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THE MECHANICAL PROPERTIES OF INOR-8

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OAK RIDGE NATIONAL LABORATORY
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ABSTRACT

Tensile, creep, and relaxation tests were performed on INOR-8, a nickel-base alloy developed for use in the Molten-Salt Reactor. The mechanical properties are summarized and discussed in relation to the composition, microstructure, and environment.

The results indicate that the minimum strength properties of INOR-8 are sufficient to permit the use of workable design stresses up to 1300°F, although certain areas are pointed out where additional information is desirable.

INTRODUCTION

The chemical, metallurgical, and nuclear properties required of a structural material for use in the Molten-Salt Reactor brought about the development of a nickel-base alloy, designated INOR-8.(ref 1) As soon as commercial heats of this material became available, mechanical properties studies were initiated by several laboratories. This report summarizes the results obtained by the Mechanical Properties Group of the Metallurgy Division at the Oak Ridge National Laboratory.

The testing program had two major objectives. The first was to obtain design data for INOR-8 under conditions similar to those in the Molten-Salt Reactor, while the second was to study the effect of various metallurgical factors on the strength and ductility of the alloy. Most of the testing was done on two heats of material, designated SP 16 and SP 19. The program

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[1] T. K. Roche, The Influence of Composition Upon the 1500°F Creep-Rupture Strength and Microstructure of Molybdenum-Chromium-Iron-Nickel-Base Alloys, ORNL-2524 (June 24, 1958).

included tensile, creep, and relaxation tests at temperatures in the range of interest for the Molten-Salt Reactor. The program is supplemented by mechanical properties data obtained by several other groups at the Oak Ridge National Laboratory, the Haynes-Stellite Company,[2] and the Battelle Memorial Institute.[3]

Because the range of testing techniques and conditions was broad, this report has been separated into sections covering each type of test. Representative data are shown and the variations discussed. More detailed data are supplied in the Appendix. Where pertinent, the mechanical properties data obtained by other investigators will be discussed.

MATERIAL

Procurement and Chemistry

Five heats of wrought material have been tested. These are SP 16, SP 19, M-1566, 8M-1, and 1327. Two heats, SP 16 and SP 19, were supplied by the Haynes-Stellite Company and were air melted. Two other air-melted heats, M-1566 and 8M-1, were procured from the Westinghouse Electric Company. Heat 1327 is identical to 8M-1, except that it was vacuum-arc remelted.

The chemical analyses of these heats are presented in Table I. The composition specified for INOR-8 is also given and a comparison of the analyses reveals that the most significant variation occurs in the carbon content which ranges from 0.02% for SP 16 to 0.14% for 8M-1 and 1327. Only SP 19 and M-1566 are within the present carbon specifications.

Annealing Response and Microstructure

The annealing treatment was chosen to be above the anticipated brazing temperature but below the temperature where excessive grain growth occurs. For most heats this treatment was for 1 hr at 2100°F. Heat SP 16 developed a coarse-grain size under these conditions, however, and the temperature was reduced to 2000°F for most of the test series on this heat. Even this treatment produced a relatively coarse-grain size.

The variations in the ASTM grain-size numbers and the Rockwell B hardness numbers corresponding to the annealing treatment are shown in Table II. Rod stock of SP 19 exhibits two grain sizes, ASTM 1-3 and 5-7, corresponding to

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[2] Developmental Data on Hastelloy Alloy N, Haynes-Stellite Company, (May, 1959).

[3] R. G. Carlson, Fatigue Studies of INOR-8, BMI-1354 (June 26, 1959).

TABLE I. The Chemical Composition of Five Heats of INOR-8 (Wt %)

Element	Specification	SP 16	SP 19	M-1566	8M-1	1327
Molybdenum	15 - 19	15.82	16.65	16.1	16.2	17.2
Chromium	6 - 8	6.99	7.43	7.9	7.47	7.0
Iron	5 max	4.85	4.83	4.2	6.1	5.1
Carbon	0.04 - 0.08	0.02	0.06	0.08	0.14	0.14
Manganese	0.8 max	0.34	0.48	0.66	0.69	0.73
Silicon	0.55 max	0.32	0.04	0.20	0.21	0.19
Tungsten	0.50 max	0.35	--	--	--	--
Cobalt	0.2 max	0.51	0.51	--	--	--
Titanium/Aluminum	0.50 max	--	--	0.08	0.08	0.07
Copper	0.50 max	--	0.02	--	--	--
Sulfur	0.01 max	--	0.015	0.004	0.006	0.001
Phosphorus	0.01 max	--	0.010	0.002	0.009	0.001
Boron	0.01 max	0.02 - 0.03	--	--	--	--
Nickel	Balance	Balance	Balance	Balance	Balance	Balance

TABLE II. The Grain Size and Hardness of Annealed INOR-8

Annealing Treatment (°F)	Annealing Treatment (hr)	Heat	Geometry	Carbon Content (Wt %)	Range of ASTM Grain-Size Number	Range of Rockwell B Hardness Number
2000	1	SP 16	Sheet	0.02	2 - 4	76 - 86
2000	1	SP 16	Rod	0.02	2 - 4	80 - 88
2100	1	SP 16	Sheet	0.02	2 - 3	76 - 86
2100	1	SP 16	Rod	0.02	2 - 3	76 - 84
2100	1	SP 19	Sheet	0.06	4 - 6	86 - 91
2100	1	SP 19-1	Rod	0.06	1 - 3	86 - 91
2100	1	SP 19-3	Rod	0.06	5 - 7	88 - 100
2100	1	M-1566	Sheet	0.08	5 - 7	87 - 93
2100	1	M-1566	Rod	0.08	5 - 7	87 - 90
2100	1	8M-1	Sheet	0.14	5 - 7	90 - 93
2100	1	1327	Sheet	0.14	5 - 7	89 - 92

two different rods designated SP 19-1 and SP 19-3, respectively. With the exception of SP 19-1 the high carbon heats have the finest grain size and highest hardness numbers.

Photomicrographs of the annealed sheet specimens are shown in Figs. 1 through 5. The microstructures reveal an equiaxed grain structure with stringers and clusters of a second phase through the grains and along the grain boundaries. This phase has been identified as a $(Ni, Mo)_6C$ carbide[4] and appears to increase with increasing carbon content. The size, number, and distribution of these carbides vary from heat to heat.

TENSILE PROPERTIES

Equipment and Procedure

Tensile tests were performed in air on sheet and rod material. The sheet specimens were 0.063-in. thick, 0.5-in. wide, with a 3-in. uniform gage length. A detailed description of the specimen design has been presented by Douglas and Manly.[5] Rod specimens were of the standard ASTM design for 0.505- or 0.357-in.-diam gage sections. Tests were performed on a Baldwin-Southwark hydraulic testing machine having a 120,000-lb capacity. In all cases the extension rate was 0.05 in. per min.

Results

Typical Data: A series of tensile curves for INOR-8 rod specimens (SP 16 annealed at 2000°F) is shown in Fig. 6. At elevated temperatures it is evident that yielding takes place quite abruptly and very little work hardening occurs during the initial stages of plastic flow. The stress at the proportional limit and the 0.2% offset yield strength (indicated by the dash on the tensile curve) exhibit very little temperature dependence between 1000 and 1400°F. This type of behavior was observed for all of the heats tested. The tensile strength and elongation are considerably more temperature dependent, as illustrated in Fig. 7.

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[4] A. E. LaMarche, Pilot Plant Development of a Nickel-Molybdenum-Base High Temperature Alloy, Report No. 2-98848-190, Materials Manufacturing Department of Westinghouse Electric Company, Blairsville, Penn. (May, 1958).

[5] D. A. Douglas and W. D. Manly, A Laboratory for the High-Temperature Creep Testing of Metals and Alloys in Controlled Environments, ORNL-2053 (Sept. 18, 1956).

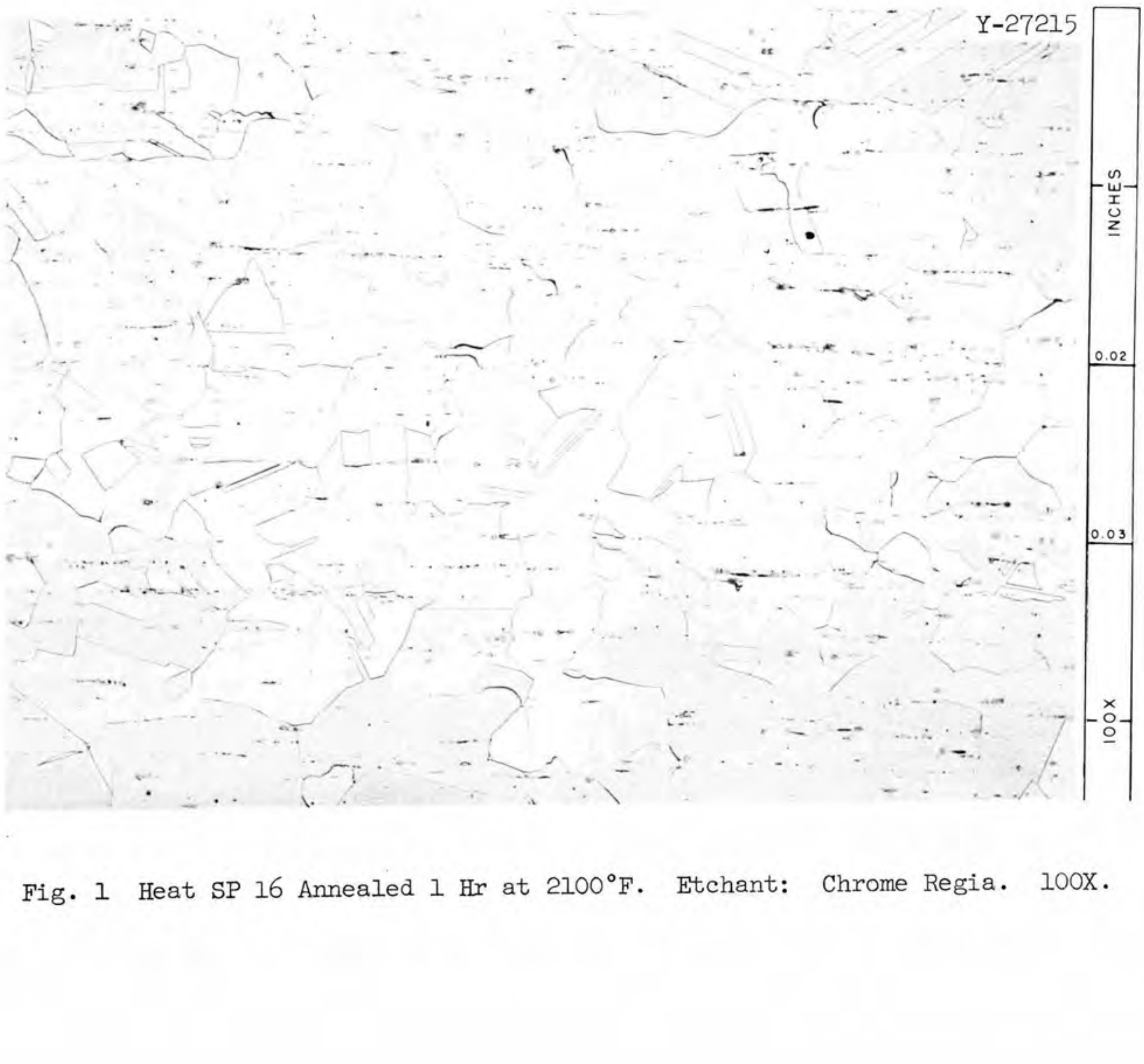

Fig. 1 Heat SP 16 Annealed 1 Hr at 2100°F. Etchant: Chrome Regia. 100X.

Fig. 2 Heat SP 19 Annealed 1 Hr at 2100°F. Etchant: Aqua Regia. 100X.

Fig. 3 Heat M-1566 Annealed 1 Hr at 2100°F. Etchant: Aqua Regia. 100X.

Fig. 4 Heat 8M-1 Annealed 1 Hr at 2100°F. Etchant: Aqua Regia. 100X.

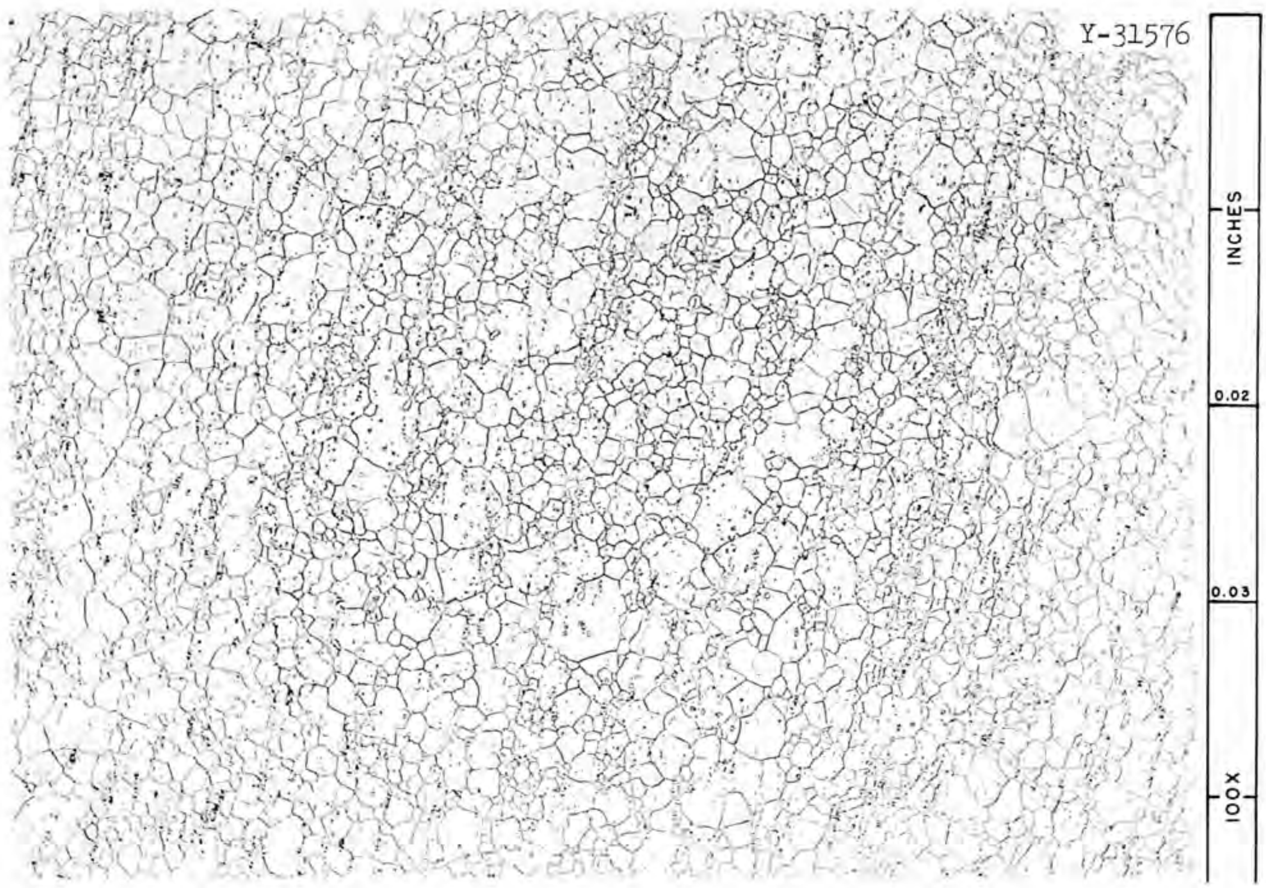

Fig. 5 Heat 1327 Annealed 1 Hr at 2100°F. Etchant: Aqua Regia. 100X.

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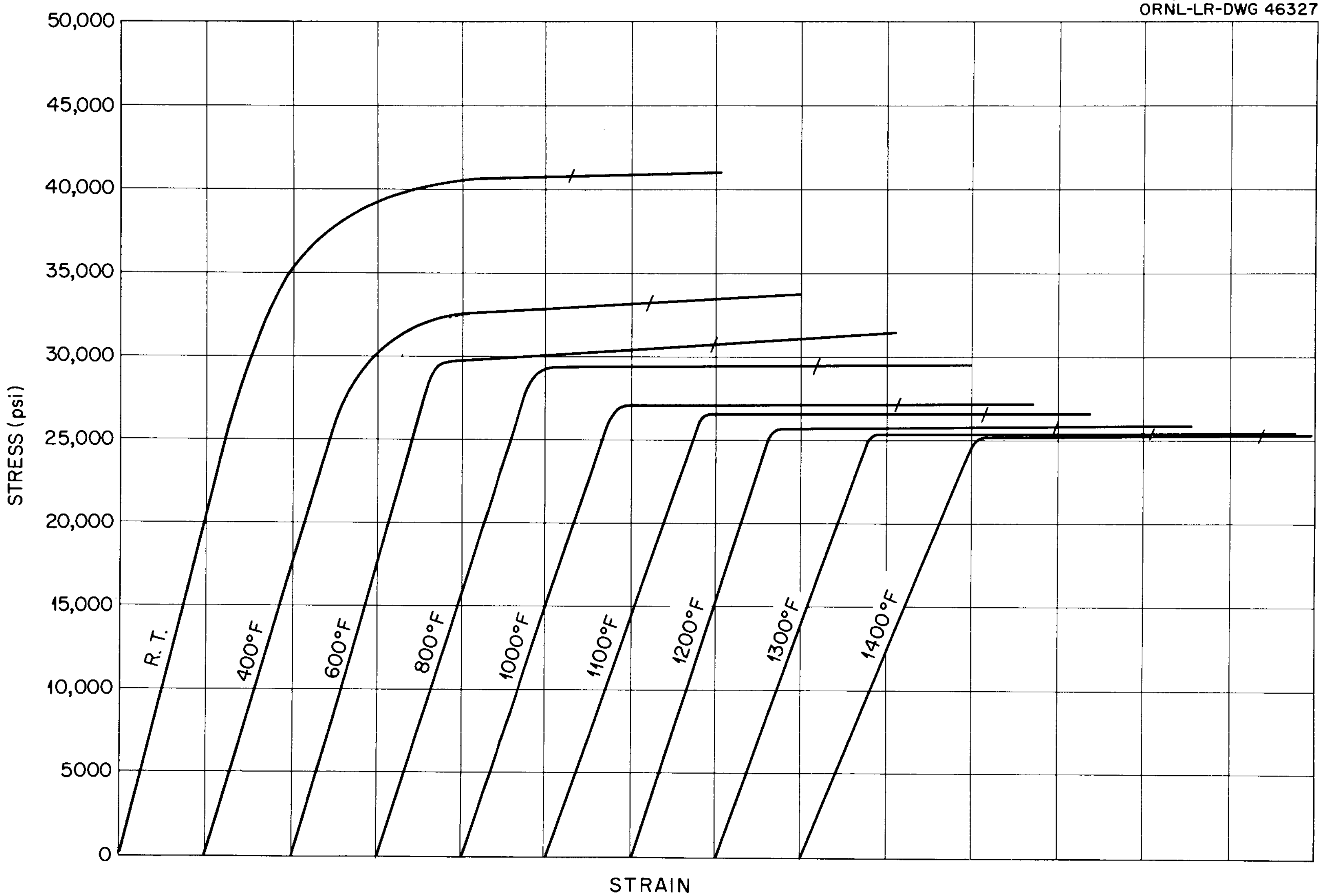

Fig. 6 Initial Portion of the Tensile Curves for INOR-8 (SP 16 Annealed at 2000°F) Rod Specimens.

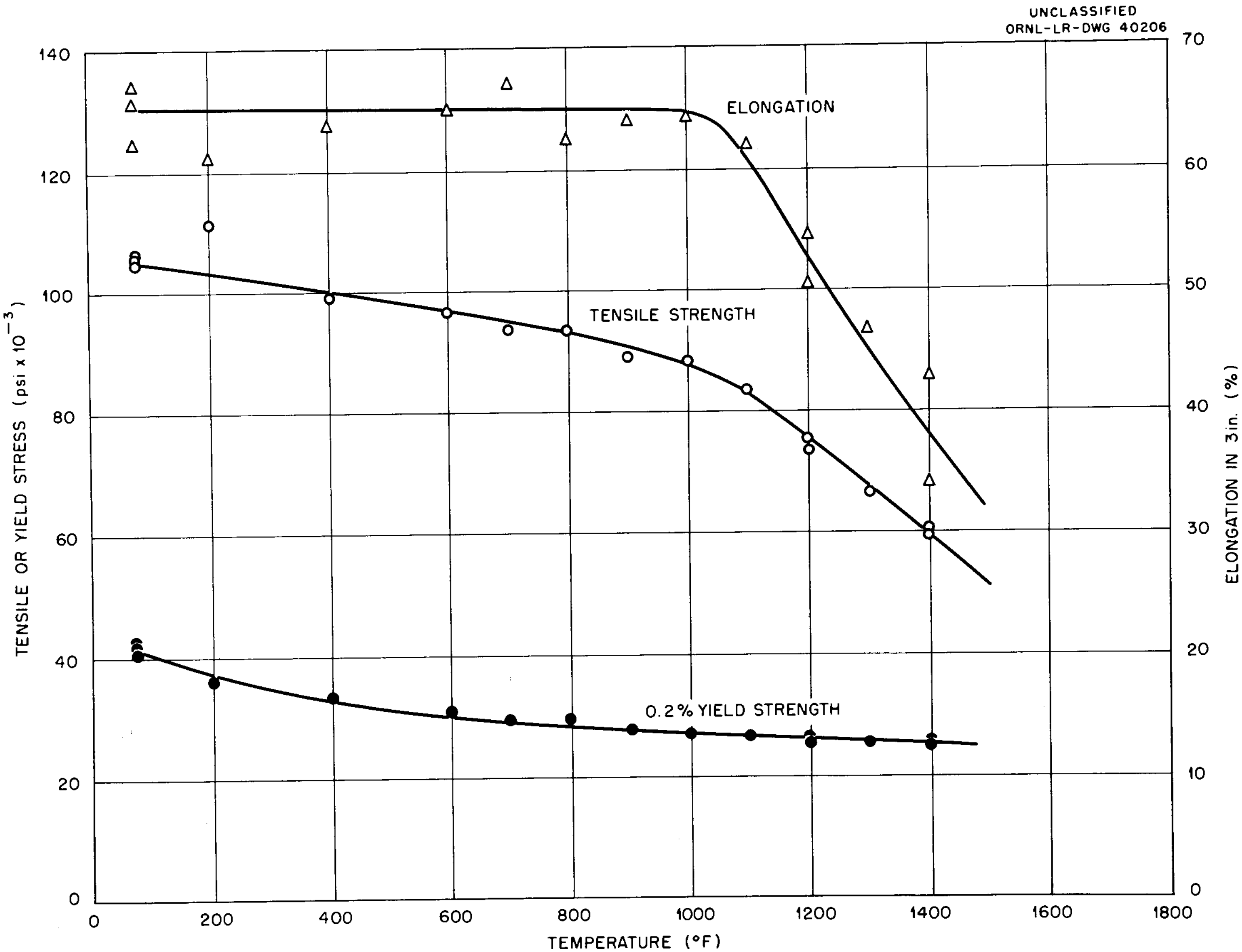

Fig. 7 Tensile Properties of INOR-8 (SP 16) 0.505-in. Rods Annealed 1 hr at 2000°F.

Effect of Composition and Grain Size: The tensile properties for sheet specimens of four heats—SP 16, SP 19, M-1566, and 8M-1 (data for SP 19 and 8M-1 are for 0.045-in.-thick sheet and were taken from a test series performed for Inouye[6]) are presented in Figs. 8, 9, and 10. The data shown in Fig. 8 indicate that the tensile strengths do not vary greatly from heat to heat. Although high-carbon and fine-grained heats are slightly stronger than coarse-grained and low-carbon heats, the tensile strengths for all heats of the sheet specimens fall within a narrow scatterband.

Figure 9 shows the variation in the yield strength from heat to heat. Heat 8M-1, high in carbon with a fine-grain size, exhibits the highest yield strength; while SP 16, low in carbon and coarse grained, is the weakest. Values range from 25,000 psi to 38,000 psi at 1300°F.

Tensile elongation data are presented in Fig. 10. The elongation is constant up to 1000°F, but rapidly drops to a minimum value near 1500°F, the highest temperature investigated. The elongation decreases with increasing carbon content and/or decreasing grain size with the exception of M-1566. Heat M-1566 is the least ductile above 1000°F. A summary of these and additional tensile data are given in Tables A-1 and A-2 in the Appendix.

Effect of Notches: Tests were performed on notched-rod specimens of SP 19-3 at several temperatures. These specimens had a gage diameter of 0.357 in. and a notch radius of 0.005 in.

As in the case of most metals, the effect of the notch is to increase the ultimate tensile strength; but at the lower temperatures, the increase for INOR-8 is only slight. The notched to unnotched strength ratios at room temperature, 1000, 1200, and 1500°F are 1.08, 1.07, 1.13, and 1.38, respectively. Data for these tests are presented in Table A-3 of the Appendix.

Effect of Aging: A few aging tests were performed on notched specimens of SP 19-3. The selected treatments were 200 hr at 1200°F, 40 hr at 1650°F, and 4 hr at 1800°F. Data are summarized in Table A-3 of the Appendix. The results do not indicate any significant aging effect, although the notch strength ratios are very close to unity below 1500°F.

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[6] H. Inouye, Met. Ann. Prog. Rep. Sept. 1, 1959, ORNL-2839, p. 195.

