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Summary

A study of the creep behavior and residual mechanical properties of two cast superalloys and several wrought bar oxide dispersion strengthened (ODS) alloys reveals that the tensile properties of the nickel-base superalloy B–1900 and cobalt-base superalloy MAR–M509 are not degraded by prior elevated temperature creep (at least up to 1 percent) straining between 1144 and 1366 K. On the other hand, the room temperature tensile properties of ODS nickel-base alloys can be reduced by prior creep strains of 0.5 percent or less between 1144 and 1477 K, with the long transverse direction being more susceptible to degradation than the longitudinal direction. The room temperature tensile properties of the ODS iron-base alloy MA–956 tested in the longitudinal direction are apparently not degraded by prior creep strains up to about 0.25 percent.

While not subject to creep degradation, the ODS alloy MA–956 is unusual in the manner in which it appears to deform at elevated temperature. Basically, MA–956 creep strained in the longitudinal direction appears to undergo slow plastic deformation by the nucleation and slow growth of cracks. On the other hand, the creep behavior of the ODS nickel-base alloys in this study is quite similar to that of previously studied ODS nickel alloys. In general, the longitudinal direction is stronger than the long transverse direction, and creep is at least partially due to a diffusional creep mechanism as dispersoid-free zones were observed after creep-rupture testing.

Introduction

Oxide dispersion strengthened (ODS) nickel- and iron-base alloys are of interest for use in gas turbine engines because of their mechanical strength and environmental resistance at high homologous temperatures. However, recent studies (refs. 1 to 3) of mechanical properties of several nickel-base ODS alloys have indicated that in some instances prior elevated temperature creep straining can severely affect subsequent room temperature tensile properties, particularly ductility. Reductions in ductility are apparently due to diffusional creep, which causes formation of dispersoid-free regions around grain boundaries. Such regions are weak in comparison to the adjacent dispersion strengthened material. Additionally, the dispersoid-free regions can act as sites for cavitation and internal oxidation during subsequent creep; these effects further weaken the alloy.

While creep degradation effects have been documented for many nickel-base ODS alloys, the behavior of iron-base ODS alloys is not clear. A recent study (ref. 4) of mechanical properties of the ODS iron-base sheet alloy MA–956E indicated that room temperature tensile properties are not affected by very small amounts of prior creep strain (less than 0.2 percent) at 1365 K. Attempts to introduce greater amounts of creep strain were unsuccessful because of the rather unique way in which this alloy deforms under conditions designed to promote slow plastic deformation. It appears that beyond transient creep (about 0.1 percent strain), the alloy does not undergo uniform plastic deformation but rather deforms by the nucleation and slow growth of cracks which eventually lead to tensile overload conditions and rapid failure.

In current gas turbine engines, most high temperature parts are manufactured from either nickel- or cobalt-base alloys. Degradation of 1033 K stress-rupture and room temperature tensile properties as a result of 1-percent creep straining at 1089 to 1366 K has been reported for the wrought nickel-base alloy Udimet 700 (ref. 5) and the cast nickel-base alloy Inco 713 (ref. 6). Unfortunately, degradation effects due to aging and/or creep-straining could not be well differentiated in these studies. A study by Tien and Gamble (ref. 7) on a simple gamma-prime strengthened nickel-base alloy (Ni-16Cr-5A1-4Ta) revealed the formation of gamma-prime-free regions during creep straining at 1255 K, which are similar to the dispersoid-free regions observed in creep-strained ODS alloys. Similar results were observed by Gibbons (ref. 8) in a study of creep at 1023 to 1123 K in high-purity Ni-20Cr-2.5Ti-1.5A1 alloy and a commercial Nimonic 80A alloy. In these alloys, the gamma-prime-free regions are likely sites for premature failure during subsequent straining. No studies of creep degradation effects on the properties of cobalt-base superalloys have been reported.

The present study was conducted to determine the effects of similar thermal/creep exposures on the residual mechanical properties of cast superalloys and advanced wrought ODS alloys. In addition to the required creep testing, tensile properties and, where possible, stress rupture properties were measured in order to more fully characterize the elevated temperature properties of the alloys. The superalloys studied included the cast nickel-base alloy B–1900 and the cast cobalt-base alloy MAR–M509; both of these alloys are vane materials in current gas turbine engines. While creep degradation effects would not be expected in MAR-M509, as it is basically a solid solution-strengthened alloy, creep degradation effects are possible in the gamma-prime strengthened B-1900. The advanced ODS alloys examined included nickel-base alloys (nominally Ni-16Cr-5Al) from three manufacturers and an iron-base alloy. All of the ODS alloys evaluated have been under consideration for or actually used as vanes in gas turbine engines (ref. 9).

The results of all the mechanical property testing are presented in appendix A, and typical microstructures of as-received and tested alloys are shown in appendix B. The results of a linear regression analysis of the stress rupture and steady state creep rate data for the tested alloys are given in appendix C.

Experimental Procedure

Materials

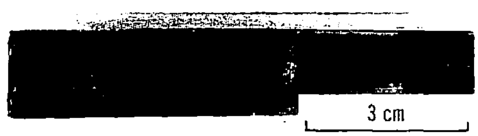
Cast bars 16 mm in diameter by 150 mm in length of MAR-M509 and B-1900 were procured from the Metals Division of TRW. Bars of each composition were cast from a single master heat, and each bar was radiographically inspected. All bars containing defects were rejected. The compositions of these two superalloys are shown in table I. Prior to being machined into test specimens, all B-1900 cast bars were heat treated as follows: 4 hours at 1350 K, air cool to room temperature, then 10 hours at 1170 K, and air cool to room temperature. MAR-M509 bars were not heat treated.

The ODS alloys evaluated included both commercial and experimental alloys. The nickel-base alloy MA-757 and iron-base alloy MA-956 were obtained from Huntington Alloys, Inc. Four pieces of hot-finished flat bar, nominally 8 by 3 cm in cross section and 80 cm in length, of each alloy in the heat-treated condition were obtained; the compositions are given in table I.

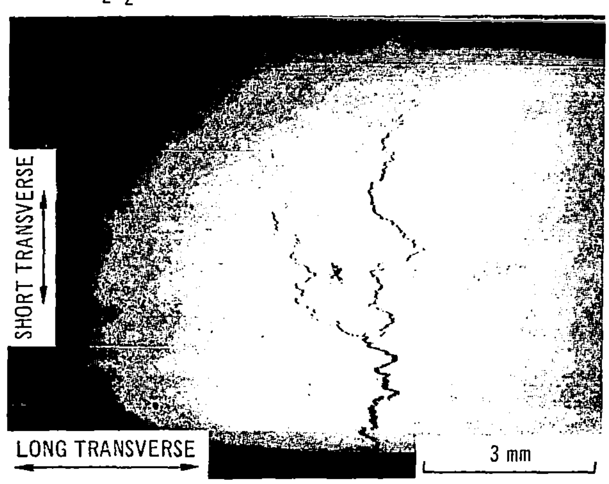
Three experimental aluminum-modified Ni-16Cr-type ODS alloys developed under NASA contract (ref. 10) at the Stellite Division of Cabot Corporation were also examined. These alloys are designated by STCA plus heat numbers and their compositions are given in table I. Extruded bar stock nominally 6.7 by 2.0 cm in cross section of each alloy composition was obtained from the contractor. In order to develop a low modulus texture, these alloys were thermomechanically processed and heat treated at the Lewis Research Center. The three alloys were canned in mild steel and rolled parallel to the extrusion direction at 1310 K in a single pass to reductions of 14 percent (262/264 and 266) or 24 percent (265). After rolling, the cans were removed and the alloys were heat treated in air. The heat treatment consisted of placing the materials in a furnace at 1475 K, raising the temperature over a 4-hour period to 1535 K, holding 1 hour at 1535 K, raising the temperature over a 2-hour period to 1590 K, holding 1 hour at 1590 K, lowering the temperature to 1475 K, and removing from the furnace and air cooling. The STCA heats given only this standard heat treatment are identified by the suffix "S". Heat numbers 265SC and 266SC were given the standard heat treatment followed by an additional 24-hour anneal at 1115 K to precipitate carbides.

In addition to the above ODS alloys, a limited amount of testing was conducted on the Special Metals experimental alloy YD-NiCrAl. One piece of heat treated bar stock approximately 3.8 by 1.3 cm in cross section and 28 cm long was obtained from the manufacturer; the nominal composition of this alloy is also listed in table I.

(a) Cross section (half piece) macroetched with 70% HCl-30% H_2O_2 mixture.



(b) Longitudinal section macroetched with 70% HCl-30% H_2O_2 mixture.



(c) Crack found in cross section of MA-956. Metallographically polished and etched with 30 g NH_4F-50 cm^3 HNO_3-20 cm^3 H_2O mixture.

Figure 1. - Structure of as-received MA-956.

The crystallographic textures and grain sizes of all alloys were determined. Both superalloys possessed a very large as-cast grain structure with a basically random texture. B–1900 exhibited a minor texture where the [100] direction was parallel to the length of the as-cast bars. Additionally, it was noted that both superalloys contained very few grains with the [111] direction parallel to the bar length; the number found was less than expected for a truly "random" orientation.

Textures and grain sizes for the ODS alloys are reported in table II. The grain sizes are arithmetic averages; wide variation about the reported sizes exists. In particular, MA–757 and STCA–262/264 exhibited diameters in the long transverse-short transverse plane as small as 8 microns and as large as 500 microns. Of the nickel-base ODS alloys, only STCA–266S had a grain aspect ratio greater than 10 in the longitudinal direction. MA–956 possessed an extremely large grain structure as shown in figure 1. The "grains" are cigar-shaped, on the order of a cm in diameter by tens of cm long in the extrusion direction. Based on the [100] texture, all of the nickel-base ODS alloys have low elastic moduli in the direction parallel to the extrusion axis of the bar; unfortunately neither the long transverse nor short transverse bar directions are low modulus directions. On the basis of crystallography, all three bar directions for MA–956 will have high elastic moduli. In general for gas turbine applications, low modulus orientations are desirable (ref. 9) to reduce thermal stresses.

Testing Procedure

Specimen geometry and machining.—All machining of test bars was done by Metcut Research Associates, Inc. Threaded grip end round bar tensile-type specimens with a 0.635-cm-diameter reduced section were machined from each alloy. While it is normal practice to utilize cast test specimens for B–1900 and MAR–M509, specimens of both alloys were machined from the as-cast bars. This procedure was followed so that both the superalloy and ODS alloy specimens possessed similar surface finishes. All superalloy specimens and many MA–956 specimens in the longitudinal direction possessed a 5.7-cm-long reduced section. All other specimens had either a 3.2- or 2.5-cm-long reduced section. Since the emphasis of this program was on the measurement of residual properties after small amounts of prior creep strain, specimens with 5.7-cm reduced sections were desired in order to more accurately measure the creep strains. However, due to limitations on the size of the bar stock (particularly for the long transverse direction) and the availability of material, shorter reduced sections had to be used for many material-test direction combinations. The reduced sections of all test specimens possessed a 16 rms or better surface finish and were free of defects as determined by dye penetrant inspection.

Generally, no difficulties were encountered in machining the alloys. However, a large fraction (about 60 percent) of MA–956 specimens with gage length parallel to the long transverse direction had to be discarded because of flaws (as revealed by dye penetrant techniques) in the reduced section. The source of the flaws has not been identified; however, several cracks were found in the as-recieved cross section of MA–956. These cracks start at the bar surfaces and generally follow the "grain" boundaries, as shown in figure 1.

Tensile testing.—Room temperature and elevated temperature tensile testing were conducted by Metcut Research Associates, Inc. All tensile testing followed the procedures outlined in ASTM Specifications E8–69 and E21–70. Elevated temperature tensile testing was conducted in air at 1144, 1255, 1366, and 1477 K except for the STCA alloys and YD-NiCrAl. The latter alloy was not tensile tested because only eleven specimens were available; only 1366 K tensile tests were run for the STCA alloys since the number of specimens for each composition-direction-heat treatment combination was also limited. The measured tensile properties included 0.02 and 0.2 percent yield stresses, ultimate tensile strength, elongation, and reduction in area.

Creep testing.—Elevated temperature creep testing was conducted at Metcut Research Associates, Inc., following the procedures outlined in ASTM Specification E139–70. For test temperatures below 1260 K an electromechanical extensometry system (LVDT which measures differential motion of extensometer arms attached to the gage sections) was generally used to determine creep strain. For temperatures exceeding 1260 K, an optical creep measuring system (creep cathetometer used in conjunction with platinum strip extensometers attached to the specimens) was used. A few 1255 K creep tests were conducted with the optical extensometry system. Tests were conducted in air at various stress levels at 1144, 1255, and 1366 K. MA–757 and MA–956 were also tested at 1477 K whereas the STCA alloys and YD-NiCrAl were only tested at 1366 K. Creep tests were conducted to rupture or were terminated after about 150 hours. The creep properties reported include plastic strain on loading; plastic strains after 0.1, 5, 10, 25, 50, 100, and 150 hours of testing; plastic strain at the end of test; minimum creep rate; and time to rupture if the specimen failed. Unfailed creep specimens were utilized in the determination of residual tensile properties.

Residual property testing.—In this study, creep tests were designed to introduce various amounts of strain into each alloy in order to determine if slow plastic deformation at elevated temperatures affects subsequent mechanical properties. Following creep testing specimens were tensile tested at room temperature. Due to the low ductility of MAR-M509 at room temperature, a few MAR-M509 specimens which had been creep tested at 1255 K were also tensile tested at 1144 K. In all cases, the measured residual tensile properties included 0.02 and 0.2 percent yield stresses, ultimate tensile stress, elongation, and reduction in area. The residual strength properties were calculated on the basis of the original (prior to creep testing) specimen diameter. Residual ductility measurements for specimens with less than 1 percent creep strain were based on the original gage dimensions while ductilities for specimens crept to more than 1 percent strain were based on gage dimensions after creep. The latter procedure was necessary since specimens with more than 1 percent creep strain had usually necked in the gage section.

Most residual property tests were conducted at Metcut Research Associates, Inc., following test procedures previously outlined for room temperature and elevated temperature tensile testing. A few interruped creep specimens which possessed damaged grip ends were tensile tested at the Lewis Research Center; only ultimate tensile strength and ductility data were obtained from these residual property tests.

Stress-rupture testing.—Stress-rupture testing of the superalloys and ODS alloys MA-757 and MA-956 was conducted at the Lewis Research Center. Tests were designed to produce rupture at times ranging from 10 to about 500 hours at 1144, 1255, and 1366 K; in addition, the two ODS alloys were tested at 1477 K. All testing was conducted in air and followed the procedures outlines in ASTM Specification E139-70. Several MA-757 and MA-956 stress-rupture specimens which had not failed after about 1000 hours of testing were unloaded and tensile tested at room temperature in order to assess the effects of long-term stress-temperature exposure on mechanical properties.

Following mechanical property testing, selected specimens were examined by standard metallographic and scanning electron microscopy (SEM) techniques.

Results and Discussion

Superalloys

A complete tabular presentation of all the

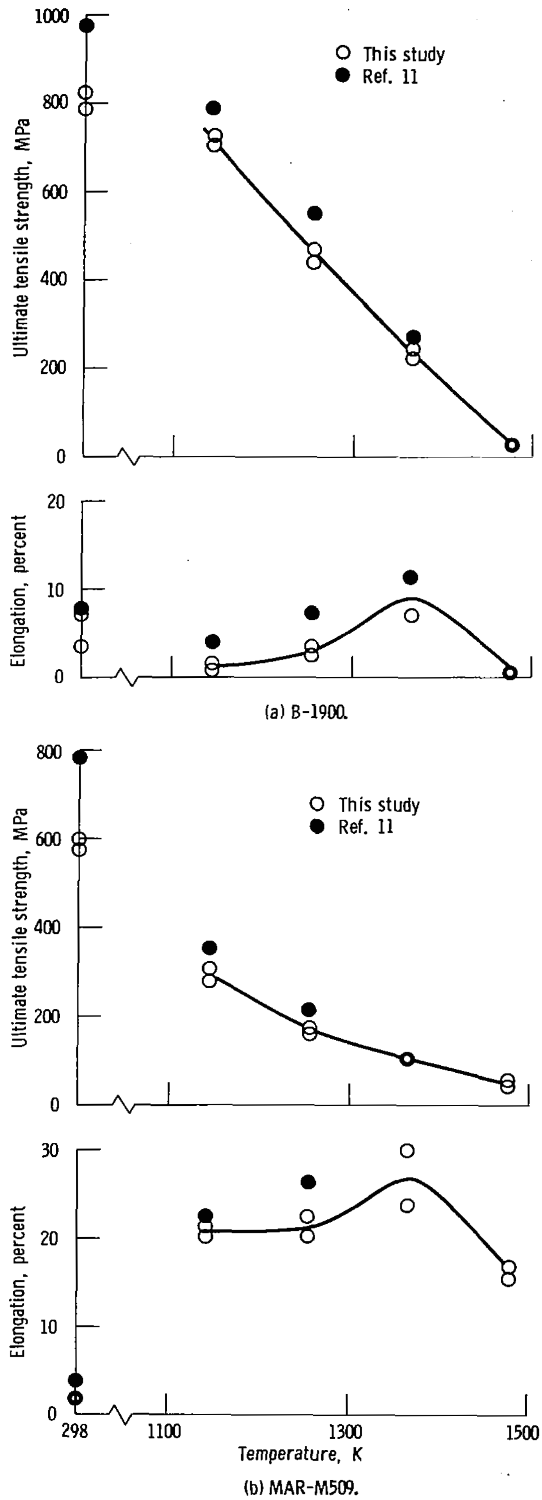


Figure 2. - Tensile properties as a function of temperature.

mechanical properties for B-1900 and MAR-M509 determined in this study is given in appendix A. Figure 2 shows the ultimate tensile strength and elongation data as a function of temperature, and figure 3 shows the stress-rupture data determined at 1255 K for both alloys. In addition, typical literature data (ref. 11) are included. The literature data for B-1900 in these two figures were determined for specimens in the as-cast condition, while the B-1900 specimens in this study had been subjected to a heat treatment. According to reference 11, it is usual practice to employ a heat treatment in order to improve the rupture life and ductility at 1033 K. Unfortunately, neither the tensile nor stress-rupture data for B-1900 bar reported in reference 11 are for the heat-treated condition. The tensile data in figures 2(a) and (b) indicate that both alloys tested in this program are weaker than typical heats of material. Also, figure 3 illustrates that the rupture strength of MAR-M509 at 1255 K is less than the typical strength while the rupture strength of B-1900 at 1255 K is equivalent to the typical strength levels. The exact reasons why the tested heats of B-1900 and

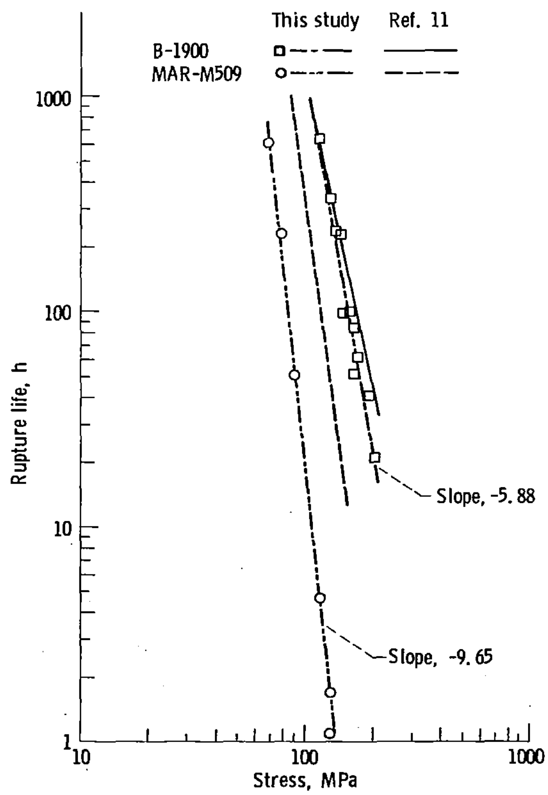


Figure 3. - Rupture life as a function of stress for B-1900 and MAR-M509 at 1255 K.

MAR-M509 are weaker than normal is not known; one possible cause is the use of test specimens machined from cylindrical castings rather than cast specimens.

Comparison of the stress-rupture data in appendix A for B-1900 and MAR-M509 at 1144 and 1366 K to literature data reveals that the material behavior at these temperatures is also similar to that seen at 1255 K. That is, the B-1900 alloy tested in this study possesses stress-rupture strengths equivalent to those previously reported in the literature while the MAR-M509 material is weaker than previously reported strengths. Typical photomicrographs of the as-recieved microstructures and the microstructures of selected stress-rupture specimens are presented in appendix B.

Typical creep curves and minimum creep rate data as a function of applied stress for B-1900 and MAR-M509 tested at 1255 K are presented in figures 4 and 5, respectively. The data in these figures demonstrate that creep in these alloys is generally well-behaved. The degree of scatter in minimum creep rates for MAR-M509 tested at the two lowest stresses (55.3 and 41.4 MPa) was unusually high (fig. 5); multiple testing for either alloy at other stresses and temperatures almost always resulted in minimum creep rates within a factor of two. Creep at 1144 and 1366 K for these two alloys was also well-behaved.

Typical residual tensile properties for the two superalloys after creep testing at 1255 K are presented in figure 6. For purposes of comparison, this figure also contains tensile data from as-received specimens and from specimens which had been thermally exposed for 150 hours in air at 1255 K. Knowledge of the effects of thermal exposure alone is important for the superalloys because their complex chemistries can induce precipitation reactions.

The residual property data for B-1900 in figure 6(a) indicate that thermal exposure alone at 1255 K slightly decreases the ultimate tensile strength and elongation. Furthermore, it appears that creep strains up to 1.25 percent do not unduly affect the residual properties. On the other hand, the test specimen which was creep strained to 1.91 percent did exhibit much lower residual properties. In fact, this specimen failed before the 0.02 percent yield strength was reached. Examination of the fracture surface revealed a large region of oxide which formed during creep testing. The clean fracture surface shown in figure 7(a) is typical for most of the B-1900 specimens; while the nodular fracture surface in figure 7(b) is the only example of a partially oxidized superalloy residual property fracture surface seen in this study.

A review of the residual property data in appendix A for B-1900 after creep testing at either 1144 or 1366 K indicates that creep at these temperatures also

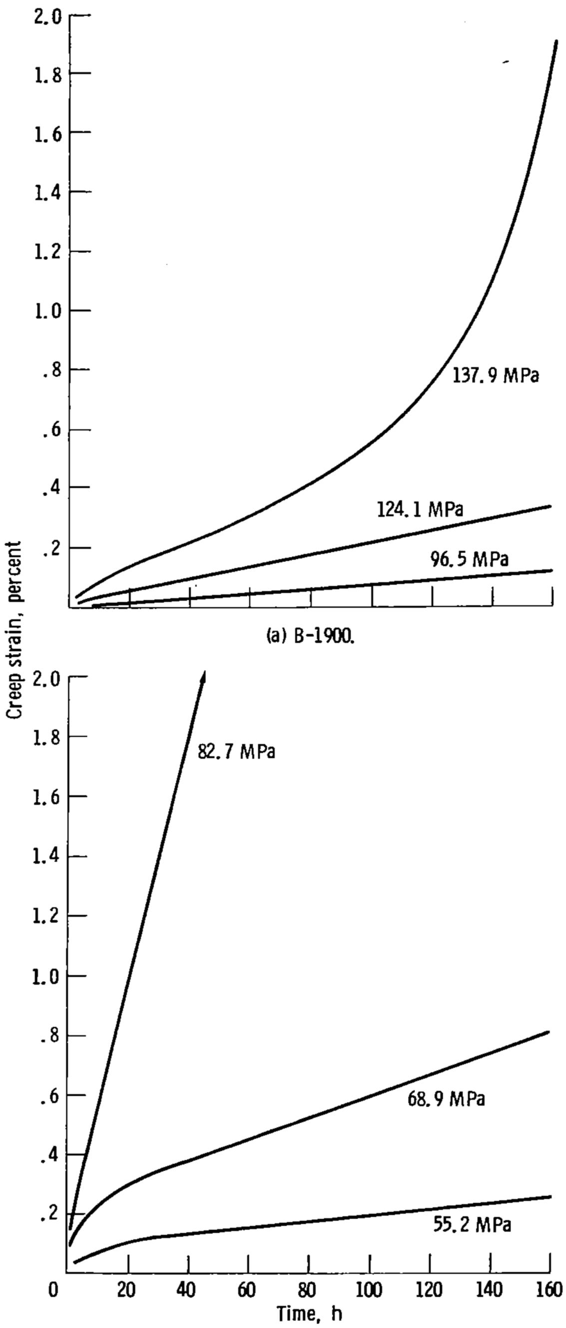


Figure 4. - Typical creep curves for B-1900 and MAR-M509 at 1255 K.

