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16. Abstract

Two aircraft turbine disk alloys, GATORIZED® AF2-1DA and INCO 718 were evaluated for their low strain long life creep-fatigue behavior.

Static (tensile and creep rupture) and cyclic properties of both alloys were characterized. The controlled strain LCF tests were conducted at 760°C (1400°F) and 649°C (1200°F) for AF2-1DA and INCO 718, respectively. Hold times were varied for tensile, compressive and tensile/compressive strain dwell (relaxation) tests. Stress (creep) hold behavior of AF2-1DA was also evaluated.

Generally, INCO 718 exhibited more pronounced reduction in cyclic life due to hold than AF2-1DA. The percent reduction in life for both alloys for strain dwell tests was greater at low strain ranges (longer life regime). Changing hold time from 0 to 0.5, 2.0 and 15.0 min. resulted in corresponding reductions in life. The continuous cycle and cyclic/dwell initiation failure mechanism was predominantly transgranular for AF2-1DA and intergranular for INCO 718.

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Creep-Fatigue	INCO 718	Unclassified — Unlimited
Strain Control	AF2-1DA	
Low Cycle Fatigue (LCF)	Strain Hold	
Life Prediction	Stress Hold	
Low Strain-Long Life	Turbine Disks	

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SUMMARY

Two aircraft turbine disk alloys, GATORIZED® AF2-1DA and INCO 718 were evaluated for their low strain long life creep-fatigue behavior.

Static (tensile and creep rupture) and cyclic properties of both alloys were characterized. The controlled strain LCF tests were conducted at 760°C (1400°F) and 649°C (1200°F) for AF2-1DA and INCO 718, respectively. Hold times were varied for tensile, compressive and tensile/compressive strain hold (relaxation) tests. Stress (creep) hold behavior of AF2-1DA was also evaluated.

Generally, INCO 718 exhibited more pronounced reduction in cyclic life due to hold than AF2-1DA. The percent reduction in life for both alloys for strain hold tests was greater at low strain ranges (longer life regime). Changing hold time from 0 to 0.5, 2.0 and 15.0 min. resulted in corresponding reductions in life. The continuous cycle and cyclic/hold initiation was predominantly transgranular for AF2-1DA and intergranular for INCO 718.

INTRODUCTION

The use of advanced, high-strength materials and processing techniques has resulted in reduced weight and increased performance for modern aircraft gas turbine engines. High-strength, corrosion-resistant nickel-based superalloys are generally used for turbine disk applications in these engines. The cost of superalloy turbine disks has increased dramatically in the last decade, due largely to the use of complex shapes and advanced materials and processing. At the same time, increased performance requirements have resulted in decreased cyclic lives for these components, and greatly increased engine life cycle costs. Since these disks are often low-cycle fatigue (LCF) limited (References 1 through 4), accurate prediction of component fatigue life is essential to maximize reliability and safety, while simultaneously minimizing potentially enormous component replacement costs resulting from overconservatism.

Aircraft gas turbine engine disks are frequently limited in service life due to LCF. Fatigue life predictions for high-strength nickel-based superalloy turbine disks are complicated by the small cyclic inelastic strains exhibited by these alloys under the stress-temperature-time cycles of interest. Consequently, a realistic approach to fatigue life predictions for these alloys is to consider the relationship between total (inelastic plus elastic) cyclic strains and cyclic life. At temperatures within the creep range, it is necessary to develop a model that considers temperature, waveform, and time, in addition to cyclic strain range. It was felt that a model could be developed for fatigue life prediction of aircraft turbine disk alloys which is compatible with the method of Strainrange Partitioning. The accuracy of the life prediction system is partly contingent upon experimental simulation of the true mechanical behavior of materials.

Typical engine disk-loading imposes low cyclic strains at critical locations and may yield long LCF lives (10^4 to 10^5 cycles). Inelastic strains at these conditions are similarly quite low, yet can have a large effect on LCF life. At temperatures in the creep range of an alloy, time-dependent inelastic strains may be induced which are important, yet difficult to handle analytically in the design of aircraft gas turbine engine components.

The objective of the program was to generate the data base required for development of the model. The alloys selected for evaluation were the high-strength nickel based turbine disk alloys:

AF2-1DA, produced by the GATORIZING® isothermal forging process, and
INCO 718 in bar stock form.

This program included tensile, creep-rupture, and axially loaded strain-controlled LCF tests for initiation under both cyclic and cyclic/hold conditions at 760°C (1400°F) for AF2-1DA alloy and at 650°C (1200°F) for INCO 718. This data base is required to develop an LCF life prediction model, which can analytically handle the effects of temperature, frequency, hold time, and waveshape in the cyclic life regime required by the gas turbine industry.

MATERIAL PROCUREMENT AND BASIC MECHANICAL PROPERTIES

Material Description, Composition, Heat Treatment and Qualification

Two nickel-base superalloys for aircraft gas engine disks were evaluated for resistance to cyclic crack initiation at low strain-range, long-life conditions. The alloys selected for evaluation were GATORIZED® AF2-1DA (produced from prealloyed powder) and INCO 718 (produced from ingot and tested in bar stock form).

GATORIZED® AF2-1DA. — The AF2-1DA alloy was produced using prealloyed powder and was vacuum atomized by Homogenous Metals, Inc., from a vacuum induction melted ingot. The starting powder conforming to AMS-5833 both in chemistry and particle size was filled into eight 15.2 cm (6 in.) cans with a 0.64 cm (0.25 in.) wall thickness. After an 8-hour soak at 1093°C (2000°F) each can was extruded at Reactive Metals, Inc., through a 5.46 cm (2.150 in.) extrusion die. After decanning all extrusions they were machined into mults, approximately 19.0 cm (7.5 in.) long. Mults were then isothermally, superplastically, forged using the GATORIZING® process into pancakes at 1121°C (2050°F) at a strain rate of 0.05 mm/mm/min, and fully heat treated in four lots. Ten of the GATORIZED® AF2-1DA forgings approximately 15.2 cm (6.0 in.) × 1.58 cm (0.625 in.) high were received from NASA. This material was processed and forged earlier by Pratt & Whitney under contract NAS3-20947. The pertinent processing, composition, heat treatment, and material qualification details are as follows.

Based on gradient bar studies, the solution heat-treatment was devised as follows:

1133°C (2075°F)	—	Vacuum and hold for 45 min.
1204°C (2200°F)	—	heat at rate of 1 deg per min; hold for 1 hr followed by an argon quench.

The AMS 5856 stabilization and precipitation heat-treat cycle consisting of the following:

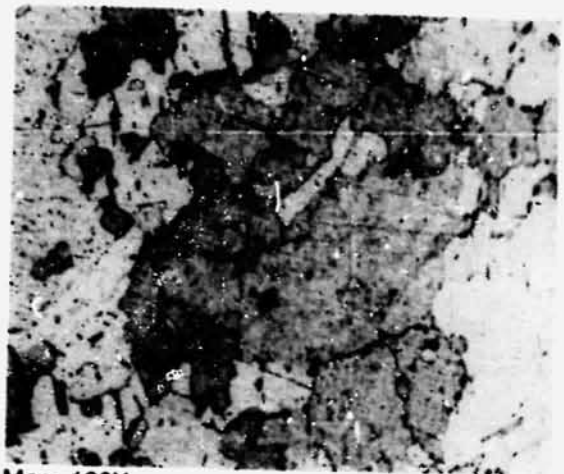
1121°C (2050°F)	—	2 hr — Air Cool
704°C (1300°F)	—	12 hr — Air Cool
815°C (1500°F)	—	8 hr — Air Cool

Typical microstructure following solution heat treatment for all four lots are shown in Figure 1. No preferential directionality of grain structure was seen in 100× photomicrographs.

A total of four pancakes, one from each heat treat lot, were selected for mechanical properties evaluation under Contract NAS3-20947 (Reference 5). The chemical composition and material qualification test data are presented in Tables 1 and 2. Overall, the material did not meet specification requirements. It was however, considered suitable for the purposes of this program. Creep and Stress rupture were below specification parameters. The tensile data had excellent ductilily, but was marginal in Room Temperature 0.2% yield strength and 816°C (1500°F) tensile strength.

Inconel 718. — Inconel 718 is a nickel-based superalloy widely used in current production gas turbine engines. This alloy is used in compressor and turbine disk applications with maximum operating temperatures approaching 649°C (1200°F). This material was furnished by NASA in the form of 25.4 mm (1.0 in) OD centerless ground bar stock. The material was originally supplied by ATEK Metals Company, Woodlawn, Ohio, for use under a separate contract "NASA Benchmark Notch Test for Life Prediction" (Reference 6) program. The material was from Teledyne ALLVac Heat No. 5108. Vendor Supplied composition and certification test results are listed in Tables 3 and 4 along with specification minimum and typical average properties. The material met all minimum specification requirements.

Kallings



Mag: 100X

Heat Treat Lot 1

Mag: 100X

Heat Treat Lot 2

ASTM Grain Size 1-3

Mag: 100X

Heat Treat Lot 3

Mag: 100X

Heat Treat Lot 4

FD 144891

Figure 1. — Typical AF2-1DA Pancake Microstructure Following Solution Heat Treatment

The INCO 718 as received (annealed) bar stock was fully heat treated to a solution cycle. The heat treatment details are as follows:

968°C (1775°F) — 1 hr — He Quench
718°C (1325°F) — 8 hr — Furnace Cool 38°C (100°F/hr)
to 612°C (1150°F) — 8 hr — Air Cool to Room Temperature

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TABLE 1. — QUALIFICATION TEST RESULTS — AF2-1DA TEST RESULTS

Heat Treat Lot No.	Tensile Test Temp °C	(°F)	YS MPa	(ksi)	TS MPa	(ksi)	816°C (1500°F) Elong %	RA %	Rupture 551.6 MPa (80 ksi) Life hr	Elong %	RA %	Creep 760°C (1400°F) 482.6 MPa (70 ksi) Life 0.1% hr	Life 0.2% hr	Elong 100 hr %	ASTM Grain Size
1	RT		969.4	(140.6)	1529.9	(221.9)	20.0	23.0	15.4	7.4	10.0	30.7	78.6	0.246	1
	816	(1500)	942.5	(136.7)	1025.9	(148.8)	20.7	30.2							
2	RT		948.7	(137.6)	1524.4	(221.1)	20.0	24.5	14.4	12.1	14.6	17.5	44.9	0.390	1
	816	(1500)	943.9	(136.9)	1043.2	(151.3)	21.3	30.6							
3	RT		924.6	(134.1)	1514.8	(219.7)	18.0	21.6	18.5	9.2	12.9	3500	73.3	0.261	1
	816	(1500)	881.8	(127.9)	997.7	(144.7)	20.0	30.2							
4	RT		924.6	(134.1)	1498.9	(217.4)	19.3	21.9	20.9	8.3	10.9	23.1	64.9	0.249	1
	816	(1500)	939.1	(136.2)	1019.0	(147.8)	24.7	31.3							
AMS	RT		965.3	(140.0)	1310.0	(190.0)	10.0	12.0	23.0	5.0	—	—	100	—	1
5881	816	(1500)	861.8	(125.0)	1034.2	(150.0)	10.0	32.0							

TABLE 2. — CHEMICAL COMPOSITION OF NICKEL BASE ALLOY AF2-1DA-100 MESH POWDER

Producer: Homogeneous Metals, Inc.
NMI Heat × 3229/30R

Chemical Composition	*Required wt %* min	max	*Actual** *wt %*
Carbon	0.30	0.35	0.31
Manganese	—	0.10	0.01
Silicon	—	0.10	0.002
Phosphorus	—	0.015	0.005
Sulphur	—	0.015	0.04
Chromium	11.50 -	12.50	12.45
Cobalt	9.50 -	10.50	10.36
Molybdenum	2.50 -	3.50	3.13
Tungsten	5.50 -	6.50	—
Titanium	2.75 -	3.25	2.84
Tantalum	1.00 -	2.00	—
Aluminum	4.20 -	4.80	4.42
Boron	0.01 -	0.02	0.015
Zirconium	0.05 -	0.15	0.10
Oxygen	—	0.010 (100 ppm)	0.0041 (41 ppm)
Nitrogen	—	0.005 (50 ppm)	0.0006 (6 ppm)
Iron	—	1.00	0.10
Lead	—	0.0002 (2 ppm)	0.0001 (1 ppm)
Bismuth	—	0.00005 (0.5 ppm)	0.00001 (0.1 ppm)
Nickel		Remainder	Remainder

* N_2O_2 taken in powder states, −100 mesh

An optical micrograph taken after heat treatment is shown in Figure 2. The resulting microstructure was fine grained and uniform with average ASTM grain size of 7 or 8.

Tensile And Creep-Rupture Properties

Tensile Testing. — Tensile tests were conducted for GATORIZED® AF2-1DA and INCO 718 to establish the average values for the mechanical properties listed below:

1. Modulus of elasticity
2. Poisson's ratio
3. 0.2% offset yield
4. Ultimate strength
5. True fracture strength
6. Strain-hardening exponent
7. Reduction of area
8. Elongation.

All tensile tests were conducted per ASTM E8-69, "Tension Testing of Metallic Materials" using smooth round specimens with a 0.640 cm (0.252 in.) gage diameter and a 5.08 cm (2.220 in.) reduced section gage length as shown in Figure 3. The strain rate was maintained at 0.005 mm/mm/min (0.005 in./in./min) to the yield point and at a crosshead speed of 0.64 mm/min (0.025 in./min) from the yield point to the fracture point.

TABLE 3. — QUA IFICATION TEST RESULTS — INCO 718*

Source	Temperature °C	Temperature °F	UTS MPa	UTS ksi	0.2% YS MPa	0.2% YS ksi	Elongation, %	RA, %	Hard. R_c
a. Mechanical Properties									
Vendor	21	70	1413	205	1152	167	21.2	41.2	43.5
Spec	21	70	1241	180	1034	150	12.0	15.0	38-48
Typ Avg	21	70	1386	201	1165	169	18.0	30.0	—
Vendor	649	1200	1152	167	960	139	21.8	48.3	44
Spec	649	1200	1000	145	862	125	10.0	15.0	38-48
Typ Avg	649	1200	1110	161	972	141	19.0	35.0	—

b. *Stress Rupture***

Source	Temperature °C	Temperature °F	Stress MPa	Stress ksi	Life, hr	Elongation, %	RA, %
Vendor	649	1200	759	110	89.1	25.8	—
Spec	649	1200	689	100	0.5	>5.0	—

c. *Grain Size*

Vendor: Avg ASTM 10
Spec Avg < ASTM 4 with Max ASTM 2

*25.4 mm (1.0 in.) diameter centerless ground bar stock Teledyne Allvac heat No. 5108, Spec B50TFISAS-10, ATEK No. AT802370 Ref 5

**Smooth 6.35 mm (0.25 in.) nominal diameter bar.

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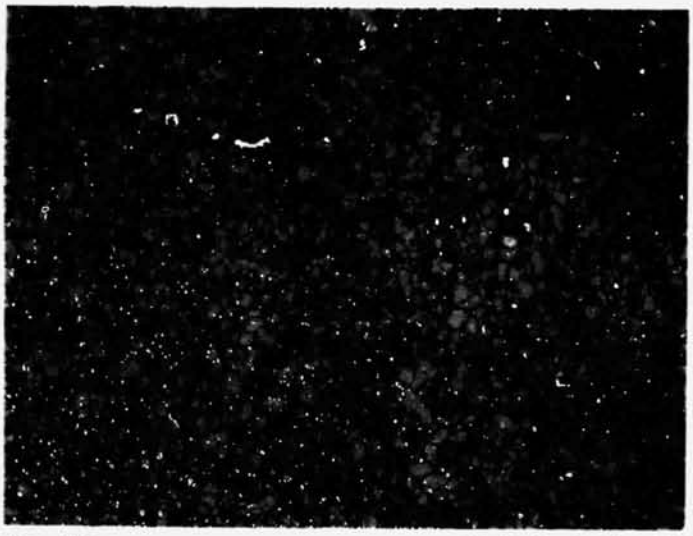
TABLE 4. —CHEMICAL COMPOSITION OF INCO 718*

Chemical Composition	Weight Percent Required	Actual
Al	0.3-0.7	0.49
B	0.006 Max	0.004
C	0.02-0.08	0.042
Cb+Ta	4.75-5.50	5.14
Co	1.0 Max	0.53
Cr	17.0-21.0	17.42
Cu	0.30 Max	0.05
Fe	15.0-21.0	Bal
Mn	0.35 Max	0.16
Mo	2.80-3.30	2.93
Ni	50.0-55.0	52.08
P	0.015 Max	0.004
S	0.015 Max	0.002
Si	0.35 Max	0.10
Ti	0.75-1.15	1.05

* Inconel 718, 25.4 mm (1.0 in.) diameter centerless ground bar stock Teledyne Allvac heat No. S108, Spec. B50TFISAS-10, ATEK No. AT802370 (Reference 6)



Mag: 120× ASTM Grain Size 7-8

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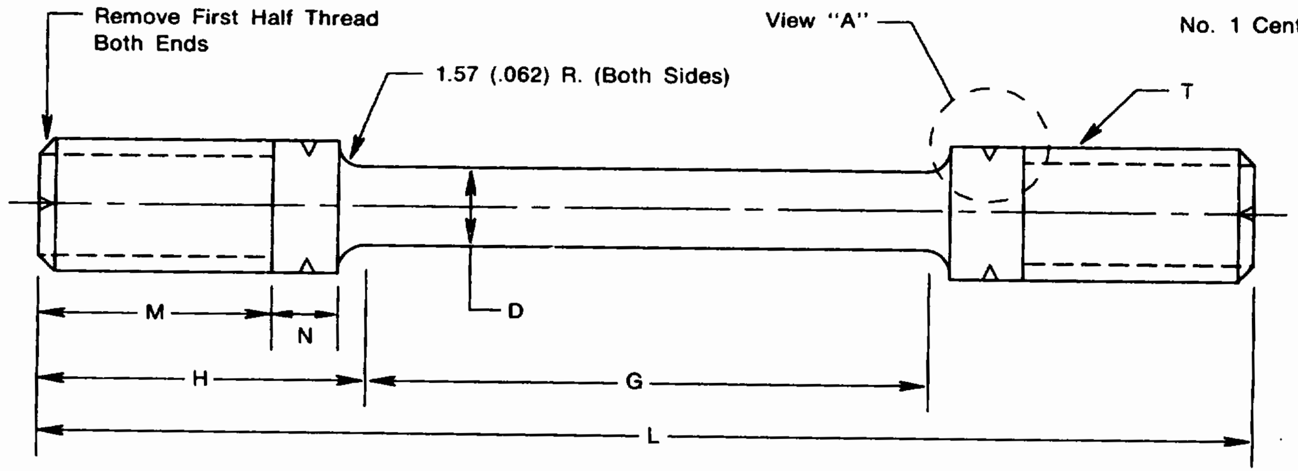
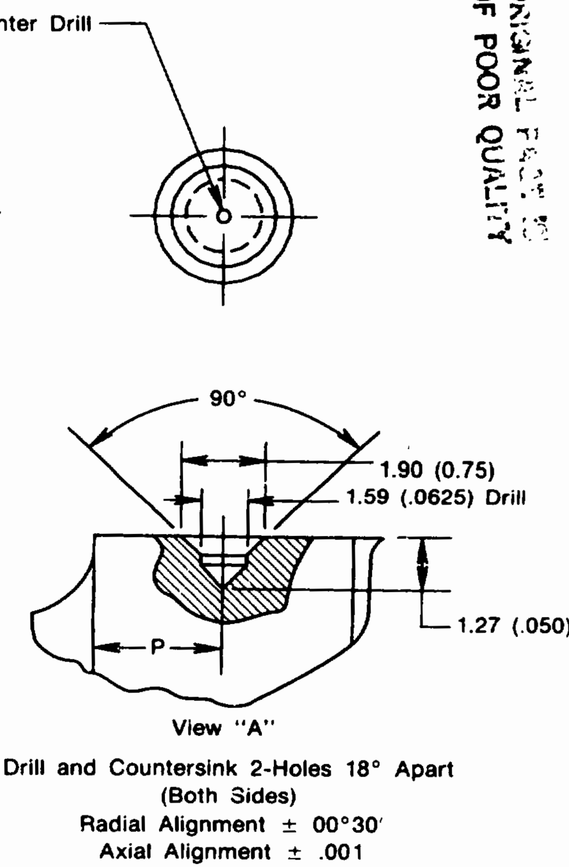
Figure 2. — Typical Inconel 718 Microstructure Following Solution Heat Treatment





Notes

1-All Dimensions in mm (in.)
2-Tolerances ± .005 U.O.S.
3-Diameters To Be Conc. To Within 0.001 F.I.R
4-Reduced Section To Be 16 ± 3 Microinch AA Grind Finish
5-Grind Per MCL Manual Sec J-61
6-Diameter of Reduced Section To Be Slightly Smaller At Center Than At Ends (Approx. .0015), But Not To Exceed 1% Of Larger Diameter
7-Identification Markings Permitted Only Only Specimen Ends
8-For Material Of Insufficient Length, Reduce Thread Length (M) Equally On Both Sides, But Final Thread Length Should Not Be Less Than Major Diameter Of Thread

Specimen No.	D ± 0.001	L	G ± 0.002	H	M	N	P ± 0.002	T
1	6.40 (0.25)	101.60 (4.00)	50.80 (2.00)	25.40 (1.00)	17.40 (0.69)	6 35 (0.25)	3.18 (0.13)	12.70 (1/2)-13 UNCJ-3A

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Figure 3 — Tensile and Creep Rupture Specimen

Tensile testing was performed on a Tinius Olsen 266.8-kN (60,000 lb) capacity tensile machine. To measure specimen strain for elevated temperature tests, an averaging-type linear variable displacement transducer (LVDT) extensometer system was used. A correction factor based on prior strain gage data was applied to displacement measured by this extensometer output. This allowed strain determination over the actual gage length of the specimen. Specimen load was determined by the tensile machine load measuring system. For determining Poisson's ratio, a diametric extensometer was used in conjunction with the axial extensometer (Figures 4 and 5). For each specimen, the Poisson's ratio was established by relating the elastic diametric and axial strain.

The modulus of elasticity was determined according to ASTM E231, "Static Determination of Young's Modulus at Low and Elevated Temperatures," from the stress-strain curves generated during each tensile test.

The strain hardening exponent (η) was established in this program from the tensile tests using the method developed by Avery and Findley (Reference 7). Strain hardening is expressed by the relationships:

$$\sigma = K\epsilon^{\eta}_{I}$$

where:

σ = true stress
ϵ_I = true inelastic strain
K = constant equal to the true stress at unit true strain.

True stress (σ) and true strain (ϵ) were calculated using the relationships:

$$\sigma = S\,(1 + e) \text{ and}$$
$$\epsilon = \ln\,(1 + e)$$

where:

S = engineering stress, load/initial area

e = engineering strain, change per unit length based on initial gage length

The tensile properties established for three GATORIZED® AF2-1DA and two INCO 718 specimens tested at 760°C (1400°F) and 649°C (1200°F) are listed in Tables 5 and 6, respectively. Stress-strain parameters, up to 2.5% plastic strain, were also established for each specimen tested for both materials and are listed in Table 7 and 8. Average curves of stress vs strain for the AF2-1DA and INCO 718 specimens tested are illustrated in Figures 6 and 7.

Creep Rupture Testing. — Creep rupture tests were conducted at 760°C (1400°F) for AF2-1DA and 649°C (1200°F) for INCO 718 to define the stress rupture curve between 10 and 1000 hours and to determine the following parameters for each test:

1. Strain on loading

2. Transient creep strain between initial loading and achievement of steady state creep

3. Steady state creep rate

4. Strain at onset of tertiary creep

5. Reduction of area after rupture

6. Elongation after rupture.

Creep tests were conducted per ASTM E139-70, "Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials," where applicable, using round, smooth specimens. A similar test specimen to that used for tensile test was used and is shown in Figure 3.

Tests were conducted on a 53.4-kN (12,000 lb) capacity Arcweld Model JE creep-rupture machine.

Five tests for AF2-1DA and four tests for INCO 718 were conducted in an iterative sequence to ensure time to rupture between 10 and 1000 hr. An LVDT extensometer was attached to each test specimen, and the extensometer output was fed to a data logger. This unit was coupled to a magnetic tape drive for data storage, and an IBM 3033 computer to allow automatic recording and data reduction.

The stress rupture response of AF2-1DA at 760°C (1400°F) and INCO 718 at 649°C (1200°F) is illustrated in Figures 8 and 9. Five creep rupture tests were required per contractual requirements for AF2-1DA, however, three additional tests were conducted without extensiometry, to further define the stress rupture curve shown in Figure 8. The creep rupture curves for both materials used to establish the various creep parameters are illustrated in Figures 10 and 11. The required creep parameters and all related data are listed in Tables 9 and 10.

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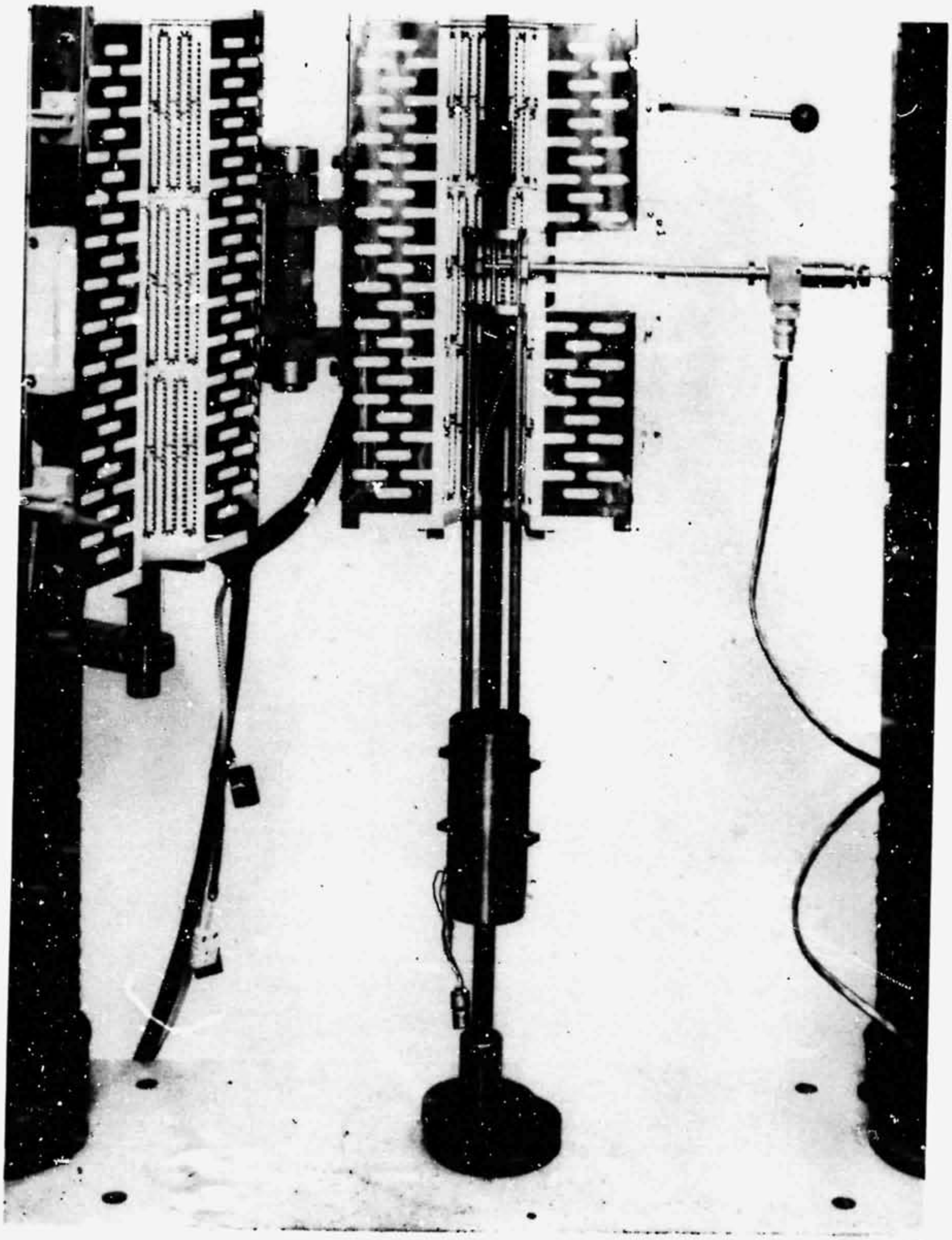

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Figure 4. — Extensometer Systems Used for Determining Poisson's Ratio for AF2-1DA and Inconel 718. Also Shown Are Tensile Load Train and Furnace System

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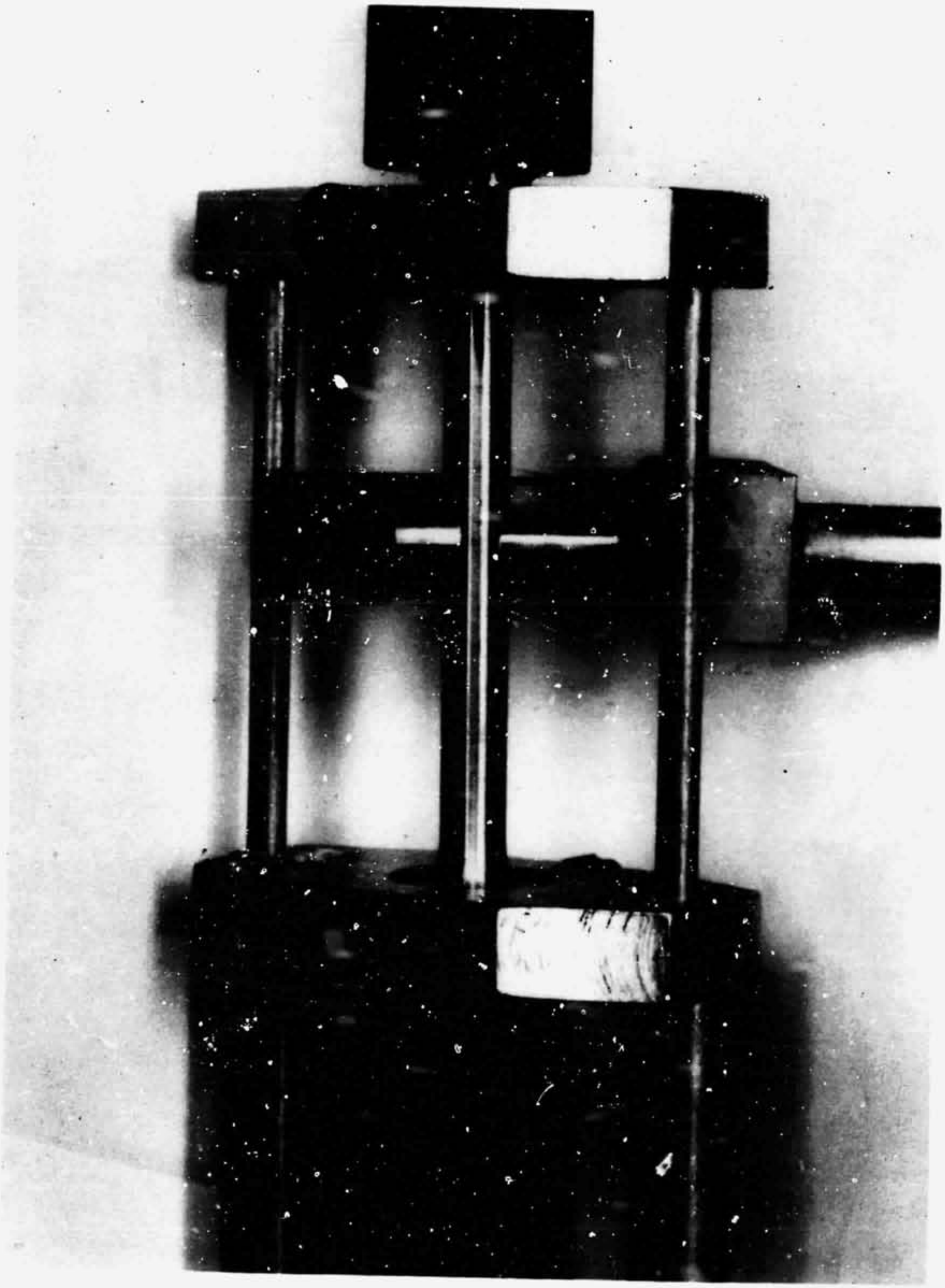

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Figure 5. — Close-up of Axial and Diametric Extensometer Systems Used To Determine Poisson's Ratio for GATORIZED® AF2- 1DA and INCO 718

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TABLE 5. — TENSILE PROPERTIES FOR GATORIZED® AF2-1DA AT 760°C (1400°F)

Specimen No.	Strength: PL MPa	PL (ksi)	0.2% Yield MPa	0.2% Yield (ksi)	Ultimate MPa	Ultimate (ksi)	True Fracture Strength* MPa	True Fracture Strength* (ksi)	Ductility EL (%)	Ductility R.A. (%)	Modulus of Elasticity MPa×10³	Modulus of Elasticity (ksi×10³)	Poisson's Ratio	Strain Hardening Exponent
AF2-1DA1	703.3	(102.0)	908.0	(131.7)	1087.3	(157.7)	1305.9	(189.4)	24.0	22.3	130.0	(26.1)	0.35 0.31**	0.136
AF2-1DA2	730.2	(105.9)	936.3	(135.8)	1097.0	(159.1)	1307.2	(189.6)	23.0	25.3	175.1	(25.4)	0.38 0.31**	0.117
AF2-1DA3	738.4	(107.1)	916.3	(132.9)	1123.8	(163.0)	1311.4	(190.2)	20.0	19.0	175.1	(25.4)	0.34 0.30**	0.136

* Actual fracture load divided by the area at fracture.
** Determined at ambient temperature.

TABLE 6. — TENSILE PROPERTIES FOR INCO 718 AT 649°C (1200°F)

Specimen No	Strength						True Fracture Strength*		Ductility		Modulus of Elasticity		Poisson's Ratio	Strain Hardening Exponent
	PL		0.2% Yield		Ultimate				EL	R.A				
	MPa	(ksi)	MPa	(ksi)	MPa	(ksi)	MPa	(ksi)	(%)	(%)	$MPa \times 10^3$	$(ksi \times 10^3)$		
4	664.0	(96.3)	881.2	(127.8)	1019.7	(147.9)	1432.0	(207.7)	10.2	42.5	153.8	(22.3)	0.29 0.28**	0.092
5	708.1	(102.7)	908.7	(131.8)	1076.3	(156.1)	1602.4	(232.4)	12.0	52.2	167.5	(24.3)	0.30 0.28**	0.096

* Actual fracture load divided by the area at fracture.
** Determined at ambient temperature.

TABLE 7. — TENSILE STRESS-STRAIN RESULTS FOR GATORIZED® AF2-1DA AT 760°C (1400°F)

Offset (PCT)	S/N AF2-1DA1 Stress MPa	S/N AF2-1DA1 Stress (ksi)	S/N AF2-1DA1 Strain IN/IN × 10^{-3}	S/N AF2-1DA2 Stress MPa	S/N AF2-1DA2 Stress (ksi)	S/N AF2-1DA2 Strain mm/mm × 10^{-3}	S/N AF2-1DA3 Stress MPa	S/N AF2-1DA3 Stress (ksi)	S/N AF2-1DA3 Strain mm/mm × 10^{-3}
PL	703.3	(102.0)	3.91	730.2	(105.9)	4.17	743.9	(107.9)	4.22
0.025	805.3	(116.8)	4.78	839.8	(121.8)	5.04	822.5	(119.3)	4.91
0.050	837.0	(121.4)	5.22	874.9	(126.9)	5.52	856.3	(124.4)	5.35
0.100	874.9	(126.9)	5.91	903.2	(131.0)	6.13	890.1	(129.1)	6.09
0.150	895.6	(129.9)	6.57	922.5	(133.8)	6.78	911.5	(132.2)	6.74
0.200	909.4	(131.9)	7.26	937.7	(136.0)	7.43	926.7	(134.4)	7.30
0.300	935.6	(131.9)	8.35	961.5	(139.5)	8.57	949.4	(137.7)	8.52
0.400	954.9	(138.5)	9.52	983.2	(142.6)	9.74	968.7	(140.5)	9.65
0.500	974.2	(141.3)	10.70	999.7	(145.0)	10.87	987.3	(143.2)	10.78
0.800	1015.6	(147.3)	14.91	1041.8	(151.1)	14.26	1030.8	(149.5)	14.17
1.000	1037.7	(150.5)	16.26	1060.4	(153.8)	16.43	1056.3	(153.2)	16.39
1.500	1068.0	(154.9)	19.35	1086.6	(157.6)	21.78	1097.0	(159.1)	21.74
2.000	1079.0	(156.5)	26.78	1095.6	(158.9)	26.96	1116.3	(161.9)	27.04
2.500	1081.8	(156.9)	31.96	1097.0	(159.1)	32.17	1123.2	(162.9)	32.26

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TABLE 8. — TENSILE STRESS-STRAIN RESULTS FOR INCO 718 AT 649°C (1200°F)

	S/N 4			S/N 5		
	Stress		Strain	Stress		Strain
Offset (PCT)	MPa	(ksi)	m/m × 10^{-3}	MPa	(ksi)	m/m × 10^{-3}
PL	664.0	(96.3)	4.34	708.1	(102.7)	4.25
0.025	775.4	(112.6)	5.31	814.3	(118.1)	5.13
0.050	818.4	(118.7)	5.84	846.7	(122.8)	5.62
0.100	846.0	(122.7)	6.59	877.7	(127.3)	6.33
0.150	867.4	(125.8)	7.30	899.1	(130.4)	6.99
0.200	881.2	(127.8)	7.63	908.7	(131.8)	7.52
0.500	923.2	(133.9)	11.28	955.6	(138.6)	10.97
1.000	957.7	(138.9)	16.86	989.4	(143.5)	16.50
1.500	979.1	(142.0)	22.35	1012.2	(146.8)	21.99
2.000	992.9	(144.0)	27.61	1026.6	(148.9)	27.26

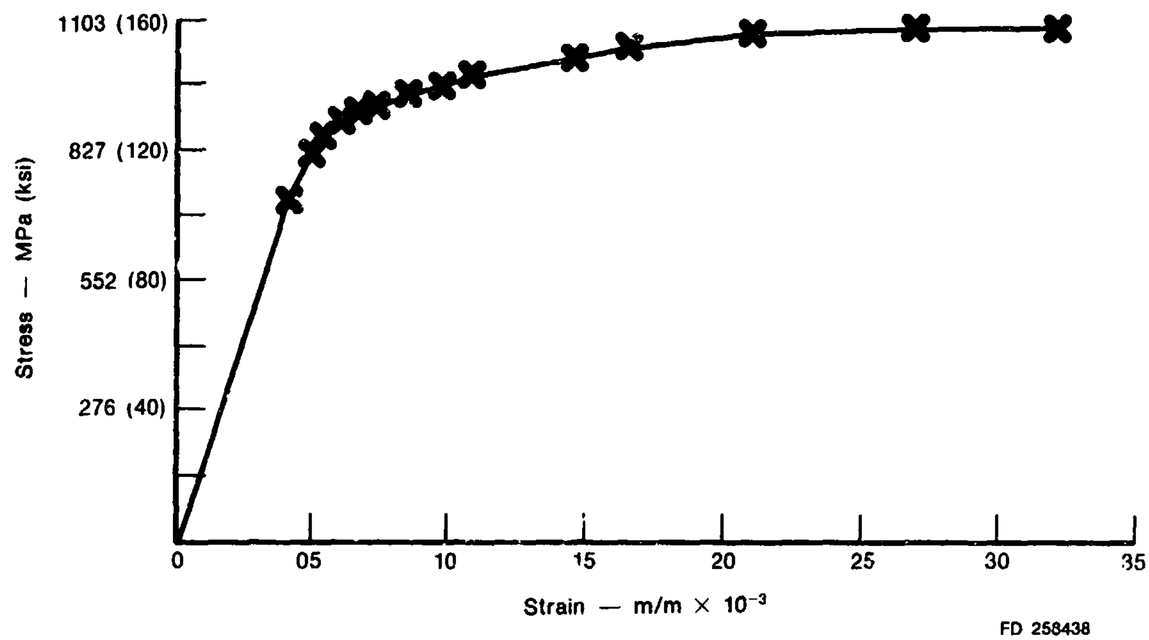

Figure 6. — Average Monotonic Tensile Stress-Strain for AF2-1DA at 760°C (1400°F)

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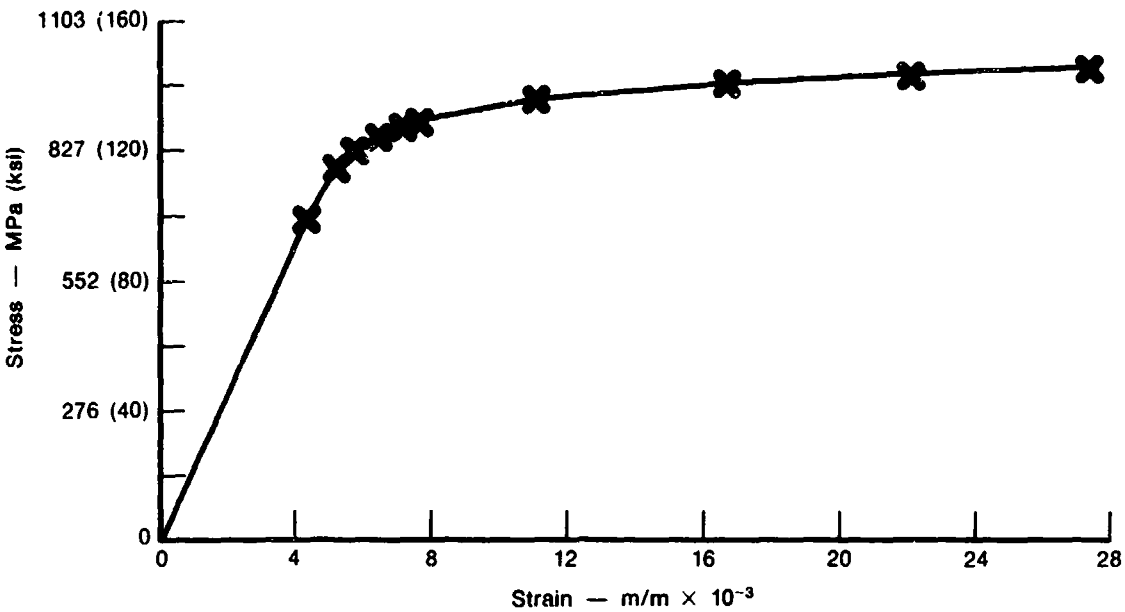

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Figure 7. — Average Monotonic Tensile Stress-Strain for Inconel 718 at 649°C (1200°F)

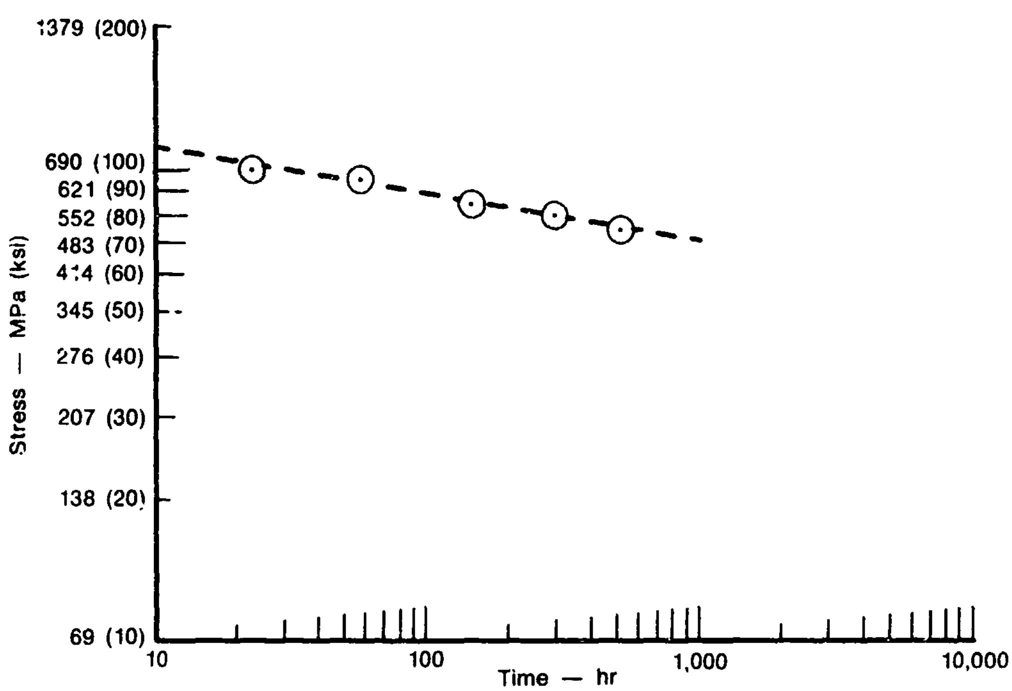

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Figure 8. — Creep Rupture Characterization of AF2-1DA at 760°C (1400°F)

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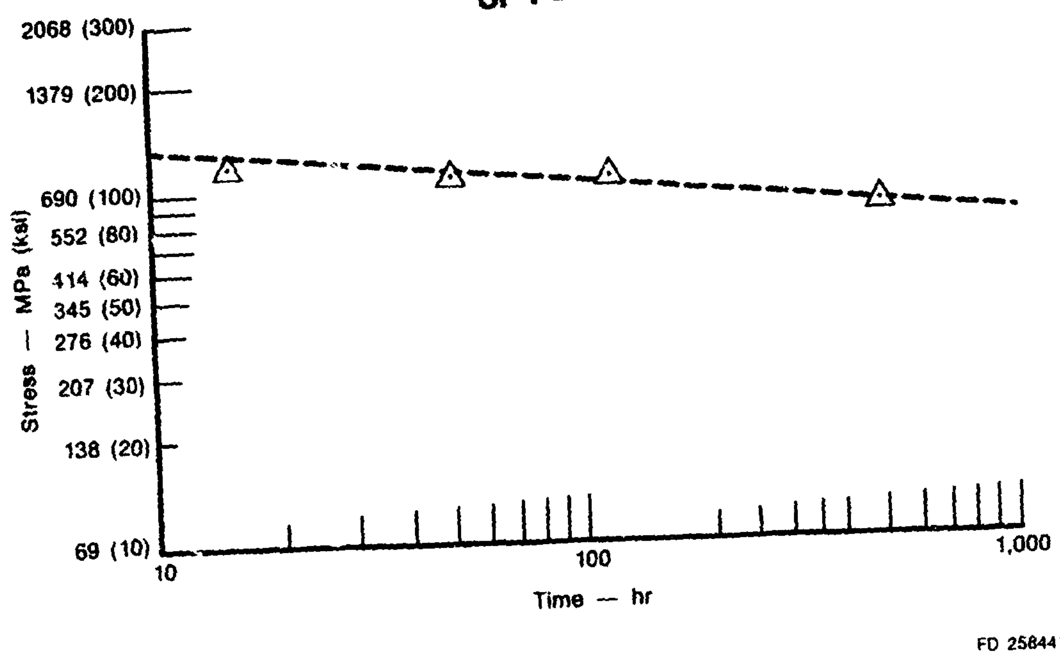