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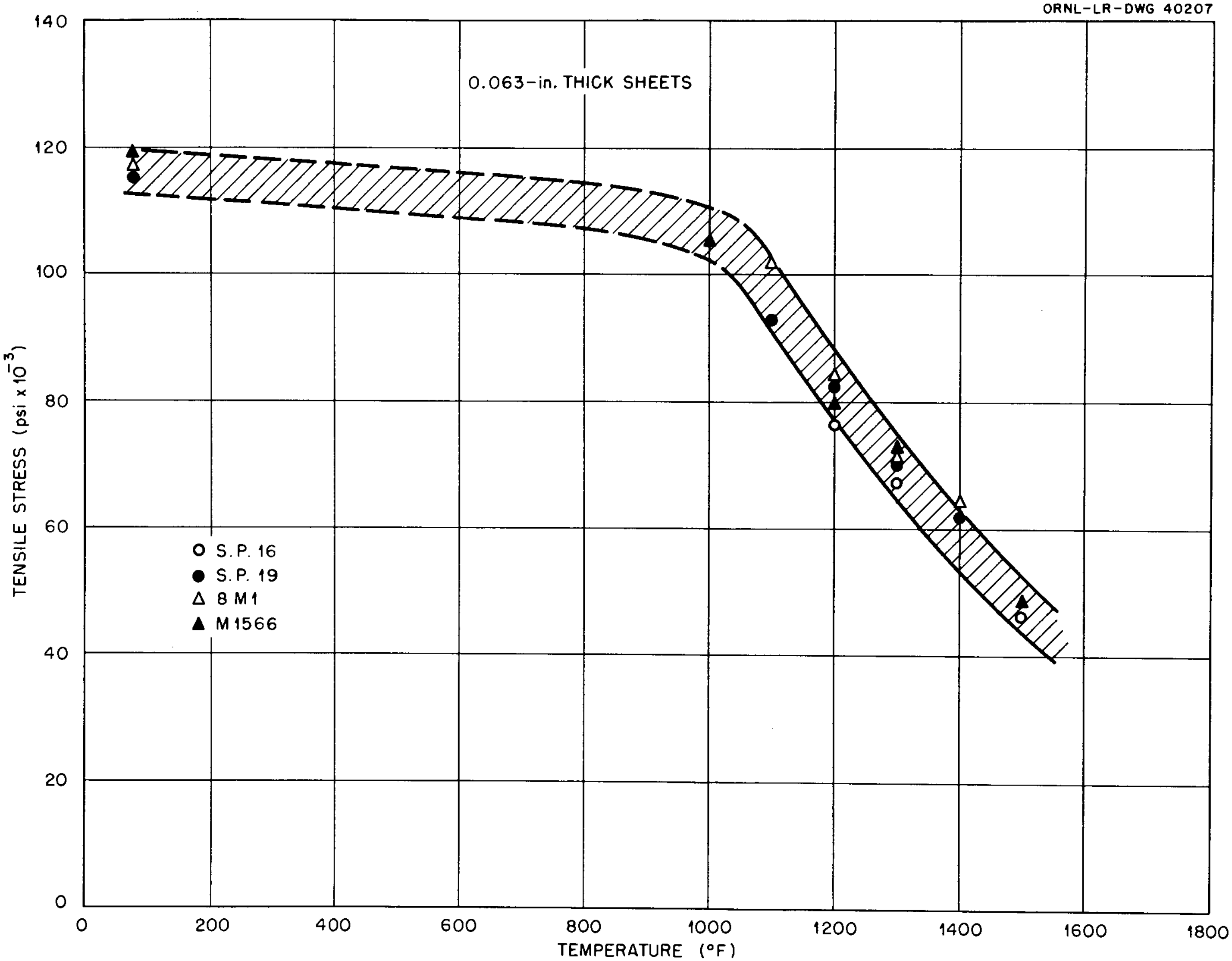

Fig. 8 Temperature Dependence of the Ultimate Tensile Strength for INOR-8.

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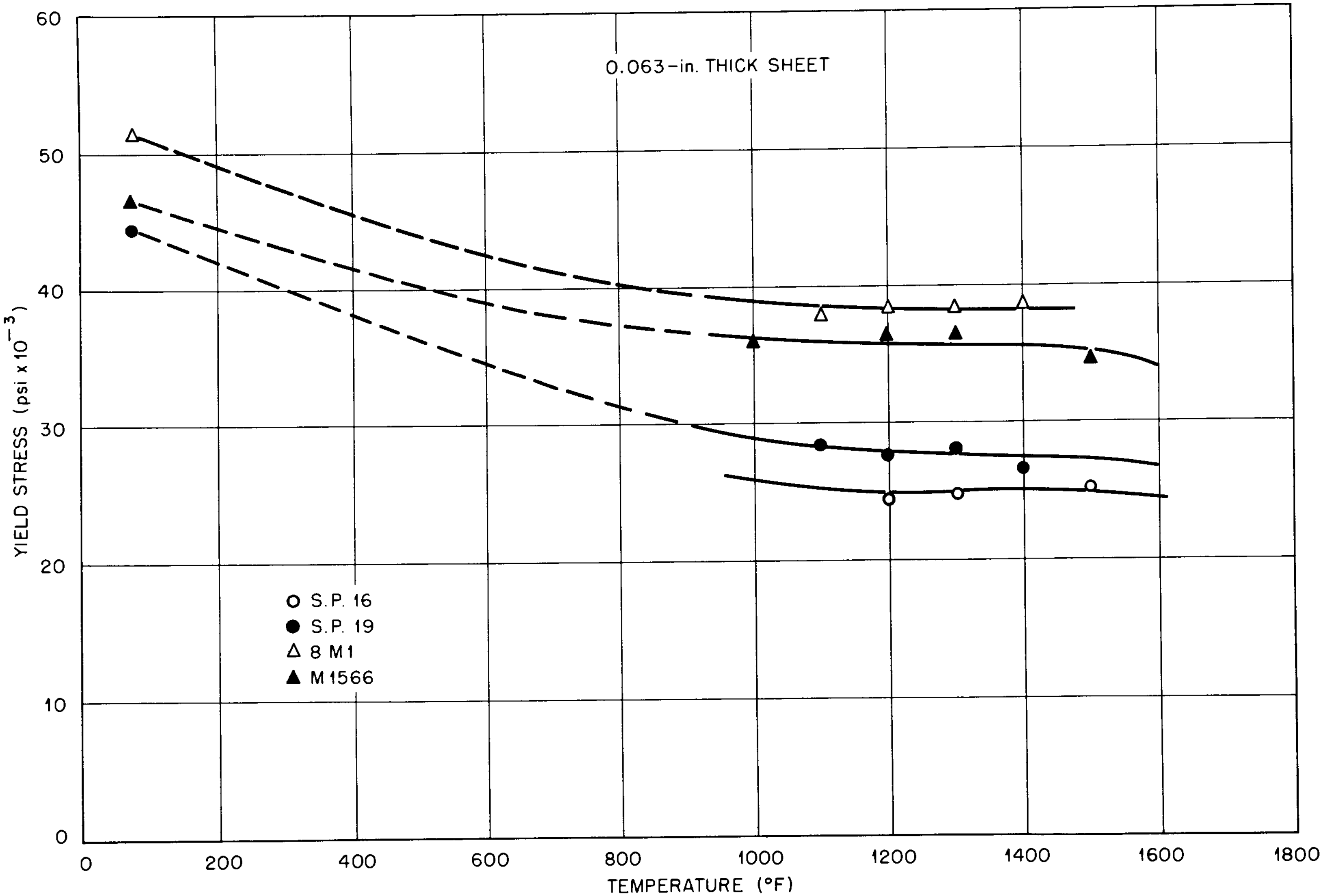

Fig. 9 Temperature Dependence of the 0.2% Offset Yield Strength for INOR-8.

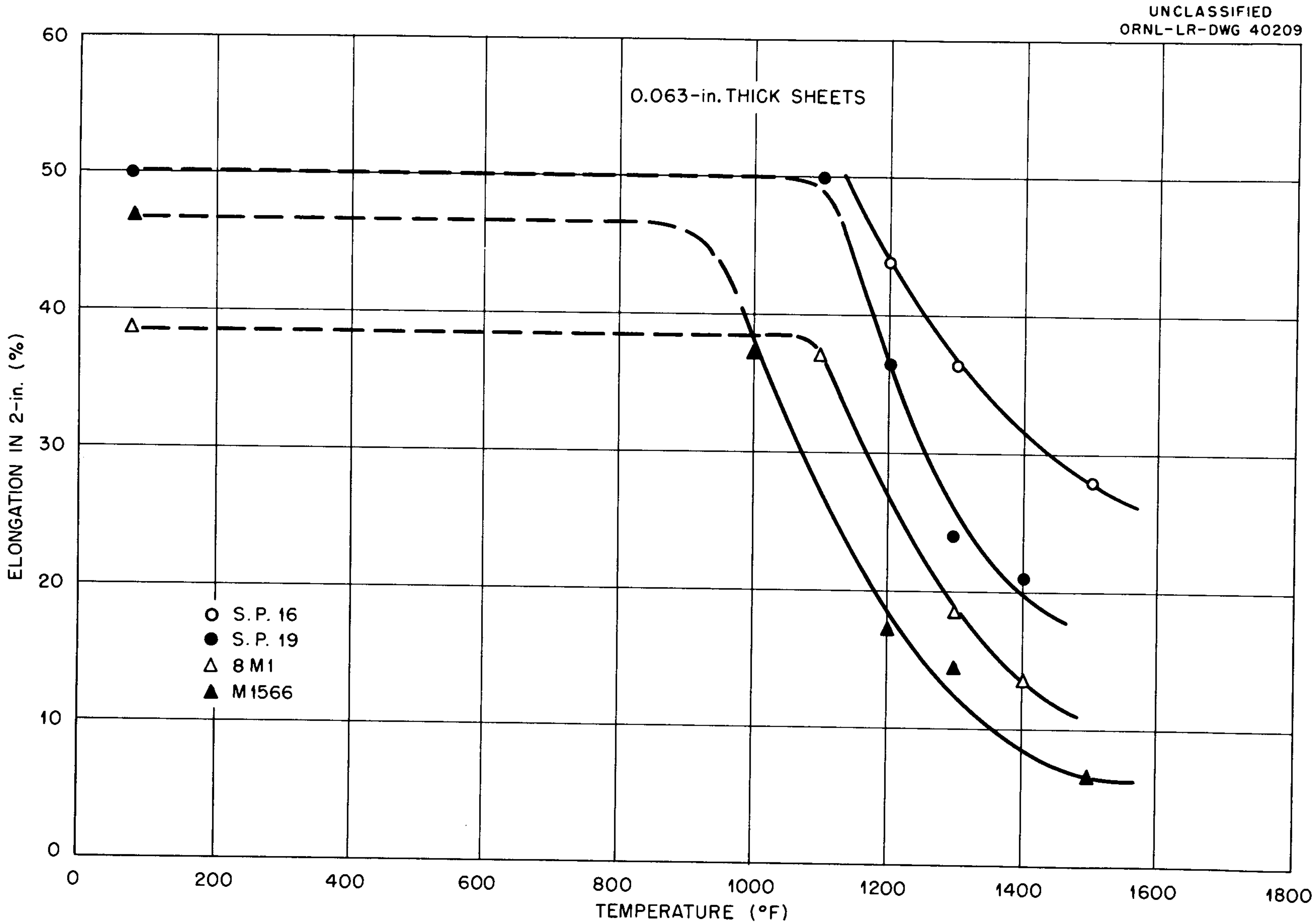

Fig. 10 Temperature Dependence of Tensile Elongation.

Data are also reported in Table A-3 of the Appendix for smooth rods of coarse-grained SP 19-1 aged 40 hr at 1650°F. No change in the strength properties is evident, but the elongation at 1500°F has increased from 20 to 50%. This improvement appears to be associated with coarsening of the carbides and evidence of this coarsening is presented in the section of the report covering creep.

Effect of Carburization: A few tensile tests were performed on smooth- and notched-rod specimens of SP 19-3 which had been carburized in sodium-graphite for 40 hr at 1650°F. This treatment resulted in a high-carbon case which penetrated to a depth of about 0.010 in. Data for smooth rods are compared to noncarburized material in Fig. 11. Up to 1200°F carburization results in a slight increase in the yield strength and a decrease in the tensile strength, elongation, and reduction in area. Data for notched specimens parallel this behavior with the notch strength ratio being less than unity when the ratio is in respect to the unnotched-uncarburized specimens. Summary data are reported in Table A-3 of the Appendix.

Fracture Characteristics and Microstructure: Metallographic studies were performed on the rod specimens of SP 19-3. This study revealed that the temperature at which the ductility begins to drop corresponds to the temperature at which grain-boundary fracture begins to occur. Below 1000°F, the fracture is predominately transgranular as shown in Fig. 12, while above this temperature the fracture becomes intergranular as indicated by Fig. 13. The effect of carburization on fracture is to change the low-temperature mechanism to one of intergranular fracture. Figures 14 and 15 show the fracture at the surface for carburized and noncarburized specimens tested at room temperature. The intergranular fracture which occurs at room temperature in the carburized zone becomes transgranular in the interior of the specimen where no carburization occurs.

CREEP PROPERTIES

Program

Creep tests were performed in molten salt and air between 1100 and 1800°F. Since the maximum temperature for long-time service was not expected to exceed 1300°F, most of the tests were conducted in the 1100 to 1300°F temperature

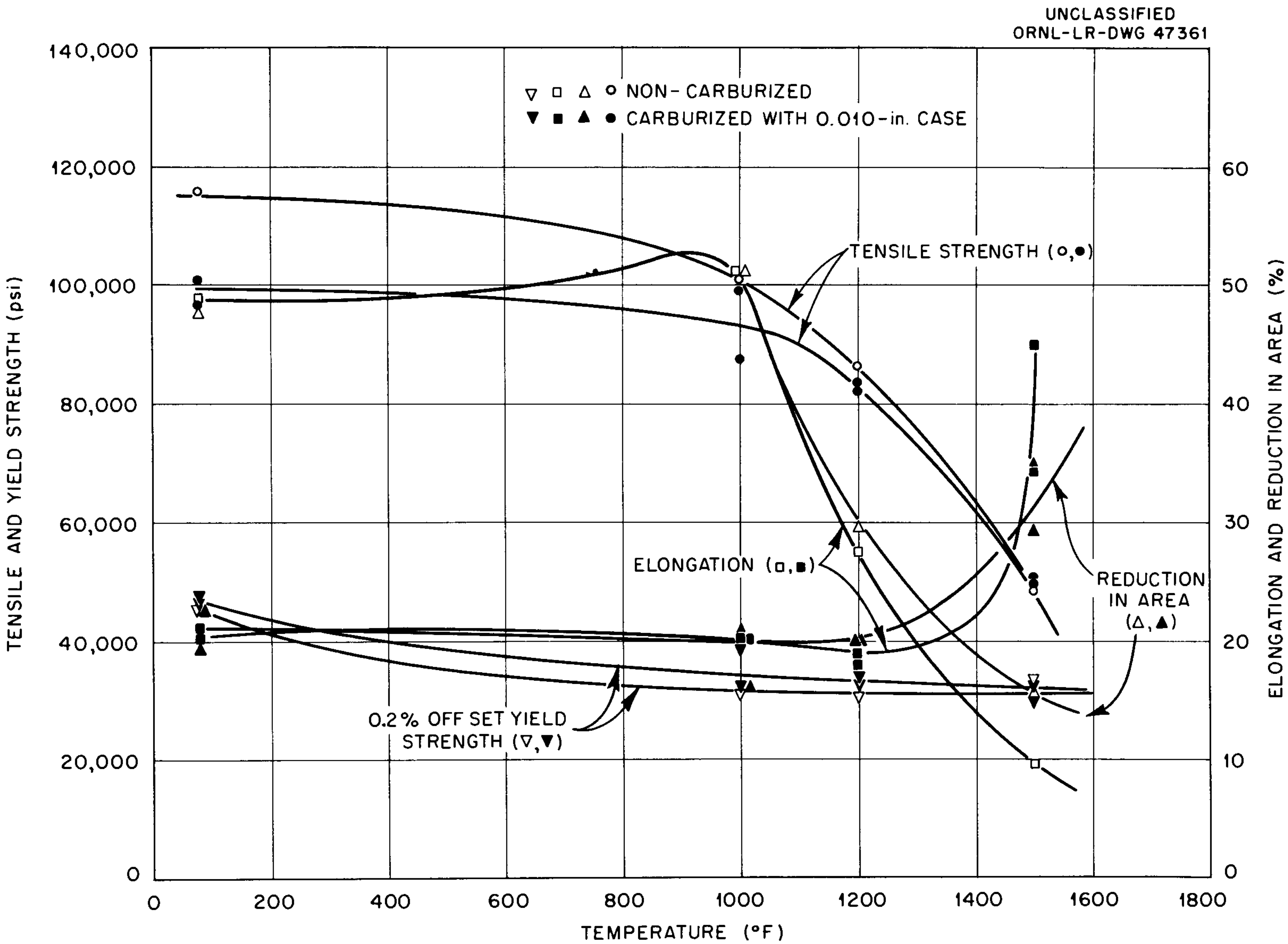

Fig. 11 Effect of Surface Carburization on the Tensile Properties of INOR-8 (SP 19) Rod Specimens.

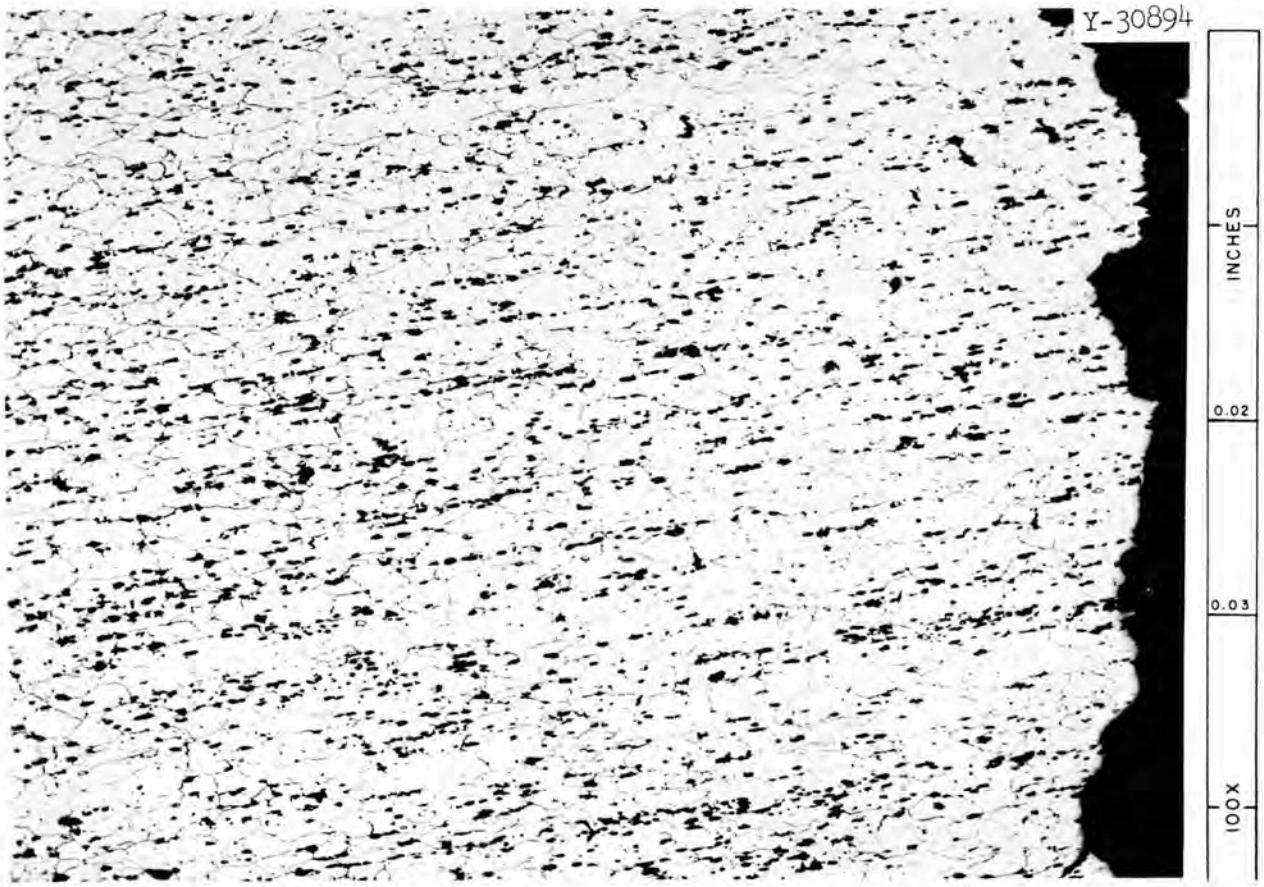

Fig. 12 Heat SP 19-3 Annealed 1 Hr at 2100°F. Tensile tested at room temperature. Etchant: Aqua Regia. 100X.

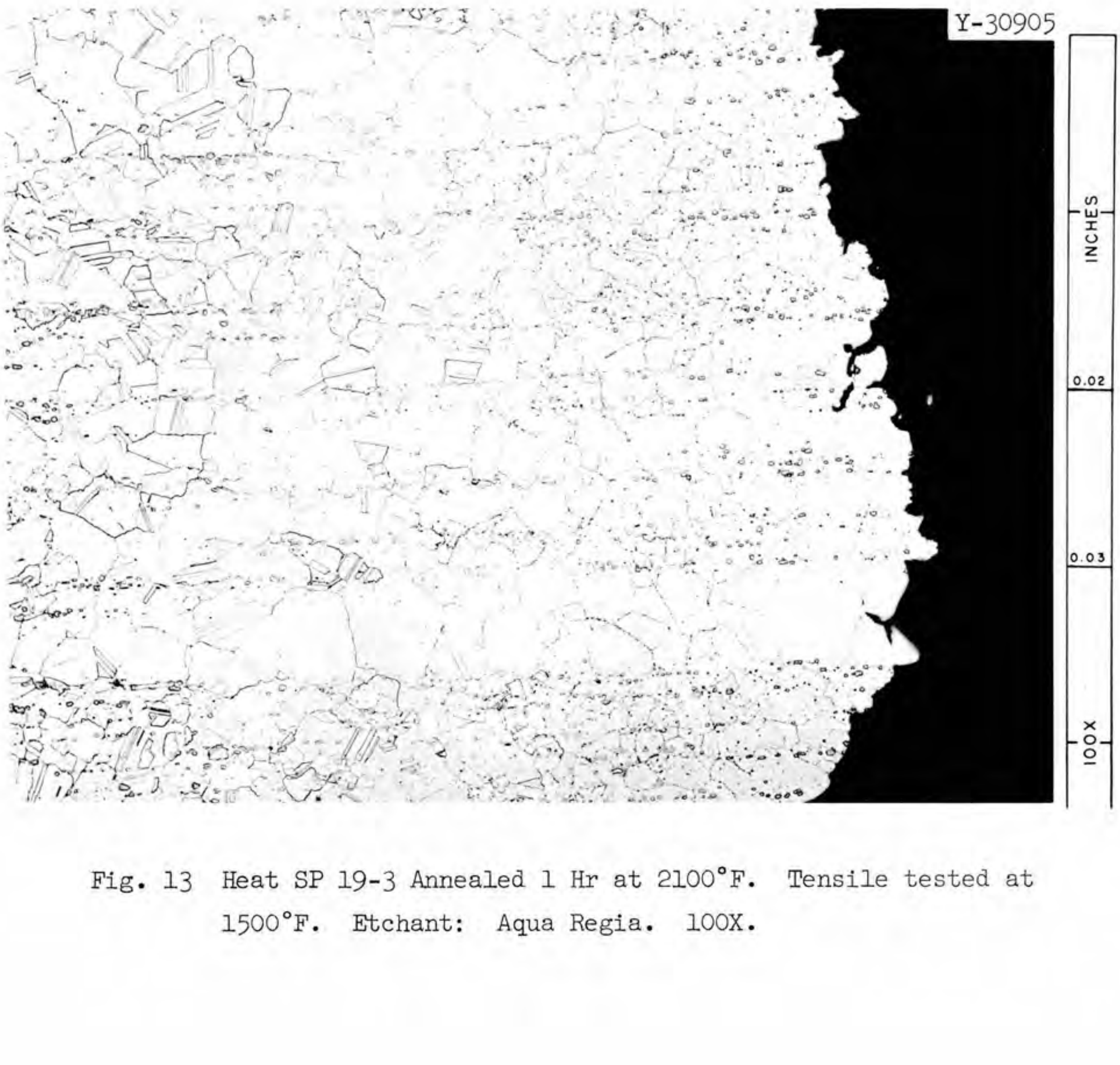

Fig. 13 Heat SP 19-3 Annealed 1 Hr at 2100°F. Tensile tested at 1500°F. Etchant: Aqua Regia. 100X.

