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Dr. # 1125

TREE-NUREG-1087
for U.S. Nuclear Regulatory Commission

DESIGN DATA FOR THE 1/4-IN. THICK ALLOY 718 IN-PILE TUBE

WALTER G. REUTER

May 1977

EG&G Idaho, Inc.

IDAHO NATIONAL ENGINEERING LABORATORY

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

IDAHO OPERATIONS OFFICE UNDER CONTRACT EY-76-C-07-1570

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Approved:

D. D. Keiser, Manager
Fuels and Materials Division

H. W. Campen, Director
Research, Engineering, and Construction

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DESIGN DATA FOR THE 1/4-IN. THICK
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by

Walter G. Reuter

EG&G IDAHO, INC.

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PREPARED FOR THE
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ABSTRACT

Design data applicable to the proposed 0.64-cm (1/4-in.) thick in-pile tube (IPT) used in the experimental test loop of the Power Burst Facility (PBF) are reported, together with fracture toughness results which were also desired to complement the design data. These data were required for temperatures ranging from room temperature (RT) to 811 K (1000°F). The material that will be used to fabricate the IPT is Alloy 718. Since the IPT will contain welds, the INEL thermal cycle [solution anneal at 1365 K (2000°F), slow cool at a nominal rate of 83 K (150°F) per hour, and age at 990 K (1325°F) for six hours plus 895 K (1150°F) for 16 hours] will be used to heat treat the part.

Tests were conducted on transverse-oriented specimens for base metal and longitudinal- and transverse-oriented weld metal specimens. Tensile test results from base metal (Heats 3 and 6) and weld metal (Heat C), for test temperatures ranging from RT to 811 K (1000°F), were used to develop curves for ultimate and yield tensile strength.

The design fatigue curves for transverse-oriented base metal and longitudinal- and transverse-oriented weld metal specimens were developed using the tensile test results plus an analytical approach. Experimental fatigue data were generated to augment the analytically determined values. The design curves for cycles to failure ranging from 10^1 to 10^6 and for temperatures for RT to 811 K (1000°F) are contained in this report.

Instrumented precracked-Charpy specimens were tested over a range of temperatures to provide some estimate of the dynamic fracture toughness (K_{Id}). On the basis of these tests, K_{Id} values for the base metal and weldments are quite satisfactory.

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DESIGN DATA FOR THE 1/4-IN. THICK ALLOY 718 IN-PILE TUBE

I. INTRODUCTION

Design data applicable to the proposed 0.64-cm (1/4-in.) thick in-pile tube (IPT) used in the experimental test loop of the Power Burst Facility (PBF) were sought. Fracture toughness results were also desired to complement the design data. These data were required for temperatures to 811 K (1000°F). The material that will be used to fabricate the IPT is Alloy 718 with a nominal chemistry as shown in Table I. Since the IPT will contain welds, the Idaho National Engineering Laboratory (INEL) thermal cycle (see Table II) will be used for heat treating the part.

The INEL heat treatment was developed to reduce thermal stresses induced during rapid cooling, in addition to restoring the desired impact properties in weldments. Since no design data have been developed for this recently devised thermal cycle, elevated temperature tests were conducted using plate material already on hand. It was recognized that differences in material response could exist between the test plate and the forged material planned for the IPT. Because timely delivery of forged material could not be obtained, design data were developed from 1.3-cm (1/2-in.) thick plate under the assumption that differences in material response, if any, would be small. Fatigue design curves were calculated from the tensile data and several fatigue tests were made to confirm these calculations.

There was also a request to evaluate the effects of thermal excursions to 1090 K (1500°F) for 20 minutes on heat treated Alloy 718. The available data did not address the topic of overaging, at least in the temperature ranges of interest. Therefore, tests were conducted using specimens from the same heat of material as that used for obtaining design data, to evaluate mechanical properties of specimens given the

INEL heat treat, then exposed to a 1090 K (1500°F) temperature for 20 minutes, and then water quenched.