Figure 9. — Creep Rupture Characterization of INCO 718 at 649°C (1200°F)

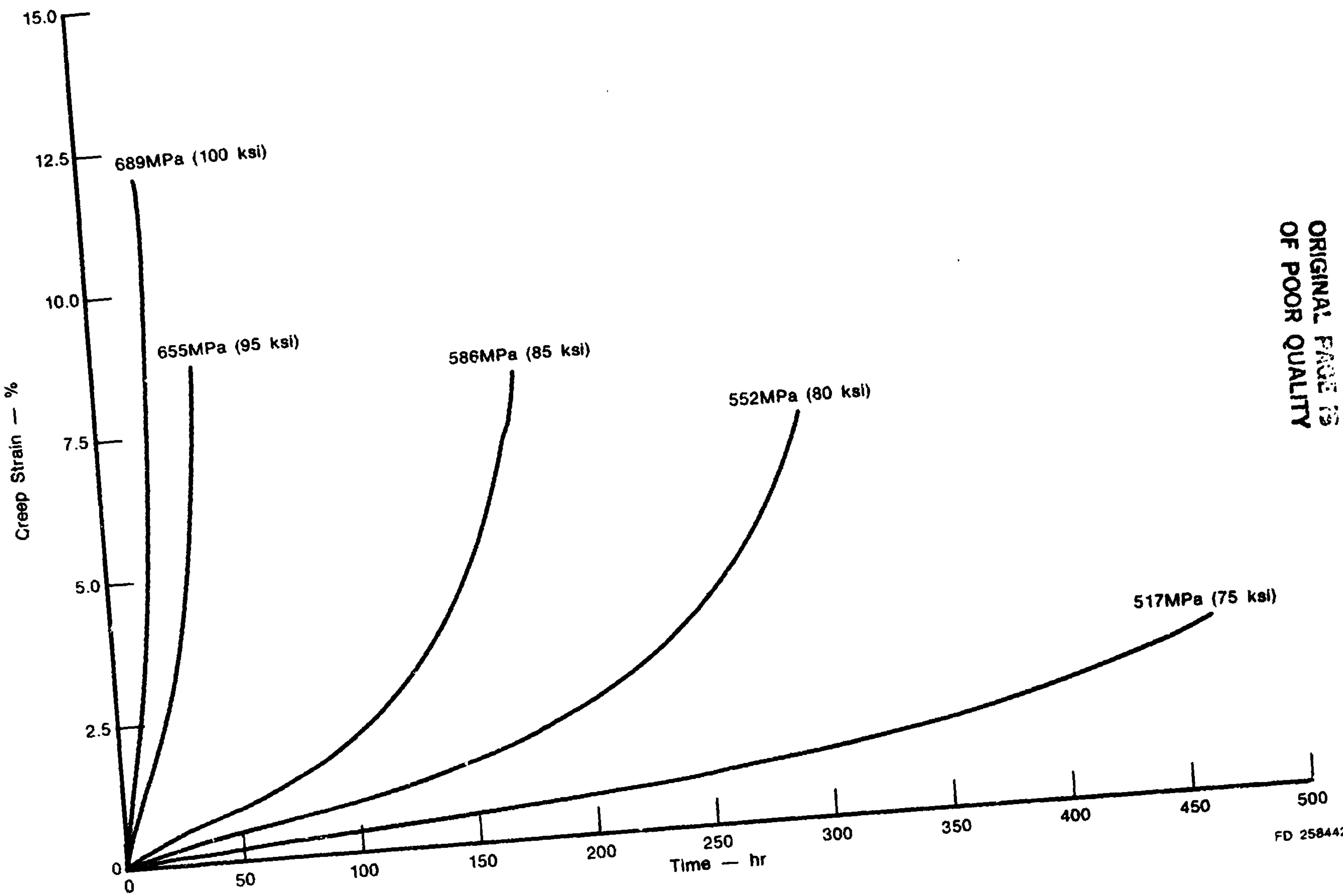

Figure 10. — Creep Strain vs Time for AF2-1DA at 760°C (1400°F)

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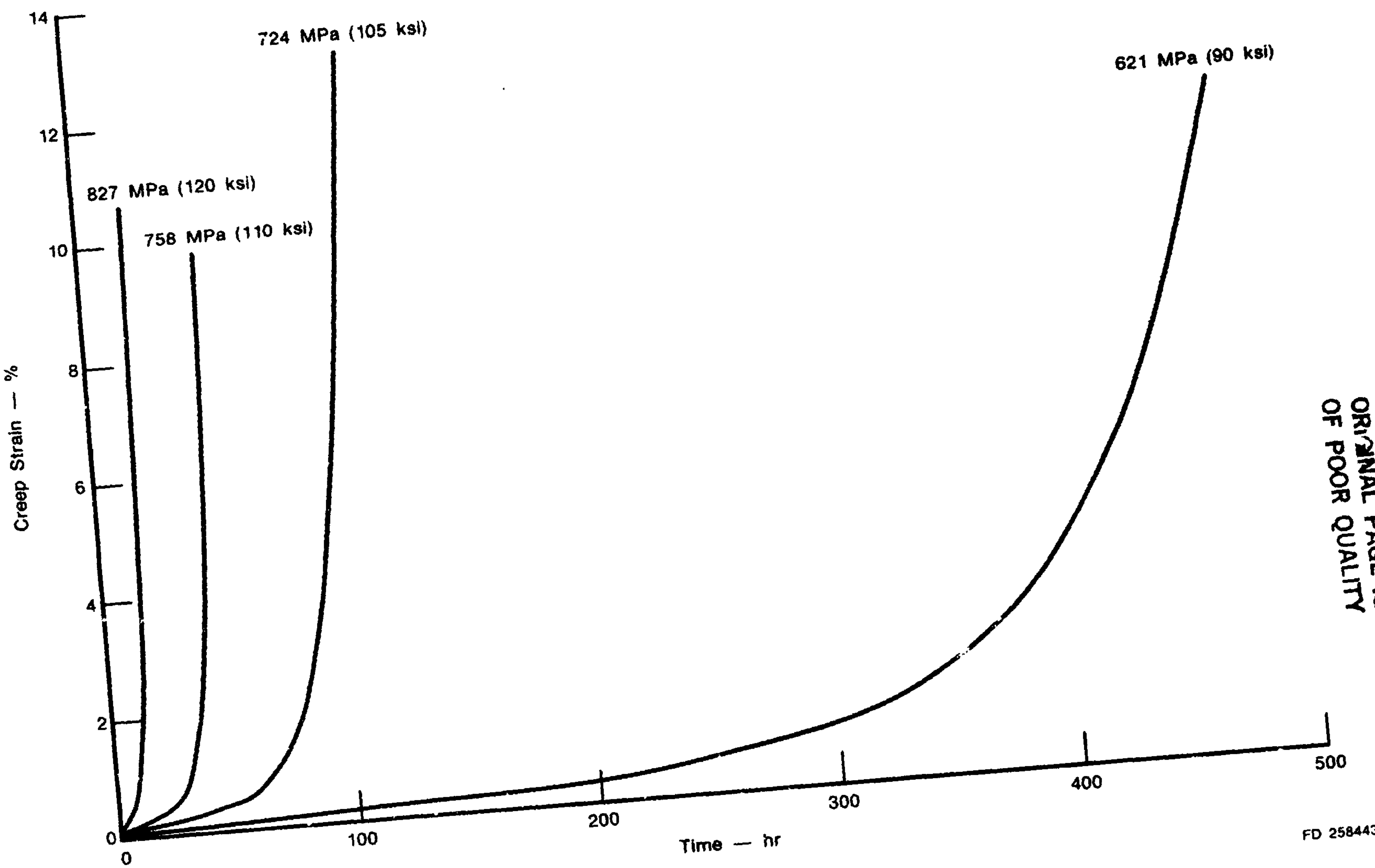

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Figure 11. — Creep Strain vs Time for INCO 718 at 649°C (1200°F)

TABLE 9. — CREEP-RUPTURE PROPERTIES OF GATORIZED® AF2-1DA AT 760°C (1400°F)

Specimen No.	Stress MPa	Stress (ksi)	Strain On Loading[1] (%)	Transient Creep Strain[2] (%)	Steady State Creep Rate (%/hr)	Strain at Onset of Tertiary Creep[3] (%)	Rupture Time (hr)	EL (%)	RA (%)
T-3	517.1	(75)	0.333	0.172	0.0028	0.428	518.1	4.8	9.2
C-1	551.6	(80)	0.347	0.281	0.0073	0.692	295.6	7.4	13.4
C-3	586.1	(85)					146.9	8.7	16.4
1	586.1	(85)	0.385	0.578	0.0137	0.921	177.0	8.1	8.3
T2	655.0	(95)					66.8	6.8	13.1
3	655.0	(95)	0.435	0.581	0.0951	2.007	46.4	10.2	15.4
T4	689.5	(100)					22.9	8.0	16.2
2	689.5	(100)	0.466	0.666	0.1890	2.775	28.5	14.9	18.1

[1] Strain on loading to indicated stress level was all elastic.
[2] Strain between initial loading and achievement of steady state creep.
[3] Strain between initial loading and onset of tertiary creep.

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TABLE 10. — CREEP-RUPTURE PROPERTIES OF INCO 718 AT 649°C (1200°F)

Specimen No.	Stress MPa	Stress (ksi)	Strain On Loading Elastic (%)	Strain On Loading Plastic (%)	Transient Creep Strain[1] (%)	Steady State Creep Rate (%/hr)	Strain at Onset of Tertiary Creep[2] (%)	Rupture Time (hr)	EL (%)	RA (%)
1	620.5	(90)	0.450	0.005	0.072	0.0013	0.184	494.8	28.0	61.3
3	723.9	(105)	0.476	0.009	0.070	0.0053	0.163	116.0	23.7	56.8
4	758.4	(110)	0.581	0.012	0.080	0.0134	0.233	48.3	14.8	52.3
2	827.4	(120)	0.597	0.060	0.175	0.0502	0.335	20.1	13.1	15.9

(1) Strain between initial loading and achievement of steady state creep; includes plastic strain occurring on loading.
(2) Strain between initial loading and onset of tertiary creep; includes plastic strain occurring on loading.

BASIC LOW CYCLE FATIGUE PROPERTIES

Strain control LCF tests characterized the behavior of the AF2-1DA and INCO 718 under both cyclic and cylic/hold conditions. All testing was performed under isothermal conditions at 760°C (1400°F) for AF2-1DA and at 649°C (1200°F) for INCO 718 which represents maximum operating temperatures for the fracture critical areas of an advanced engine turbine compo-nents. In addition, strain control LCF tests were done at other mean stresses, mean strains, variable cyclic hold times, and hold modes (stress hold vs strain hold) to determine the corresponding effects on LCF life. The latter two additional testing types are dicussed later in this report under Creep-Fatigue Evaluations.

Specimen Design, Experimental Procedure and Data Reduction

Specimen Design. — The smooth, cylindrical test specimen used in this program is shown schematically in Figure 12. Specimens of this general configuration have been used extensively for uniaxially loaded strain control LCF testing.

The ratio of net thread area to gage area was increased fom 3:1 to 5:1 for INCO 718 specimens to minimize possiblity of thread failure. This modified version for cylindrical specimens (Figure 13) was used for all INCO 718 cyclic tests.

Specimens were machined by fine mechanical grinding, followed by polishing to provide a smooth surface condition with minimum residual stresses.

All test specimens were visually examined prior to testing in normal light and with fluorescent penetrant to screen for machining anomalies or surface discontinuities. Additionally randomly selected samples underwent through dimensional inspection to ensure conformance to print requirements.

Experimental Procedure. — Currently, there are no ASTM or other accepted industry-wide standards for elevated temperature controlled strain LCF testing. The techniques and specimen for data generation and analysis to be used in this program are discussed below. Where applicable, they conform to ASTM Recommended Practice for Room Temperature Low-Cycle Fatigue Testing (E606).

All testing machines were controlled under a system of calibration and preventive maintenance schedules. System accuracies are within 2%. Approved calibration procedures, records, and National Bureau of Standards (NBS) traceability were retained for all test equipment from which data were obtained.

Isothermal strain-controlled LCF characteristics were determined for this program using servohydraulic, closed-loop-on-axial strain, LCF testing machines designed and built at P&WA/GPD. A typical test machine with controls and readout instrumentation is shown in Figure 14.

Specimen axial strain were measured and controlled by means of a proximity probe extensometer (Figure 15). The extensometer were spring-loaded, rounded knife-edge contact points located within the cylindrical gage length of the specimen. Specimen axial strain causes a relative displacement of the knife edges which was picked up by the proximity probe. The strain output signal from the proximity probe was sent to the electronic control console for demodulation, amplification, filtering, and data processing.

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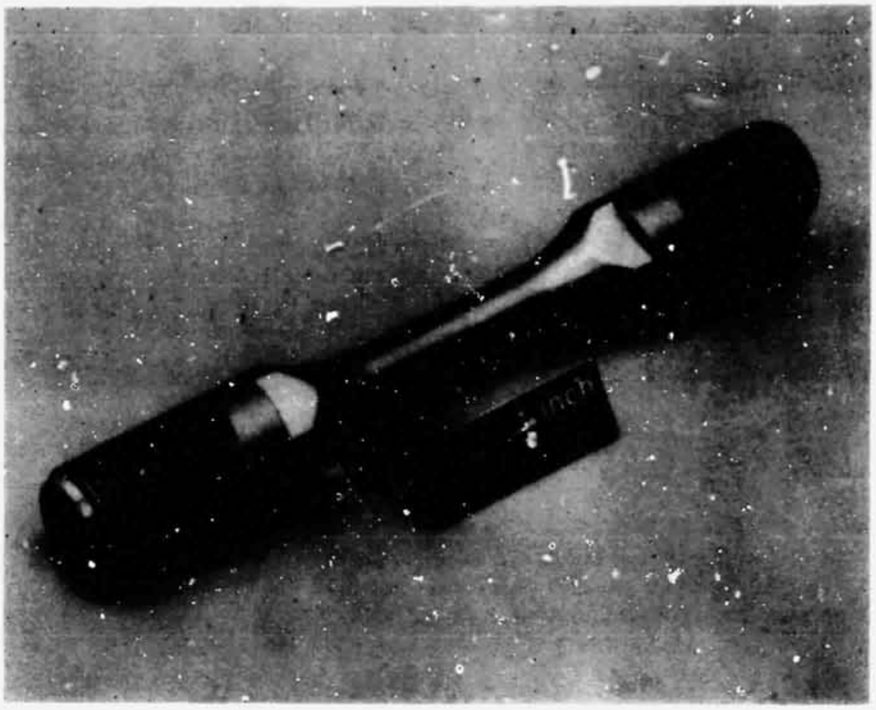

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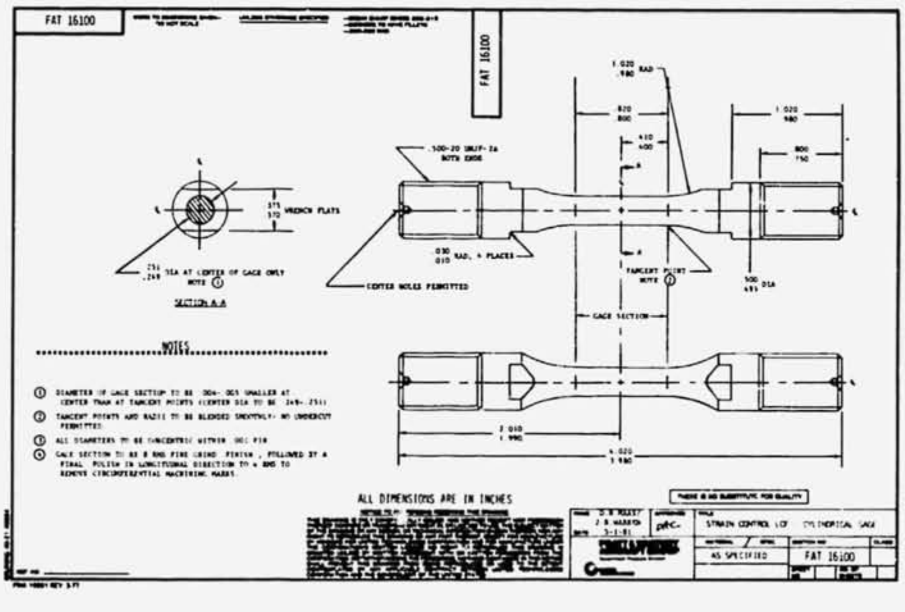

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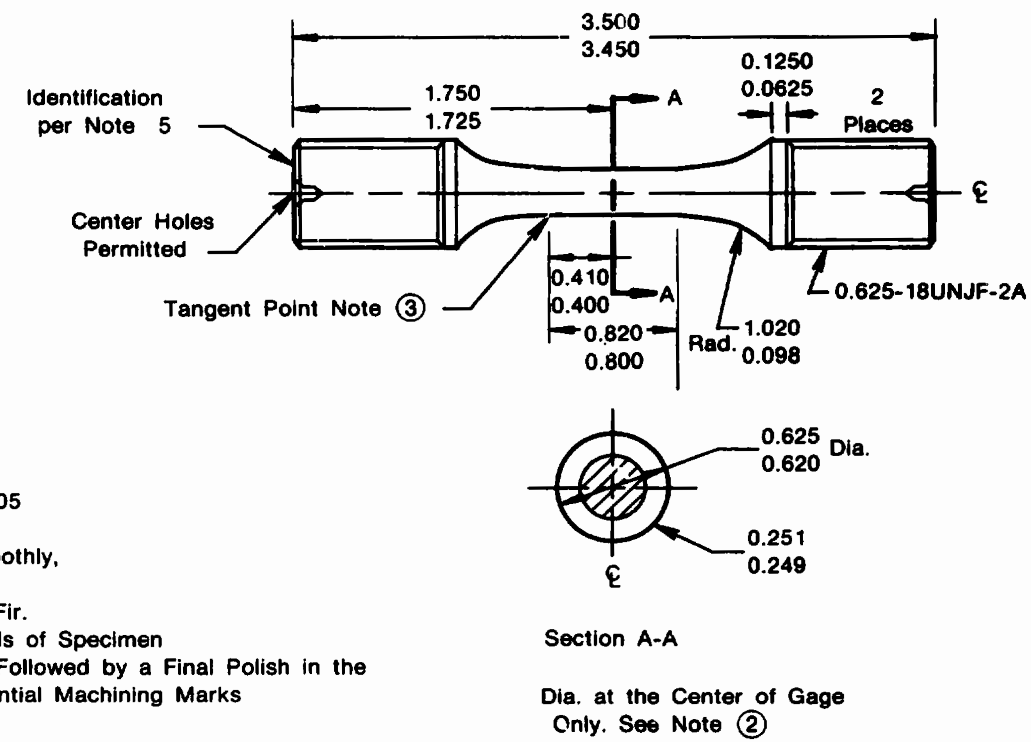
Figure 12. — Strain Control Low Cycle Fatigue (LCF) Specimen (Cylindrical Gage) for Gatorized® AF2-1DA



***** Notes *****

① All Dimensions are in Inches
② Diameter of Gage Section to be 0.004 to 0.005 Smaller than at Tangent Points
③ Tangent Points and Radii to be Blended Smoothly, No Undercut Permitted
④ All Diameters to be Concentric Within 0.001 Fir.
⑤ Identification Markings Permitted Only on Ends of Specimen
⑥ Gage Section to be 8 AA Fine Grind Finish, Followed by a Final Polish in the Longitudinal Direction to Remove Circumferential Machining Marks

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Figure 13. — Strain Control Low Cycle Fatigue (LCF) Specimen (Cylindrical Gage) for Inconel 718

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Figure 14. — Servohydraulic Closed-Loop LCF Test Machine

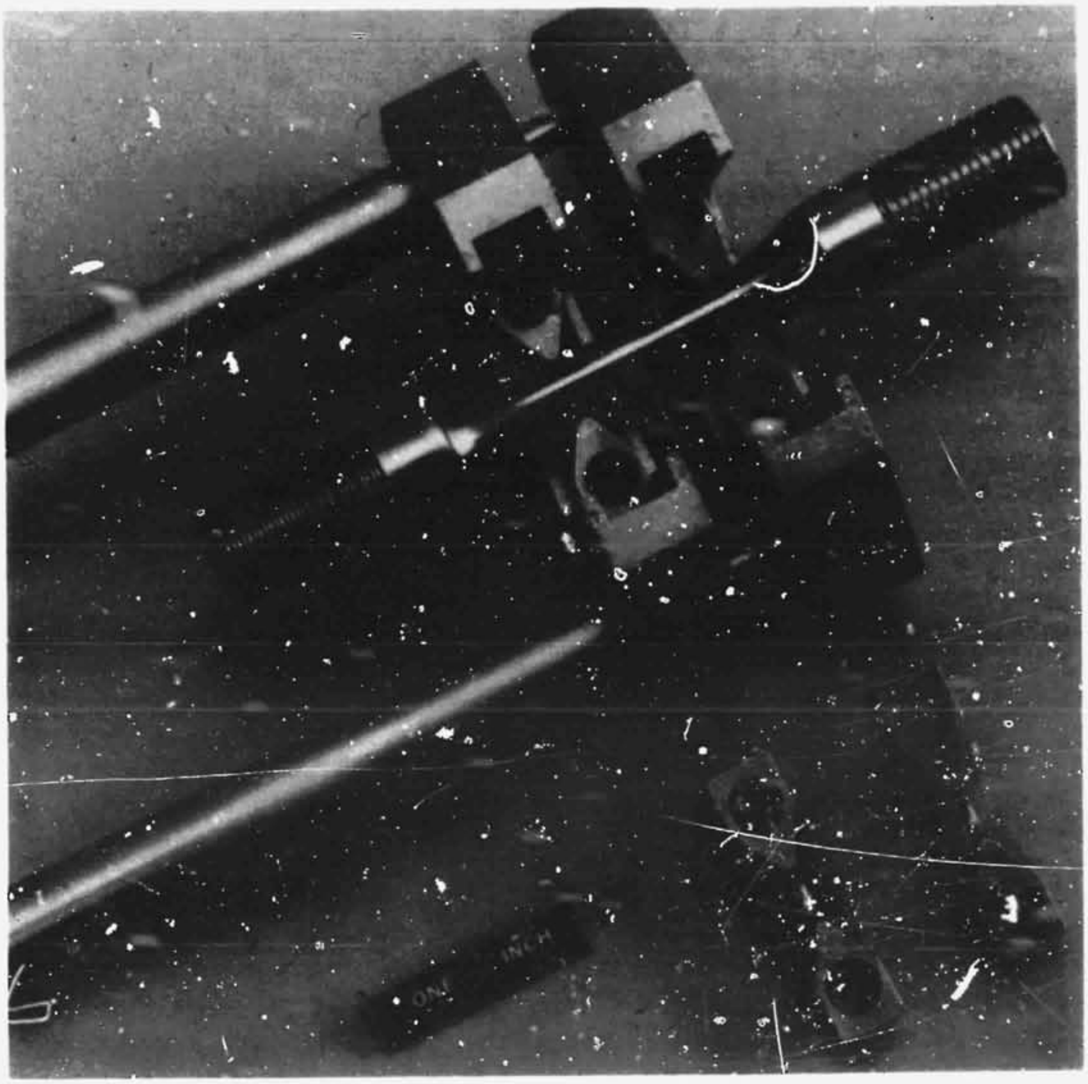

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Figure 15. — Blowup of Extensometer Setup

Load measurement was obtained by a commercial tension-compression load cell and associated electronic equipment for amplification and processing.

An x-y recorder was used for recording load vs strain plots at predetermined cyclic intervals during testing. The recorder was calibrated with the extensometer so that the ratio of specimen collar deflection to x-y recorder pen movement in the x direction was known. The y axis of the x-y recorder was calibrated with the load cell so the ratio of specimen load to x-y recorder y axis pen movement was known. Digital output of all variables (strain, load, temperature) was monitored.

In addition, dual pen stripchart recorders gave a periodic data record of stress range and strain range vs time, inelastic strain vs time for crack initiation determination, and for determination of cycles a particular percent change in stress range drop.

The command signal for the strain cycle was produced by a triangular wave signal generator with feedback from the extensometer output to complete the closed-loop-on-strain circuit necessary for the triangular strain waveform. The frequency and ramp of the triangular wave, and therefore, the strain rate can be adjusted from 11×10^{-5} to 6×10^{-2} cm/cm/sec.

For the hold tests, an adjustable timing circuit in the cycle control unit of the LCF testing machine was used to maintain hold at the required stress or strain. The specimen was strained at the rate set by the signal generator until the required strain (or stress) limit was attained. At this point, the signal generator was switched to a timed "sense and hold" sequence which then maintained the strain (or stress) for the prescribed time period or until a final strain limit was reached. Then the signal generator ramped in the reverse direction to change the strain at the proper strain rate to the opposite limit. When the set point was reached, the command signal reversed direction, and the cycle was repeated.

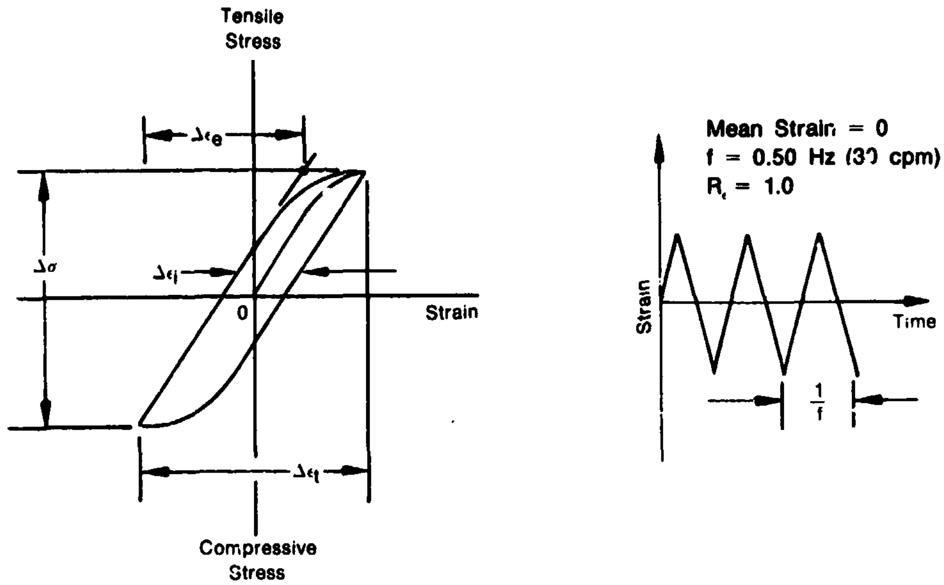
One advantageous feature of these function generators was their ability to be controlled or switched at one endpoint by one variable (i.e., stress) and switched at the other endpoint of the test cycle by a second variable (i.e., strain). In addition, a stress hold could be programmed on one end of the test cycle which used strain as the final control limit (i.e., the variable to be held was relatively independent of the variable which controls the final endpoints).

The continuous cycle strain-controlled LCF tests were conducted at constant total strain ranges to establish cycles to failure in the 10^2 to 10^6 cyclic life range.

The cyclic LCF tests were performed using a sawtooth strain vs time waveform at a frequency of 0.50 Hz (30 cpm). The strain cycle was fully reversed (mean strain equal to zero, R_ϵ minimum strain/maximum strain = −1.0). A typical cyclic LCF test waveform and hysteresis loop are shown in Figure 16.

All specimens were cycled to failure in the strain-controlled test mode. Load-strain hysteresis plots were obtained at intervals throughout the life of the specimen.

The number of cycles to complete specimen separation (N_f), and the number of cycles to produce a 5% drop in the cyclic load range (N_5) were determined for each test. The changes in specimen compliance causing the drop in cyclic load range was used as an indicator for crack initiation.



$\Delta\sigma$ = Total Stress Range
$\Delta\epsilon_t$ = Total Strain Range = $\Delta\epsilon_e + \Delta\epsilon_i$
$\Delta\epsilon_i$ = Inelastic Strain Range
$\Delta\epsilon_e$ = Elastic Strain Range = $\Delta\epsilon_t - \Delta\epsilon_i$
R_ϵ = Minimum Strain/Maximum Strain
f = Cyclic Frequency

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Figure 16. — Typical LCF Cycle, R_ϵ −1

The total strain and the elastic and inelastic strain components were determined at the specimen half-life ($N_f/2$) from the hysteresis plots taken during each test. The strain components are described in Figure 16.

All tests were conducted in air at 760°C (1400°F) for AF2-1DA and at 649°C (1200°F), respectively. Temperature was controlled uniformly over the specimen gage section using calibrated thermocouple temperature readout and control instrumentation.

Data Analysis. — All specimens were cycled to failure with load-strain hysteresis plots obtained at intervals throughout the life of the specimen. Stripchart monitoring of creep strain, stress relaxation, and stress or strain ranges were obtained. The number of cycles to first indication of failure by cracking, N_o, was determined by the first indication of deviation in the stabilized stress range or by deviation in the inelastic compliance vs life stripchart plot.

In addition, where applicable, the following were determined: (a) the number of cycles to 10% drop in the stabilized ratio of peak tensile stress to peak compressive stress, N_i; (b) the number of cycles to 5 and 50% drop in the stabilized load rage, N_5 and N_{50}; and (c) the cycles to failure by complete separation of the specimen, N_f.

From the hysteresis plots obtained during each test, the total, elastic, inelastic, and creep strain ranges at the half-life cycle, $N_{f/2}$, were calculated. Further, the stress range, stress relaxation per cycle, and mean stress were reported at $N_{f/2}$.

The cyclic hardening or softening percentage defined as

$$\mathrm{CHP} = \frac{\Delta\sigma_{N_{f/2}} - \Delta\sigma_1}{\Delta\sigma_1} \times 100\,\%,$$

where

CHP = Cyclic Hardening (Softening) Percentage,
$\Delta\sigma_{Nf/2}$ = stress range at half life,

and

$\Delta\sigma_1$ = stress range on 1st cycle

were obtained.

Results for each cyclic test are summarized in Appendixes B and C which include:

1. Number of cycles to first indication of failure by cracking, N_o
2. Number of cycles to 10 percent drop in stabilized ratio of peak tensile stress to peak compressive stress, N_i
3. Number of cycles to 5 percent drop in stablilized load range, N_5
4. Number of cycles to 50 percent drop in stabilized load range, N_{50}
5. Number of cycles to failure by complete separation of the specimen, N_f
6. Total strain range at $N_{f/2}$
7. Elastic strain range at $N_{f/2}$
8. Inelastic strain range at $N_{f/2}$
9. Creep strains per cycle at $N_{f/2}$
10. Stress range at $N_{f/2}$
11. Amount of stress relaxation per cycle at $N_{f/2}$
12. Mean stress at $N_{f/2}$
13. Average cyclic frequency of the test
14. Cyclic hardening or softening percentage.

The load range vs number of cycles, N curves were plotted for each test and are contained in Appendix A.

The N_f life data for each test waveform were plotted vs total, elastic, and inelastic strain range. Regression analysis was performed to establish mean life curves for the above data.

The regression model used for the cyclic (0.50 Hz, 30 cpm) tests is a composite exponential function of the form $Y = AN^B + CN^D$, which relates total strain range (Y) to cyclic life (N). The inelastic strain component in this model is the AN^B term, and the elastic strain component consists of the CN^D terms. The inelastic strain was statistically regressed as a log-linear (straight line on log-log paper) function ($Y_I = AN^B$). The elastic strain had the best statistically regressed curve fit as a nonlinear log (straight line on log-log paper) function ($Y_E = CN^D$).

Inelastic strain range data for all alloys has been adjusted to conform to the following reporting system:

If measured $\Delta\epsilon_I$ was:	*Then reported $\Delta\epsilon_I$ was:*
$0.00005 < \Delta\epsilon_I < 0.00015$	0.0001

This was required due to the relative inaccuracy of the inelastic strain data on this order of magnitude and due to the significant effect that these data could exhibit on the linear regressions of inelastic strain. Inelastic strain range data less than 0.0001 (< 0.0001) as reported, were not used for regression analyses.

The methodology of summing independent log-linear (or nonlinear) regressions of the elastic and inelastic strain components ($Y = Y_I + Y_E$ where Y = total strain, Y_I = inelastic strain, and Y_E = elastic strain) has been used with excellent agreeement with the actual total strain data generated in this program. Figure 17 illustrates this method of component strain summation.

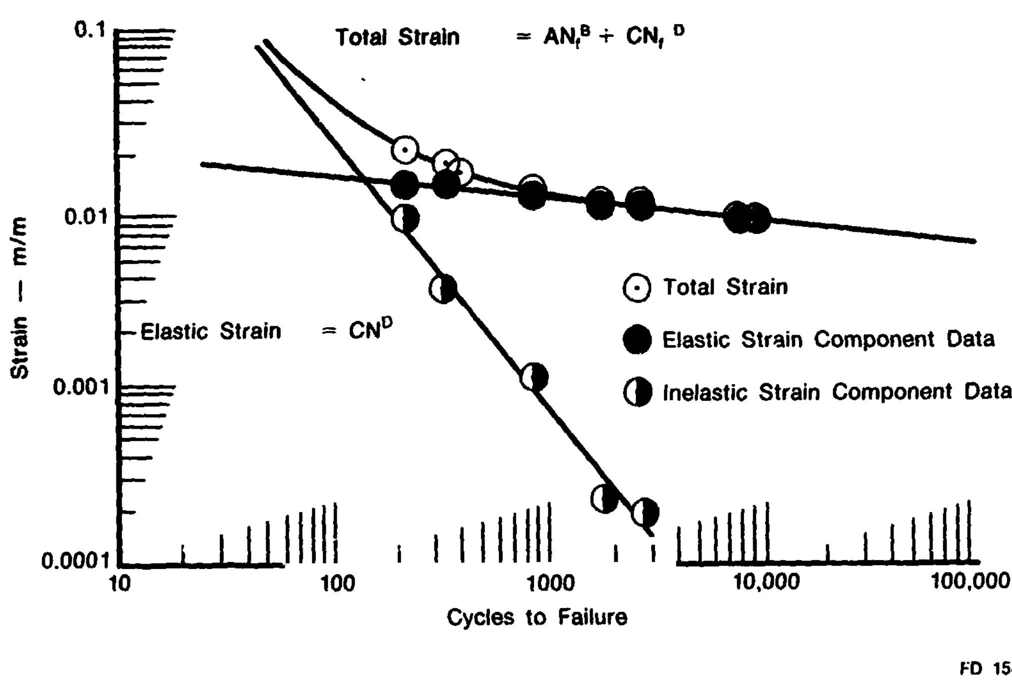

Figure 17. — Composite Experimental Fatigue Life Model Using Summation of Elastic and Inelastic Strain Components

The coefficients and exponents of this model can be rearranged into a more general form:

$$\Delta\epsilon_T = A(N_f)^B + C(N_f)^D$$

The basic composite exponential function model may be expanded and modified to account for the effects of varying hold time, mean strain (or mean stress) effects, and hold mode (strain-hold or stress-hold).

Also the cyclic inelastic strains can be separated into two categories: time independent or plastic strain, and time dependent or creep strain. The total cyclic inelastic strain may be partitioned into four basic categories:

$\Delta\epsilon_{pp}$: tensile plastic strain reversed by compressive plastic strain
$\Delta\epsilon_{cc}$: tensile creep strain reversed by compressive creep strain
$\Delta\epsilon_{cp}$: tensile creep strain reversed by compressive plastic strain
$\Delta\epsilon_{pc}$: tensile plastic strain reversed by compressive creep strain.

It may then be possible to establish strain-life relationships for each of the four generic cycle types. The strain-life relations are expressed in the form

$$\Delta\epsilon_{ij} = A_{ij}\, N_{ij}^{\ B_{ij}}$$

where the first subscript refers to the predominant tensile inelastic strain component (i.e., plastic or creep), and the second subscript refers to the corresponding predominant compressive component.

Upon completion of testing, all data was screened statistically for outliers based on the mean regression lives established for each alloy. Spurious observations were repeated when necessary. Any test results which appeared incongruous were subjected to metallographic and fractographic evaluation to aid in explanation of the anomaly.

Continuous Cycle Fatigue Properties

Completely Reversed Continuous Cycle. — Isothermal axial strain controlled LCF tests were performed on AF2-1DA at 760°C (1400°F) and on INCO 718 at 649°C (1200°F) under completely reversed strain conditions. Six tests each were performed at a frequency of 0.5 Hz (30 cpm) using a triangular strain vs time waveform. The tests were performed in an iterative sequence to define the number of cycles to failure between 100 and 100,000 cycles.

The test results are summarized in Tables 11 and 12 for GATORIZED® AF2-1DA and INCO 718, respectively. The baseline strain vs life curves are plotted in Figures 18 and 19, respectively.

The results of LCF test are presented in Tables 11 and 12 as N_f — cycles to failure (complete separation, of the test specimen as a function of total strain range, $\Delta\epsilon_T$. The total strain range for half-life ($N_{f/2}$ hysteresis loop) was analyzed to separate elastic ($\Delta\epsilon_e$) and inelastic strain ($\Delta\epsilon_I$) strain components. Stress range for the first cycle 1 ($\Delta\Sigma_1$) and for the half-life cycle ($\Delta\Sigma_{Nf/2}$) and mean stress at half-life (Σ_m) are also presented. The hardening and softening behavior of each test as compared to its initial cycle were also computed as per method discussed previously.

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TABLE 11. — CONTINUOUS CYCLE CONTROLLED STRAIN LCF RESULTS FOR GATORIZED® AF2-1DA

Testing Conducted in Air at 760°C (1400°F) at 0.3 Hz (30 cpm) Ramp Frequency, $R_\epsilon = -1$

	Strain (m/m at $N_{f/2}$)				Mean Stress	Stress Range			N_f	T_f (Min)
Spec S/N	Range %	Elastic %	Inelastic %	Creep %	$N_{f/2}$ MPa (ksi)	Cycle 1 MPa (ksi)	$N_{f/2}$ MPa (ksi)	Cyclic Stability %	Cycles to Failure	Time to Failure
7	1.485	1.150	0.335	—	−26.3 (−3.8)	2050.5 (297.4)	2208.4 (320.3)	7.7 Hardening	114	4
12	1.260	1.085	0.175	—	−40.7 (−5.9)	1900.9 (275.7)	1971.2 (285.9)	3.7 Hardening	221	11
9	1.000	0.930	0.070	—	−29.9 (−4.3)	1752.0 (254.1)	1730.6 (251.0)	1.2 Softening	678	23
10	0.735	0.720	0.015	—	−54.5 (−7.9)	1418.3 (205.7)	1386.5 (201.1)	2.2 Softening	4,957	165
13	0.650	0.645	0.005	—	38.3* (5.6)	1208.7 (175.3)	1190.7 (172.7)	1.5 Softening	27,087	903
14	0.500	0.495	0.005	—	−39.5 (−5.7)	982.5 (142.5)	974.2 (141.3)	0.9 Softening	196,657	6,555

*Mean strain at $N_f/2$ was not zero

TABLE 12. — CONTINUOUS CYCLE CONTROLLED STRAIN LCF RESULTS FOR INCO 718

Testing Conducted in Air at 649°C (1200°F) at 0.5 Hz (30 cpm) Ramp Frequency, $R_\epsilon = -1$

Spec S/N	Strain (m/m at $N_{f/2}$) Range %	Elastic %	Inelastic %	Creep %	Mean Stress $N_{f/2}$ MPa (ksi)	Stress Range Cycle 1 MPa (ksi)	$N_{f/2}$ MPa (ksi)	Cyclic Stability %	N_f Cycles to Failure	T_f (Min) Time to Failure
9	1.500	0.765	0.735	—	0.0 (0.0)	1876.1 (271.1)	1394.8 (202.3)	25.7 Softening	542	18
6	1.250	0.782	0.468	—	0.0 (0.0)	1740.9 (252.5)	1323.1 (191.9)	24.0 Softening	825	28
2	1.000	0.750	0.250	—	−31.7 (−4.6)	1643.0 (238.3)	1235.5 (179.2)	24.8 Softening	3,362	112
10	0.930	0.720	0.210	—	−31.7 (−4.6)	1555.5 (225.6)	1236.2 (179.3)	20.6 Softening	5,163	172
11	0.800	0.700	0.100	—	−17.9 (−2.6)	1416.9 (205.5)	1249.2 (181.2)	11.8 Softening	237,391	7,913
4	0.750	0.671	0.079	—	−35.2 (−5.1)	1228.2 (178.2)	1159.0 (168.1)	5.7 Softening	540,944*	18,031

* DNF — Did Not Fail

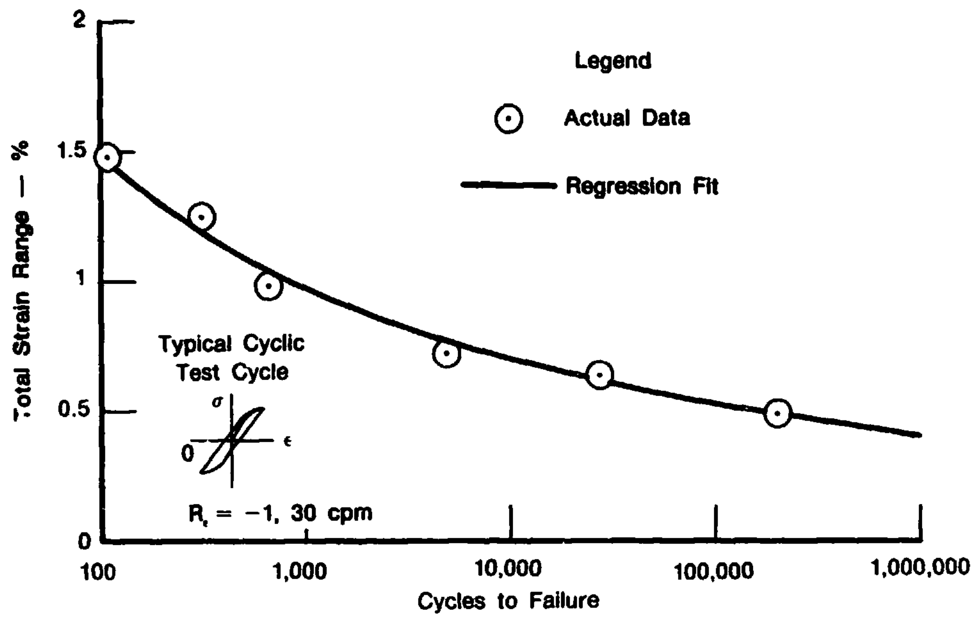

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Figure 18. — Total Strain Range vs Cycles to Failure for Fully Reversed Continuous Cycle GATORIZED® AF2-1DA Data at 760°C (1400°F)

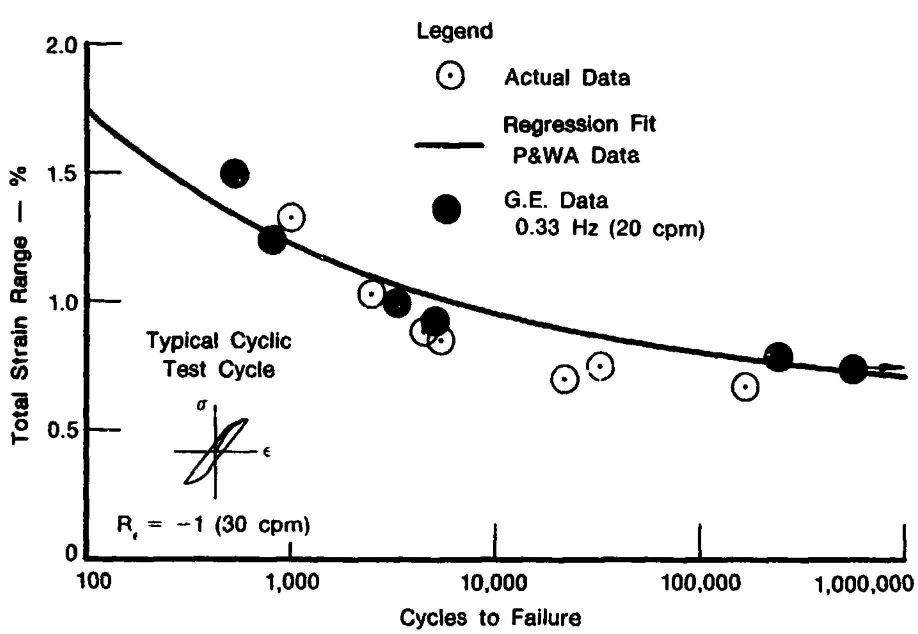

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Figure 19. — Total Strain Range vs Cycles to Failure for Fully Reversed Continuous Cycle INCO 718 Data at 649°C (1200°F)

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In addition, the hysteresis plots generated periodically were analyzed to determine (1) the number of cycles to first indication of failure by cracking, N_o; (2) number of cycles to 10 percent drop in stabilized ratio of peak tensile stress to peak compressive stress, N_i; (3) number of cycles to 5 and 50 percent drop in stabilized load range N_5 and N_{50}; and (4) stress range vs cycle (plots are summarized in Appendix B).

A good agreement is shown in Figure 19 between P&WA and G.E. Data (Reference 8) for INCO 718 generated at similar temperatures and strain ratios. G.E. data are slightly lower at longer lives which may be attributable to frequency effect. All of G.E. data were generated at 0.33 Hz (20 cpm).

Significant cyclic softening was observed at half-life for INCO 718 compared to AF2-1DA. INCO 718 exhibited significant softening for all strain range levels. The magnitude of softening was proportional to the total strain range.

The stress range vs inelastic strain ranges plots for both AF2-1DA and INCO 718 were log-log linear and are shown in Figures 20 and 21, respectively.

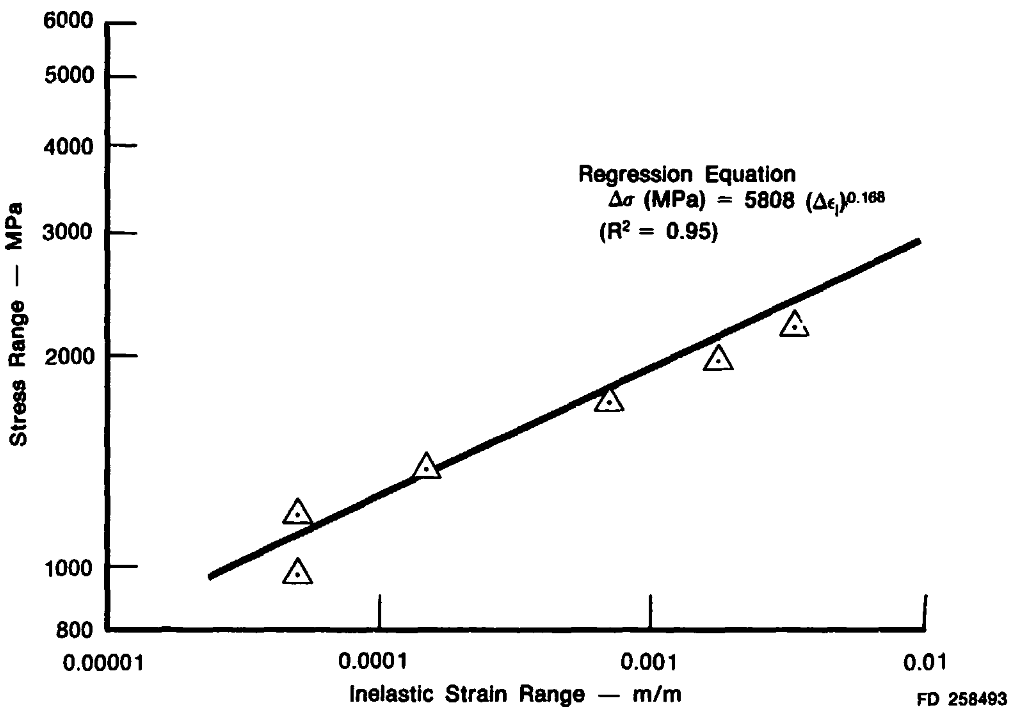

Figure 20. — Stress Range vs Inelastic Strain Range for AF2-1DA, 760°C (1400°F), 30 cpm, Strain Ratio of −1

Figures 22 and 23 illustrate typical stress-strain hysteresis loops at half life for AF2-1DA and INCO 718 respectively.