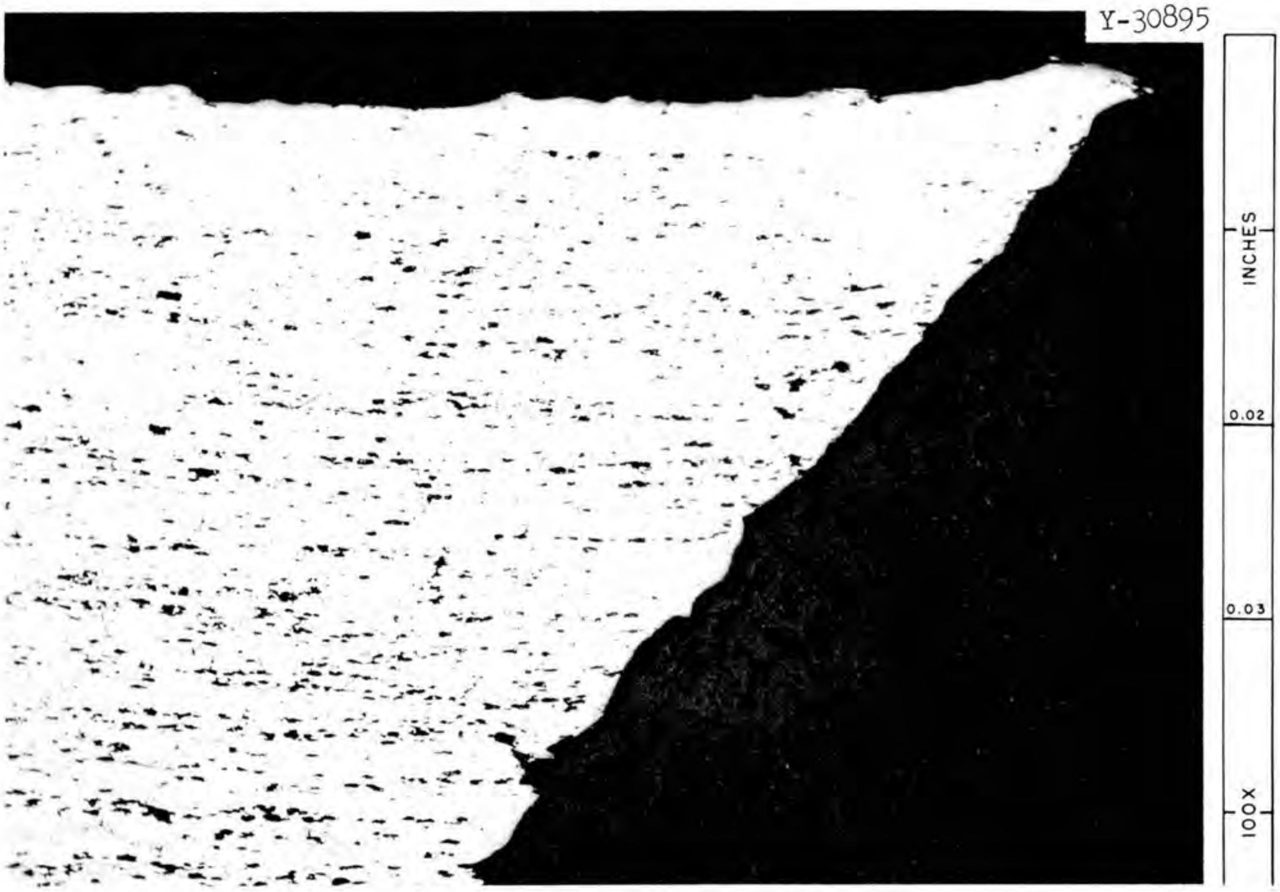

Fig. 14 Heat SP 19-3 Annealed 1 Hr at 2100°F. Tensile tested at room temperature. Etchant: Aqua Regia. 100X.

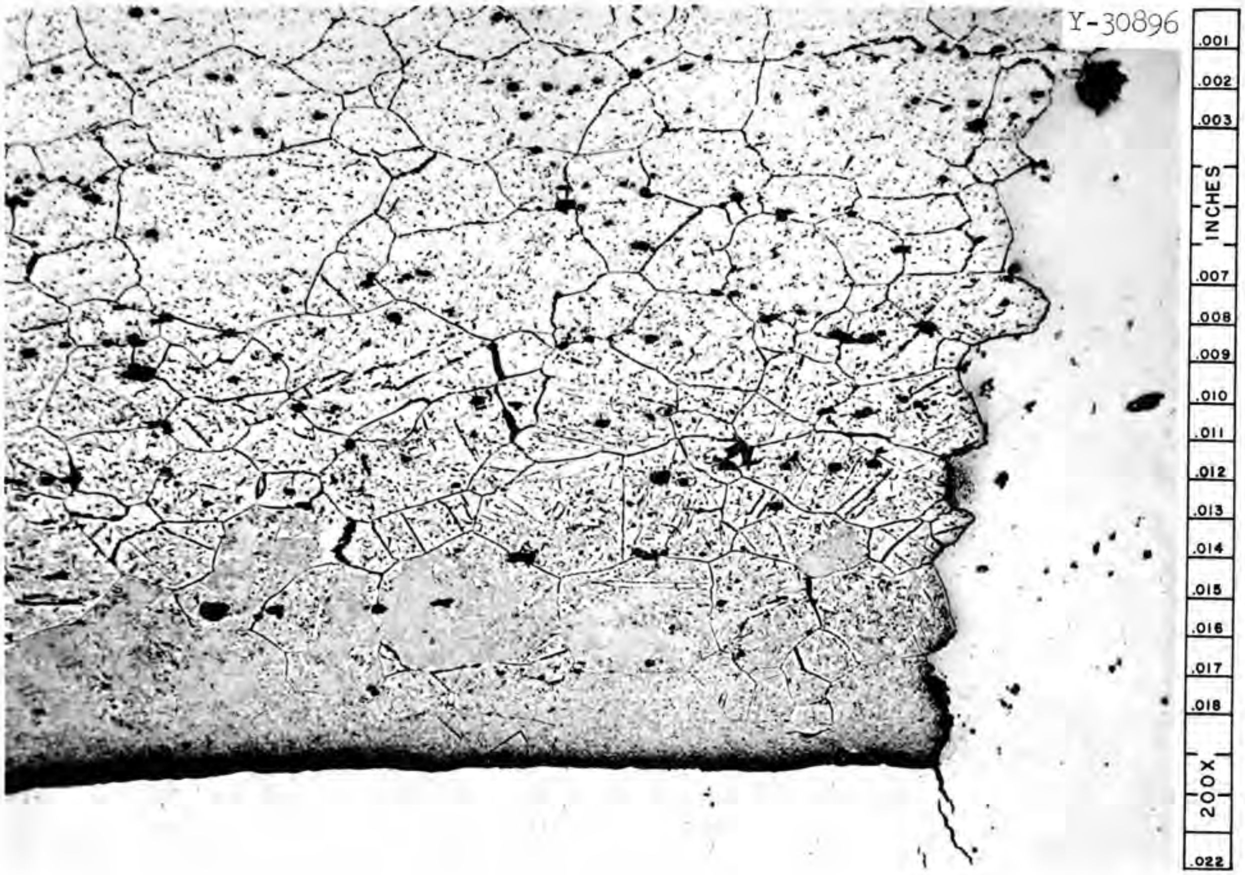

Fig. 15 Heat SP 19-3 Annealed 1 Hr at 2100°F. Carburized in Sodium-Graphite for 40 hr at 1650°F. Tensile tested at room temperature. Etchant: 10% Oxalic Acid. 200X.

range. The bulk of the testing was done on heats SP 16 and SP 19, but a few tests were performed on the other three heats for comparative purposes.

Equipment and Procedure for Tests in Salt

Sheet specimens were tested in molten-salt No. 107; the nominal composition of which, in terms of the mole percentage, is NaF–11.2, KF–41, LiF–45.3, and UF_4–2.5. A static system was used, but in some cases the salt was periodically changed. The testing chambers were constructed of Inconel, Hastelloy B, or Hastelloy C and are described together with other equipment in a report written by Douglas and Manly.[7]

Extension measurements were obtained from a dial gage which recorded the upward travel of the pull rod on the exterior of the testing chamber. Such a technique lead to scatter and inaccuracies in the strain measurements especially for strains less than 0.5%. This point should be considered in evaluating the low-strain creep data reported for molten-salt tests.

Results for Tests in Salt

Typical Data: Typical creep curves for tests in salt at 1300°F are shown in Fig. 16. These are for SP 16. (Unless otherwise stated, SP 16 has been given a 1-hr anneal at 2000°F.) Creep occurs in the three classical stages: transient, steady, and accelerating. The change in strain rate during the transient period is quite small and similarly, the acceleration in creep before failure is not large. Most tests in salt exhibited this type of curve, although many of the low stress tests on SP 16 at 1500°F and above exhibited a continually decreasing creep rate to rupture.

Figure 17 is a comparison of the creep curves for the five heats at 1300°F and 20,000 psi. With the exception of heat M-1566, the curves show fairly good agreement. Heat 8M-1 exhibits the lowest creep rate while heat 1327 is the most ductile. Heat M-1566 exhibits an inflection at the end of transient creep and accelerates immediately to rupture after a short time and small strain.

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[7] D. A. Douglas and W. D. Manly, A Laboratory for the High-Temperature Creep Testing of Metals and Alloys in Controlled Environments, ORNL-2053 (Sept. 18, 1956).

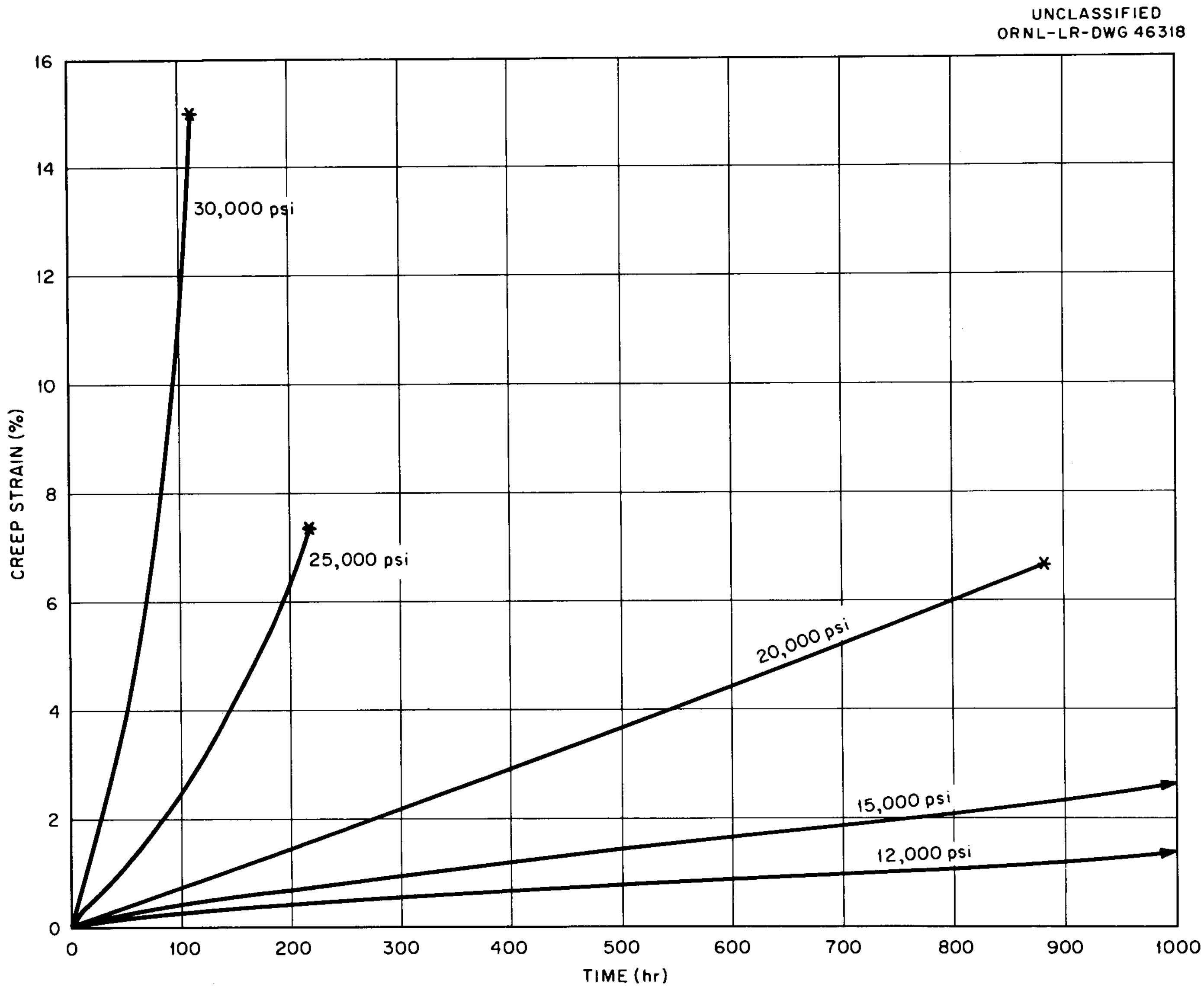

Fig. 16 Creep Curves for INOR-8 (SP 16) Tested in Molten Salt at 1300°F.

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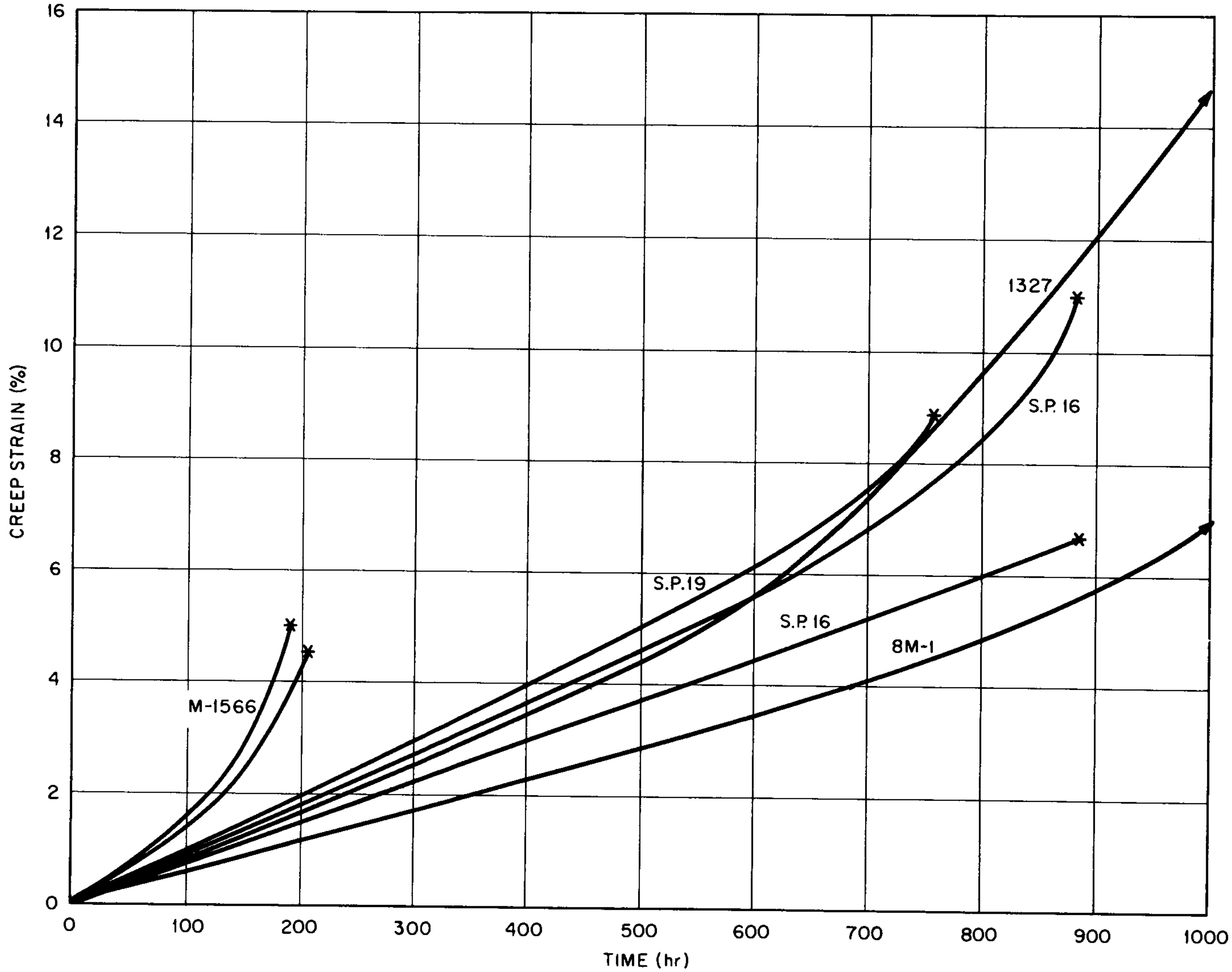

Fig. 17 Comparison of the Creep Curves for Various Heats of INOR-8 Tested in Molten Salt at 1300°F and 20,000 psi.

Summary Data: A digest of the creep data obtained from tests in molten salt is presented in Table A-4 of the Appendix. Data include the time to specified creep strains for each test conducted. These values were taken from smooth curves as plotted on log-log coordinates. The rupture life and elongation are also reported. Summary data taken from this table are presented in Figs. 18, 19, and 20. Figure 18 is a log-log plot of the stress vs time to 1% creep strain. Scatterbands have been drawn to cover the data corresponding to various temperatures. At 1100, 1200, and 1300°F these bands are nearly parallel, while the slopes at 1650 and 1800°F are apparently different. Air test data indicate a break in the curves above 20,000 psi, near the yield strength, but the data obtained from tests in molten salt exhibit too much scatter to define this break clearly.

Figure 19 is a log-log plot of the stress vs the minimum creep rate. The scatterbands exhibit the same characteristics as Fig. 18, except that: (1) the scatterband for 1100°F data is not parallel to that at 1200 and 1300°F, and (2) the data at 1500°F and above show considerably greater stress dependency.

Figure 20 is a log-log plot of the stress vs the rupture life. Scatterbands resemble those for 1% creep at 1100, 1200, and 1300°F, but here again a considerable stress dependency occurs at 1500°F and above.

The rupture ductility values recorded for INOR-8 are lowest at 1100°F. The minimum value listed in Table A-4 of the Appendix is 1.7% which corresponds to 12,725 hr at 1100°F. Ductilities are greater at the higher temperatures, but the rupture lives corresponding to these ductilities are short. The maximum value reported is 22% for heat 1327 at 1800°F after 23 hr.

Microstructure: Photomicrographs are shown in Figs. 21 through 25 for the various heats of INOR-8 tested in molten salt at 1300°F and 20,000 psi. (The creep curves for this series are shown in Fig. 17.) Fracture occurs by intergranular cracking, but the grain size apparently has not affected the rupture life at this temperature. Heat 1327, for example, exhibits a structure and crack pattern similar to heat M-1566, yet one lasted 1177 hr and the other only 180 hr. Heat SP 16, which is coarse grained as compared to heats 1327 and M-1566, failed after 882 hr, a time between the two extremes.

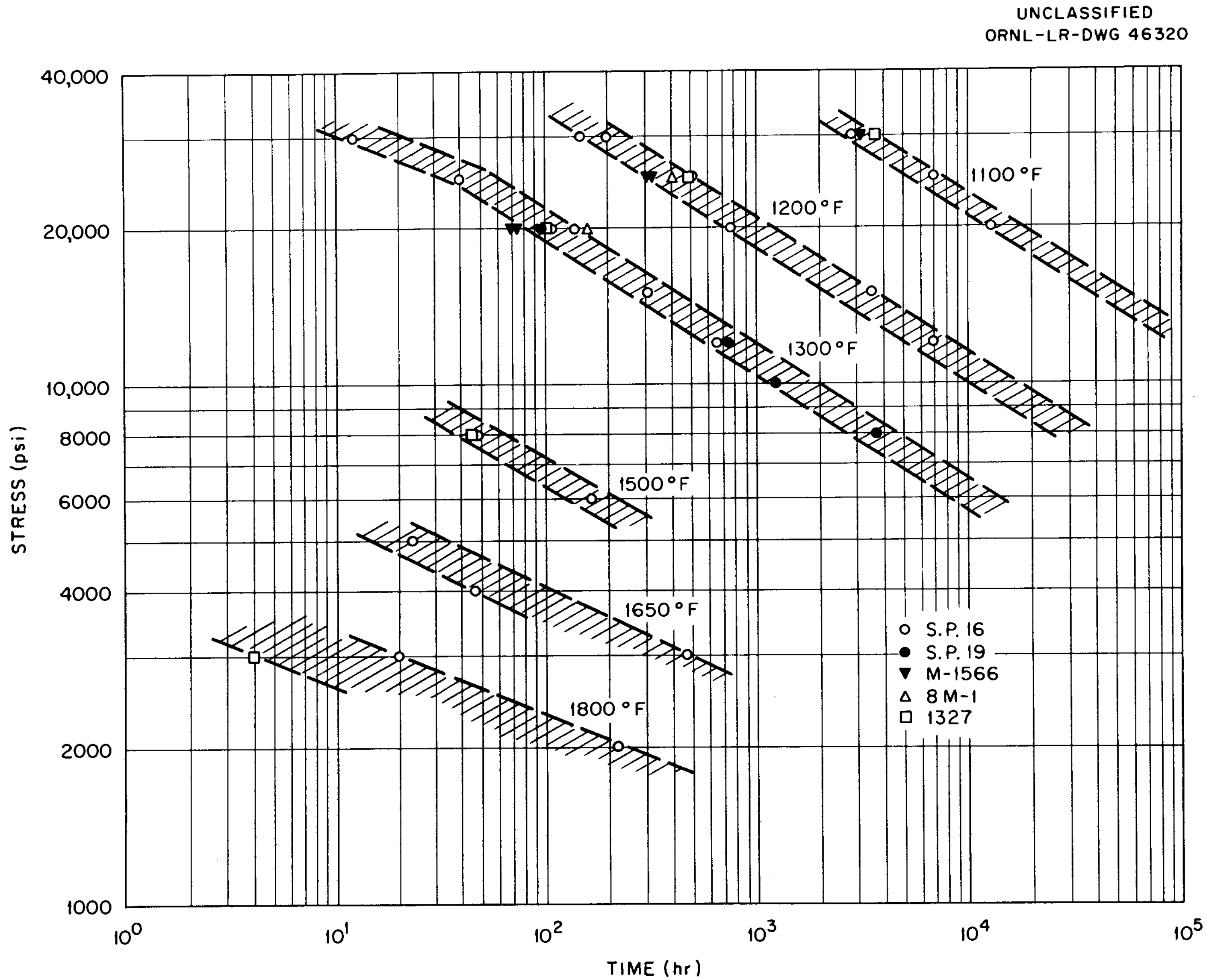

Fig. 18 Stress vs Time to 1.0% Creep Strain for INOR-8 Sheet Specimens in Molten Salt.

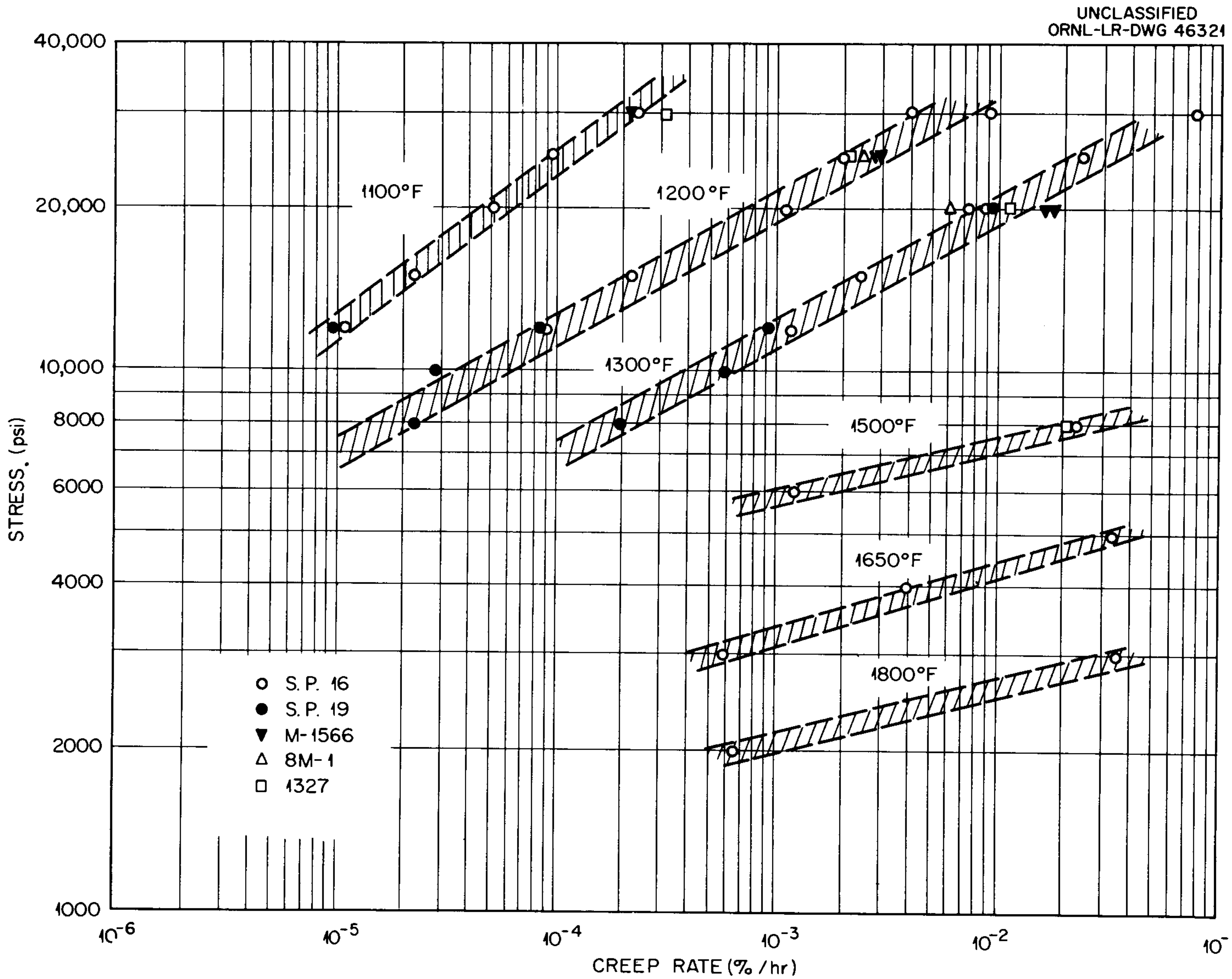

Fig. 19 Stress vs Minimum Creep Rate for INOR-8 Sheet Specimens in Molten Salt.