TABLE I

MILL-SUPPLIED CHEMISTRY AND TEST RESULTS FOR ALLOY 718

Heat No.	Cr	Fe	C	Si	% Co	Ni	Mn	Cb + Ta
2180-4-9478 ^[a] (Heat 6)	18.21	bal	0.05	0.10	0.30	52.63	0.21	5.08
52C9EK (Heat 3)	18.11	18.19	0.07	0.17	0.03	53.44	0.08	5.10
52 B0E ^[b] (Heat C)	17.91	17.60	0.04	0.19	0.04	54.58	0.04	5.07 Cb 0.01 Ta
	Mo	P	S	Al	Ti	B	Cu	Melt Practice ^[c]
	3.05	0.005	0.005	0.54	0.97	0.002	0.02	VIM-ESR
	3.00	0.007	0.007	0.59	1.08	0.0034	0.11	VIM-ESR
	2.96	0.011	0.007	0.49	0.99	0.0031	0.05	VIM

[a] Specification AMS-5596C

Tensile Properties
Test Temperature

FTU

FTY

%EL

%RA

RT

194.0

155.0

24.0

43.5

1200

146.5

128.0

18.2

18.9

[b] Specification AMS-5832
0.045 in. diam. weld wire[c] VIM - vacuum induction melting
ESR - electro-slag remelting

TABLE II

HEAT TREAT CYCLE FOR ALLOY 718 IPT CONTAINING WELDS

(a) INEL Heat Treat

- (1) Heat from room temperature to 1365^{+14}_{-0} K (2000^{+25}_{-0} °F) at a maximum rate of 140 K (250°F) per hour.
- (2) Hold for 7 hour $^{+15}_{-0}$ minutes (solution anneal).
- (3) Furnace cool to 990 ± 8 K (1325 ± 15 °F) at a rate of 83 ± 28 K (150 ± 50 °F) per hour.
- (4) Hold for 4 hours ± 15 minutes (age).
- (5) Cool at 894 ± 8 K (1150 ± 15 °F) at a rate of 56 ± 8 K (100 ± 15 °F) per hour.
- (6) Hold for 16 hours ± 15 minutes (age).
- (7) Furnace cool to below 644 K (700°F) at a maximum rate of 140 K (250°F) per hour.
- (8) Part may be removed from furnace at 644 K (700°F) and air cooled to room temperature.

(b) Standard Heat Treat

- (1) Solution anneal at 1225 K (1750°F).
 - (2) Air cool.
 - (3) Age at 990 K (1325°F) for 8 hours, cool at 56 K (100°F) per hour to 895 K (1150°F) and hold for 8 hours.
 - (4) Air cool.
-

II. SUMMARY AND CONCLUSION

Design data applicable to the proposed 0.64-cm (1/4-in.) thick in-pile tube used in the experimental test loop of the Power Burst Facility are reported. Fracture toughness results were also desired to complement the design data. These data were required for temperatures ranging from room temperature (RT) to 811 K (1000°F). The material that will be used to fabricate the IPT is Alloy 718. Since the IPT will contain welds, the INEL thermal cycle identified in Table II will be used to heat treat the part.

There was also a request to evaluate the effect on heat treated Alloy 718 of thermal excursions to 1090 K (1500°F) for 20 minutes. Specimens of material from the same heat of Alloy 718 used for obtaining some of the design data were tested to evaluate mechanical properties. The specimens were given the INEL heat treat, then exposed at 1090 K (1500°F) temperature for 20 minutes, and water quenched.

Tests were conducted on transverse-oriented specimens for base metal and longitudinal- and transverse-oriented weld metal specimens. Tensile test results from base metal (Heats 3 and 6) and weld metal (Heat C), for test temperatures ranging from RT to 811 K (1000°F), were used to develop curves for ultimate and yield tensile strength. The lower results of the test were used to develop the curves in Figure 12.

The design fatigue curves were developed using tensile test results in Tables IV and X plus the analytical approach identified in Appendix A. Experimental fatigue data were used to augment the analytically determined values. The design fatigue curves are plotted in Figures 13 through 15 for Heats 3 and 6 base metal and Heat C weld metal.

It is recognized that the data used to develop the curves in Figures 12 through 15 were not based on test results at 56 K (100°F)

intervals for the complete temperature range for five heats as required in Reference 11. The base metal tensile test results in Figure 12 were developed from test data collected for two heats (Heats 3 and 6); the weld metal results in Figure 12 were developed from test data collected from a single heat of weld wire (Heat C). Even though the weld data were collected from a single heat of material the fatigue design curves were modified to take into consideration heat-to-heat variations on the basis of differences observed between results from Heats 3 and 6. Because the ultimate tensile strength is the limiting design requirement, for the 0.64-cm (1/4-in.) thick IPT, and it varied only slightly for the results shown in Tables IV and X, it was assumed that the curves in Figures 12 through 15 were applicable for design purposes. An additional safety factor is that a number of specimens from the forging will be heat treated with the IPT in order to establish mechanical properties for the actual heat of Alloy 718 used in fabrication.

