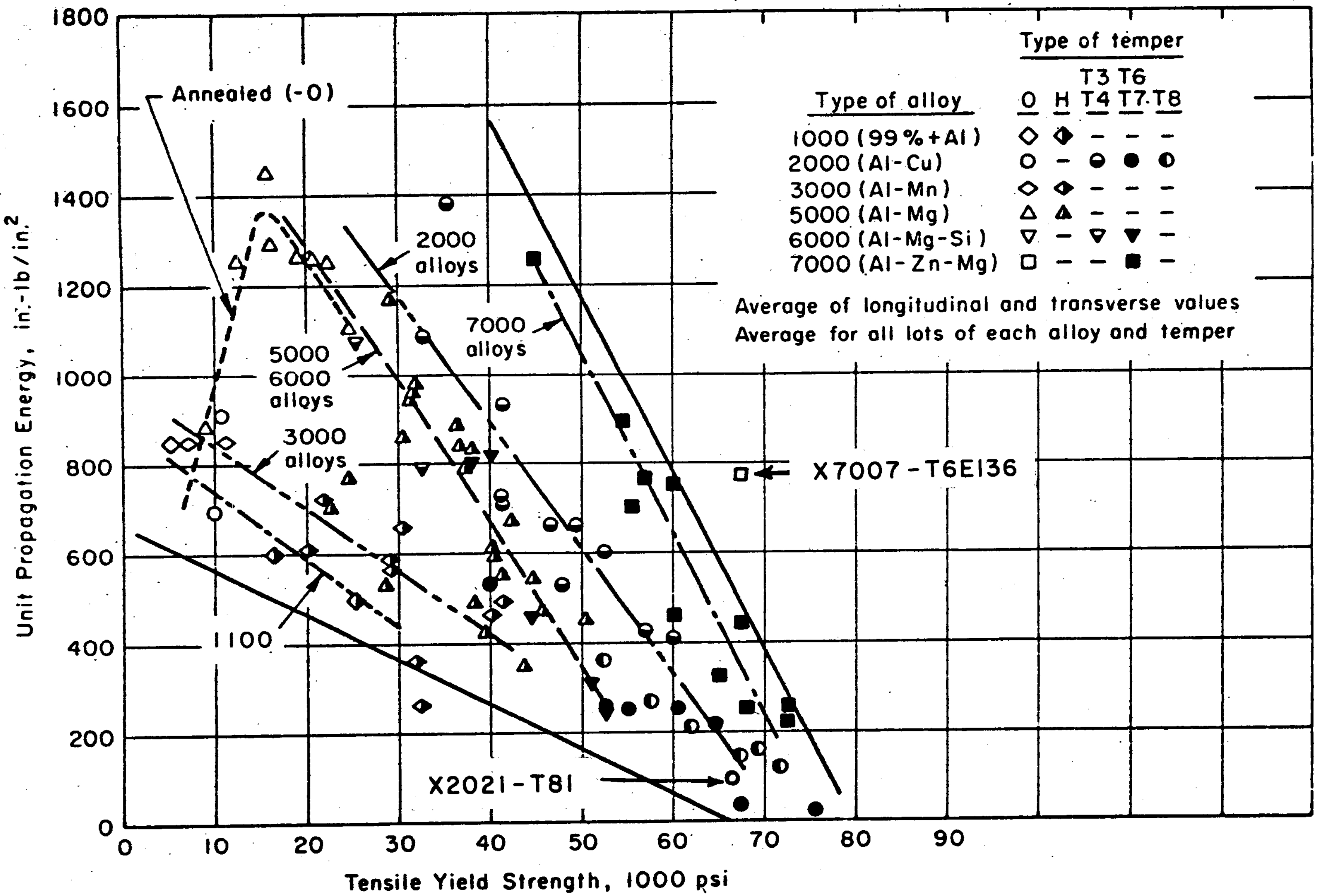


FIGURE 20 - UNIT PROPAGATION ENERGY VS. TENSILE YIELD STRENGTH (0.063 INCH ALUMINUM ALLOY SHEET.)