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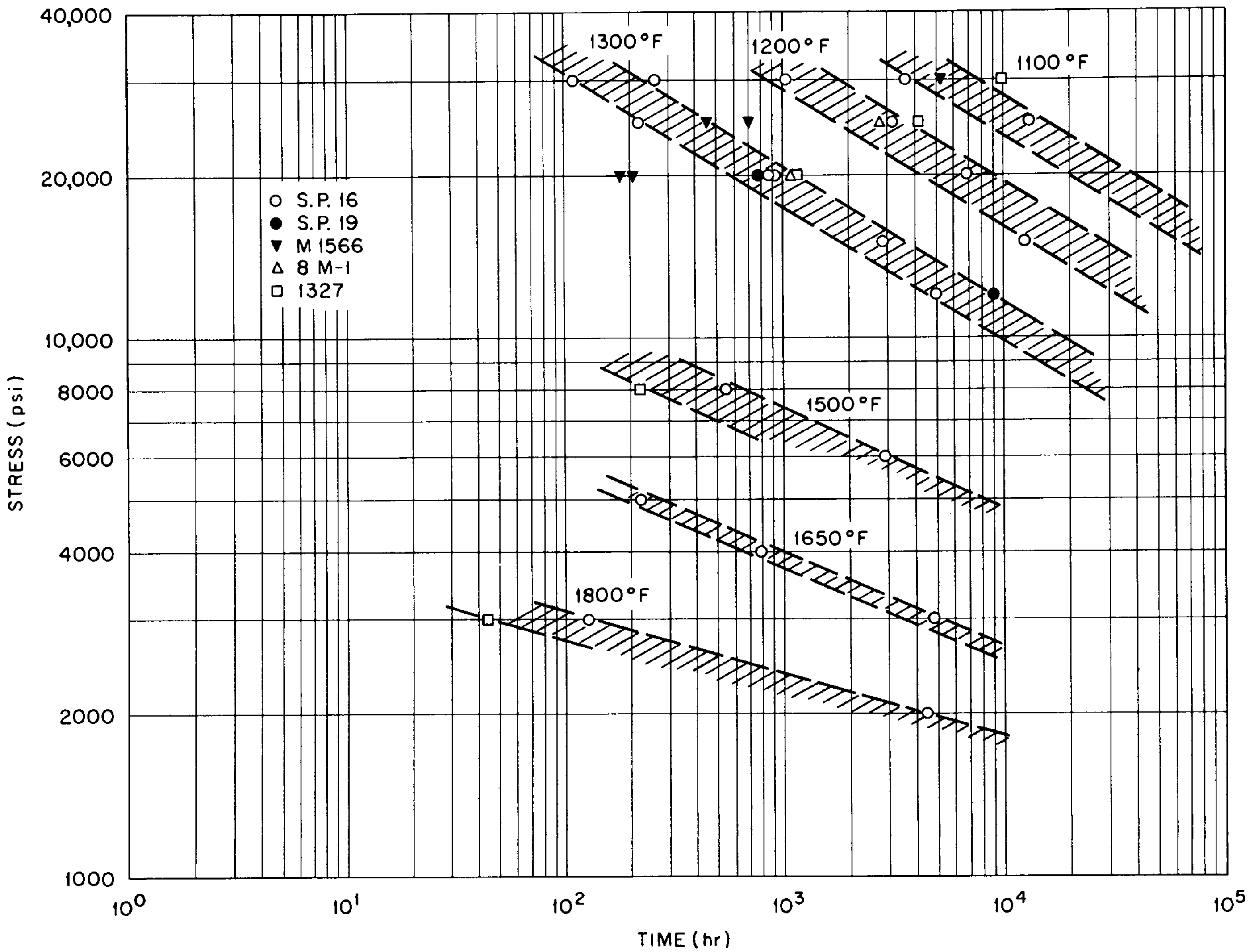

Fig. 20 Stress vs Time to Rupture for INOR-8 Sheet Specimens in Molten Salt.

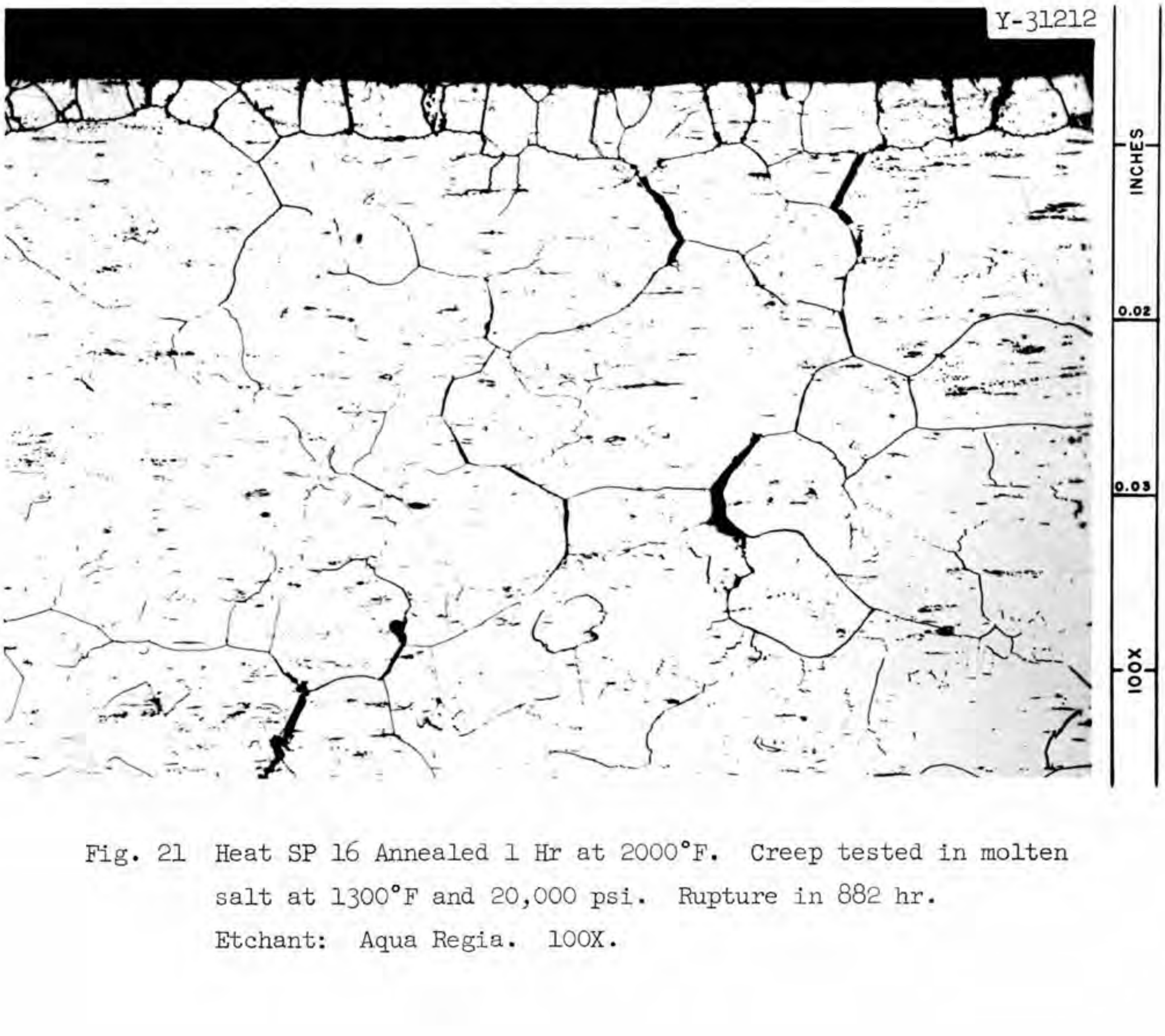

Fig. 21 Heat SP 16 Annealed 1 Hr at 2000°F. Creep tested in molten salt at 1300°F and 20,000 psi. Rupture in 882 hr. Etchant: Aqua Regia. 100X.

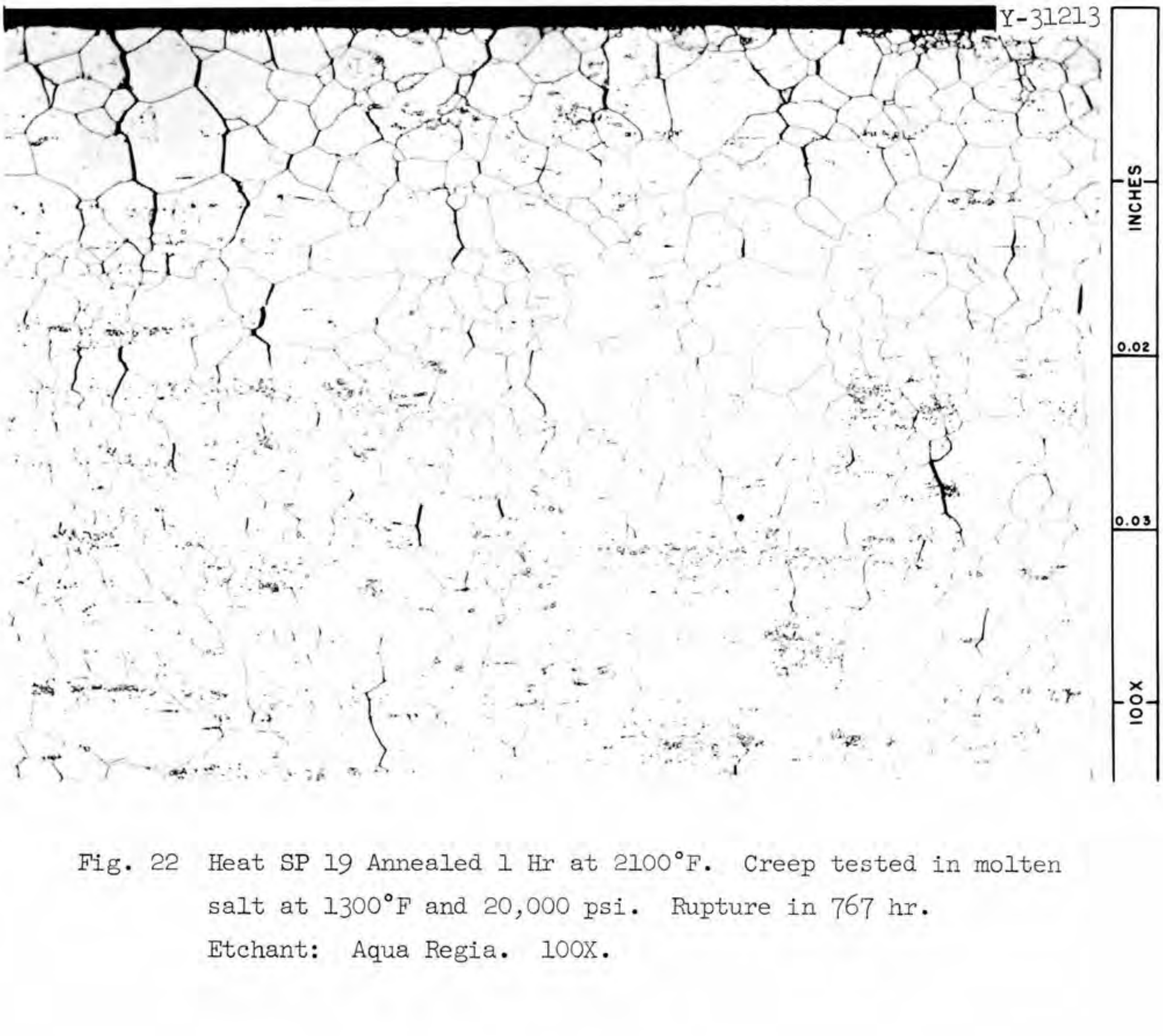

Fig. 22 Heat SP 19 Annealed 1 Hr at 2100°F. Creep tested in molten salt at 1300°F and 20,000 psi. Rupture in 767 hr. Etchant: Aqua Regia. 100X.

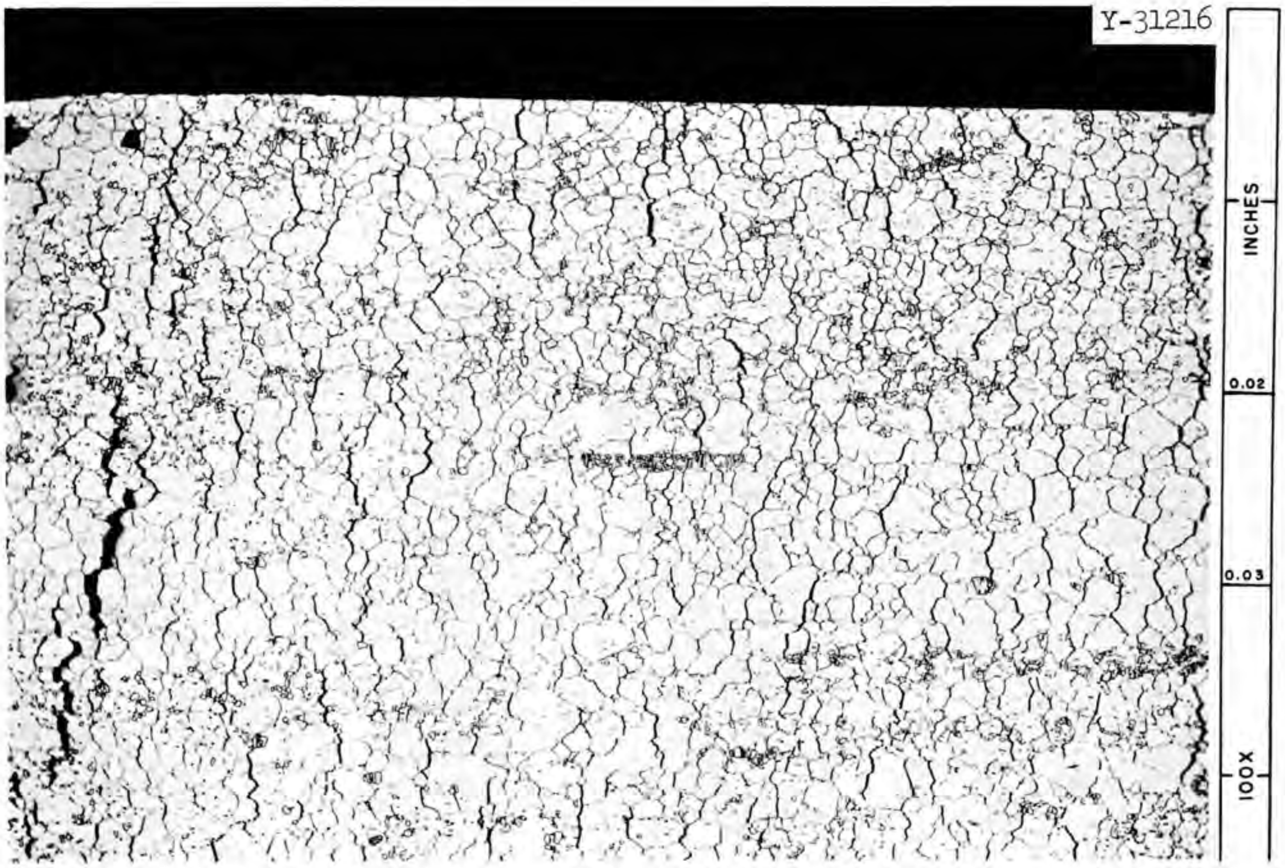

Fig. 23 Heat M-1566 Annealed 1 Hr at 2100°F. Creep tested in molten salt at 1300°F and 20,000 psi. Rupture in 180 hr. Etchant: Aqua Regia. 100X.

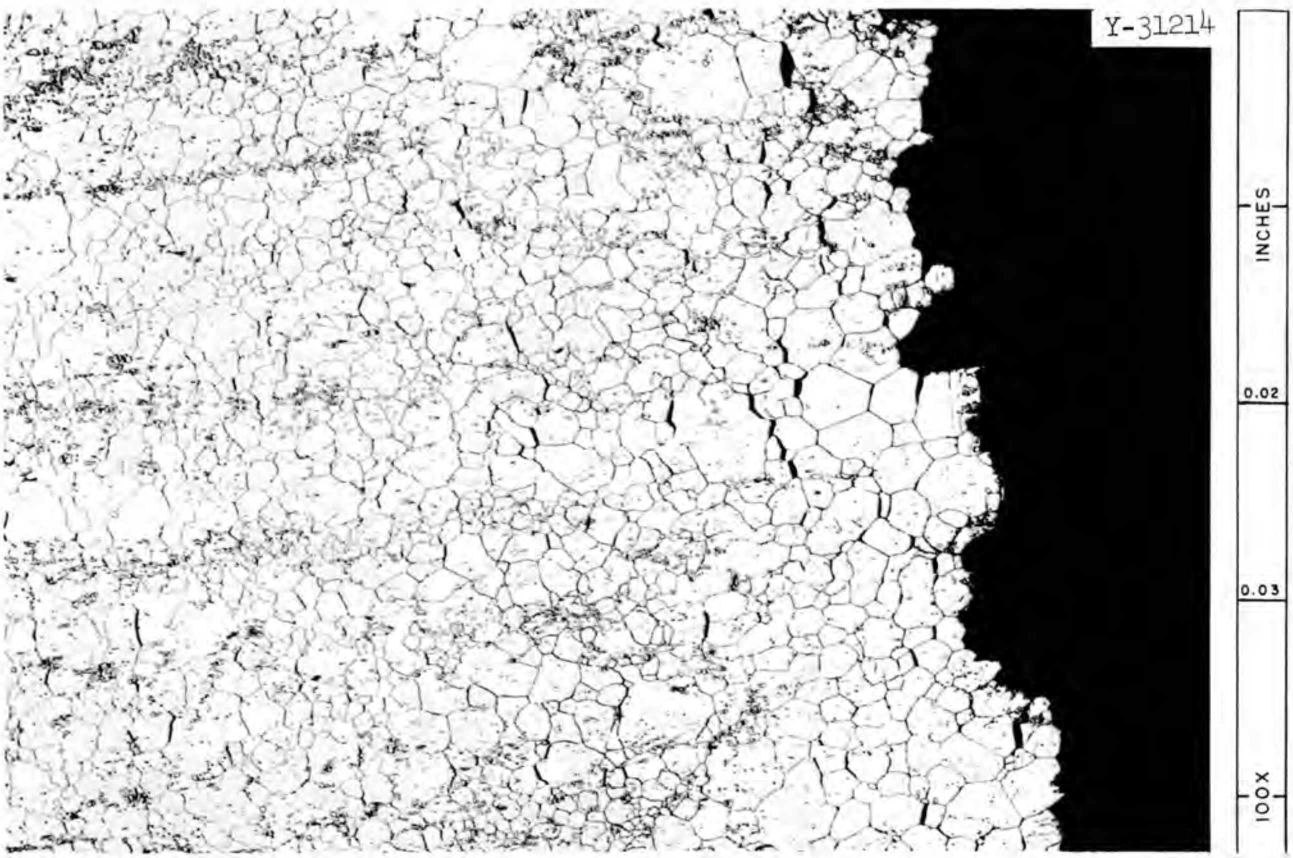

Fig. 24 Heat 8M-1 Annealed 1 Hr at 2100°F. Creep tested in molten salt at 1300°F and 20,000 psi. Rupture in 1115 hr. Etchant: Aqua Regia. 100X.

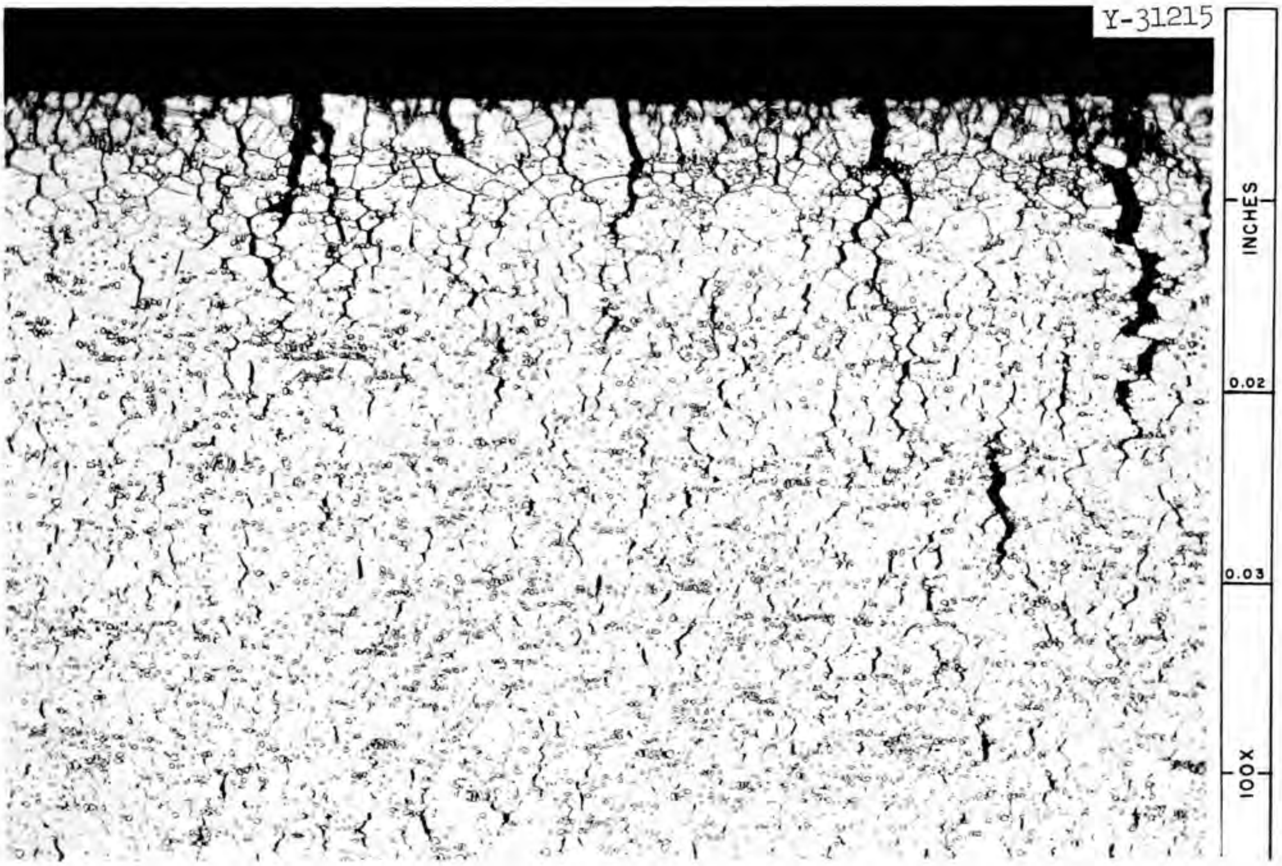

Fig. 25 Heat 1327 Annealed 1 Hr at 2100°F. Creep tested in molten salt at 1300°F and 20,000 psi. Rupture in 1178 hr. Etchant: Aqua Regia. 100X.

Photomicrographs showing the effect of environment and exposure time on the microstructure are presented in Figs. 26 through 33. These structures are for SP 16 at temperatures of 1100, 1200, 1300, 1500, 1650, and 1800°F. A precipitate forms at all temperatures and becomes coarser and more evident as the temperature and time increase. There does not appear to be evidence of severe corrosion, but surface roughening occurs at nearly all temperatures.

Equipment and Procedure for Tests in Air

The creep program in air consisted of a series of tests on rod and sheet specimens of SP 16 at 1250°F and on sheet specimens of SP 19 at several temperatures. All specimens in these programs were annealed 1 hr at 2100°F. Tests were performed in Arcweld Model C.E. lever arm creep machines. Extensometers were clamped on the gage length of standard 0.063-in.-thick sheet specimens and on the shoulders of the standard 0.505-in.-diam rod specimens.

Results for Sheet Specimens in Air

Typical Data: Typical creep curves for SP 16 in air at 1250°F are shown in Fig. 34. In contrast to the tests in molten salt, no transient creep occurs. The initial stage is rather one of nil or slowly accelerating creep which in some cases extends as long as 1000 hr. For several tests a period of slightly negative creep was even observed. This nil creep rate, of course, made it impossible to define a minimum creep rate in the usual sense; hence, only plots of the 1% creep and rupture data are presented here.

Summary Data: Summary-type data taken from Table A-5 of the Appendix are shown in Figs. 35 and 36 and include data reported by the Haynes-Stellite Company for fine-grained SP 16 (ASTM 4-6). Figure 35 is a log-log plot of the stress vs the time to 1% creep strain in which scatterbands have been drawn which cover most of the data. In contrast to the tests in molten salt, the scatterbands at 1500 and 1700°F are roughly parallel to the low-temperature data. Figure 36 is a log-log plot of the stress vs the time to rupture. Here again the scatterbands have been drawn to cover all data, although the data obtained by the Haynes-Stellite Company indicate greater creep strength at 1300°F and less strength at 1700°F.

Fig. 26 Heat SP 16 Annealed 1 Hr at 2000°F. Creep tested in molten salt at 1100°F and 30,000 psi. Rupture in 3537 hr. Etchant: Aqua Regia. 100X.