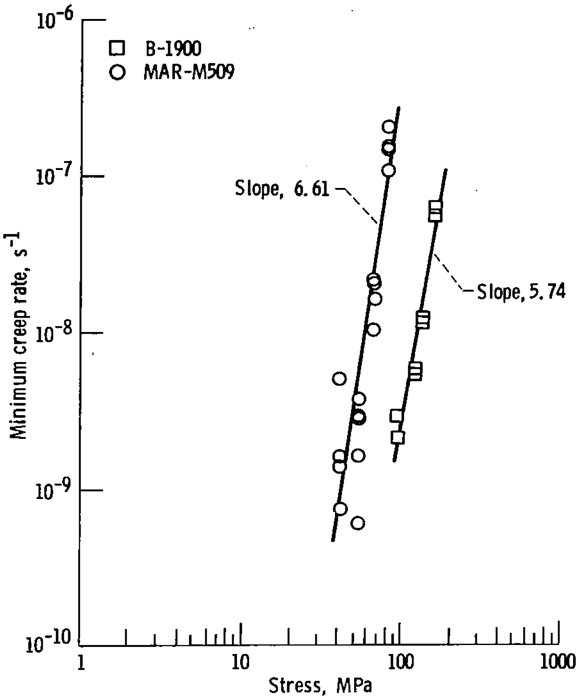


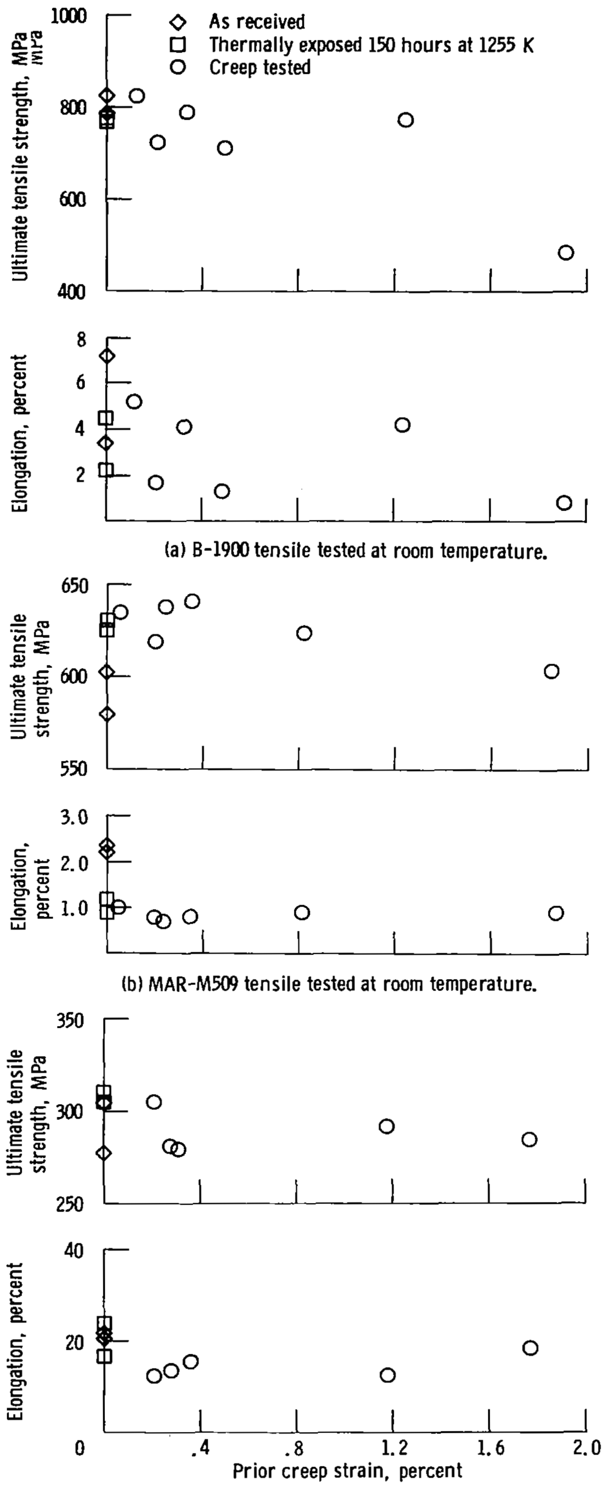
Figure 5. - Minimum creep rate as a function of stress for B-1900 and MAR-M509 at 1255 K.

has little influence beyond that due to thermal exposure alone on residual room temperature tensile properties. For example, neither prior creep strains up to about 4 percent at 1144 K nor creep strains up to 0.7 percent at 1366 K affected the residual tensile properties.

Examination of the microstructures of selected residual property specimens did not reveal gamma-prime-free regions similar to those reported by Tien and Gamble (ref. 7) or Gibbons (ref. 8). The absence of gamma-prime-free regions is probably due to the much larger grain size (greater than a factor of ten) in the present B-1900 as compared to the alloys discussed in references 7 and 8. Thus it appears that nickel-base alloys with large grain size cast microstructures will not be subject to creep degradation effects.

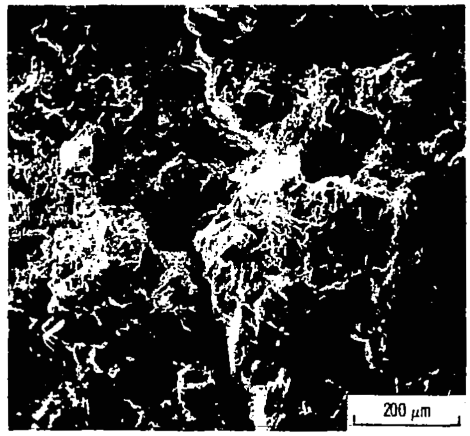
The room temperature residual property data for MAR-M509 after being creep tested for about 150 hours at 1255 K are presented in figure 6(b). This figure also contains tensile properties for as-received specimens and specimens which had been exposed 150 hours in air at 1255 K. Thermal exposure alone slightly increases the strength and decreases the ductility. Creep strains up to about 1.8 percent do not appear to further reduce tensile properties by any significant amount. The SEM fractograph shown in figure 7(c) is typical of both heat treated and creep strained residual property specimens.

Because of the rather low room temperature ductility of MAR-M509, residual tensile property tests were also conducted at 1144 K following creep testing for about 150 hours at 1255 K. The 1144 K residual tensile property data are shown in figure

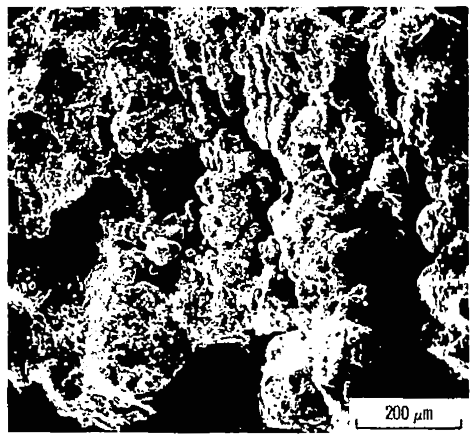


(c) MAR-M509 tensile tested at 1144 K.

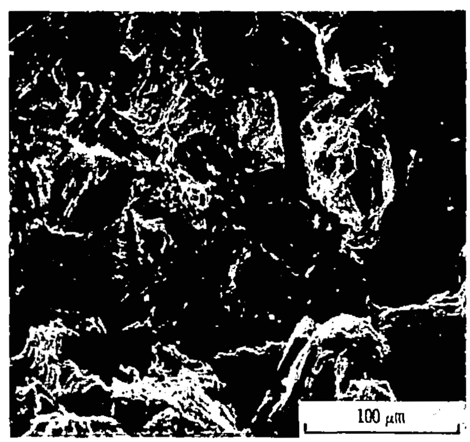
Figure 6. - Residual tensile properties as a function of prior creep strain for B-1900 and MAR-M509 creep tested at 1255 K for approximately 150 hours.



(a) B-1900 strained 0.12 percent at 96.5 MPa before tensile testing.



(b) B-1900 strained 1.91 percent at 137.9 MPa before tensile testing.



(c) MAR-M509 strained 0.82 percent at 68.9 MPa before tensile testing.

Figure 7. - SEM fractographs of B-1900 and MAR-M509 residual property specimens strained in creep at 1255 K for approximately 150 hours and tensile tested at room temperature.

6(c). At this temperature, prior thermal exposure alone has little effect on the tensile properties. While prior creep up to approximately 1.8 percent strain does not greatly influence the ultimate tensile strength, the tensile elongation was reduced from about 20 percent for as-received and thermally exposed to about 13 percent after creep straining. However, the ductility of as-crept specimens is still reasonable.

A review of the room temperature residual property data for MAR-M509 in appendix A indicates that 1144 K creep straining has no effect while the effect at 1366 K is not clear. In comparison to as-received properties, thermal exposure at 1144 K increases ultimate tensile strength by 15 percent and reduces the tensile elongation from about 2 percent to about 1 percent; these changes are maintained even after 6.83 percent creep strain at 1144 K. Compared to as-received properties, thermal exposure at 1366 K has little effect on ultimate tensile strength, while elongation is decreased to about 1 percent. Of the six possible 1366 K residual property specimens, two (with 0.08 and 0.31 percent creep strain) failed while being removed from the test fixtures, one (with 0.09 percent strain) failed before reaching the 0.2 percent yield stress, and the remaining three (0.17, 0.18, and 0.53 percent strain) possessed tensile properties similar to the thermally exposed specimens. Thus, while it appears that creep strains up to at least 0.53 percent can be tolerated at 1366 K, the large number of questionable failures is disquieting.

Summary of superalloy behavior.—In summary for the superalloys B-1900 and MAR-M509, prior creep at temperatures ranging from 1144 to 1366 K to strains on the order of 1 percent generally have little effect on subsequent tensile properties beyond those changes in tensile properties ascribed to thermal exposure alone.

Oxide Dispersion Strengthened Alloys

A complete tabular presentation of all the mechanical properties determined for the ODS alloys is given in appendix A. For simplicity, typical mechanical properties for each ODS alloy are presented in the following sections.

MA-757.—Typical elevated temperature tensile properties are presented in figure 8 and stress-rupture properties at 1366 K in the longitudinal and long transverse bar directions are presented in figure 9. While the elevated temperature tensile strength is not dependent on testing direction, both tensile ductility and rupture strengths are directionally dependent. In rupture testing, the longitudinal direction was always stronger than the long transverse direction, irrespective of test temperature (appendix A).

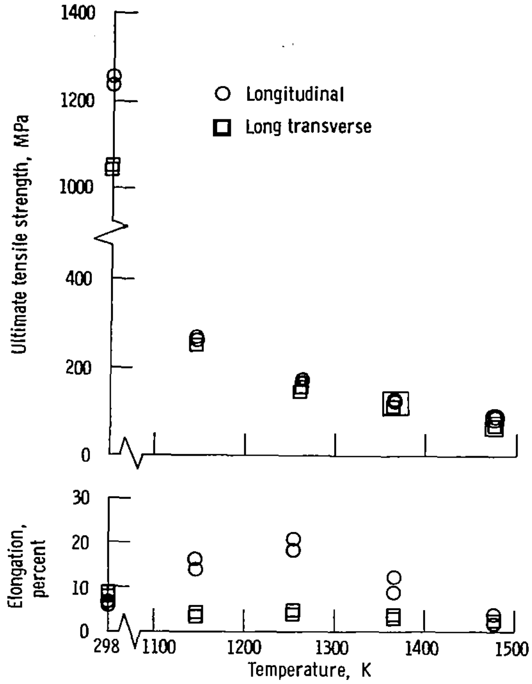


Figure 8. - Tensile properties as function of temperature and test direction for MA-757.

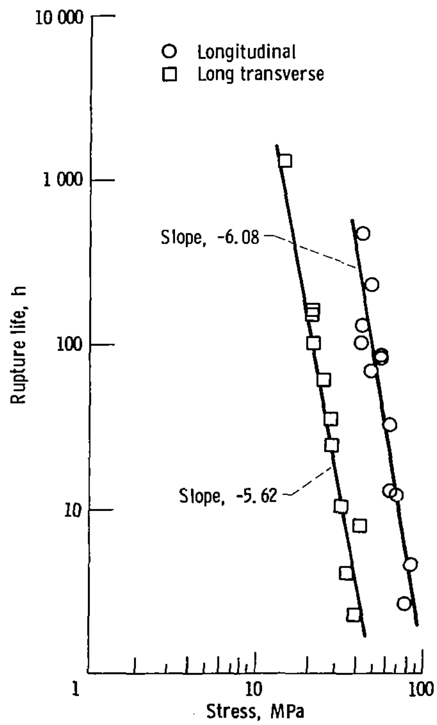
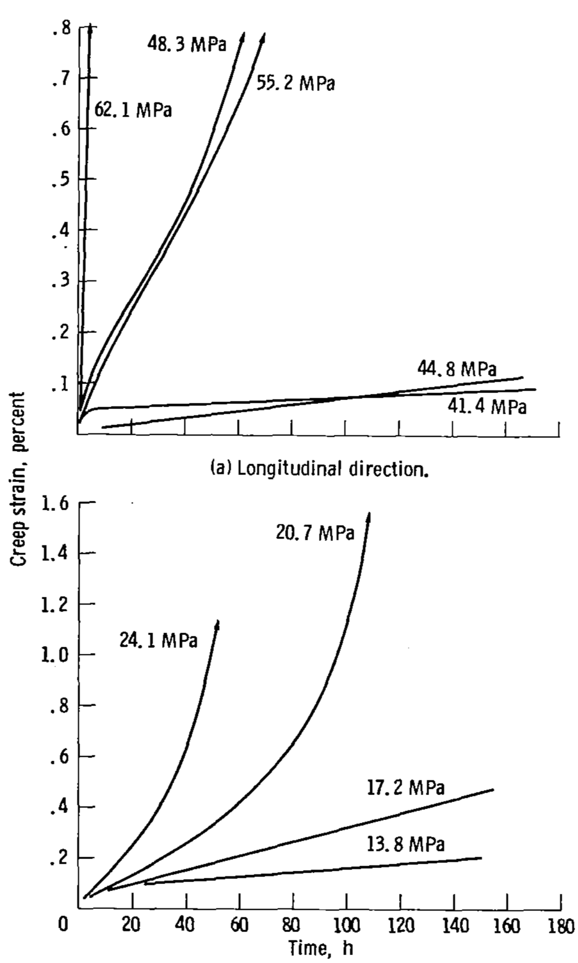


Figure 9. - Rupture life as a function of stress for MA-757 at 1366 K.

Photomicrographs of representative stress-rupture specimens are presented in appendix B. Of particular importance are the presence of dispersoid-free regions, extensive grain boundary cavitation and cracking, and massive internal oxidation (which leads to extended stress-rupture life and high rupture ductilities). All of these effects reduce the usefulness of stress-rupture data for design purposes (ref. 1).

Typical 1366 K creep curves and minimum creep rates as a function of stress are shown in figures 10 and 11, respectively. As is the case for most ODS bar alloys, the longitudinal direction is stronger than the long transverse direction. Also it should be noted that very small changes in stress (about 3.5 MPa) can produce very large changes in creep strain. Thus it proved difficult to induce moderate amounts of creep strain (from about 0.4 to about 1.0 percent) under the testing conditions (strain after 150 h of testing) used in this study.



(b) Long transverse direction.

Figure 10. - Typical creep curves for MA-757 at 1366 K.

The creep data in appendix A for MA-757 reveals that creep behavior at 1144, 1255, and 1477 K is similar to that at 1366 K; the longitudinal direction is stronger than the long transverse direction and small changes in stress can result in large changes in creep strain.

Residual tensile properties after prior elevated temperature creep straining are presented in figure 12. Previous residual property studies of ODS alloys (refs. 2 and 3) have indicated that tensile ductility and fractography are the most sensitive indicators of creep damage; in general, rather severe creep damage (very large scale dispersoid-free bands, cavitation, and internal oxidation) must take place before significant changes in residual strengths are noted.

The residual mechanical property data in figure 12(a) indicate that both the ultimate tensile strength and ductility in the longitudinal direction can be affected by prior creep. In general, the ultimate tensile strengths are not greatly reduced (maximum reduction observed was 25 percent) by creep strains up to about 0.55 percent. The behavior of the residual ductility shown in figure 12(a) is erratic; both increases and decreases as compared to as-received ductility are observed. Thus, while prior

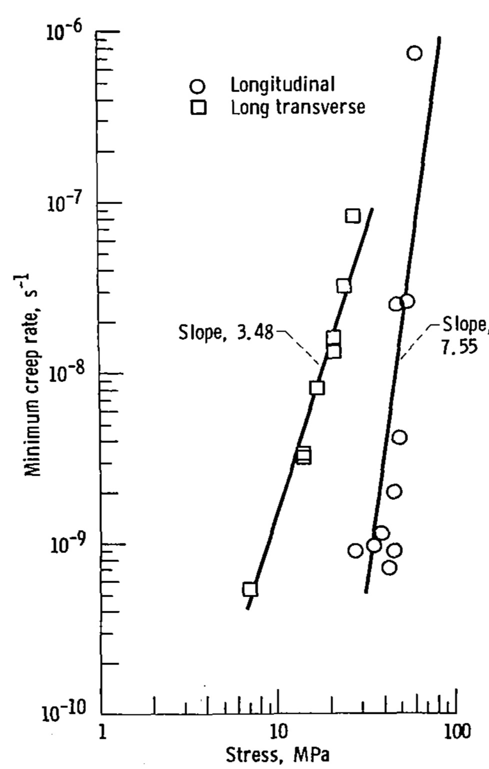
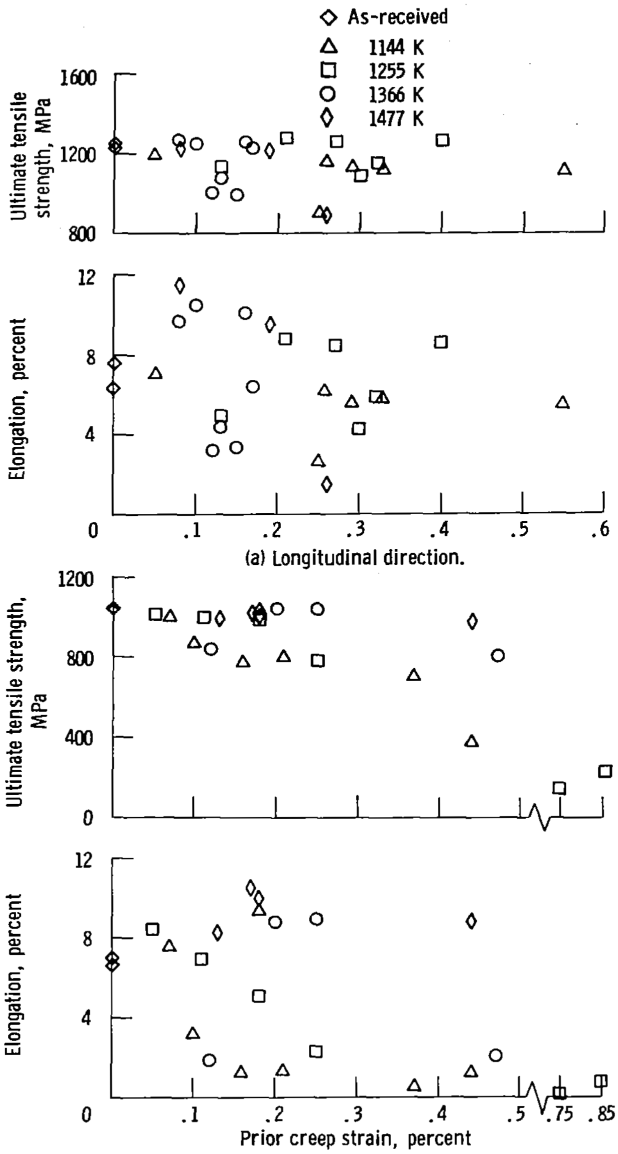
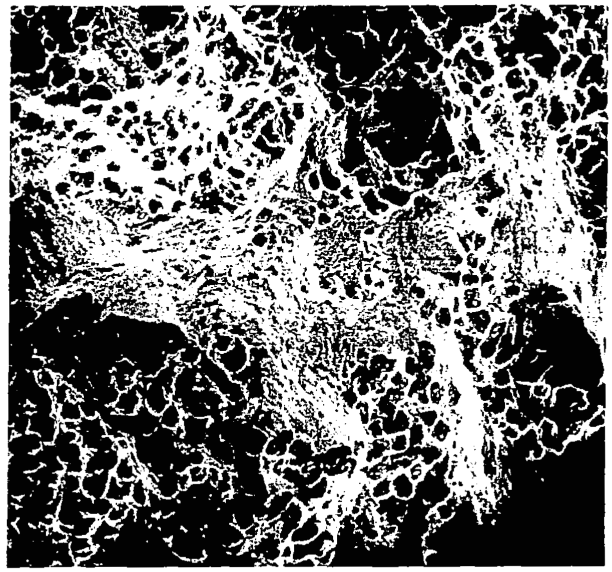


Figure 11. - Minimum creep rate as a function of stress for MA-757 at 1366 K.

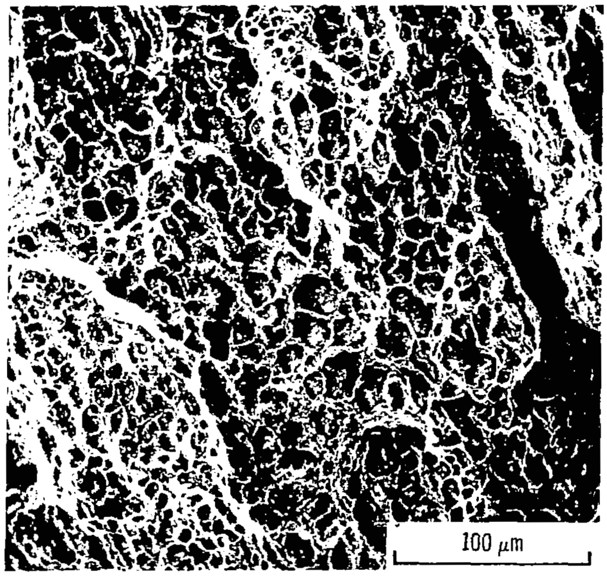


(b) Long transverse direction.

Figure 12. - Residual room temperature tensile properties as a function of prior creep strain for MA-757 strained at 1144 to 1477 K for approximately 150 hours.



(a) Longitudinal specimen strained 0.32 percent at 68.9 MPa before tensile testing.



(b) Long transverse specimen strained 0.25 percent at 34.5 MPa before tensile testing.

Figure 13. - SEM fractographs of MA-757 residual property specimens strained in creep at 1255 K for approximately 150 hours and tensile tested at room temperature.

creep straining apparently does not produce creep degradation in every instance, the mechanical property data illustrate that creep degradation can occur in the longitudinal direction.

Fractographs of residual property specimens (fig. 13) and microstructures of stress-rupture tested specimens (appendix B) indicate that microstructural changes (refs. 2 and 3) which lead to degradation of mechanical properties are occurring during creep. In particular, pock-marked fracture surfaces are considered indicative of damage associated with the formation of weakened, dispersoid-free regions during prior creep straining. Thus, the eventual reduction of mechanical properties in the longitudinal direction after long term elevated temperature creep straining should be expected.

The residual mechanical property data in figure 12(b) also indicate that creep damage has occurred for tests conducted in the long transverse direction. In general, for prior creep exposures between 1144 and 1366 K, creep damage occurs at about 0.1 percent strain while prior creep at 1477 K to about 0.44 percent strain does not appear to affect residual properties. Fractography of residual property specimens which had previously been creep strained at 1255 K (fig. 13) and metallography of failed stress-rupture specimens tested at 1144 and 1477 K (appendix B) reveal microstructural features intimately connected with creep degradation.

MA-956.—Of the alloys tested in this program, MA-956 is by far the most unusual and interesting. Because of this, the majority of the MA-956 data on longitudinal properties will be graphically presented. In general, data for MA-956 in the long transverse direction will be only summarily presented. Only a few tests in the long transverse direction were conducted due to difficulties in obtaining sound specimens. All mechanical property data obtained for MA-956 are presented in appendix A.

Typical elevated temperature tensile properties for MA-956 tested in the longitudinal and long transverse bar directions are shown in figure 14. In general, the longitudinal direction was stronger and more ductile than the long transverse direction. The strength data in the long transverse direction at 1144 and 1255 K exhibited considerable scatter, possibly due to internal defects (see fig. 1). Except at room temperature, the strength and ductility results in the longitudinal direction were consistent. At room temperature the long transverse specimen and one longitudinal specimen failed by cleavage at low elongations; the other longitudinal specimen also failed by cleavage but only after considerable deformation.

The stress-rupture characteristics of MA-956 tested in the longitudinal direction are shown in figure 15. These data reveal that the stresses to produce rupture in times ranging from 0.1 to greater than 1000 hours for temperatures ranging from 1144 to 1477 K lie in a band about 30 MPa in width. Rupture life is thus highly dependent on stress.

Typical creep curves for longitudinal MA-956 tested at 1255 K are shown in figure 16 and steady state creep rate data as a function of stress and temperature are presented in figure 17. Examination of the creep curves in figure 16 illustrates an important characteristic concerning creep failure of MA-956. When failure occurs, there is almost an instantaneous transition from an apparently slowly deforming specimen to a failed specimen. The process or processes which control the final few moments of life must be very rapid and allow considerable deformation to occur as indicated by the final elongation and reduction-in-area data for the failed specimens (appendix A). Except for the short life tests (failure times less than 10 h), MA-956 does not exhibit third stage creep. This behavior was noted at all four test temperatures.