Instrumented precracked Charpy impact specimens were tested to provide some estimate of the dynamic fracture toughness (K_{Id}). On the basis of these tests, K_{Id} values for the base metal and weldments are quite satisfactory. Appendix B presents observations useful to the utilization of Alloy 718 but not required for the 0.64-cm (1/4-in.) thick IPT.

Exposing INEL heat treated Alloy 718 (Heat 6) for 20 minutes to 1050 K (1500°F), and then water-quenching, resulted in changes in mechanical properties for tests conducted at RT and 616 K (650°F). Tensile tests conducted at 616 K (650°F) resulted in a reduction of 10 to 20% for yield and ultimate tensile strength and a substantial (30 to 38%) increase in ductility as a result of the thermal excursion. Instrumented-precracked-Charpy-impact tests conducted at room temperature indicated an increase of 45% in K_{Id} as a result of the thermal excursion.

III. RECOMMENDATIONS

Based on the results of the investigation, the following recommendations are made:

- (1) Figure 12 should be used for tensile strength (ultimate and yield) values for Alloy 718 base metal and weld metal given the INEL heat treat
- (2) Figures 13 through 15 should be used for design fatigue values for Alloy 718 base metal and weld metal given the INEL heat treat
- (3) The results of the test specimens attached to the IPT should be monitored to establish that the Alloy 718 responded, as expected, to the INEL heat treat.

IV. TEST PROCEDURE AND ANALYTICAL APPROACH

1. DESIGN DATA

1.1 Tensile Strength Design Curves

1.1.1 Base Metal. Tensile specimens were fabricated according to ANC Drawing 403351-1 from 1.3-cm (1/2-in.) thick rolled plate. The heat identification (Heat 6), chemistry, mill-determined mechanical properties, etc., are shown in Table I. The tensile specimens were all from the transverse orientation, which means that the specimen major axis was perpendicular to the rolling direction of the plate. Figures 1 and 2 show the location and thus the orientation for base metal specimens 6-18-20 through -31. These base metal specimens were tested at room temperature, 616 K (650°F), 700 K (800°F), and 811 K (1000°F) per ASTM E 21-70.

1.1.2 Weld Metal. The weld metal specimens came from two different weldments. In all instances pieces from Heat 6 were welded using filler metal C. The chemistry and other information for filler metal C are shown in Table I. The specific pieces of Heat 6 (refer to Figure 1) used for welding are identified in the applicable figures. The locations of longitudinal weld specimens 6-C-6-104 through -114 are shown in Figure 3. These specimens were designated as longitudinal since the axis was parallel to the weld axis and the gage length contained only weld metal. Figure 4 shows a schematic of the location and orientation (transverse) of specimens 6-C-6-26, -50, -51, and -52. The procedures used to weld the above specimens are shown in Table III.

Since additional specimens of the transverse orientation were needed, specimens 6-C-6-133 through -137 were taken from a second weldment, as shown in Figure 5. These specimens were all oriented perpendicular to the weld. The 1.3-cm x 15.2-cm x 45.7-cm (1/2-in. x 6-in. x 18-in.) plate of Alloy 718 was welded by the manual gas-tungsten-arc process, utilizing the practices of ANC welding procedure I-20. A groove 0.8-cm (5/16-in.) deep, 60-degree angle and 0.2-cm (1/16-in.)

Alloy 718: Heat Number 2180-4-9478
Heat 6

EGG-A-847

Fig. 1 Schematic showing location and orientation of Alloy 718 plates from Heat 6.

Fig. 2 Schematic showing location and orientation of base-metal specimens from Alloy 718 plates 6-18 and -19.

Heat 6, Weld Batch C

Specimen Identification Corresponding to

Plate No.	a	b	c
6-1-11A	6-C-6-103	6-C-6-104	6-C-6-105
6-1-11B	6-C-6-106	6-C-6-107	6-C-6-108
6-1-11C	6-C-6-109	6-C-6-110	6-C-6-111
6-1-8A	6-C-6-112	6-C-6-113	6-C-6-114

EGG-A-851

Fig. 3 Schematic showing location of longitudinal-oriented Alloy 718 weld tensile specimens 6-C-6-103 through -111.

Fig. 4 Schematic showing location of transverse-oriented tensile and Charpy Alloy 718 weld specimens 6-C-6-1 through -52.

Fig. 4 Continued.