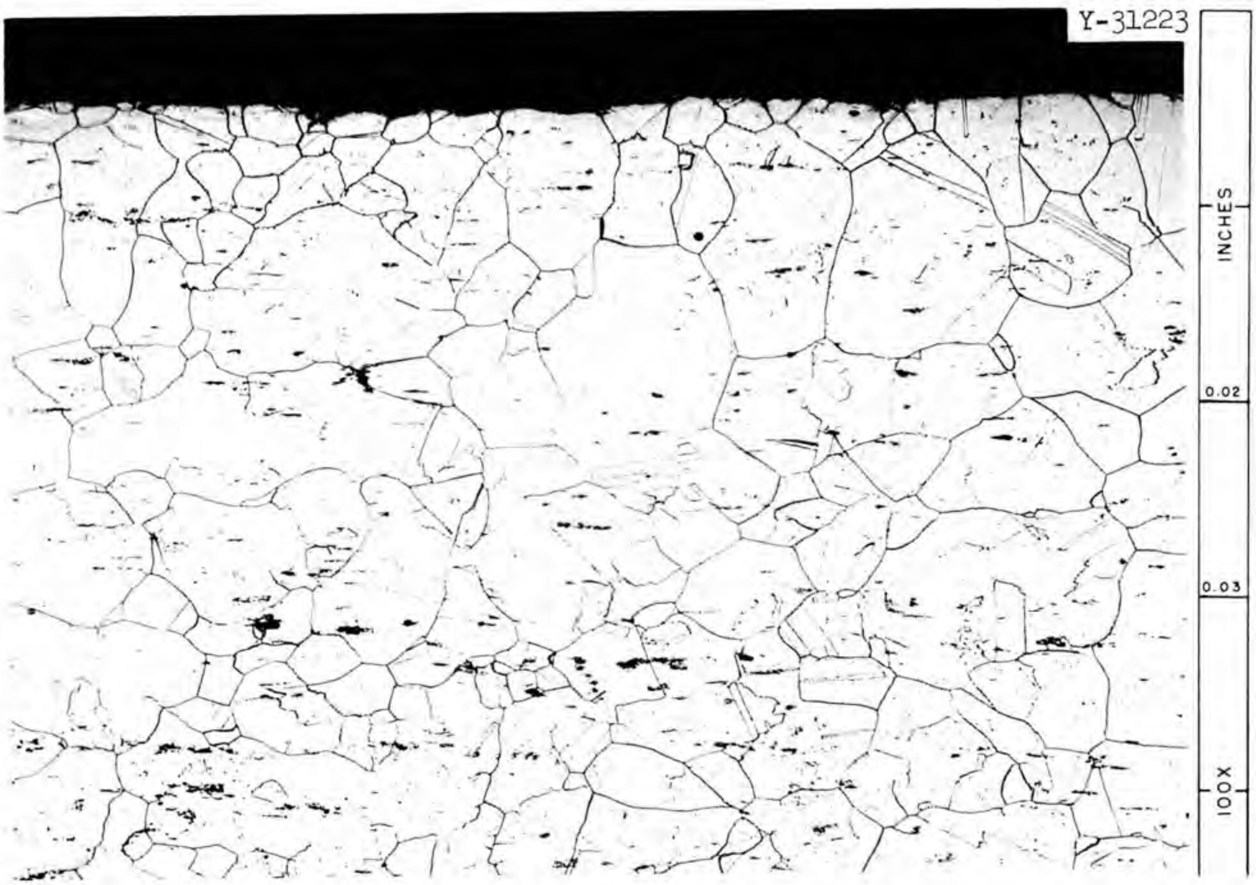

Fig. 27 Heat SP 16 Annealed 1 Hr at 2000°F. Creep tested in molten salt at 1100°F and 25,000 psi. Rupture in 12,725 hr. Etchant: Aqua Regia. 100X.

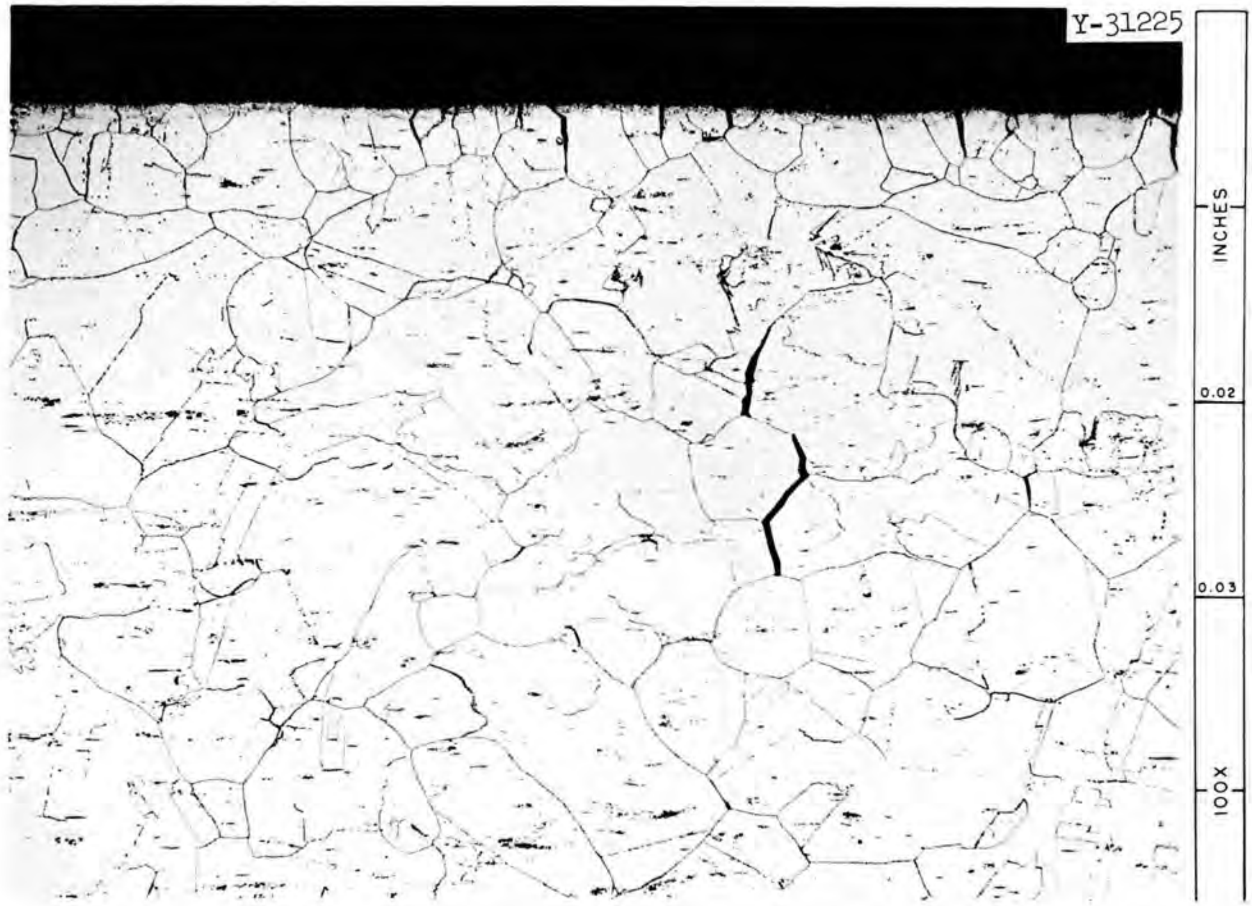

Fig. 28 Heat SP 16 Annealed 1 Hr at 2000°F. Creep tested in molten salt at 1200°F and 20,000 psi. Rupture in 6685 hr. Etchant: Aqua Regia. 100X.

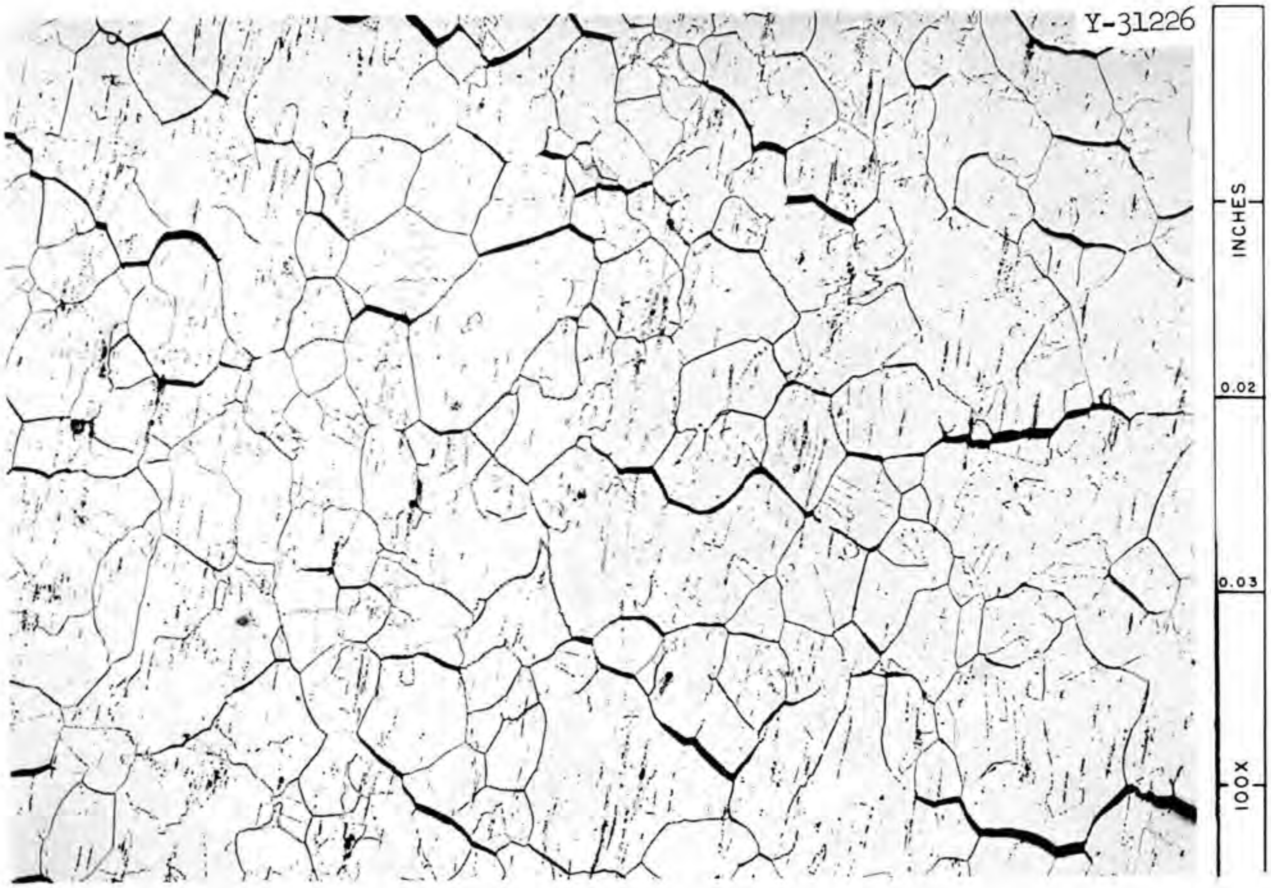

Fig. 29 Heat SP 16 Annealed 1 Hr at 2000°F. Creep tested in molten salt at 1300°F and 12,000 psi. Rupture in 5007 hr. Etchant: Aqua Regia. 100X.

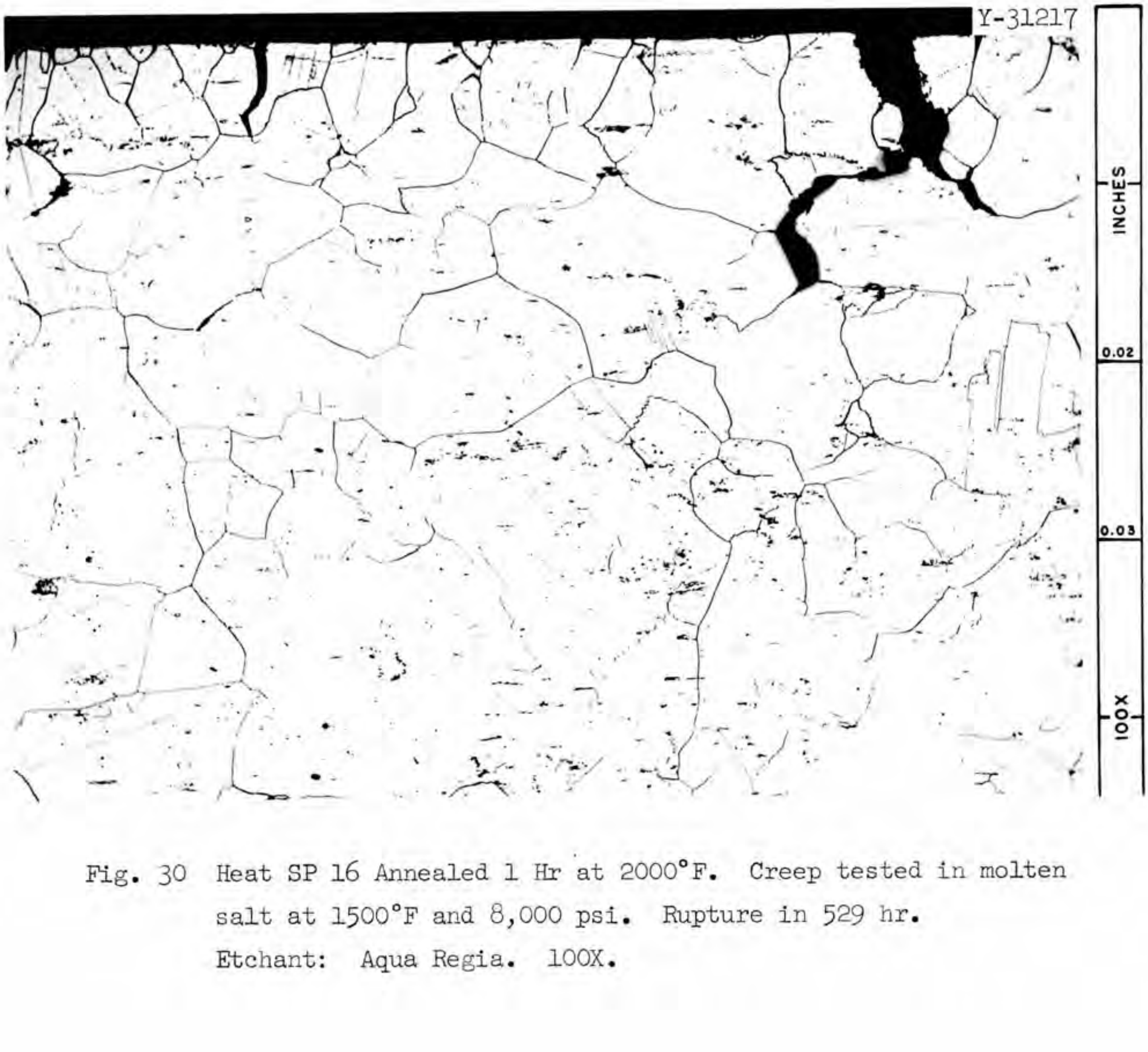

Fig. 30 Heat SP 16 Annealed 1 Hr at 2000°F. Creep tested in molten salt at 1500°F and 8,000 psi. Rupture in 529 hr. Etchant: Aqua Regia. 100X.

Fig. 31 Heat SP 16 Annealed 1 Hr at 2000°F. Creep tested in molten salt at 1500°F and 6,000 psi. Rupture in 3238 hr. Etchant: Aqua Regia. 100X.

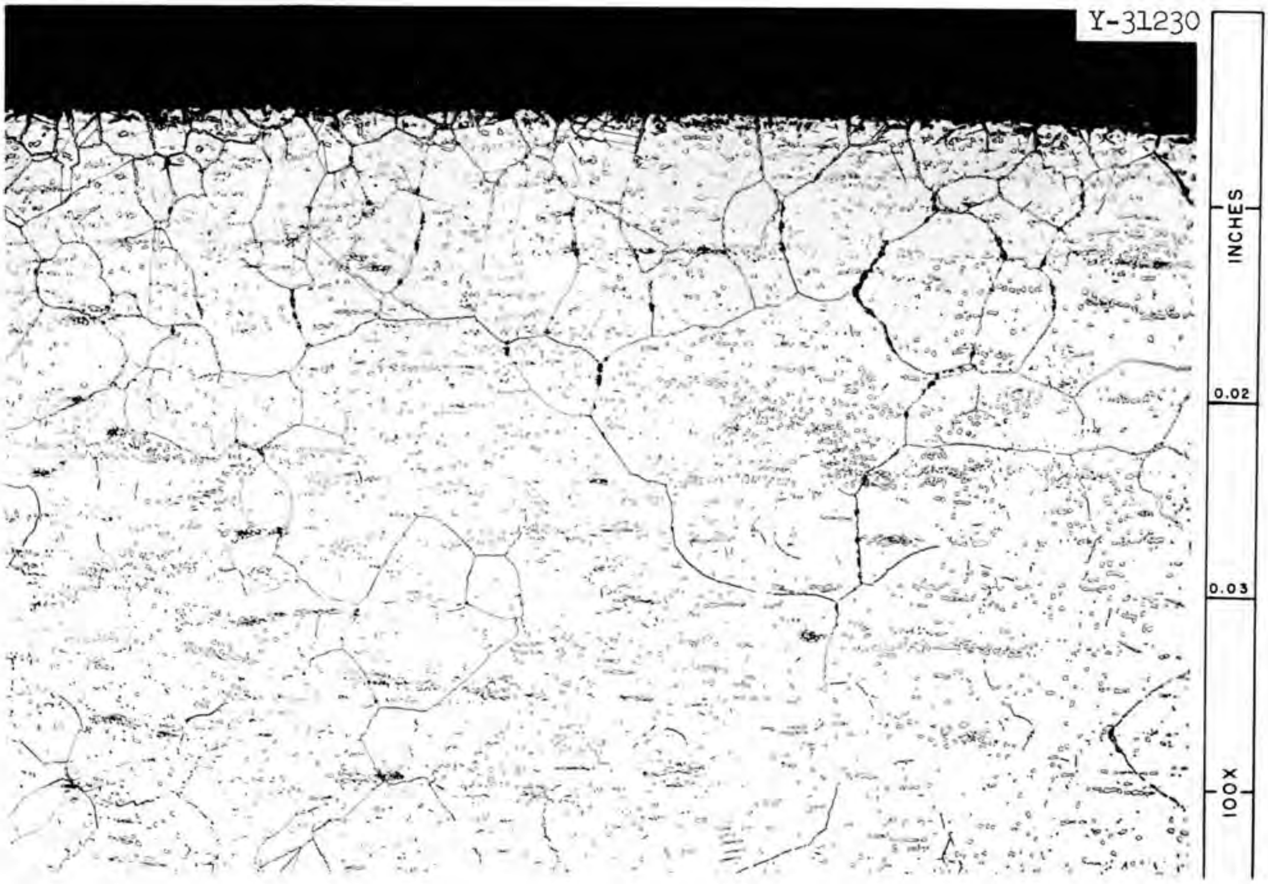

Fig. 32 Heat SP 16 Annealed 1 Hr at 2000°F. Creep tested in molten salt at 1650°F and 4,000 psi. Rupture in 768 hr. Etchant: Aqua Regia. 100X.

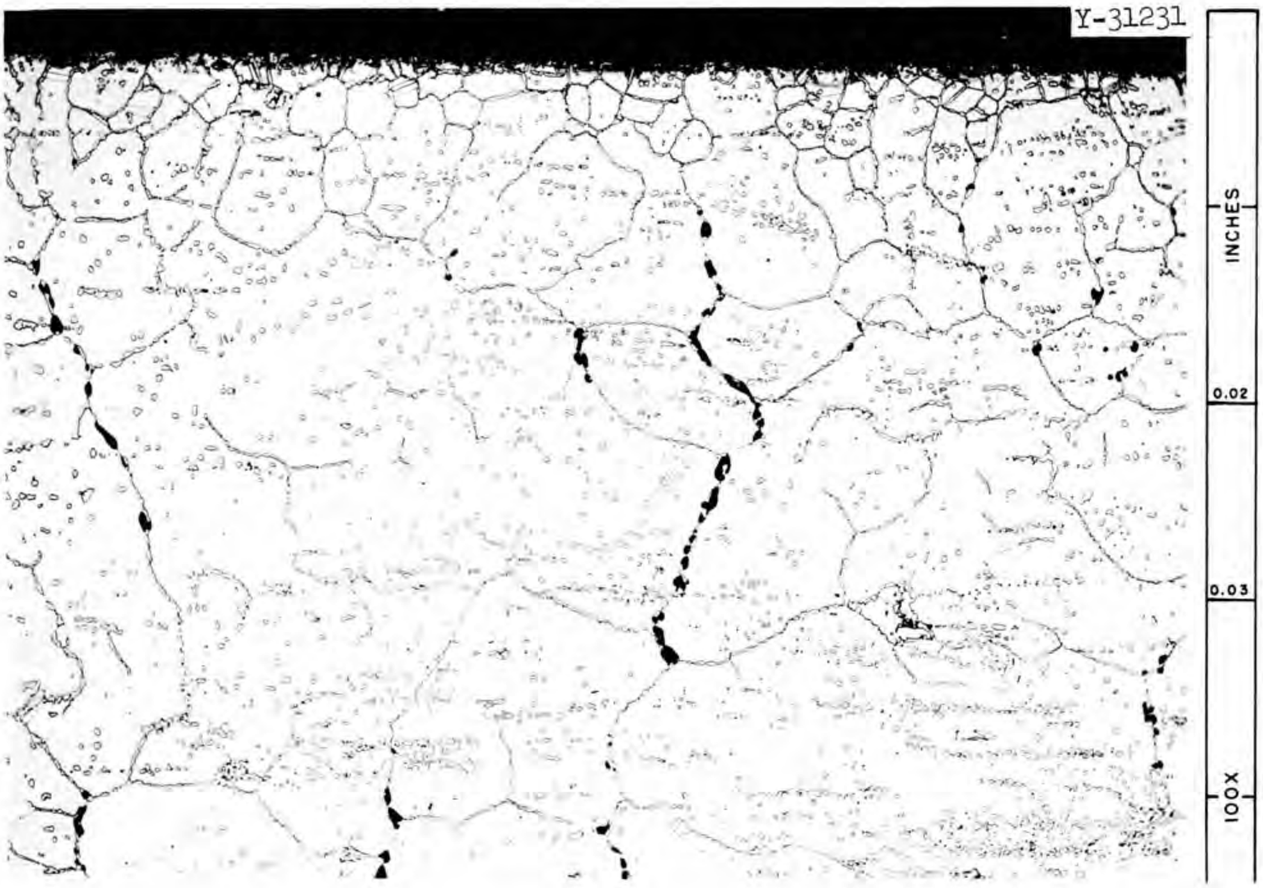

Fig. 33 Heat SP 16 Annealed 1 Hr at 2000°F. Creep tested in molten salt at 1800°F and 2,000 psi. Rupture in 4481 hr. Etchant: Aqua Regia. 100X.

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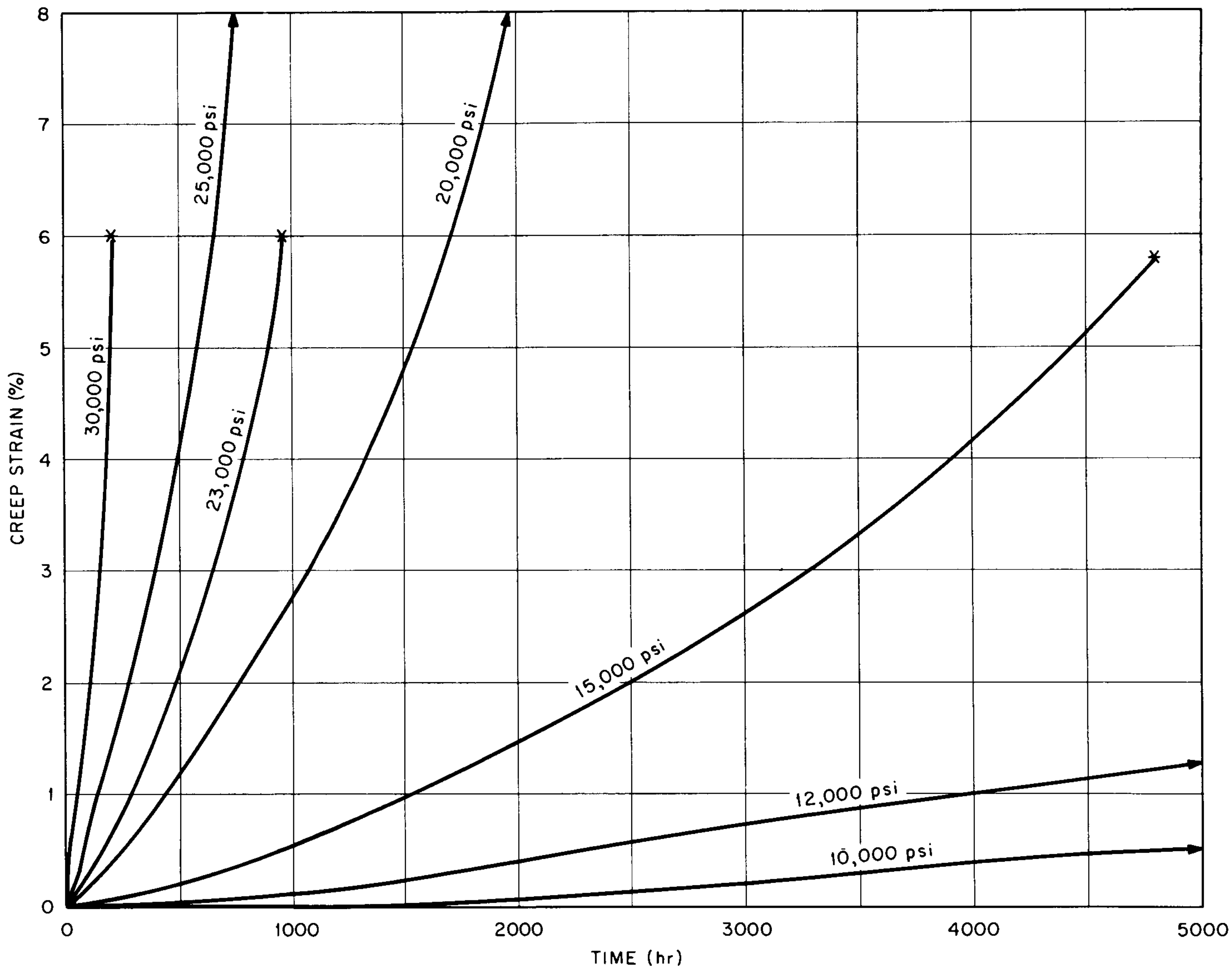

Fig. 34 Creep Curves for INOR-8 (SP 16) Tested in Air at 1250°F.