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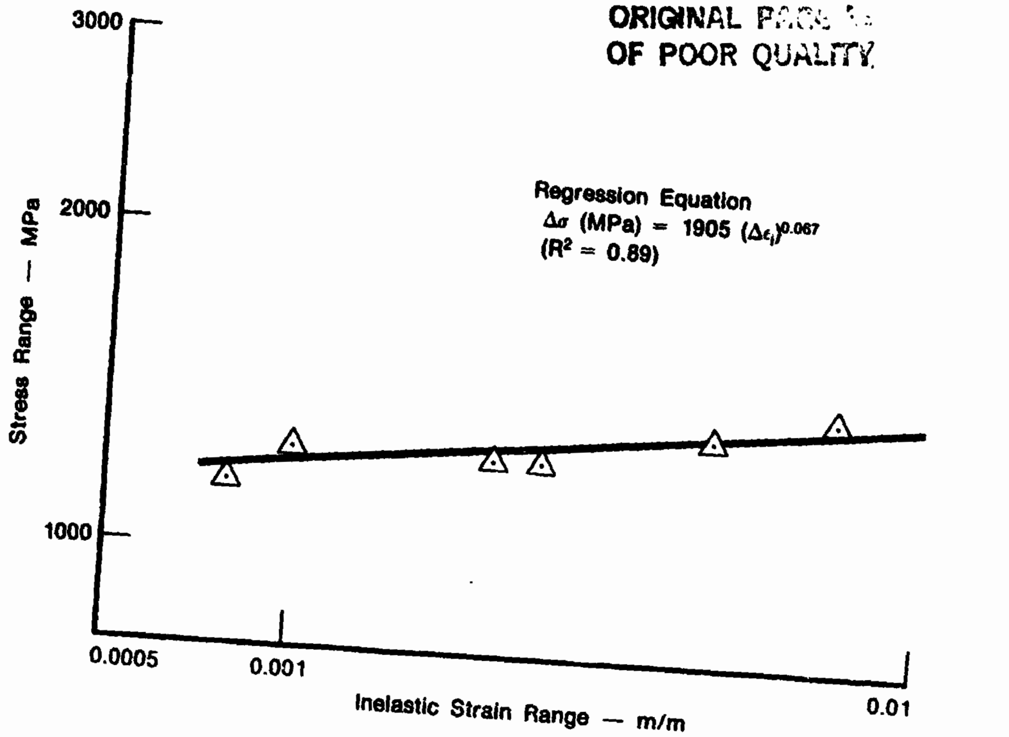

Figure 21. — Stress Range vs Inelastic Strain Range for INCO 718 649°C (1200°F) 30 cpm Strain Ratio of −1

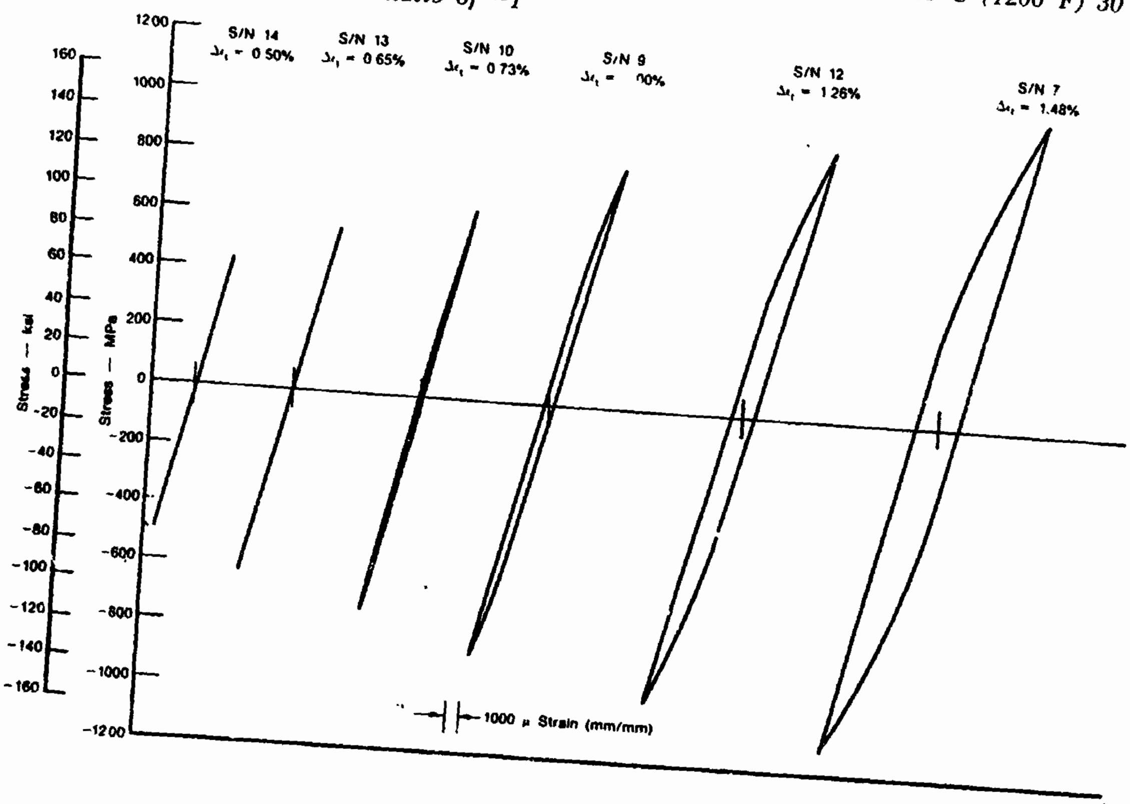

Figure 22. — Typical Hysteresis Loops for GATORIZED® AF2-1DA Cyclic Strain Controlled LCF Tests (Test Frequency = 0.5 Hz; Temp = 760°C (1400°F); Cycles Shown Taken at $N_{f/2}$); R_ϵ = -1

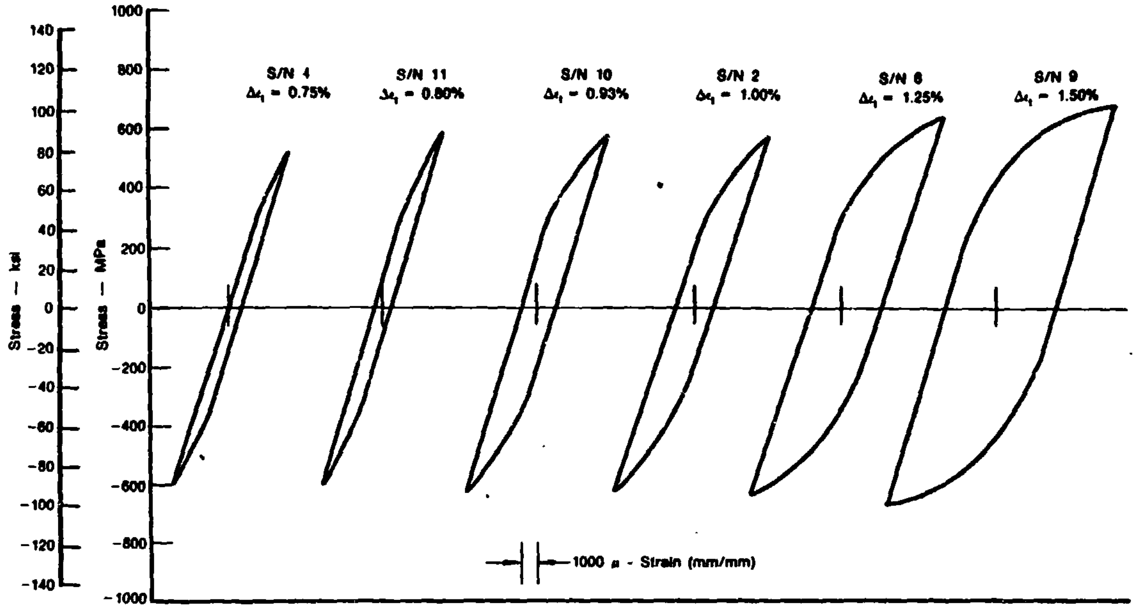

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Figure 23. — Typical Stress Strain Hysteresis Loops for INCO 718 Cyclic-Strain-Controlled LCF Tests (Test Frequency = 0.5 Hz; Temp. = 649°C (1200°F); Cycles Shown Taken at $N_{f/2}$); R_ϵ = -1

CREEP — FATIGUE PROPERTIES

Significant differences occur in the local stress-strain-time material response for different fracture critical locations of aircraft engine turbine disks. Boltholes in disk web areas, for example, may be sufficiently constrained by surrounding essentially elastic material so that their LCF-creep behavior may be approximated by a stress relaxation, or strain-hold cycle. Blade attachment areas at the disk rim, however, may experience some net section creep and, consequently, may be better represented by a creep hold, or constant stress-hold cycle.

Initial waveforms for this phase of testing were selected in an attempt to evaluate differences between a stress-hold cycle (creep hold) and a strain-hold cycle (stress relaxation). Additional waveforms separated the contributions of mean stress and progressively increasing mean strains (due to cyclically unreversed creep) on the LCF life.

Tests were conducted to investigate differences between a basic creep, or stress hold cycle and the relaxation, or strain hold cycle. Both tensile and compressive strain hold types individually and combined were used.

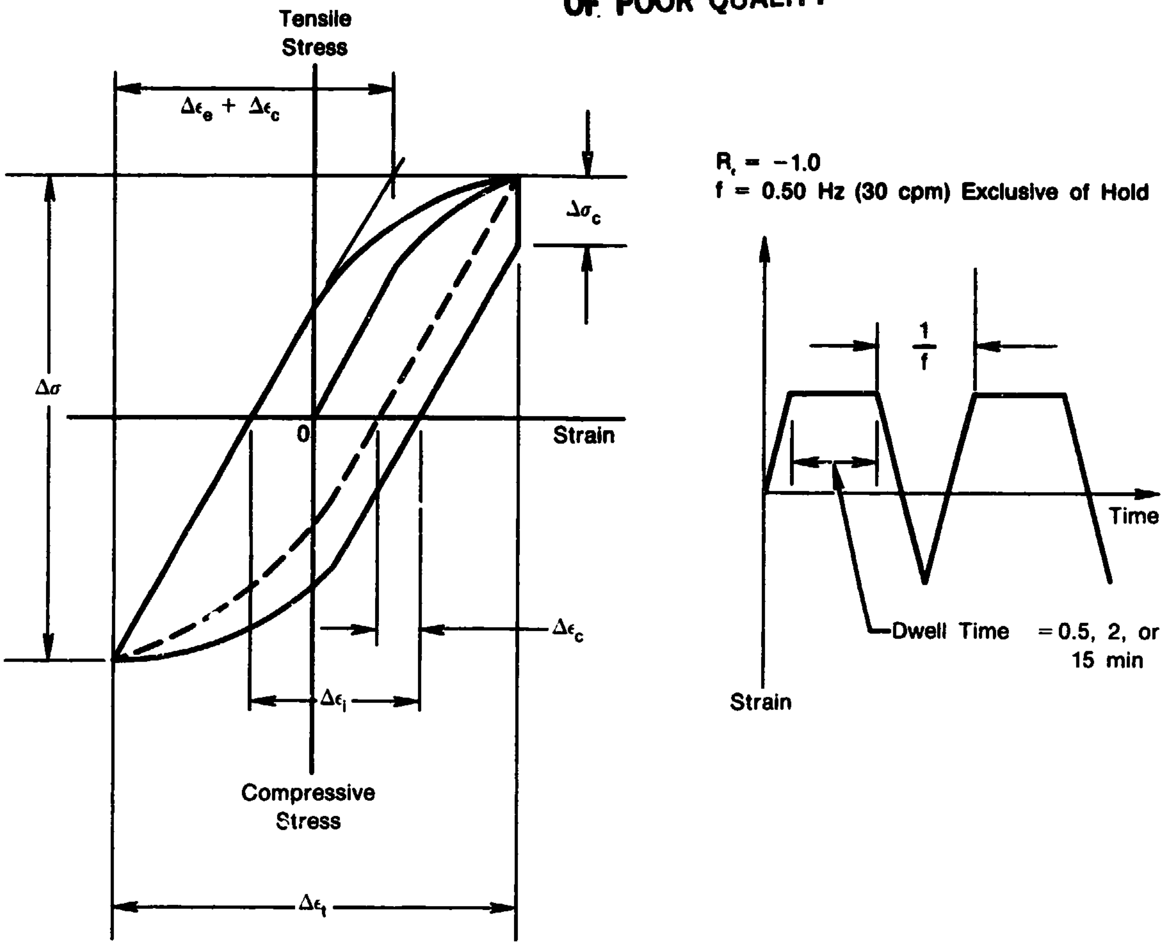
Strain Hold Tests

The strain was held constant for these tests at either maximum tensile, compressive, or tensile and compressive peak strain. The peak stress was allowed to relax for a specified time.

These tests were performed at the same temperature, mean strain, and ramp frequency as the continuous cyclic tests mentioned above, but had a hold time at the maximum peak strain (stress relaxation). The balance of the cycle was performed using the basic frequency used above. Three tests were conducted each of three different hold times of 0.5, 2 and 15 min per cycle. The tests were performed in an iterative sequence to define the number of cycles to failure from 1,000 cycles to a number of cycles equivalent to 1000 hours of testing. The tests were done at 760°C (1400°F) for AF2-1DA® and at 649°C (1200°F) for INCO 718.

Peak Tensile Strain Hold. — These tests had a hold time at maximum peak tensile strain (stress relaxation). A typical peak tensile strain hold cycle is shown in Figure 24. The test results for both GATORIZED® AF2-1DA and INCO 718 are summarized in Tables 13 and 14, respectively. The total strain range vs cycles to failure for all three (0.5 min, 2 min and 15 min) hold times are plotted in Figures 25 and 26 for GATORIZED® AF2-1DA and INCO 718, respectively.

All of the tensile strain hold tests for AF2-1DA had negative mean stresses. Only 15 minute hold cycles showed detrimental effects of hold time compared to continuous cycle data (Figure 25). Stress range at half-life for AF2-1DA indicated little or no (hardening or softening) compared to INCO 718. The degree of strain softening for INCO 718 was higher for the high strain range tests than for the lower strain range tests. Also evident is the degrading effect of hold time on INCO 718 life. Almost all of the tests for INCO 718 showed reduction in cyclic life for tensile strain hold data compared to fully reversed continuous cycle (solid line in Figure 26). The magnitude of life reduction was greater at lower total strain ranges than at the higher total strain ranges.



$\Delta\sigma$ = Total Stress Range
$\Delta\sigma_c$ = Creep Relaxation Stress
$\Delta\epsilon_t$ = Total Strain Range = $\Delta\epsilon_e + \Delta\epsilon_i$
$\Delta\epsilon_i$ = Inelastic Strain Range
$\Delta\epsilon_c$ = Creep Strain Range = $\Delta\epsilon_c$ /E
$\Delta\epsilon_e$ = Elastic Strain Range = $\Delta\epsilon_t - \Delta\epsilon_i$
R = Minimum Strain/Maximum Strain
f = Ramp Frequency (Equivalent to 30 cpm No-Dwell Test)
E = Elastic Modulus

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Figure 24. Typical Tensile Strain Hold LCF Test

Peak Compressive Strain Hold. — Peak compressive strain was held 0.5, 2.0 and 15.0 minutes for these tests. A typical compressive strain hold cycle is shown in Figure 27. A minimum of three tests were done with each of three different hold times of 0.5, 2, and 15 minute per cycle for both alloys.

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TABLE 13. — TENSILE STRAIN HOLD CONTROLLED STRAIN LCF RESULTS FOR GATORIZED® AF2-1DA

Testing Conducted in Air at 760°C (1400°F) AT 0.5 Hz (30 CPM) Ramp Frequency Exclusive of Hold, $R_\epsilon = -1$

Spec S/N	Strain (m/m at $N_f/2$) Range %	Elastic %	Inelastic %	Creep %	Mean Stress $N_f/2$ MPa	(ksi)	Stress Range Cycle 1 MPa	(ksi)	Stress Range $N_f/2$ MPa	(ksi)	Cyclic Stability %		N_f Cycles to Failure	T_f (min) Time to Failure
Peak Tensile Strain 0.5 min Hold				(tensile)										
16	1.245	1.007	0.238	0.093	−112.4	(−16.3)	2109.8	(306.0)	2218.7	(321.8)	5.2	Hardening	396	211
17	1.025	0.910	0.115	0.044	−133.1	(−19.3)	1990.5	(288.7)	2022.2	(293.3)	1.6	Hardening	928	495
18	0.750	0.722	0.028	0.008	−153.8	(−22.3)	1603.7	(232.6)	1539.6	(223.3)	4.0	Softening	17,400	9,280
Peak Tensile Strain 2.0 min Hold														
19	1.200	0.995	0.205	0.110	−113.8	(−16.5)	1881.6	(272.9)	1913.3	(277.5)	1.7	Hardening	312	634
20	1.030	0.892	0.138	0.075	−129.6	(−18.8)	1755.4	(254.6)	1740.9	(252.5)	0.8	Softening	812	1,651
21	0.768	0.713	0.055	0.024	−133.1	(−19.3)	1415.5	(205.3)	1394.8	(202.3)	1.5	Softening	5,380	10,939
Peak Tensile Strain 15.0 min Hold														
24	1.210	0.940	0.270	0.126	−202.0	(−29.3)	2166.3	(314.2)	2124.3	(308.1)	1.9	Softening	197	2,962
23	1.000	0.850	0.150	0.080	−239.9	(−34.8)	2016.0	(292.4)	1942.9	(281.8)	3.6	Softening	716	10,764
26	0.750	0.690	0.060	0.027	−173.7	(−25.2)	1268.6	(184.0)	1183.1	(171.6)	6.7	Softening	3,522	52,947

TABLE 14. — TENSILE STRAIN HOLD CONTROLLED STRAIN LCF RESULTS FOR INCO 718

Testing Conducted in Air at 649°C (1200°F) at 0.5 Hz (30 CPM) Ramp Frequency Exclusive of Hold, $R_\epsilon = -1$

Spec S/N	Strain (m/m at $N_f/2$) Range %	Elastic %	Inelastic %	Creep %	Mean Stress $N_f/2$ MPa	(ksi)	Stress Range Cycle 1 MPa	(ksi)	Stress Range $N_f/2$ MPa	(ksi)	Cyclic Stability %		N_f Cycles to Failure	T_f (min) Time to Failure
Peak Tensile Strain 0.5 min Hold				(tensile)										
13	1.250	0.710	0.540	0.023	−29.6	(−4.3)	1766.4	(256.2)	1309.3	(189.9)	25.9	Softening	606	323*
12	1.060	0.690	0.370	0.043	−6.9	(−1.0)	1671.3	(242.4)	1225.2	(177.7)	26.7	Softening	1,506	803
14	0.800	0.625	0.175	0.020	−43.4	(−6.3)	1403.7	(203.6)	1110.7	(161.1)	20.9	Softening	24,026	12,814*
Peak Tensile Strain 2.0 min Hold														
23	1.250	0.750	0.500	0.031	−67.0	(−9.7)	1757.4	(254.6)	1328.7	(192.5)	24.4	Softening	870	1,769
16	1.000	0.650	0.350	0.046	−28.3	(−4.1)	1540.9	(223.5)	1193.5	(173.1)	22.6	Softening	1,505	3,060
17	0.850	0.665	0.185	0.025	−70.3	(−10.2)	1492.0	(216.4)	1137.6	(165.0)	23.8	Softening	3,941	8,013*
Peak Tensile Strain 15.0 min Hold														
21	1.275	0.785	0.490	0.050	−47.6	(−6.9)	1780.2	(258.2)	1383.8	(200.7)	23.3	Softening	538	8,068
19	1.015	0.740	0.275	0.048	−70.3	(−10.2)	1730.6	(251.0)	1334.1	(193.5)	22.9	Softening	1,329	19,979
24	0.840	0.690	0.150	0.024	−14.5	(−2.1)	1483.1	(215.1)	1245.9	(180.7)	16.0	Softening	5,041	75,783**

*Possible extensometer induced failure
**DNF — Did Not Fail

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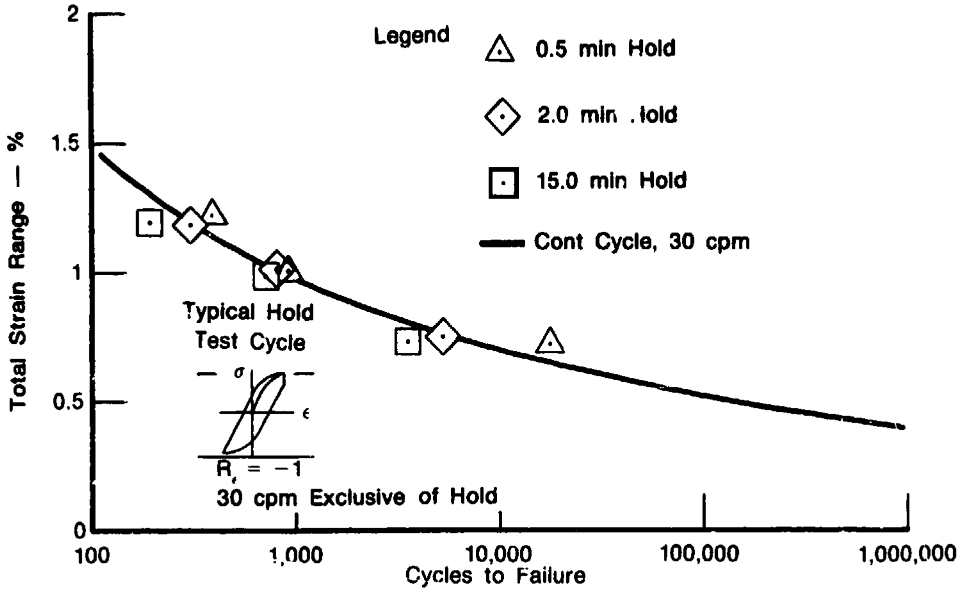

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Figure 25. — Peak Tensile Strain Hold Time Data Results for GATORIZED® AF2-1DA at 760°C (1400°F)

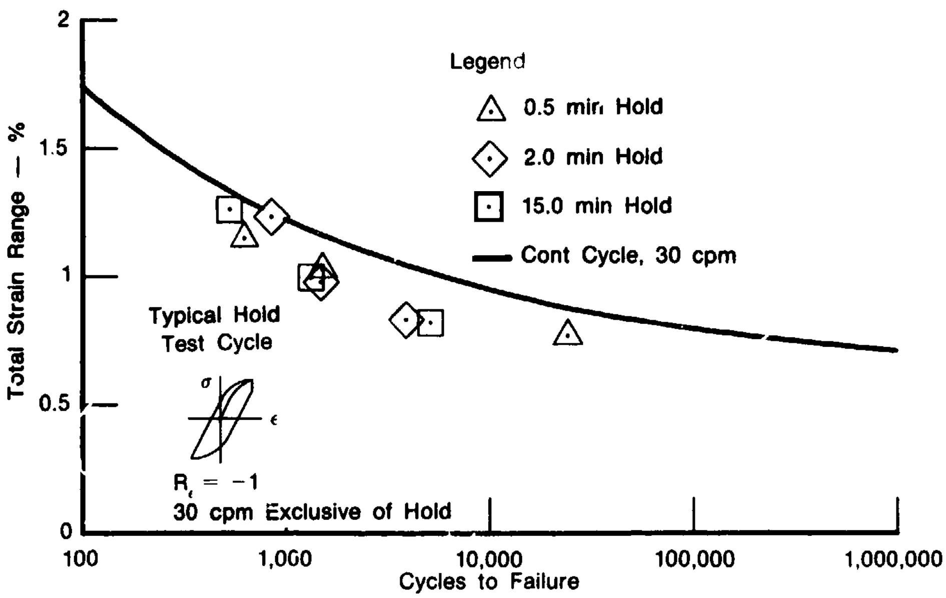

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Figure 26. — Peak Tensile Strain Hold Time Test Results for INCO 718 at 649°C (1200°F)

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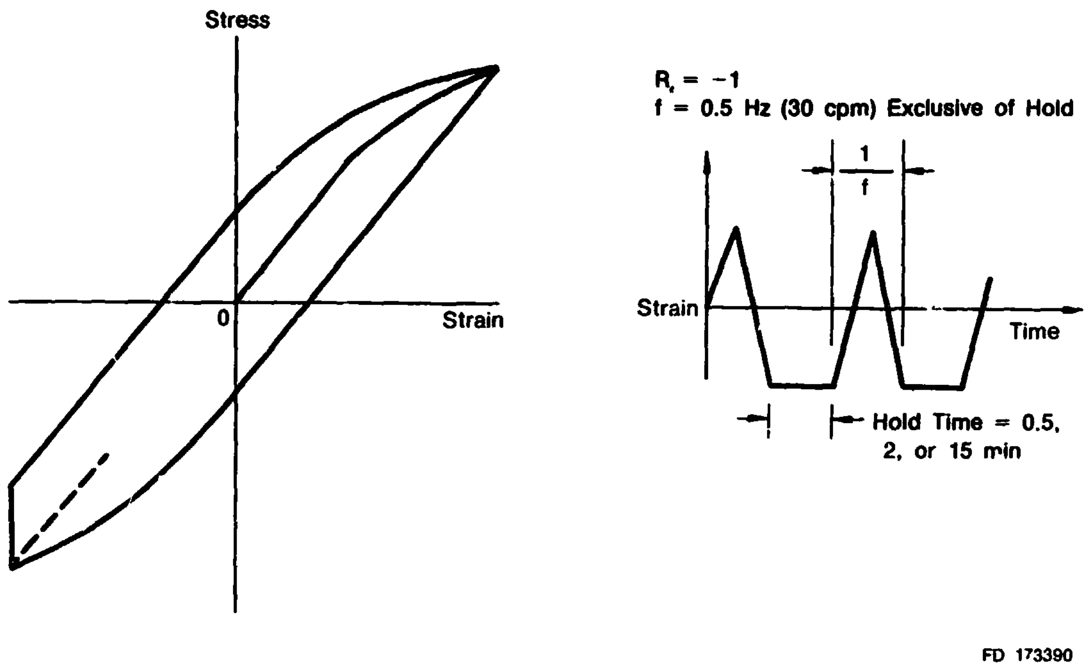

Figure 27. — Typical Compressive Strain Hold LCF Test

The test results for GATORIZED® AF2-1DA and INCO 718 are summarized in Tables 15 and 16, respectively. The assessment of cyclic life debit for both alloys is depicted in Figures 28 and 29.

The effect of compressive strain hold cycle on failure life of both alloys was observed to be detrimental compared to tensile strain hold cycle. The plausible explanation could be the presence of positive mean stresses. The life debit due to compressive strain hold on INCO 718 (Figure 29) was more pronounced compared to AF2-1DA (Figure 28). The magnitude of life debit increased at lower strain ranges and higher hold time (15 min as compared to 0.5 min) for INCO 718.

Peak Tensile and Compressive Strain Hold. — A combination tensile and compressive strain hold LCF test was done similar to those strain hold tests mentioned above but having a hold period at both the peak tensile and peak compressive strains of the cycle. A typical cycle is shown in Figure 30. A total of three tests were performed at 0.5 min hold time for GATORIZED® AF2-1DA. INCO 718 was characterized at all three hold times (0.5, 2.0 and 15.0 min).

The test results are summarized in Tables 17 and 18 for both alloys. Figures 31 and 32 show the comparison of peak tensile and compressive strain hold tests with continuous cycle data.

TABLE 15. — COMPRESSIVE STRAIN HOLD CONTROLLED STRAIN LCF RESULTS FOR GATORIZED® AF2-1DA

Testing Conducted in Air at 760°C (1400°F) at 0.5 Hz (30 CPM) Ramp Frequency Plus Hold, $R_\epsilon = -1$

Spec S/N	Strain (m/m at $N_f/2$) Range %	Elastic %	Inelastic %	Creep %	Mean Stress $N_f/2$ MPa (ksi)	Stress Range Cycle 1 MPa (ksi)	Stress Range $N_f/2$ MPa (ksi)	Cyclic Stability %	N_f Cycles to Failure	T_f (min) Time to Failure
Peak Compressive Strain 0.5 Hold				(compressive)						
27	1.215	1.030	0.185	0.076	31.0 (4.5)	1967.8 (285.4)	1936.0 (280.8)	1.6 Softening	270	144
28	1.015	0.925	0.090	0.047	35.2 (5.1)	1773.3 (257.2)	1752.0 (254.1)	1.2 Softening	880	469
30	0.505	0.500	0.005	0.005	111.7 (16.2)	922.5 (133.8)	961.1 (139.4)	4.2 Hardening	31,174	16,626
Peak Compressive Strain 2.0 min Hold										
33	1.200	0.950	0.250	0.105	56.5 (8.2)	1965.7 (285.1)	2050.5 (297.4)	4.3 Hardening	185	376
34	1.005	0.895	0.110	0.058	83.4 (12.1)	1705.8 (247.4)	1709.9 (248.0)	0.2 Hardening	399	811
31	0.525	0.515	0.010	0.009	150.3 (21.8)	950.8 (137.9)	997.7 (144.7)	4.9 Hardening	22,163	45,065
Peak Compressive Strain 15.0 min Hold										
35	1.200	0.930	0.270	0.123	105.5 (15.3)	1906.4 (276.5)	1980.2 (287.2)	3.9 Hardening	179	2,691
36	1.015	0.885	0.130	0.067	155.1 (22.5)	1744.4 (253.0)	1674.7 (242.9)	3.9 Softening	285	4,285
47	0.750	0.735	0.015	0.020	191.7 (27.8)	1358.3 (197.0)	1323.8 (192.0)	2.6 Softening	1,156	17,379

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TABLE 16. — COMPRESSIVE STRAIN HOLD CONTROLLED STRAIN LCF RESULTS FOR INCO 718

Testing Conducted in Air at 649°C (1200°F) at 0.5 Hz (30 CPM) Ramp Frequency Plus Hold, $R_\epsilon = -1$

Spec S/N	Strain (m/m at $N_f/2$) Range %	Elastic %	Inelastic %	Creep % (compressive)	Mean Stress $N_f/2$ MPa	(ksi)	Stress Range Cycle 1 MPa	(ksi)	Stress Range $N_f/2$ MPa	(ksi)	Cyclic Stability %		N_f Cycles to Failure	T_f (min) Time to Failure
Peak Compressive Strain 0.5 min Hold														
22	1.250	0.762	0.488	0.025	−20.7	(−3.0)	1744.3	(253.0)	1295.5	(187.9)	25.7	Softening	690	368
25	1.020	0.735	0.285	0.030	0.0	(0.0)	1643.0	(238.3)	1214.8	(176.2)	26.2	Softening	2,432	1,29[illegible]
26	0.800	0.640	0.160	0.021	12.4	(1.8)	1385.8	(201.0)	1100.4	(159.6)	25.9	Softening	9,500	5,067
Peak Compressive Strain 2.0 min Hold														
27	1.255	0.725	0.500	0.040	−10.3	(−1.5)	1740.9	(252.5)	1274.8	(184.9)	26.8	Softening	748	1,521
28	1.000	0.700	0.300	0.020	−3.4	(−0.5)	1623.0	(235.4)	1204.4	(174.7)	25.8	Softening	1,587	3,227
29	0.800	0.665	0.135	0.020	61.4	(8.9)	1334.1	(193.5)	1176.2	(170.6)	11.8	Softening	6,872	13,973
Peak Compressive Strain 15.0 min Hold														
30	1.210	0.780	0.430	0.055	49.0	(7.1)	1737.5	(252.0)	1341.5	(194.5)	22.8	Softening	525	7,893
31	1.000	0.750	0.250	0.041	73.8	(10.7)	1576.2	(228.6)	1291.4	(187.4)	18.0	Softening	1,335	20,070
32	0.800	0.700	0.100	0.010	22.8	(3.3)	1348.0	(195.5)	1204.5	(174.7)	10.6	Softening	3,237	48,663

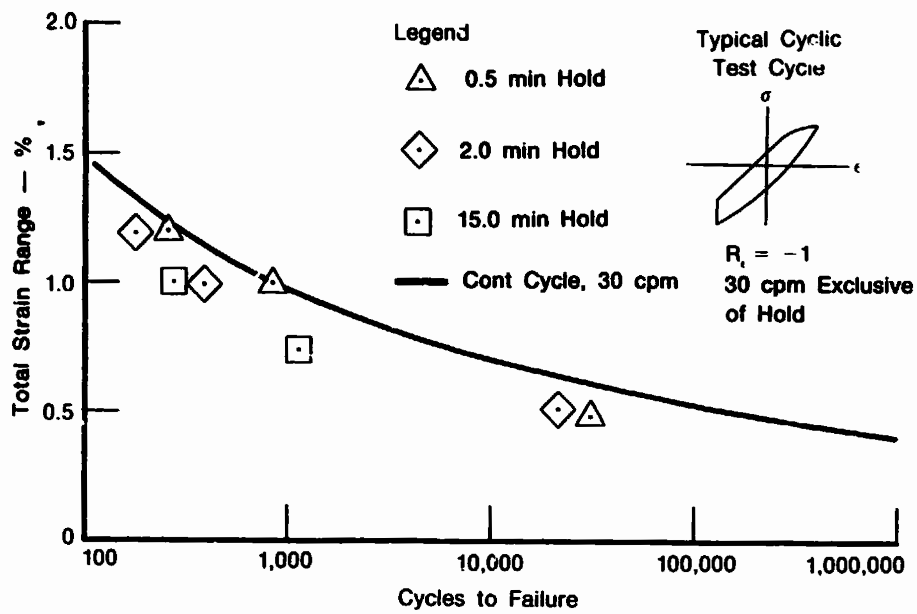

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Figure 28. — Peak Compressive Strain Hold Time Test Results for GATORIZED® AF2-1DA at 760°C (1400°F)

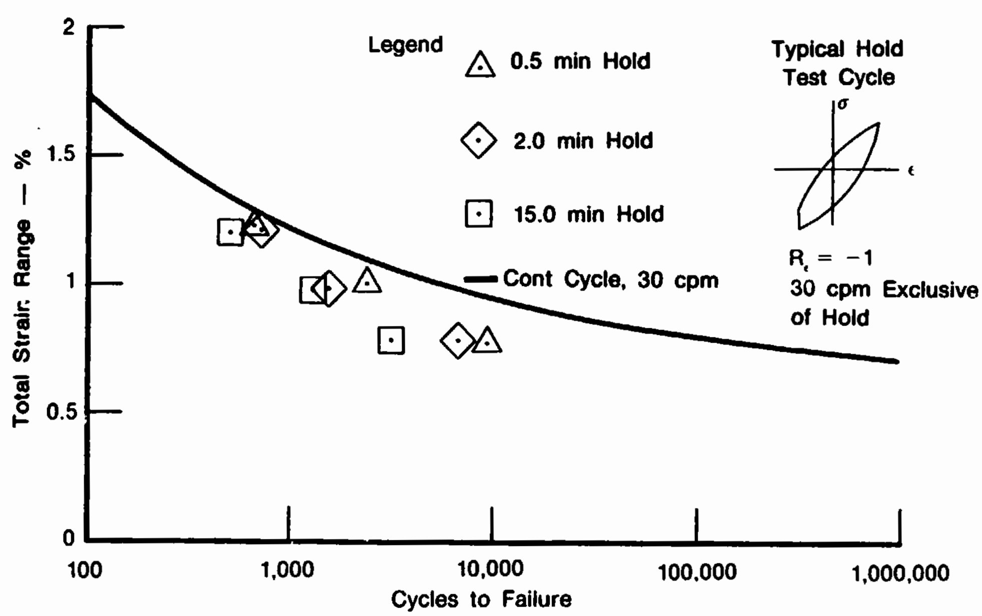

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Figure 29. — Peak Compressive Hold Time Test Results for INCO 718 at 649°C (1200°F)

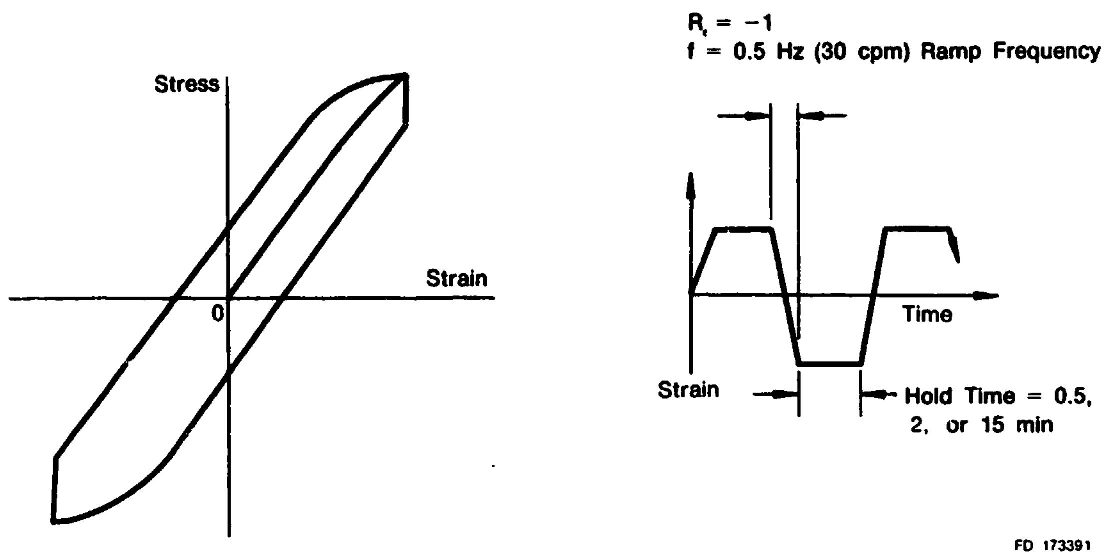

Figure 30. — Typical Tensile-Compressive Strain Hold LCF Test

TABLE 17. — TENSILE AND COMPRESSIVE STRAIN HOLD CONTROLLED STRAIN LCF RESULTS FOR GATORIZED® AF2-1DA

Testing Conducted in Air at 760°C (1400°F) at 0.5 Hz (30 CPM) Ramp Frequency Plus Hold, $R_\epsilon = -1$

Spec S/N	Strain (m/m at $N_f/2$) Range %	Elastic %	Inelastic %	Creep % (ten.)	Creep % (comp)	Mean Stress $N_f/2$ MPa	(ksi)	Stress Range Cycle 1 MPa	(ksi)	Stress Range $N_f/2$ MPa	(ksi)	Cyclic Stability %		N_f Cycles to Failure	T_f (min) Time to Failure
Peak Tensile and Compressive Strain 0.5 Min Hold															
38	1.210	0.970	0.240	0.085	0.053	6.9	(1.0)	1836.8	(266.4)	1967.8	(285.4)	0.7	Hardening	96	99
39	1.000	0.845	0.155	0.056	0.056	−17.9	(−2.6)	1738.2	(252.1)	1734.0	(251.5)	0.2	Softening	771	797
41	0.500	0.490	0.010	0.009	0.009	−56.5	(−8.2)	961.8	(139.5)	958.4	(139.0)	0.4	Softening	25,919	26,783

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TABLE 18. TENSILE AND COMPRESSIVE STRAIN HOLD CONTROLLED STRAIN LCF RESULTS FOR INCO 718

Testing Conducted in Air at 640°C (1200°F) at 0.5 Hz (30 CPM) Ramp Frequency Plus Hold, $R_\epsilon = -1$

Spec S/N	Strain (m/m at $N_f/2$) Range %	Elastic %	Inelastic %	Creep % (ten.)	Creep % (comp)	Mean Stress $N_f/2$ MPa	(ksi)	Stress Range Cycle 1 MPa	(ksi)	Stress Range $N_f/2$ MPa	(ksi)	Cyclic Stability %		N_f Cycles to Failure	T_f (min) Time to Failure
Peak Tensile and Compressive Strain 0.5 Min Hold															
33	1.295	0.675	0.620	0.057	0.048	−40.7	(−5.9)	1794.0	(260.2)	1253.5	(181.8)	30.1	Softening	649	671
38	0.980	0.630	0.350	0.030	0.028	−6.9	(−1.0)	1649.9	(239.3)	1158.3	(168.0)	29.8	Softening	1,632	1,686
42	0.765	0.595	0.170	0.016	0.016	−24.8	(−3.6)	1344.5	(195.0)	1091.4	(158.3)	19.6	Softening	3,411	3,524*
Peak Tensile and Compressive Strain 2.0 Min Hold															
51	1.200	0.650	0.550	0.042	0.036	55.8	(8.1)	1734.0	(251.5)	1192.8	(173.0)	30.9	Softening	723	2,916
54	0.980	0.715	0.265	0.021	0.021	9.0	(1.3)	1624.4	(235.6)	1185.9	(172.0)	27.0	Softening	759	2,916
41	0.800	0.625	0.175	0.026	0.030	35.9	(5.2)	1338.3	(194.1)	1106.6	(160.5)	17.3	Softening	2,358	9,511
Peak Tensile and Compressive Strain 15.0 min Hold															
35	1.205	0.655	0.550	0.067	0.065	−24.8	(−3.6)	1776.8	(257.7)	1259.7	(182.7)	29.1	Softening	321	9,641
37	1.000	0.625	0.375	0.047	0.050	−24.8	(−3.6)	1712.7	(248.4)	1288.7	(186.9)	24.8	Softening	494	14,837
36	0.800	0.615	0.185	0.050	0.050	11.0	(1.6)	1397.6	(202.7)	1158.3	(168.0)	17.2	Softening	840	25,228**

*Possible extensometer induced failure.
**Overload at next cycle.

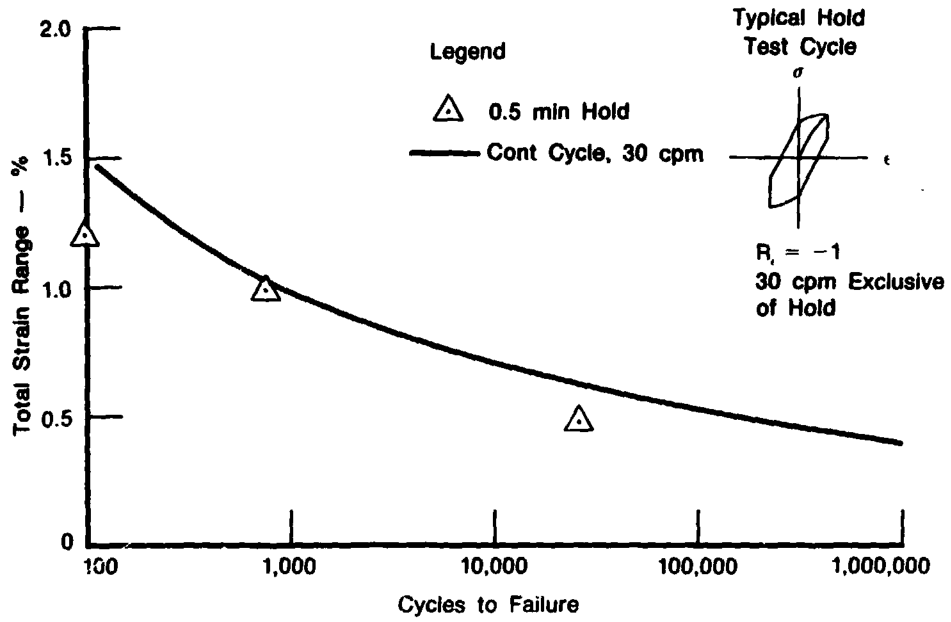

Figure 31. — Peak Tensile and Compressive Strain Hold Data for GATORIZED® AF2-1DA at 760°C

The effect of tensile and compressive hold time on failure life of AF2-1DA was somewhat less than observed for INCO 718 (Figures 31 and 32). As noted previously for tensile only and compressive only strain hold, the magnitude of life degradation due to hold cycle on INCO 718 was higher for lower strain ranges and higher hold time duration. As expected for a balanced loop, the mean stresses for all tests for both alloys were (at or near) zero.

Stress Hold Tests

Completely reversed strain-controlled fatigue tests were performed having a hold time at the peak tensile stress, and a ramp frequency, mean strain, and temperature similar to the cyclic tests. The tensile stress was held at a constant value until the specimen crept to a preselected maximum tensile strain limit, whereupon the balance of the cycle was completed using the basic frequency as described before. Because of cyclic hardening or softening of the specimen, it was necessary to periodically increase or decrease the peak tensile creep stress in order to maintain a repetitive time per cycle. Three different maximum tensile stress levels were selected. For each tensile stress level, the total strain range was iteratively selected to define the number of cycles to failure from 100 cycles to a number of cycles equivalent to 1,000 hours of testing. Tensile stress hold tests were performed only on GATORIZED® AF2-1DA.

Tensile Stress Hold. — Tensile stress hold tests were conducted for GATORIZED® AF2-1DA at peak tensile stress of 620.5 MPa (90 ksi), 482.5 MPa (70 ksi) and 310.3 MPa (45 ksi) at 760°C (1400°F). The tensile stress was held constant until the specimen had crept to a preselected maximum tensile strain limit, then the specimen was unloaded in the compression direction such that the strain cycle was completely reversed. A typical tensile stress hold LCF cycle is shown in Figure 33. Idealized first-cycle hysteresis loops for tensile stress hold LCF testing are shown in Figure 34.