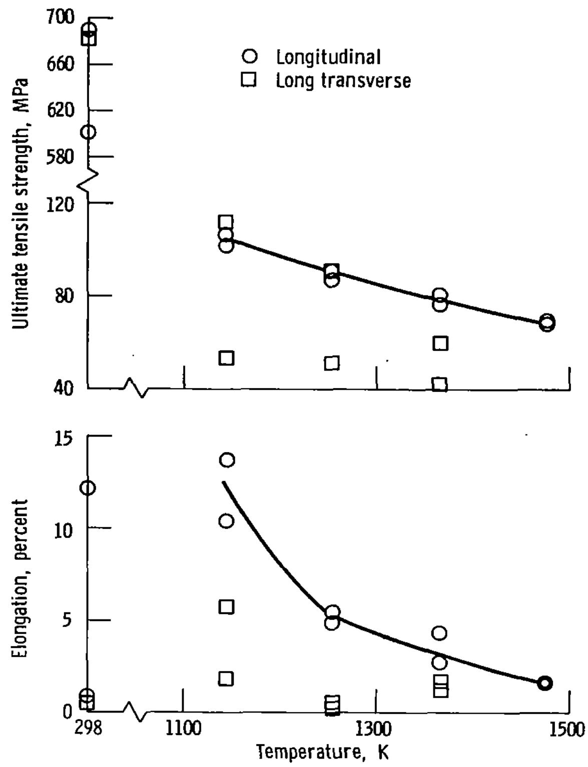


Figure 14. - Tensile properties as a function of temperature and test direction for MA-956.

A macrograph of a typical failed MA-956 specimen is shown in figure 18. As can be seen, considerable localized deformation (reduction in area) has occurred. Note, however, that the observed deformation has apparently taken place only on one side of the test specimen while the other side has remained essentially parallel to the stress axis.

Typical SEM fractographs of the fracture surface of the same MA-956 specimen shown in figure 18 are presented in figure 19. Figure 19(a) shows a flat crack-like surface which is perpendicular to the applied stress, and figure 19(b) illustrates a region, ahead of the crack-like surface, which is composed of small flat areas on many different levels. Similar fracture surfaces have been seen on specimens of MA-956E after stress-rupture testing at 1365 K (ref. 4) and on MA-956 bar after slow tension testing at 1366 K (ref. 12). The latter work presents evidence that the flat regions found on the fracture surfaces of

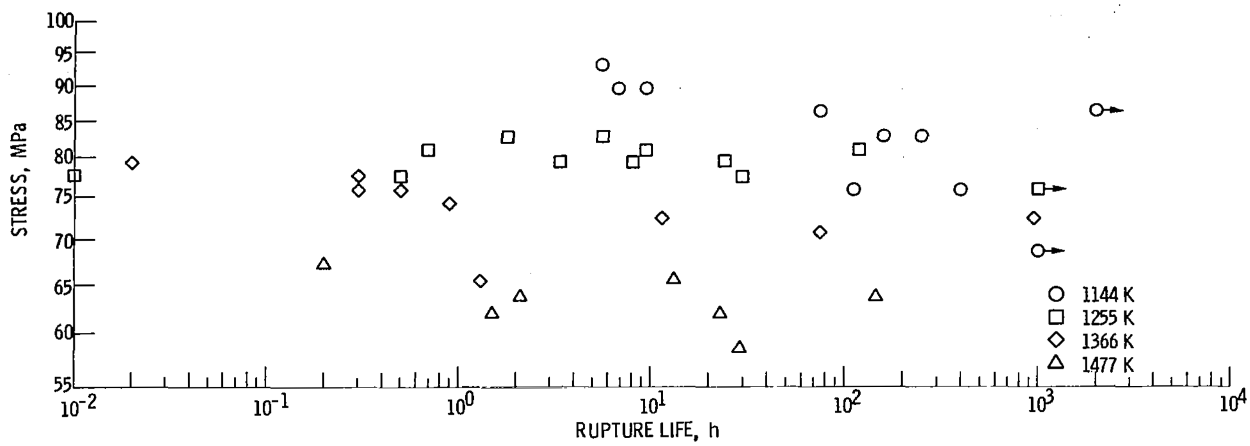


Figure 15. - Rupture life as a function of stress in longitudinal direction for MA-956 at 1144 to 1477 K.

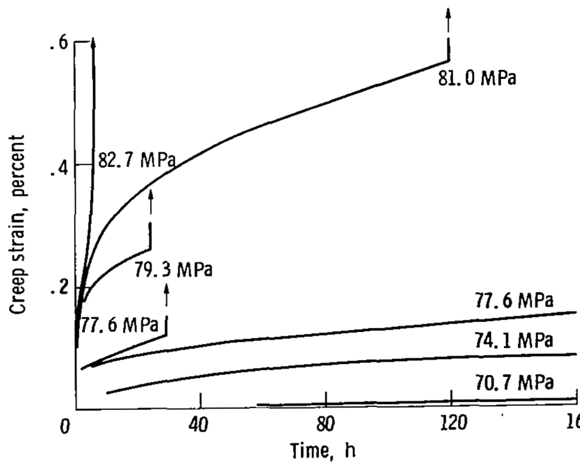


Figure 16. - Typical creep curves in longitudinal direction for MA-956 at 1255 K.

MA-956 are indeed the result of slow growth of a crack and that the multilevel region ahead of the crack occurs when the running crack is undergoing the transformation from slow to fast growth. Crack growth processes apparently take place in MA-956 until the remaining load-bearing area is reduced to the point where fast ductile deformation can occur. Since the running crack starts at or near the surface of the test specimen and slowly grows until overload conditions occur, metallographic sections parallel to the stress axis should reveal a structure which has a deformed and undeformed appearance on opposite sides of the specimen. This is consistent with the structure shown in figure 18.

Because of the slow crack growth mechanism by which MA-956 apparently undergoes slow plastic deformation, the measurement and reporting of minimum creep rates may not be meaningful. However, for completeness, these data were characterized and are graphically presented in figure 17. This figure contains approximate minimum creep rate data for two tests which underwent no deformation after about 150 hours of testing (points plotted at rate $= 10^{-10}$ s^{-1} and five tests which underwent considerable deformation in a short time. The minimum creep rate data in figure 17 are very similar to the stress-rupture data in figure 15 in that both deformation rates and rupture lives are highly dependent on stress.

The creep data in figure 17 also illustrate the very strong dependency of creep rate on stress, where small changes in stress produce dramatic differences in behavior. Although many attempts were made, it proved impossible to induce moderate amounts of creep strain into MA-956 specimens. There were only 12 unfailed creep specimens out of a total of 34 creep tests; of these specimens, one had 0.25 percent strain, two had about 0.15 percent strain, and the remaining had 0.1 percent or less strain. Except for the short life tests, very little creep deformation was observed. The maximum amount of creep strain seen in any test (prior to the rapid failure processes, if failure occurred) is shown in figure 16 by the test conducted at 81 MPa.

Typical room temperature residual tensile properties of MA-956 in the longitudinal direction are presented in figure 20. These data indicate that for prior elevated temperature creep strains of less than 0.25 percent, MA-956 is not subject to creep degradation. Attempts to introduce larger creep strains were not successful. No evidence of creep damage was seen during SEM examination of selected fracture surfaces. Only cleavage type

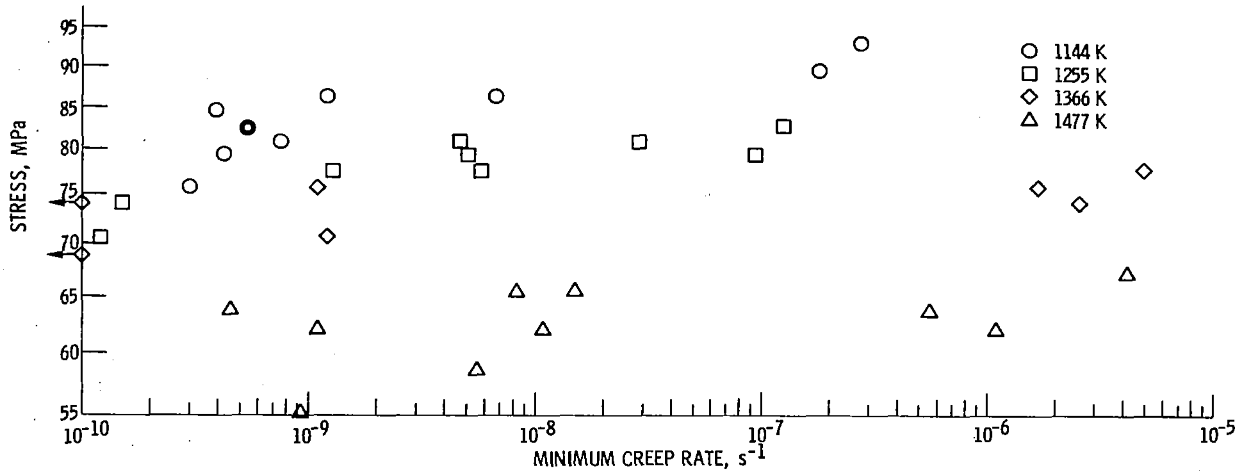


Figure 17. - Minimum creep rate at a function of stress for MA-956 tested in longitudinal direction at 1144 to 1477 K.

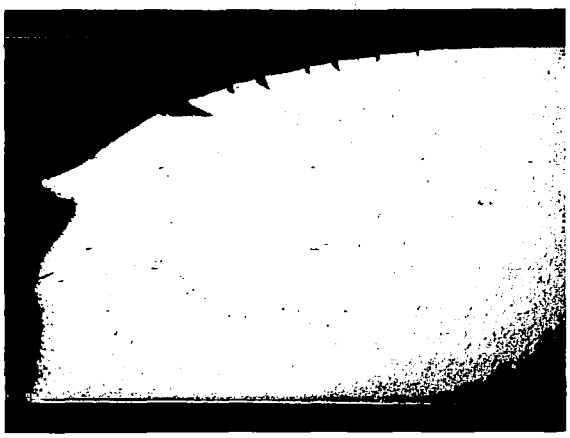


Figure 18. - Macrograph of failure region of MA-956 rupture tested in longitudinal direction for 943.1 hours at 72.4 MPa and 1366 K.

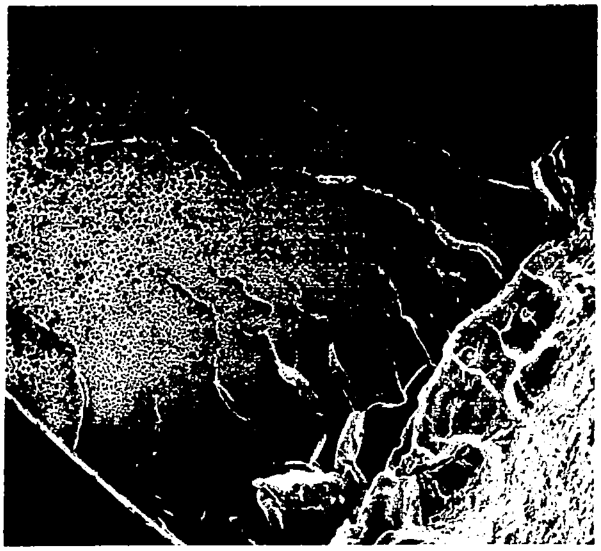
features were seen on the fracture surface of as-received room temperature test specimens, whereas regions of ductile failure as well as cleavage failure were seen on the residual property test specimens. Typical examples of residual fracture surfaces are presented in figure 21.

In summary, the elevated temperature deformation characteristics of MA-956 tested in the longitudinal direction are unusual. Under test conditions designed to promote slow plastic flow, the alloy apparently deforms by the growth of cracks. This process is rather insensitive to test temperature but extremely sensitive to stress. With regard to residual properties, MA-956 is not subject to creep degradation in the longitudinal direction at least up to prior creep strains on the order of 0.25 percent.

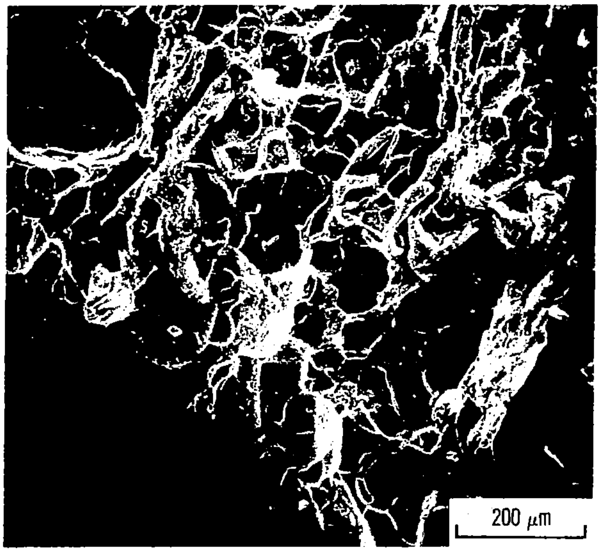
STCA alloys.—Only room temperature and 1366 K tensile testing, 1366 K creep testing, and room temperature residual property testing were conducted on STCA alloys; all test results are tabulated in appendix A.

The 1366 K tensile data (appendix A) reveal that the tensile strength of STCA alloys is independent of chemistry and test direction. While tensile elongation appears to vary with chemistry, the reduction-in-area ductility data do not indicate significant differences based on chemistry. Both ductility indicators reveal, however, that the longitudinal direction is more ductile than the long transverse direction at 1366 K.

Typical creep curves and minimum creep rates as a function of stress, testing direction, and heat treatment are presented in figures 22 and 23, respectively, for STCA-266 tested at 1366 K. This alloy contains about 1.2 weight percent Ta in addition to nominally 16Cr and 4.5Al (table I); STCA-266SC was given a carbide precipitation heat treatment following the standard heat treatment. The creep rate data in figure 23 indicate that the alloy in the longitudinal direction is more creep resistant than in the long transverse direction; additionally, it appears that the carbide heat treatment lowers the creep strength of heat STCA-266 in the long transverse direction. As is the case for most ODS alloys, small changes in stress can produce large changes in creep strain. Thus, it proved difficult to induce moderate creep strains in specimens for residual property testing. Whereas the creep behavior in figures 22 and 23 is typical, discrepancies in behavior were observed; for example, the carbide precipitation heat treatment lowered the creep strength of STCA-266 but did not affect the strength of STCA-265 (appendix A). Also in the longitudinal



(a) Fracture surface in crack-like region.



(b) Fracture surface ahead of crack.

Figure 19. - SEM fractrographs of MA-956 specimen ruptured tested in longitudinal direction for 943.1 hours at 72.4 MPa and 1366 K.

testing direction the Ta-free alloy (STCA-262/264S) and the Ta-rich alloy (STCA-265S) are stronger than the intermediate Ta level alloy (STCA-266S); however in the long transverse direction the Ta-free and the intermediate level Ta alloys are stronger than the Ta-rich alloy. The reasons for this behavior are not known. Photomicrographs of representative failed creep specimens are presented in appendix B. As was the case for MA-757, these photomicrographs reveal the presence of extensive grain boundary cavitation and cracking. Dispersoid-free regions and massive internal oxidation were also noted on some specimens.

Room temperature residual tensile properties for STCA alloys after 1366 K creep straining are compared to as-received properties in figure 24. The as-received room temperature strength properties are dependent on test direction and essentially independent of chemistry. The ultimate tensile strengths are about 1300 and 1100 MPa in the longitudinal and long transverse directions, respectively, and both testing directions and all chemistries exhibit from 5 to 6 percent elongation. In the longitudinal test direction, prior creep straining up to 0.11 percent had no effect on residual properties except for the STCA-265SC specimen pre-crept 0.09 percent (fig. 24(a)); SEM examination of this specimen revealed an internal defect on the fracture surface which produced the premature failure. Prior creep exposure involving creep strains between 0.13 and 0.55 percent in the longitudinal

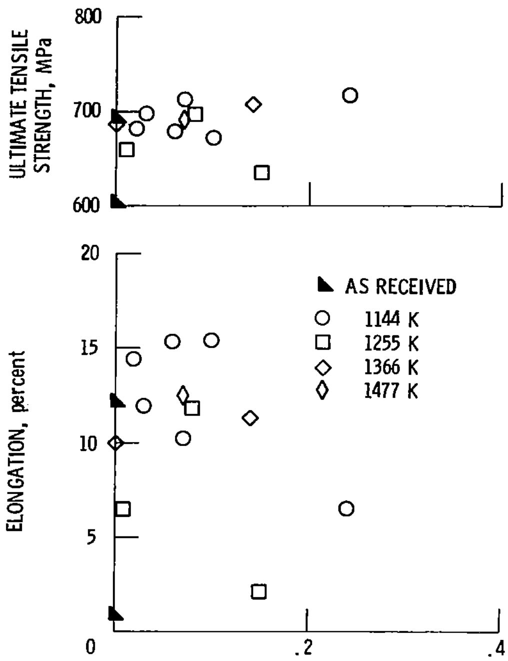
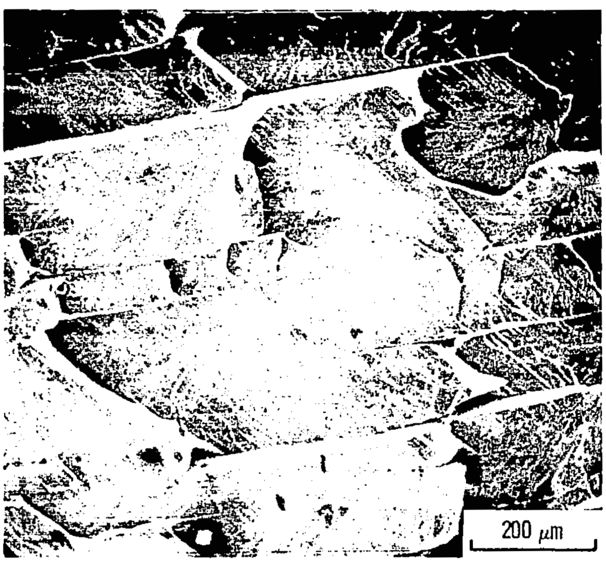


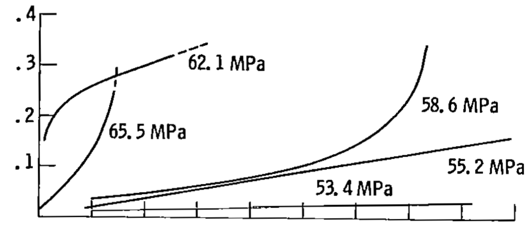
Figure 20. - Residual room temperature tensile properties as a function of prior creep strain for MA-956 strained in longitudinal direction at 1144 to 1477 K.

(a) Strained 0.08 percent at 74.1 MPa before tensile testing. Ductile plus cleavage fracture.

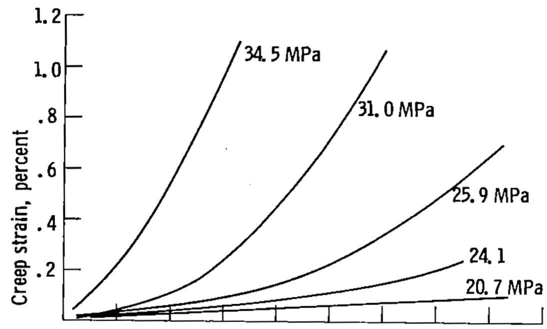


(b) Strained 0.15 percent at 77.6 MPa before tensile testing. Cleavage fracture.

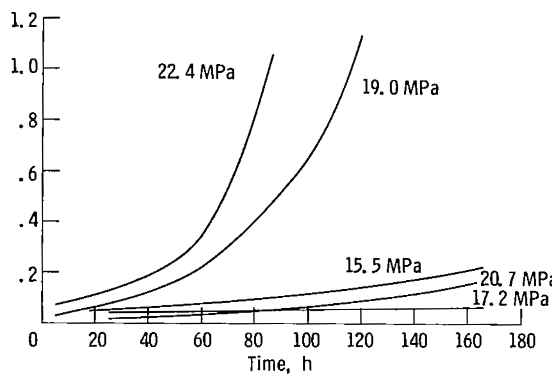
Figure 21. - SEM fractographs of longitudinal MA-956 residual property specimens strained in creep for approximately 150 hours at 1255 K and tensile tested at room temperature.



(a) STCA-266S in longitudinal direction.



(b) STCA-266S in long transverse direction.



(c) STCA-266SC in long transverse direction.

Figure 22. - Typical creep curves for STCA-266S and STCA-266SC at 1366 K.

direction lowered the tensile strength about 15 percent to nominally 1000 MPa, whereas the tensile elongation was progressively lowered from 6 percent to about 1 percent as the prior creep strain increased.

The residual property data in figure 24(b) for the long transverse direction indicate that prior creep strain up to about 0.1 percent has no effect on room temperature properties. However, at greater than 0.1 percent strain the residual tensile properties are severely degraded. In many cases tensile failure occurred before the 0.2 percent offset yield strength was reached. Two typical SEM fractographs illustrating creep-damaged areas on STCA residual property fracture surfaces are presented in figure 25.

YD-NiCrAl.—As only a few YD-NiCrAl specimens were available for testing, only 1366 K creep and residual property tests were conducted.

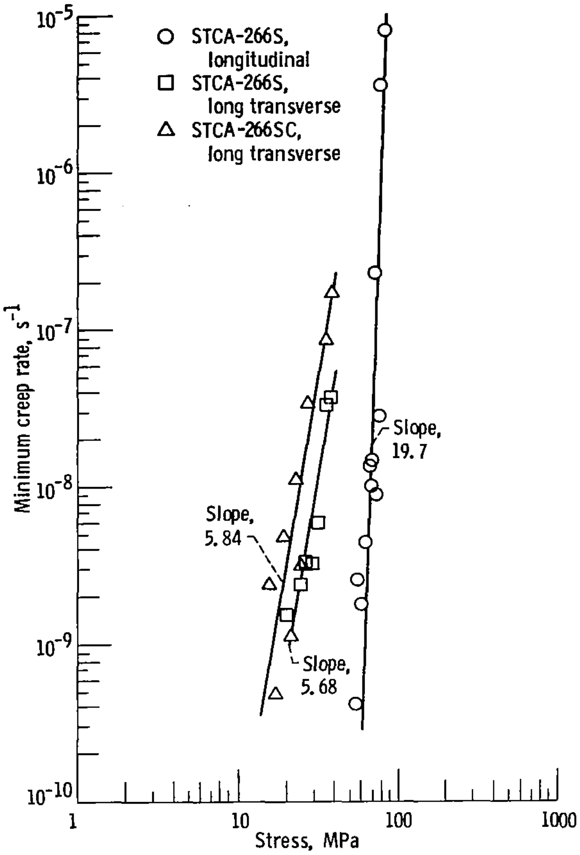


Figure 23. - Minimum creep rate as a function of stress for STCA-266S and STCA-266SC at 1366 K.

Typical creep curves are shown in figure 26 and minimum creep rates as a function of stress are shown in figure 27. This alloy was reasonably ductile in creep because strains up to about 0.7 percent after about 150 hours of testing could be readily induced (fig. 26). Figure 27 also indicates that creep rates in YD-NiCrAl are highly dependent on stress.