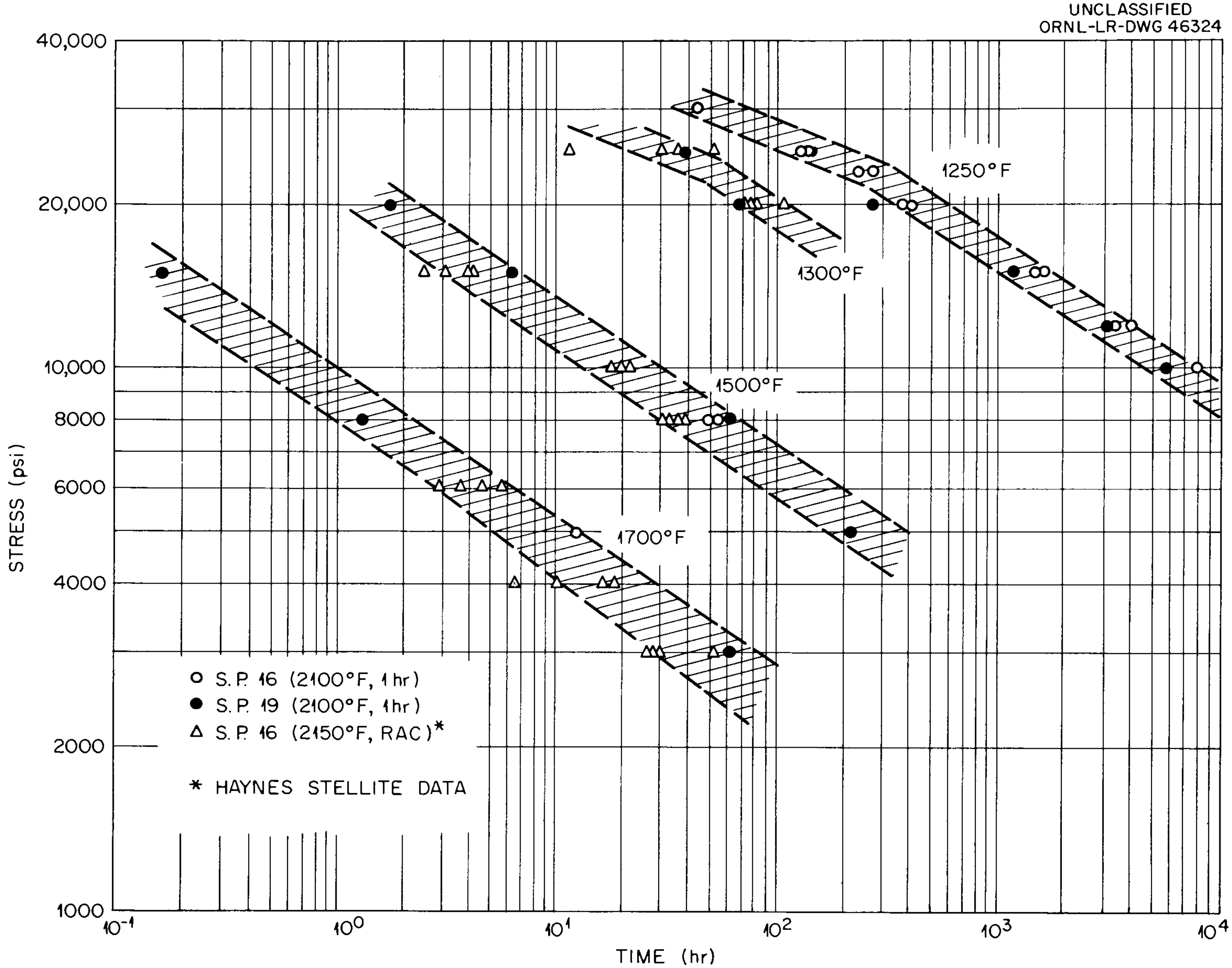

Fig. 35 Stress vs Time to 1.0% Creep Strain for INOR-8 Sheet Specimens in Air.

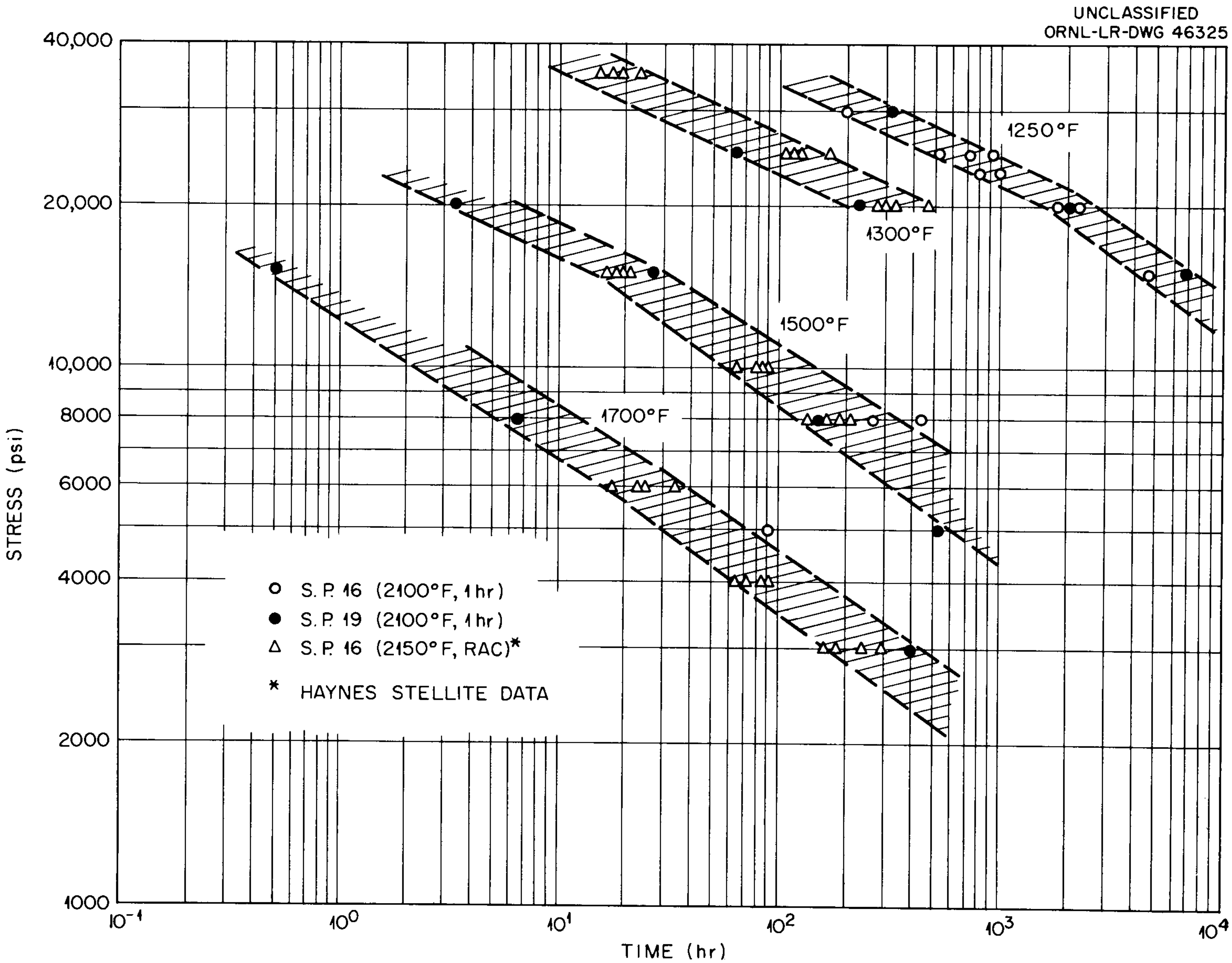

Fig. 36 Stress vs Time to Rupture for INOR-8 Sheet Specimens in Air.

The creep ductilities for tests in air are low and values range from 2.7% at 1200°F to 14.5% at 1700°F. Many of the failures in sheet specimens were under the knife edge of the extensometer clamp.

Microstructure: Photomicrographs for two SP 16 specimens tested in air at 1250°F are shown in Figs. 37 and 38. Here, after 4562 hr in test at 15,000 psi, there is evidence of a fine precipitate.

Results for Rod Specimens in Air

Data for rod specimens of SP 16 tested at 1250°F are given in A-6 of the Appendix. A series of creep curves are shown in Fig. 39, and summary-type data are presented in Fig. 40. The creep curves show a short period of accelerating creep followed by a steady creep rate. Rod specimens are stronger than the sheet at the higher stresses.

Effect of Aging and Carburization

Several creep tests on specimens aged 50 hr at 1300°F have been performed in molten salt. Heat SP 16 was tested at 1500 and 1800°F and heat 1327 was tested at 1200, 1500, and 1800°F. These data are included in Table A-4 of the Appendix. Data do not indicate any significant aging effects, although there does appear to be an increase in creep rate and loss in rupture life at 1800°F.

Several creep tests have been performed on heavily carburized material and these are discussed in another report.[8] Typical results are plotted in Fig. 41 for untreated and carburized SP 16, in this instance tested at 20,000 psi in molten salt at 1300°F. A curve for a specimen tested in a carburizing atmosphere is also shown. The creep rate for the carburized specimen is nearly half of that for the untreated specimen, while the creep rate of the specimen tested in the carburizing atmosphere is intermediate. It should be noted, however, that the early portion of the curves (for strains below 1%) do not reflect the over-all trends which have just been summarized.

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[8] R. W. Swindeman and D. A. Douglas, "Improvement of the High-Temperature Strength Properties of Reactor Materials after Fabrication," J. Nuclear Materials 1, 49–57 (1959).

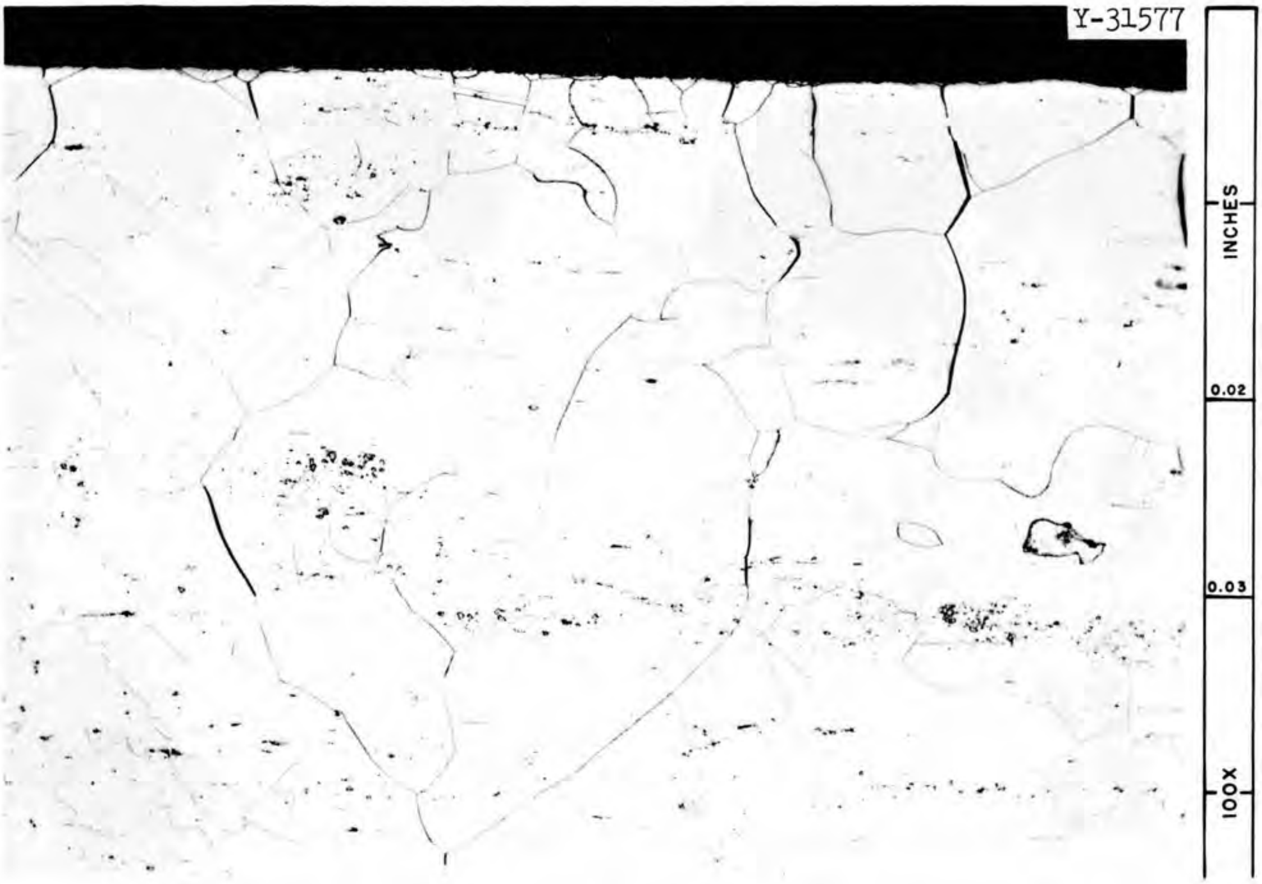

Fig. 37 Heat SP 16 Annealed 1 Hr at 2100°F. Creep tested in air at 1250°F and 30,000 psi. Rupture in 204 hr. Etchant: Aqua Regia. 100X.

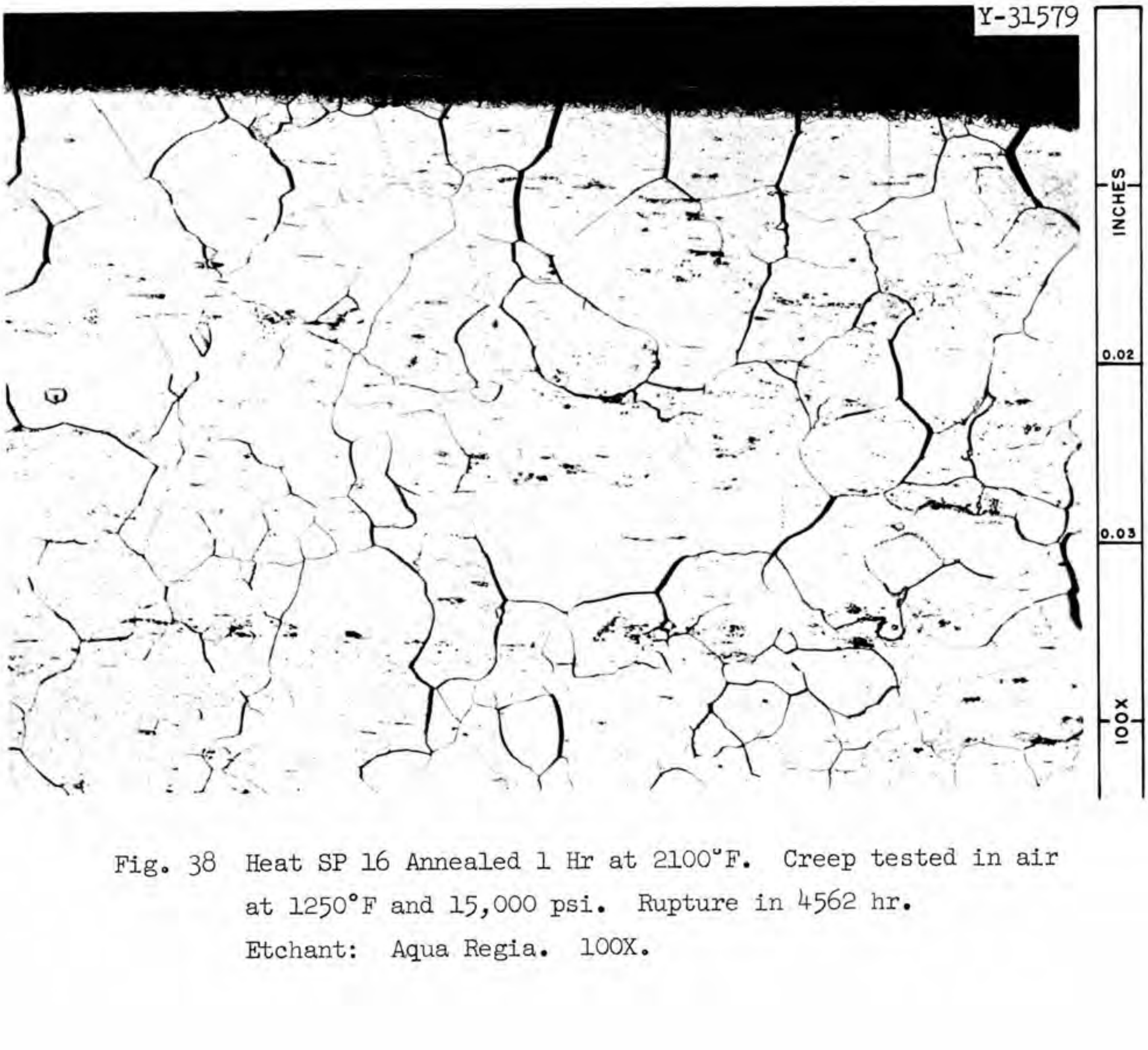

Fig. 38 Heat SP 16 Annealed 1 Hr at 2100°F. Creep tested in air at 1250°F and 15,000 psi. Rupture in 4562 hr. Etchant: Aqua Regia. 100X.

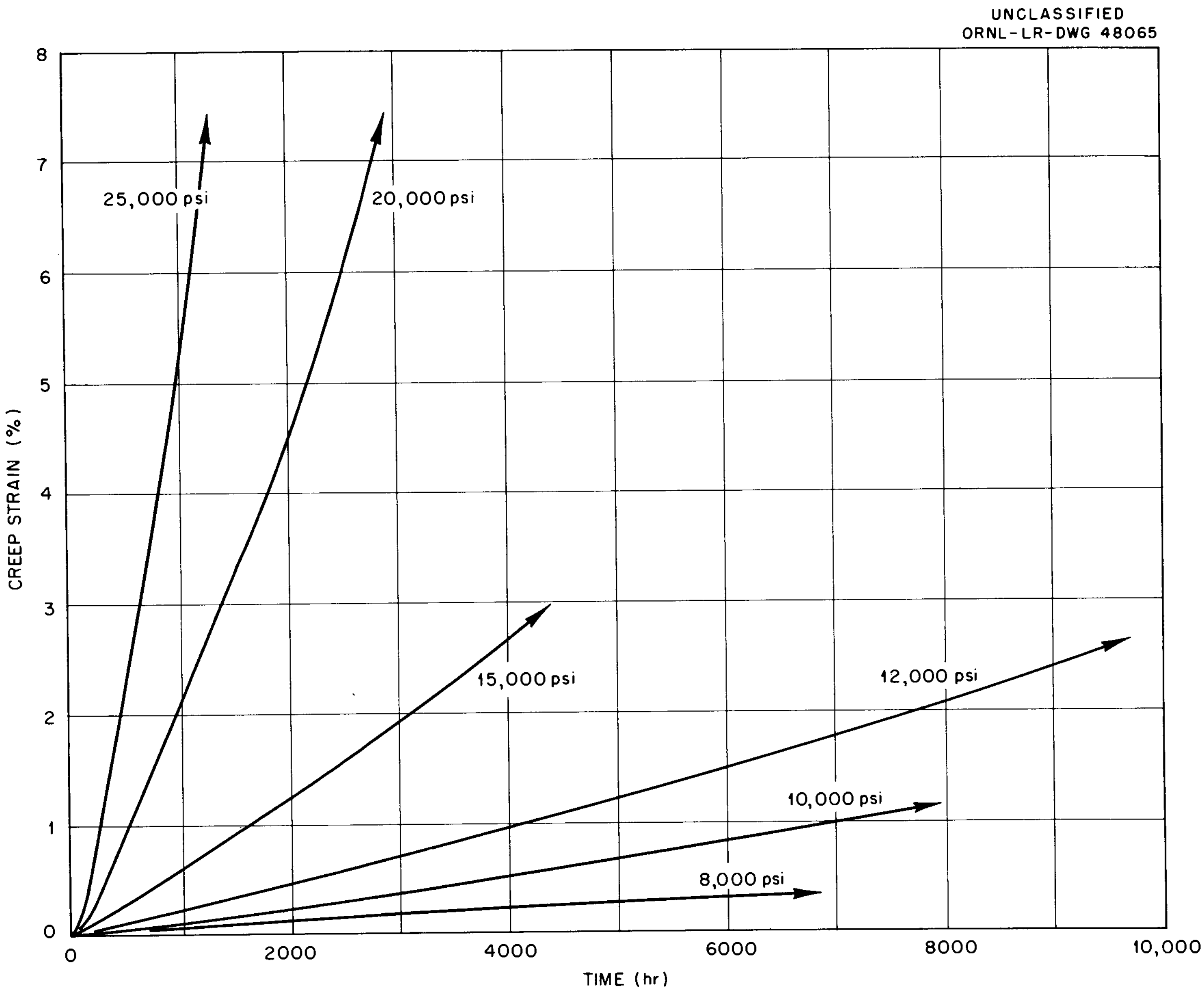

Fig. 39 Creep Curves for INOR-8 (SP 16) Rods Tested in Air at 1250°F.

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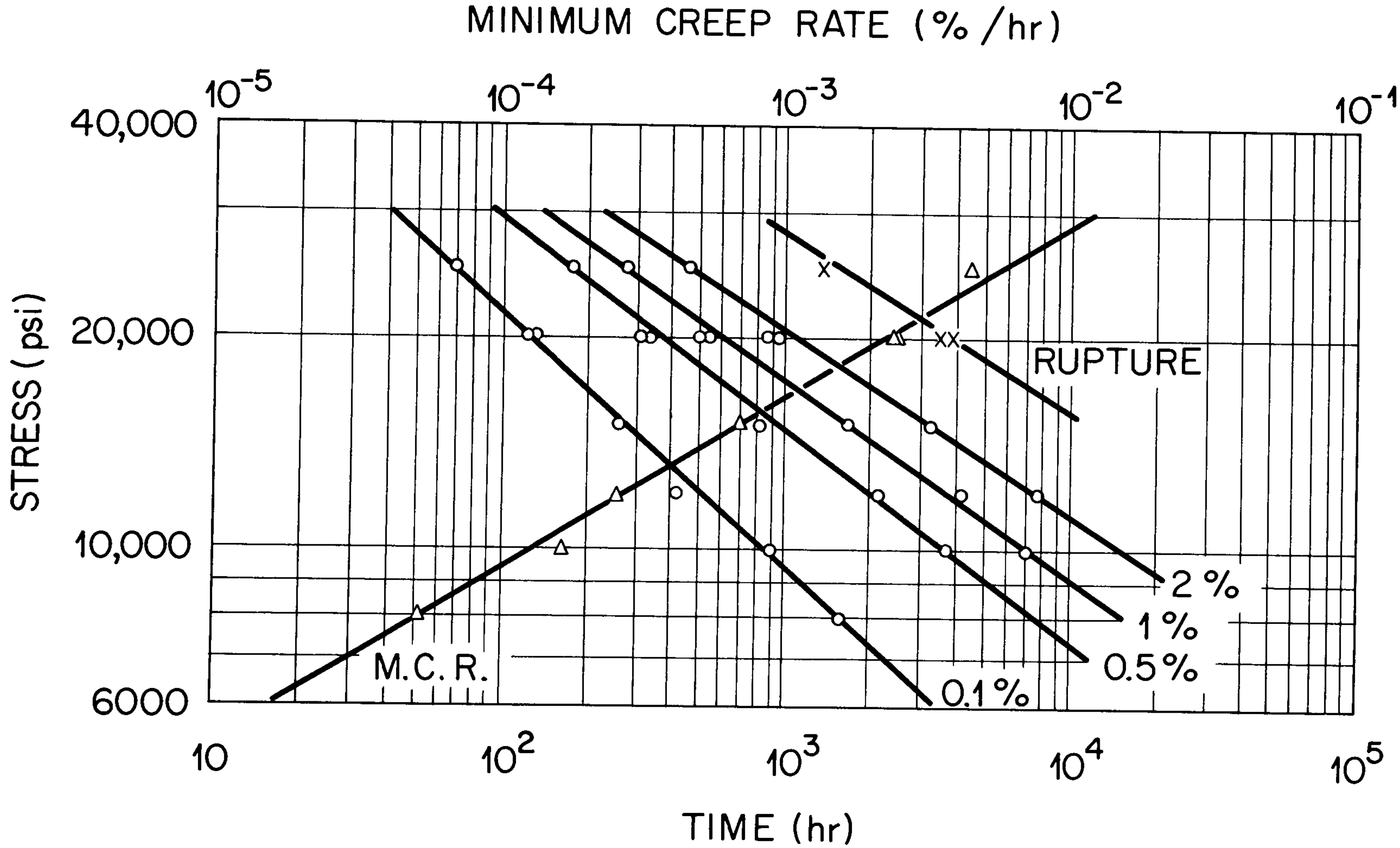

Fig. 40 Creep Properties of INOR-8 (SP 16) Rod Tested in Air at 1250°F.