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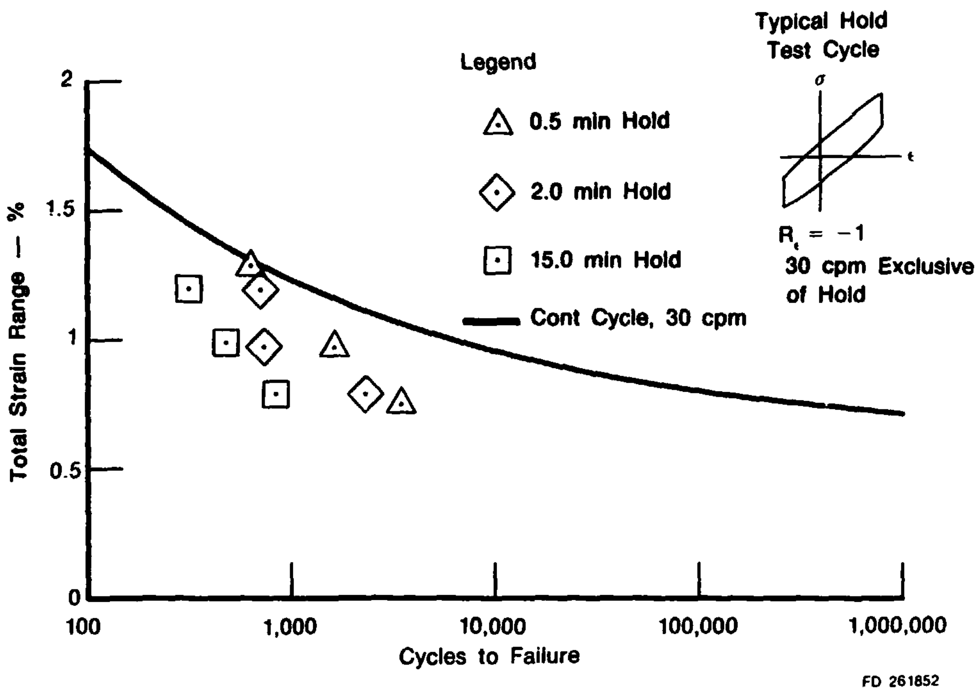
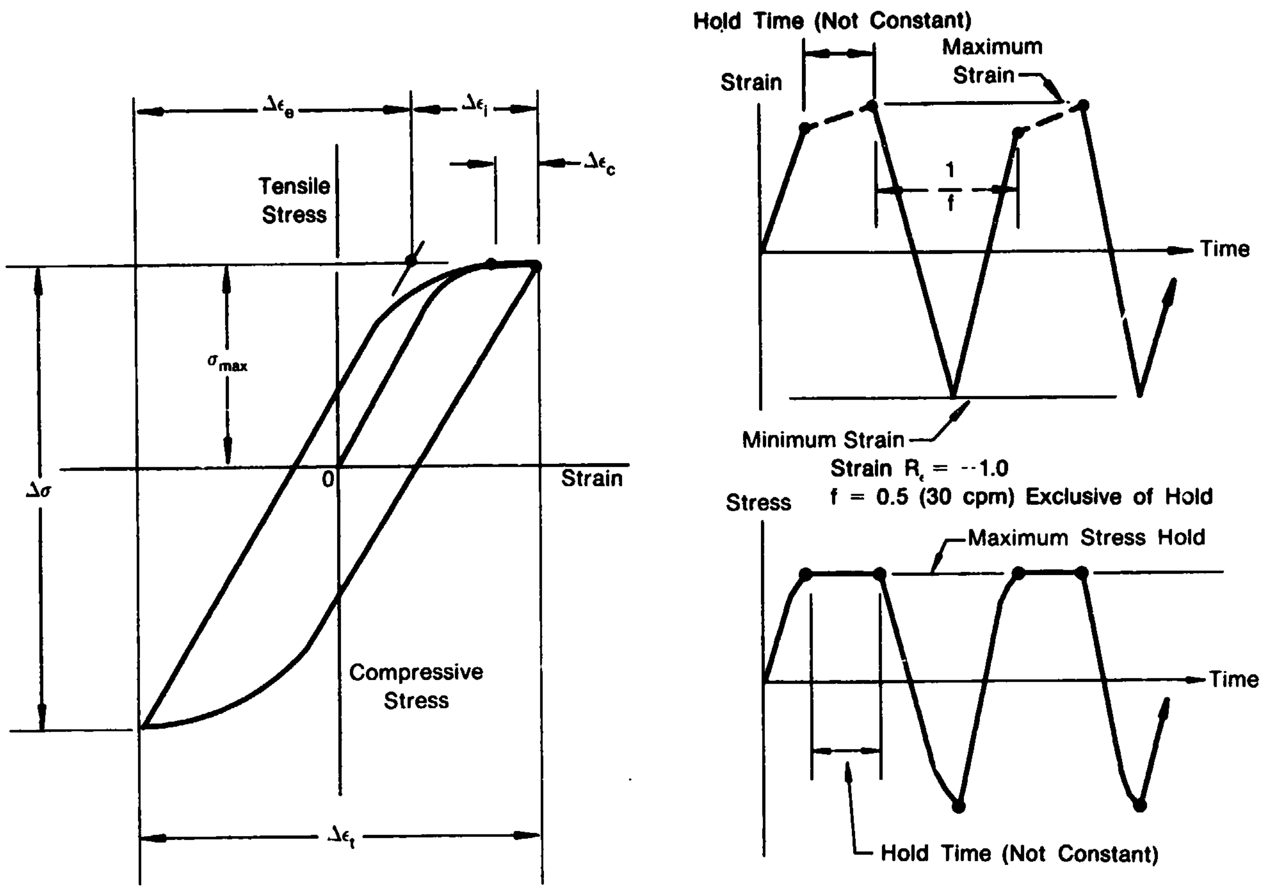


Figure 32. — Peak Tensile and Compressive Strain Hold Data for INCO 718 at 649°C (1200°F)



$\Delta\sigma$	= Total Stress Range
σmax	= Creep Stress (Held Constant to Allow Specimen to Creep)
$\Delta\epsilon_t$	= Total Strain Range
$\Delta\epsilon_i$	= Inelastic Strain Range
$\Delta\epsilon_c$	= Creep Strain Range
$\Delta\epsilon_e$	= Elastic Strain Range
Hold Time	= Hold Time at Max Stress, May Vary Due to Creep Rate
R	= Strain Ratio, Minimum Strain/Maximum Strain
f	= Ramp Frequency (Equivalent to 30 cpm Nondwell Tests)

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Figure 33. — Typical Tensile Stress Hold LCF Test

Compressive Stress Hold. — Compressive stress LCF tests were done at 620.5 MPa (90 ksi) and 482.5 MPa (70 ksi) peak compressive stress similar to the tensile stress hold tests, with the exception that the hold period was held at the maximum compressive stress. The compressive stress was held constant until the specimen crept to a preselected maximum compressive strain limit, then the specimen was loaded in the tension direction such that the strain cycle was completely reversed. Two different maximum compressive stress levels were selected to define

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LCF life from 100 cycles to a number of cycles equivalent to 1000 hours of testing. A typical hysteresis loop and test cycle is presented in Figure 35.

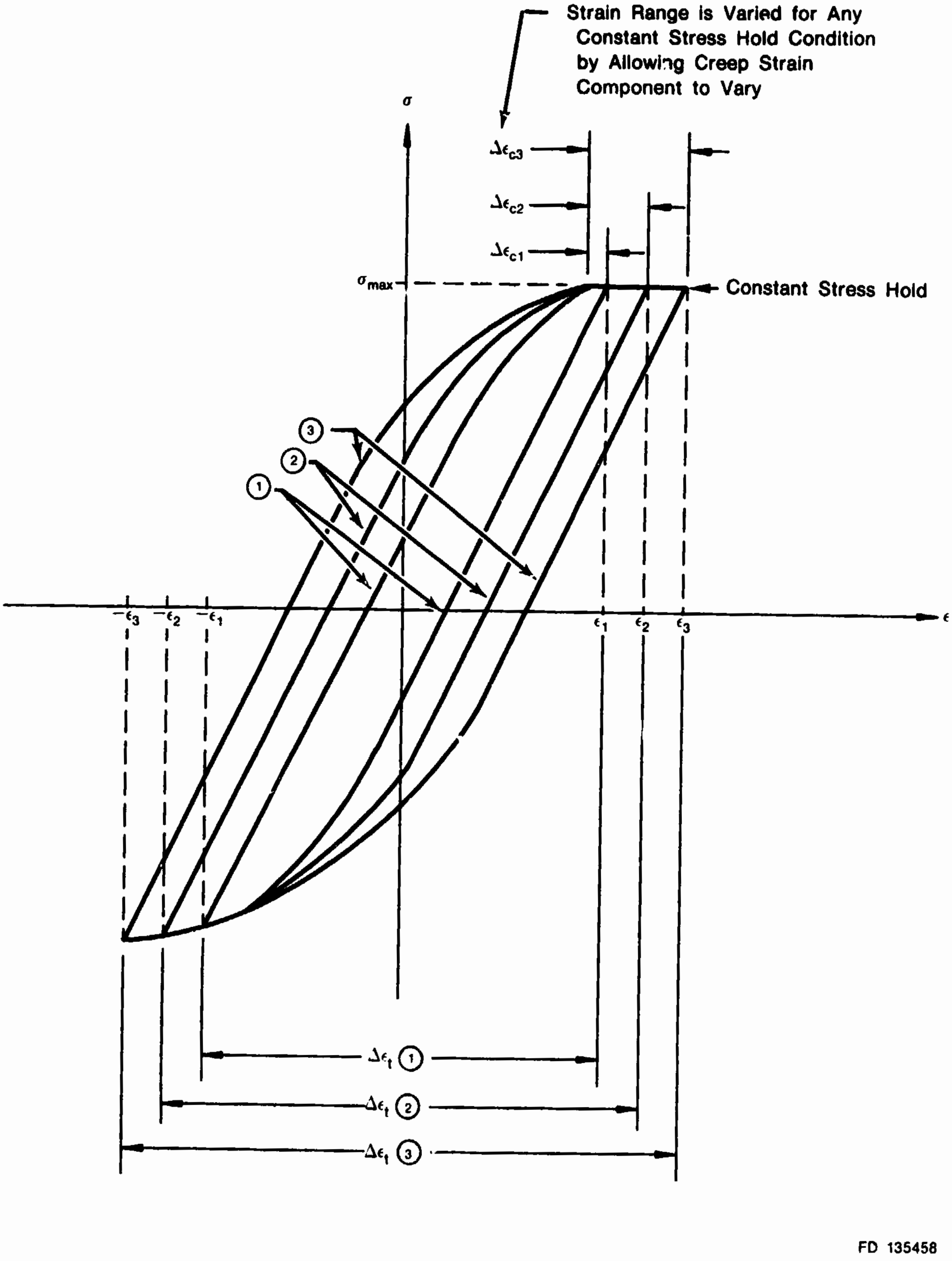

Figure 34. — Idealized First-Cycle Hysteresis Plots for Tensile Stress-Hold LCF Testing

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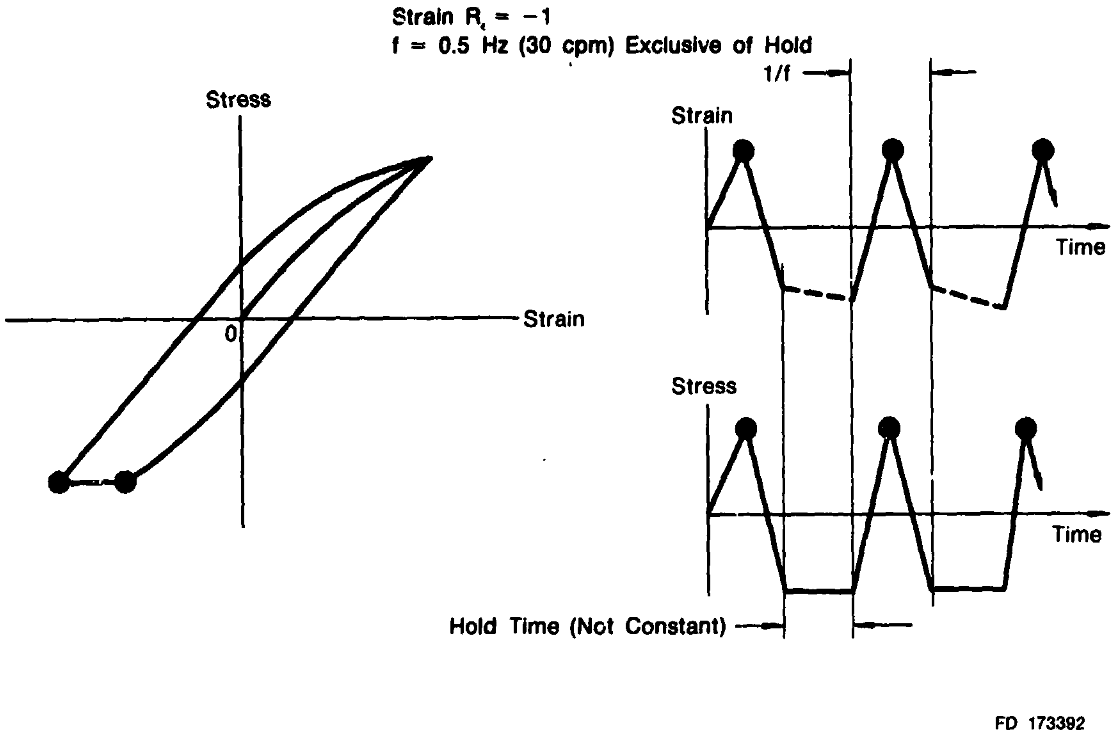

Figure 35. — Typical Compressive Stress Hold LCF Test

Combination Tensile and Compressive Stress Hold. — Combination tensile and compressive stress hold LCF tests were done similar to the stress hold tests mentioned above but having a hold period at both the peak tensile and peak compressive stresses of the cycle. This test cycle is illustrated in Figure 36. Two tests were performed at 620.5 MPa (90 ksi) peak tensile and compressive peak stress.

The combination tensile and compressive stress hold test could simply be conducted with preselected tensile and compressive stresses with fixed hold times at both ends. A small amount of cyclic creep ratcheting may occur if the tensile and compressive creep rates are not equal.

The test results for all stress hold tests for GATORIZED® AF2-1DA are enumerated in Table 19.

The test results showing percent strain range vs life for all stress hold tests and continuous cycle tests are plotted in Figure 37.

The tensile stress hold effect on cyclic life of AF2-1DA seems negligible for 620.5 MPa (90 ksi) and 482.5 MPa (70 ksi) hold cycles. The 310-3 MPa (45 ksi) peak stress hold test ran 41,595 min. (approx 700 hours) and was discontinued. Compressive only and tensile and compressive stress hold tests generally showed life debit (Figure 37).

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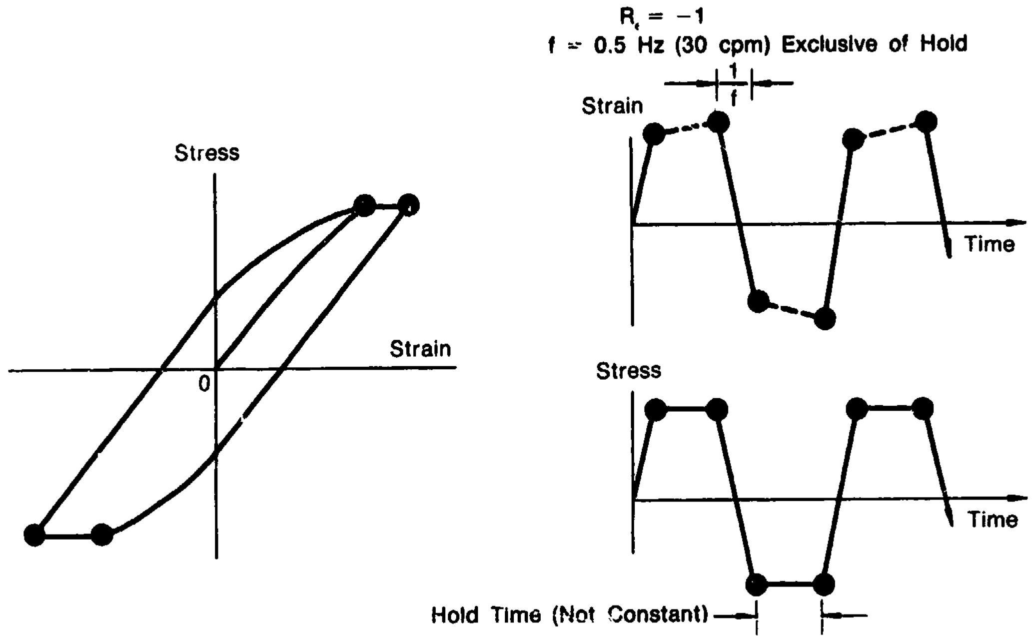

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Figure 36. — Typical Tensile-Compressive Stress Hold LCF Test

Auxiliary Tests. — Several additional tests were performed to enhance understanding of high temperature creep-fatigue behavior. Most of these tests were done on GATORIZED® AF2-1DA.

Creep-Extension (Ratcheting) of AF2-1DA. — Significant differences occur in the local stress-strain-time material response for different fracture critical locations of aircraft engine turbine disks. Boltholes in disk web areas, for example, may be sufficiently constrained by surrounding essentially elastic material so that their LCF-creep behavior may be approximated by a stress relaxation, or strain-hold cycle. Blade attachment areas at the disk rim, however, may experience some net section creep and, consequently, may be better represented by a creep hold, or constant stress hold cycle.

Initial waveforms for this phase of testing were selected in an attempt to evaluate differences between a stress-hold cycle (creep hold) and a strain-hold cycle (stress relaxation). Additional waveforms separated the contributions of mean stress and progressively increasing mean strains (due to cyclically unreversed creep) on the LCF life.

In an attempt to separate effects of the high net accumulated creep strain and the effects of mean stress, an additional hold cycle was run with a constant peak (mean stress) but kept total reversed strain range constant. There was significant creep strain (cyclically unreversed) for the stress-hold cycle.

A typical stress-hold, stress control LCF test cycle is shown in Figure 38. The test results are summarized in Table 20 and are plotted in Figure 39.

TABLE 19. — STRESS HOLD CONTROLLED STRAIN LCF RESULTS FOR GATORIZED® AF2-1DA

Testing Conducted in Air at 760°C (1400°F) at 0.5 Hz (30 CPM) Ramp Frequency Plus Hold, $R_\epsilon = -1$

Spec S/N	Strain (m/m at $N_f/2$) Range %	Elastic %	Inelastic %	Creep % Ten.	Creep % Comp.	Mean Stress $N_f/2$ MPa	(ksi)	Stress Range Cycle 1 MPa	(ksi)	Stress Range $N_f/2$ MPa	(ksi)	Cyclic Stability %	N_f Cycles to Failure	T_f (min) Time to Failure
Peak Tensile 620.5 MPa (90 ksi) Stress Hold														
45	1.200	0.905	0.295	[illegible]		228.9	(−33.2)	1638.9	(237.7)	1692.0	(245.4)	3.2 Hardening	263	5,232
48	1.000	0.900	0.100	0.050	-	−167.5	(−24.3)	1586.5	(230.1)	1603.7	(232.6)	1.1 Hardening	836	1,585
Peak Tensile 482.5 MPa (70 ksi) Stress Hold														
49	0.750	0.725	0.925	0.020	-	−150.3	(−21.8)	1252.8	(181.7)	1256.9	(182.3)	0.3 Hardening	7,407	31,950*
Peak Tensile 310.3 MPa (45 ksi) Stress Hold														
51	0.500	0.485	0.015	0.015	-	−140.7	(−20.4)	912.9	(132.4)	912.9	(132.4)	0.0 Stable	1,287	41,595**
Peak Compressive 482.5 MPa (70 ksi) Stress Hold														
73	0.750	0.725	0.025	-	0.025	160.6	(23.3)	1285.2	(186.4)	1320.3	(191.5)	2.9 Hardening	2,053	12,300
Peak Compressive 620.5 MPa (90 ksi) Stress Hold														
52	1.200	0.925	0.275	-	0.175	237.2	(34.4)	1674.0	(242.8)	1713.3	(248.5)	2.4 Softening	69	1,095
61	1.000	0.895	0.105	-	0.050	197.9	(28.7)	1592.7	(231.0)	1641.0	(238.0)	3.0 Hardening	540	4,275*
Peak Compressive and Tensile 620.5 MPa (90 ksi) Stress Hold														
72	1.190	0.660	0.530	0.470	0.440	6.9	(1.0)	1241.1	(180.0)	1228.0	(178.1)	1.1 Hardening	26	20,250
65	1.000	0.675	0.325	0.275	0.240	0.0	(0.0)	1241.1	(180.0)	1241.1	(180.0)	3.0 Stable	317	22,332*

*Possible extensometer induced failure.
**DNF — Did Not Fail

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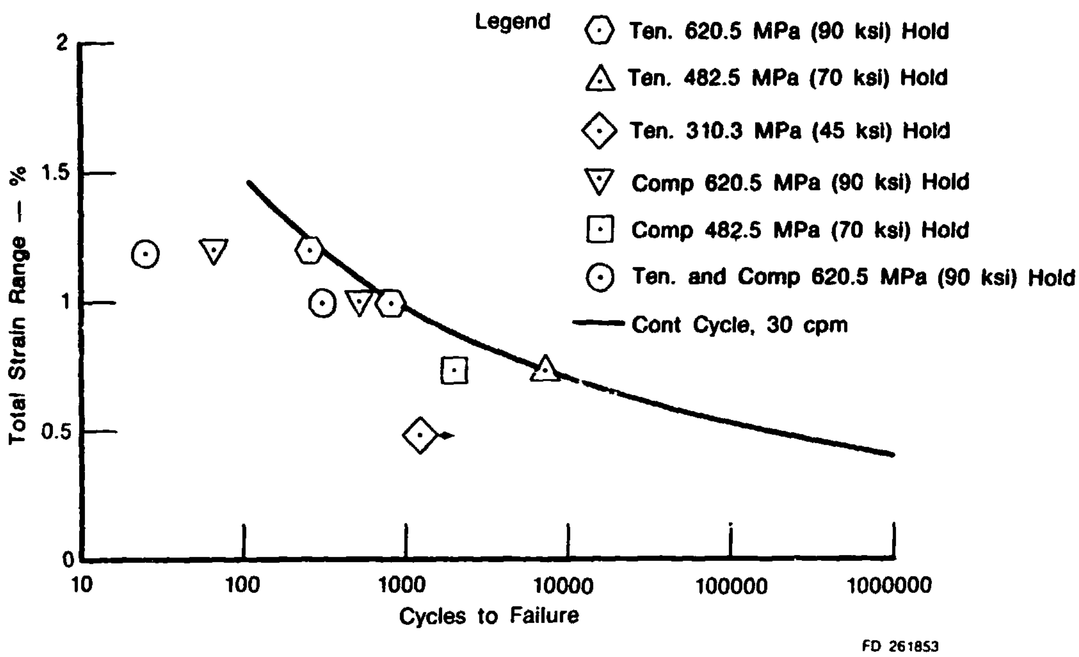
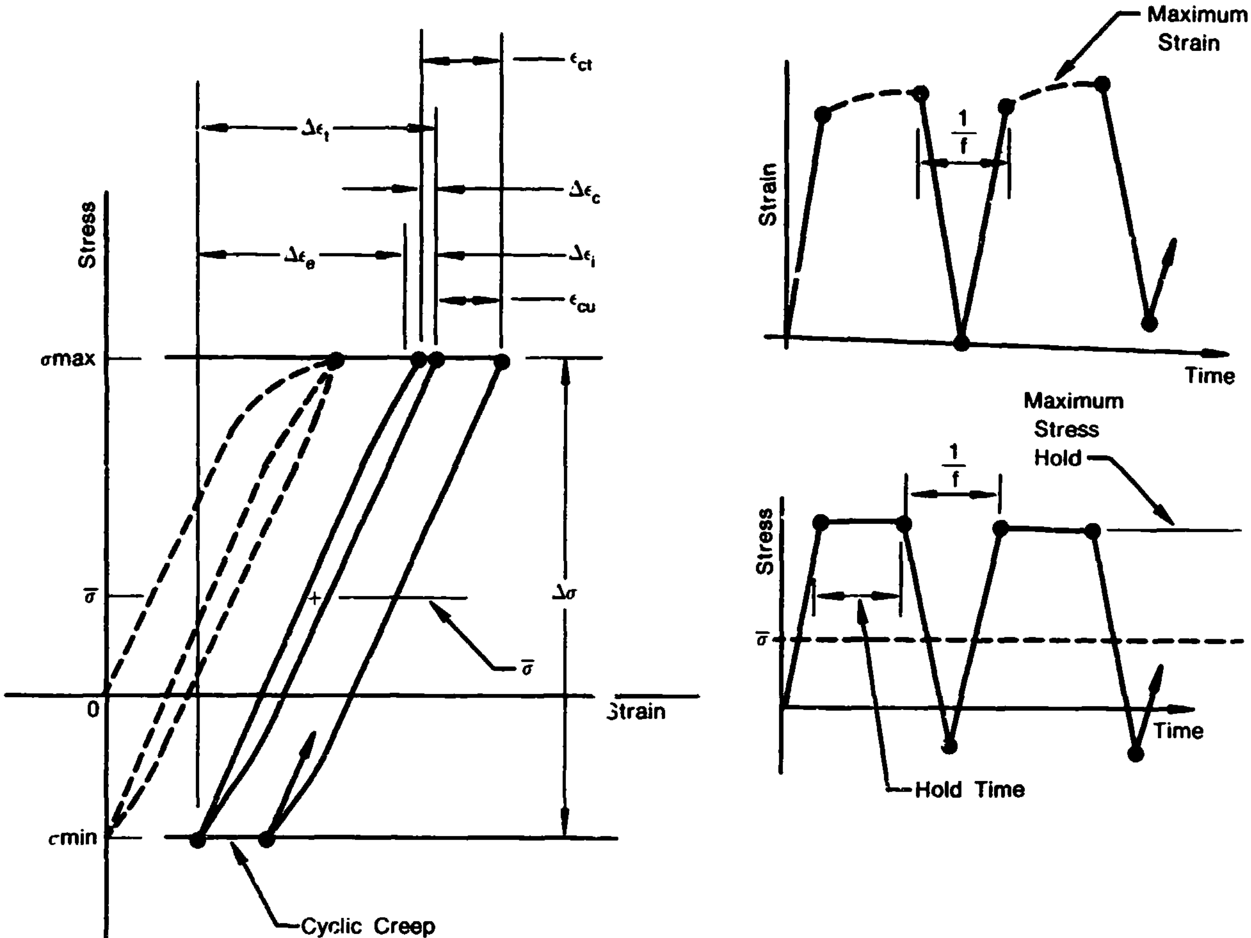


Figure 37. — Peak Stress Hold Data for GATORIZED® AF2-1DA at 760° (1400°F), $R_\epsilon = -1$



Stress R = Variable (Depends on $\Delta\epsilon$)
f = 0.50 Hz (30 cpm) Exclusive of Dwell

$\Delta\sigma$	= Total Stress Range
σ_{max}	= Creep Stress (Held Constant to Allow Specimen to Creep)
σ_{min}	= Minimum Stress (Stress Necessary to Set Minimum Strain = 0 at Start of Test)
$\bar{\sigma}$	= Tensile Mean Stress
$\Delta\epsilon_t$	= Total Strain Range
$\Delta\epsilon_i$	= Inelastic Strain Range
$\Delta\epsilon_{cr}$	= Cyclic Creep Strain Range (Reversed)
ϵ_{ct}	= Total Creep Strain per Cycle
ϵ_{cu}	= Unreversed Creep Strain per Cycle
$\Delta\epsilon_e$	= Elastic Strain Range
Hold Time	= Hold Time at Maximum Stress, 900 sec
R	= Stress Ratio, Minimum Stress/ Maximum Stress
f	= Ramp Frequency (Equivalent to 30 cpm Nondwell Tests)
E	= $\Delta\sigma/\Delta\epsilon_e$

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Figure 38. — Typical Stress-Hold, Stress Control LCF Test

TABLE 20. — CREEP EXTENSION (RATCHETING TYPE) LCF RESULTS FOR GATORIZED® AF2-1DA

Testing Conducted in Air at 760°C (1400°F) at 0.5 Hz (30 CPM) Ramp Frequency Plus Hold, R_ϵ = Variable

Spec S/N	Strain (m/m at $N_f/2$) Range %	Elastic %	Inelastic %	Creep %	Mean Stress $N_f/2$ MPa	(ksi)	Stress Range Cycle 1 MPa	(ksi)	Stress Range $N_f/2$ MPa	(ksi)	Cyclic Stability %	N_f Cycles to Failure	T_f (min) Time to Failure
Creep Extension (Ratcheting Type) (0.5 min Hold at 827.4 MPa (120 ksi))													
69	1.150	1.025	0.125	0.075	−81.4	(−11.8)	1823.0	(264.4)	1823.0	(264.4)	0.0 Stable	361	180
(2 min Hold at 827.4 MPa (120 ksi))													
68	1.150	1.035	0.115	0.075	−80.0	(−11.6)	1823.0	(264.4)	1823.0	(264.4)	0.0 Stable	94	213
(15 min Hold at 827.4 MPa 120 ksi))													
66	1.350	1.065	0.285	0.210	−68.9	(−10.0)	1808.5	(262.3)	1808.5	(262.3)	0.0 Stable	61	870
(15 min Hold at 372.3 MPa (54 ksi))													
70	0.563	0.555	0.008	—	−147.5	(−21.4)	1037.0	(150.4)	1037.0	(150.4)	0.0 Stable	3,754	5,631**

**DNF — Did Not Fail

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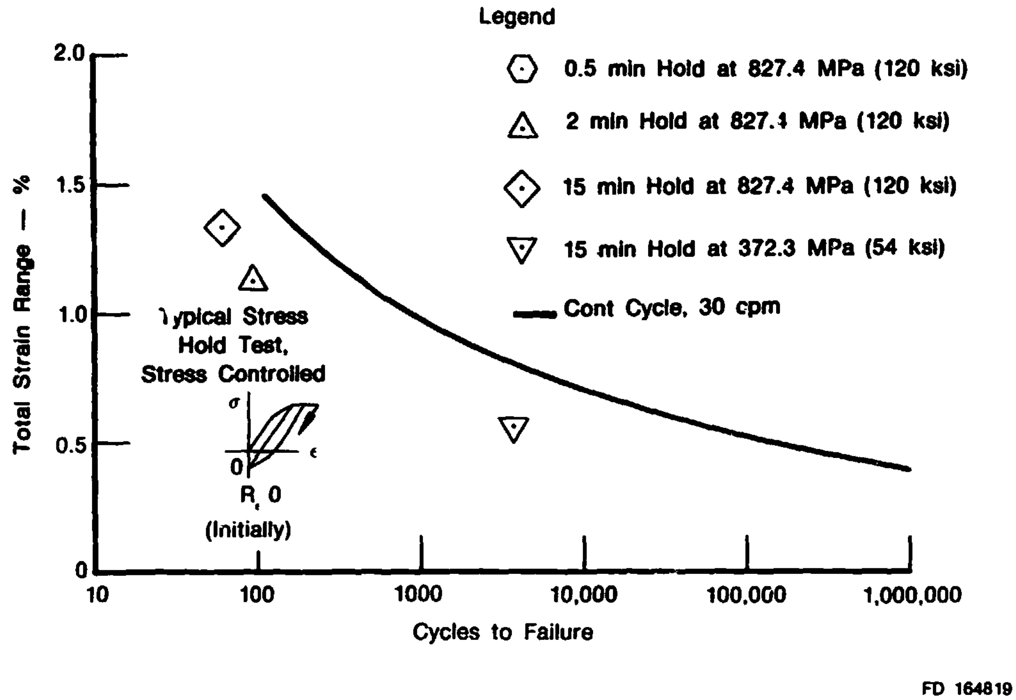

Figure 39. — Creep Extension (Ratcheting Type) Data for AF2-1DA at 760°C (1400°F), R_ϵ = Variable

Of three tests that were conducted at 827-4 MPa (120 ksi), no cyclic degradation was observed for 0.5 min hold, whereas significant reduction was evident for 2 min and 15 min hold cycles. At lower peak stress level 372.3 MPa (54 ksi), same percent reduction of life for 15 min hold test cycle was observed. The creep extension (ratcheting type) cycle seems detrimental compared to tensile strain hold cycle for the similar hold duration.

Alternate Temperature Tests for GATORIZEDD AF2-1DA at 649°C (1200°F). — Three representative tests were performed at total strain range of 1.0%, and at an alternate temperature of 649°C (1200°F) to ascertain strain rate and creep effects. In previous investigations, (Reference 3) it was observed that the fall-off in strength for AF2-1DA began at ~ 700°C (1300°F) and it was a strong function of strain rate. (Figure 40.)

The three tests were conducted, one each, under (1) continuous fully reversed cycle, (2) 2 min tensile strain hold, and (3) 2 min compressive strain hold cycles.

The test results are summarized in Table 21 and are plotted in Figure 41. The 760°C (1400°F) temperature does show a degrading influence for all three cycle types compared to 649°C (1200°F) tests. The comparison of failure lines at both temperatures is further graphically illustrated in the bar chart (Figure 42.) A cyclic credit of 2 minute compressive strain hold was observed at 649°C (1200°F) compared to life debit at 760°C (1400°F).

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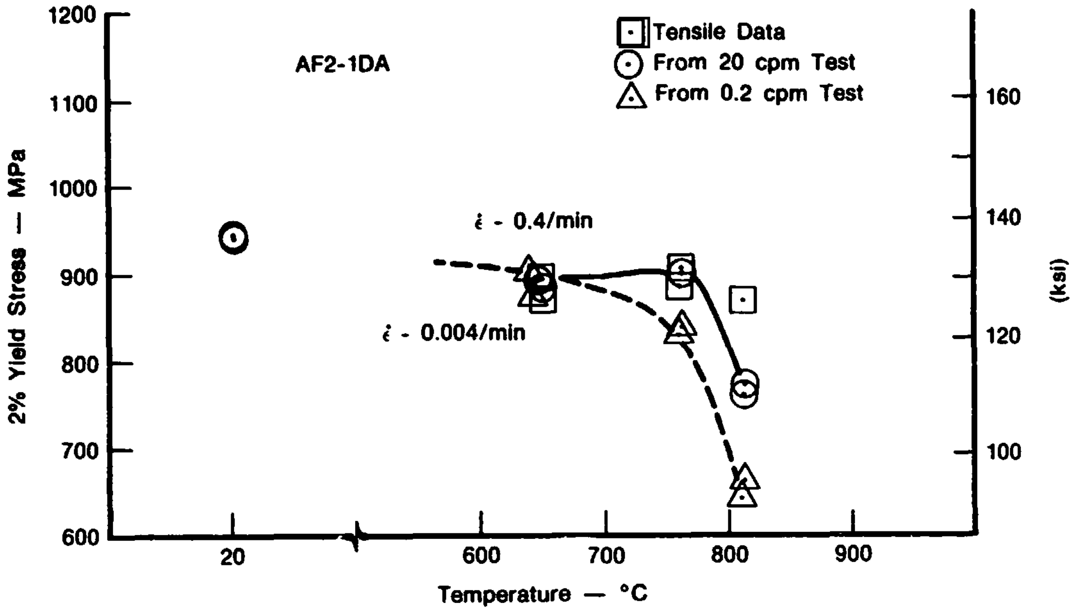

Figure 40.— 0.2% Yield Strength vs Temperature for AF2-1DA (Reference 3)

The test results are summarized in Table 21 and are plotted in Figure 40.

Mean Stress Effect Tests. — Mean stress has been reported by several investigators to be a parameter having primary influence on LCF life. An investigation was undertaken to ascertain this effect. All of the earlier continuous cycle testing was conducted at $R_\epsilon = -1$ where mean stress was at or near zero. Additional tests were scheduled at $R_\epsilon = 0$ (all tensile strain cycles). In general, strain R ratio imparts little effect at high total strain ranges and large effects at lower strain ranges. At the lower strain ranges, mean stress is generally high. At high strain ranges, mean stress approaches zero. The effect of decreasing mean stress with increasing strain range (for all-tensile strain tests) is shown in Figure 43. It should be noted that the yield stress was a critical factor in determining at what total strain range the mean stress reduction begins.

The mean stress was varied from 0 MPa (0 ksi) to 344.7 MPa (ksi). Test results for GATORIZED® AF2-1DA are summarized in Table 22 and are plotted in Figure 44.

Generally, cyclic life seems to be insensitive to mean stress variations for AF2-1DA under fully reversed loading conditions and at 760°C (1400°F), Figure 44.

Zero Strain Ratio Tests (INCO 718). — A limited number of tests were conducted on INCO 718 at zero strain ratios ($R_\epsilon = 0$) to distinguish between oxidation degradation and time at temperature effects. Continuous cycle (nonhold) and hold (strain hold) tests were conducted for INCO 718 at 649°C (1200°F). A typical (nonhold) LCF cycle with $R_\epsilon = 0$ is shown in Figure 45 at 649°C (1200°F). The test results are summarized in Table 23 and are plotted in Figure 46.

TABLE 21. — LCF RESULTS FOR GATORIZED® AF2-1DA

Testing Conducted in Air at 649°C (1200°F) at 0.5 Hz (30 CPM) Ramp Frequency Plus Hold, $R_\epsilon = -1$

Spec S/N	Strain (m/m at $N_f/2$) Range %	Elastic %	Inelastic %	Creep %	Mean Stress $N_f/2$ MPa (ksi)	Stress Range Cycle 1 MPa (ksi)	Stress Range $N_f/2$ MPa (ksi)	Cyclic Stability %	N_f Cycles to Failure	T_f (min) Time to Failure
Alternate Temperature 649°C (1200°F) (2 min Tensile Strain Hold)				Ten. Comp						
62	1.000	0.910	0.090	0.018	−56.5 (−8.2)	1847.1 (267.9)	1769.9 (256.7)	4.2 Softening	1,577	3,207
(2 min Compressive Strain Hold)										
63	1.000	0.910	0.090	0.011	−6.9 (−1.0)	1758.9 (255.1)	1769.2 (256.6)	5.9 Hardening	1,406	2,857
(Continuous Cycle)										
64	1.000	0.900	0.100	—	40.7 (5.9)	1811.3 (262.7)	1955.4 (283.6)	8.0 Hardening	862	29

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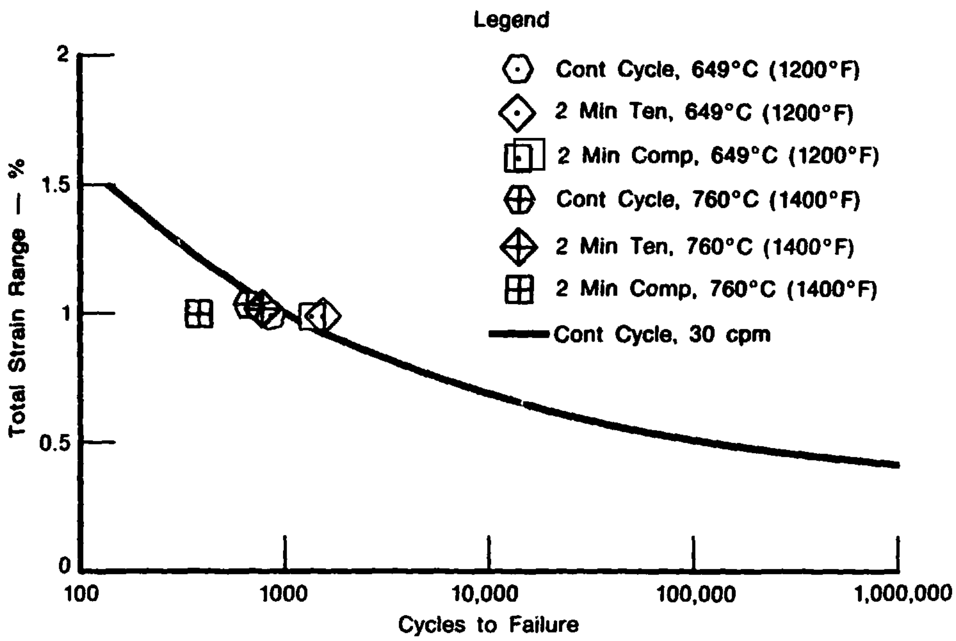

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Figure 41.— Temperature Effect on Strain Hold Data for GATORIZED® AF2-1DA $R_\epsilon = -1$

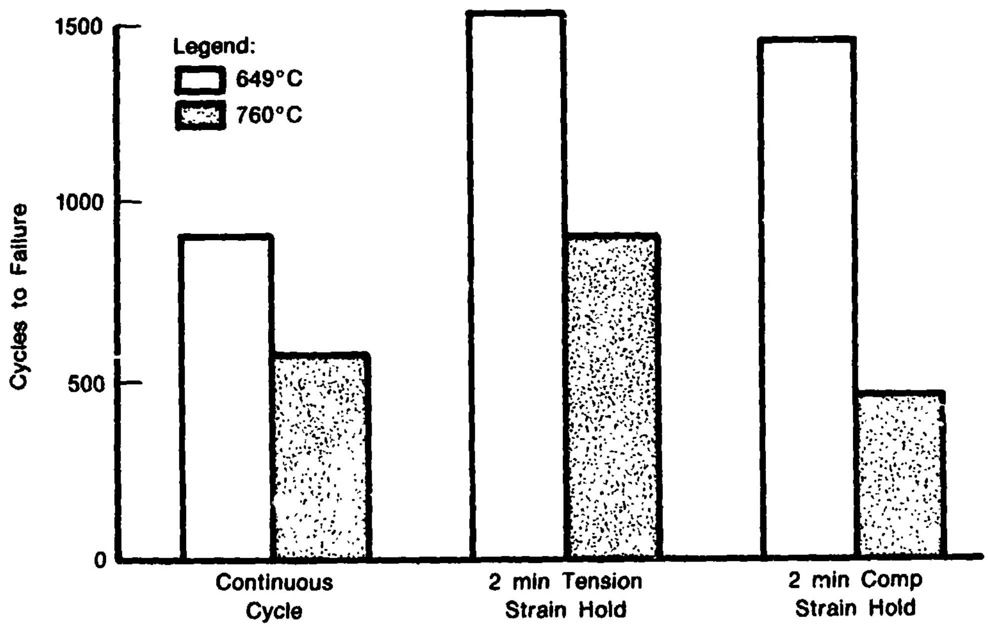

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Figure 42.— Temperature Effect on Strain Hold Data for AF2-1DA 30 cpm, Total Strain Range 1% Strain Ratio of −1

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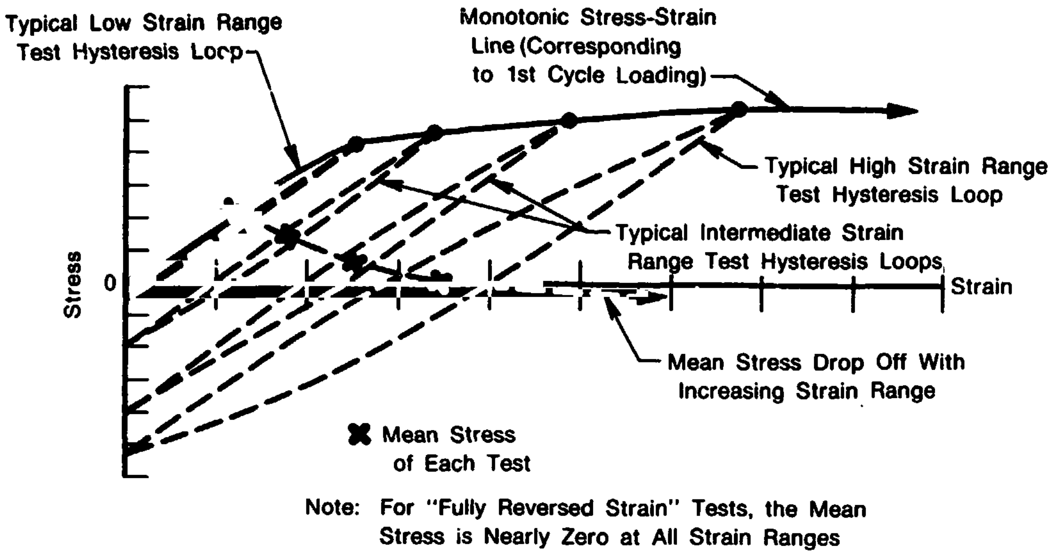

Figure 43. — Mean Stress vs Total Strain Range for a Typical Turbine Disk Alloy

As discussed before, the mean stress for all tensile strain cycle tests tends to zero at higher strain ranges, thus minimizing any mean stress influence on life. This can be seen from Figure 46 for continuous cycle data. At lower strain ranges, all tensile cycles have higher mean stress compared to fully reversed cycles and show mean stress effect – i.e., lower cyclic life. The same behavior was observed for tensile and compressive hold cycles at higher strain ranges (1.0%) where all tensile cycle and fully reversed cycle lives are comparable. The reduced life for R = 0 at lower strain range was not observed for tensile strain hold cycle.