Figure 28 presents residual tensile property data for YD-NiCrAl after creep straining at 1366 K. Unfortunately, as-received tensile properties are not available for comparison; however, the residual property data indicate that YD-NiCrAl is not severely affected by prior creep straining in the longitudinal direction. In general, the ductility is good (8 percent elongation or greater) and tensile strength is high (about 1050 MPa) even after 0.72 percent prior creep strain. While the residual mechanical properties are excellent in terms of resistance to creep degradation, SEM fractography (fig. 29) of residual property specimens did reveal areas which were creep-damaged. Thus, long term application under slow strain rate conditions might

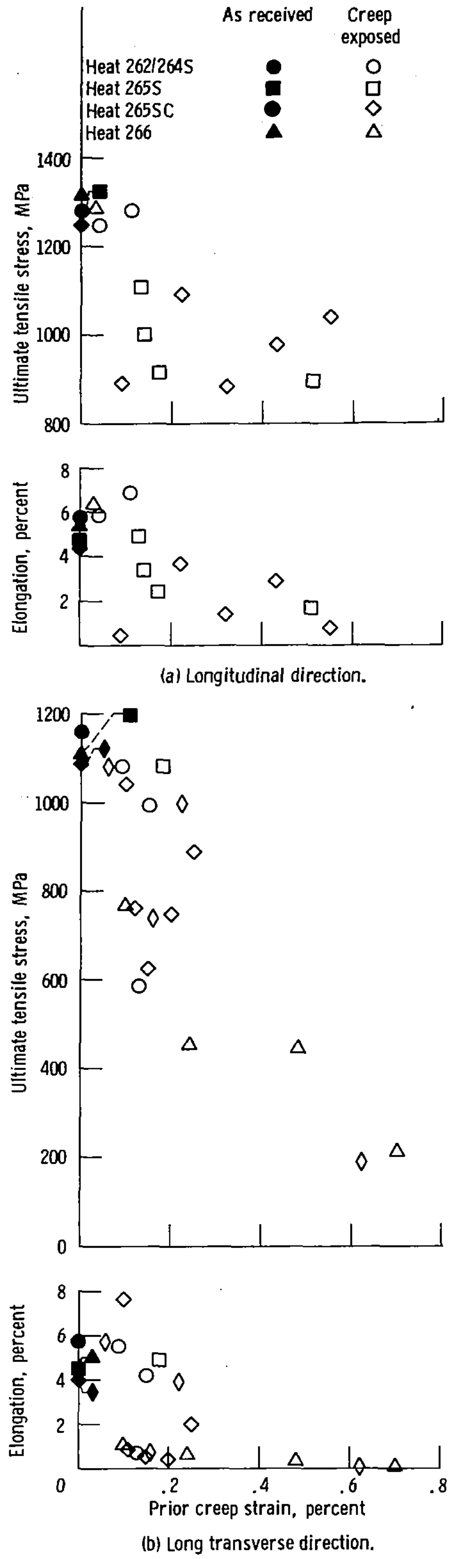
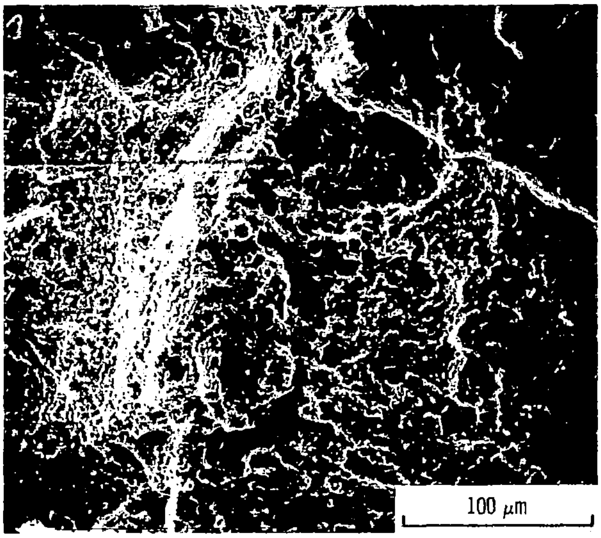
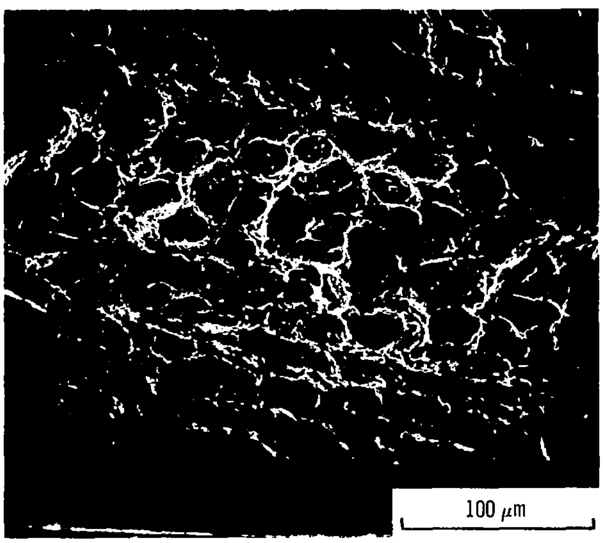


Figure 24. - Residual room temperature tensile properties as a function of prior creep strain for STCA alloys strained at 1366 K for approximately 150 hours.



(a) STCA-265SC longitudinal specimen strained 0.32 percent at 68.9 MPa before tensile testing.



(b) STCA-266S long transverse specimen strained 0.10 percent at 20.7 MPa before tensile testing.

Figure 25. - SEM fractographs of STCA residual property specimens strained in creep for approximately 150 hours at 1366 K and tensile tested at room temperature.

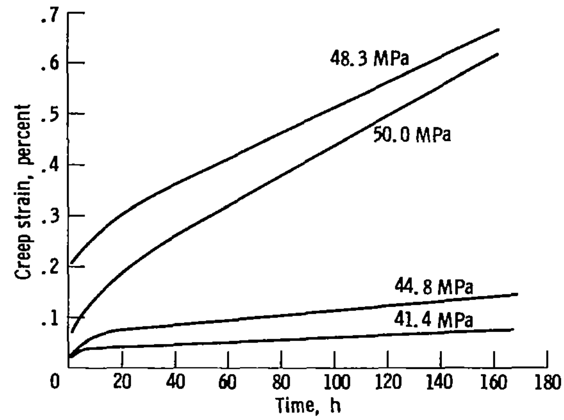


Figure 26. - Typical creep curves for YD-NiCrAl in longitudinal direction at 1366 K.

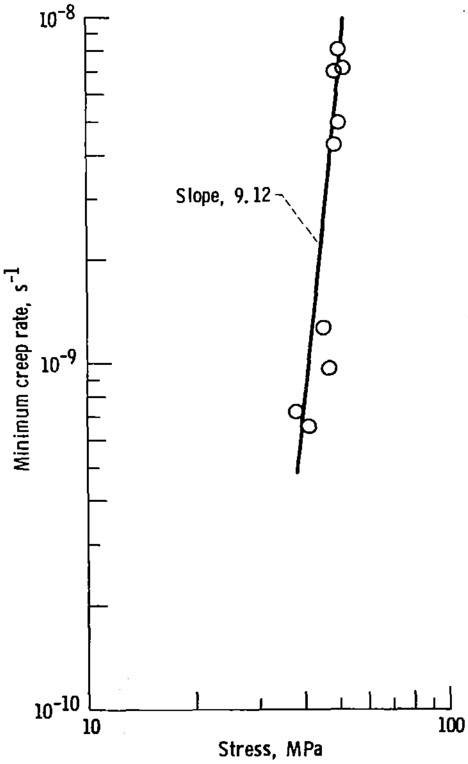


Figure 27. - Minimum creep rate as a function of stress for YD-NiCrAl tested in longitudinal direction at 1366 K.

lead to severe degradation of subsequent tensile properties in YD-NiCrAl as damaged regions increase in size during creep.

Summary and comparison of ODS alloy behavior.—All of the nickel-base ODS alloys examined in this study revealed signs of creep degradation. The longitudinal bar direction is more resistant to degradation than the long transverse bar direction. In the longitudinal direction, creep strains up to about 0.5 percent in 150 hours do not significantly reduce residual room temperature

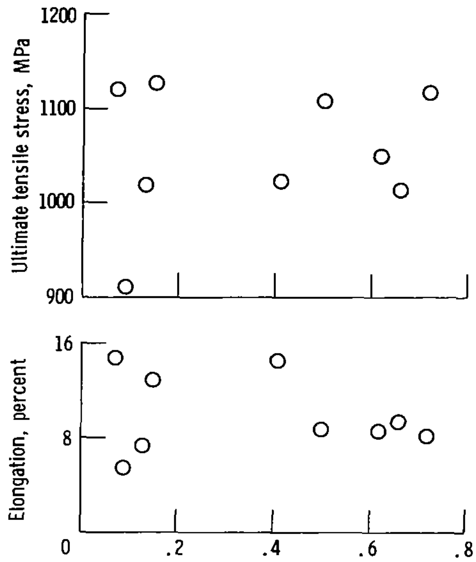
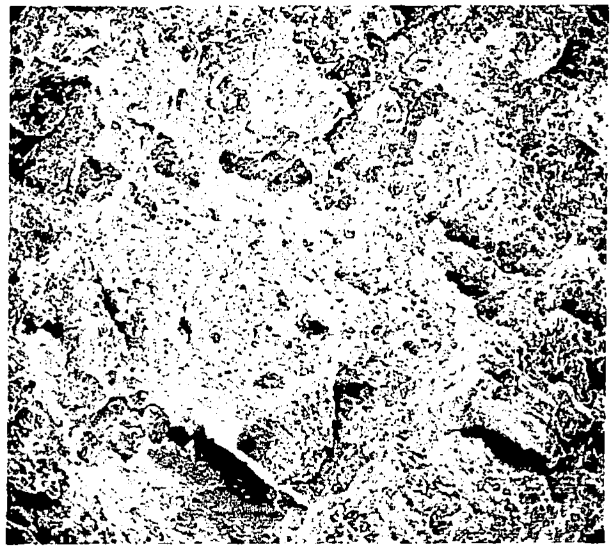
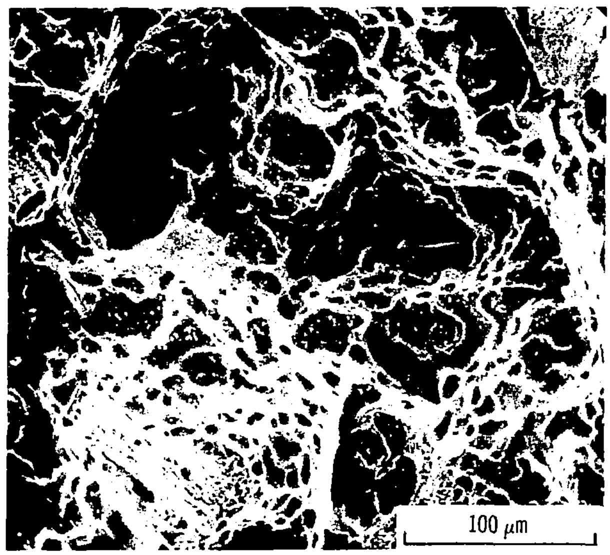


Figure 28. - Residual room temperature tensile properties as a function of prior creep strain for YD-NiCrAl strained in longitudinal direction at 1366 K for approximately 150 hours.



(a) Strained 0.07 percent at 41.4 MPa before tensile testing.



(b) Strained 0.66 percent at 48.3 MPa before tensile testing.

Figure 29. - SEM fractographs of YD-NiCrAl residual property specimens strained in creep at 1366 K for approximately 150 hours and tensile tested at room temperature.

tensile properties. However, the observation of microstructural artifacts thought to be connected to creep degradation on longitudinal test specimens indicates that severe damage is possible for very long time creep exposures even if they involve only small strains. In the long transverse direction, prior creep exposures involving as little as 0.1 percent strain can produce significant reduction in residual properties. Overall, the residual property behavior of nickel-base ODS alloys in this study is similar to that of MA-754 (ref. 3), where the degree of creep damage was dependent on testing direction as well as the amount of prior creep strain. Finally, on the basis of MA-757 testing and previous results for TD-NiCr (ref 2), it appears that creep degradation will occur in practically all nickel-base ODS alloys when creep strained between 1144 and 1477 K.

The ODS iron-base alloy MA-956 is apparently not subject to creep degradation for prior creep strains up to 0.25 percent in the longitudinal bar direction. It should be noted, however, that it was not possible to induce larger creep strains into this alloy because of the unusual manner in which MA-956 deforms at elevated temperatures.

With regards to long term elevated temperature creep strength of ODS alloys, the longitudinal bar direction was always stronger than the long transverse bar direction. Comparison of the long term creep strength at 1366 K in the longitudinal direction of iron-base MA-956 (fig. 17) to those of nickel-base alloys (figs. 9, 23, and 27) reveals that MA-956 is more creep resistant than the nickel-base alloys. The data in appendix A reveal that the long term creep strength of MA-757 at 1144 K in the longitudinal direction is greater than that of MA-956; however, between 1255 and 1477 K the opposite behavior is observed, with MA-956 being the stronger alloy.

Conclusions

The following conclusions are drawn from this study of creep and residual mechanical properties of high temperature superalloys and advanced ODS alloys:

1. The tensile properties of the large grain size cast superalloys B-1900 (nickel-base) and MAR-509 (cobalt-base) are not degraded by creep at least up to about one percent strain at 1144 to 1366 K.
2. The room temperature properties of the wrought Ni-Cr-Al ODS alloys MA-757, STCA, and YD-NiCrAl can be degraded by prior creep strains of 0.5 percent or less at 1144 to 1477 K. The longitudinal direction is less susceptible to creep damage than the long transverse direction.
3. The residual room temperature tensile properties of the iron-base ODS alloy MA-956 are apparently not degraded by prior creep straining up to 0.25 percent at 1144 to 1477 K. However, MA-956 exhibits unusual creep behavior which apparently involves nucleation and slow growth of cracks.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 21, 1980

Appendix A

Mechanical Properties of Test Alloys

This appendix presents a tabular summary of all mechanical property data generated during this study. Each alloy and its pertinent tables are listed here:

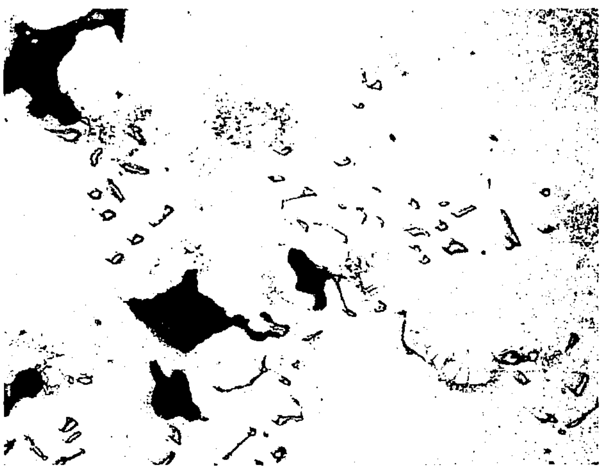
B-1900	Tables III(a) to (d)
MAR-M509	Tables IV (a) to (e)
MA-757	Tables V (a) to (d)
MA-956	Tables VI (a) to (d)
STCA	Tables VII (a) to (c)
YD-NiCrAl	Tables VIII (a) and (b)

Appendix B

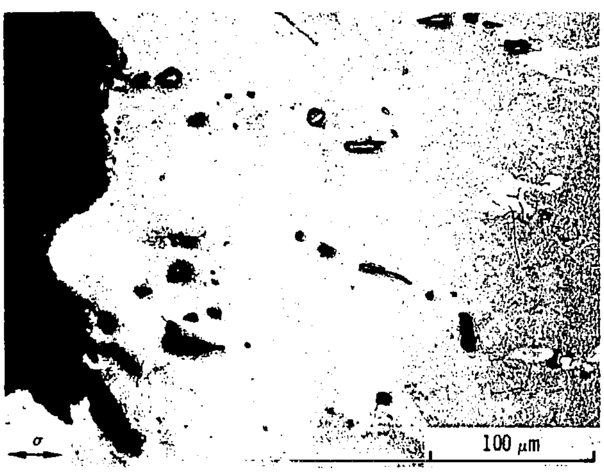
Microstructure of Several Tested Alloys

The following appendix contains typical photomicrographs of the alloys which were extensively studied. Where meaningful, photomicrographs of both as-received and test alloys are presented.

Figure 30 contains photomicrographs of as-received and stress-rupture tested B–1900. As can be most easily seen in figure 30(a), the as-received B–1900 contains porosity due to the casting process. Figure 30(b) shows a typical microstructure for long term B–1900 stress-rupture specimens. Comparison of figures 30(a) and (b) indicates that the gamma-prime phase grows during rupture testing. Also figure 30(b) shows oxide penetration along grain boundaries. Both specimens were etched with a mixed acid solution containing 33 parts by volume HCl, 33 parts acetic acid, 33 parts HNO_3, and 1 part HF.

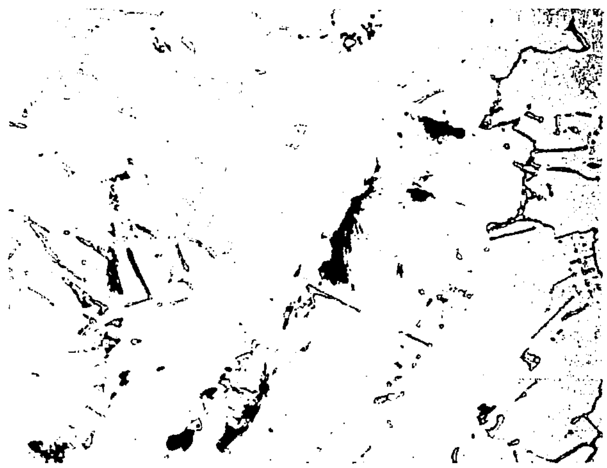


(a) As-received.

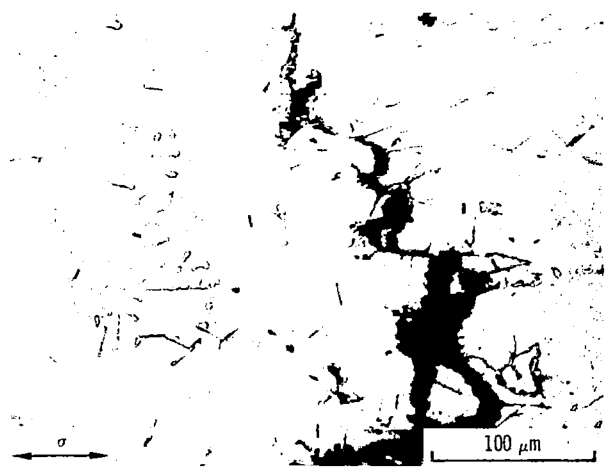


(b) Stress rupture tested for 624.6 hours at 117.1 MPa and 1255 K.

Figure 30. - Microstructures of B-1900.



(a) As-received.



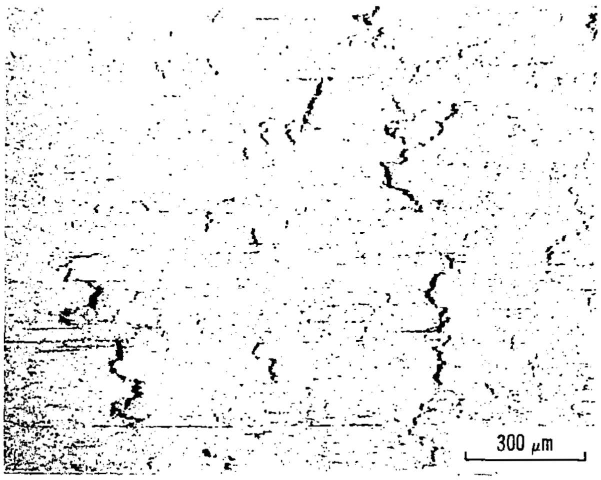
(b) Stress rupture tested for 606.2 hours at 68.9 MPa and 1255 K.

Figure 31. - Microstructures of MAR-M509.

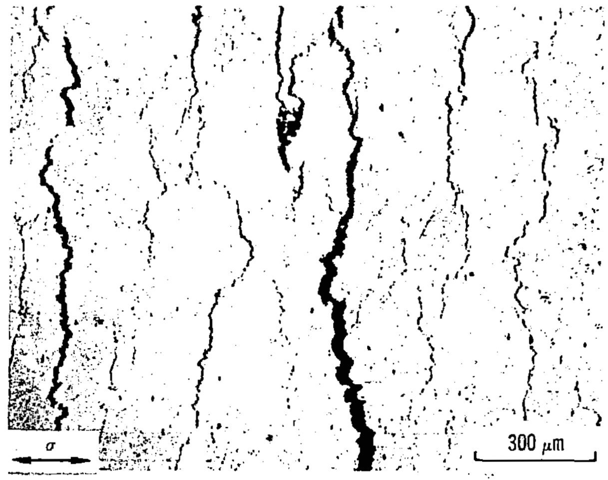
The microstructure of as-received MAR-M509 is shown in figure 31(a) where the Chinese script pattern of the carbides can be easily seen. A typical microstructure of long time stress-rupture tested MAR-M509 is presented in figure 31(b). Carbides and oxide penetration along grain boundaries are evident in this figure. All MAR-M509 specimens were etched with the mixed acid solution.

Examples of the microstructure found in stress-rupture tested MA-757 are shown in figure 32. Extensive intergranular cracking is evident in specimens tested at 1144 K, while intergranular void formation is seen in specimens tested at 1477 K. Dispersoid-free zones are also visible after testing at both temperatures. These microstructures are similar to those observed in other nickel-base ODS alloys (refs. 1 to 3). All specimens were electrolytically stain etched with a chromic acid mixture (100 ml H_2O, 10 ml H_2SO_4, and 2 g chromic acid).

Finally, typical examples of the microstructure of failed STCA creep test specimens are shown in figure 33. The microstructures shown are similar to those presented for MA-757, and contain dispersoid-free bands, grain boundary cracking and cavitation, and massive internal oxide. All alloys were electrolytically etched with a buffered aqua regia solution containing 33 percent glycerine by volume.

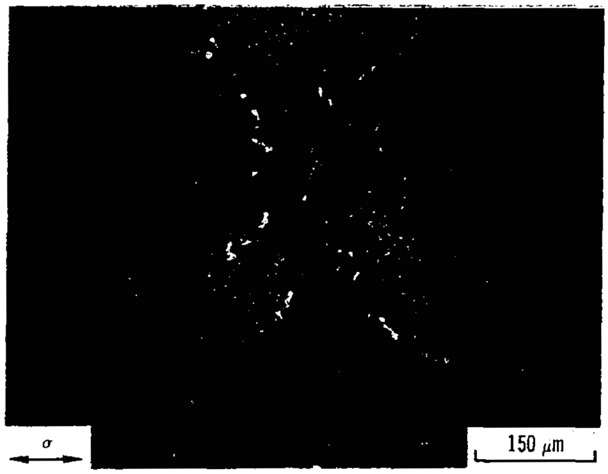


(a) Longitudinal specimen stress rupture tested for 160.8 hours at 130.9 MPa and 1144 K.



(b) Long transverse specimen stress rupture tested for 110.4 hours at 82.7 MPa and 1144 K.

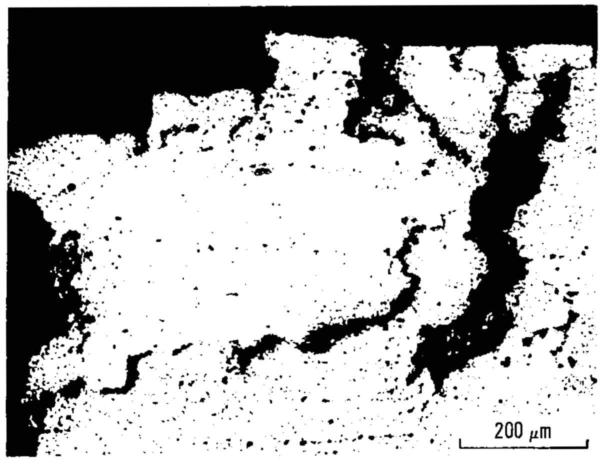
(c) Longitudinal specimen stress rupture tested 200.6 hours at 31.0 MPa and 1477 K.



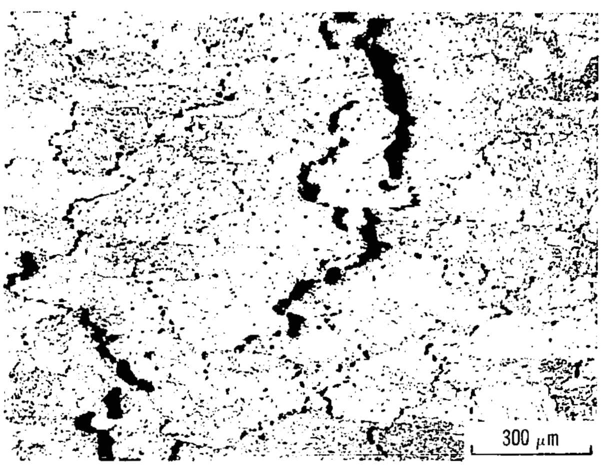
(d) Long transverse specimen stress rupture tested for /24.1 hours at 3.4 MPa and 1477 K.

Figure 32. - Microstructures of MA-757.

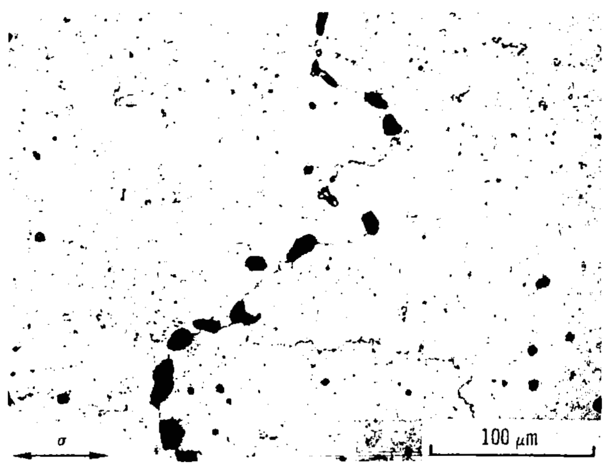
(a) Longitudinal specimen of STCA-265SC creep rupture tested for 116.2 hours at 72.4 MPa and 1366 K.



(b) Longitudinal specimen of STCA-266S creep rupture tested for 146.6 hours at 58.6 MPa and 1366 K.



(c) Long transverse specimen of STCA-265S creep rupture tested for 165.4 hours at 19.0 MPa and 1366 K.



(d) Long transverse specimen of STCA 262/264S creep tested for 166.5 hours at 31.0 MPa and 1366 K.

Figure 33. - Microstructures of STCA alloys.