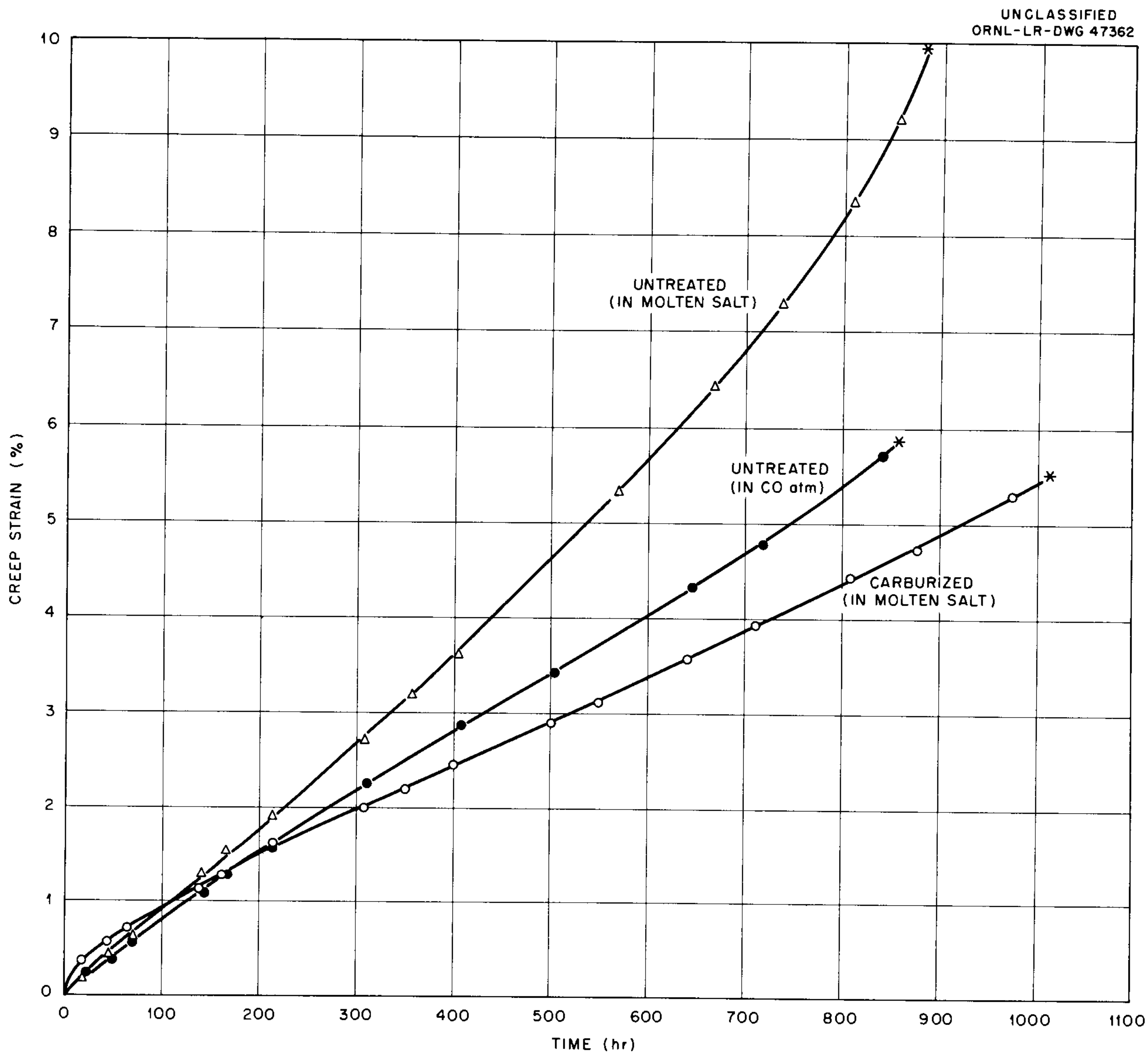

Fig. 41 The Effect of Carburization on the Creep Curve for INOR-8 (SP 16) at 20,000 psi and 1300°F.

RELAXATION PROPERTIES

Equipment and Procedure

Relaxation tests were performed on 0.357-in.-diam rod specimens of SP 16, with equipment described by Kennedy and Douglas.[9] The tests were performed in air over a temperature range from 1150 to 1600°F. Extensions between 0.05 and 0.2% were employed, although most tests were conducted at 0.05 or 0.1%. Both of these strains are in the elastic region.

Results

Typical data are illustrated in Figs. 42 and 43. These curves show selected data at 1200, 1300, 1400, 1500, and 1600°F for extensions of 0.05 and 0.1%. Additional data are provided in Table A-7 of the Appendix.

The curves at 1200 and 1300°F reveal an interesting phenomenon which was common in relaxation testing of INOR-8. That is, the stress often exhibits an increase, or at least no decrease, for some time after loading. This "induction period" may be caused by the same phenomenon which produces negative or nil creep during the initial period of creep testing in air. The length of this induction period depends upon the temperature. Near 1200°F it appears to last between 10 and 50 hr, while above 1300°F it is present only for a fraction of an hour. At the end of this period relaxation occurs in the normal manner, with the relaxation rate decreasing with time.

DISCUSSION

For an alloy, whose composition and microstructure are permitted to vary as much as in the case of INOR-8, reasonable variations in the mechanical properties should also be expected. In general, the tensile properties conform to expectations. The creep behavior, on the other hand, is not so easily understood. Variations do occur with changes in composition and microstructure, but creep-stress and temperature complicate the behavior pattern.

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[9] C. R. Kennedy and D. A. Douglas, Relaxation Characteristics of Inconel at Elevated Temperatures, ORNL-2407 (Jan. 29, 1960).

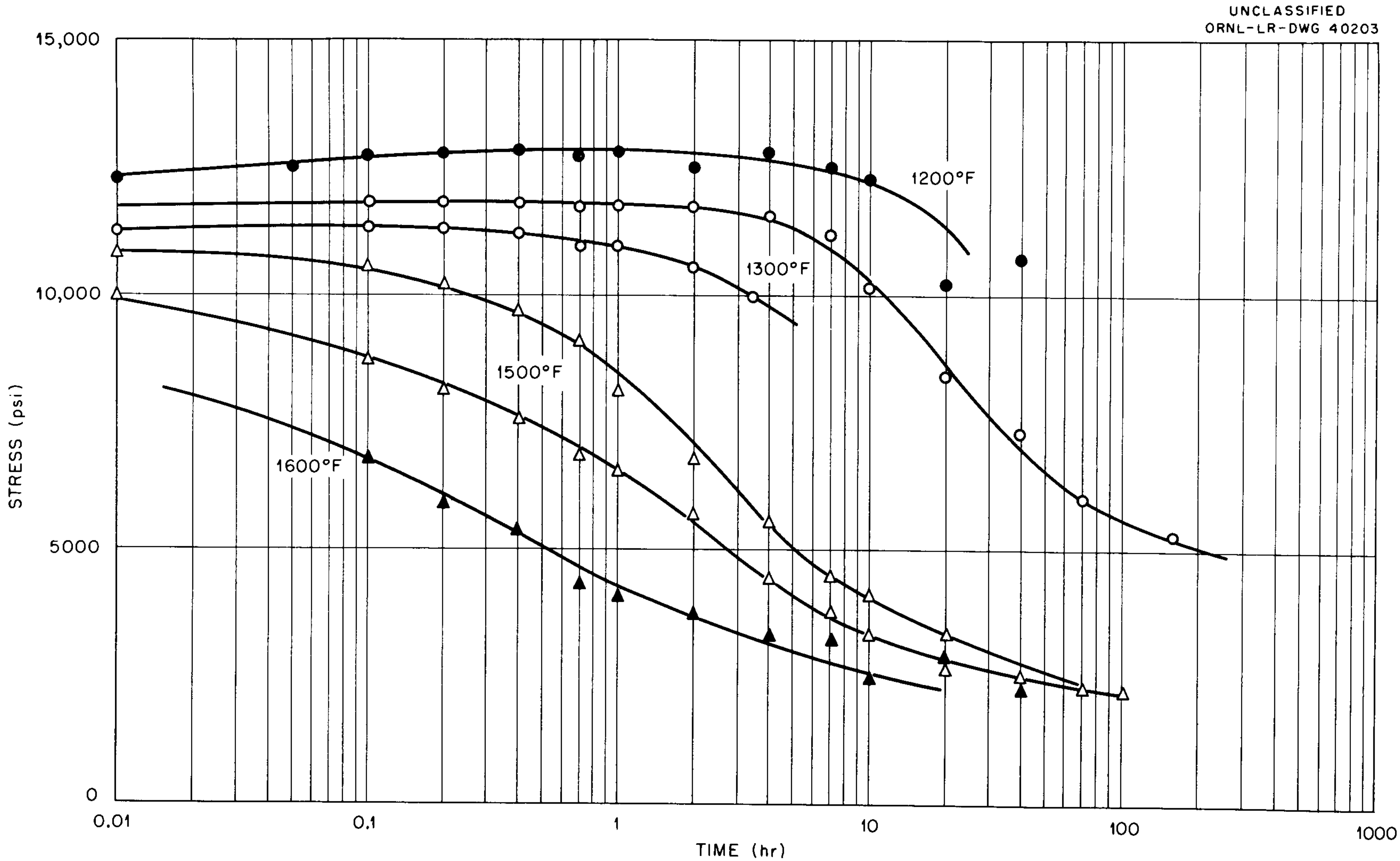

Fig. 42 Stress Relaxation Curves for INOR-8 (SP 16) Rods, 0.05% Extension.

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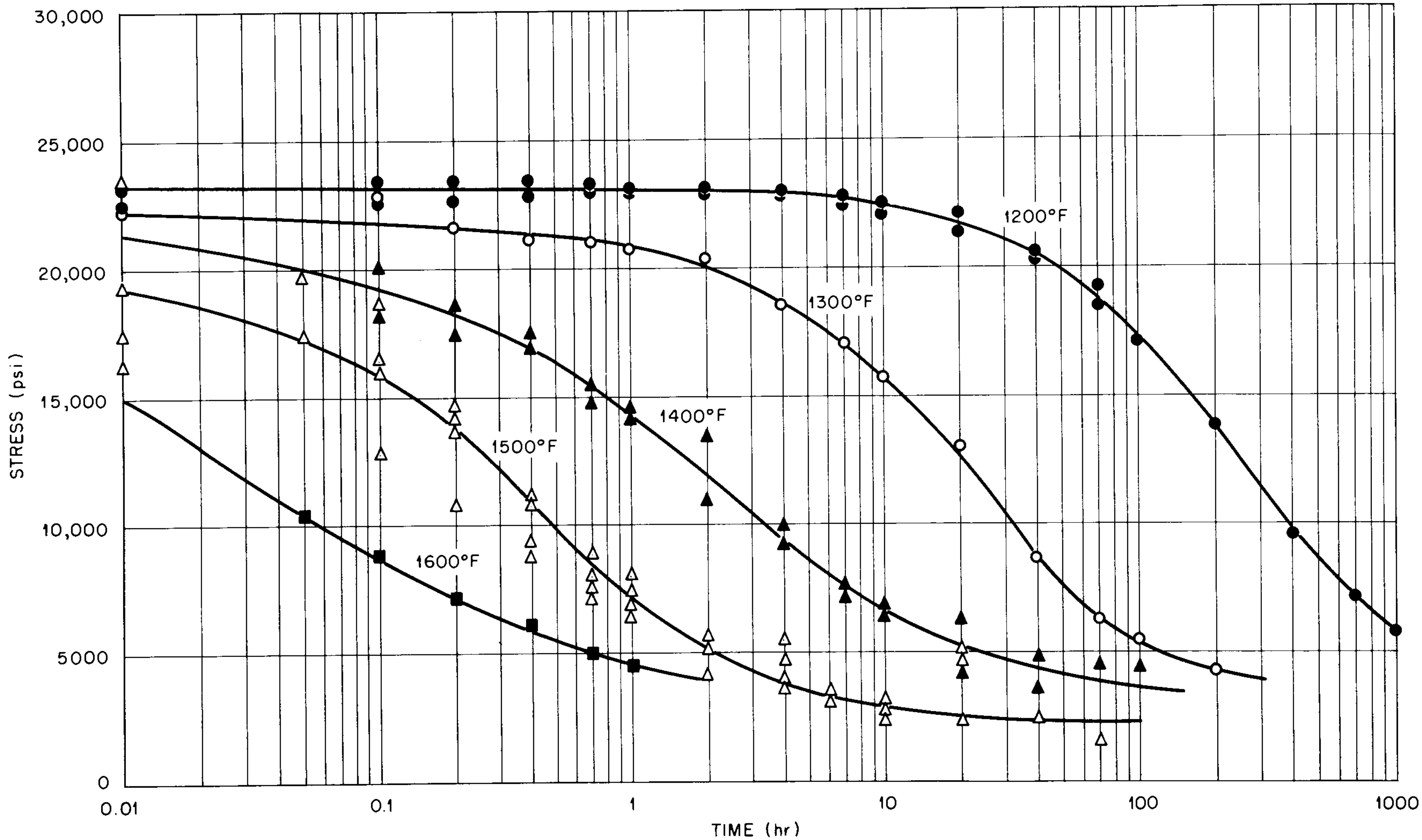

Fig. 43 Stress Relaxation Curves for INOR-8 (SP 16) Rods, 0.1% Extension.

At 1100 and 1200°F there are indications that the creep strength improves with increasing carbon and decreasing grain size. At 1300°F, however, heat M-1566, which has an "average" composition, is the weakest while the high-carbon and fine-grained heats are not significantly stronger than SP 16. Above 1300°F further variations arise which cannot be clarified without additional data. It is possible, of course, that 1300°F is a transition temperature above which the coarse-grained SP 16 is stronger than the fine-grained heats.

There are at least two additional features of the microstructure which may also have an influence on the creep properties. These are substructure and carbide precipitation. Different substructures developed in SP 16 for anneals at 2000, 2100, or 2150°F (the treatment used by Haynes-Stellite) might explain why the initial stage of creep in some cases is transient while in other cases it is accelerating. Parker[10] has shown some of the effects which substructure can have in this regard.

Carbide precipitation could also play a role in creep. The very slight contraction, sometimes observed in SP 16 during the initial period of creep or relaxation tests, might be explained by assuming a volume contraction associated with precipitation. Furthermore, the continually decreasing strain rates in SP 16 for low stresses at 1500°F and above might be explained by the strengthening produced through the precipitation and coarsening of the carbides along the grain boundaries. Unfortunately no coarse-grained, high-carbon heats were tested at these low stresses to check this possibility.

It should also be remembered that carbon is not the sole compositional variable. The disposition of the boron in SP 16, for example, has not been established but it is possible that this element could have an influence on the behavior of this heat.

Attempts have been made to establish a time-temperature correlation for creep and rupture properties of INOR-8. Haynes-Stellite presents Larson-Miller plots but a correlation can also be obtained for the Dorn-Shepard Parameter.[11] The activation energy for creep, relaxation, and

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[10] E. R. Parker, "Modern Concepts of Flow and Fracture," _Trans. ASM_, Vol. L, 52 (1958).

[11] J. E. Dorn and L. A. Shepard, "What We Need to Know About Creep," _Am. Soc. Testing Materials_, Special Tech. Pub. No. 165, p. 3 (1954).

recrystallization were calculated to be near 83,200 cal/mole-°K. This activation energy has been used to correlate the creep data at all temperatures and stresses. Data for tests in molten salt and air are shown in Fig. 44. This is a plot of the Dorn-Shepard parameter for 1% creep strain against the log of stress. Most of the creep data for INOR-8 is included in the plot although the various heats are not distinguished from one another. The scatterband has been drawn to include most of the data, but it appears that the data for air tests often fall near the top of the band and data for salt tests lie near the bottom at the low stresses.

The data obtained by the Mechanical Testing Group constitute a major portion of the mechanical property data available on INOR-8. Significant contributions have been made by other investigators, however, and their results should be considered in evaluating the over-all strength properties of INOR-8. For example, the Haynes-Stellite Company reports stress-rupture, tensile, impact, and creep data for both cast and wrought SP 16. Inouye[12] has performed aging studies on several heats of INOR-8 for temperatures up to 1400°F and times as long as 10,000 hr and the Welding and Brazing Group[13,14,15] has studied the weld metal tensile and bending properties of several heats. The cold work and recrystallization characteristics of SP 16 have been reported by Spruiell[16] while Carlson[17] has conducted high-temperature fatigue tests on SP 19. Finally, Cook and Jansen[18] are presently investigating the effect of carburization on the tensile and creep properties of SP 16.

Most of the data accumulated on INOR-8 indicate that the strength properties at 1300°F and below are comparable to those of the stainless

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[12] H. Inouye, Met Ann. Prog. Rep. Sept. 1, 1959, ORNL-2839, p. 195.

[13] MSR Quar. Prog. Rep., ORNL-2551 (June 30, 1958) p. 71.

[14] MSR Quar. Prog. Rep., ORNL-2723 (April 30, 1959) p. 68.

[15] MSR Quar. Prog. Rep., ORNL-2684 (Jan. 31, 1959) p. 90.

[16] J. Spruiell, Recrystallization of INOR-8, ORNL CF-57-11-119 (Nov. 25, 1957).

[17] R. G. Carlson, Fatigue Studies of INOR-8, BMI-1354 (June 26, 1959).

[18] W. H. Cook and D. H. Jansen, A Preliminary Summary of Studies of INOR-8, Inconel, Graphite, and Fluoride System for the MSRP for the Period from May 1, 1958, to Dec. 31, 1958, ORNL CF-59-1-4 (Jan. 30, 1959).

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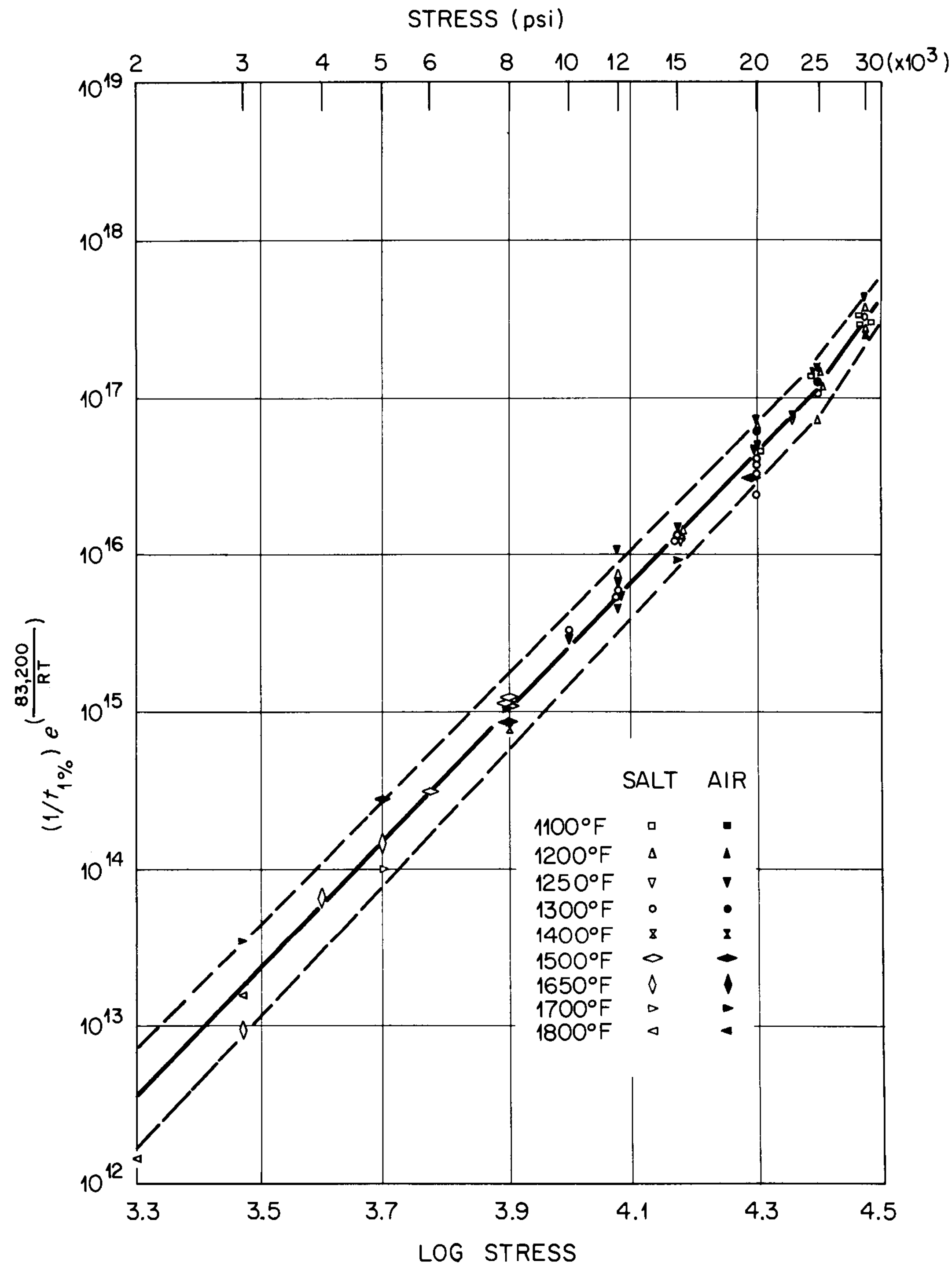

Fig. 44 Dorn-Shepard Parameter for 1% Creep Strain vs Log Stress Including All Heats of INOR-8 Tested in Molten Salt and Air.

steels. Since the creep and tensile properties of the stainless steels, with a few exceptions, vary sharply with annealing treatment an actual numerical comparison between INOR-8 and these alloys is not too significant. Possibly one of the fairest comparisons which could be made would be for types 316 and 304 stainless steel and INOR-8 rod material in air at 1250°F. The stress to produce a minimum creep rate of 10^{-5}%/hr (usually stated 0.01% in 1000 hr), a criterion on which high-temperature design stresses are often based, is about 5250 psi for type 316 stainless steel, 3200 for type 304 stainless steel,[19] and 5350 psi for INOR-8. If the stress to produce 1% creep in 100,000 hr were selected from the salt data, however, the value for INOR-8 would be 4300 psi. This figure is still above the design stress for type 304 stainless steel. It is possible to be even more conservative by selecting the lower stress for the design criterion or interest from the scatterbands shown in the summary data curves. Fractions of the minimum observed yield strength and tensile strength could also be obtained in accordance with the Unfired Pressure Vessel Code.[20] Such data have been plotted in Fig. 45 and compared with design stresses for type 316 stainless steel.

Although the tensile and creep ductility do not directly enter into the design of a component intended for long-time service, they can be considered important from a safety viewpoint. The tensile ductility up to 1300°F appears to be satisfactory for wrought, cast, and weld metal, but Cook and Jansen[18] report a figure of only 7.75% for SP 16 carburized at 1600°F and tested at room temperature. In addition, the low-notch strength ratios and low-relaxation rates may suggest poor ductility or notch sensitivity in stress rupture. The poorest creep ductilities occur at 1100°F, but are still above 1% even after more than 12,000 hr of exposure. To determine the maximum effect to be expected, one should study the tensile properties of specimens after creep testing under the worst conditions.

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[19] Digest of Steels for High Temperature Service, Timken Roller Bearing Company, 6th ed., pp. 55, 59 (1957).

[20] "Rules for Construction of Unfired Pressure Vessels," ASME Boiler and Pressure Vessel Code, Sec. VIII, ASME, N. Y. (1956).

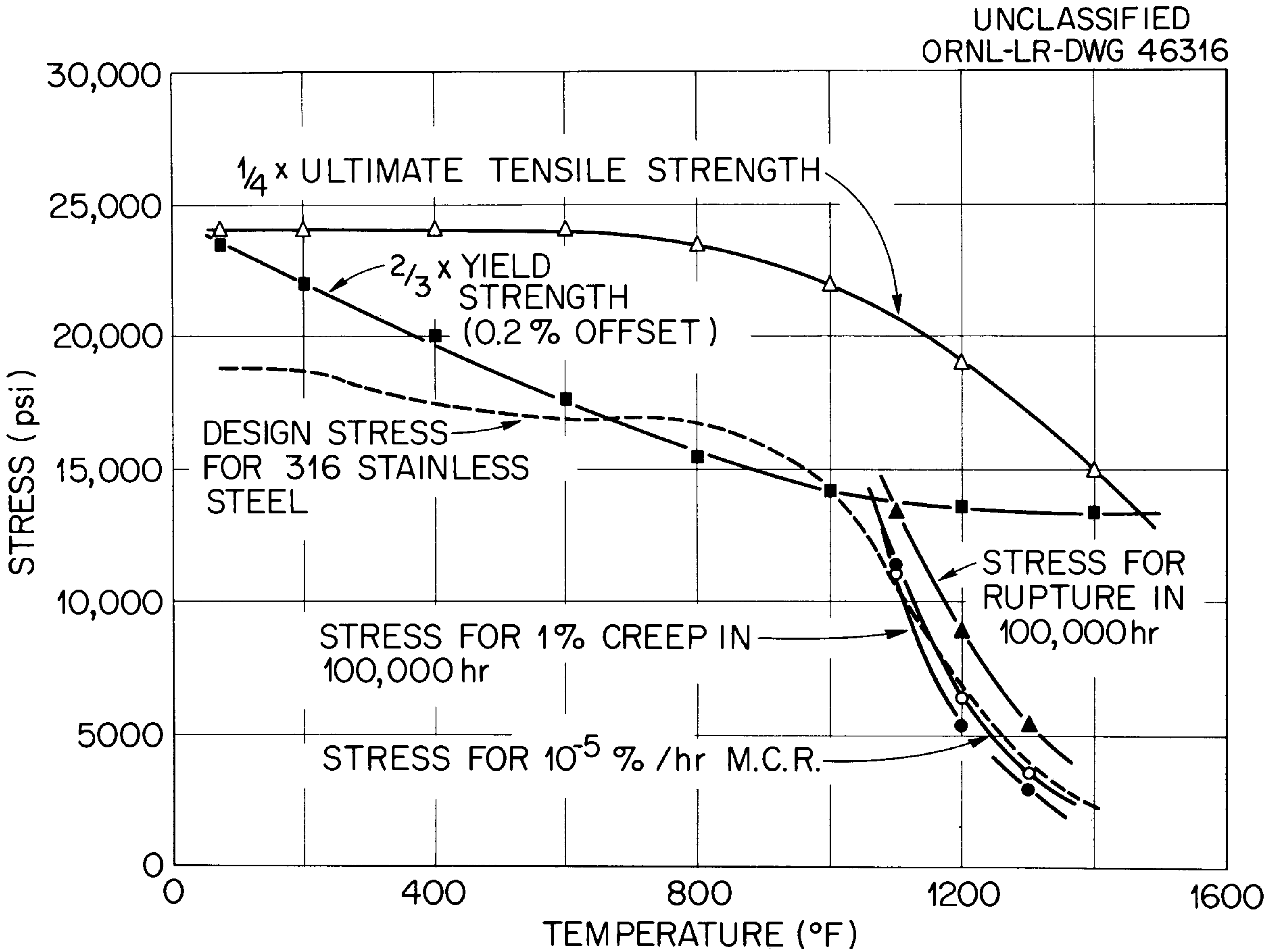

Fig. 45 Various Criteria for the Determination of the Design Stresses for INOR-8.