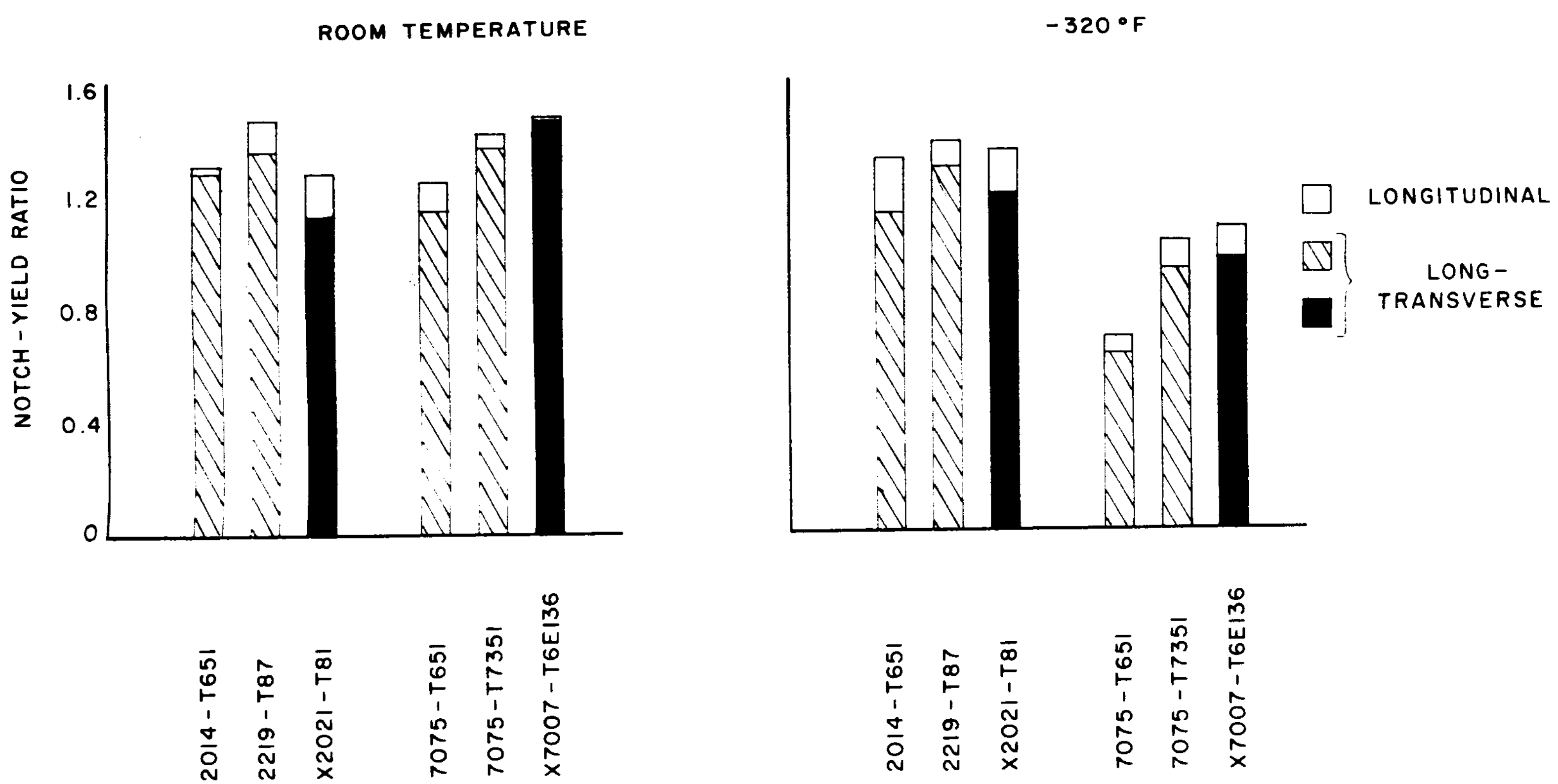


FIGURE 21 - NOTCH-YIELD RATIOS FOR SOME HIGH-STRENGTH ALUMINUM ALLOY PLATE AT ROOM TEMPERATURE AND -320°F (SPECIMEN GEOMETRY SHOWN IN FIGURE 12)