TABLE 22. — CONTINUOUS CYCLE LCF RESULTS FOR GATORIZED® AF2-1DA

Testing Conducted in Air at 760°C (1400°F) at 0.5 Hz (30 CPM) Ramp Frequency, $R_\epsilon = 0$

Spec S/N	Strain (m/m at $N_f/2$) Range %	Elastic %	Inelastic %	Creep %	Mean Stress $N_f/2$ MPa (ksi)	Stress Range Cycle 1 MPa (ksi)	Stress Range $N_f/2$ MPa (ksi)	Cyclic Stability %	N_f Cycles to Failure	T_f (min) Time to Failure
Mean Stress Effect										
55	0.815	0.790	0.025		370.2 (53.7)	1427.2 (207.0)	1425.1 (206.7)	0.1 Softening	1,340	45
53	0.500	0.495	0.005		359.9 (52.2)	912.9 (132.4)	894.9 (129.8)	1.2 Softening	107,996	3,600
3	0.800	0.782	0.018		164.7 (23.9)	1411.4 (204.7)	1316.2 (190.9)	7.2 Softening	4,179	139
4	1.000	0.980	0.020		80.7 (11.7)	1702.3 (246.9)	1678.2 (243.4)	1.4 Softening	1,169	39
5	1.515	1.245	0.270		14.2 (2.1)	2025.7 (293.8)	2146.3 (311.3)	6.0 Hardening	176	6

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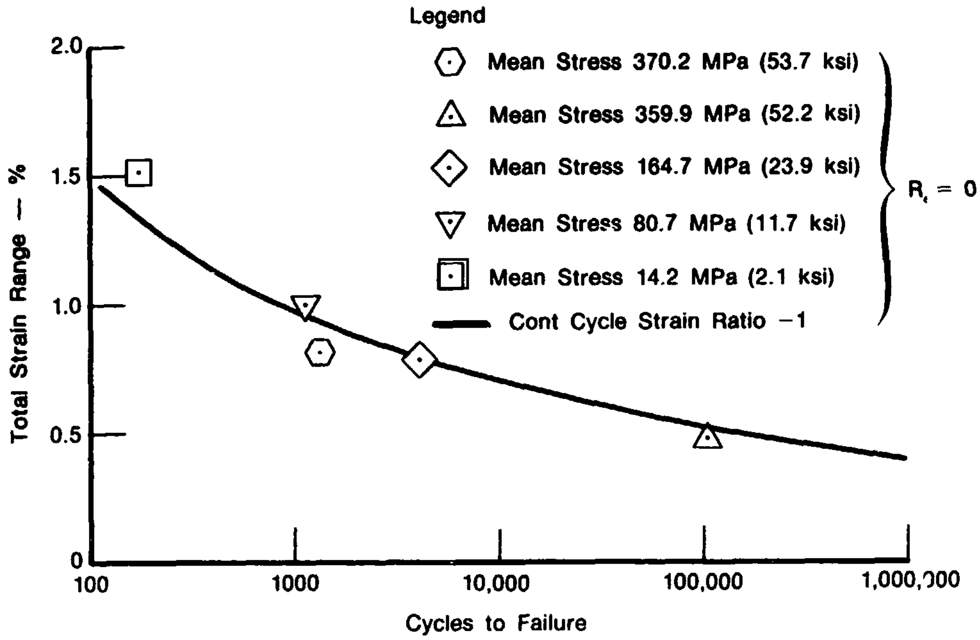

Figure 44. — Mean Stress Effect on LCF Data for GATORIZED® AF2-1DA at 760°C (1400°F), 30 cpm, R_ϵ = 0

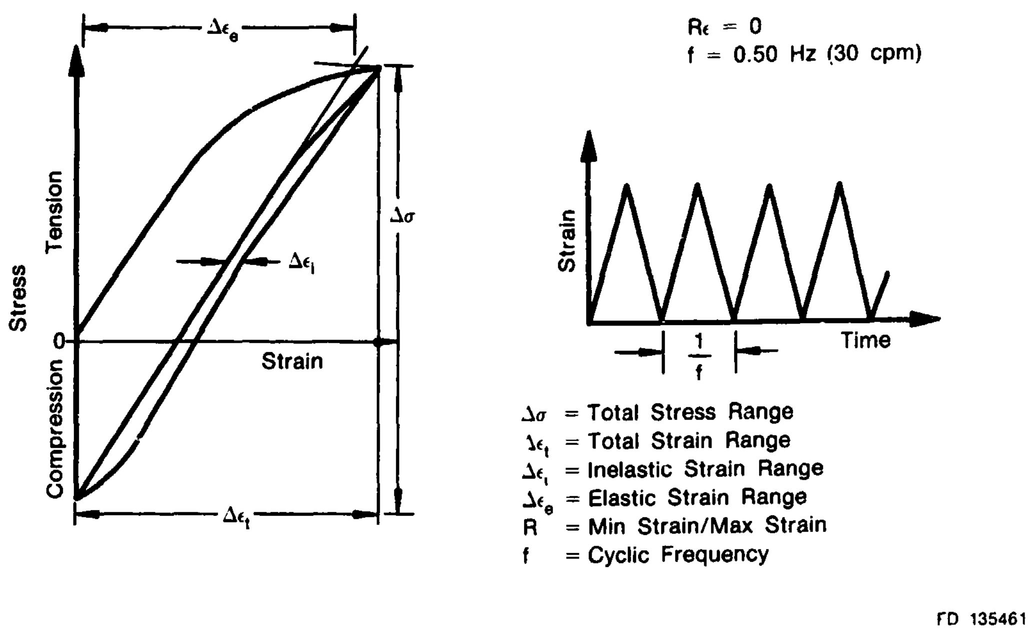

Figure 45. — Typical All Tensile Strain Hold LCF Test

TABLE 23. — STRAIN HOLD EFFECTS AT R_ϵ = 0 FOR INCO 718

Testing Conducted in Air at 649°C (1200°F) at 0.5 Hz (30 CPM) Ramp Frequency (Discretionary Tests)

Spec S/N	Strain (m/m at $N_f/2$) Range %	Elastic %	Inelastic %	Creep % Ten.	Creep % Comp	Mean Stress $N_f/2$ MPa (ksi)	Stress Range Cycle 1 MPa (ksi)	Stress Range $N_f/2$ MPa (ksi)	Cyclic Stability %	N_f Cycles to Failure	T_f (min) Time to Failure
Continuous Cycle											
43	1.000	0.720	0.280			52.4 (7.6)	1507.9 (218.7)	1232.8 (178.8)	18.2 Softening	1,504	50
48	0.800	0.690	0.110			152.4 (22.1)	1283.1 (186.1)	1178.3 (170.9)	8.2 Softening	7,690	256*
Peak Tensile Strain Hold 1.0 min											
45	1.000	0.705	0.295	0.029		−15.9 (−2.3)	1544.4 (224.0)	1260.4 (182.8)	18.4 Softening	933	1,897
49	0.780	0.640	0.140	0.023		−70.3 (−10.2)	1305.9 (189.4)	1172.8 (170.1)	10.2 Softening	16,665	33,886*
Peak Compressive Strain Hold 2.0 min											
52	1.000	0.715	0.285		0.032	66.2 (9.6)	1545.1 (224.1)	1181.8 (171.4)	9.6 Softening	1,493	3,036
50	0.800	0.655	0.145		0.020	131.0 (19.0)	1330.7 (193.0)	1171.4 (169.9)	12.0 Softening	3,181	6,468

*Possible extensometer induced failure.

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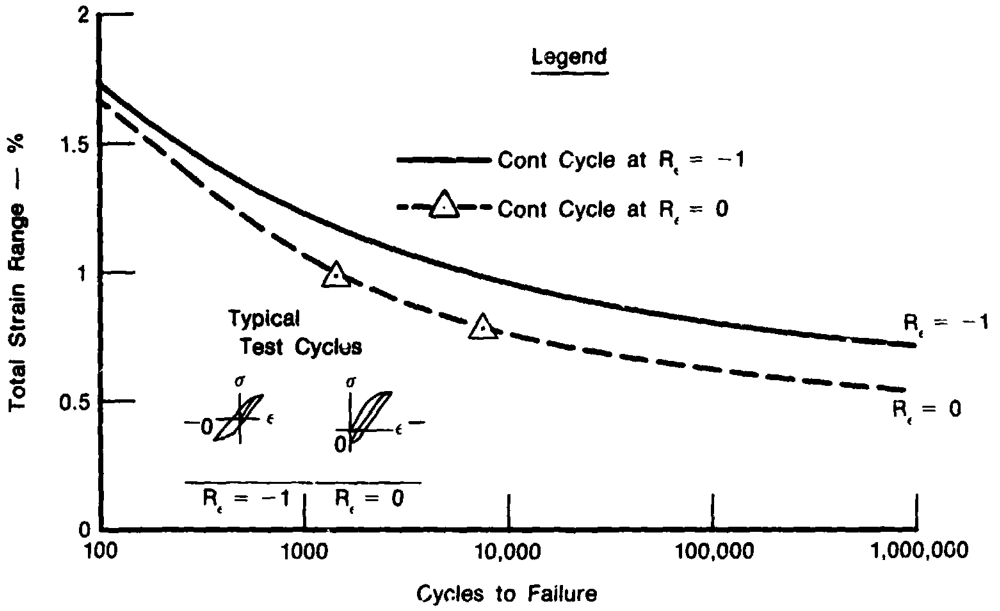

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Figure 46. — Strain Ratio Effect on Continuous Cycle Data for INCO 718 at 649°C (1200°F), 30 cpm

METALLOGRAPHIC EVALUATIONS

Fractographic and metallographic studies were performed on strain control low-cycle fatigue samples for both GATORIZED® AF2-1DA and INCO 718. Representative high and low strain range cyclic and cyclic/hold samples from each of the alloys were characterized to determine the mechanisms of crack initiation, especially in the low-strain long-life regime. These studies were done by direct viewing of the fracture with a scanning electron microscope (SEM). The metallographic section taken through the origin of each sample enabled identification of both the location and character of the fatigue origin, and the morphology of the early stage of crack growth.

The sample numbers and corresponding test conditions for both alloys are listed in Table 24. The results are summarized in Table 25. The general observations for both alloys are as follows.

TABLE 24. — CONTROLLED STRAIN LOW-CYCLE FATIGUE SAMPLES CHARACTERIZED BY FRACTOGRAPHY

	Spec. S/N	*Type Test*	*Temp. °C*	$\Delta\epsilon_T$ (1) %	N_f (2)
AF2-1DA	14	Continuous cycle ($R_\epsilon = -1$)	760	0.500	196,657
	18	0.5 min ten strain hold	760	0.750	17,400
	21	2.0 min ten. strain hold	760	0.768	5300
	26	15.0 min ten. strain hold	760	0.750	3522
	30	0.5 min comp. strain hold	760	0.505	31174
	31	2.0 min comp. strain hold	760	0.525	22163
	41	0.5 min ten. and comp. strain hold	760	0.500	1156
	47	15.0 min comp. strain hold	760	0.750	25919
	62	2.0 min ten. strain hold	649	1.000	1577
	63	2.0 min comp. strain hold	649	1.000	1405
	64	Continuous cycle ($R_\epsilon = -1$)	649	1.000	862
	66	827.4 MPa (120 ksi) creep extension	760	1.350	61
	73	482.5 MPa (70 ksi) comp. stress hold	760	0.750	2053
INCO 718	10	Continuous cycle ($R_\epsilon = -1$)	649	0.930	5163
	14	0.5 min ten. strain hold	649	0.800	24026
	17	2.0 min ten. strain hold	649	0.850	3941
	19	15.0 min ten. strain hold	649	1.015	1329
	26	0.5 min comp. strain hold	649	0.800	9500
	29	2.0 min comp. strain hold	649	0.800	6872
	31	15.0 min comp. strain hold	649	1.000	1335
	37	15.0 min ten. and comp. strain hold	649	1.000	494
	41	2.0 min ten. and comp. strain hold	649	0.800	2358
	42	0.5 min ten. and comp. temp strain hold	649	0.765	3411
	48	Continuous cycle ($R_\epsilon = 0$)	649	0.800	7690
	50	2.0 min. comp. strain hold ($R_\epsilon = 0$)	649	0.800	3181
	33	0.5 min ten. and comp. strain hold	649	1.295	649
	38	0.5 min ten. and comp strain hold	649	0.980	1632
	51	2.0 min ten. and comp strain hold	649	1.200	723

(1) Total strain range
(2) Cycles to failure

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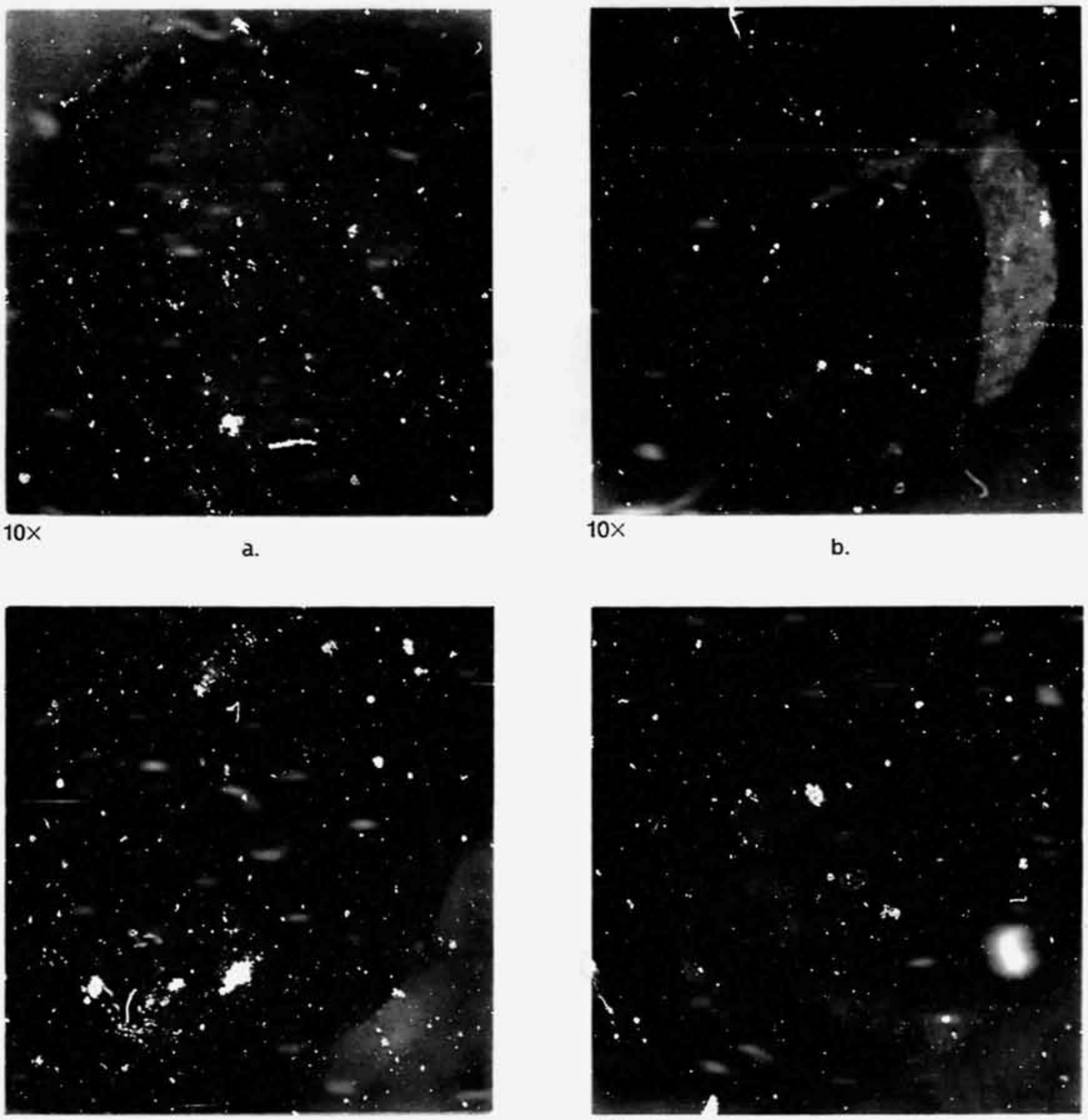
TABLE 25. — SUMMARY OF FRACTOGRAPHIC AND METALLOGRAPHIC STUDIES

Material	Spec S/N	Type* Test	Initiation
AF2-1DA	14	C-L	Stage I oxidized origin, transgranular
	18	C/D-L	Subsurface origin, oxidized, transgranular
	21	C/D-L	Surface origin, oxidized, transgranular
	26	C/D-L	Surface origin, secondary cracks, intermixed
	30	C/D-L	Multiple origins, Ti, Cr may be carbides present
	31	C/D-L	No defects, probably transgranular
	41	C/D-L	Faceted origin, transgranular cleavage fracture
	47	C/D-L	Multiple origins, transgranular
	62	C/D-H	Multiple origins, transgranular
	63	C/D-H	Multiple origins, oxidized, transgranular
	64	C-H	Multiple origins, Stage I facets, transgranular
	66	C/D-H	Multiple origins, Stage I facets, transgranular
	73	C/D-L	Multiple origins - Stage I, facet, transgranular
INCO 718	10	C-H	Stage I faceted origin, intergranular, turning to transgranular
	14	C/D-L	Locally intergranular cracking
	17	C/D-L	Locally intergranular cracking
	19	C/D-H	Locally intergranular cracking
	26	C/D-L	Stage I faceted intergranular origin, turning to transgranular cracking
	29	C/D-L	Stage I faceted intergranular origin, turning to transgranular cracking
	31	C/D-H	Multiple origins, intergranular fracture
	37	C/D-H	Multiple origins, intergranular fracture
	41	C/D-L	Origin at scratch, intergranular fracture
	42	C/D-L	Origin smeared, mixed fracture
	48	C-L	Stage I faceted origin, intergranular
	50	C/D-L	Origin at machining mark, intergranular, turning to transgranular
	33	C/D-H	Origin at machining marks, mixed fracture
	38	C/D-H	Origin at surface, intergranular switching to mixed mode
	51	C/D-H	Multiple origins, intergranular.

* C = Cyclic
C/D = Cyclic Hold
H = High Strain Range
L = Low Strain Range

GATORIZED® AF2-1DA

The SEM examination of all AF2-1DA elevated temperature failures showed that the crack nucleation sites for the dominant cracks were from surface or near surface location rather than internal origins. The continuous cycle (Figure 47A) as well as cyclic/hold samples (Figure 47B, C and D) exhibited multiple origins. The most prevalent mode of initiation and early growth for all the samples examined was transgranular initiation normal to the tensile direction. On the fracture surface, these sites were usually flat and featureless as shown in Figures 48 and 49 for different specimens. In each case, the shape of the crack and the morphology of the tear lines indicated that the crack originated at the specimen's surface, although there was generally no obvious microstructural feature or defect that could be associated with the origin. One exception was for specimen No. 18 where initiation nucleated at a subsurface void. The microscopic resolution was limited, in the area of the origin due to oxidation and rubbing of the fracture surfaces during fatigue cycling.



10× a. 10× b.

10× c. 10× d.

(a) S/N 14, Cyclic, $\Delta\epsilon_t = 0.5\%$, 196,657 Cycles
(b) S/N 21, 2.0 Min Ten. Strain Hold, $\Delta\epsilon_t = 0.75\%$, 10,939 Cycles
(c) S/N 31, 2.0 Min Comp Strain Hold, $\Delta\epsilon_t = 0.525\%$, 2,163 Cycles
(d) S/N 73, Peak Comp 482.5 MPa (70 ksi) Stress Hold, 2,053 Cycles

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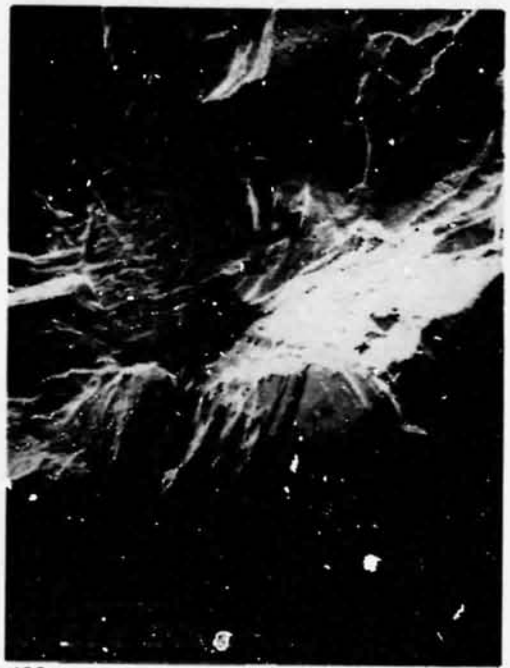
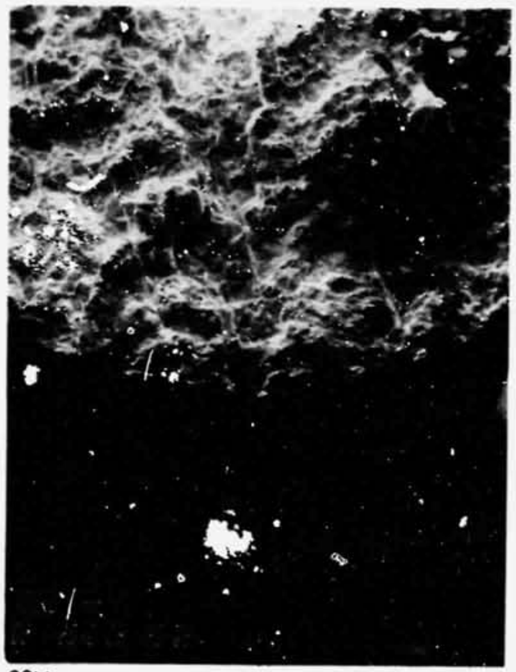
Figure 47. — GATORIZED® AF2-1DA Strain Control LCF Fracture Faces



100× a.

2000× b.



20× c.

500× d.

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Figure 48. — SEM Fractographs of GATORIZED® AF2-1DA Samples No. 14 (Top) and No. 21 (Bottom) Showing Faceted Stage I Origin (a), Heavily Oxidized Transgranular Fracture (b), and Surface Origins (c), Oxidized Transgranular Fracture With Striations (d)

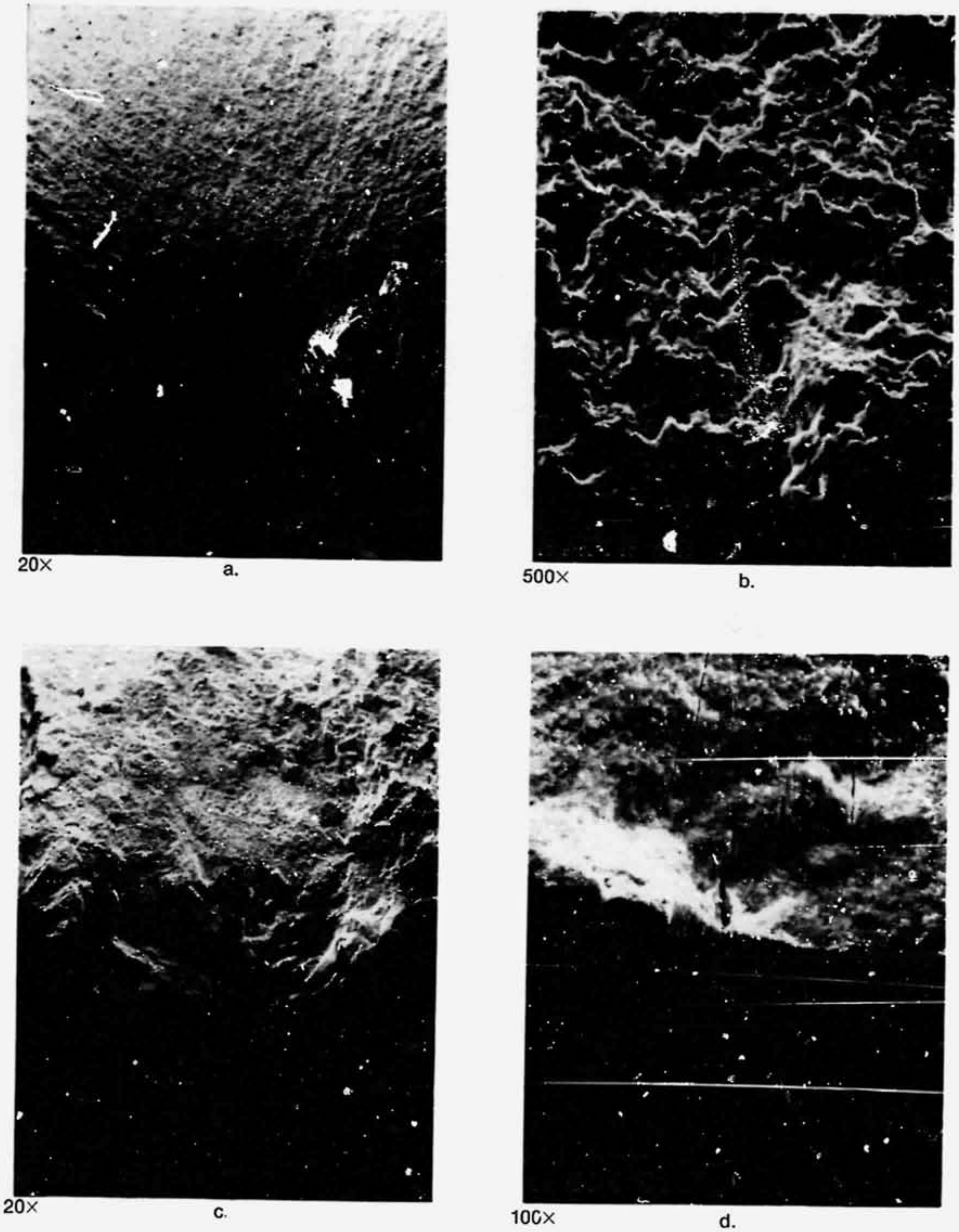

Figure 49. — SEM Fractographs of GATORIZED® AF2-1DA Samples No. 31 (Top) and No. 73 (Bottom) Showing Surface Origin (a), Transgranular Fracture (b), Stage I Faceted Origins (c), and Transgranular Fracture With Secondary Cracking

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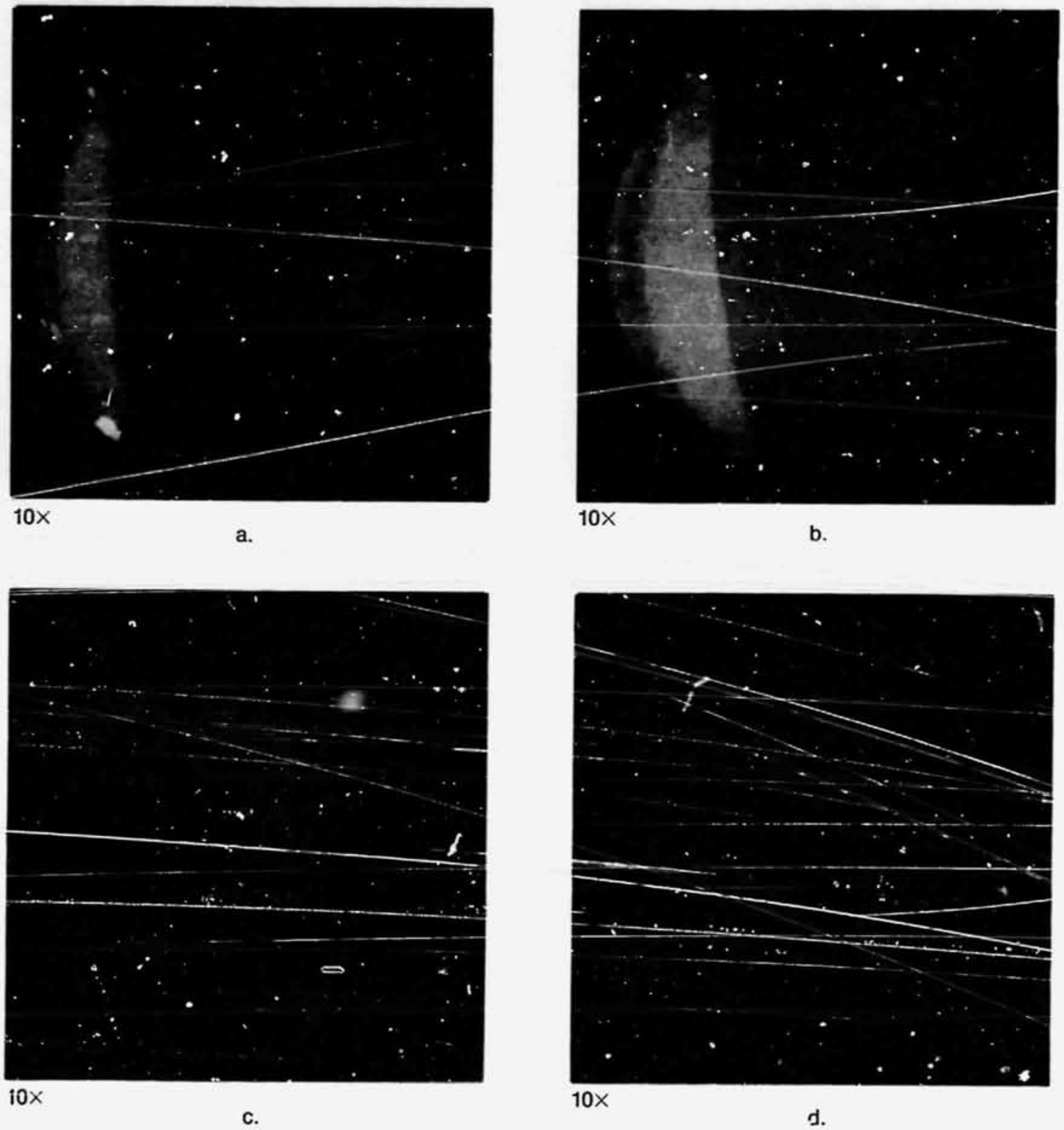

(a) S/N 10, Continuous Cycle, $\Delta\epsilon_t$ = 0.930, 5,163 Cycles
(b) S/N 29, Peak Comp Strain 2.0 Min Hold, 6,872 Cycles
(c) S/N 42, Peak Ten. and Comp Strain 0.5 Min Hold, 3,411 Cycles
(d) S/N 50, Peak Comp Strain 2.0 Min Hold (R_ϵ = 0) 3,181 Cycles

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Figure 50. — INCO 718 Strain Control LCF Fracture Faces

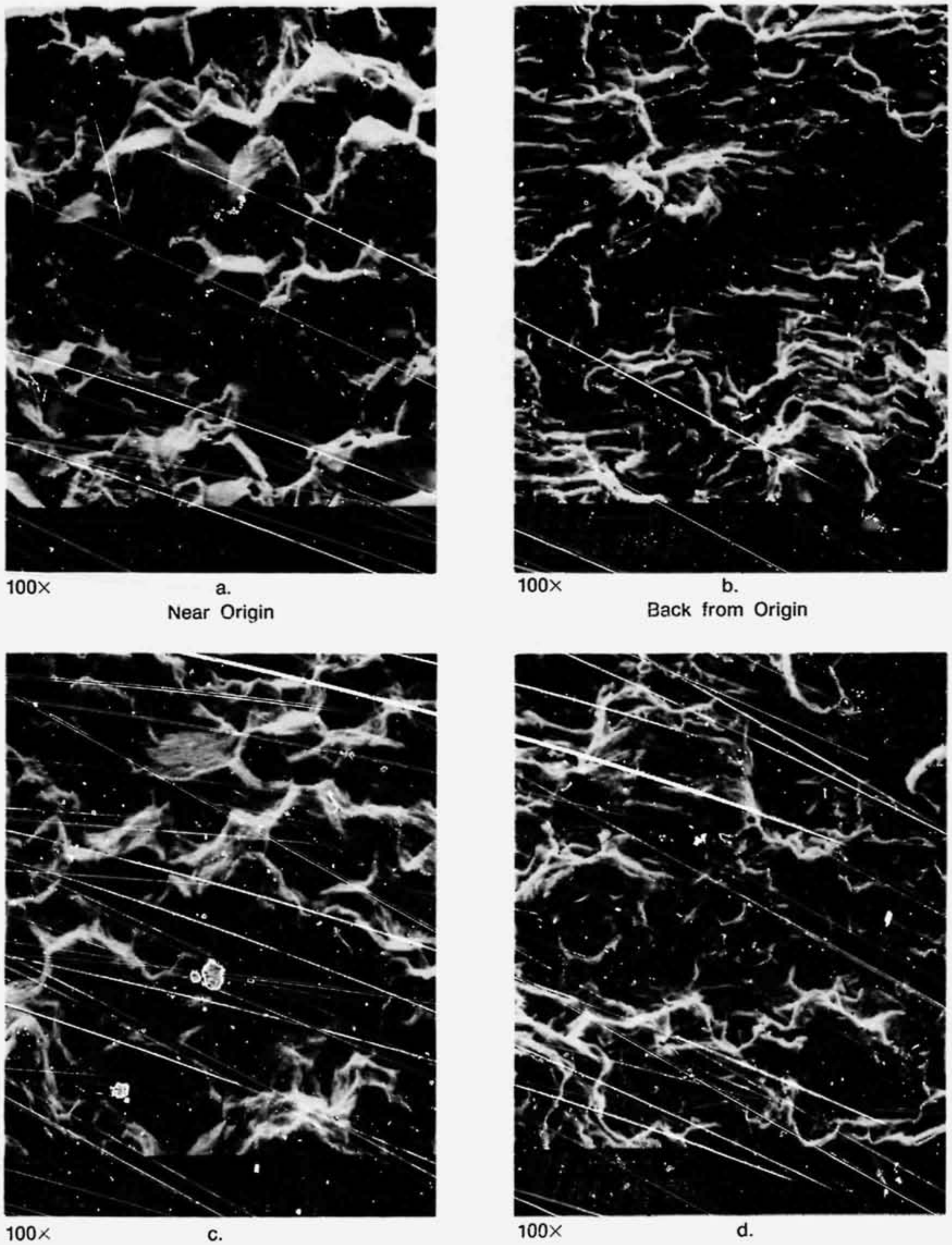

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Figure 51. — SEM Fractograph of INCO 718 Samples No. 10 (Top) and No. 29 (Bottom) Showing Intergranular Fracture at Origin (a and c) Turning Transgranular at a Later Stage (b and d)

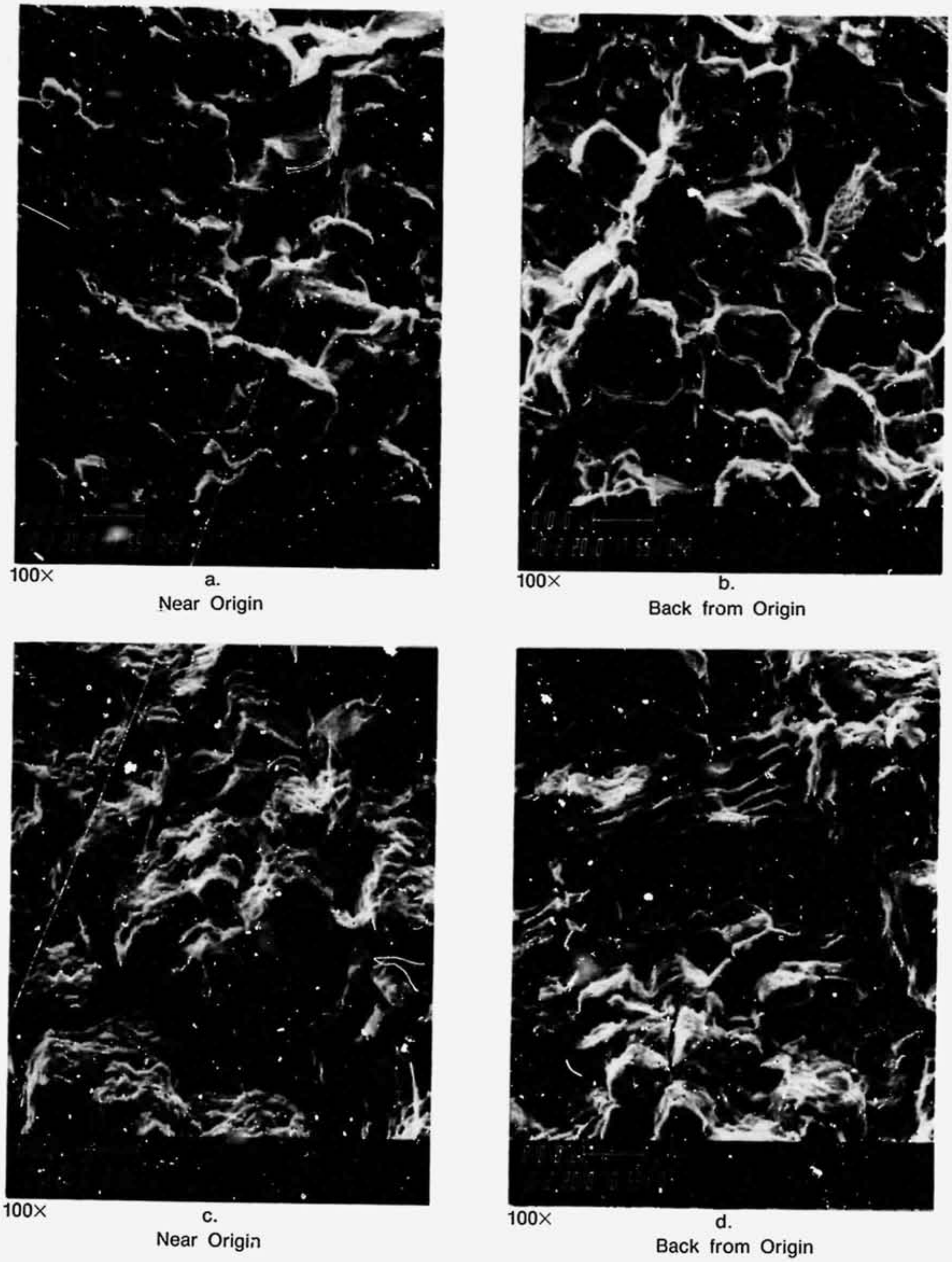

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Figure 52. — SEM Fractograph of INCO 718 Samples No. 42 (Top) and No. 50 (Bottom) Showing Mixed Mode Fracture at Origin (a) Turning Transgranular (b), Intergranular Fracture (c) Turning Transgranular With Distinct Striation Marks

The compressive stress hold failure (Sample No. 73) showed Stage I ι ::ted crack nucleation (Figure 49C) followed by transgranular fracture with clear indications of secondary cracking (Figure 49D). The surface-subsurface transition (SST) phenomenon observed in other studies (Reference 3) where dominant crack nucleation at a near surface pore for high strain range tests changed to crack nucleation at a subsurface metallic inclusion was not confirmed here.

The grain structure for this alloy, as reported earlier was coarser (ASTM 1-3) for all four heat treat lots.

''NCO 718

INCO 718 fractures also nucleated at or near surface locations. The continuous cycle (Figure 50A) and cyclic/hold sample (Figures 50B, C, and D) initiations were predominantly multiple surface origins. Cracking generally began as stage I mode and changed subsequently to transgranular in most cases. Figures 51 and 52 A and C show a typical cross-sectional view of intergranular crack initiation from the specimen's surface. Cracking occurred on grain boundaries perpendicular to the tensile stress axis. The subsequent :rack growth was primarily transgranular or mixed mode with clear evidence of striation marks (Figures 51 and 52 C and D).

ıe INCO 718 had finer grain size (ASTM 7-8) compared to AF2-1DA.

CONCLUSIONS AND SUMMARY

Two aircraft turbine disk alloys, GATORIZED® AF2-1DA and INCO 718, were evaluated for their low strain long life creep-fatigue behavior.

Static (tensile and creep rupture) and cyclic properties of both alloys were evaluated. The controlled strain LCF tests were conducted at 760°C (1400°F) and 649°C (1200°F) for AF2-1DA and INCO 718 respectively. Hold times were varied for tensile, compressive and tensile/compressive strain hold (relaxation) tests. Additionally, stress (creep) hold behavior of AF2-1DA was evaluated.

The results of this experimental program are summarized as follows:

1. Generally, INCO 718 exhibited a more significant reduction in fatigue life due to hold than AF2-1DA.

2. At low strain ranges (long life), the percent reduction in life for both alloys for strain hold were generally larger.

3. All tensile strain cycle ($R_\epsilon = 0$) tests indicated lower cyclic lives compared to fully reversed strain cycle ($R_\epsilon = -1$) tests especially for INCO 718. This was due to higher mean stresses at comparable strain ranges.

4. Changing hold time from zero to 0.5, 2.0, and 15.0 min. resulted in corresponding reductions in life. Reductions in life could be attributable to exposure time at temperature as well as cyclic creep deformation damage.

5. INCO 718 showed far greater life than AF2-1DA for fully reversed continuous cycle tests at 649°C (1200°F). This could be attributed to lower tensile strength (higher ductility) for INCO 718. However, no appreciable differences were seen under hold cycles for the conditions tested.

6. Mean stress and accumulated creep strain (in stress hold cycles) for both alloys significantly affected LCF life. Life differences between stress hold and strain hold cycles are attributed to mean stress and cumulative creep strains.

7. Metallographic and fractographic evaluations were performed on failed strain control LCF specimens. Crack initiation for cyclic tests were generally transgranular for AF2-1DA alloys while for INCO 718 they were generally intergranular, except where cracks initiated in voids and inclusions.

APPENDIX A
REGRESSION PLOTS VERSUS CYCLES TO FAILURE

This Appendix contains regressed typical plots of elastic strain ($\Delta\epsilon_e$), inelastic strain ($\Delta\epsilon_I$) and total strain ($\Delta\epsilon_T$) vs cycles to failure for GATORIZED® AF2-1DA and INCO 718 for few selected groups of tests. The regression equations for all other groups of cycle types which had at least three data points for three distinct strain ranges.

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TABLE A-1. — CONTINUOUS CYCLE CONTROLLED STRAIN (AF2-1DA) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.15821E+03	
STRENGH COEFF., K'	0.46850E+03	
STRAIN-HARD EXP., N'	0.17469E+00	
FATIGUE STRENGH COEFF., SIGMA	0.28064E+03	0.988
FATIGUE STRENGH EXP.,B	-0.11563E+00	
FATIGUE DUCTILITY COEFF., EF'	0.53207E-01	0.928
FATIGUE DUCTILITY EXP., C	-0.66192E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.67263E+01 D=-0.66195E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.20211E+01 B=-0.11564E+00

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.20211E+01 B=-0.11564E+00 C= 0.67263E+01 D=-0.66195E+00

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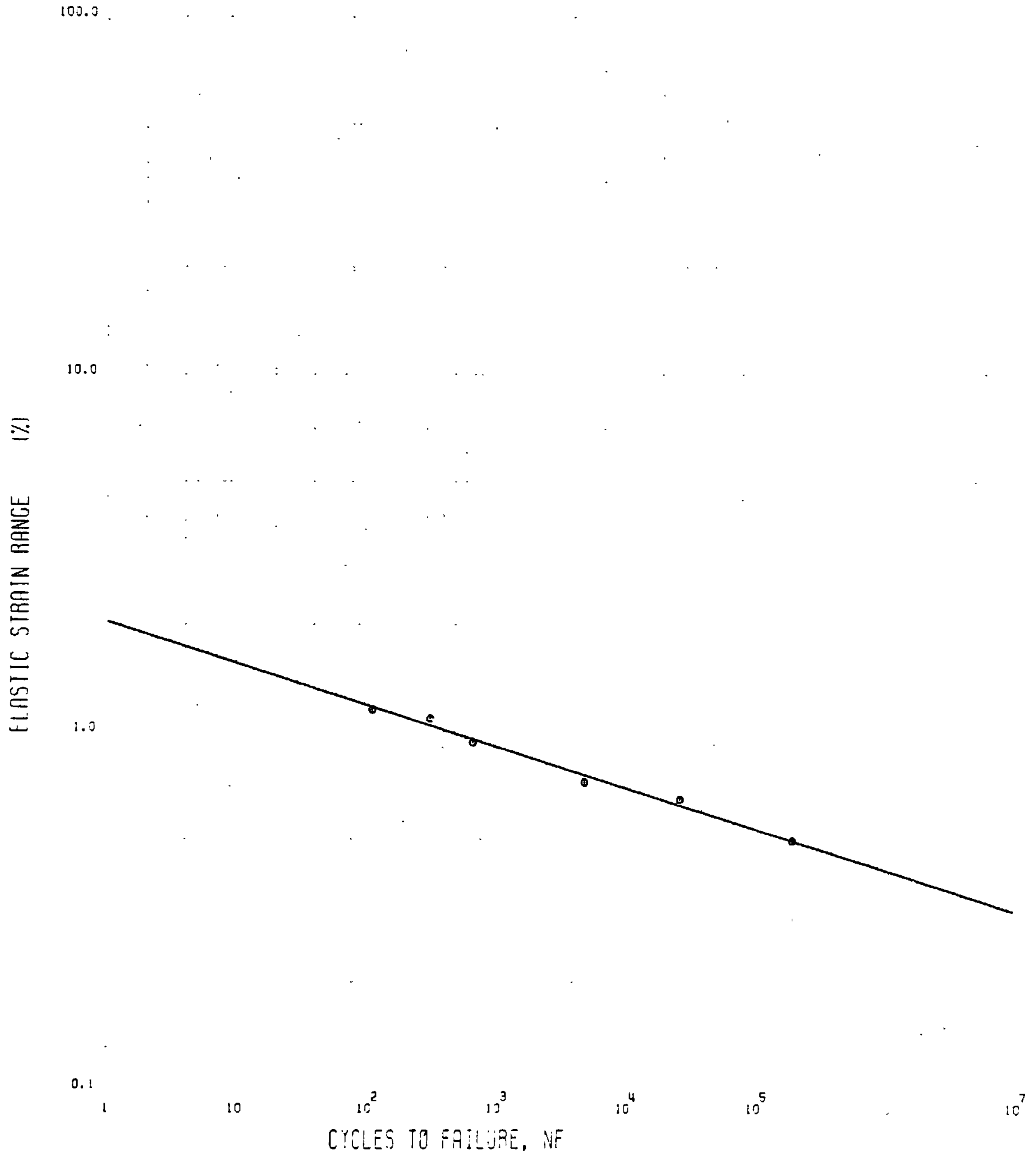

Figure A-1. — Elastic Strain Range vs Cycles to Failure for Fully Reversed Continuous Cycle Controlled Strain AF2-1DA Data at 760°C (1400°F)

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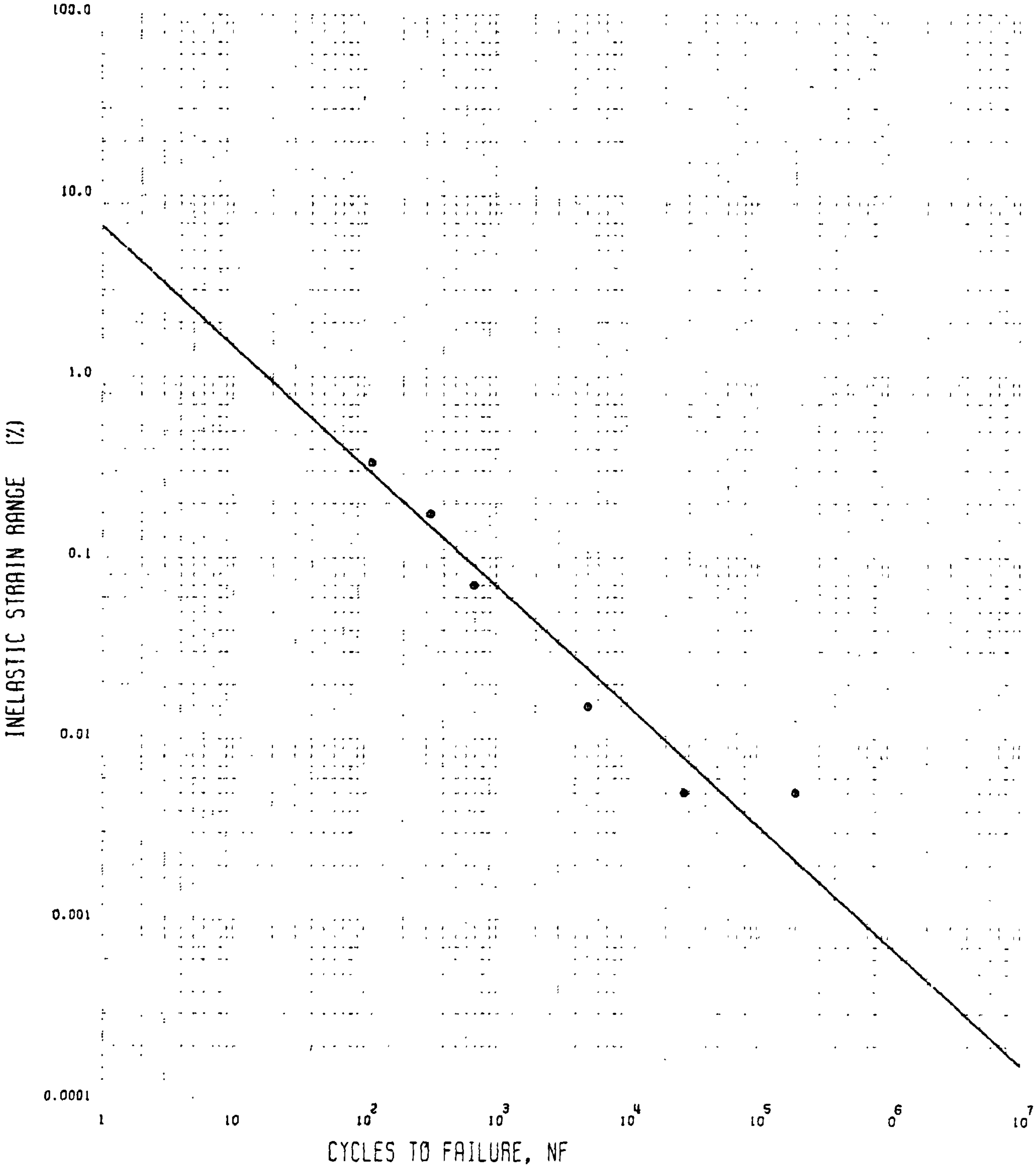