Appendix C

Regression Analysis of Stress Rupture and Creep Data

As part of this study, a considerable amount of creep and stress-rupture data were generated. In order to develop equations which could be used for prediction and comparison to theoretical models, the time to rupture and steady state creep rate data from appendix A were fitted to the standard semi-empirical stress-temperature equations by means of a computerized linear regression program. The equations used in this work are:

$$\left.\begin{array}{l}\ln tr\\ \ln \dot{e}\end{array}\right\} = A + n(\ln s) \qquad \text{(C-1)}$$

$$\left.\begin{array}{l}\ln tr\\ \\ \ln \dot{e}\end{array}\right\} = B + \frac{Q}{RT} + n(\ln s) \qquad \text{(C-2)}$$

where tr is the time to rupture in hours, $\dot{e}$ is the steady state creep rate in reciprocal seconds, A and B are constants, n is a stress exponent, s is the applied stress in MPa, Q is an activation energy in joules/g-mol-K, R is the gas constant (8.314 joules/g-mol-K), and T is the absolute temperature in Kelvin.

Whereas equations (C-1) and (C-2) can be independently applied to the experimental data, the activation energy(s) determined by equation (C-2) is (are) only theoretically meaningful when the stress exponents calculated at different temperatures via equation (C-1) are equal. Due to the limited testing at each temperature, it would be fortuitous if the stress exponents at each temperature were determined to be exactly equal. However confidence limits for the stress exponents can be calculated and examined to see if a common overlap region exists. When an overlap exists and the stress exponents determined from equation (C-2) fall within this overlap, a statistically meaningful activation energy has been calculated, and it can be used in theoretical models of deformation. If these two conditions are not met, the "activation energy" and "stress exponent" data reported in table IX to XIX are simply coefficients which best describe the behavior of the material in question.

Where possible all the experimental data were used in the regression analysis; however, in some instances, particularly for the ODS alloys, editing of the data was necessary to develop reasonable equations. The pertinent regression equations as well as the regression coefficient, R**2, for each alloy system are presented in tables IX to XIX.

Applicability of equations (C-2) to determine a meaningful activation energy(s) was based on 95 percent confidence limits on the stress exponents calculated from equations (C-1). In this work only stress-temperature fits of the data obtained at 1144 K and progressively higher temperatures were determined.

Each alloy and its pertinent tables are listed here:

B-1900	Table IX
MAR-M509	Table X
MA-757	Tables XI to XIV
MA-956	Tables XV and XVI
STCA	Tables XVII and XVIII
YD-NiCrAl	Table XIX

B-1900

The data presented in table XI indicates that equations (C-1) well describe the rupture and creep data at each test temperature. While the stress-temperature fits are good for the 1144-1255 K interval, fits based on equations (C-2) for the larger temperature intervals are not as good. Only the activation energies calculated for the 1144-1255 K interval satisfy the previously stated requirements on stress exponents, and both the activation energy for creep and activation energy for rupture are higher than that for diffusion in nickel or nickel-base superalloys ($Q \approx 280$kJ/g-mol-K, ref. 13).

Since the stress exponents calculated from equations (C-1) have common overlap regions (-5.24 to -6.00 for rupture data and 4.63 to 6.28 for creep data), it is possible that the stress dependency is independent of temperature. Thus, it appears that the inability of equations (C-2) to successfully predict behavior at the larger temperature intervals is due to changes in the thermally activated processes. For example the amount, distribution, size and shape of gamma-prime are functions of time at temperature, and such changes in gamma-prime will most certainly affect deformation processes. While such reasoning is appealing, it can not be proven because of the statistical correlation between stress and temperature. This correlation is the result of the decreasing strength with increasing temperature and the limitations placed on testing (e.g., time to rupture less than 500 and measureable creep strain after 150 h of testing). For B-1900 the following equations relate the stresses for creep testing *se* and the stresses for rupture testing *sr* to the absolute temperature:

$$\ln se = -5.24 + \frac{12\,427}{T} \qquad (R^{**}2 = 0.92)$$

$$\ln se = -5.52 \frac{13\,106}{T} \qquad (R^{**}2 = 0.92)$$

Because of the high correlation, it is difficult to separate effects due solely to temperature or stress.

MAR-M509

Only the activation energy for rupture in table X calculated from the 1144–1255 K temperature interval is statistically sound. This activation energy (510.6 kJ) compares unfavorably with the activation energy measured for diffusion in Co-Ni alloys containing 10 to 25 percent nickel ($Q \approx 250$ kJ/g-mol-K, ref. 14).

MA-757

Some editing of the raw data was required to produce reasonable fits. The results for both the unedited and edited data are shown in tables IX to XIV. Only the activation energies for rupture and creep for testing in the longitudinal direction (590 kJ/g-mol-K) and the activation energy for rupture in the long transverse direction (518 kJ/g-mol-K) calculated from the 1144–1255 K interval are statistically significant for theoretical purposes. These activation energies are higher than that for diffusion in nickel or nickel-base alloys (280 kJ/g-mol-K). Both high activation energies and high stress exponents have been observed during creep and rupture (ref 15).

MA-956

As can be seen from the regression coefficients in tables XV and XVI, editing of the MA-956 data was required. In addition to deletion, data was added: for example, ultimate tensile strength data from table VI was used as 0.1 hour rupture life strength and ultimate tensile strength-strain rate data at 1366 K from slow tensile testing (ref. 12) was used in the 1366 K creep rate regression fit. While editing significantly improved the fits of the stress rupture data, the fits of the creep data at 1366 and 1477 K are poor.

Although the stress exponents in tables XV and XVI are quite high, they were not unexpected since similar high values were observed during slow tensile testing (ref. 12). None of the activation energies calculated for rupture are meaningful for theoretical work, whereas all the activation energies for creep satisfy the stress exponent criteria. The latter is true because the permissible confidence interval is large extending from 29 to 67 due to the poorness of fit. Hence the activation energies for creep are of questionable value other than for best description of material behavior.

STCA Alloys

While editing of the creep data for the STCA alloys was not necessary for the longitudinal direction (table XVII), minor editing was required for the long transverse direction (table XVIII). Application of "F" tests to the longitudinal data in table XVII permitted comparisons of the various alloy chemistries (table I) and heat treatments (see the section Materials under Experimental Procedures). Such testing indicated that (1) the carbide heat treatment had no effect on the creep strength of STCA-265, (2) the creep strengths of heats STCA-262/264S and –265S are similar, and (3) there is a strength difference between STCA-262/264S (–265S) and –266S where heat STCA-266S is weaker. Because of these observations, the data from STCA-262/264S and –265S and STCA-265S and –265SC were pooled and fitted; the results of this procedure are also given in table XVII.

In a like manner, the edited data fits in table XVIII for the long transverse direction can be tested for differences in chemistry and heat treatment. The results of the "F" tests are as follows:

(1) The creep strengths of STCA-265S and –265SC are similar, but STCA-266S is stronger than STCA-266SC.

(2) STCA-262/264S and –266S possess similar strength while STCA-262/264S is stronger than STCA-265S.

(3) The strengths of STCA-265S and –266SC are similar. "F" tests conducted on unedited data yielded the same behavior. For completeness the results of regression fits of the pooled data from heats of similar strength are also presented in table XVIII.

Examination of the results for both test directions with regard to the effects of chemistry and heat treatment reveals several discrepancies. A carbide heat treatment has no effect on the strength of STCA-265 but apparently reduces the strength of the low tantalum alloy STCA-266. While the Ta-free alloy (STCA-262/264S) and the Ta-rich alloy (STCA-265S) are stronger than the intermediate Ta alloy (STCA-266S) in the longitudinal direction, for the long transverse testing direction the Ta-free and intermediate Ta level alloys are stronger than the Ta-rich alloy. This paradox with respect to the chemistry cannot be explained on the basis of grain size or grain aspect ratio (table II) as one would expect the largest grain size, highest grain aspect ratio alloy to possess the best strength.

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TABLE I. - COMPOSITION OF EXPERIMENTAL MATERIALS AS PROVIDED BY VENDORS

ALLOY	HEAT NUMBER	COMPOSITION, WT PCT																	
		AL	B	C	CO	CR	FE	HF	MO	NI	O	S	SI	TA	TI	W	Y	Y_2O_3	ZR
									SUPERALLOYS										
B-1900	FP5255	6.15	.016	.098	10.1	7.74	.21	1.2	5.98	BAL	-	.006	*.05	4.22	1.09	*.05	-	-	.08
MAR-M509	CJ5098	-	*.005	.62	BAL	23.6	.26	-	-	10.5	-	.007	.18	3.41	.23	6.90	-	-	.31
									OXIDE DISPERSION STRENGTHENED ALLOYS										
MA-757	DT01A8D	4.04	-	.06	-	15.7	.91	-	-	BAL	.63	.005	-	-	.60	-	-	.59	-
MA-956	DH0001F3	5.09	-	.02	-	20.7	BAL	-	-	-	-	.017	-	-	-	-	-	.76	-
STCA	**262/264	4.61	-	.05	1.1	15.7	.40	-	-	BAL	.54	*.002	-	*.01	-	-	1.52	-	-
STCA	265	4.69	-	.05	.7	15.8	.24	-	-	BAL	.52	*.002	-	1.76	-	-	1.50	-	-
STCA	266	4.77	-	.05	.4	15.9	.23	-	-	BAL	.53	*.002	-	1.25	-	-	1.52	-	-
YD-NiCrAl	173	4.	-	-	-	16.	-	-	-	BAL	-	-	-	-	-	-	-	1.	-

* LESS THAN AMOUNT INDICATED.
** AVERAGE OF TWO HEATS.

TABLE II. - GRAIN SIZE PARAMETERS AND CRYSTALLOGRAPHIC ORIENTATIONS FOR ODS ALLOYS

ALLOY	CHARACTERISTIC LENGTH, MICRONS			AVERAGE GRAIN SIZE, MICRONS	GRAIN ASPECT RATIO		CRYSTALLOGRAPHIC ORIENTATION		
	EXTRUSION AXIS L_1	LONG TRANSVERSE L_2	SHORT TRANSVERSE L_3	$0.85 \sqrt[3]{L_1 L_2 L_3}$	LONGITUDINAL $L_1/\sqrt{L_2 L_3}$	LONG TRANSVERSE $L_2/\sqrt{L_1 L_3}$	EXTRUSION AXIS	LONG TRANSVERSE	SHORT TRANSVERSE
MA-757	265	130	70	110	2.8	.95	[100]	[011]	$[0\bar{1}1]$
MA-956	*	*	*	-	-	-	$[\bar{1}13]$	[110]	$[\bar{3}3\bar{2}]$
STCA 262/264	810	330	145	290	3.7	.96	**[100]	-	-
STCA 265	1500	440	160	400	5.7	.90	**[100]	-	-
STCA 266	>6500	660	275	>900	>15	<.5	**[100]	-	-
YD-NiCrAl	2500	520	310	630	6.2	.6	[100]	[011]	$[0\bar{1}1]$

* GREATER THAN 1 CM.

** WIRE TEXTURE.

TABLE III. - MECHANICAL PROPERTIES OF B-1900

(a) Elevated temperature tensile properties.

TEMPERATURE, K	0.02 PERCENT YIELD STRESS, MEGAPASCALS	0.2 PERCENT YIELD STRESS, MEGAPASCALS	ULTIMATE TENSILE STRESS, MEGAPASCALS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
298	560.5	686.7	828.1	7.2	11.7
298	535.0	707.4	789.5	3.6	8.1
1144	428.9	586.1	729.5	1.6	3.2
1144	413.0	599.2	707.4	1.3	2.4
1255	204.1	341.3	439.9	2.8	7.4
1255	194.4	326.1	468.8	3.5	6.0
1366	97.2	151.7	242.0	7.0	11.6
1366	98.6	162.7	221.3	11.7	15.3
1477	29.0	(A)	29.0	.6	NIL
1477	26.2	(A)	27.6	.9	.4

(b) Stress-rupture behavior.

TEMPERATURE, K	STRESS, MEGAPASCALS	LIFE, HOURS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
1144	241.2	958.9	3.5	4.7
1144	275.6	392.6	2.8	4.7
1144	303.2	108.7	6.0	13.8
1144	323.8	212.8	7.0	10.6
1144	344.7	47.4	1.0	3.2
1144	344.7	136.9	6.9	10.5
1144	358.3	54.7	3.3	7.0
1144	385.8	49.8	4.7	6.8
1144	434.1	21.0	5.6	6.7
1144	482.3	6.1	2.5	2.4
1255	117.2	624.1	6.0	12.3
1255	130.9	340.9	5.1	11.0
1255	137.8	236.8	4.2	7.6
1255	144.7	228.8	6.5	11.3
1255	148.1	98.5	4.2	11.6
1255	158.5	100.5	6.0	7.8
1255	165.5	83.5	6.1	12.2
1255	165.5	51.5	2.4	7.0
1255	172.3	62.4	3.0	6.3
1255	192.9	41.3	5.0	7.0
1255	206.7	20.8	5.5	10.1
1366	41.3	626.4	10.2	11.0
1366	48.2	362.6	10.2	18.8
1366	51.7	317.4	3.7	3.2
1366	55.1	151.5	4.7	6.2
1366	58.6	123.6	9.0	17.0
1366	58.6	103.0	3.8	9.9
1366	62.0	116.8	5.6	13.1
1366	68.9	35.8	3.7	7.8
1366	82.7	23.6	11.0	29.2
1366	96.5	7.8	2.6	15.2
1477	13.8	77.4	3.7	24.0
1477	20.7	7.7	9.3	38.4
1477	27.6	1.9	8.8	24.5
1477	37.9	.1	1.9	4.6

(A) SPECIMEN FAILED BEFORE DATA OBTAINED.

TABLE III. - Continued.

(c) Elevated temperature creep behavior.

TEMPERATURE, K	STRESS, MEGAPASCALS	PLASTIC STRAIN ON LOADING, PERCENT	PLASTIC STRAIN (PERCENT) AT HOURS SHOWN 0.1	5.0	10.0	25.0	50.0	100.0	150.0	STEADY STATE CREEP RATE, S**-1	TEST DURATION, HOURS	FINAL STRAIN, PERCENT
1144	206.8	NIL	.05	.08	.09	.11	.15	.20	.24	2.22E-09	160.5	.25
1144	206.8	NIL	NIL	.03	.05	.10	.17	.22	.29	2.78E-09	158.6	.30
1144	241.3	NIL	.02	.08	.11	.17	.25	.40	----	7.81E-09	147.3	.52
1144	241.3	NIL	.01	.08	.10	.15	.22	.32	.45	5.56E-09	162.1	.49
1144	275.8	NIL	NIL	.08	.10	.17	.23	.38	.56	7.64E-09	159.4	.60
1144	275.8	NIL	.02	.07	.09	.14	.22	.37	.53	7.46E-09	186.5	.71
1144	310.3	NIL	.04	.20	.25	.40	.70	1.47	2.65	3.16E-08	165.8	3.22
1144	310.3	.02	.05	.14	.22	.39	.73	1.73	3.12	3.28E-08	159.2	3.82
1144	344.7	NIL	.04	.20	.28	.54	----	----	----	5.36E-08	47.4 (A)	1.0
1144	344.7	NIL	.01	.09	.17	.42	.9;	2.78	----	4.63E-08	136.9 (A)	6.9
1255	96.5	NIL	NIL	.04	.04	.06	.10	.15	.20	2.86E-09	161.5	.21
1255	96.5	NIL	NIL	.01	.01	.02	.03	.07	.11	2.15E-09	160.0	.12
1255	124.1	NIL	.01	.02	.03	.05	.11	.22	.32	5.73E-09	158.5	.33
1255	124.1	NIL	NIL	.11	.13	.18	.25	.34	.45	5.00E-09	162.2	.49
1255	137.9	NIL	NIL	.05	.08	.14	.25	.55	1.04	1.22E-08	164.0	1.24
1255	137.9	NIL	NIL	.05	.08	.16	.25	.58	1.46	1.15E-08	159.5	1.91
1255	165.5	NIL	.02	.18	.25	.58	1.40	----	----	5.40E-08	83.5 (A)	6.1
1255	165.5	NIL	.02	.18	.30	.67	1.72	----	----	6.17E-08	51.5 (A)	2.4
1366	34.5	NIL	.01	.03	.05	.08	.12	.17	.20	1.69E-09	166.1	.20
1366	34.5	NIL	.01	.04	.06	.10	.16	.24	.30	2.72E-09	165.6	.31
1366	41.4	NIL	.01	.06	.09	.14	.20	.29	.35	2.78E-09	167.8	.37
1366	41.4	NIL	.02	.04	.06	.10	.15	.22	.31	3.82E-09	166.0	.34
1366	48.3	NIL	NIL	.09	.12	.19	.29	.45	.60	8.33E-09	163.2	.65
1366	48.3	NIL	NIL	.07	.09	.16	.25	.42	.61	9.54E-09	167.9	.69
1366	58.6	NIL	.01	.11	.18	.32	.59	2.15	----	2.96A-08	123.6 (A)	9.0
1366	58.6	NIL	.01	.10	.15	.29	.55	----	----	2.73E-08	103.0 (A)	3.8

(A) FAILED AT TIME SHOWN.

TABLE III. - Concluded.

(d) Residual room temperature properties.

Prior creep history				Residual tensile properties				
TEMPERATURE, K	STRESS, MEGAPASCALS	TIME, HOURS	PLASTIC CREEP STRAIN, PERCENT	0.02 PERCENT YIELD STRESS, MEGAPASCALS	0.2 PERCENT YIELD STRESS, MEGAPASCALS	ULTIMATE TENSILE STRESS, MEGAPASCALS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
	AS RECEIVED			560.5	686.7	828.1	7.2	11.7
	AS RECEIVED			535.0	707.4	789.5	3.6	8.1
	THERMALLY EXPOSED			660.5	686.7	766.0	1.2	4.2
	150 H AT 1144K			575.7	646.1	777.0	5.5	17.8
1144	206.8	160.5	.25	615.0	679.1	726.7	2.7	9.3
1144	206.8	156.6	.30	627.4	686.0	755.0	2.9	11.6
1144	241.3	147.3	.52	632.3	704.6	777.0	4.5	12.0 (A)
1144	241.3	162.1	.49	606.1	683.3	751.5	3.7	11.3
1144	275.8	159.4	.60	649.5	697.8	732.9	1.6	7.6
1144	275.8	186.5	.71	637.8	695.7	725.3	1.5	7.0
1144	310.3	165.6	3.22	599.8	681.9	717.1	1.1	6.0
1144	310.3	159.2	3.82	597.8	664.0	708.1	1.5	11.5
	THERMALLY EXPOSED			582.6	701.9	775.0	2.2	12.0
	150 H AT 1255K			585.4	672.9	769.5	4.5	9.3
1255	96.5	161.5	.21	593.0	677.0	724.0	1.7	13.7
1255	96.5	160.0	.12	617.1	692.9	826.0	5.2	6.9
1255	124.1	156.5	.33	591.6	677.1	788.1	4.1	14.5
1255	124.1	162.2	.49	568.1	662.6	711.5	1.3	8.8
1255	137.9	164.0	1.24	545.4	652.9	775.0	4.2	7.9
1255	137.9	159.5	1.91	(B)		486.8	.8	4.1
	THERMALLY EXPOSED			621.2	732.9	803.0	3.4	11.8
	150 H AT 1366K			653.6	730.2	848.7	4.3	10.8
1366	34.5	166.1	.29	555.7	660.5	768.8	4.9	8.6
1366	34.5	165.6	.31	559.9	652.2	752.2	5.1	12.0
1366	41.4	167.8	.37	548.1	667.4	801.9	6.1	8.6
1366	41.4	166.0	.34	546.1	636.4	755.0	5.5	5.3
1366	48.3	163.2	.65	543.3	641.2	668.8	1.4	7.8
1366	48.3	167.9	.69	539.2	653.6	776.4	4.5	7.0
	THERMALLY EXPOSED			786.0	840.5	917.0	4.4	10.5
	150 H AT 1477K			668.8	819.1	933.6	5.0	9.3

(A) SPECIMEN FAILED NEAR RADIUS.
(B) SPECIMEN FAILED BEFORE DATA WAS OBTAINED.

TABLE IV. - MECHANICAL PROPERTIES OF MAR-509

(a) Elevated temperature tensile properties.

TEMPERATURE, K	0.02 PERCENT YIELD STRESS, MEGAPASCALS	0.2 PERCENT YIELD STRESS, MEGAPASCALS	ULTIMATE TENSILE STRESS, MEGAPASCALS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
298	320.6	427.5	603.3	2.3	1.0
298	291.7	402.0	580.5	2.2	2.2
1144	180.0	220.6	305.4	21.0	31.6
1144	163.4	206.9	278.5	22.4	38.1
1255	114.5	139.3	168.9	20.0	34.2
1255	113.1	148.2	175.8	22.2	33.9
1366	62.1	84.1	105.5	23.3	41.5
1366	53.8	72.4	107.6	29.4	42.6
1477	42.7	47.6	57.9	16.5	19.2
1477	35.9	40.7	49.6	14.9	18.6

(b) Stress-rupture behavior.

TEMPERATURE, K	STRESS, MEGAPASCALS	LIFE, HOURS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
1144	131.9	582.5	12.0	36.0
1144	137.8	>142.1	(A)	----
1144	144.7	70.3	16.3	48.9
1144	155.0	61.8	15.8	23.7
1144	158.6	80.3	14.9	34.9
1144	158.6	134.9	21.5	36.2
1144	165.4	77.6	26.0	35.7
1144	165.4	68.2	15.3	36.7
1144	172.3	19.4	20.9	45.5
1144	186.0	54.1	11.1	24.5
1144	206.7	2.3	20.5	38.6
1255	68.9	612.3	14.0	14.6
1255	79.2	228.7	16.7	45.2
1255	89.6	50.7	19.5	24.4
1255	117.1	4.7	25.6	28.5
1255	130.9	1.7	24.1	37.0
1255	130.9	1.1	12.1	41.5
1366	27.6	950.0	5.6	7.0
1366	34.5	326.2	6.5	6.1
1366	41.3	117.5	7.4	11.0
1366	41.3	179.3	13.6	9.0
1366	44.8	45.3	13.4	15.9
1366	51.7	27.8	16.2	19.6
1366	51.7	32.1	11.1	16.5
1366	55.1	21.2	17.2	29.3
1366	62.0	9.3	14.8	40.6
1477	10.3	0.1	11.0	14.6
1477	13.8	76.4	7.4	----
1477	18.6	10.8	6.5	----
1477	24.1	43.2	7.0	22.3
1477	24.1	0.1	15.5	32.6
1477	27.6	3.4	11.1	21.7

(A) SPECIMEN DID NOT FAIL DUE TO CONTROLLER MALFUNCTION.

TABLE IV. - Continued.

(c) Elevated temperature creep behavior.

TEMPERATURE, K	STRESS, MEGAPASCALS	PLASTIC STRAIN ON LOADING, PERCENT	PLASTIC STRAIN (PERCENT) AT HOURS SHOWN							STEADY STATE CREEP RATE, S**-1	TEST DURATION, HOURS	FINAL STRAIN, PERCENT
			0.1	5.0	10.0	25.0	50.0	100.0	150.0			
1144	96.5	NIL	NIL	.06	.09	.15	.20	.25	.27	1.21E-09	159.4	.28
1144	96.5	NIL	.09	.31	.40	.60	.74	.83	.88	1.91E-09	159.3	.88
1144	117.2	NIL	NIL	.38	.57	.98	1.27	1.57	1.77	1.04E-08	159.3	1.80
1144	117.2	NIL	.02	.24	.35	.59	.79	.98	1.10	5.56E-09	158.9	1.12
1144	117.2	NIL	.04	.38	.55	.82	1.03	1.25	1.40	5.43E-09	163.7	1.44
1144	137.9	NIL	.05	.85	1.30	1.95	2.85	4.36	6.37	8.60E-08	161.2	6.83
1144	137.9	NIL	.03	.68	.98	1.66	2.33	3.47	4.78	6.90E-08	161.6	5.10
1144	158.6	NIL	.26	2.43	3.35	5.27	9.17	----	----	3.62E-07	80.3 (A)	14.9
1144	158.6	NIL	.13	1.38	1.82	3.30	5.80	11.51	----	3.07E-07	134.9 (A)	21.5
1255	41.4	NIL	NIL	.05	.07	.10	.14	.17	.19	1.57E-09	160.3	.20
1255	41.4	NIL	NIL	.01	.02	.02	.03	.04	.05	7.25E-10	159.7	.05
1255	41.4	NIL	.01	.11	.15	.19	.25	.33	.42	4.95E-09	158.2	.43
1255	41.4	NIL	NIL	.03	.05	.10	.14	.20	.21	1.33E-09	159.6	.21
1255	55.2	NIL	.01	.04	.07	.12	.14	.20	.24	2.77E-09	159.0	.24
1255	55.2	NIL	.02	.11	.14	.20	.25	.31	.35	1.63E-09	159.0	.35
1255	55.2	NIL	.01	.06	.09	.16	.23	.30	.35	2.83E-09	158.8	.36
1255	55.2	NIL	.01	.11	.14	.18	.22	.25	.28	6.04E-10	158.4	.28
1255	55.2	NIL	.01	.06	.07	.09	.13	.19	.26	3.68E-09	160.2	.27
1255	68.9	NIL	.02	.17	.23	.31	.41	.59	.78	1.06E-08	160.0	.82
1255	68.9	NIL	.04	.22	.35	.59	.87	1.35	1.77	2.18E-08	160.1	1.85
1255 (B)	68.9	NIL	.03	.21	.28	.39	.60	1.23	1.72	2.53E-08	159.0	1.77
1255	68.9	NIL	.01	.11	.16	.27	.45	.74	1.10	1.62E-08	160.3	1.18
1255	82.7	NIL	.04	.38	.60	1.22	2.33	5.16	8.10	1.08E-07	161.9	8.87
1255	82.7	NIL	.04	.38	.74	1.88	3.62	6.85	12.16	2.02E-07	160.6	14.25
1255	82.7	NIL	.04	.66	.95	1.67	3.08	6.35	11.25	1.50E-07	161.5	13.14
1255	82.7	NIL	.03	.59	.81	1.70	3.02	6.07	10.18	1.50E-07	162.2	11.36
1366	17.2	NIL	NIL	.01	.02	.03	.04	.06	.09	1.43E-09	150.0	.09
1366	17.2	NIL	NIL	.01	.01	.02	.03	.05	.07	1.21E-09	166.3	.08
1366	24.1	NIL	.02	.04	.04	.06	.08	.12	.16	2.34E-09	166.3	.18
1366	24.1	NIL	.03	.04	.05	.06	.09	.14	.17	1.57E-09	150.0	.17
1366	31.0	NIL	.02	.04	.05	.08	.13	.25	.42	5.56E-09	166.6	.53
1366	31.0	NIL	NIL	.01	.02	.04	.08	.16	.26	4.34E-09	167.5	.31
1366	41.4	NIL	.01	.07	.10	.21	.43	1.56	5.72	2.26E-08	179.3 (A)	13.6
1366	41.4	NIL	.24	1.32	2.43	7.65	----	----	----	6.06E-07	32.1 (A)	11.1

(A) FAILED AT TIME SHOWN.
(B) SPECIMEN OVER TEMPERATURE 7 TO 20 K BETWEEN 90 AND 140 HOURS.