There are several other questions which have not been completely answered regarding the mechanical properties of INOR-8. The more important of these are:

1. What are the effects of grain size and annealing treatment on the long-time creep properties?

2. What is the notch strength ratio in stress rupture?

3. How significant is the effect of notches on the fatigue strength?

4. How do the creep properties of weld metal compare with wrought materials?

5. What is the effect of irradiation on the mechanical properties?

6. What is the effect of carburization on the mechanical properties during service?

Mechanical property data which answer these questions might eliminate the use of unnecessary safety factors in the design of a reactor. This, in turn, would reduce the material required and thereby decrease overall structural costs.

CONCLUSIONS

The results of this investigation reveal the range of tensile and creep properties which INOR-8 can be expected to exhibit when the composition and grain size are permitted to vary significantly. For low-temperature applications a fine-grain size produces the best strength properties, although even the weakest of the coarse-grained material is superior to many of the stainless steels.

Since most of the long-time creep tests were performed on relatively coarse-grained material, a clear picture of the range in creep strength cannot be presented. The short-time data, however, reveal that at 1100°F the fine-grained material is slightly stronger while at temperatures above 1300°F a coarse-grain size is desirable. The long-time creep properties of coarse-grained INOR-8 are better than many of the stainless steels.

The only area of concern regarding this alloy is that of ductility. Certain heats exhibit low values, especially at temperatures above 1300°F for tensile tests and around 1100°F in creep tests. This behavior points toward possible problems should carburization or notches occur in the metal. The effect of these two variables on the stress-rupture and tensile properties is a subject that should be studied further.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the contributions of D. A. Douglas, Jr., C. R. Kennedy, J. W. Woods, and C. W. Dollins, all of whom played a part in the programming of tests. The experimental work was conducted by J. T. East, C. K. Thomas, V. G. Lane, F. L. Beeler, C. W. Walker, B. McNabb, Jr., and metallography was performed by H. R. Tinch of the Metallography Group of the Metallurgy Division.

APPENDIX

TABLE A-1. Tensile Properties of Sheet Specimens of INOR-8

Heat	Grain Size Range (ASTM No.)	Temperature (°F)	Proportional Limit (psi)	0.2% Offset Yield Strength (psi)	Tensile Strength (psi)	Elongation in 2 in. (%)	Modulus of Elasticity (psi x 10^{-6})
M-1566	5 - 7	Room	24,000	46,900	119,000	48	30.7
M-1566	5 - 7	1000	--	35,900	105,300	37	--
SP 16	2 - 4	1200	19,100	24,800	66,800	44	27
M-1566	5 - 7	1200	--	36,400	79,900	17	--
SP 16	2 - 4	1300	21,000	24,400	57,700	36.5	--
M-1566	5 - 7	1300	--	37,100	71,800	14.5	--
SP 16	2 - 4	1500	21,000	25,400	46,900	28	24.5
M-1566	5 - 7	1500	--	34,600	48,200	6.5	--

TABLE A-2. Tensile Properties of Rod Specimens of INOR-8

Heat	Grain Size Range (ASTM No.)	Temperature (°F)	Proportional Limit (psi)	0.2% Offset Yield Strength (psi)	Tensile Strength (psi)	Elongation[a] (%)	Reduction in Area (%)	Modulus of Elasticity (psi x 10^{-6})
SP 16	2 - 4	Room	25,000	40,900	105,900	65.6	57.3	34.7
SP 16	2 - 4	Room	29,000	40,900	106,200	67	58.8	24.7
SP 16	2 - 4	Room	24,000	40,800	105,500	62	59.3	23.7
SP 19	5 - 7	Room	24,300	45,700	115,800	49	48	33.1
SP 16	2 - 4	200	26,500	38,000	105,900	65.6	57.3	32.8
SP 16	2 - 4	400	24,000	33,300	99,200	63.6	59.8	30.5
SP 16	2 - 4	600	--	30,800	96,900	65	63.1	28.6
SP 16	2 - 4	700	26,500	29,600	93,900	67	64.1	27.8
SP 16	2 - 4	800	23,000	29,500	93,800	62.3	64	26.3
SP 16	2 - 4	900	23,500	27,200	89,100	64	62.6	26.7
SP 16	2 - 4	1000	25,000	27,000	88,700	64.3	61.8	25
SP 19	5 - 7	1000	25,200	31,600	101,100	51	51	24.7
SP 16	2 - 4	1100	26,500	26,500	83,900	62	58.6	25
SP 16	2 - 4	1200	24,800	25,600	73,900	50.5	52.5	25.2
SP 16	2 - 4	1200	23,000	25,800	75,600	54.5	50.4	20
SP 19	5 - 7	1200	25,200	30,200	86,700	27.5	29.5	22.7
SP 19	1 - 3	1200	15,500	21,900	75,700	42.5	38	24.7
SP 16	2 - 4	1300	23,800	24,500	67,000	46.6	44.9	24.3
SP 16	2 - 4	1400	24,000	25,900	59,900	--	--	20
SP 16	2 - 4	1400	24,500	25,300	60,800	43.5	41.6	23.5
SP 19	5 - 7	1500	25,700	32,900	48,400	9.5	15.5	22.8
SP 19	1 - 3	1500	18,000	22,700	48,700	20	20.5	22.7

[a]Elongation in 3 in. for SP 16 and in 2 in. for SP 19.

TABLE A-3. Tensile Properties of Notched, Carburized, and Aged Rod Specimens of INOR-8 (SP 19)

Grain Size (ASTM No.)	Geometry[a]	Treatment[b] (hr-°F)	Temperature (°F)	0.2% Offset Yield Strength (psi)	Tensile Strength (psi)	Elongation in 2 in. (%)	Reduction in Area (%)	Notched[c] to Notched Strength Ratio
5 - 7	Notched	None	Room	--	125,100	--	19	1.08
5 - 7	Notched	None	1000	--	108,600	--	18	1.07
5 - 7	Notched	None	1200	--	97,600	--	8	1.13
5 - 7	Notched	None	1500	--	66,500	--	8	1.38
5 - 7	Smooth	Carburized	Room	46,500	101,000	20	25.8	--
5 - 7	Smooth	Carburized	Room	45,600	98,100	21.5	19.9	--
5 - 7	Smooth	Carburized	1000	38,900	99,900	20	15.8	--
5 - 7	Smooth	Carburized	1000	32,500	87,500	20	20.5	--
5 - 7	Smooth	Carburized	1200	34,200	83,400	18.8	20	--
5 - 7	Smooth	Carburized	1200	33,500	82,500	17.5	20	--
5 - 7	Smooth	Carburized	1500	30,000	49,600	34	29.2	--
5 - 7	Smooth	Carburized	1500	31,520	50,700	45	34.6	--
5 - 7	Notched	Carburized	Room	--	113,600	--	10.6	0.97
5 - 7	Notched	Carburized	Room	--	107,500	--	7.1	0.93
5 - 7	Notched	Carburized	1000	--	90,400	--	11	0.89
5 - 7	Notched	Carburized	1000	--	96,200	--	7.4	0.95
5 - 7	Notched	Carburized	1200	--	84,200	--	10.9	0.97
5 - 7	Notched	Carburized	1200	--	82,700	--	7.1	0.95
5 - 7	Notched	Carburized	1500	--	34,900	--	7.1	0.72
5 - 7	Notched	Carburized	1500	--	74,900	--	7.1	1.54
5 - 7	Notched	40 - 1650	Room	--	127,700	--	15.1	1.1
5 - 7	Notched	40 - 1650	1000	--	103,000	--	19.4	1.02
5 - 7	Notched	40 - 1650	1200	--	86,400	--	13.2	0.99
5 - 7	Notched	4 - 1800	1200	--	96,500	--	16.5	1.1
5 - 7	Notched	200 - 1200	1200	--	87,500	--	12.5	1.01
5 - 7	Notched	40 - 1650	1500	--	65,100	--	9.3	1.35

TABLE A-3 continued --

Grain Size (ASTM No.)	Geometry[a]	Treatment[b] (hr-°F)	Temperature (°F)	0.2% Offset Yield Strength (psi)	Tensile Strength (psi)	Elongation in 2 in. (%)	Reduction in Area (%)	Notched[c] to Notched Strength Ratio
5 - 7	Notched	4 - 1800	1500	--	70,800	--	8.5	1.46
5 - 7	Notched	200 - 1200	1500	--	62,100	--	8.5	1.29
1 - 3	Smooth	40 - 1650	Room	37,900	109,200	52	43	--
1 - 3	Smooth	40 - 1650	1000	22,300	88,500	57.5	51	--
1 - 3	Smooth	40 - 1650	1200	22,700	76,800	40	40.1	--
1 - 3	Smooth	40 - 1650	1200	21,200	75,200	38.5	38.5	--
1 - 3	Smooth	40 - 1650	1500	22,500	51,600	55	44.8	--
1 - 3	Smooth	40 - 1650	1500	22,300	50,600	51	50.8	--

[a]Notched specimens had a 0.005 in. notch radius.

[b]Carburization treatment was 40 hr at 1650°F in sodium-graphite.

[c]Ratio taken with respect to smooth annealed specimens.

TABLE A-4. Creep Data for INOR-8 Sheet Specimens in Molten Salt

Stress (psi)	Heat[a]	Time (Hr) to Specified Creep Strain (%) 0.1	0.2	0.3	0.4	0.5	0.75	1.0	2.0	3.0	5.0	Rupture Life (hr)	Rupture Strain (%)	Minimum Creep Rate (%/hr)
1100°F														
10,000	SP 19	300	>10,000	--	--	--	--	--	--	--	--	--	--	--
12,000	SP 19	42	550	5300	14,500	--	--	--	--	--	--	--	--	0.95×10^{-5}
12,000	SP 16	6	195	2750	12,500	22,000	--	--	--	--	--	--	--	1.1×10^{-5}
15,000	SP 16	35	650	2700	12,000	16,500	>20,000	--	--	--	--	--	--	2.3×10^{-5}
20,000	SP 16	5.5	43	390	1,600	3,800	8,600	12,800	>15,000	--	--	--	--	5.2×10^{-5}
25,000	SP 16	20	195	750	1,650	2,550	4,450	7,500	--	--	--	12,725	1.7	9.7×10^{-5}
30,000	SP 16	2	21	84	330	800	1,900	2,880	--	--	--	3,537	2.2	2.4×10^{-4}
30,000	M-1566	10	70	200	760	1,200	2,150	3,050	4,400	--	--	5,062	3.2	2.2×10^{-4}
30,000	1327	.35	2.7	16	120	580	1,900	3,100	6,500	9,200	--	9,817	3.6	3.15×10^{-4}
1200°F														
8,000	SP 19	57	510	2000	5,500	8,400	>10,000	--	--	--	--	--	--	2.3×10^{-5}
10,000	SP 19	520	2,600	6100	9,400	13,300	>15,000	--	--	--	--	--	--	2.8×10^{-5}
12,000	SP 19	30	140	700	1,750	2,800	> 3,000	--	--	--	--	--	--	8.7×10^{-5}
12,000	SP 16	1.2	7	30	425	1,050	2,900	5,800	18,000	--	--	--	--	8.8×10^{-5}
15,000	SP 16	6.5	75	300	645	1,080	2,180	3,400	7,500	10,000	--	--	--	2.2×10^{-4}
20,000	SP 16	20	51	140	245	330	560	760	1,680	2,550	4,300	6,685	9.2	1.1×10^{-3}
25,000	SP 16	6.8	42	115	185	235	380	510	1,000	1,500	2,400	2,783	7.2	2×10^{-3}
25,000	M-1566	2	23	54	90	128	220	320	560	680	--	712	3.5	2.7×10^{-3}
25,000	M-1566	2	17	43	85	150	240	330	--	--	--	455	2.41	2.9×10^{-3}
25,000	8M-1	20	54	110	165	212	310	410	650	1,120	1,800	2,368	8.5	2.5×10^{-3}
25,000	1327	8	25	70	138	205	360	500	950	1,310	2,000	3,560	15.7	2.05×10^{-3}
25,000[b]	1327	4	24	50	83	115	175	235	450	640	1,000	2,250	1.9	3.3×10^{-3}
30,000	SP 16	0.1	15	32	54	72	104	138	262	--	--	272	3	9.2×10^{-3}
30,000	SP 16	2.5	21	37	57	78	140	195	440	660	1,000	1,014	5.5	4.05×10^{-3}
1300°F														
8,000	SP 19	10	130	480	830	1,300	2,550	3,800	9,400	>10,000	--	--	--	1.95×10^{-4}
10,000	SP 19	8	48	140	280	430	840	1,250	2,950	>4,000	--	--	--	5.8×10^{-4}
12,000	SP 19	6.6	16	44	120	205	450	740	1,950	3,400	4,900	9,000	8.5	9.2×10^{-4}
12,000	SP 16	15	47	100	165	245	445	660	1,550	2,450	3,700	5,007	7.3	1.2×10^{-3}
15,000	SP 16	10	36	67	98	128	215	310	740	1,120	1,750	2,893	10.7	2.4×10^{-3}
20,000	SP 16	8	21	33	44	54	80	105	215	330	540	882	11.04	9.4×10^{-3}
20,000	SP 16	3.5	19	36	52	65	100	135	275	400	670	905	6.5	7.3×10^{-3}
20,000	SP 19	4.4	12.5	33.5	35	46	74	100	150	200	500	767	10.7	8.8×10^{-3}
20,000	M-1566	1	9	24	33	41	59	74	122	150	--	180	5.0	1.7×10^{-2}
20,000	M-1566	2	11	28	36	42	60	75	130	167	--	202	4.5	1.8×10^{-2}
20,000	8M-1	7	20	36	42	71	118	165	350	520	810	1,115	7.0	6.1×10^{-3}
20,000	1327	4	12	22	33	44	74	103	225	345	560	1,177	18	1.1×10^{-2}
25,000	SP 16	1.6	4	6.5	9.5	13	23	40	80	112	165	213	8.07	2.5×10^{-2}
30,000	SP 16	1	2.1	3.4	4.6	5.8	9.1	12.3	25.5	38	59	110	15.3	7.7×10^{-2}

TABLE A-4 continued--

Stress (psi)	Heat[a]	Time (Hr) to Specified Creep Strain (%) 0.1	0.2	0.3	0.4	0.5	0.75	1.0	2.0	3.0	5.0	Rupture Life (hr)	Rupture Strain (%)	Minimum Creep Rate (%/hr)
1400°F														
8,000	SP 19	9	41	100	145	195	340	485	980	1,500	2,700	3,850	8.5	1.6×10^{-3}
1500°F														
8,000	SP 16	1.4	4.4	8.2	12.8	18	32	48	115	175	290	529	13	2.2×10^{-2}
8,000[b]	SP 16	0.5	1.7	4.2	7.2	11	25	40	115	185	320	610	10	1.3×10^{-2}
8,000	1327	1	3.5	7.5	12.5	19	33	45	82	110	150	208	13.4	2.1×10^{-2}
8,000[b]	1327	1.5	4.6	8.8	13.5	18.5	28	36	59	75	96	125	15.5	2.1×10^{-2}
6,000	SP 16	3	12	27	44	62	112	165	420	800	1,800	3,238	6.35	1.2×10^{-3}
1650°F														
3,000	SP 16	3	15	35	60	93	225	480	2,100	3,800	--	4,785	4.4	5.8×10^{-4}
4,000	SP 16	1	3.2	6	9.6	14	28	46	175	400	--	768	3.3	4×10^{-3}
5,000	SP 16	1.5	3.2	4	7	9.2	15.5	23	55	85	150	217	9.3	3.25×10^{-2}
1700°F														
5,000	SP 16	1	2	3.2	4.6	6	10	14.5	33	52	155	270	8.2	2.65×10^{-2}
1800°F														
2,000	SP 16	1.6	5.5	16	29	48	112	215	1,050	2,600	--	4,481	4.6	6.4×10^{-4}
3,000	SP 16	--	1.6	3.1	5	7.1	13.2	20.5	49	78	115	135	7.0	3.5×10^{-2}
3,000	1327	--	--	1	1.4	1.8	2.9	4	8	11.5	17.5	43.8	20.3	2.3×10^{-1}
3,000[b]	1327	--	--	--	--	--	--	2.2	3.7	5.2	7.6	23	22.0	5×10^{-1}
3,000[b]	SP 16	0.6	1.7	3	4.6	5.4	11.5	17.5	41	64	--	66	5.6	4.3×10^{-2}

[a]Heat SP 16 was ASTM grain size No. 2 - 4, SP 19 was 4 - 6, and M-1566, 8M-1, and 1327 were 5 - 7.

[b]Aged 50 hr at 1300°F.

TABLE A-5. Creep Data for INOR-8 Sheet Specimens in Air

Stress (psi)	Heat[a]	Time (Hr) to Specified Creep Strain (%) 0.1	0.2	0.3	0.4	0.5	0.75	1.0	2.0	3.0	5.0	Rupture Life (hr)	Rupture Strain (%)
1200°F													
30,000	SP 19	20	49	82	104	125	163	196	300	--	--	320	2.7
1250°F													
10,000	SP 16	1820	2650	3450	4350	5200	>6000	--	--	--	--	--	--
10,000	SP 16	2180	2880	3520	4180	4800	6250	7750	>10,000	--	--	--	--
10,000	SP 19	530	1400	2000	2560	3150	4650	5900	--	--	--	--	--
12,000	SP 16	650	1100	1440	1760	2050	2750	3450	6000	8400	12,000	14,395	8.6
12,000	SP 16	870	1230	1560	1900	2250	3150	4000	--	--	--	--	--
12,000	SP 19	450	810	1110	1390	1680	2400	3300	6500	--	--	--	--
15,000	SP 16	245	440	605	750	880	1190	1520	2850	--	--	--	--
15,000	SP 16	315	500	650	790	910	1200	1500	2500	3350	4,450	4,562	5.8
15,000	SP 19	230	335	430	525	625	880	1180	2380	3550	5,750	6,980	6.2
20,000	SP 16	60	105	145	190	215	300	385	730	1100	1,750	1,786	5.5
20,000	SP 16	60	115	262	205	245	335	410	760	1080	1,550	2,177	9.8
20,000	SP 19	34	57	80	105	130	195	265	570	900	1,650	2,000	5.9
23,000	SP 16	27	60	88	115	138	190	235	400	550	700	783	5.2
23,000	SP 16	30	70	103	132	150	220	270	455	630	900	954	5.9
25,000	SP 16	16	35	50	64	77	105	130	230	340	550	702	6.0
25,000	SP 16	15	36	52	69	82	112	140	240	330	500	509	5.4
25,000	SP 16	21	40	57	72	85	116	145	255	370	590	892	9.6
30,000	SP 16	1.8	6.4	10	14	17	31	45	100	145	190	204	6.0
1300°F													
20,000	SP 19	20	30	34	37.5	41	51	67	130	175	215	229	7.0
25,000	SP 19	8	14	18.5	22.5	25.5	32	37	58	64	--	63	3.0
1500°F													
5,000	SP 19	26	49	73	97	120	170	210	345	455	--	508	3.9
8,000	SP 19	4.8	11.5	17	24.5	31	45	60	112	--	--	148	2.8
8,000	SP 16	8.8	14	19	23.5	28.5	40.5	55	122	190	300	439	10.5
8,000	SP 16	9.4	15	20	24.5	29	39	49	88	125	190	263	8.5
15,000	SP 19	1.1	1.75	2.4	3.0	3.6	4.9	6.2	11	15.5	24	26.2	5.6
20,000	SP 19	0.59	0.76	0.92	1.05	1.18	1.46	1.77	2.85	--	--	3.4	2.5
1700°F													
3,000	SP 19	4	11	19	26	37.5	48	61	104	140	190	387	14.5
5,000	SP 16	1.3	2.6	3.7	5.0	6.3	9.4	12.6	25	38	60	90.6	10.4
8,000	SP 19	0.34	0.49	0.61	0.73	0.83	1.08	1.32	2.2	2.95	4.0	6.3	13.5
15,000	SP 19	--	--	--	--	--	0.11	0.155	0.275	0.35	0.45	0.5	6.1
1800°F													
3,000	SP 16	--	1.0	2.0	4.0	6.5	14.5	24.5	70.0	120.0	--	137	3.3
3,000	SP 16	1.6	2.9	4.3	5.9	7.6	12.5	18.5	38.0	54.0	--	74	4.8

[a]Heat SP 16 was ASTM grain size No. 2 - 3, and SP 19 was 4 - 6.

TABLE A-6. Creep Data for INOR-8 Rod Specimens in Air

Stress (psi)	Heat[a]	Time (Hr) to Specified Creep Strain (%) 0.1	0.2	0.3	0.4	0.5	0.75	1.0	2.0	3.0	5.0	Rupture Life (hr)	Rupture Strain (%)
1250°F													
8,000	SP 16	1550	3450	5300	7100	8800	>10,000	--	--	--	--	--	--
10,000	SP 16	880	1750	2500	3150	3850	5,300	6900	>10,000	--	--	--	--
12,000	SP 16	430	950	1380	1820	2250	3,250	4250	7,600	10,300	>14,000	--	--
15,000	SP 16	260	400	530	680	830	1,230	1630	3,050	> 4,000	--	--	--
20,000	SP 16	115	175	225	270	310	410	515	890	1,280	1,900	3535	15.5
20,000	SP 16	120	185	240	290	330	440	550	940	1,370	2,200	3828	13.5
25,000	SP 16	70	109	138	160	180	230	275	460	640	980	--	--

[a] ASTM grain size No. 2 - 3.

TABLE A-7. Relaxation Data for INOR-8

(SP 16 Rod Specimen Tested in Air)

Temperature (°F)	Total Strain (%)	Initial Stress (psi)	Stress after Specified Time (psi)							
			0.01 hr	0.1 hr	1 hr	10 hr	50 hr	100 hr	500 hr	1000 hr
1150	0.05	12,600	13,600	13,100	13,000	12,600	12,300	12,000	11,300	10,400
1175	0.05	9,100	9,400	9,300	9,200	7,700	7,500	--	--	--
1200	0.05	12,000	12,400	12,800	12,800	12,300	11,300	--	--	--
1300	0.05	11,900	12,300	--	--	--	--	--	--	--
1300	0.05	11,300	11,100	11,800	12,000	10,200	7,400	6,700	--	--
1300	0.05	10,800	11,270	11,400	11,000	--	--	--	--	--
1300[a]	0.05	10,000	9,400	9,900	10,100	9,400	7,900	8,800	--	--
1300[a]	0.05	11,500	11,800	11,000	11,200	9,800	8,500	6,000	4,000	--
1350	0.05	10,500	10,600	10,500	10,200	8,500	6,600	5,500	--	--
1400	0.05	14,500	9,800	8,300	7,100	4,200	3,100	--	--	--
1400	0.05	10,100	--	9,000	7,200	3,800	--	--	--	--
1400	0.05	8,700	--	8,500	5,500	--	--	--	--	--
1500	0.05	11,000	10,800	10,700	8,100	4,100	2,800	2,300	--	--
1500	0.05	10,800	10,100	8,700	6,600	3,300	--	--	--	--
1600	0.05	8,400	6,900	4,500	4,100	2,500	2,400	--	--	--
1200	0.075	18,000	--	--	18,100	17,300	16,000	15,000	--	--
1175	0.1	19,300	19,500	19,600	19,700	20,800	20,000	21,400	16,000	--
1175	0.1	26,000	--	27,500	28,300	26,200	23,800	21,400	13,000	--
1175	0.1	21,900	22,000	21,300	21,000	20,700	17,300	12,800	11,800	--
1200	0.1	21,400	22,200	22,300	22,300	21,900	--	--	--	--
1200	0.1	22,500	22,700	22,700	23,300	22,500	20,300	--	--	--
1200	0.1	22,900	23,300	23,500	23,100	22,100	19,500	17,000	9,000	5,800
1275	0.1	18,800	19,500	20,100	20,300	20,100	18,600	17,200	--	--
1300	0.1	21,700	22,300	22,900	20,800	15,800	8,000	5,500	--	--
1350	0.1	22,500	22,300	21,700	18,600	8,900	4,600	--	--	--
1400	0.1	19,700	15,700	14,300	6,200	3,000	--	--	--	--
1400	0.1	21,300	--	20,000	14,400	6,800	4,700	4,300	--	--
1500	0.1	17,400	17,300	12,800	6,600	3,100	1,800	--	--	--
1500	0.1	20,300	19,400	16,000	7,400	3,000	--	--	--	--
1500	0.1	23,400	22,500	18,600	6,700	2,500	--	--	--	--
1500	0.1	16,200	16,300	16,500	8,000	3,000	--	--	--	--
1600	0.1	20,300	16,700	8,800	4,500	3,000	2,700	--	--	--
1300	0.2	30,000	29,700	27,700	20,600	10,200	5,600	--	--	--

[a]0.063 in. thick sheet specimens.

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