Figure A-2. — Inelastic Strain Range vs Cycles to Failure for Fully Reversed Continuous Cycle Controlled Strain AF2-1DA Data at 760°C (1400°F)

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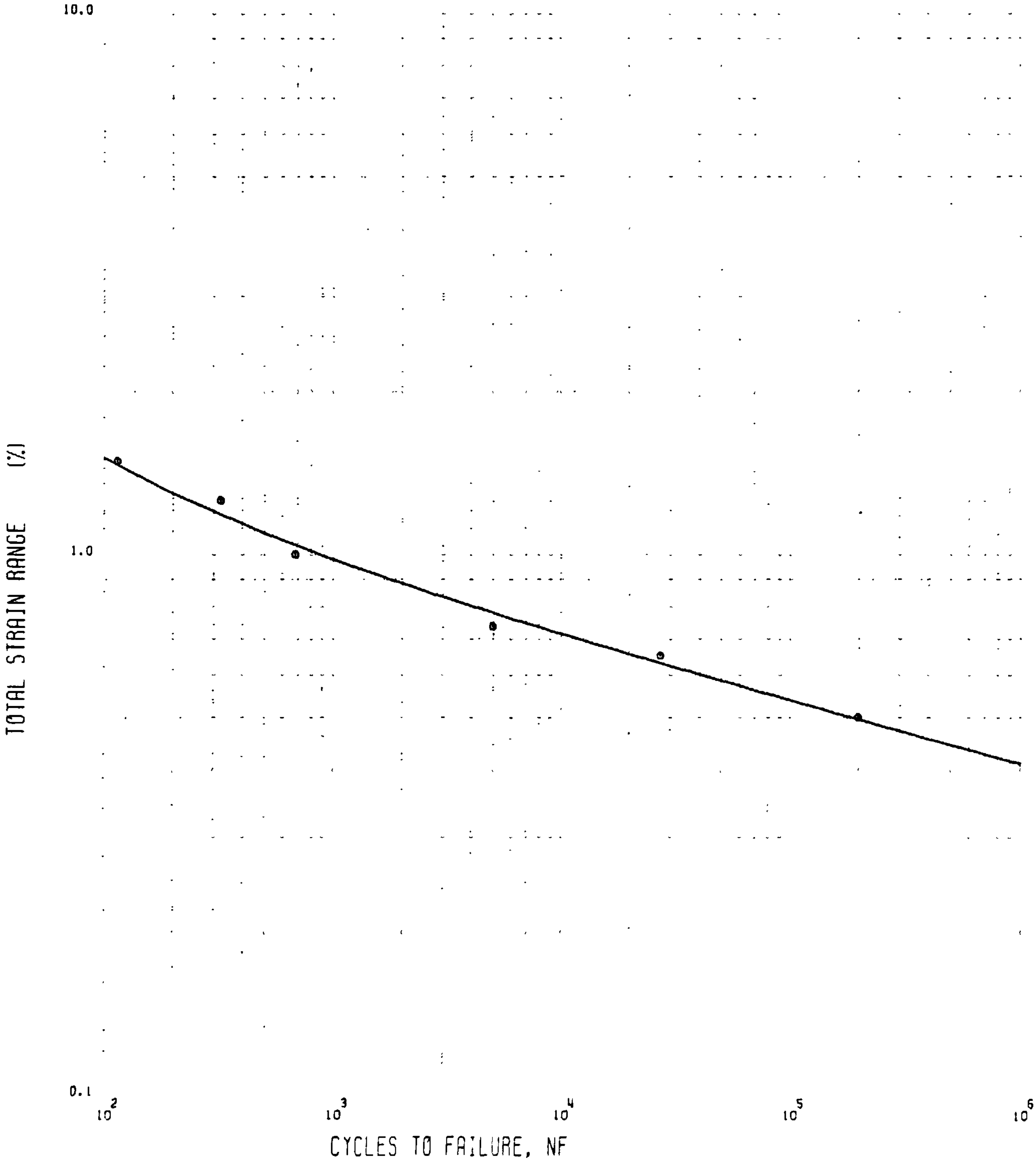

Figure A-3. — Total Strain Range vs Cycles to Failure for Fully Reversed Continuous Cycle Controlled Strain AF2-1DA Data at 760°C (1400°F)

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TABLE A-2. — 0.5 MINUTE TENSILE STRAIN HOLD (AF2-1DA) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.14032E+03	
STRENGH COEFF., K'	0.36761E+03	
STRAIN-HARD EXP., N'	0.15497E+00	
FATIGUE STRENGH COEFF., SIGMA	0.21673E+03	0.940
FATIGUE STRENGH EXP.,B	-0.82824E-01	
FATIGUE DUCTILITY COEFF., EF'	0.33061E-01	0.920
FATIGUE DUCTILITY EXP., C	-0.53445E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.45656E+01 D=-0.53445E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.15975E+01 B=-0.82865E-01

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.15975E+01 B=-0.82865E-01 C= 0.45656E+01 D=-0.53445E+00

TABLE A-3. — 2.0 MINUTES TENSILE STRAIN HOLD (AF2-1DA) CYCLIC PROPERTIES

2.0 MIN TENSILE STRAIN DWELL
CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.15002E+03	
STRENGH COEFF., K'	0.71494E+03	
STRAIN-HARD EXP., N'	0.25126E+00	
FATIGUE STRENGH COEFF., SIGMA	0.27091E+03	1.000
FATIGUE STRENGH EXP.,B	-0.11712E+00	
FATIGUE DUCTILITY COEFF., EF'	0.21020E-01	0.998
FATIGUE DUCTILITY EXP., C	-0.46615E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.30439E+01 D=-0.46618E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.19523E+01 B=-0.11724E+00

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.19523E+01 B=-0.11724E+00 C= 0.30439E+01 D=-0.46618E+00

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TABLE A-4. — 15.0 MINUTES TENSILE STRAIN HOLD (AF2-1DA) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.13204E+03	
STRENGH COEFF., K'	0.48540E+03	
STRAIN-HARD EXP., N'	0.20949E+00	
FATIGUE STRENGH COEFF., SIGMA	0.23656E+03	0.981
FATIGUE STRENGH EXP.,B	-0.11025E+00	
FATIGUE DUCTILITY COEFF., EF'	0.32353E-01	0.996
FATIGUE DUCTILITY EXP., C	-0.52584E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.44962E+01   D=-0.52587E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.17105E+01   B=-0.11022E+00

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.17105E+01   B=-0.11022E+00   C= 0.44962E+01   D=-0.52587E+00

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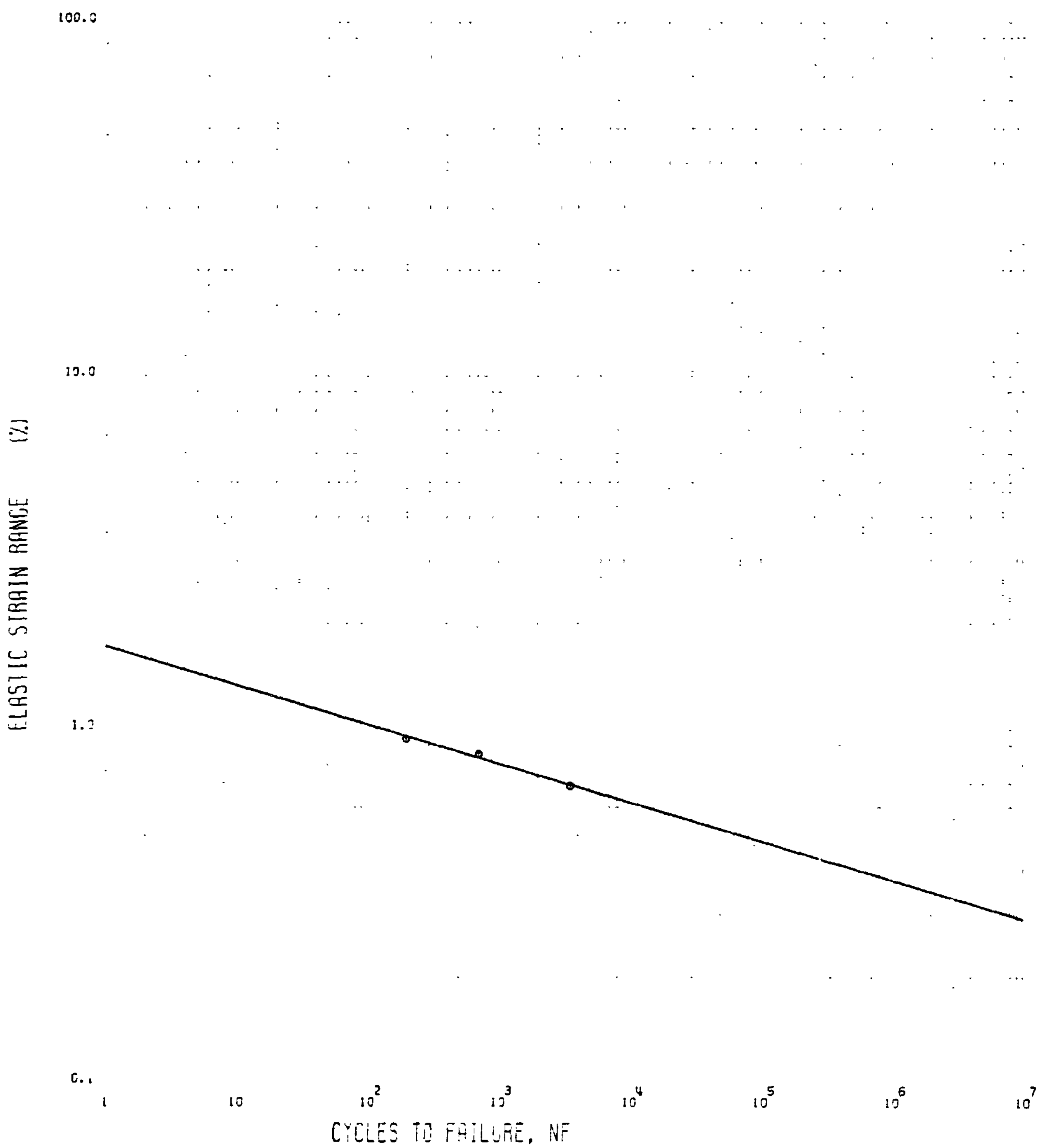

Figure A-4. — Elastic Strain Range vs Cycles to Failure for Fully Reversed Peak Tensile Strain 15.0 Minutes Hold AF2-1DA Data at 760°C (1400°F)

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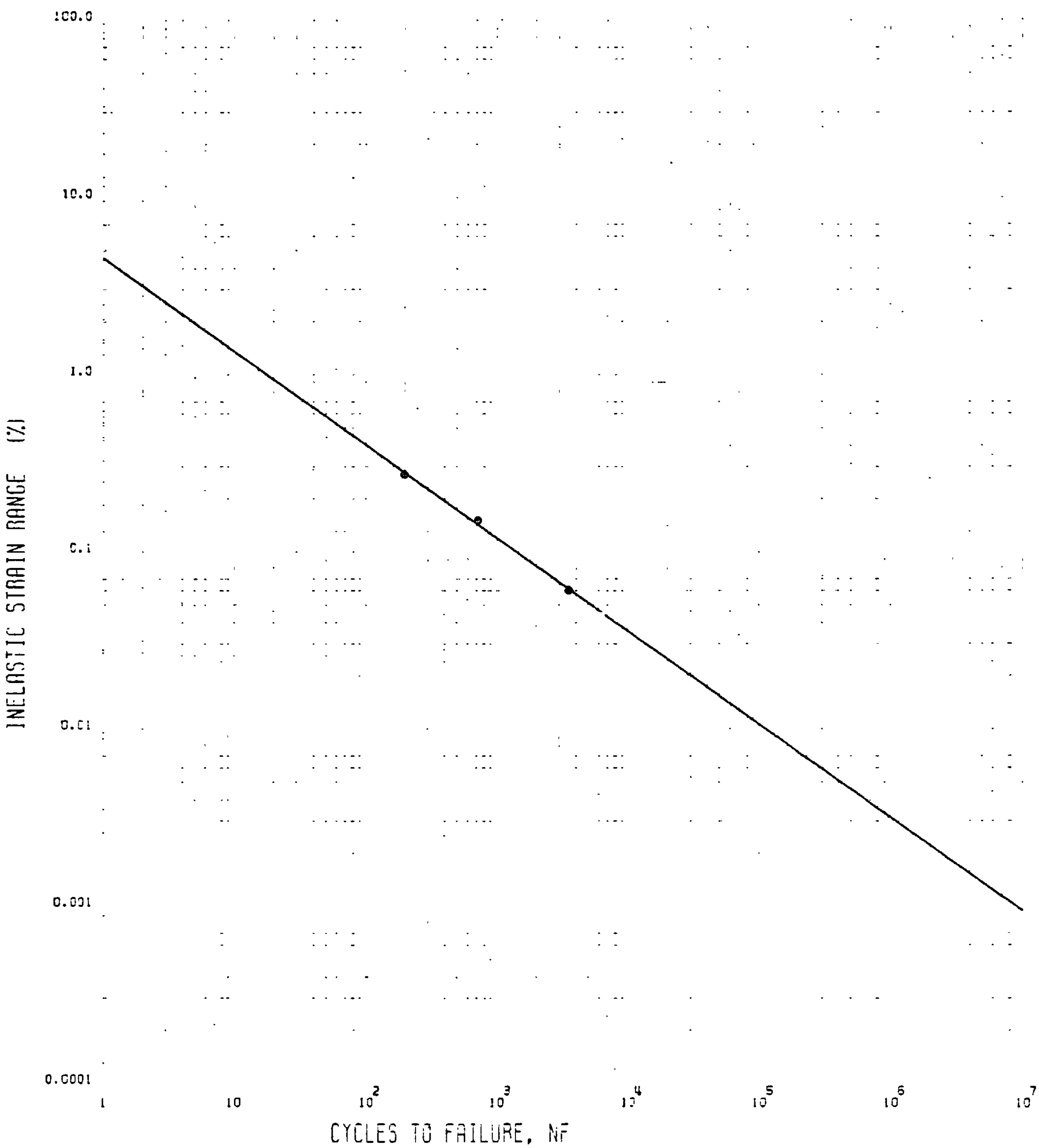

Figure A-5. — Inelastic Strain Range vs Cycles to Failure for Fully Reversed Peak Tensile Strain 15.0 Minutes Hold AF2-1DA Data at 760°C (1400°F)

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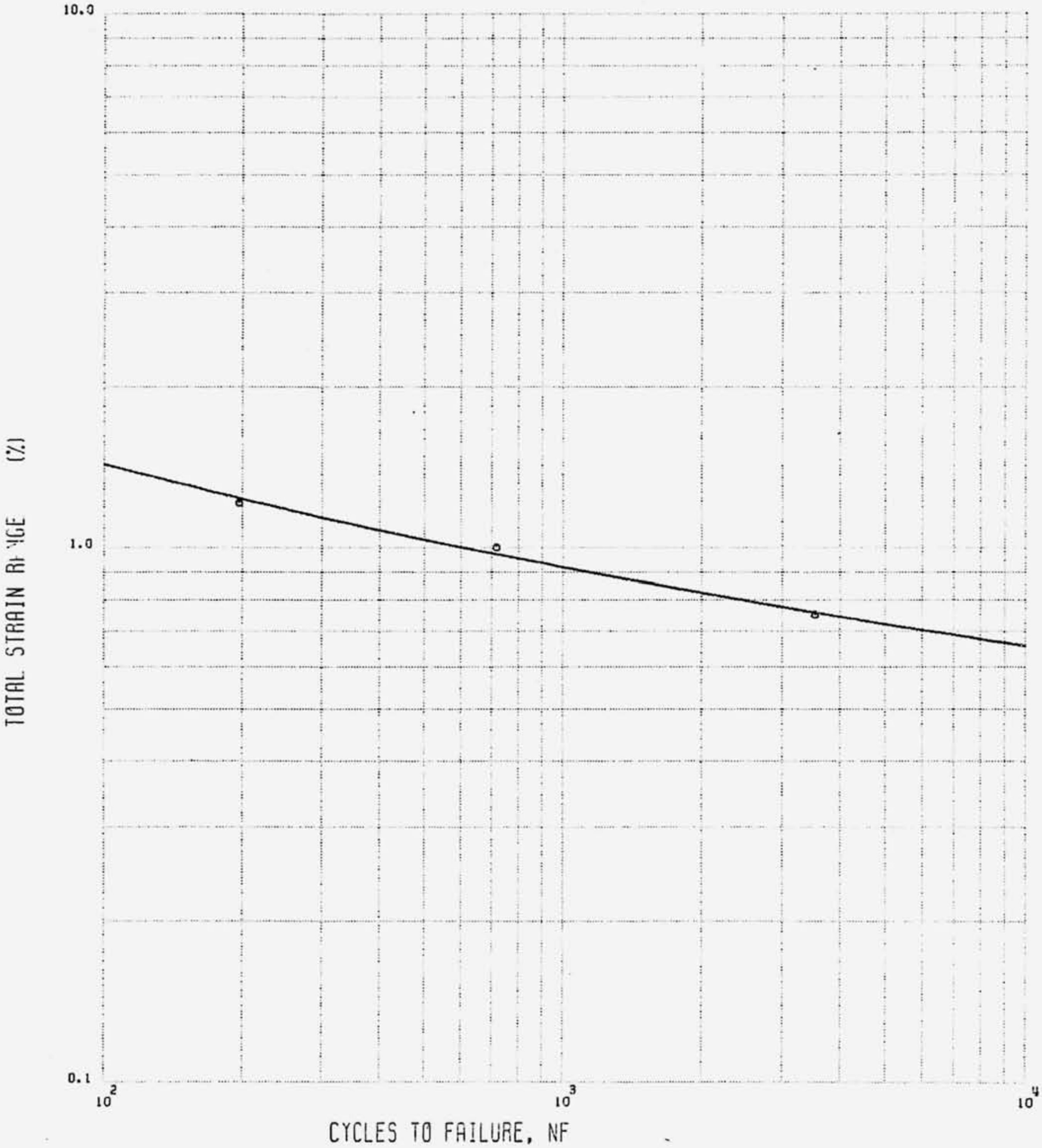

Figure A-6. — Total Strain Range vs Cycles to Failure for Fully Reversed Peak Tensile Strain 15.0 Minutes Hold AF2-1DA Data at 760°C (1400°F)

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TABLE A-5. — 0.5 MINUTE COMPRESSIVE STRAIN HOLD (AF2-1DA) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.15753E+03	
STRENGH COEFF., K'	0.56269E+03	
STRAIN-HARD EXP., N'	0.20486E+00	
FATIGUE STRENGH COEFF., SIGMA	0.37126E+03	0.989
FATIGUE STRENGH EXP.,B	-0.15856E+00	
FATIGUE DUCTILITY COEFF., EF'	0.13135E+00	0.997
FATIGUE DUCTILITY EXP., C	-0.77399E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.15364E+02 D=-0.77399E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.25957E+01 B=-0.15858E+00

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.25957E+01 B=-0.15858E+00 C= 0.15364E+02 D=-0.77399E+00

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TABLE A-6. — 2.0 MINUTES COMPRESSIVE STRAIN HOLD (AF2-1DA) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.14027E+03	
STRENGH COEFF., K'	0.48989E+03	
STRAIN-HARD EXP., N'	0.20124E+00	
FATIGUE STRENGH COEFF., SIGMA	0.27037E+03	0.996
FATIGUE STRENGH EXP.,B	-0.13159E+00	
FATIGUE DUCTILITY COEFF., EF'	0.52148E-01	0.990
FATIGUE DUCTILITY EXP., C	-0.65391E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.66291E+01 D=-0.65391E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.19256E+01 B=-0.13163E+00

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.19256E+01 B=-0.13163E+00 C= 0.66291E+01 D=-0.65391E+00

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TABLE A-7. — 15.0 MINUTES COMPRESSIVE STRAIN HOLD (AF2-1DA) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.12367E+03	
STRENGH COEFF., K'	0.20652E+03	
STRAIN-HARD EXP., N'	0.82514E-01	
FATIGUE STRENGH COEFF., SIGMA	0.25087E+03	0.999
FATIGUE STRENGH EXP., '	-0.12592E+00	
FATIGUE DUCTILITY COEFF., EF'	0.10565E+02	1.000
FATIGUE DUCTILITY EXP., C	-0.15261E+01	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.73362E+03 D=-0.15261E+01

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.17981E+01 B=-0.12603E+00

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.17981E+01 B=-0.12603E+00 C= 0.73362E+03 D=-0.15261E+01

STRESS - STRAIN RESPONSE

TOTAL STRAIN = STRESS/E + (STRESS/K')**(1/N')
E= 0.25633E+05 K'= 0.20652E+03 N'= 0.82514E-01

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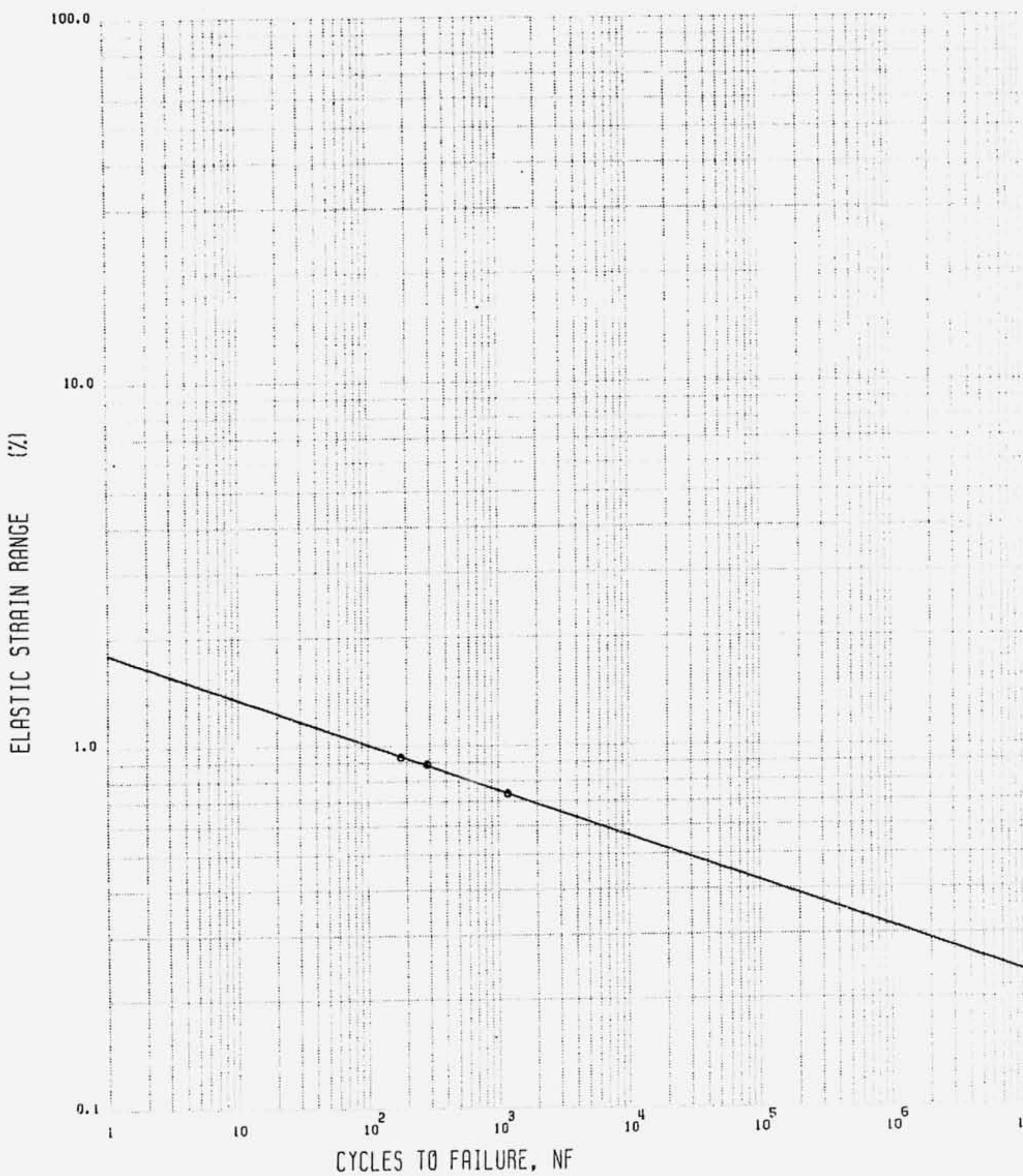

Figure A-7. — Elastic Strain Range vs Cycles to Failure for Fully Reversed Peak Compressive Strain 15.0 Minutes Hold AF2-1DA Data at 760°C (1400°F)

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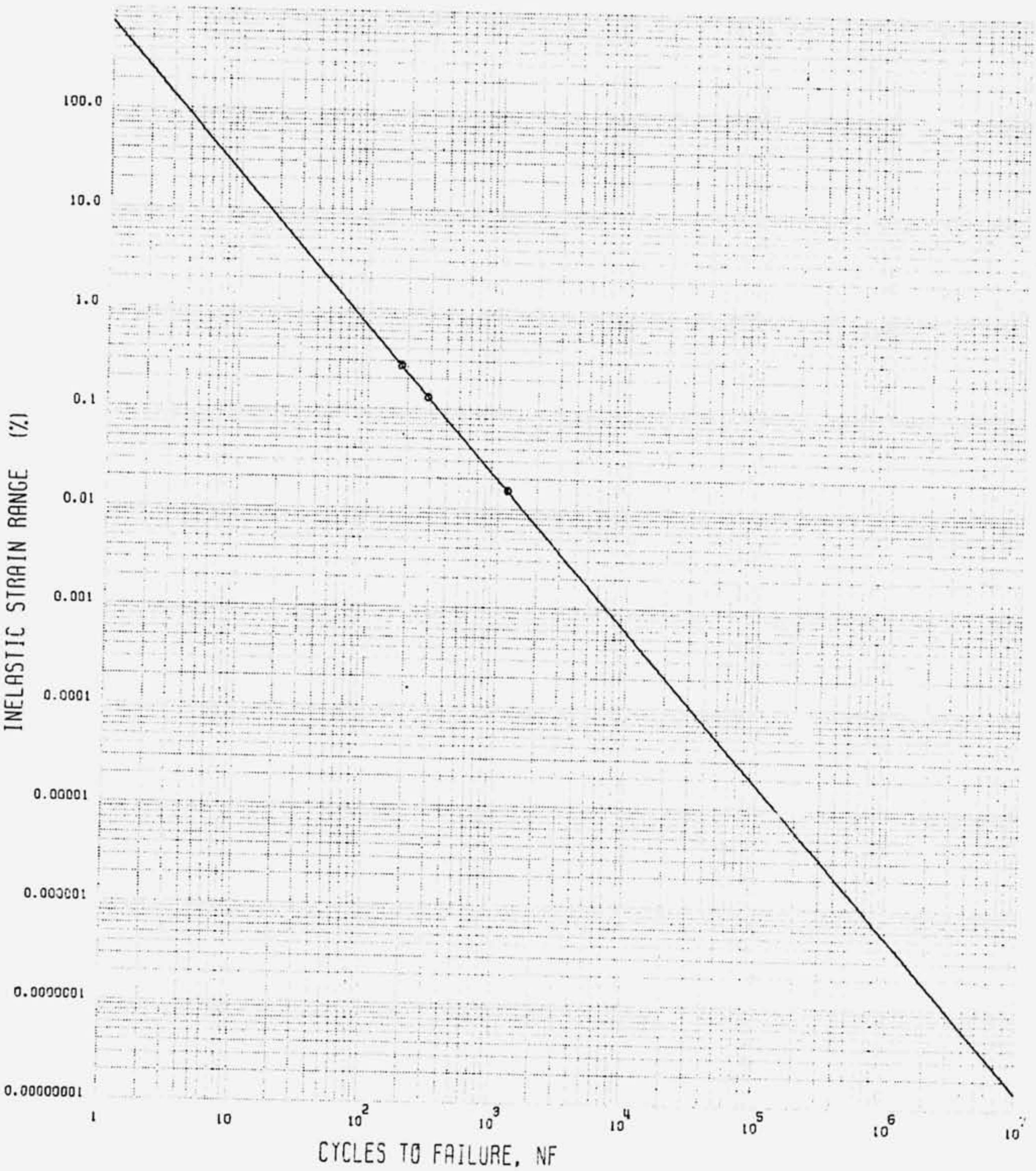

Figure A-8. — Inelastic Strain Range vs Cycles to Failure for Fully Reversed Peak Compressive Strain 15.0 Minutes Hold AF2-1DA Data at 760°C (1400°F)

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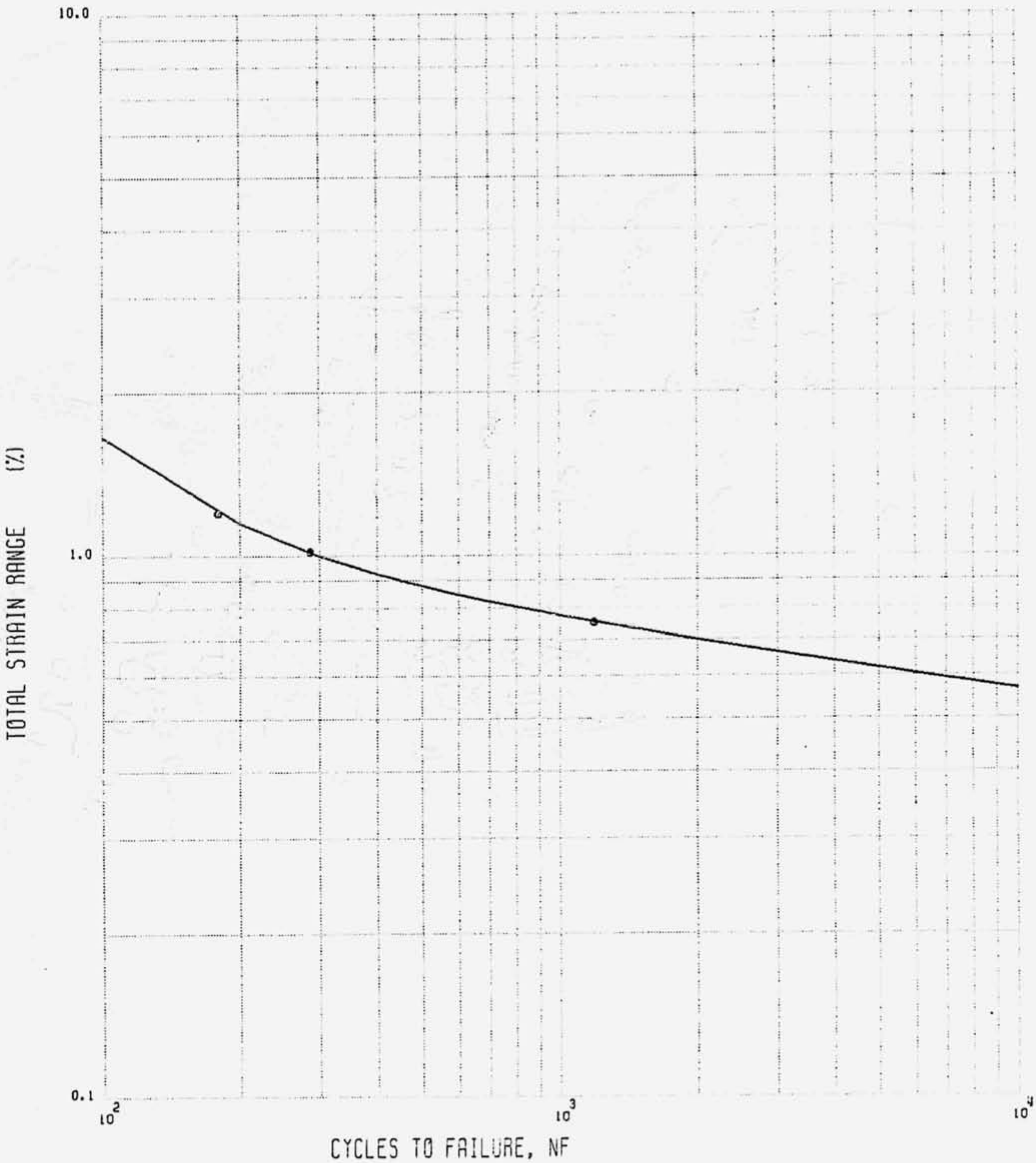

Figure A-9. — Total Strain Range vs Cycles to Failure for Fully Reversed Peak Compressive Strain 15.0 Minutes Hold AF2-1DA Data at 760°C (1400°F)

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TABLE A-8. — TENSILE AND COMPRESSIVE 0.5 MINUTE HOLD (AF2-1DA) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.13483E+03	
STRENGH COEFF., K'	0.48682E+03	
STRAIN-HARD EXP., N'	0.20659E+00	
FATIGUE STRENGH COEFF., SIGMA	0.26094E+03	0.966
FATIGUE STRENGH EXP.,B	-0.12979E+00	
FATIGUE DUCTILITY COEFF., EF'	0.48866E-01	0.939
FATIGUE DUCTILITY EXP., C	-0.62827E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.63234E+01 D=-0.62827E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.18608E+01 B=-0.12983E+00

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.18608E+01 B=-0.12983E+00 C= 0.63234E+01 D=-0.62827E+00

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TABLE A-9. — CONTINUOUS CYCLE CONTROLLED STRAIN (INCO 718) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.88229E+02	
STRENGH COEFF., K'	0.13442E+03	
STRAIN-HARD EXP., N'	0.67753E-01	
FATIGUE STRENGH COEFF., SIGMA	0.10433E+03	0.899
FATIGUE STRENGH EXP., B	-0.20759E-01	
FATIGUE DUCTILITY COEFF., EF'	0.23754E-01	0.933
FATIGUE DUCTILITY EXP., C	-0.30639E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.38419E+01 D=-0.30640E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.88495E+00 B=-0.20874E-01

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.88495E+00 B=-0.20874E-01 C= 0.38419E+01 D=-0.30640E+00

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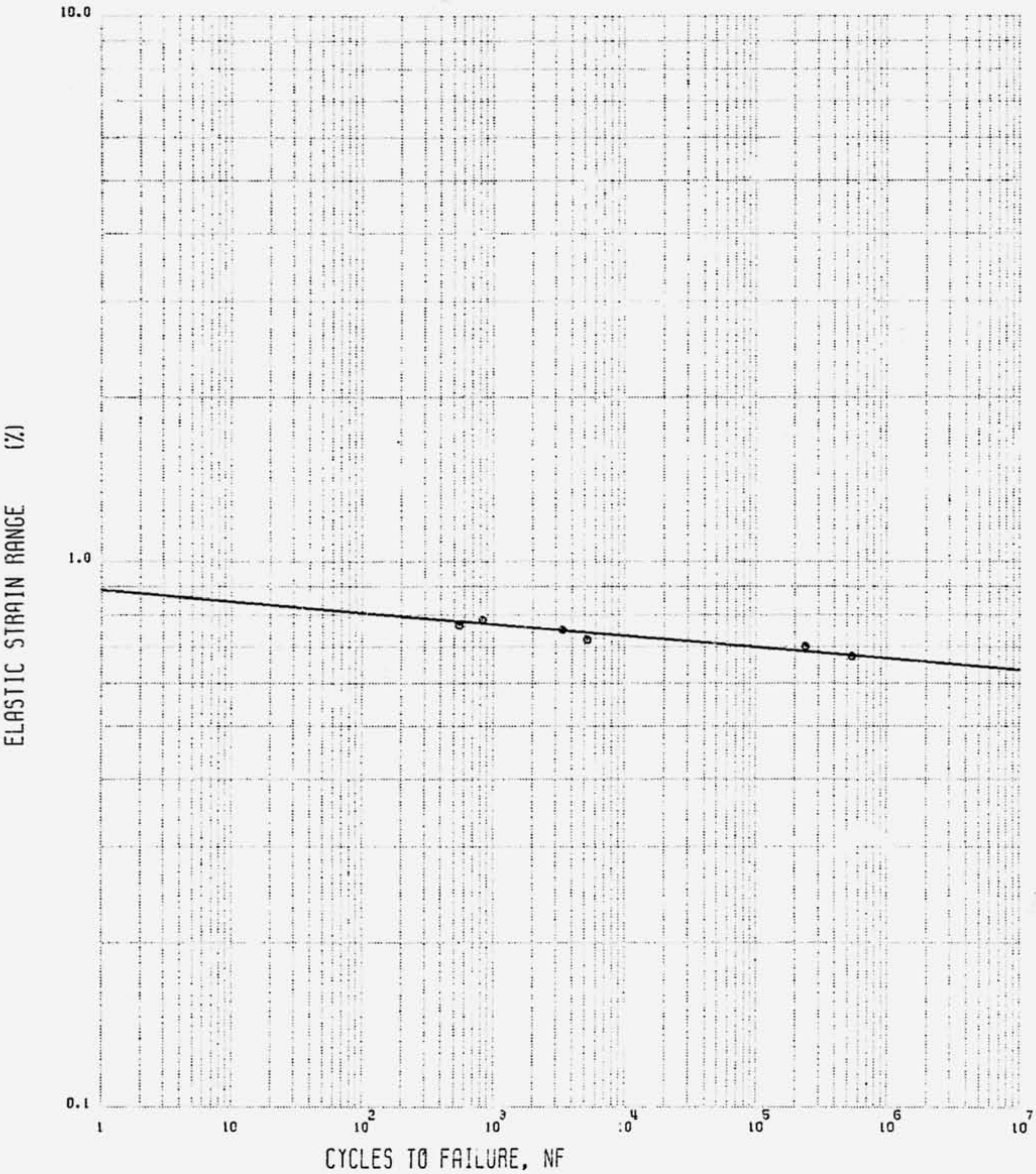

Figure A-10. — Elastic Strain Range vs Cycles to Failure for Fully Reversed Peak Continuous Cycle Controlled Strain Hold Cycle INCO 718 Data at 649°C (1200°F)

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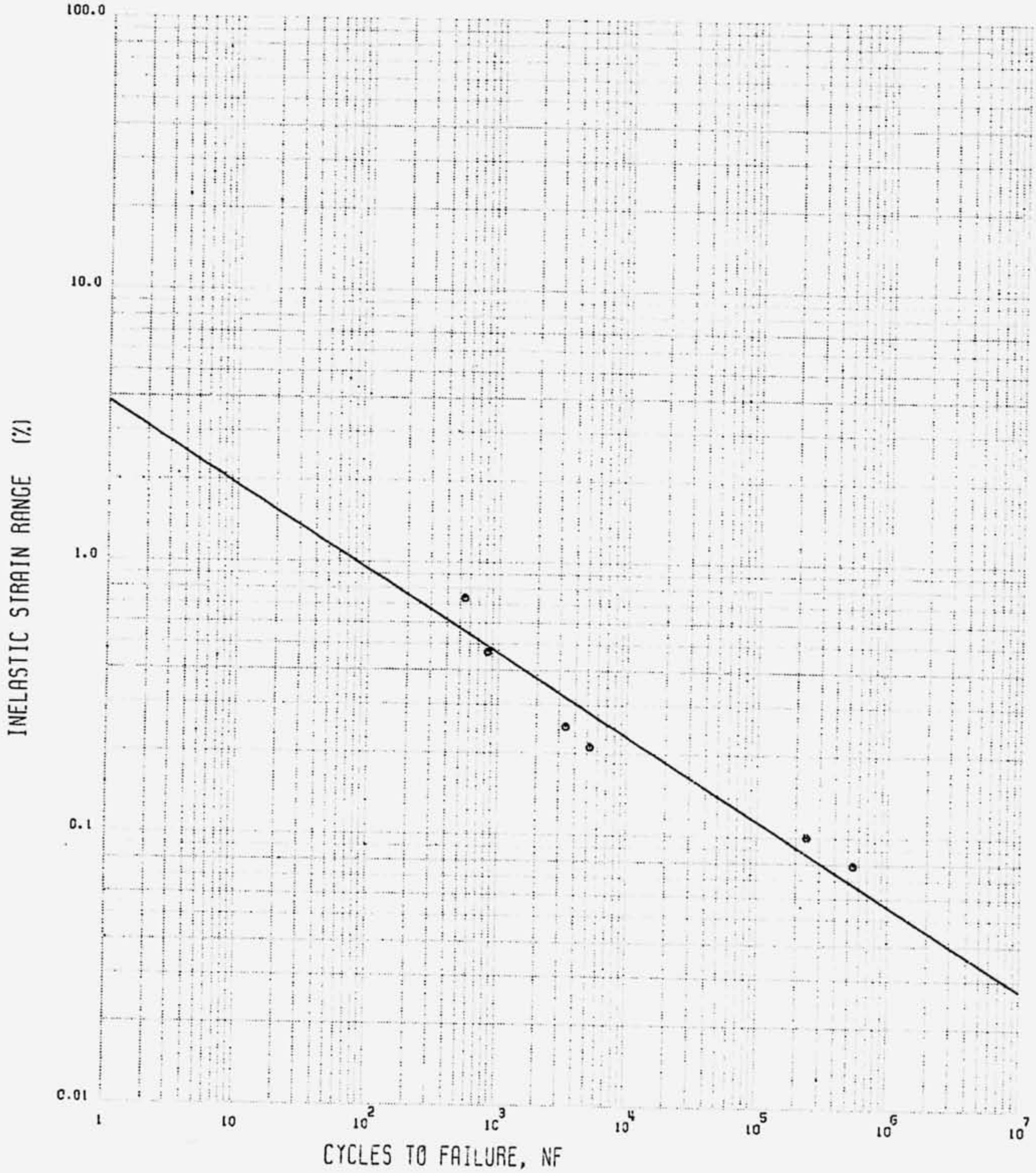

Figure A-11. — Inelastic Strain Range vs Cycles to Failure for Fully Reversed Continuous Cycle Controlled Strain Hold Cycle INCO 718 Data at 649°C (1200°F)

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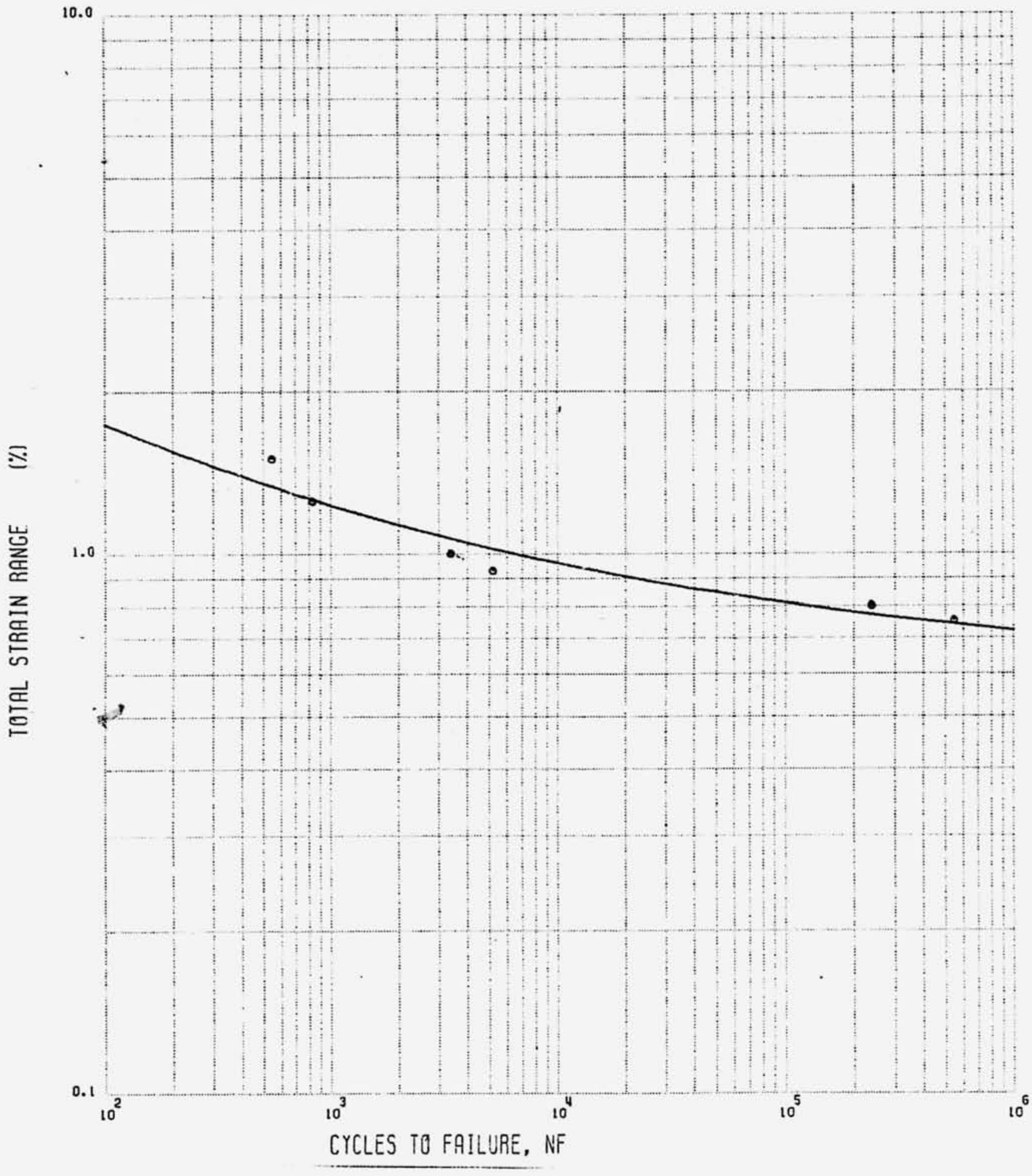

Figure A-12. — Total Strain Range vs Cycles to Failure for Fully Reversed Peak Continuous Cycle Controlled Strain Hold Cycle INCO 718 Data at 649°C (1200°F)

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TABLE A-10. — 0.5 MINUTE TENSILE STRAIN HOLD (INCO 718) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.80368E+02	
STRENGH COEFF., K'	0.16441E+03	
STRAIN-HARD EXP., N'	0.11517E+00	
FATIGUE STRENGH COEFF., SIGMA	0.10586E+03	0.999
FATIGUE STRENGH EXP., B	-0.34613E-01	
FATIGUE DUCTILITY COEFF., EF'	0.21879E-01	0.991
FATIGUE DUCTILITY EXP., C	-0.30055E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.35534E+01 D=-0.30055E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.88976E+00 B=-0.34911E-01

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.88976E+00 B=-0.34911E-01 C= 0.35534E+01 D=-0.30055E+00

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TABLE A-11. — 2.0 MINUTES TENSILE STRAIN HOLD (INCO 718) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH .2% SY (KSI)	0.83811E+02	
STRENGH COEFF., K'	0.34276E+03	
STRAIN-HARD. EXP., N'	0.22664E+00	
FATIGUE STRENGTH COEFF., SIGMA	0.26864E+03	0.453
FATIGUE STRENGTH EXP., B	-0.14927E+00	
FATIGUE DUCTILITY COEFF., EF'	0.34123E+00	1.000
FATIGUE DUCTILITY EXP., C	-0.65863E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.43201E+02   D=-0.65859E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.20910E+01   B=-0.14884E+00

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.2091 E+01   B=-0.14884E+00   C= 0.43201E+02   D=-0.65859E+00