TABLE IV. - Continued.

(d) Residual room temperature properties.

PRIOR CREEP HISTORY				RESIDUAL TENSILE PROPERTIES				
TEMPERATURE, K	STRESS, MEGAPASCALS	TIME, HOURS	PLASTIC CREEP STRAIN, PERCENT	0.02 PERCENT YIELD STRESS, MEGAPASCALS	0.2 PERCENT YIELD STRESS, MEGAPASCALS	ULTIMATE TENSILE STRESS, MEGAPASCALS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
	AS RECEIVED			320.6	427.5	603.3	2.3	1.0
	AS RECEIVED			291.7	402.0	580.5	2.2	2.2
	THERMALLY EXPOSED			376.5	548.8	692.2	.8	.4
	150 H AT 1144K			368.2	536.4	672.9	.7	.5
1144	96.5	159.4	.28	390.9	558.5	674.3	.8	.6
1144	96.5	159.9	.88	381.3	547.4	683.3	.6	1.0
1144	117.2	159.3	1.80	396.5	555.7	677.1	1.6	.8
1144	137.9	161.2	6.83	369.6	544.7	660.5	.8	11.8
1144	137.9	161.6	5.10	417.8	553.0	664.0	.6	6.0
	THERMALLY EXPOSED			318.5	494.4	631.6	1.0	.2
	150 H AT 1255K			322.0	484.0	626.7	1.2	.2 (A)
1255	41.4	160.3	.20	295.1	477.1	619.2	.8	.6
1255	41.4	159.7	.05	333.7	504.7	635.7	1.0	.2
1255	55.2	159.0	.24	342.0	506.1	638.5	.7	.6
1255	55.2	159.0	.35	331.6	489.5	641.2	.8	1.2
1255	68.9	160.0	.82	328.9	488.2	624.0	.9	.6
1255	68.9	160.1	1.85	322.0	469.5	604.0	.9	.9
1255	82.7	161.9	3.87	326.1	468.8	541.2	.5	12.3
1255	82.7	160.6	14.25	343.4	(B)	400.6	.3	21.9
	THERMALLY EXPOSED			442.0	507.5	585.4	1.3	1.2
	150 H AT 1366K			328.9	455.7	578.5	1.3	NIL
1366	17.2	150.0	.09	407.5	(B)	489.5	1.6	NIL
1366	17.2	166.3	.08	(C)				
1366	24.1	166.3	.16	338.5	455.1	571.6	1.2	.8
1366	24.1	150.0	.17	359.9	480.0	585.4	1.0	2.4
1366	31.0	166.6	.53	292.3	425.4	521.2	1.0	.8
1366	31.0	167.5	.31	(C)				
	THERMALLY EXPOSED			271.0	365.4	494.4	3.1	6.1
	150 H AT 1477K			278.5	393.0	546.1	3.8	8.2

(A) FAILED NEAR RADIUS.
(B) SPECIMEN FAILED BEFORE DATA OBTAINED.
(C) SPECIMEN FAILED WHILE BEING REMOVED FROM CREEP TEST.

TABLE IV. - Concluded.

(e) Residual 1255 K properties.

PRIOR CREEP HISTORY				RESIDUAL TENSILE PROPERTIES				
TEMPERATURE, K	STRESS, MEGAPASCALS	TIME, HOURS	PLASTIC CREEP STRAIN, PERCENT	0.02 PERCENT YIELD STRESS, MEGAPASCALS	0.2 PERCENT YIELD STRESS, MEGAPASCALS	ULTIMATE TENSILE STRESS, MEGAPASCALS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
	AS RECEIVED			180.0	220.6	305.4	21.0	31.6
	AS RECEIVED			163.4	208.9	278.5	22.4	38.1
	THERMALLY EXPOSED			184.8	222.0	311.0	15.9	32.3
	150 H AT 1255K			175.1	213.0	305.4	24.0	31.8
1255	41.4	158.2	.43	195.8	240.6	(A)	14.8	26.0
1255	41.4	159.6	.21	210.3	245.5	310.3	12.3	22.1
1255	55.2	158.6	.36	196.5	213.7	279.2	15.5	22.8
1255	55.2	158.4	.28	194.4	233.7	281.3	13.6	19.6
1255(B)	68.9	159.0	1.77	197.2	235.8	284.8	18.3	33.8
1255	68.9	160.3	1.18	208.9	245.5	291.0	12.5	22.0
1255	82.9	161.5	13.14	182.7	233.7	259.9	8.0	18.0
1255	82.9	162.2	11.36	172.4	217.2	242.7	7.4	17.9

(A) TEST MACHINE MALFUNCTION, UTS NOT MEASURED.
(B) SPECIMEN OVER TEMPERATURE 7 TO 20 K BETWEEN 90 AND 140 HOURS.

TABLE V. - MECHANICAL PROPERTIES OF MA-757

(a) Elevated temperature tensile properties.

TEMPERATURE, K	0.02 PERCENT YIELD STRESS, MEGAPASCALS	0.2 PERCENT YIELD STRESS, MEGAPASCALS	ULTIMATE TENSILE STRESS, MEGAPASCALS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
		LONGITUDINAL			
298	696.4	899.1	1236.2	5.4	7.4
298	790.1	895.6	1252.8	6.6	7.8
1144	189.2	242.7	253.7	14.1	16.8
1144	177.9	246.9	266.8	16.7	25.8
1255	113.1	128.9	153.1	18.2	28.0
1255	102.0	130.3	153.1	21.0	33.8
1366	93.1	104.8	115.1	9.0	18.0
1366	99.3	113.8	120.7	12.2	18.6
1477	79.3	84.1	86.2	3.5	4.7
1477	81.4	84.8	85.5	1.6	3.2
		LONG TRANSVERSE			
298	745.3	820.5	1049.4	6.6	8.6
298	759.1	815.0	1052.1	7.0	7.4
1144	208.2	249.6	259.2	3.9	10.4
1144	206.2	239.9	248.2	4.5	4.7
1255	108.9	122.0	134.4	4.5	3.5
1255	100.0	126.2	140.0	3.7	3.1
1366	99.3	113.1	113.8	3.1	.4 (A)
1366	106.9	114.5	115.8	2.5	1.0
1477	66.9	71.7	71.7	2.0	.2
1477	66.9	(B)	71.0	1.6	.4

(A) SPECIMEN FAILED AT RADIUS.
(B) SPECIMEN FAILED BEFORE DATA POINT OBTAINED.

TABLE V. - Continued.

(b) Stress-rupture behavior.

TEMPERATURE, K	STRESS, MEGAPASCALS	LIFE, HOURS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
		LONGITUDINAL		
1144	103.4	3603.6	4.0	0.8
1144	110.3	1419.5(A)	----	----
1144	117.1	278.3	5.0	3.0
1144	130.9	160.8	6.0	2.2
1144	137.8	76.1	3.8	6.7
1144	144.7	34.6	5.0	4.6
1144	158.5	9.2	7.0	10.7
1255	62.0	4522.9(A)	----	----
1255	68.9	653.4	2.4	0.5
1255	75.8	285.2	8.0	18.8
1255	82.7	104.8	2.9	4.8
1255	89.6	15.4	3.2	7.8
1255	89.6	164.5	5.0	2.4
1255	96.5	34.8	7.0	10.1
1255	103.4	14.0	3.0	3.8
1255	117.1	1.5	9.8	14.0
1366	41.4	106.1	0.8	NIL(B)
1366	41.4	134.1	2.0	NIL
1366	41.4	482.1	0.8	NIL(B)
1366	48.2	71.5	1.8	NIL
1366	48.2	238.9	0.8	NIL(B)
1366	55.1	87.6	3.0	NIL(B)
1366	55.1	85.1	2.3	NIL
1366	62.0	33.1	2.5	NIL(B)
1366	62.0	12.9	1.8	0.9
1366	68.9	12.3	4.0	2.1
1366	75.8	2.7	5.0	NIL(B)
1366	82.7	4.8	6.0	8.0
1477	27.6	183.3	2.4	NIL
1477	31.0	200.6	1.5	NIL
1477	31.0	39.7	5.8	NIL
1477	34.5	18.1	3.0	NIL
1477	34.5	79.8	1.4	0.4
1477	34.5	131.2	1.3	NIL
1477	37.9	13.4	4.0	NIL(B)
1477	37.9	1.4	3.0	NIL
1477	41.3	14.0	1.0	NIL
1477	41.3	3.4	1.0	NIL
1477	55.1	2.3	3.0	NIL(B)

TABLE V. - Continued.

(b) Concluded.

TEMPERATURE, K	STRESS, MEGAPASCALS	LIFE, HOURS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
LONG TRANSVERSE				
1144	55.1	1773.6	2.0	0.8
1144	68.9	501.0	2.0	NIL
1144	79.3	141.4	2.6	0.6
1144	79.3	141.4	2.6	0.6
1144	82.7	110.4	1.0	NIL
1144	96.5	27.3	NIL	NIL
1144	110.3	12.8	2.4	1.0
1255	34.5	406.2	2.0	NIL
1255	37.9	157.7	1.7	NIL
1255	41.3	127.5	NIL	NIL
1255	48.2	123.0	7.6	2.0
1255	48.2	30.2	(C)	NIL
1255	55.1	21.6	1.0	NIL
1255	62.0	0.8	0.8	NIL
1366	13.8	1340.4	4.8	NIL
1366	20.7	163.2	6.7	NIL
1366	20.7	103.9	2.0	NIL
1366	20.7	154.0	9.0	NIL
1366	24.1	62.1	3.6	NIL
1366	27.6	35.7	6.0	NIL
1366	27.6	24.4	(C)	NIL(B)
1366	31.0	10.4	3.0	NIL(B)
1366	34.5	4.2	(C)	NIL(B)
1366	37.9	2.3	2.5	NIL(B)
1366	41.3	8.1	(C)	NIL(B)
1477	3.4	724.4	3.0	NIL
1477	6.9	187.3	0.8	NIL
1477	10.3	73.5	2.0	NIL
1477	10.3	87.4	3.1	NIL
1477	13.8	29.6	4.0	NIL
1477	13.8	38.2	2.6	NIL
1477	20.7	10.9	2.4	1.0

(A) UNLOADED AT TIME SHOWN.
(B) FAILED NEAR SHOULDER.
(C) COULD NOT BE MEASURED.

TABLE V. - Continued.

(c) Elevated temperature creep behavior.

TEMPERATURE, K	STRESS, MEGAPASCALS	PLASTIC STRAIN ON LOADING, PERCENT	PLASTIC STRAIN (PERCENT) AT HOURS SHOWN 0.1	5.0	10.0	25.0	50.0	100.0	150.0	STEADY STATE CREEP RATE, S**-1	TEST DURATION, HOURS	FINAL STRAIN, PERCENT
						LONGITUDINAL						
1144	89.7	NIL	NIL	.03	.04	.05	.06	.08	.10	1.09E-09	161.1	.10
1144	96.5	NIL	NIL	.01	.01	.02	.03	.04	.05 (A)	6.88E-10	160.1	.05 (A)
1144	103.4	NIL	NIL	.05	.10	.15	.21	.28	.32	2.53E-09	159.0	.33
1144	110.3	NIL	NIL	.06	.08	.10	.13	.19	.25	3.99E-09	162.6	.26
1144	117.2	NIL	.03	.15	.19	.27	.33	.43	.53	5.79E-09	159.9	.55
1144	124.1	NIL	NIL	.02	.04	.07	.11	.19	.27	3.86E-09	162.7	.29
1144	131.0	NIL	NIL	.03	.04	.08	.12	.19	.25	3.14E-09	150.0	.25
1144	137.9	NIL	.01	.10	.18	.50	1.16	----	----	5.14E-08	76.1 (B)	3.8
1255	48.3	NIL	.01	.09	.12	.16	.20	.24	.27	1.87E-09	159.5	.27
1255	55.2	NIL	.01	.06	.08	.11	.14	.17	.20	1.81E-09	161.3	.21
1255	62.1	NIL	.04	.07	.10	.14	.19	.29	.39	5.50E-09	159.5	.40
1255	68.9	NIL	.01	.06	.08	.12	.16	.24	.31	4.35E-09	162.5	.32
1255	75.8	NIL	.01	.03	.04	.07	.11	.19	.28	4.70E-09	162.3	.30
1255	82.7	NIL	.01	.13	.19	.31	.52	1.15	----	2.36E-08	104.8 (B)	2.9
1255	82.7	NIL	.02	.07	.08	.09	.10	.11	.13	9.06E-10	165.0	.13
1255	89.7	NIL	.06	1.11	----	----	----	----	----	5.91E-07	15.4 (B)	3.2
1366	27.6	NIL	.04	.07	.09	.11	.12	.14	.16	9.06E-10	164.7	.16
1366	34.5	NIL	.03	.07	.09	.11	.13	.15	.16	9.66E-10	166.6	.17
1366	37.9	NIL	.08	.08	.08	.09	.10	.12	.14	1.15E-09	164.9	.15
1366	41.4	NIL	.03	.05	.05	.06	.07	.07	.08	7.25E-10	166.4	.08
1366	44.8	NIL	NIL	.01	.01	.02	.04	.08	.11	2.05E-09	165.8	.13
1366	44.8	NIL	.02	.05	.06	.07	.08	.10	.11	9.06E-10	172.4	.12
1366	48.3	NIL	.03	.12	.17	.31	.58	----	----	2.48E-08	71.5 (B)	1.8
1366	48.3	NIL	NIL	.01	.02	.04	.07			4.10E-09	67.5 (C)	----
1366	55.2	NIL	.01	.09	.14	.29	.53	----	----	2.57E-08	85.1 (B)	2.3
1366	62.1	NIL	.02	.80	----	----	----	----	----	7.41E-07	12.9 (B)	1.8
1477	20.7	NIL	.02	.04	.05	.05	.06	.07	.08	6.04E-10	164.7	.08
1477	24.1	NIL	.10	.16	.18	.20	.22	.24	.25	1.09E-09	164.0	.26
1477	27.6	NIL	.02	.05	.06	.07	.08	.12	.16	1.75E-09	163.9	.19
1477	31.0	NIL	.01	.02	.02	.03	.05	.10	----	2.17E-09	128.2 (C)	.13
1477	31.0	NIL	NIL	.20	.34	.58	----	----	----	1.03E-07	39.7 (B)	5.8
1477	34.5	NIL	.01	.08	.10	.12	.17	.25	----	4.71E-09	131.2 (B)	1.3
1477	34.5	NIL	.04	.06	.08	.15	.39	----	----	1.26E-08	79.8 (B)	1.4

TABLE V. - Continued.

(c) Concluded.

TEMPERATURE, K	STRESS, MEGAPASCALS	PLASTIC STRAIN ON LOADING, PERCENT	PLASTIC STRAIN (PERCENT) AT HOURS SHOWN 0.1	5.0	10.0	25.0	50.0	100.0	150.0	STEADY STATE CREEP RATE, S**-1	TEST DURATION, HOURS	FINAL STRAIN, PERCENT
LONG TRANSVERSE												
1144	41.4	NIL	.02	.03	.04	.05	.05	.06	.07	5.80E-10	160.6	.07
1144	48.3	NIL	NIL	.03	.04	.05	.05	.06	.09	1.09E-09	161.9	.10
1144	55.2	NIL	NIL	.07	.09	.12	.14	.17	.20	1.75E-09	164.2	.21
1144	55.2	NIL	.03	.08	.10	.12	.14	.16	.19	1.45E-09	160.8	.19
1144	62.1	NIL	NIL	.02	.03	.05	.07	.11	.15	2.17E-09	162.0	.16
1144	68.9	NIL	.03	.16	.19	.23	.25	.30	.36	2.95E-09	161.8	.37
1144	75.8	NIL	.02	.06	.07	.08	.13	.23	.38	4.59E-09	159.9	.44
1144	79.3	NIL	.01	.04	.06	.10	.17	.38	----	6.34E-09	141.4 (B)	2.6
1255	24.1	NIL	.03	.06	.06	.08	.09	.10	.11	9.30E-10	164.2	.11
1255	27.6	NIL	NIL	.01	.01	.01	.02	.03	.04	7.25E-10	160.2	.05
1255	31.0	NIL	NIL	.04	.05	.07	.09	.13	.17	2.11E-09	160.6	.18
1255	34.5	NIL	NIL	.02	.03	.06	.09	.17	.24	3.86E-09	160.3	.25
1255	36.2	NIL	.03	.08	.11	.15	.21	.32	.43	6.22E-09	172.0	.48
1255	37.9	NIL	.01	.05	.08	.14	.23	.44	1.02	8.94E-09	157.7 (B)	1.7
1255	37.9	NIL	NIL	.05	.10	.18	.29	.44	.66	7.81E-09	162.6	.75
1255	41.3	NIL	NIL	.05	.08	.16	.23	.37	.73	7.25E-09	161.2	.86
1255	48.2	NIL	NIL	.03	.07	.23	.79	3.80	----	1.99E-08	123.0 (B)	7.6
1366	6.9	NIL	.06	.08	.09	.10	.10	.11	.12	5.43E-10	162.3	.12
1366	10.3 (D)										163.8	
1366	13.8	NIL	.01	.04	.05	.08	.11	.17	.23	3.44E-09	167.2	.25
1366	13.8	NIL	.01	.06	.08	.10	.12	.16	.20	3.26E-09	151.1	.20
1366	17.2	NIL	.01	.06	.08	.11	.18	.32	.47	8.21E-09	150.5	.47
1366	20.7	NIL	.01	.06	.09	.17	.34	1.10	----	1.33E-08	154.0 (B)	9.0
1366	20.7	NIL	.02	.06	.08	.15	.35	1.08	6.05	1.63E-08	163.2 (B)	6.7
1366	24.1	NIL	.01	.08	.14	.33	1.03	----	----	3.22E-08	62.1 (B)	3.6
1366	27.6	NIL	.01	.23	.74	4.82	----	----	----	8.23E-08	35.7 (B)	6.0
1477	3.5	NIL	.01	.01	.02	.03	.06	.11	.16	2.90E-09	164.3	.18
1477	5.2	NIL	.06	.11	.12	.13	.15	.16	.17	9.66E-10	163.3	.17
1477	6.9	NIL	.03	.06	.07	.08	.09	.11	.12	1.09E-09	162.7	.13
1477	6.9	NIL	.03	.11	.15	.22	.29	.38	.44	3.14E-09	154.2	.44
1477	10.3	NIL	.01	.06	.11	.21	.41	----	----	2.02E-08	87.4 (B)	3.1
1477	13.8	NIL	.01	.11	.20	.63	----	----	----	5.63E-08	38.2 (B)	2.6

(A) EXTRAPOLATED VALUE, CREEP RECORDER MALFUNCTION AT APPROXIMATELY 130 HOURS.
(B) SPECIMEN FAILED AT TIME SHOWN.
(C) PULL ROD FAILED AT TIME SHOWN.
(D) DEFECTIVE EXTENSOMETER; NO VALID CREEP DATA.

TABLE V. - Continued.

(d) Residual room temperature properties.

PRIOR CREEP HISTORY				RESIDUAL TENSILE PROPERTIES				
TEMPERATURE, K	STRESS, MEGAPASCALS	TIME, HOURS	PLASTIC CREEP STRAIN, PERCENT	0.02 PERCENT YIELD STRESS, MEGAPASCALS	0.2 PERCENT YIELD STRESS, MEGAPASCALS	ULTIMATE TENSILE STRESS, MEGAPASCALS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
				LONGITUDINAL				
1144	89.7	161.1	.10	732.9	797.0	1244.5	10.5	12.0
1144	96.5	160.1	.05	773.6	830.8	1192.8	7.0	5.2 (A)
1144	103.4	159.0	.33	766.0	820.5	1110.1	5.8	4.1 (A)
1144	110.3	162.6	.26	749.5	809.4	1156.3	6.2	4.8 (A)
1144	110.3	1413.5	----	514.4	(B)	718.4	0.9	0.2
1144	117.2	159.9	.55	752.2	817.7	1104.5	5.5	4.7 (A)
1144	124.1	162.7	.29	739.8	805.3	1127.3	5.6	6.3
1144	131.0	150.0	.25	758.4	818.7	997.0	2.6	3.9
1255	48.3	159.5	.27	758.4	852.3	1259.0	8.5	11.3
1255	55.2	161.3	.21	752.2	876.2	1279.0	8.8	7.8
1255	62.0	4322.9	----	655.0	835.0	1170.7	5.1	6.3 (A)
1255	62.1	159.5	.40	779.1	856.3	1261.1	8.6	6.5 (A)
1255	68.9	162.5	.32	764.6	850.1	1149.4	5.9	4.4 (A)
1255	75.8	162.3	.39	768.8	854.3	1094.9	4.3	3.5 (A)
1255	87.7	155.0	.13	721.9	795.7	1130.7	4.9	3.6 (A)
1366	27.6	164.7	.16	702.6	812.2	1251.4	10.1	13.1
1366	34.5	166.6	.17	682.6	766.0	1220.4	6.4	12.4
1366	37.9	154.9	.15	738.4	802.6	990.8	3.4	6.1
1366	41.4	150.4	.08	706.7	810.1	1259.0	9.7	12.0
1366	44.8	155.6	.13	720.5	796.3	1075.6	4.4	6.0
1366	44.8	172.4	.12	694.3	794.3	1012.8	3.2	5.0
1477	20.7	164.7	.08	617.1	752.9	1225.9	11.5	12.5
1477	24.1	160.0	.26	641.2	761.9	894.3	1.5	0.6 (A)
1477	24.1	153.0	.19	692.2	766.7	1212.1	9.5	6.7 (A)

TABLE V. - Concluded.

(d) Concluded.

PRIOR CREEP HISTORY				RESIDUAL TENSILE PROPERTIES				
TEMPERATURE, K	STRESS, MEGAPASCALS	TIME, HOURS	PLASTIC CREEP STRAIN, PERCENT	0.02 PERCENT YIELD STRESS, MEGAPASCALS	0.2 PERCENT YIELD STRESS, MEGAPASCALS	ULTIMATE TENSILE STRESS, MEGAPASCALS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
LONG TRANSVERSE								
1144	41.4	160.6	.07	704.0	750.8	1003.2	7.6	11.6
1144	48.3	161.9	.10	682.6	741.9	873.6	3.3	1.3 (A)
1144	55.2	164.2	.21	687.4	751.5	805.3	1.4	1.5
1144	55.2	160.8	.19	677.1	752.2	1046.6	9.4	10.8
1144	62.1	162.0	.16	708.1	775.0	781.9	1.3	2.5 (A)
1144	68.9	161.8	.37	700.5	(B)	712.9	.6	2.1 (A)
1144	75.8	159.9	.44	(C)	----	373.0	1.3	.1 (A)
1255	24.1	164.2	.11	559.0	741.9	1003.9	7.0	12.3
1255	27.6	160.2	.05	685.3	732.9	1012.2	8.5	11.6
1255	31.0	160.6	.18	616.4	802.6	970.1	5.1	1.3 (A)
1255	34.5	160.3	.25	674.3	728.1	787.4	2.3	2.8 (A)
1255	37.9	162.6	.75	(C)		153.1	0.2	NIL
1255	41.3	161.2	.86	(C)		233.0	0.8	NIL (A)
1366	6.9	162.3	.12	614.3	739.8	848.7	2.0	3.8
1366	13.8	167.2	.25	660.5	742.6	1048.0	9.0	7.0
1366	13.8	151.1	.20	676.4	751.5	1052.8	8.8	9.7
1366	17.2	150.5	.47	522.6	743.9	802.6	2.1	1.0
1477	3.5	164.3	.18	626.7	698.4	999.1	10.0	8.6
1477	5.2	163.3	.17	622.6	711.5	1021.8	10.5	10.3
1477	6.9	162.7	.13	627.4	712.2	993.5	8.3	14.0
1477	6.9	154.2	.44	628.1	708.1	983.2	8.9	11.9

(A) SPECIMEN FAILED NEAR RADIUS.
(B) FAILED BEFORE 0.2 PERCENT YIELD STRESS REACHED.
(C) FAILED BEFORE 0.02 PERCENT YIELD STRESS REACHED.