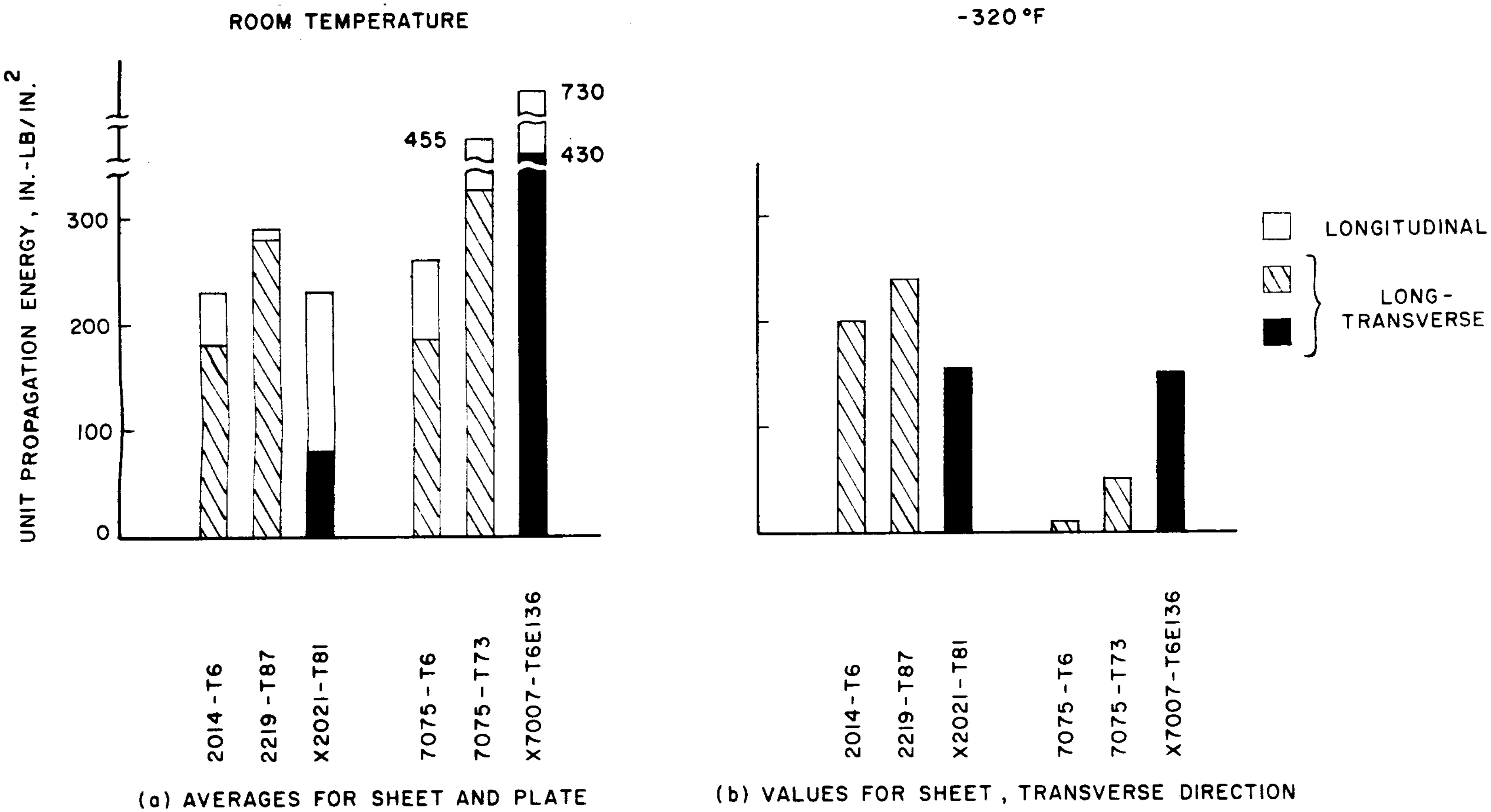


FIGURE 22 - UNIT PROPAGATION ENERGIES FOR SOME HIGH-STRENGTH ALUMINUM ALLOY SHEET AND PLATE AT ROOM TEMPERATURE AND -320 F.

APPENDIX II

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