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TABLE A-12. — 15.0 MINUTES TENSILE STRAIN HOLD (INCO 718) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.89395E+02	
STRENGH COEFF., K'	0.17572E+03	
STRAIN-HARD EXP., N'	0.10875E+00	
FATIGUE STRENGH COEFF., SIGMA	0.13599E+03	0.995
FATIGUE STRENGH EXP.,B	-0.57451E-01	
FATIGUE DUCTILITY COEFF., EF'	0.94721E-01	0.991
FATIGUE DUCTILITY EXP., C	-0.52829E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.13133E+02 D=-0.52834E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.11227E+01 B=-0.57451E-01

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.11227E+01 B=-0.57451E-01 C= 0.13133E+02 D=-0.52834E+00

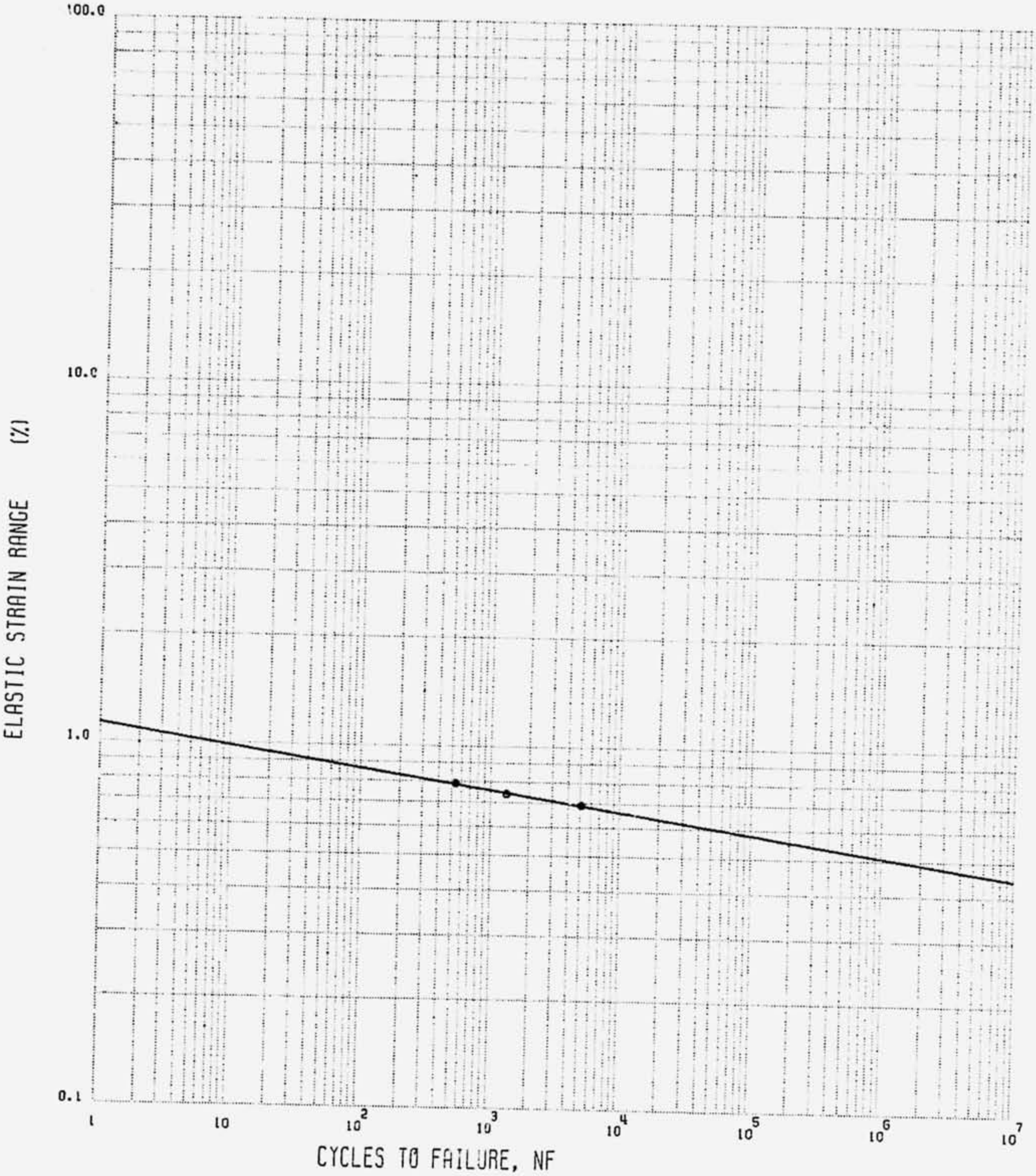

Figure A-13. — *Elastic Strain Range vs Cycles to Failure for Fully Reversed Peak Tensile Strain 15.0 Minutes Hold Cycle INCO 718 Data at 649°C (1200°F)*

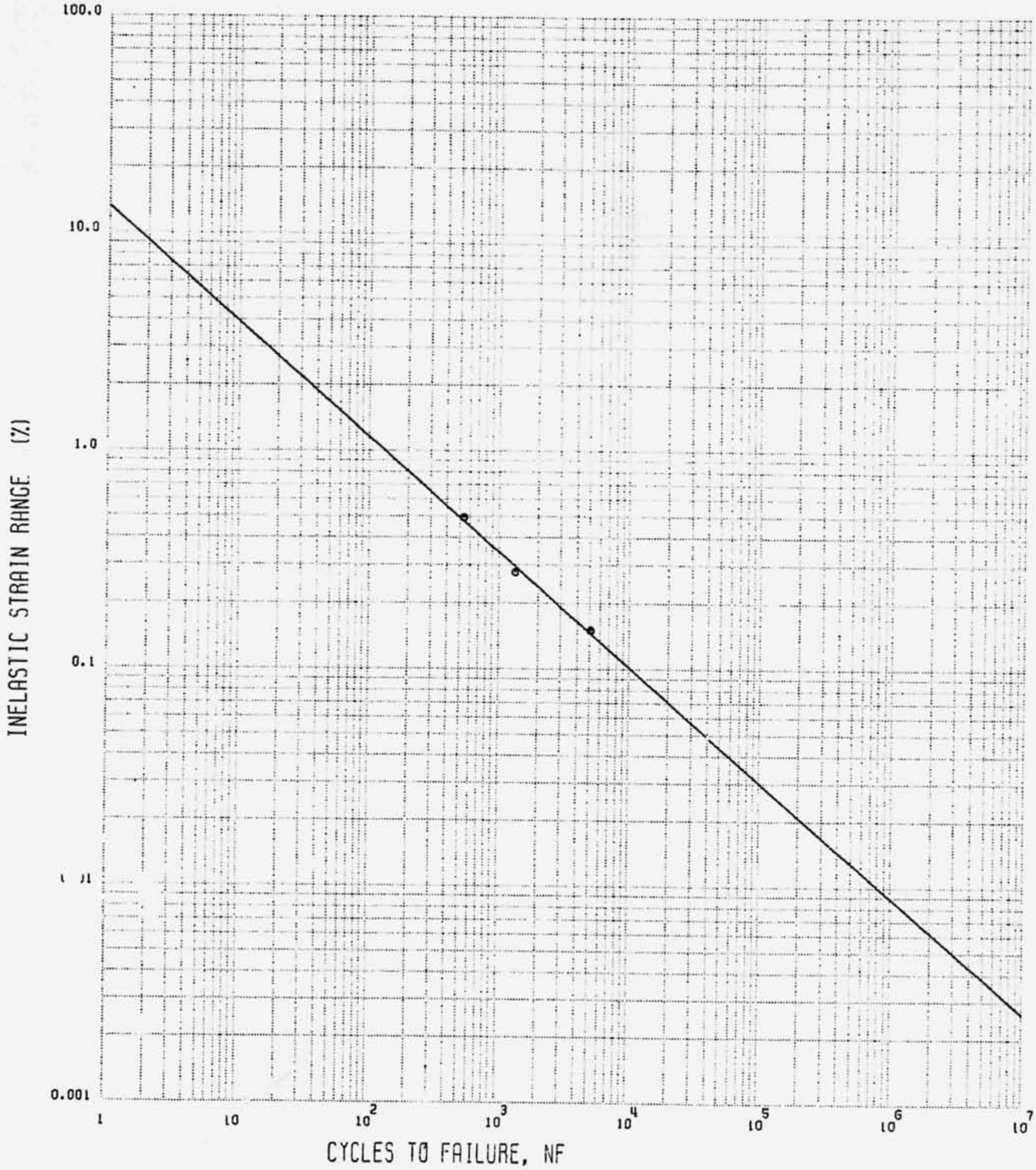

Figure A-14. — Inelastic Strain Range vs Cycles to Failure for Fully Reversed Peak Tensile Strain 15.0 Minutes Hold Cycle INCO 718 Data at 649°C (1200°F)

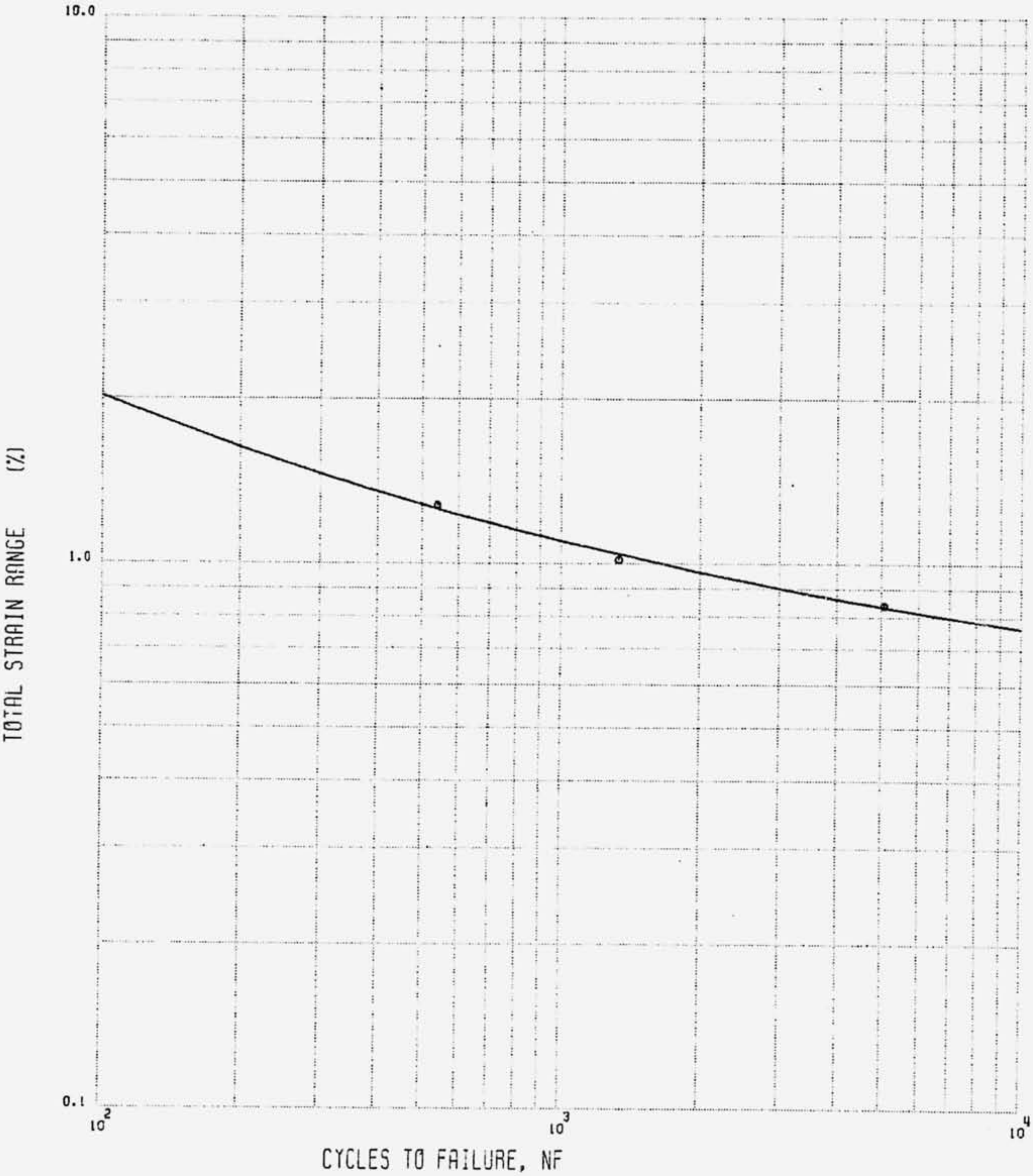

Figure A-15. — Total Strain Range vs Cycles to Failure for Fully Reversed Peak Tensile Strain 15.0 Minutes Hold Cycle INCO 718 Data at 649°C (1200°F)

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TABLE A-13. — 0.5 MINUTE COMPRESSIVE STRAIN HOLD (INCO 718) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.87951E+02	
STRENGH COEFF., K'	0.25787E+03	
STRAIN-HARD EXP., N'	0.17309E+00	
FATIGUE STRENGH COEFF., SIGMA	0.15497E+03	0.910
FATIGUE STRENGH EXP., B	-0.73605E-01	
FATIGUE DUCTILITY COEFF., EF'	0.52757E-01	1.000
FATIGUE DUCTILITY EXP., C	-0.42525E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.78573E+01 D=-0.42520E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.12641E+01 B=-0.73605E-01

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.12641E+01 B=-0.73605E-01 C= 0.78573E+01 D=-0.42520E+00

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TABLE A-14. — 2.0 MINUTES COMPRESSIVE STRAIN HOLD (INCO 718)
CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.83101E+02	
STRENGH COEFF., K'	0.12451E+03	
STRAIN-HARD EXP., N'	0.65064E-01	
FATIGUE STRENGH COEFF., SIGMA	0.11123E+03	0.994
FATIGUE STRENGH EXP.,B	-0.38129E-01	
FATIGUE DUCTILITY COEFF., EF'	0.17672E+00	0.997
FATIGUE DUCTILITY EXP., C	-0.58603E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.23535E+02 D=-0.58607E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.93106E+00 B=-0.38369E-01

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.93106E+00 B=-0.38369E-01 C= 0.23535E+02 D=-0.58607E+00

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TABLE A-15. — 15.0 MINUTES COMPRESSIVE STRAIN HOLD (INCO 718)
CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.90119E+02	
STRENGH COEFF., K'	0.14243E+03	
STRAIN-HARD EXP., N'	0.73651E-01	
FATIGUE STRENGH COEFF., SIGMA	0.13888E+03	0.966
FATIGUE STRENGH EXP., B	-0.60491E-01	
FATIGUE DUCTILITY COEFF., EF'	0.70993E+00	0.974
FATIGUE DUCTILITY EXP., C	-0.82133E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.80345E+02 D=-0.82127E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.11515E+01 B=-0.61273E-01

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.11515E+01 B=-0.61273E-01 C= 0.80345E+02 D=-0.82127E+00

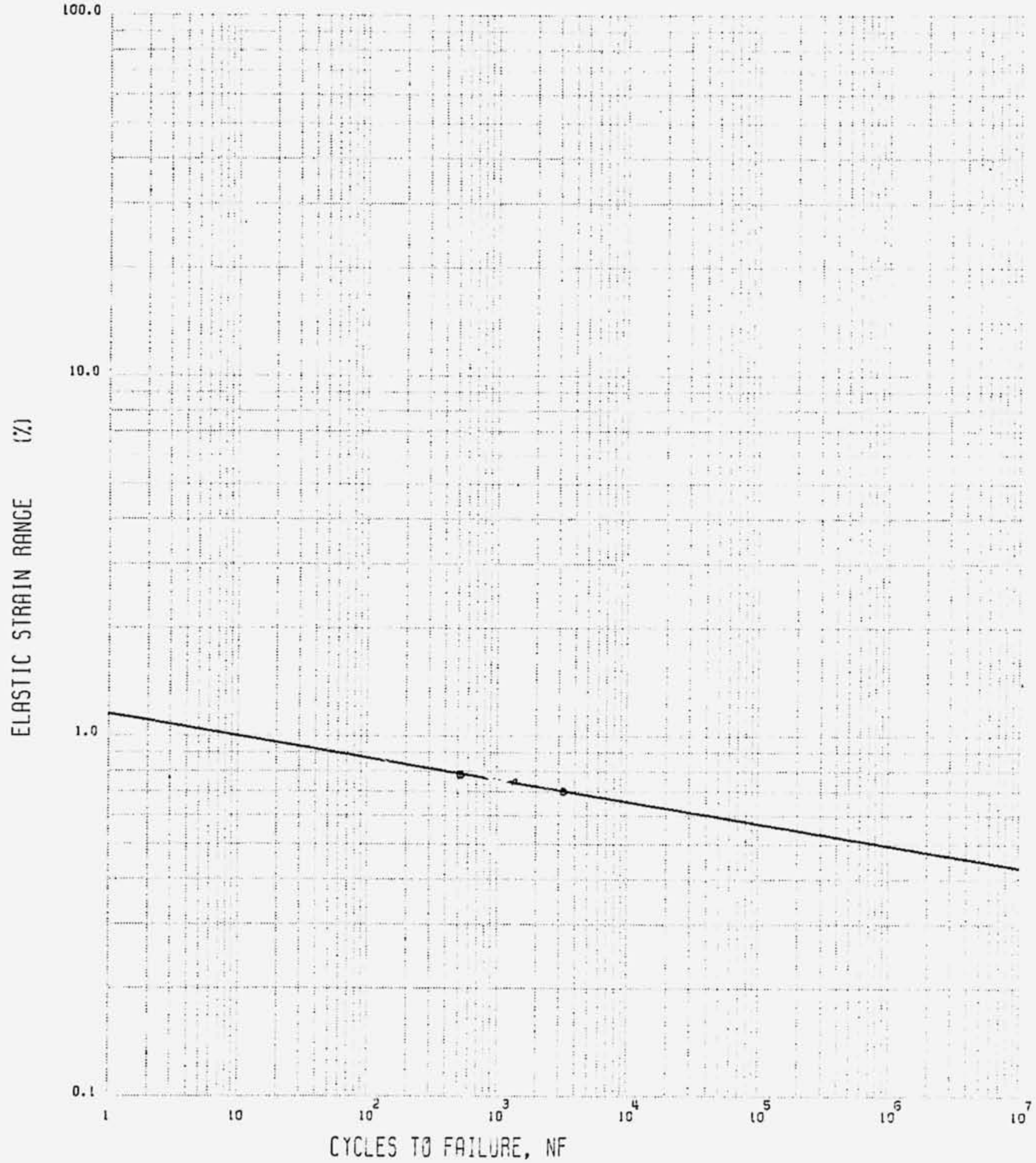

Figure A-16. — Elastic Strain Range vs Cycles to Failure for Fully Reversed Peak Compressive Strain 15.0 Minutes Hold Cycle INCO 718 Data at 649°C (1200°F)

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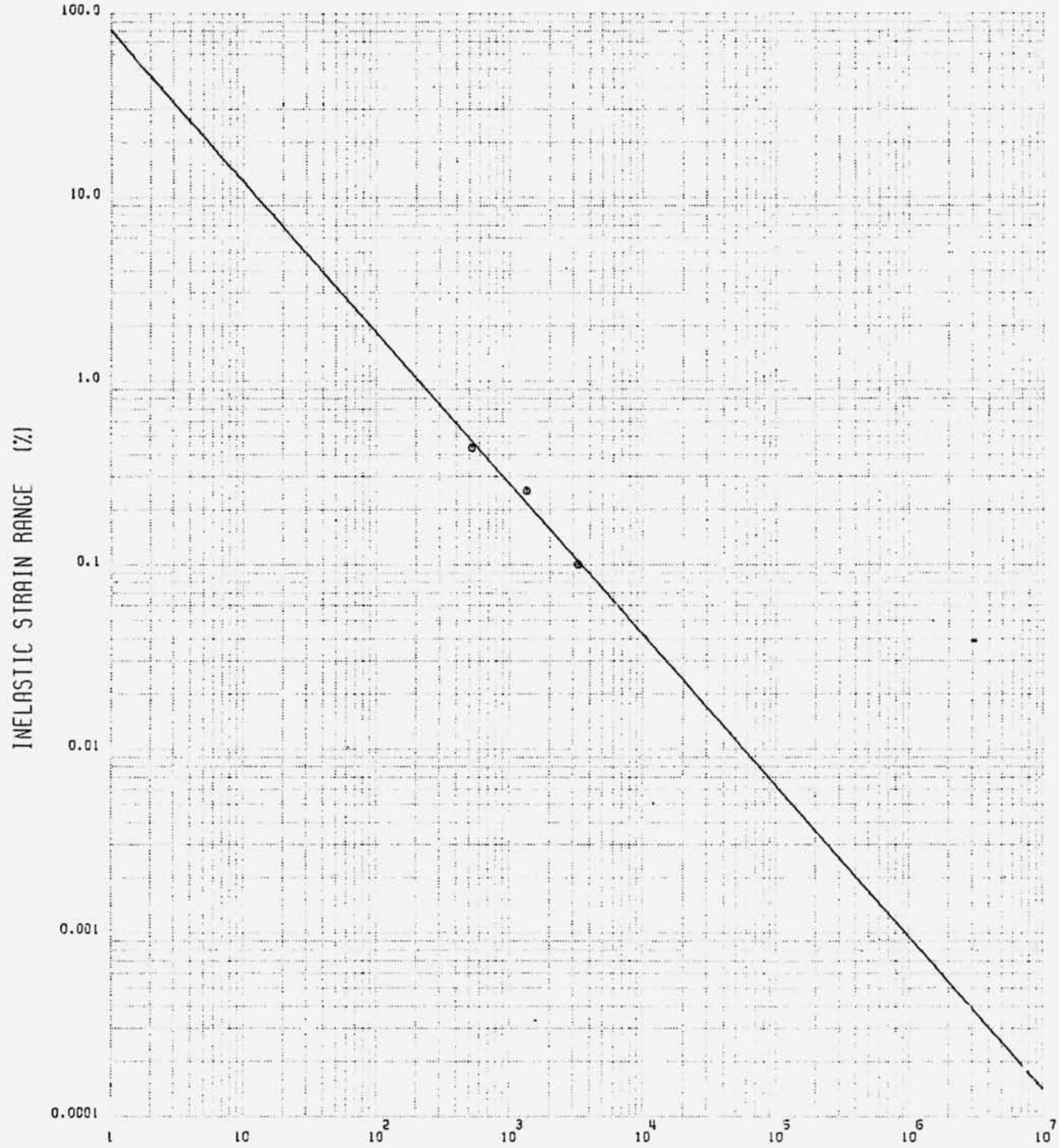

Figure A-17. — Inelastic Strain Range vs Cycles to Failure for Fully Reversed Peak Tensile Strain 15.0 Minutes Hold Cycle INCO 718 Data at 649°C (1200°F)

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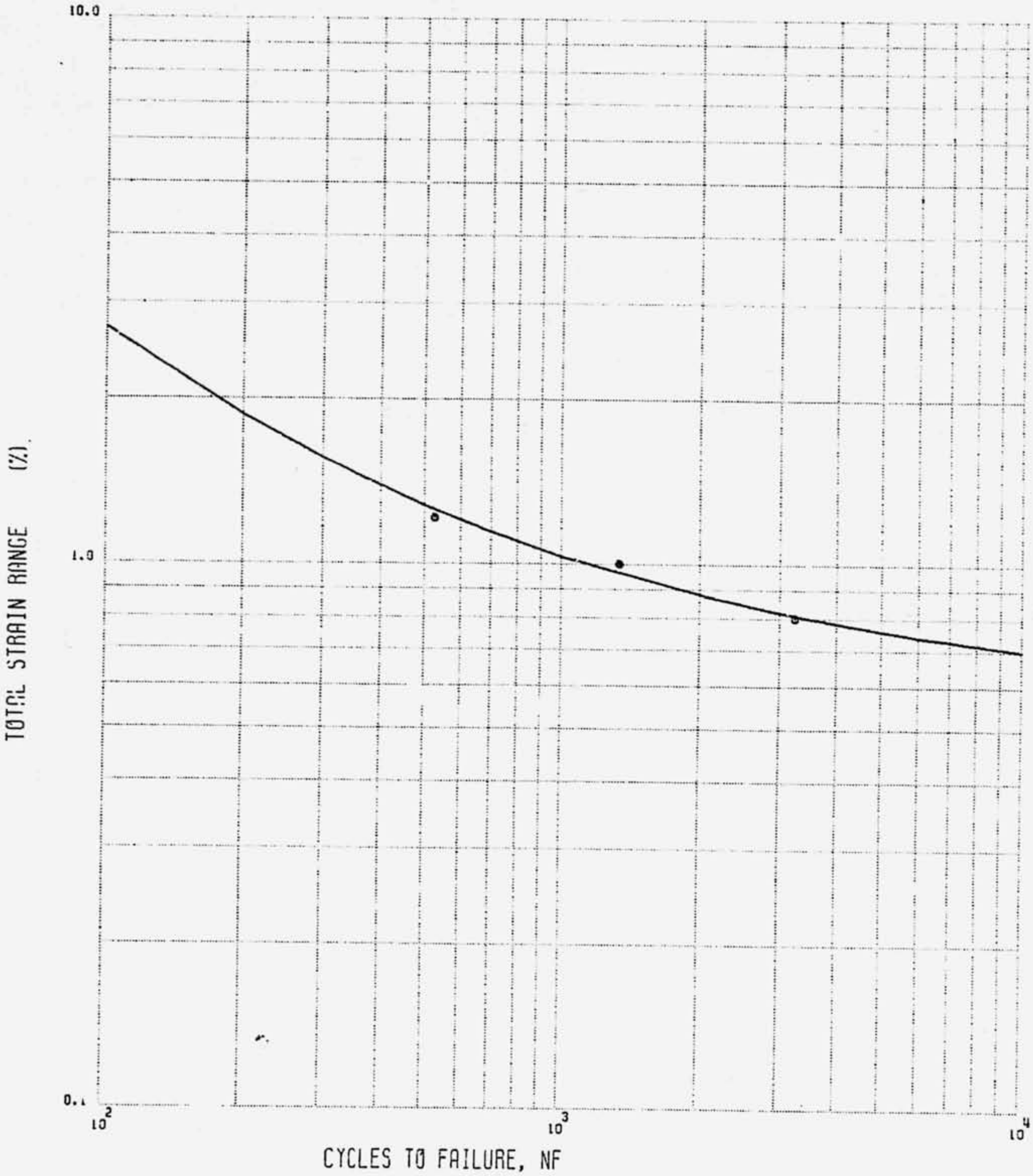

Figure A-18. — Total Strain Range vs Cycles to Failure for Fully Reversed Peak Compressive Strain 15.0 Minutes Hold Cycle INCO 718 Data at 649°C (1200°F)

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TABLE A-16. — 0.5 MINUTE TENSILE AND COMPRESSIVE STRAIN HOLD (INCO 718) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.74330E+02	
STRENGH COEFF., K'	0.13562E+03	
STRAIN-HARD EXP., N'	0.96761E-01	
FATIGUE STRENGH COEFF., SIGMA	0.13455E+03	0.969
FATIGUE STRENGH EXP.,B	-0.76122E-01	
FATIGUE DUCTILITY COEFF., EF'	0.92144E+00	0.983
FATIGUE DUCTILITY EXP., C	-0.78671E+00	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.10681E+03 D=-0.78667E+00

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.11028E+01 B=-0.76055E-01

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.11028E+01 B=-0.76055E-01 C= 0.10681E+03 D=-0.78667E+00

TABLE A-17. — 2.0 MINUTES TENSILE AND COMPRESSIVE STRAIN HOLD (INCO 718) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.8[illegible]447E+02	
STRENGH COEFF., K'	0.18701E+03	
STRAIN-HARD EXP., N'	0.13574E+00	
FATIGUE STRENGH COEFF., SIGMA	0.23925E+03	0.489
FATIGUE STRENGH EXP., B	-0.147[illegible]1E+00	
FATIGUE DUCTILITY COEFF., EF'	0.61409E+01	0.639
FATIGUE DUCTILITY EXP., C	-0.10845E+01	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.57950E+03 D=-0.10845E+01

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.18625E+01 B=-0.14806E+00

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.18625E+01 B=-0.14806E+00 C= 0.57950E+03 D=-0.10845E+01

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TABLE A-18. — 15 MINUTES TENSILE AND COMPRESSIVE STRAIN HOLD (INCO 718) CYCLIC PROPERTIES

		R-SQUARE
YIELD STRENGTH, .2% SY (KSI)	0.74419E+02	
STRENGH COEFF., K'	0.10887E+03	
STRAIN-HARD EXP., N'	0.61221E-01	
FATIGUE STRENGH COEFF., SIGMA	0.12016E+03	0.890
FATIGUE STRENGH EXP.,B	-0.70660E-01	
FATIGUE DUCTILITY COEFF., EF'	0.50079E+01	0.988
FATIGUE DUCTILITY EXP., C	-0.11542E+01	

EQUATIONS AND COEFFICIENTS

STRAIN - LIFE RESPONSE

INELASTIC STRAIN RANGE = C*(CYCLES TO FAILURE)**D
C= 0.44987E+03 D=-0.11540E+01

ELASTIC STRAIN RANGE = A*(CYCLES TO FAILURE)**B
A= 0.98592E+00 B=-0.71648E-01

TOTAL STRAIN RANGE = A*(CYCLES TO FAILURE)**B + C*(CYCLES TO FAILURE)**D
A= 0.98592E+00 B=-0.71648E-01 C= 0.44987E+03 D=-0.11540E+01

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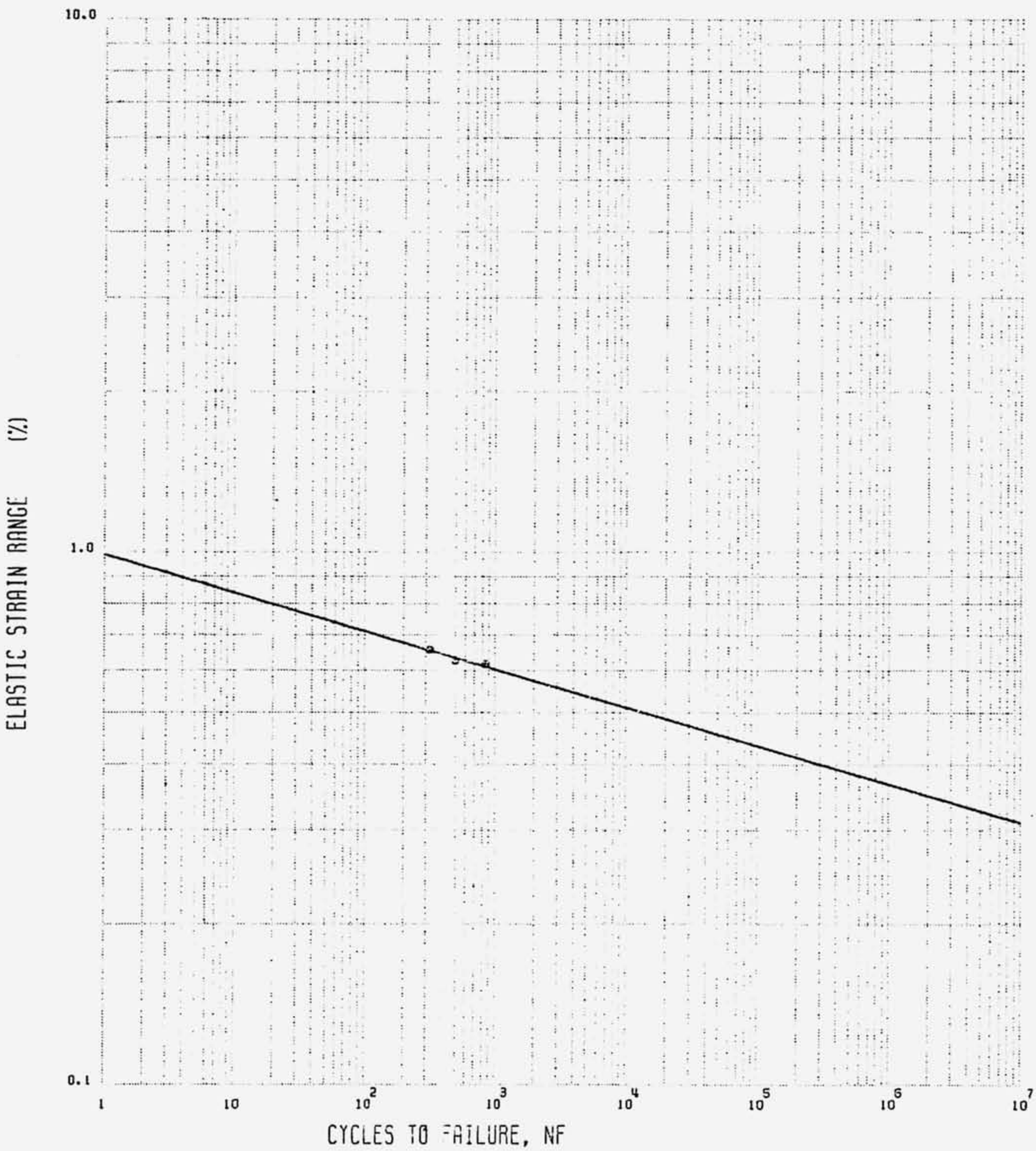

Figure A-19. — Elastic Strain Range vs Cycles to Failure for Fully Reversed Peak Tensile and Compressive Strain 15.0 Minutes Hold Cycle INCO 718 Data at 649°C (1200°F)

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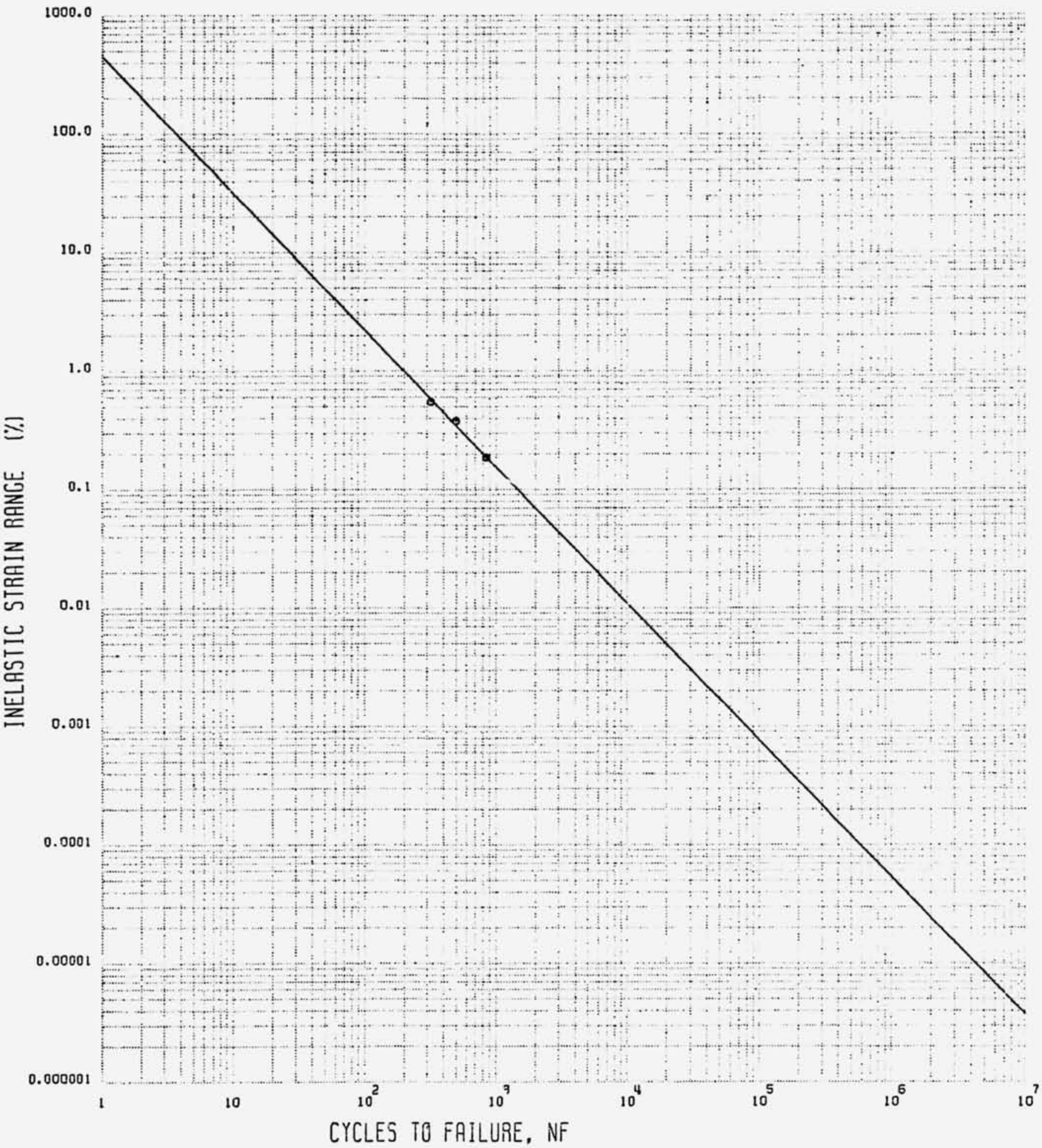

Figure A-20. — Inelastic Strain Range vs Cycles to Failure for Fully Reversed Peak Tensile and Compressive Strain 15.0 Minutes Hold Cycle INCO 718 Data at 649°C (1200°F)

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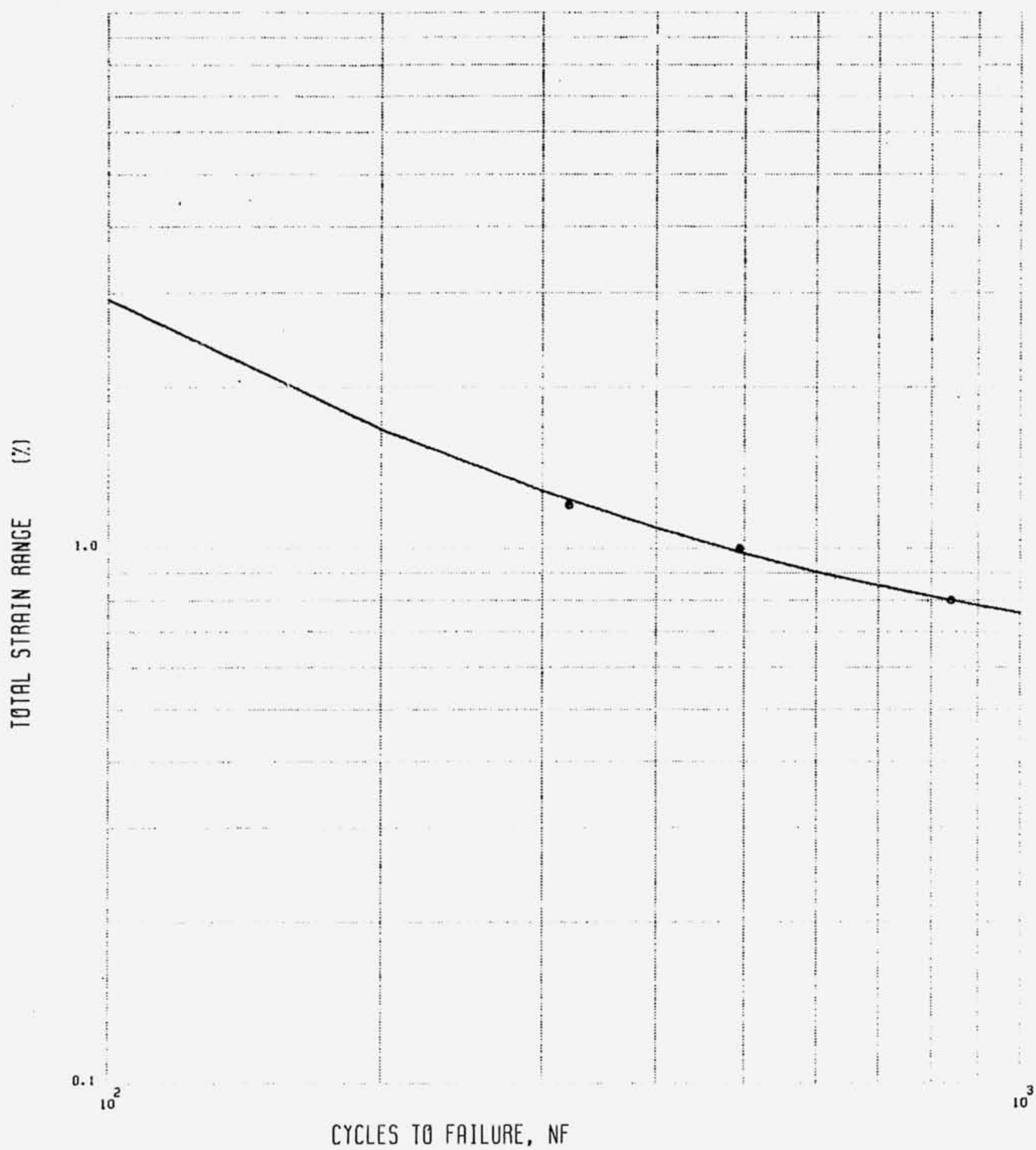

Figure A-21. — Total Strain Range vs Cycles to Failure for Fully Reversed Peak Tensile and Compressive Strain 15.0 Minutes Hold Cycle INCO 718 Data at 649°C (1200°F)

APPENDIX B
STRESS RANGE VS CYCLE PLOTS FOR GATORIZED® AF2-1DA AND INCO 718

This appendix contains stress range vs cycle plots for selected cyclic tests for GATORIZED® AF2-1DA and INCO 718. Also included are the tabulations containing: (1) the number of cycles to first indication of failure by cracking, N_0, which was determined by first indication of deviation (by 2%) in the stabilized stress range; (2) the number of cycles to 10% drop in the stabilized ratio of peak tensile stress to peak compressive stress, N_{10}; (3) the number of cycles to 5 and 50% drop in the stabilized load range. N_5 and N_{50}; and (4) the cycles to failure by complete separation of the specimen, N_f.