TABLE VI. - MECHANICAL PROPERTIES OF MA-956

(a) Elevated temperature tensile properties.

TEMPERATURE, K	0.02 PERCENT YIELD STRESS, MEGAPASCALS	0.2 PERCENT YIELD STRESS, MEGAPASCALS	ULTIMATE TENSILE STRESS, MEGAPASCALS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
		LONGITUDINAL			
298	557.1	586.7	689.5	12.1	20.4
298	553.7	591.6	601.2	0.9	1.2
1144	82.0	97.9	102.0	13.7	53.7
1144	93.8	104.8	106.9	10.6	44.0
1255	82.7	89.6	91.0	4.7	40.3
1255	83.4	85.5	87.6	5.8	33.2
1366	77.2	80.0	81.4	4.3	17.2
1366	66.9	73.1	77.2	2.4	9.4
1477	66.2	69.6	69.6	1.6	2.8
1477	66.2	68.3	68.9	1.5	4.0
		LONG TRANSVERSE			
298	652.9	669.5	670.9	0.7	0.2
1144	48.3	53.1	53.1	1.8	1.2
1144	88.3	110.3	112.4	5.7	8.2
1255	51.7	51.7	51.7	0.6	NIL
1255	85.5	(A)	91.0	0.4	0.2
1366	40.7	(A)	42.1	1.8	0.2
1366	57.9	(A)	60.0	1.2	0.6

(A) SPECIMEN FAILED BEFORE 0.2 PERCENT YIELD STRESS OBTAINED.

TABLE VI. - Continued.

(b) Stress-rupture behavior.

TEMPERATURE, K	STRESS, MEGAPASCALS	LIFE, HOURS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
		LONGITUDINAL		
1144	68.9	1005.4 (A)	----	----
1144	75.8	111.4	6.0	(B)
1144	75.8	393.1	3.7	(B)
1144	82.7	157.6	6.0	(B)
1144	82.7	248.3	4.7	(B)
1144	86.2	2061.5 (A)	----	----
1144	86.2	75.1	6.2	32.1
1144	89.6	9.5	7.4	36.9
1144	89.6	6.8	4.7	26.8
1144	93.1	5.6	7.1	17.9
1255	75.8	1005.4 (A)	----	----
1255	77.6	.01	20.0	>97.
1255	77.6	.5	7.4	(B)
1255	77.6	29.7	5.5	35.5
1255	79.3	8.1	9.3	50.5
1255	79.3	3.4	5.9	41.6
1255	79.3	24.2	4.4	10.2
1255	81.0	.7	10.7	45.4
1255	81.0	9.5	6.5	32.0
1255	81.0	119.7	5.5	33.0
1255	82.7	5.7	5.6	30.4
1255	82.7	1.8	6.5	16.4
1366	65.4	1.3	3.2	(B)
1366	70.7	75.3	6.3	19.0
1366	72.4	11.4	----	(B)
1366	72.4	943.1	6.0	36.1
1366	74.1	.9	5.6	31.0
1366	75.8	.3	5.6	55.0
1366	75.8	.5	3.5	28.8
1366	77.6	.3	8.7	42.1
1366	79.2	.02	8.3	38.0
1477	58.6	28.8	3.9	32.2
1477	62.1	1.5	5.4	(B)
1477	62.1	23.0	4.4	40.3
1477	63.8	144.8	5.4	25.5
1477	63.8	2.1	3.6	31.8
1477	65.5	13.1	4.5	30.1
1477	67.2	.2	5.2	47.5

(A) SPECIMEN UNLOADED AT TIME SHOWN.
(B) FRACTURE NEAR RADIUS; RA COULD NOT BE MEASURED.

TABLE VI. - Continued.

(c) Elevated temperature creep behavior.

TEMPERATURE, K	STRESS, MEGAPASCALS	PLASTIC STRAIN ON LOADING, PERCENT	PLASTIC STRAIN (PERCENT) AT HOURS SHOWN							STEADY STATE CREEP RATE, S**-1	TEST DURATION, HOURS	FINAL STRAIN, PERCENT
			0.1	5.0	10.0	25.0	50.0	100.0	150.0			
LONGITUDINAL												
1144	75.8	NIL	NIL	NIL	NIL	NIL	NIL	.01	.01	3.02E-10	160.6	.02
1144	79.3	NIL	.01	.01	.01	.01	.02	.03	----	4.22E-10	128.5(A)	----
1144	81.0	.013	.02	.04	.05	.06	.07	.08	.09	7.55E-10	161.4	.10
1144	82.7	NIL	NIL	NIL	.01	.01	.02	.02	.03	5.43E-10	163.1	.03
1144	82.7	NIL	NIL	.02	.03	.05	.05	.06	.07	5.44E-10	150.4	.07
1144	84.5	NIL	.01	.03	.04	.04	.05	.05	.06	3.93E-10	161.0	.06
1144	86.2	.009	.02	.09	.12	.15	.18	.21	.24	1.21E-09	161.7	.24
1144	86.2	.04	.04	.05	.07	.11	.19	----	----	6.76E-09	75.1(B)	6.2
1144	89.6	.03	.09	.40	----	----	----	----	----	1.81E-07	6.8(B)	4.7
1144	93.1	.08	.13	.70	----	----	----	----	----	2.78E-07	5.6(B)	7.1
1255	70.7	NIL	NIL	NIL	NIL	NIL	.01	.01	.01	1.20E-10	160.0	.01
1255	74.1	NIL	NIL	.01	.02	.04	.06	.07	.08	1.51E-10	160.4	.08
1255	77.6	NIL	.02	.07	.08	.09	.10	.13	.15	1.27E-09	159.6	.15
1255	77.6	.04	.04	.05	.08	.11	----	----	----	5.74E-09	29.7(B)	5.5
1255	79.3	.035	.05	----	----	----	----	----	----	9.49E-08	3.4(B)	5.9
1255	79.3	.09	.10	.20	.22	----	----	----	----	5.09E-09	24.2(B)	4.4
1255	81.0	.025	.05	.13	----	----	----	----	----	2.87E-08	9.5(B)	6.5
1255	81.0	.06	.08	.25	.30	.37	.44	.53	----	4.63E-09	119.7(B)	5.5
1255	82.7	.05	.08	.35	----	----	----	----	----	1.25E-07	5.7(B)	5.6
1366	68.9	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	150.1	NIL
1366	70.7	NIL	.01	.05	.06	.08	.10	----	----	1.21E-09	75.3(B)	6.1
1366	74.1	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	163.5	NIL
1366	74.1	.035	.13	----	----	----	----	----	----	2.60E-06(C)	.9(B)	5.6
1366	75.8	NIL	NIL	.01	.02	.04	.05	.06	.10	1.06E-09	168.2	.14
1366	75.8	.06	.12	----	----	----	----	----	----	1.70E-06(C)	.5(B)	3.5
1366	77.6	.04	.22	----	----	----	----	----	----	5.00E-06(C)	.3(B)	6.7
1477	55.1	NIL	NIL	NIL	.01	.01	.02	.04	.09	9.25E-10	162.6	.12
1477	58.6	NIL	NIL	.03	.04	.07	----	----	----	5.56E-09	28.8(B)	3.9
1477	62.1	NIL	.04	----	----	----	----	----	----	1.10E-06(C)	1.5(B)	5.4
1477	62.1	NIL	NIL	NIL	.01	.01	.02	.04	.06	1.09E-09	165.6	.07
1477	62.1	NIL	NIL	.03	.05	----	----	----	----	1.09E-08	23.0(B)	4.4
1477	63.8	NIL	.01	.02	.02	.02	.03	.03	----	4.53E-10	144.8(B)	5.4
1477	63.8	NIL	.02	----	----	----	----	----	----	5.56E-07	2.1(B)	3.6
1477	65.5	NIL	.01	.03	.05	----	----	----	----	8.33E-09	13.1(B)	4.5
1477	65.5	.04	.05	.11	.15	----	----	----	----	2.02E-08	14.6(A)	----
1477	67.2	NIL	.15	----	----	----	----	----	----	4.20E-06(C)	.2(B)	5.2

TABLE VI. - Continued.

(c) Concluded.

TEMPERATURE, K	STRESS, MEGAPASCALS	PLASTIC STRAIN ON LOADING, PERCENT	PLASTIC STRAIN (PERCENT) AT HOURS SHOWN							STEADY STATE CREEP RATE, S**-1	TEST DURATION, HOURS	FINAL STRAIN, PERCENT
			0.1	5.0	10.0	25.0	50.0	100.0	150.0			
						LONG TRANSVERSE						
1144	72.4										.9(B)	1.6
1144	75.8										FOL(D)	1.9
1144	79.3										.1(B)	1.9
1144	82.7										FOL	2.3
1255	65.5										FOL	4.2
1255	68.9										FOL	.7
1255	72.4										FOL	1.0
1255	75.8										FOL	(E)
1366	10.3	NIL	.02	.04	.05	.06	.07	.09	.10	9.06E-10	163.4	.11
1366	13.8	NIL	NIL	.01	.01	.02	.03	.06	.09	1.63E-09	149.4	.09
1366	15.5	NIL	(F)								118.2(B)	(E)
1366	17.2	NIL	NIL	.01	.01	.02	.04	.08	.12	2.17E-09	163.6	.13
1366	17.2	NIL	NIL								1.0(B)	1.8
1366	18.9	NIL	.01								1.7(B)	.5
1366	24.1	NIL	.01								2.9(B)	1.5
1366	27.6	NIL	NIL								.7(B)	1.7
1366	31.0										(G)	1.8

(A) TEST INTERRUPTED DUE TO TESTING MACHINE FAILURE.
(B) FAILED AT TIME SHOWN.
(C) NO CREEP CURVE AVAILABLE; CREEP RATE ESTIMATED FROM STRAINS ON LOADING AND 0.1 HOUR.
(D) FAILED ON LOADING.
(E) MULTIPLE FRACTURE.
(F) ALL CREEP READINGS WERE NEGATIVE.
(G) SPECIMEN FAILED WHILE BEING STEP LOADED.

TABLE VI. - *Concluded.*

(d) Residual room temperature properties.

Prior creep history: Temperature, K	Stress, megapascals	Time, hours	Plastic creep strain, percent	Residual tensile properties: 0.02 percent yield stress, megapascals	0.2 percent yield stress, megapascals	Ultimate tensile stress, megapascals	Elongation, percent	Reduction of area, percent
				LONGITUDINAL				
1144	68.9	1005.4 (A)	----	596.4	597.8	684.0	13.6	39.6
1144	75.8	160.6	.02	561.9	579.9	682.6	14.4	46.0
1144	81.0	161.4	.10	584.7	586.8	672.9	15.6	39.3
1144	82.7	163.1	.03	598.5	604.0	697.6	11.7	43.4
1144	82.7	150.4	.07	566.1	619.2	712.2	10.4	27.8
1144	84.5	161.0	.06	590.2	597.1	679.8	15.5	43.0
1144	86.2	161.7	.24	577.8	590.2	718.4	6.5	4.0 (B)
1144	86.2	2061.5 (A)	----	598.5	604.0	653.6	15.0	42.6
1255	70.7	160.0	.01	581.2	588.1	659.8	6.5	3.3 (B)
1255	74.1	160.4	.08	620.5	632.3	692.2	11.8	40.7
1255	75.8	1005.4 (A)	----	592.3	595.0	650.9	13.5	41.5
1255	77.6	159.8	.15	564.7	598.8	635.0	2.1	1.4 (B)
1366	74.1	163.5	NIL	608.8	631.2	688.1	9.9	47.3
1366	75.8	168.2	.14	593.6	639.1	713.6	11.3	43.8
1477	62.1	165.6	.07	590.2	593.0	691.5	12.5	41.3
1477	65.5	14.8 (C)	.18	(D)		659.7	11.8	42.6
				LONG TRANSVERSE				
1366	10.3	163.4	.11	637.1	652.2	657.6	12.5	32.8
1366	13.6	149.4	.09	(E)		467.5	1.6 (F)	.3
1366	17.2	163.6	.13	607.4	628.1	641.2	2.3 (F)	3.6

(A) STRESS RUPTURE SPECIMEN UNLOADED AT TIME SHOWN; NO MEASUREABLE DEFORMATION.
(B) CLEAVAGE FAILURE.
(C) TEST FIXTURE FAILED AT TIME SHOWN.
(D) THREADED GRIP END DESTROYED; SPECIMEN TESTED AT LEWIS RESEARCH CENTER ; YIELD STRENGTHS COULD NOT BE DETERMINED.
(E) FAILED BEFORE 0.02 PERCENT STRESS REACHED.
(F) FAILED IN SHOULDER.

TABLE VII. - MECHANICAL PROPERTIES OF STCA ALLOYS

(a) Tensile properties.

HEAT	0.02 PERCENT YIELD STRESS, MEGAPASCALS	0.2 PERCENT YIELD STRESS, MEGAPASCALS	ULTIMATE TENSILE STRESS, MEGAPASCALS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
		298 K			
		LONGITUDINAL			
262/264S	815.7	923.2	1280.4	5.8	4.3 (A)
265S	850.8	954.9	1261.1	4.7	6.6
265SC	801.2	998.4	1252.1	4.5	3.9 (A)
266S	866.7	948.7	1316.9	5.4	5.5
		LONG TRANSVERSE			
262/264S	777.0	971.5	1160.4	5.7	2.4 (A)
265S	810.8	886.7	1096.3	4.7	7.4
265SC	843.9	941.1	1090.8	4.0	4.3
266S	788.8	881.2	1109.4	4.8	9.3
266SC	834.3	927.4	1081.1	4.0	6.6
		1366K			
		LONGITUDINAL			
262/264S	79.3	97.9	105.5	9.8	19.3
265S	76.5	97.9	105.1	14.1	19.8
265SC	75.8	95.8	102.0	9.7	16.8
266S	65.5	100.0	104.0	6.8	15.0
		LONG TRANSVERSE			
262/264S	84.8	95.8	97.2	2.1	1.3
265S	82.7	95.1	95.8	1.0	.6
265SC	84.8	97.2	97.9	5.4	1.2
266S	81.4	101.4	101.4	1.2	.6
266SC	78.6	95.1	95.8	1.7	.4

(A) SPECIMEN FAILED AT RADIUS.

TABLE VII. - Continued.

(b) Creep behavior at 1366 K.

STRESS, MEGAPASCALS	PLASTIC STRAIN ON LOADING, PERCENT	PLASTIC STRAIN (PERCENT) AT HOURS SHOWN							STEADY STATE CREEP RATE, S**-1	TEST DURATION, HOURS	FINAL STRAIN, PERCENT	REDUCTION OF AREA, PERCENT
		0.1	5.0	10.0	25.0	50.0	100.0	150.0				
LONGITUDINAL												
HEAT 262/264S												
65.5	NIL	NIL	.01	.01	.02	.02	.03	.04	4.91E-10	163.5	.04	----
68.9	NIL	.02	.06	.07	.08	.09	.10	.11	6.00E-10	163.5	.11	----
72.4	NIL	.04	.13	.19	.30	.44	----	----	1.50E-08	62.2(A)	1.4	11.0
75.8	NIL	.02	.11	.16	.29	.52	----	----	2.46E-08	111.9(A)	8.6	12.8
79.3	NIL	.08	.49	.85	----	----	----	----	1.90E-07	24.3(A)	9.3	10.6
82.7	NIL	.12	----	----	----	----	----	----	7.20E-07	4.8(A)	5.8	15.2
HEAT 265S												
65.5	NIL	.02	.03	.04	.05	.07	.10	.12	1.39E-09	168.1	.14	----
67.2	NIL	.02	.03	.04	.05	.07	.10	.15	1.57E-09	161.0	.17	----
70.7	NIL	.03	.07	.09	.15	.22	----	----	5.86E-09	87.3(A)	4.3	8.8
72.4	NIL	.01	.04	.05	.06	.08	.11	.13	1.81E-09	149.7	.13	----
74.1	NIL	.02	.09	.13	.24	.41	----	----	1.86E-08	82.5(A)	7.9	.9
75.8	NIL	.01	.04	.06	.10	.16	.30	.51	6.40E-09	149.9	.51	----
79.3	NIL	.03	.41	.68	----	----	----	----	1.40E-07	26.7(A)	5.7	16.1
82.7	NIL	.15	----	----	----	----	----	----	4.10E-06	3.0(A)	8.1	12.5
HEAT 265SC												
63.8	NIL	.04	.15	.20	.26	.36	.46	.53	3.44E-09	165.3	.55	----
65.5	NIL	.08	.12	.14	.17	.18	.20	.22	1.09E-09	165.3	.22	----
65.5	NIL	.01	.01	.01	.02	.03	.05	.07	1.21E-09	190.0	.09	(B)
67.2	NIL	.01	.02	.02	.03	.04	.06	.08	1.27E-09	163.4	.09	----
68.9	NIL	.04	.06	.10	.14	.18	.22	.28	2.78E-09	164.8	.32	----
70.7	NIL	.01	.06	.08	.12	.16	.21	.31	1.93E-09	173.9	.43	----
72.4	NIL	NIL	.06	.10	.22	.37	.64	----	1.45E-08	116.2(A)	4.0	4.4
75.8	NIL	.02	.28	.43	.90	----	----	----	8.06E-08	45.2(A)	6.6	13.0
79.3	.02	.11	.87	----	----	----	----	----	4.30E-07	10.0(A)	5.9	2.4
82.7	NIL	.09	1.55	----	----	----	----	----	6.00E-07	5.5(A)	4.2	6.3

TABLE VII. - Continued.

(b) Continued.

STRESS, MEGAPASCALS	PLASTIC STRAIN ON LOADING, PERCENT	PLASTIC STRAIN (PERCENT) AT HOURS SHOWN 0.1	5.0	10.0	25.0	50.0	100.0	150.0	STEADY STATE CREEP RATE, S**-1	TEST DURATION, HOURS	FINAL STRAIN, PERCENT	REDUCTION OF AREA, PERCENT
						LONGITUDINAL						
						HEAT 266S						
53.4	NIL	.01	.01	.01	.02	.02	.03	.03	4.23E-10	163.3	.03	----
55.2	NIL	NIL	.01	.01	.02	.05	.09	.14	2.57E-09	178.2	.16(E)	----
55.2	NIL	(C)								165.5	----	----
56.9	NIL	-.02	-.02	-.03	-.04	-.05	-.06	-.04		166.1	-.02	----
58.6	NIL	.01	.02	.02	.04	.05	.11	----	1.81E-09	146.3(A)	1.2	(D)
62.1	NIL	.03	.20	.23	.27	.32	----	----	4.43E-09	63.3(A)	2.1	.3
65.5	NIL	.01	.04	.06	.20	----	----	----	1.35E-08	29.0(A)	2.2	4.3
67.2	NIL	.02	.05	.08	.13	----	----	----	1.00E-08	48.5(A)	3.2	4.2
68.9	NIL	.01	.06	.09	.17	.30	----	----	1.48E-08	64.7(A)	2.7	5.1
70.7	NIL	.09	.40	----	----	----	----	----	2.30E-07	7.7(A)	1.6	2.8
72.4	.02	.01	.05	.07	.12	.20	----	----	8.94E-09	89.1(A)	2.7	8.3
75.8	NIL	.04	.16	.22	.38	.71	----	----	2.78E-08	73.2(A)	9.5	22.0
79.3	.04	.17	----	----	----	----	----	----	3.60E-06	1.6(A)	2.3	10.8
82.7	.06	.84	----	----	----	----	----	----	2.16E-05	.2(A)	3.8	3.0
						LONG TRANSVERSE						
						HEAT 262/264S						
22.4	NIL	NIL	.04	.04	.05	.06	.08	.09	9.66E-10	149.3	.09	----
25.9	NIL	NIL	.04	,05	.06	.08	.10	.14	1.93E-09	166.7	.15	----
27.6	NIL	NIL	.01	.01	.02	.04	.07	.11	2.17E-09	164.7	.13	----
29.3	NIL	.01	.03	.04	.06	.11	.23	.44	4.89E-09	163.2	.54	(B)
31.0	NIL	NIL	.03	.04	.07	.15	.61	1.66	7.49E-09	166.5	2.14	(E)
34.5	NIL	NIL	.08	.19	1.01	4.53	----	----	4.83E-08	65.9(A)	7.6	NIL
37.9	NIL	NIL	.08	.15	.59	----	----	----	3.14E-08	51.1(A)	3.9	NIL(D)
						HEAT 265S						
15.5	NIL	.01	.02	.02	.03	.04	.09	.15	1.81E-09	164.7	.18	----
19.0	NIL	.02	.03	.05	.09	.18	.46	1.09	8.21E-09	165.4	1.46	(B)
22.4	NIL	.01	.03	.05	.08	.21	1.06	(F)	7.00E-09	188.1	6.7	----
25.9	NIL	.01	.11	.15	.27	.92	----	----	1.98E-08	96.4(A)	4.3	.3
27.6	NIL	NIL	.03	.05	.09	.19	.54	1.14	6.28E-09	165.5	1.31	----
29.3	NIL	.45	.70	----	----	----	----	----	3.20E-07	21.1(A)	2.6	.4
34.5	NIL	.01	.12	.19	----	----	----	----	4.03E-08	21.8(A)	(G)	----
37.9	NIL	.02	.20	.37	----	----	----	----	9.44E-08	19.9(A)	2.1	NIL(D)

TABLE VII. - Continued.

(b) Concluded.

STRESS, MEGAPASCALS	PLASTIC STRAIN ON LOADING, PERCENT	PLASTIC STRAIN (PERCENT) AT HOURS SHOWN							STEADY STATE CREEP RATE, S**-1	TEST DURATION, HOURS	FINAL STRAIN, PERCENT	REDUCTION OF AREA, PERCENT
		0.1	5.0	10.0	25.0	50.0	100.0	150.0				
LONG TRANSVERSE												
HEAT 265SC												
15.5	NIL	NIL	.01	.01	.02	.03	.05	.08	9.92E-10	162.6	.10	----
17.2	NIL	NIL	.01	.01	.02	.03	.06	.10	1.30E-09	163.5	.12	----
19.0	NIL	.02	.04	.06	.09	.13	.18	.23	2.70E-09	165.2	.25	----
20.7	NIL	NIL	.04	.05	.06	.08	.11	.15	1.97E-09	164.2	.15	----
22.4	NIL	.01	.03	.04	.05	.06	.09	.12	1.54E-09	215.3	.20	----
24.1	NIL	NIL	.03	.05	.12	.33	2.35	5.02	1.44E-08	151.1	5.3	(B)
25.9	NIL	.02	.06	.08	.14	.30	1.05	3.07	1.11E-08	150.0	4.6	(E)
27.6	NIL	NIL	.01	.01	.03	.09	.45	1.29	2.90E-09	166.9	1.66	----
31.0	NIL	.01	.01	.02	.05	.21	2.12	4.52	8.45E-09	167.1	5.35	(B)
34.5	NIL	.01	.07	.17	.76	3.41	----	----	5.79E-08	64.2(A)	5.2	NIL(D)
37.9	NIL	NIL	.12	----	----	----	----	----	4.03E-08	9.2(A)	1.0	NIL(D)
HEAT 266S												
20.7	NIL	.01	.02	.02	.03	.04	.06	.09	1.53E-09	166.9	.10	----
24.1	NIL	.01	.02	.02	.03	.04	.12	.24	2.42E-09	149.8	.24	----
25.9	NIL	.01	.01	.02	.04	.07	.23	.57	3.44E-09	164.2	.70	----
27.6	NIL	NIL	NIL	.01	.03	.06	.18	.48	3.26E-09	150.0	.48	----
31.0	NIL	NIL	.01	.02	.05	.16	.74	1.65	5.92E-09	151.5	1.68	----
34.5	NIL	.02	.06	.11	.29	.76	2.30	4.63	3.32E-08	150.0	4.63	----
37.9	NIL	NIL	.05	.14	.66	1.97	5.00	8.70	3.70E-08	166.1	10.4	NIL(B)
HEAT 266SC												
15.5	NIL	.01	.03	.04	.05	.07	.12	.19	2.39E-09	165.3	.22	----
17.2	NIL	.01	.02	.03	.04	.04	.05	.06	4.83E-10	163.3	.06	----
19.0	NIL	.01	.03	.04	.08	.17	.65	2.44	4.83E-09	167.3	3.49	----
20.7	NIL	NIL	.01	.02	.02	.03	.06	.13	1.14E-09	163.0	.16	----
22.4	NIL	.02	.07	.09	.13	.24	1.98	5.77	1.09E-08	162.6	6.69	----
24.1	NIL	.01	.03	.04	.06	.09	.19	.44	3.20E-09	163.3	.62	----
27.6	NIL	NIL	.03	.04	.35	3.42	----	----	3.32E-08	103.2(A)	10.4	.2
31.0	NIL	NIL	.02	.08	.11	----	----	----		24.1(H)	----	----
34.5	NIL	NIL	.02	.19	.43	2.25	5.88	----	8.57E-08	67.4(A)	9.0	.6
37.9	NIL	NIL	.42	----	----	----	----	----	1.71E-07	8.4(A)	.8	.2

(A) FAILED AT TIME SHOWN.
(B) SPECIMEN FAILED WHILE BEING REMOVED FROM THE ADAPTER.
(C) ERRATIC CREEP READINGS - NO MEASUREABLE DEFORMATION AFTER TESTING.
(D) FAILED AT RADIUS.
(E) FAILED WHILE COOLING
(F) EXTENSOMETER SLIPPED; STRAIN COULD NOT BE DETERMINED.
(G) SPECIMEN COULD NOT BE FITTED TOGETHER.
(H) SPECIMEN WAS c5 K OVER TEMPERATURE WHEN FAILED AT TIME SHOWN.