TABLE B-1. — CONTINUOUS CYCLE CONTROLLED STRAIN

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
□ 2.0	35	291	2009	297.4	1.0
5.0	39	282	1948		
10.0	44	269	1845		
20.0	58	238	1640		
50.0	--	149	1025		
N_{10} =47 CYCLES, RATIO CHANGED BY 10% ; NF = 114					
○ 2.0	255	276	1901	281.3	177.0
5.0	292	267	1843		
10.0	300	253	1746		
25.0	308	211	1455		
50.0	--	141	970		
N_{10} =321 CYCLES, RATIO CHANGED BY 10% ; NF = 321					
△ 2.0	277	256	1765	261.2	64.0
5.0	456	248	1711		
10.0	660	235	1621		
25.0	667	196	1351		
50.0	677	131	900		
N_{10} =678 CYCLES, RATIO CHANGED BY 10% ; NF = 678					
* 2.0	4579	195	1345	199.1	2715.0
5.0	4754	189	1304		
10.0	4847	179	1235		
25.0	4884	149	1029		
50.0	--	100	686		
N_{10} =4839 CYCLES, RATIO CHANGED BY 10% ; NF = 4957					
× 2.0	21651	167	1150	170.2	21168.0
5.0	22397	162	1115		
10.0	23697	153	1056		
25.0	26984	128	880		
50.0	--	85	587		
N_{10} =26969 CYCLES, RATIO CHANGED BY 10% ; NF = 27087					
◇ 2.0	186538	138	950	140.5	99733.0
5.0	195244	134	920		
10.0	196246	126	872		
25.0	196633	105	727		
50.0	--	70	484		
N_{10} =196131 CYCLES, RATIO CHANGED BY 10% ; NF = 196657					

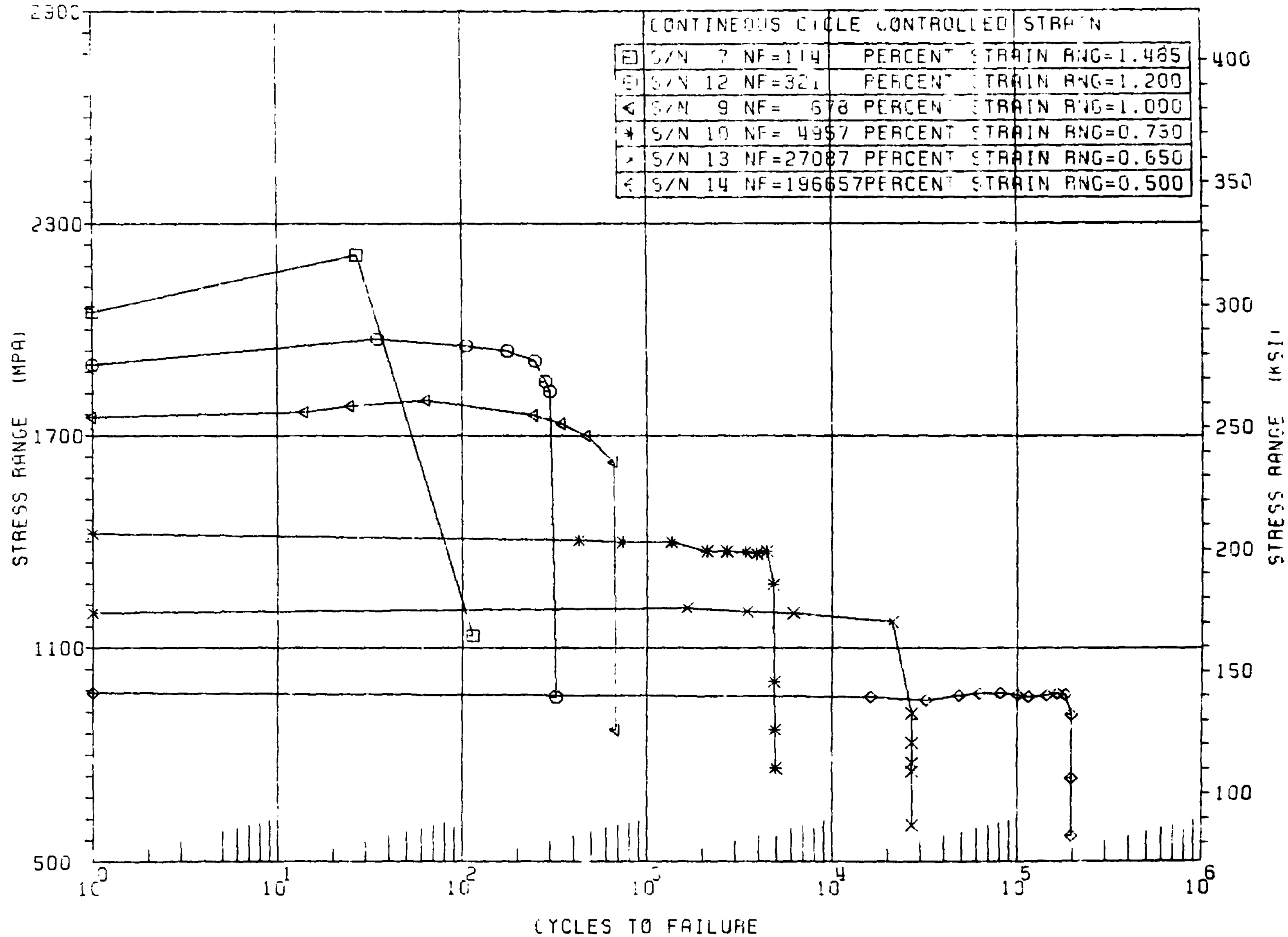

Figure B-1. — Stress Range vs Cycles for AF2-1DA at 760°C (1400°F) (30 cpm, R = 1)

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TABLE B-2. — PEAK TENSILE STRAIN 15 MIN HOLD

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
□ 2.0	133	306	2109	312.1	56.0
5.0	187	297	2044		
10.0	189	281	1937		
20.0	191	250	1722		
50.0	--	156	1076		

N_{10} =197 CYCLES, RATIO CHANGED BY 10% ; NF= 197

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
○ 2.0	542	275	1894	280.3	412.0
5.0	648	266	1836		
10.0	674	252	1739		
20.0	696	224	1546		
50.0	--	140	966		

N_{10} =689 CYCLES, RATIO CHANGED BY 10% ; NF= 716

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
△ 2.0	2849	168	1159	171.6	1662.0
5.0	3191	163	1124		
10.0	3306	154	1065		
20.0	3359	137	946		
50.0	--	86	592		

N_{10} =3244 CYCLES, RATIO CHANGED BY 10% ; NF= 3522

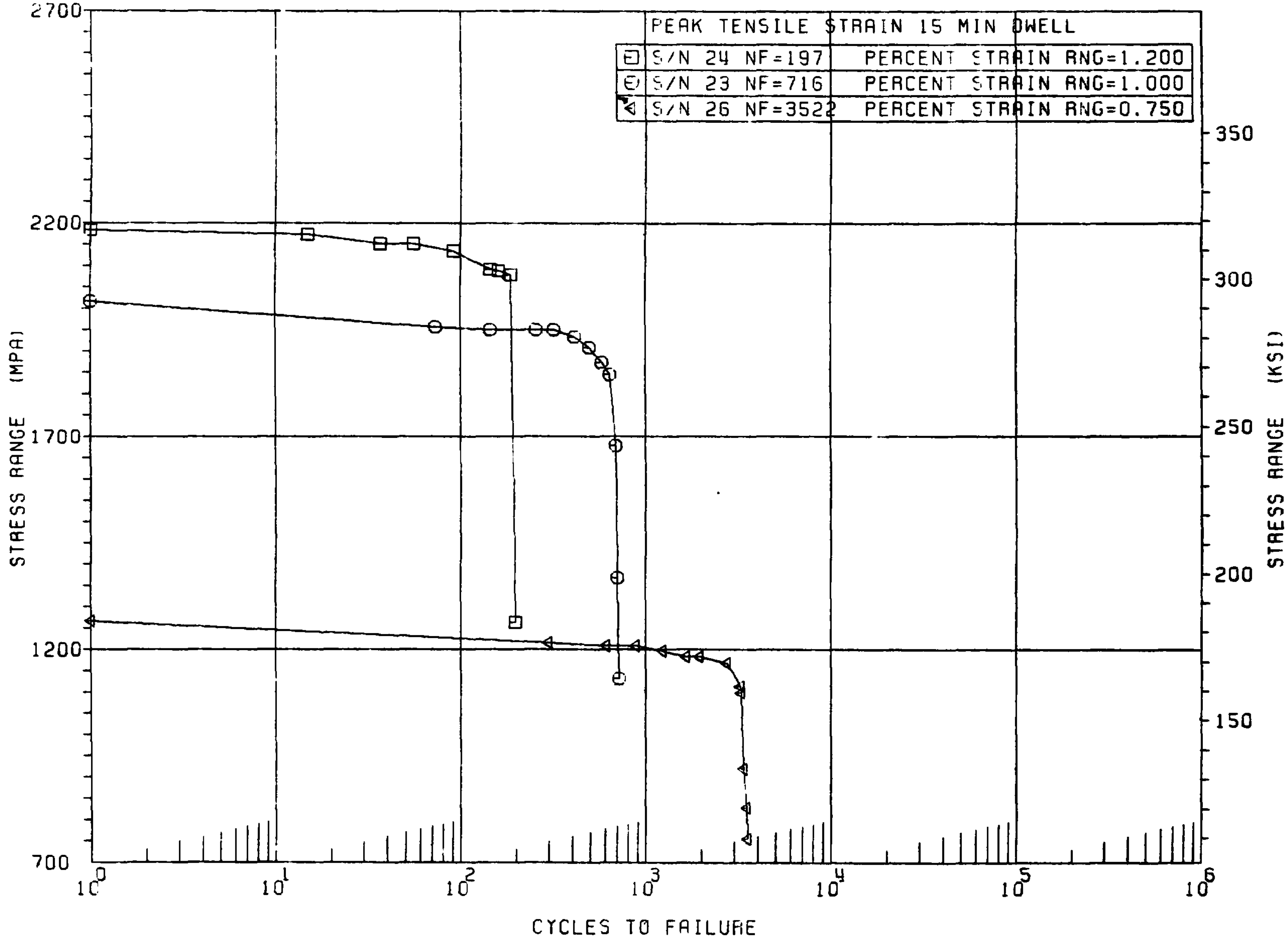

Figure B-2. — Stress Range vs Cycles for AF2-1DA at 760°C (1400°F) (30 cpm, R = 1)

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TABLE B-3. — PEAK COMPRESSIVE STRAIN 15 MIN HOLD

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
□ 2.0	157	281	1940	287.2	91.0
5.0	158	273	1881		
10.0	160	258	1782		
25.0	166	215	1485		
50.0	177	144	990		
	N_{10} =179	CYCLES,RATIO CHANGED BY 10% ;		NF= 179	
○ 2.0	236	238	1638	242.4	97.0
5.0	239	230	1588		
10.0	242	218	1504		
25.0	254	182	1254		
50.0	276	121	836		
	N_{10} =285	CYCLES,RATIO CHANGED BY 10% ;		NF= 285	
△ 2.0	1013	190	1307	193.5	573.0
5.0	1129	184	1267		
10.0	1131	174	1201		
25.0	1138	145	1001		
50.0	1149	97	667		
	N_{10} =1156	CYCLES,RATIO CHANGED BY 10% ;		NF= 1156	

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TABLE B-4. — PEAK TENSILE STRESS HOLD

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
□ 2.0	255	236	1630	241.3	3.0
5.0	255	229	1580		
10.0	257	217	1497		
25.0	260	181	1248		
50.0	--	121	832		
	N_{10} =263	CYCLES, RATIO CHANGED BY 10% ;		NF= 263	
⊙ 2.0	567	230	1589	235.2	300.0
5.0	725	223	1540		
10.0	783	212	1459		
25.0	823	176	1216		
50.0	--	118	811		
	N_{10} =815	CYCLES, RATIO CHANGED BY 10% ;		NF= 836	
△ 2.0	5109	178	1224	181.2	1639.0
5.0	5971	172	1187		
10.0	6150	163	1124		
20.0	6525	145	1000		
50.0	--	91	625		
	N_{10} =7407	CYCLES, RATIO CHANGED BY 10% ;		NF= 7407	
✳ 2.0	919	130	894	132.4	100.0
5.0	948	126	867		
10.0	999	119	821		
25.0	1170	99	685		
50.0	--	66	456		
	N_{10} =1287	CYCLES, RATIO CHANGED BY 10% ;		NF= 1287	

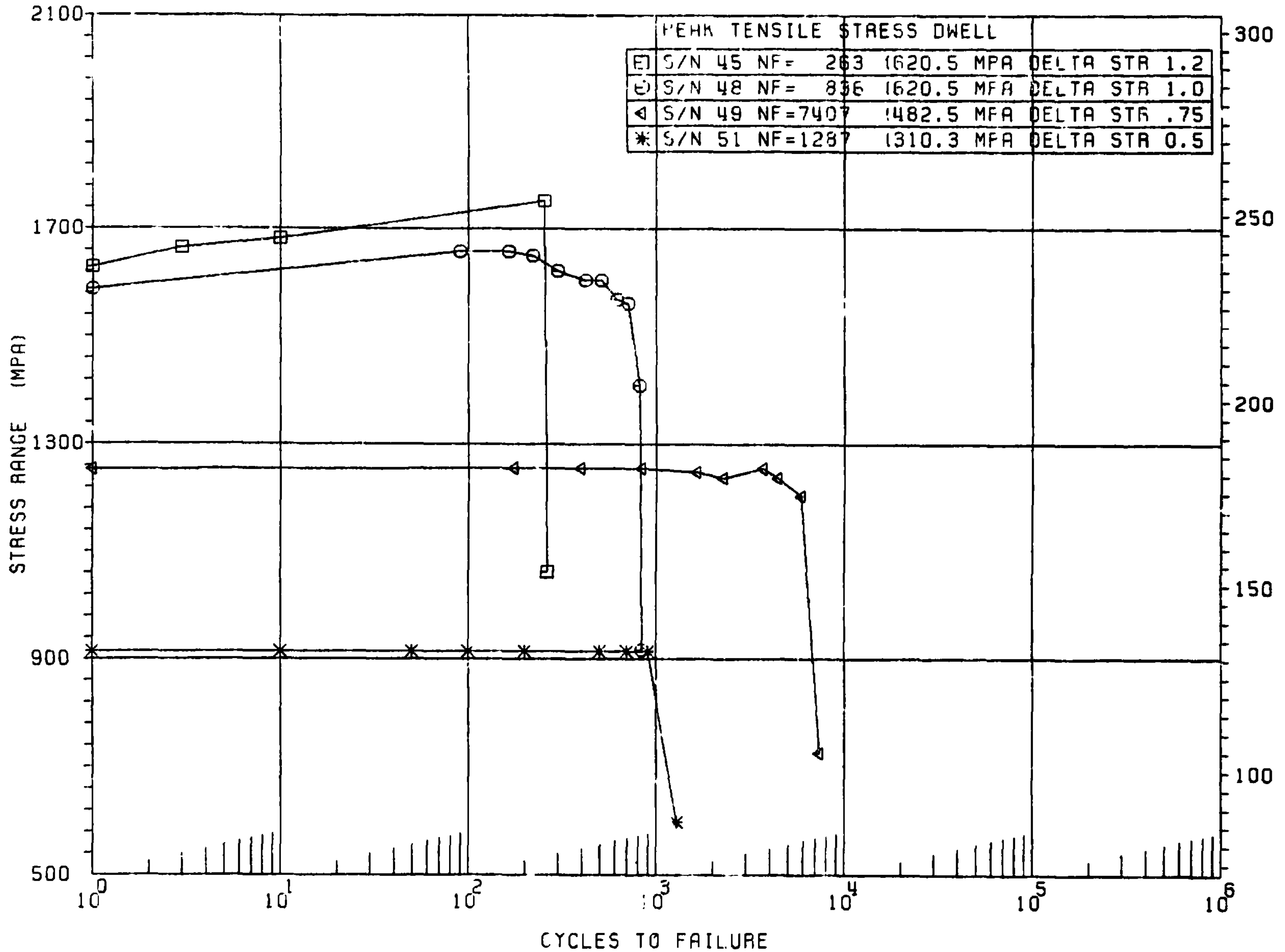

Figure B-3. — Stress Range vs Cycles for AF2-1DA at 760°C (1400°F) (30 cpm, R = 1)

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TABLE B-5. — CONTINUOUS CYCLE CONTROLLED STRAIN

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
□ 2.0	1	271	1866	276.2	1.0
5.0	2	262	1809		
10.0	6	249	1714		
50.0	530	138	952		
95.0	542	14	95		

N_{10} =518 CYCLES, RATIO CHANGED BY 10% ; NF= 542

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
○ 2.0	1	254	1751	259.1	1.0
5.0	3	246	1697		
10.0	7	233	1608		
50.0	806	130	893		
95.0	--	13	89		

N_{10} =772 CYCLES, RATIO CHANGED BY 10% ; NF= 825

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
△ 2.0	2	235	1620	239.8	1.0
5.0	5	228	1571		
10.0	23	216	1488		
50.0	3125	120	827		
95.0	3354	12	83		

N_{10} =3362 CYCLES, RATIO CHANGED BY 10% ; NF= 3362

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
✱ 2.0	2	220	1514	224.0	1.0
5.0	6	213	1467		
10.0	40	202	1390		
50.0	5163	112	772		
95.0	5163	11	77		

N_{10} =5163 C.CLES, RATIO CHANGED BY 10% ; NF= 5163

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
× 2.0	5	203	1399	207.0	1.0
5.0	47	197	1356		
10.0	2180	186	1285		
50.0	237390	104	714		
95.0	237390	10	71		

N_{10} =237391 CYCLES, RATIO CHANGED BY 10% ; NF= 237391

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
◇ 2.0	2957	171	1177	174.1	1.0
5.0		165	1141		
10.0		157	1081		
50.0		87	600		
95.0		9	60		

N_{10} =429497 CYCLES, RATIO CHANGED BY 10% ; NF= 540944

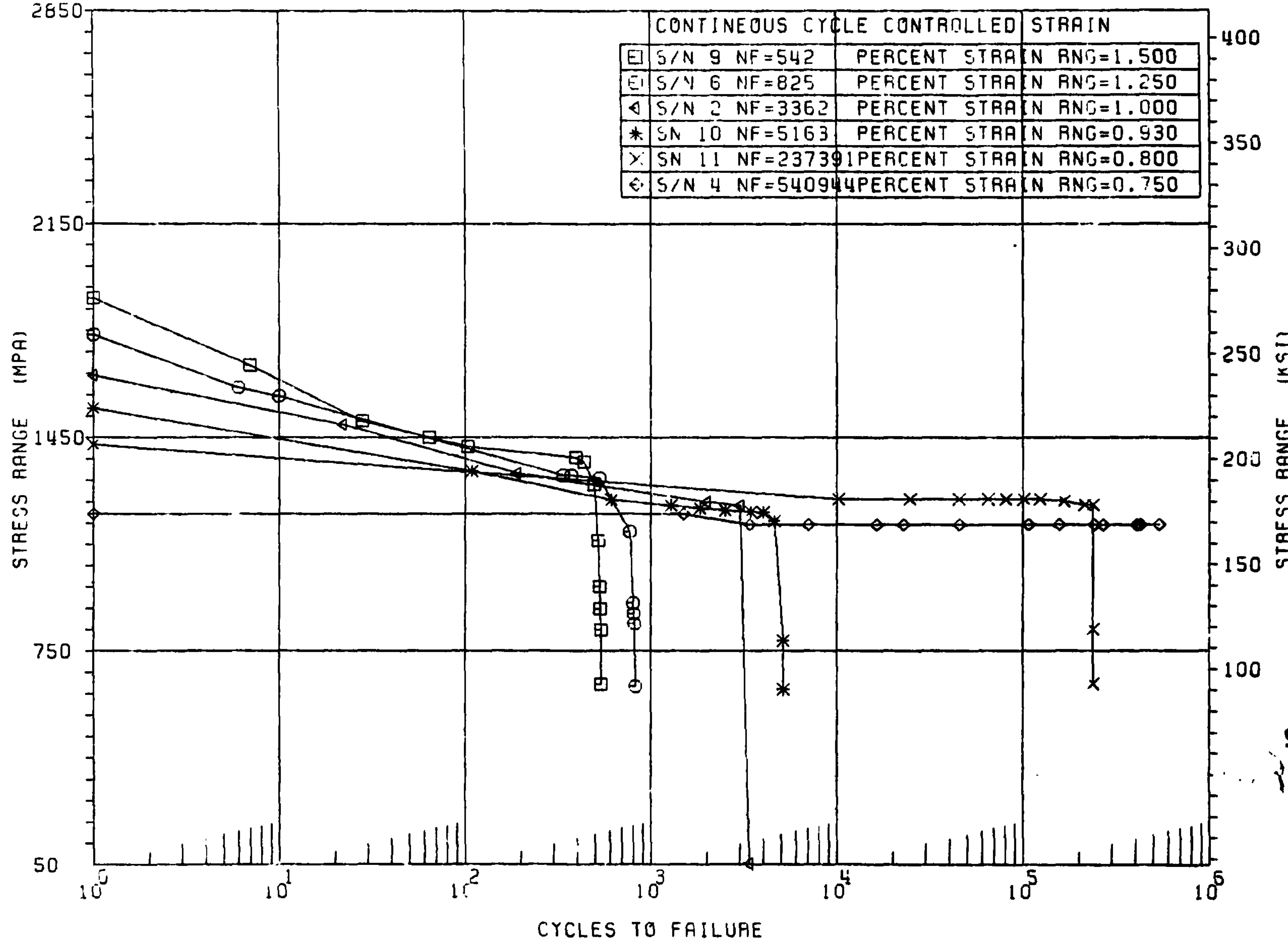

Figure B-4. — *Stress Range vs Cycles for INCO 718 at 649°C (1200°F) (0.5 Hz 30 cpm)*

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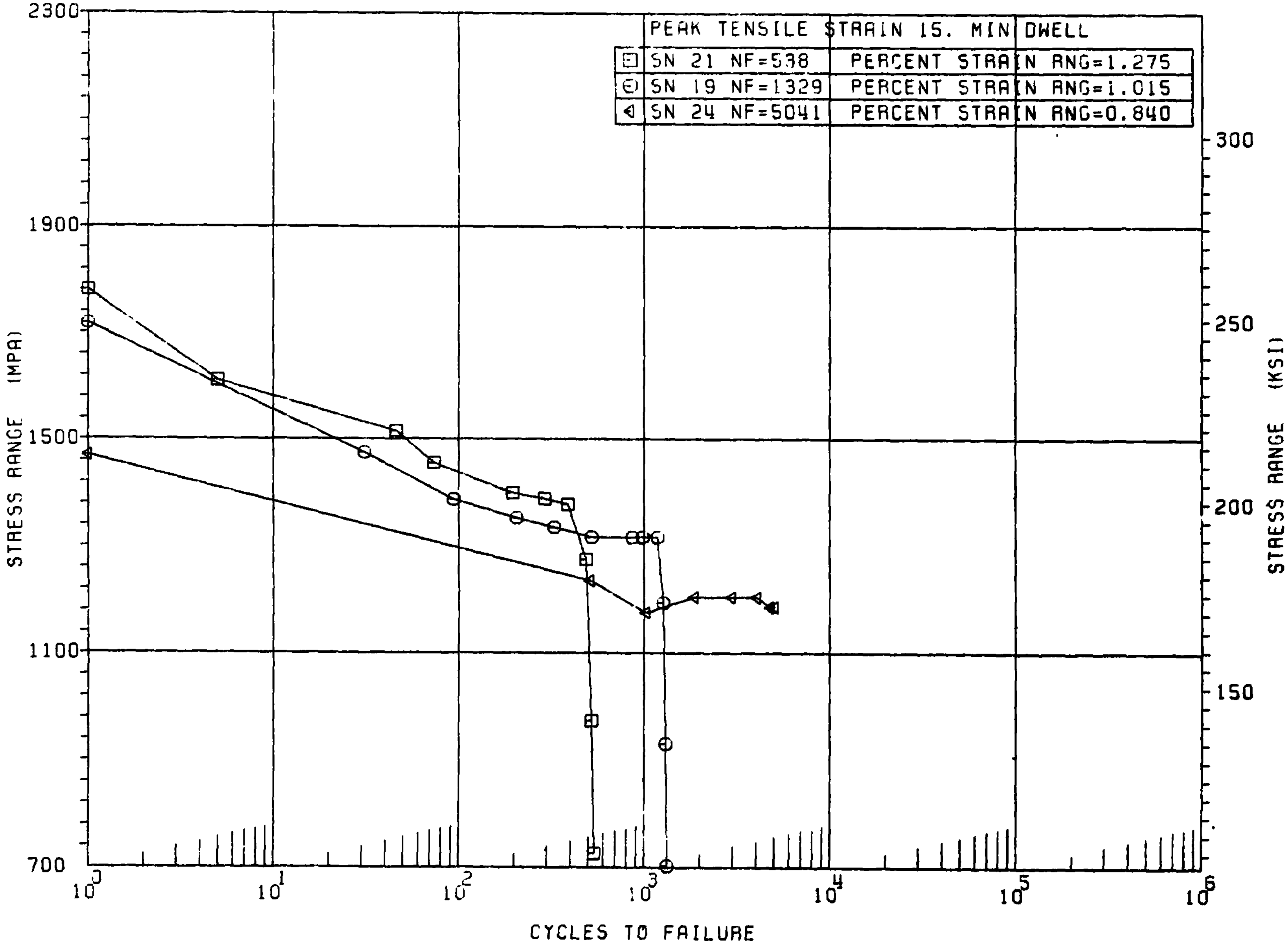

Figure B-5. — Stress Range vs Cycles for INCO 718 649°C (1200°F) (0.5 Hz 30 cpm)

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TABLE B-6. — PEAK TENSILE STRAIN 15 MIN HOLD

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
□ 2.0	1	253	1745	258.2	1.0
5.0	2	245	1691		
10.0	6	232	1602		
50.0	527	129	890		
95.0	--	13	89		

N_{10} =487 CYCLES, RATIO CHANGED BY 10% ; NF= 538

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
○ 2.0	2	244	1682	249.0	1.0
5.0	4	237	1631		
10.0	12	224	1545		
50.0	1317	124	858		
95.0	--	12	86		

N_{10} =1271 CYCLES, RATIO CHANGED BY 10% ; NF= 1329

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
△ 2.0	2	209	1439	213.0	1.0
5.0	8	202	1395		
10.0	58	192	1322		
50.0	--	107	734		
95.0	--	11	73		

N_{10} =4767 CYCLES, RATIO CHANGED BY 10% ; NF= 5041

TABLE B-7. — PEAK COMPRESSIVE STRAIN 15 MIN HOLD

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
□ 2.0	1	247	1703	252.0	1.0
5.0	3	239	1651		
10.0	7	227	1564		
50.0	508	126	869		
95.0	--	13	87		

N_{10} =489 CYCLES,RATIO CHANGED BY 10% ; NF= 525

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
○ 2.0	5	224	1545	228.6	1.0
5.0	18	217	1497		
10.0	73	206	1419		
50.0	1314	114	788		
95.0	--	11	79		

N_{10} =1243 CYCLES,RATIO CHANGED BY 10% ; NF= 1335

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
△ 2.0	4	194	1334	197.5	1.0
5.0	41	188	1293		
10.0	344	178	1225		
50.0	3227	99	681		
95.0	--	10	68		

N_{10} =3176 CYCLES,RATIO CHANGED BY 10% ; NF= 3237

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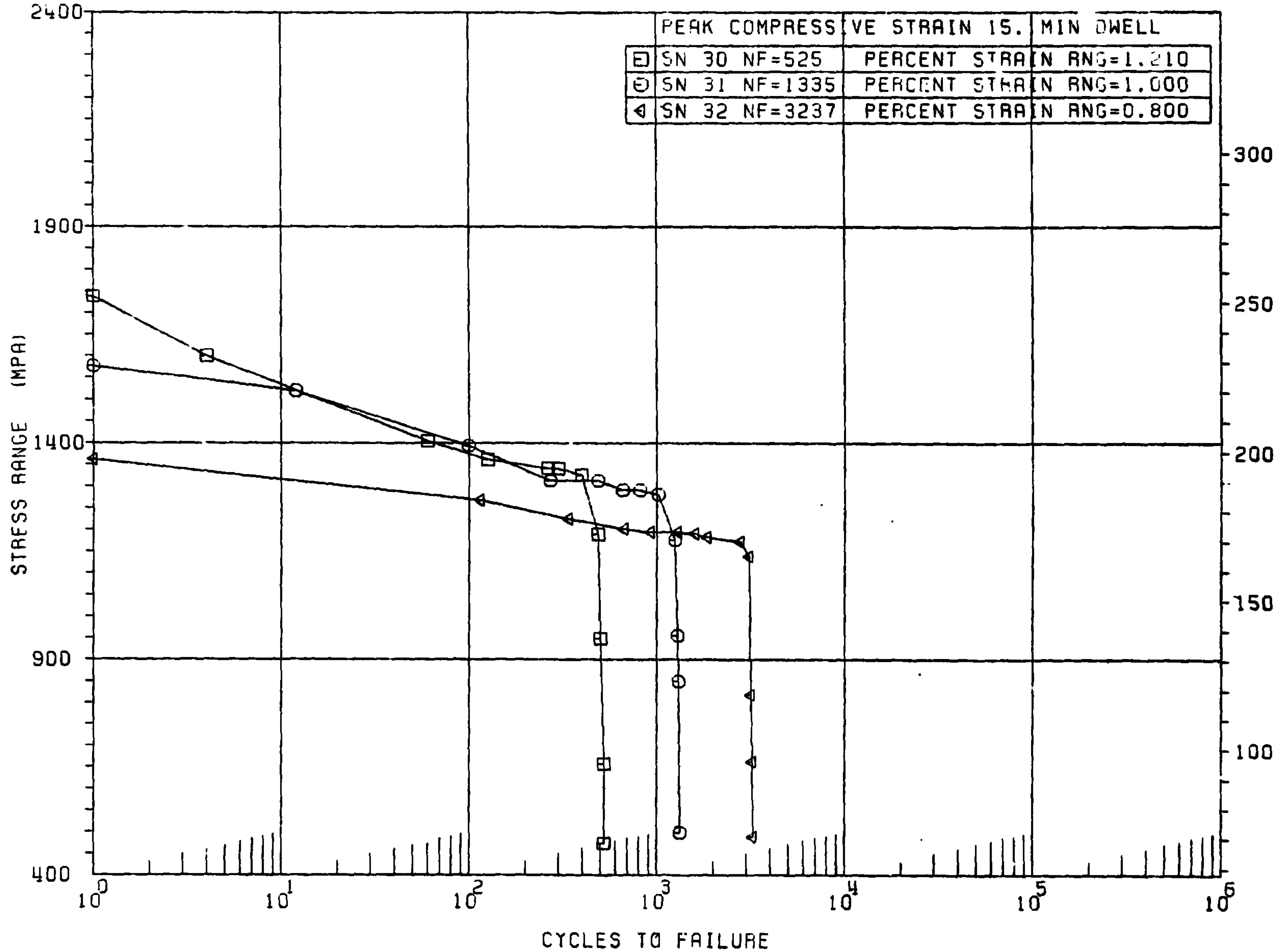

Figure B-6. — Stress Range vs Cycles for INCO 718 649°C (1200°F) (0.5 Hz 30 cpm)

TABLE B-8. — PEAK TENSILE AND COMPRESSIVE STRAIN 15 MIN HOLD

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
□ 2.0	1	253	1741	257.7	1.0
5.0	2	245	1688		
10.0	4	232	1599		
50.0	319	129	888		
95.0	--	13	89		

N_{10} =205 CYCLES, RATIO CHANGED BY 10% ; NF= 321

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
○ 2.0	2	243	1679	248.5	1.0
5.0	3	236	1627		
10.0	8	224	1542		
50.0	475	124	857		
95.0	494	12	86		

N_{10} =494 CYCLES, RATIO CHANGED BY 10% ; NF= 494

PERCENT STABILIZED LOAD DROP	CYCLES	STRS RNG KSI	STRS RNG MPA	STABILIZATION CONDITION STRS RNG (KSI)	STABILIZATION CONDITION NUMBER OF CYCLES
△ 2.0	34	182	125[illegible]	185.8	1.0
5.0	144	177	1217		
10.0	792	167	1153		
50.0	934	93	641		
95.0	--	9	64		

N_{10} =840 CYCLES, RATIO CHANGED BY 10% ; NF= 840

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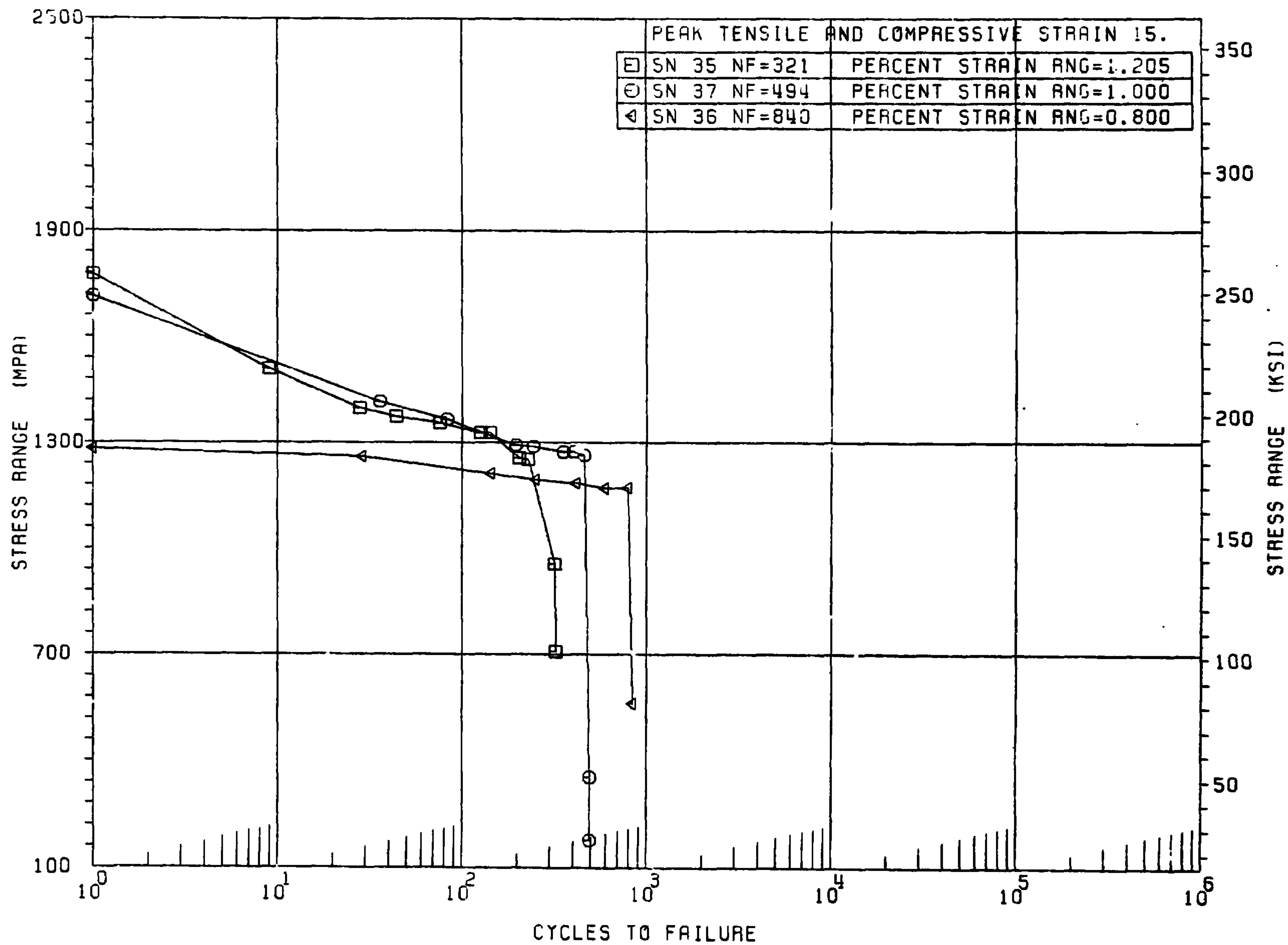

Figure B-7. — Stress Range vs Cycles for INCO 718 649°C (1200°F) (0.5 Hz 30 cpm)

APPENDIX C
LCF RESULTS FOR GATORIZED® AF2-1DA AND INCO 718

This appendix contains the results of all cyclic tests for GATORIZED® AF2-1DA and INCO 718 along with pertinent strain range parameters (total, elastic, inelastic, and creep) stress parameters (mean stress, initial cycle and half life ranges), hardening and softening characteristics at half life, and cycles/time to failure for each test performed under this program.

TABLE C-1. — LCF RESULTS FOR GATORIZED® AF2-1DA TESTING CONDUCTED AT 760°C (1400°F) AT 0.5 Hz (30 cpm) RAMP FREQUENCY

S/N	%STRAIN RANGE TOTAL	ELASTIC	INELASTIC	CREEP (TEN.)	CREEP (COMP.)	MEAN STRESS (MPA)	MEAN STRESS (KSI)	STRESS RANGE INITIAL (MPA)	INITIAL (KSI)	HALF LIFE (MPA)	HALF LIFE (KSI)	FAILURE LIFE (CYC.)	FAILURE LIFE (MIN.)
CONTINUOUS CYCLE CONTROLLED STRAIN													
7	1.485	1.150	0.335			-26.3	-3.8	2050.5	297.4	2208.4	320.3	114.	4.
12	1.260	1.085	0.175			-40.7	-5.9	1900.9	275.7	1971.2	285.9	321.	11.
9	1.000	0.930	0.070			-29.9	-4.3	1752.0	254.1	1730.6	251.0	678.	23.
10	0.735	0.720	0.015			-54.5	-7.9	1418.3	205.7	1386.5	201.1	4957.	165.
13	0.650	0.645	0.005			38.3	5.6	1208.7	175.3	1190.7	172.7	27087.	933.
14	0.500	0.495	0.005			-39.5	-5.7	982.5	142.5	974.2	141.3	196657.	6555.
PEAK TENSILE STRAIN 0.5 MIN DWELL TESTS													
16	1.245	1.007	0.238	0.093		-112.4	-16.3	2109.8	306.0	2218.7	321.8	395.	211.
17	1.025	0.910	0.115	0.044		-133.1	-19.3	1990.5	288.7	2022.2	293.3	928.	495.
18	0.750	0.722	0.028	0.008		-153.8	-22.3	1603.7	232.6	1539.6	223.3	17400.	9280.
PEAK TENSILE STRAIN 2.0 MIN DWELL TESTS													
19	1.200	0.995	0.205	0.110		-113.8	-16.5	1881.6	272.9	1913.3	277.5	312.	634.
20	1.030	0.892	0.138	0.075		-129.6	-18.8	1755.4	254.6	1740.9	252.5	812.	1651.
21	0.768	0.713	0.055	0.024		-133.1	-19.3	1415.5	205.3	1394.8	202.3	5380.	10939.
PEAK TENSILE STRAIN 15.0 MIN DWELL TEST													
24	1.210	0.940	0.270	0.126		-202.0	-29.3	2166.3	314.2	2124.3	308.1	197.	2962.
23	1.000	0.850	0.150	0.080		-239.9	-34.8	2016.0	292.4	1942.9	281.8	716.	10764.
26	0.750	0.690	0.060	0.027		-173.7	-25.2	1268.6	184.0	1183.1	171.6	3522.	52947.
PEAK COMPRESSIVE STRAIN 0.5 MIN DWELL													
27	1.215	1.030	0.185		0.075	31.0	4.5	1967.8	285.4	1936.0	280.8	270.	144.
28	1.015	0.925	0.090		0.047	35.2	5.1	1773.3	257.2	1752.0	254.1	880.	469.
30	0.505	0.500	0.005		0.005	111.7	16.2	922.5	133.8	961.1	139.4	31174.	16626.
PEAK COMPRESSIVE STRAIN 2.0 MIN. DWELL													
33	1.200	0.950	0.250		0.105	56.5	8.2	1965.7	285.1	2050.5	297.4	185.	376.
34	1.005	0.895	0.110		0.059	83.4	12.1	1705.8	247.4	1709.9	248.0	399.	811.
31	0.525	0.515	0.010		0.009	150.3	21.8	950.8	137.9	997.7	144.7	22163.	45065.
PEAK COMPRESSIVE STRAIN 15.0 MIN. DWELL													
35	1.200	0.930	0.270		0.123	105.5	15.3	1996.4	276.5	1980.2	287.2	179.	2691.
36	1.015	0.885	0.130		0.067	155.1	22.5	1744.4	253.0	1674.7	242.9	285.	4205.
47	0.750	0.735	0.015		0.020	191.7	27.8	1353.3	197.0	1323.8	192.0	1156.	17379.
PEAK TENSILE AND COMPRESSIVE STRAIN 0.5 MIN DWELL													
38	1.210	0.970	0.240	0.085	0.083	6.9	1.0	1835.8	266.4	1967.8	285.4	96.	99.
39	1.000	0.845	0.155	0.056	0.056	-17.9	-2.6	1738.2	252.1	1734.0	251.5	771.	797.
41	0.500	0.490	0.010	0.009	0.009	-56.5	-8.2	961.8	139.5	958.4	139.0	25919.	26783.
PEAK TENSILE 620.5MPA(90 KSI) STRESS DWELL													
45	1.200	0.905	0.295	0.210		-228.9	-33.2	1638.9	237.7	1692.0	245.4	263.	5232.
48	1.000	0.900	0.100	0.050		-167.5	-24.3	1586.5	230.1	1603.7	232.6	836.	1585.
PEAK TENSILE 482.5MPA(70 KSI) STRESS DWELL													
49	0.750	0.725	0.025	0.020		-159.3	-21.8	1252.8	181.7	1256.9	182.3	7407.	31950.(B)
PEAK TENSILE 310.3MPA(45 KSI) STRESS DWELL													
51	0.500	0.485	0.015	0.015		-140.7	-20.4	912.9	132.4	912.9	132.4	1287.	41595.

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TABLE C-1. — LCF RESULTS FOR GATORIZED® AF2-1DA TESTING CONDUCTED AT 760°C (1400°F) AT 0.5 Hz (30 cpm) RAMP FREQUENCY (Continued)

PEAK COMPRESSIVE 482.5MPA(70 KSI) STRESS DWELL													
73	0.750	0.725	0.025		0.025	160.6	23.3	1285.2	186.4	1320.3	191.5	2053.	12300.
PEAK COMPRESSIVE 620.5MPA(90 KSI) STRESS DWELL													
52	1.200	0.925	0.275		0.175	237.2	34.4	1674.0	242.8	1713.3	248.5	69.	1095.
61	1.000	0.895	0.105		0.050	197.9	28.7	1592.7	231.0	1641.0	238.0	540.	4275. (B)
PEAK COMPRESSIVE & TENSILE 620.5MPA(90KSI) STRESS DWELL													
72	1.190	0.660	0.530	0.470	0.440	6.9	1.0	1241.1	180.0	1228.0	178.1	26.	20250.
65	1.000	0.675	0.325	0.275	0.240	0.0	0.0	1241.1	180.0	1241.1	180.0	317.	22332.(B)
MEAN STRESS EFFECT													
55	0.815	0.790	0.025			370.2	53.7	1427.2	207.0	1425.1	206.7	1340.	45.
53	0.500	0.495	0.005			359.9	52.2	912.9	132.4	894.9	129.8	107996.	3600.
3	0.800	0.782	0.018			164.7	23.9	1411.4	204.7	1316.2	190.9	4179.	139.
4	1.000	0.980	0.020			80.7	11.7	1702.3	246.9	1678.2	243.4	1169.	39.
5	1.515	1.245	0.270			14.2	2.1	2025.7	293.8	2146.3	311.3	176.	6.
ALTERNATE TEMPERATURE 649C(1200F)													
(2 MIN TENSILE STRAIN DWELL)													
62	1.000	0.910	0.090	0.018		-56.5	-8.2	1847.1	267.9	1769.9	256.7	1577.	3207.
(2 MIN COMPRESSIVE STRAIN DWELL)													
63	1.000	0.910	0.090		0.011	-6.9	-1.0	1758.9	255.1	1769.2	256.6	1405.	2857.
(CONTINUOUS CYCLE)													
64	1.000	0.900	0.100			40.7	5.9	1811.3	262.7	1955.4	283.6	862.	29.
CREEP EXTENSION (RATCHETING TYPE)													
(0.5 MIN. DWELL @827.4MPA(120 KSI))													
69	1.150	1.025	0.125	0.075		-81.4	-11.8	1823.0	264.4	1823.0	264.4	361.	180.
(2 MIN. DWELL @ 827.4MPA(120 KSI))													
68	1.150	1.035	0.115	0.075		-80.0	-11.6	1823.0	264.4	1823.0	264.4	94.	213.
(15 MIN. DWELL @ 627.4MPA(120 KSI))													
66	1.350	1.065	0.285	0.210		-68.9	-10.0	1808.5	262.3	1808.5	262.3	61.	870.
(15 MIN. DWELL @ 372.3MPA(54 KSI))													
70	0.563	0.555	0.008			-147.5	-21.4	1037.0	150.4	1037.0	150.4	3754.	5631. (A)

A - DID NOT FAIL
B - FAILED AT EXTENSOMETER CONTACT POINT

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TABLE C-2. — LCF RESULTS FOR INCO 718 TESTING CONDUCTED IN AIR AT 649°C (1200°F) AT 0.5 Hz (30 cpm) RAMP FREQUENCY

S/N	% STRAIN RANGE TOTAL	ELASTIC	INELASTIC	CREEP (TEN.)	CREEP (COMP.)	MEAN STRESS (MPA)	MEAN STRESS (KSI)	STRESS RANGE INITIAL (MPA)	INITIAL (KSI)	HALF LIFE (MPA)	HALF LIFE (KSI)	FAILURE LIFE (CYC.)	FAILURE LIFE (MIN.)
CONTINUOUS CYCLE CONTROLLED STRAIN(R =-1)													
9	1.500	0.765	0.735			0.0	0.0	1876.1	271.1	1394.8	202.3	542.	18.
6	1.250	0.782	0.468			0.0	0.0	1740.9	252.5	1323.1	191.9	825.	28.
2	1.000	0.750	0.250			-31.7	-4.6	1643.0	238.3	1235.5	179.2	3362.	112.
10	0.930	0.720	0.210			-31.7	-4.6	1555.5	225.6	1236.2	179.3	5163.	172.
11	0.800	0.700	0.100			-17.9	-2.6	1416.9	205.5	1249.2	181.2	237391.	7913.
4	0.750	0.671	0.079			-35.2	-5.1	1228.7	178.2	1159.0	168.1	540944.	18031.(A)
PEAK TENSILE STRAIN 0.5 MIN. DWELL													
13	1.250	0.710	0.540	0.023		-29.6	-4.3	1766.4	256.2	1309.3	189.9	606.	323. (B)
12	1.060	0.690	0.370	0.043		-6.9	-1.0	1671.3	242.4	1225.2	177.7	1505.	803.
14	0.800	0.625	0.175	0.020		-43.4	-6.3	1403.7	203.6	1110.7	161.1	24026.	12814.(B)
PEAK TENSILE STRAIN 2.0 MIN. DWELL													
23	1.250	0.750	0.500	0.031		-67.0	-9.7	1757.4	254.6	1328.7	192.5	870.	1769.
16	1.000	0.650	0.350	0.046		-28.3	-4.1	1540.9	223.5	1193.5	173.1	1505.	3060.
17	0.850	0.665	0.185	0.025		-70.3	-10.2	1492.0	216.4	1137.6	165.0	3941.	8013.(B)
PEAK TENSILE STRAIN 15.0 MIN. DWELL													
21	1.275	0.785	0.490	0.050		-47.6	-6.9	1780.2	258.2	1383.8	200.7	538.	8088.
19	1.015	0.740	0.275	0.048		-70.3	-10.2	1730.6	251.0	1334.1	193.5	1329.	19979.
24	0.840	0.690	0.150	0.024		-14.5	-2.1	1483.1	215.1	1245.9	180.7	5041.	75783.(A)
PEAK COMPRESSIVE STRAIN 0.5 MIN. DWELL													
22	1.250	0.762	0.488		0.025	-20.7	-3.0	1744.3	253.0	1295.5	187.9	690.	368.
15	1.020	0.735	0.285		0.030	0.0	0.0	1643.0	238.3	1214.8	176.2	2432.	1297.
26	0.800	0.640	0.160		0.021	12.4	1.8	1385.8	201.0	1100.4	159.6	9500.	5067.
PEAK COMPRESSIVE STRAIN 2.0 MIN. DWELL													
27	1.225	0.725	0.500		0.040	-10.3	-1.5	1740.9	252.5	1274.8	184.9	748.	1521.
28	1.000	0.700	0.300		0.020	-3.4	-0.5	1623.0	235.4	1204.4	174.7	1587.	3227.
29	0.800	0.665	0.135		0.020	61.4	8.9	1334.1	193.5	1176.2	170.6	6872.	13973.
PEAK COMPRESSIVE 15.0 MIN. STRAIN DWELL													
30	1.210	0.780	0.430		0.055	49.0	7.1	1737.5	252.0	1341.0	194.5	525.	7893.
31	1.000	0.750	0.250		0.041	73.8	10.7	1576.2	228.6	1291.4	187.4	1335.	20070.
32	0.800	0.700	0.100		0.010	22.0	3.3	1348.0	195.5	1204.5	174.7	3237.	48663.
PEAK TENSILE AND COMPRESSIVE STRAIN 0.5 MIN. DWELL													
33	1.295	0.675	0.620	0.057	0.048	-40.7	-5.9	1794.0	260.2	1253.5	181.8	649.	671.
38	0.980	0.630	0.350	0.030	0.028	-6.9	-1.0	1649.9	239.3	1158.3	168.0	1632.	1686.
42	0.765	0.595	0.170	0.016	0.016	-24.8	-3.6	1344.5	195.0	1091.4	158.3	3411.	3524. (B)
PEAK TENSILE AND COMPRESSIVE STRAIN 2.0 MIN. DWELL													
51	1.200	0.650	0.550	0.042	0.036	55.8	8.1	1734.0	251.5	1192.8	173.0	723.	2916.
54	0.980	0.715	0.265	0.021	0.021	9.0	1.3	1624.4	235.6	1185.9	172.0	759.	3061.
41	0.800	0.625	0.175	0.026	0.030	35.9	5.2	1338.3	194.1	1106.6	160.5	2358.	9511.
PEAK TENSILE AND COMPRESSIVE STRAIN 15.0 MIN. DWELL													
35	1.205	0.655	0.550	0.067	0.065	-24.8	-3.6	1776.8	257.7	1259.7	182.7	321.	9641.
37	1.000	0.625	0.375	0.047	0.050	-24.8	-3.6	1712.7	248.4	1288.7	186.9	494.	14837.
36	0.800	0.615	0.185	0.050	0.050	11.0	1.6	1397.6	202.7	1158.3	168.0	840.	25228.(C)

TABLE C-2. — LCF RESULTS FOR INCO 718 TESTING CONDUCTED IN AIR AT 649°C (1200°F) AT 0.5 Hz (30 cpm) RAMP FREQUENCY (Continued)

CONTINUOUS CYCLE CONTROLLED STRAIN(R =0)													
43	1.000	0.720	0.280			52.4	7.6	1507.9	218.7	1232.8	178.8	1504.	58.
48	0.800	0.690	0.110			152.4	22.1	1283.1	186.1	1178.3	170.9	7690.	256. (B)
PEAK TENSILE STRAIN 2.0 MIN. DWELL(R =0)													
45	1.000	0.705	0.295	0.029		-15.9	-2.3	1544.6	224.0	1260.4	182.8	933.	1897.
49	0.780	0.640	0.140	0.023		-70.3	-10.2	1305.9	189.4	1172.8	170.1	16665.	33886.(B)
PEAK COMPRESSIVE STRAIN 2.0 MIN. DWELL(R =0)													
52	1.000	0.715	0.285		0.032	66.2	9.6	1545.1	224.1	1181.8	171.4	1493.	3036.
50	0.800	0.655	0.145		0.020	131.0	19.0	1330.7	193.0	1171.4	169.9	3181.	6468.

A - DID NOT FAIL

B - FAILED AT EXTENSOMETER CONTACT POINT

C - OVERLOAD AT NEXT CYCLE

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