TABLE VII. - Continued.

(c) Residual room temperature properties.

PRIOR CREEP HISTORY				RESIDUAL TENSILE PROPERTIES				
TEMPERATURE, K	STRESS, MEGAPASCALS	TIME, HOURS	PLASTIC CREEP STRAIN, PERCENT	0.02 PERCENT YIELD STRESS, MEGAPASCALS	0.2 PERCENT YIELD STRESS, MEGAPASCALS	ULTIMATE TENSILE STRESS, MEGAPASCALS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
				LONGITUDINAL				
				HEAT 262/264S				
1366	65.5	163.5	.04	733.6	823.9	1248.6	5.9	4.9
1366	68.9	163.5	.11	731.5	814.3	1282.4	6.9	5.2
				HEAT 265S				
1366	65.5	168.1	.14	760.5	805.3	1001.8	3.4	4.7
1366	67.2	161.0	.17	695.0	800.5	916.3	2.4	4.0
1366	72.3	149.2	.13	686.7	828.1	1107.3	4.9	5.9
1366	75.8	149.9	.51	727.4	840.5	895.6	1.7	2.1
				HEAT 265SC				
1366	63.8	165.3	.55	(A)	-----	1040.4	.8	2.4
1366	65.5	165.3	.22	706.0	869.4	1093.5	3.7	2.2
1366	67.2	153.4	.09	732.9	870.8	891.5 (B)	.4	2.4
1366	68.9	164.8	.32	745.3	817.0	886.0	1.4	2.4
1366	70.6	173.9	.43	651.6	808.1	979.8	2.9	3.3 (C)
				HEAT 266S				
1366	53.4	163.3	.03	817.7	868.7	1288.6	6.4	5.0 (C)
1366	55.1	165.5	(D)	733.6	812.9	1199.0	5.8	4.9 (C)
1366	56.9	166.1	-.02	772.2	870.8	1039.0	3.2	3.3

TABLE VII. - Continued.

(c) Continued.

PRIOR CREEP HISTORY				RESIDUAL TENSILE PROPERTIES				
TEMPERATURE, K	STRESS, MEGAPASCALS	TIME, HOURS	PLASTIC CREEP STRAIN, PERCENT	0.02 PERCENT YIELD STRESS, MEGAPASCALS	0.2 PERCENT YIELD STRESS, MEGAPASCALS	ULTIMATE TENSILE STRESS, MEGAPASCALS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
LONG TRANSVERSE								
HEAT 262/264S								
1366	22.4	149.3	.09	644.0	788.1	1081.1	5.5	8.8
1366	25.8	166.7	.15	700.5	788.8	992.9	4.2	3.6
1366	27.6	164.7	.13	586.1	(E)	586.1	.7	.4
HEAT 265S								
1366	15.5	164.7	.18	728.1	842.5	1031.1	4.9	3.5
1366	22.4	188.1	6.7	(F)	-----	55.2	3.6	NIL(C)
HEAT 265SC								
1366	15.5	162.6	.10	679.8	761.9	1041.1	7.6	5.5
1366	17.2	163.5	.12	667.4	748.8	761.2	.8	.6(C)
1366	19.0	165.2	.22	602.6	801.9	886.0	2.0	3.8
1366	20.7	164.2	.15	566.1	(E)	623.3	.5	.5
1366	22.4	215.3	.20	553.0	748.1	748.1	.4	.8(C)
1366	27.6	166.9	1.66	121.3	(E)	137.9	.2	.2

TABLE VII. - Concluded.

(c) Concluded.

PRIOR CREEP HISTORY				RESIDUAL TENSILE PROPERTIES				
TEMPERATURE, K	STRESS, MEGAPASCALS	TIME, HOURS	PLASTIC CREEP STRAIN, PERCENT	0.02 PERCENT YIELD STRESS, MEGAPASCALS	0.2 PERCENT YIELD STRESS, MEGAPASCALS	ULTIMATE TENSILE STRESS, MEGAPASCALS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
				LONG TRANSVERSE				
				HEAT 266S				
1366	20.7	166.9	.10	653.6	(E)	767.4	1.0	.2 (C)
1366	24.1	169.8	.24	(F)	-----	452.3	.6	NIL (C)
1366	25.8	164.2	.70	(F)	-----	212.4	NIL	NIL (C)
1366	27.6	150.0	.48	302.0	(E)	346.1	.3	.3
1366	31.0	151.5	1.68	41.4	44.1	44.1	NIL	NIL
1366	34.5	150.0	4.63	41.4	(E)	41.4	.6	.2
				HEAT 266SC				
1366	15.5	165.3	.22	674.0	814.3	998.4	3.9	2.2
1366	17.2	163.3	.06	661.9	786.0	1081.1	5.7	6.3
1366	19.0	167.3	3.49	(F), (G)	-----	82.0	1.4	NIL
1366	20.7	163.0	.10	675.8	(E)	738.4	.5	.8 (C)
1366	22.4	162.6	6.69	(F), (G)	-----	6.9	.4	NIL
1366	24.1	163.3	.62	181.3	(E)	191.0	.1	.2

(A) THREADED GRIP ENDS DESTROYED; SPECIMEN TESTED AT LEWIS RESEARCH CENTER; YIELD STRENGTHS COULD NOT BE DETERMINED.
(B) DEFECT FOUND ON FRACTURE SURFACE.
(C) SPECIMEN FAILED NEAR RADIUS.
(D) NO MEASUREABLE DEFORMATION AFTER TESTING; ERRATIC CREEP READINGS.
(E) FAILED BEFORE 0.2 PERCENT YIELD STRESS WAS OBTAINED.
(F) FAILED BEFORE 0.02 PERCENT YIELD STRESS WAS OBTAINED.
(G) CRACKS IN GAGE SECTION PRIOR TO TENSILE TESTING.

TABLE VIII. - MECHANICAL PROPERTIES OF YD-NiCrAl

(a) Creep behavior at 1366 K.

STRESS, MEGAPASCALS	PLASTIC STRAIN ON LOADING, PERCENT	PLASTIC STRAIN (PERCENT) AT HOURS SHOWN							STEADY STATE CREEP RATE, S**-1	TEST DURATION, HOURS	FINAL STRAIN, PERCENT
		0.1	5.0	10.0	25.0	50.0	100.0	150.0			
LONGITUDINAL											
37.9	NIL	.01	.04	.04	.05	.06	.07	.08	7.25E-10	173.8	.09
41.4	NIL	.02	.04	.04	.05	.05	.06	.07	6.64E-10	163.6	.07
44.8	NIL	.02	.05	.06	.08	.09	.11	.13	1.27E-09	163.7	.15
46.5	NIL	.01	.04	.05	.07	.09	.11	.12	9.66E-10	172.7	.13
48.3	NIL	.04	.11	.13	.18	.23	.31	.39	4.29E-09	165.3	.41
48.3	NIL	.13	.22	.26	.32	.39	.51	.63	6.96E-09	162.7	.66
50.0	NIL	.02	.10	.14	.20	.29	.44	.58	8.10E-09	162.8	.62
50.0	NIL	.04	.09	.12	.16	.22	.32	.44	5.00E-09	164.0	.50
51.7	NIL	.02	.14	.19	.30	.41	.55	.66	7.23E-09	164.8	.72
53.4	NIL	.22	2.23	----	----	----	----	----	--------	10.8 (A)	

(b) Residual room temperature properties.

PRIOR CREEP HISTORY				RESIDUAL TENSILE PROPERTIES				
TEMPERATURE, K	STRESS, MEGAPASCALS	TIME, HOURS	PLASTIC CREEP STRAIN, PERCENT	0.02 PERCENT YIELD STRESS, MEGAPASCALS	0.2 PERCENT YIELD STRESS, MEGAPASCALS	ULTIMATE TENSILE STRESS, MEGAPASCALS	ELONGATION, PERCENT	REDUCTION OF AREA, PERCENT
1366	37.9	173.8	.09	597.1	686.0	922.5	5.5	9.6
1366	41.4	163.6	.07	666.7	695.7	1139.0	14.8	19.2
1366	44.8	163.7	.15	677.1	706.0	1152.1	12.9	16.6
1366	46.5	172.7	.13	667.0	710.2	1038.4	7.4	8.0
1366	48.3	165.3	.41	642.6	655.0	1045.9	14.6	16.9
1366	48.3	162.7	.66	661.9	699.1	1028.7	9.4	7.3
1366	50.0	162.8	.62	662.6	699.1	1098.3	8.6	15.7
1366	50.0	164.0	.50	659.1	716.4	1115.6	8.8	14.7
1366	51.7	164.8	.72	726.7	737.7	1131.4	8.1	13.1

(A) FAILED AT TIME SHOWN; 29.5 % ELONGATION; 62.6% RA.

TABLE IX. - REGRESSION ANALYSIS OF B-1900

CONSTANT	STRESS EXPONENT	TEMPERATURE, K	ACTIVATION ENERGY, kJ/g-mol-K	TEMPERATURE RANGE, K	REGRESSION COEFFICIENT, R**2
TIME TO RUPTURE					
44.32	-6.83	1144	-	-	0.93
34.41	-5.88	1255	-	-	0.95
26.31	-5.29	1366	-	-	0.97
21.38	-6.41	1477	-	-	0.98
-12.35	-6.43	-	516.6	1144-1255	0.93
-18.16	-5.04	-	497.5	1144-1366	0.78
-21.96	-3.48	-	452.7	1144-1477	0.35
STEADY STATE CREEP RATE					
-51.41	5.91	1144	-	-	0.93
-46.33	5.74	1255	-	-	0.93
-37.97	5.03	1366	-	-	0.94
-3.58	5.83	-	-450.5	1144-1255	0.93
1.30	4.38	-	-421.7	1144-1366	0.76

TABLE X. - REGRESSION ANALYSIS OF MAR-M509

CONSTANT	STRESS EXPONENT	TEMPERATURE, K	ACTIVATION ENERGY, kJ/g-mol-K	TEMPERATURE RANGE, K	REGRESSION COEFFICIENT, R**2
TIME TO RUPTURE					
54.00	-9.80	1144	-	-	0.75
47.39	-9.65	1255	-	-	0.99
26.28	-5.80	1366	-	-	0.97
-12.51	-9.69	-	627.1	1144-1255	0.92
-15.80	-7.37	-	546.7	1144-1366	0.87
STEADY STATE CREEP RATE					
-72.16	11.28	1144	-	-	0.97
-45.62	6.61	1255	-	-	0.77
-34.86	4.80	1366	-	-	0.81
-0.68	7.59	-	-510.6	1144-1255	0.80
1.35	6.17	-	-457.4	1144-1366	0.74

TABLE XI. - REGRESSION ANALYSIS OF TIME TO RUPTURE FOR MA-757 TESTED IN THE LONGITUDINAL DIRECTION

CONSTANT	STRESS EXPONENT	TEMPERATURE, K	ACTIVATION ENERGY, kJ/g-mol-K	TEMPERATURE RANGE, K	REGRESSION COEFFICIENT, R**2
		UNEDITED DATA			
68.59	-13.08	1144	-	-	0.97
52.48	-10.81	1255	-	-	0.87
28.19	- 6.08	1366	-	-	0.83
29.75	- 7.42	1477	-	-	0.61
0.83	-11.65	-	578.1	1144-1255	0.91
- 4.99	- 7.81	-	456.5	1144-1366	0.80
- 8.76	- 7.42	-	477.0	1144-1477	0.73
		EDITED DATA *			
68.57	-13.08	1144	-	-	0.97
52.48	-10.81	1255	-	-	0.87
28.19	- 6.08	1366	-	-	0.83
32.07	- 7.95	1477	-	-	0.74
0.83	-11.65	-	578.1	1144-1255	0.91
- 4.99	- 7.81	-	456.5	1144-1366	0.80
- 7.24	- 7.74	-	476.2	1144-1477	0.79

* FOLLOWING DATA DELETED FROM ANALYSIS

TEMPERATURE, K	STRESS, MEGAPASCALS	LIFE, HOURS
1477	27.6	183.3
1477	31.0	39.7
1477	37.9	1.4

TABLE XII. - REGRESSION ANALYSIS OF STEADY STATE CREEP RATE DATA FOR MA-757

TESTED IN THE LONGITUDINAL DIRECTION

CONSTANT	STRESS EXPONENT	TEMPERATURE, K	ACTIVATION ENERGY, kJ/g-mol-K	TEMPERATURE RANGE, K	REGRESSION COEFFICIENT, R**2
		UNEDITED DATA			
-52.26	6.94	1144	-	-	0.66
-41.49	5.35	1255	-	-	0.32
-47.73	7.55	1366	-	-	0.62
-39.64	6.05	1477	-	-	0.44
		EDITED DATA *			
-64.52	9.63	1144	-	-	0.93
-97.68	18.34	1255	-	-	0.81
-83.72	16.74	1366	-	-	0.90
-36.02	4.83	1477	-	-	0.84
-11.70	11.80	-	-599.1	1144-1255	0.33
-11.65	13.66	-	-682.8	1144-1366	0.84
-10.36	9.41	-	-505.8	1144-1477	0.72

* FOLLOWING DATA DELETED FROM ANALYSIS

TEMPERATURE, K	STRESS, MEGAPASCALS	STEADY STATE CREEP RATE, S**-1
1144	124.1	3.86E-09
1144	131.0	3.14E-09
1255	48.3	1.87E-09
1255	55.2	1.81E-09
1255	62.1	5.50E-09
1255	82.7	9.06E-10
1366	27.6	9.06E-10
1366	34.5	9.66E-10
1366	37.9	1.15E-09
1477	31.0	1.03E-07

TABLE XIII. - REGRESSION ANALYSIS OF TIME TO RUPTURE DATA FOR MA-757 TESTED IN THE LONG TRANSVERSE DIRECTION

CONSTANT	STRESS EXPONENT	TEMPERATURE, K	ACTIVATION ENERGY, kJ/g-mol-K	TEMPERATURE RANGE, K	REGRESSION COEFFICIENT, R**2
		UNEDITED DATA			
37.21	-7.33	1144	-	-	0.99
37.89	-8.90	1255	-	-	0.80
21.92	-5.62	1366	-	-	0.94
9.59	-2.31	1477	-	-	0.98
-22.10	-8.03	-	593.3	1144-1255	0.33
-19.34	-6.43	-	500.3	1144-1366	0.88
-15.16	-3.80	-	350.0	1144-1477	0.70
		EDITED DATA *			
37.21	-7.38	1144	-	-	0.99
28.43	-6.38	1255	-	-	0.96
21.92	-5.62	1366	-	-	0.94
9.59	-2.31	1477	-	-	0.98
-18.67	-7.06	-	513.2	1144-1255	0.93
-18.34	-6.06	-	473.9	1144-1366	0.95
-14.46	-3.56	-	334.6	1144-1477	0.77

* FOLLOWING DATA DELETED FROM ANALYSIS

TEMPERATURE, K	STRESS, MEGAPASCALS	LIFE, HOURS
1255	48.2	123.0
1255	62.0	0.8

TABLE XIV. - REGRESSION ANALYSIS OF STEADY STATE CREEP RATE FOR MA-757

TESTED IN THE LONG TRANSVERSE DIRECTION

CONSTANT	STRESS EXPONENT	TEMPERATURE, K	ACTIVATION ENERGY, kJ/g-mol-K	TEMPERATURE RANGE, K	REGRESSION COEFFICIENT, R**2
		UNEDITED DATA			
-34.02	3.43	1144	-	-	0.93
-37.10	5.02	1255	-	-	0.92
-28.42	3.48	1366	-	-	0.96
-24.28	2.61	1477	-	-	0.60
- 3.61	4.23	-	-320.1	1144-1255	0.92
1.24	3.49	-	-339.7	1144-1366	0.89
0.66	3.10	-	-318.9	1144-1477	0.90
		EDITED DATA *			
-34.02	3.43	1144	-	-	0.98
-37.10	5.02	1255	-	-	0.92
-28.42	3.48	1366	-	-	0.96
-27.72	4.23	1477	-	-	0.99
- 3.61	4.23	-	-320.1	1144-1255	0.92
1.24	3.49	-	-339.7	1144-1366	0.89
2.37	3.58	-	-354.4	1144-1477	0.90

* FOLLOWING DATA DELETED FROM ANALYSIS

TEMPERATURE, K	STRESS, MEGAPASCALS	STEADY STATE CREEP RATE, S**-1
1477	3.5	2.90E-09
1477	6.9	1.09E-09

TABLE XV. - REGRESSION ANALYSIS OF TIME TO RUPTURE DATA FOR MA-956 TESTED

IN THE LONGITUDINAL DIRECTION

CONSTANT	STRESS EXPONENT	TEMPERATURE, K	ACTIVATION ENERGY, kJ/g-mol-K	TEMPERATURE RANGE, K	REGRESSION COEFFICIENT, R**2
UNEDITED DATA					
80.27	-17.11	1144 *	-	-	0.37
52.56	-11.62	1255	-	-	0.01
126.91	-29.35	1366	-	-	0.26
102.24	-24.19	1477	-	-	0.23
EDITED DATA **					
115.73	-25.25	1144	-	-	0.90
212.31	-47.76	1255	-	-	0.83
280.08	-64.71	1366	-	-	0.73
271.29	-64.54	1477	-	-	0.81
102.81	-29.49	-	303.4	1144-1255	0.80
104.85	-32.95	-	434.2	1144-1366	0.70
101.23	-33.03	-	473.7	1144-1477	0.68

* 86.2 MPA - 2061.5 H (UNFAILED) INCLUDED;
68.9 MPA - 1005.4 H (UNFAILED) NOT INCLUDED.

** FOLLOWING DATA DELETED FROM OR ADDED TO ANALYSIS

TEMPERATURE, K	STRESS, MEGAPASCALS	LIFE, HOURS
DELETED DATA		
1144	68.9	1005.4 (UNFAILED)
1144	86.2	2061.5 (UNFAILED)
1255	77.6	0.01
1255	77.6	0.5
1255	79.3	3.4
1255	81.0	0.7
1366	65.4	1.3
1477	58.6	28.8
1477	62.1	1.5
1477	63.8	2.1
ADDITIONAL DATA		
1144	106.9	0.1
1144	102.0	0.1
1255	87.6	0.1
1255	91.0	0.1
1366	77.2	0.1
1366	81.4	0.1
1366	68.9	1005.4 (UNFAILED)
1477	69.6	0.1
1477	68.9	0.1

TABLE XVI. - REGRESSION ANALYSIS OF STEADY STATE CREEP RATE OF MA-956 TESTED IN THE LONGITUDINAL DIRECTION

CONSTANT	STRESS EXPONENT	TEMPERATURE, K	ACTIVATION ENERGY, kJ/g-mol-K	TEMPERATURE RANGE, K	REGRESSION COEFFICIENT, R**2
		UNEDITED DATA			
-182.57	36.72	1144	-	-	0.72
-213.29	44.55	1255	-	-	0.76
-405.74	90.00	1366	-	-	0.43
-126.20	26.24	1477	-	-	0.23
-154.97	39.66	-	-386.5	1144-1255	0.74
		EDITED DATA *			
-225.98	46.45	1144	-	-	0.80
-213.29	44.55	1255	-	-	0.76
-355.91	78.89	1366	-	-	0.58
-184.42	40.52	1477	-	-	0.66
-173.09	45.52	-	-463.9	1144-1255	0.78
-204.45	57.16	-	-660.0	1144-1366	0.68
-130.46	38.92	-	-597.9	1144-1477	0.58

* FOLLOWING DATA DELETED FROM OR ADDED TO ANALYSIS

TEMPERATURE, K	STRESS, MEGAPASCALS	STEADY STATE CREEP RATE, S**-1
	DELETED DATA	
1144	75.8	3.02E-10
1366	74.1	1.00E-11
1477	62.1	1.10E-06
1477	63.8	4.53E-10
1477	65.5	8.33E-09
1477	65.5	2.02E-08
	ADDED DATA	
1366	77.1	3.33E-06
1366	76.9	3.33E-06
1366	77.8	8.33E-07
1366	73.3	8.33E-08
1366	70.7	8.33E-08

TABLE XVII. - REGRESSION ANALYSIS OF STEADY STATE CREEP RATE OF STCA ALLOYS

TESTED IN THE LONGITUDINAL DIRECTION AT 1366 K

HEAT	CONSTANT	STRESS EXPONENT	REGRESSION COEFFICIENT, R**2
262/4S	-160.62	33.16	0.96
265S	-150.87	30.93	0.78
265SC	-130.76	26.36	0.87
266S	-100.42	19.73	0.75
265S 265SC	-135.65	27.45	0.81
262/4S 265S	-155.18	31.91	0.86

TABLE XVIII. - REGRESSION ANALYSIS OF STEADY STATE CREEP RATE OF STCA ALLOYS

TESTED IN THE LONG TRANSVERSE DIRECTION AT 1366 K

HEAT	CONSTANT	STRESS EXPONENT	REGRESSION COEFFICIENT, R**2
		UNEDITED DATA	
262/4S	-45.58	7.87	0.90
265S	-31.85	4.34	0.60
265SC	-32.66	4.27	0.75
266S	-37.93	5.68	0.89
266SC	-37.05	5.84	0.80
		EDITED DATA *	
262/4S	-45.58	7.87	0.90
265S	-30.77	3.96	0.95
265SC	-33.82	4.75	0.93
266S	-37.93	5.68	0.89
266SC	-33.12	4.79	0.99
265S 265SC	-32.72	4.47	0.90
262/4S 266S	-40.79	6.50	0.86
265S 266SC	-31.98	4.39	0.96

* FOLLOWING DATA DELETED FROM ANALYSIS

HEAT	STRESS, MEGAPASCALS	STEADY STATE CREEP RATE, S**-1
265S	27.6	6.28E-09
265S	29.3	3.20E-07
265SC	22.4	1.54E-09
265SC	27.6	2.90E-09
265SC	31.0	8.45E-09
266SC	17.2	4.83E-10
266SC	20.7	1.14E-09
266SC	24.1	3.20E-09

TABLE XIX. - REGRESSION ANALYSIS OF STEADY STATE CREEP RATE OF YD-NiCrAl

TESTED IN THE LONGITUDINAL DIRECTION AT 1366 K

HEAT	CONSTANT	STRESS EXPONENT	REGRESSION COEFFICIENT, R**2
–	-54.76	9.12	0.75

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16. Abstract

Tensile, stress-rupture, creep, and residual tensile properties after creep testing were determined for two typical cast superalloys and four advanced oxide dispersion strengthened (ODS) alloys. The superalloys examined included the nickel-base alloy B-1900 and the cobalt-base alloy MAR-M509. The nickel-base ODS alloy MA-757 (Ni-16Cr-4Al-0.6Y_2O_3 and the iron-base ODS alloy MA-956 (Fe-20Cr-5Al-0.8Y_2O_3) were extensively studied, while limited testing was conducted on the ODS nickel-base alloys STCA (Ni-16Cr-4.5Al-2Y_2O_3) with and without Ta and YD-NiCrAl (Ni-16Cr-5Al-2Y_2O_3). Elevated temperature testing was conducted from 1144 to 1477 K except for STCA and YD-NiCrAl alloys, which were only tested at 1366 K. The residual tensile properties of B-1900 and MAR-M509 are not reduced by prior creep testing (strains at least up to 1 percent), while the room temperature tensile properties of ODS nickel-base alloys can be reduced by small amounts of prior creep strain (less than 0.5 percent). The iron-base ODS alloy MA-956 does not appear to be susceptible to creep degradation at least up to strains of about 0.25 percent. However, MA-956 exhibits unusual creep behavior which apparently involves crack nucleation and growth.

17. Key Words (Suggested by Author(s)) High temperature mechanical properties; Oxide dispersion strength (ODS) alloys; ODS alloys; Nickel-base alloy; Iron-base alloy	18. Distribution Statement Unclassified - unlimited STAR Category 26

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