TABLE III

WELDING PROCEDURE FOR ALLOY 718

FOR THE WELDING OF Inconel 718 Plate No. 6-1-20-4 P-NUMBER _____

PROCEDURE LIMITATIONS:

WELDING PROCESS Gas Tungsten Arc Weld (GTAW)
 BASE MATERIALS Inconel 718
 PIPE DIAMETER _____ JOINT TYPE "V" Groove
 WELD THICKNESS 1/2" POSITION Flat SINGLE PASS _____ MULTIPLE PASS X
 AUTOMATIC _____ MACHINE _____ MANUAL X GAS TYPE Argon, welding grade
 TYPE OF NON-CONSUMABLE ELECTRODE 2% Thoriated Tungsten
 WELD FILLER MATERIALS: TYPE Inconel 718
 ASW/ASME _____ RDT _____
 CONSUMABLE INSERT _____ SPECIFICATION _____
 ELECTRICAL CHARACTERISTICS: AC _____ DCSP X DCRP _____
 CURRENT RANGE 130 to 160 Amps VOLTAGE RANGE _____
 INDUCTANCE _____ SLOPE _____
 PREHEAT TEMPERATURE 60° Minimum INTERPASS TEMPERATURE 250° Maximum
 POST HEAT REQUIREMENTS None
 WELDING TECHNIQUE: FOREHAND X BACKHAND _____
 VERTICAL PROGRESSION, UP _____ DOWN _____

OPERATING INSTRUCTIONS:

CLEANING De-grease with acetone before welding and wire brush after each pass
 PREPARATION OF JOINTS Machine to joint dimensions on page 2
 TEMPERATURE MEASUREMENTS BY Temperature indicating crayon
 METHOD OF HEATING (PREHEAT & POSTHEAT) _____
 FIXTURES _____
 METHOD FOR STARTING THE ARC High Frequency
 METHOD FOR STOPPING OR BREAKING THE ARC Foot controlled current decay
 PREHEAT _____
 REPAIRS Grind or machine out defects and re-weld using procedure parameters
 ELECTRODE OSCILLATION LIMIT, MACHINE _____ MANUAL 3/8" Maximum
 TYPE OF GAS CUP, SHAW _____ ETAW Ceramic
 FLUX COMPOSITION AND PARTICLE SIZE (SUBMERGED ARC) _____
 CHEMISTRY REQUIREMENTS FOR NON-CORROSION CLADDING _____

OTHER REQUIREMENTS:

Weld first side until approximately 3/4 full. Machine groove on back side and complete weld, alternating sides as necessary to control plate warpage

TABLE III (Continued)

FORM ANC-7928 (REV. 8-73)

SHEET NO. 2 OF 2 CHANGE

WELDING PROCEDURE

PROCEDURE NO. _____

SKETCHES

WELD JOINT									
PASS NUMBER	A11								
POSITION	Flat								
TORCH ANGLE									
ARC INITIATION	HF								
WELDING ROD/WIRE (TYPE)	Inconel 718, Heat No. 52B0 E								
FILLER METAL DIAMETER	3/32" equivalent (four strands of 0.045" twisted)								
CURRENT (AMPS)	130-160								
VOLTS (ARC LENGTH)									
ELECTRODE POLARITY	DCSP								
TORCH GAS CFH	15-20								
PURGE GAS CFH									
INTERPASS TEMP	250° Max								
CUP SIZE (ORIFICE DIA.)	1/2"								
ELECTRODE EXTENSION	1/2" Max								
TUNGSTEN DIAMETER	3/32"								
TRAVEL SPEED IN./MIN.									
AUTOMATIC/MANUAL									
HEAT MEASUREMENT (METHOD)									
FIXTURING									
RESTRAINTS	None								
TORCH SIZE	300 Amp								
INSERT SIZE									
INSERT (TYPE)									
CONTACT TUBE TO WORK DISTANCE									
PREHEAT TEMPERATURE	60° Min								
POST HEAT TEMPERATURE	None								
RADIOGRAPHY									
DYE PENETRANT									
MAG. PARTICLE									
VISUAL									
APPROVED _____	PREPARED BY _____								
APPROVED _____	DATE _____

EGG-A-850

Fig. 5 Schematic showing location of transverse-oriented tensile (6-C-6-133 through -138) and Charpy (6-C-6-127 through -132) Alloy 718 weld specimens.

root radius was machined and filled with two weld passes. The opposite side was then machined with the same groove geometry to a depth of 0.6-cm (1/4-in.) and filled with three weld passes. Two final passes were then made on the first side and one final pass on the second side. Filler wire was 0.11-cm (0.045-in.) diameter Heat C wound in five strands. Amperage utilized was 140-150.

1.2 Fatigue Design Curves

The fatigue design curves were calculated from the tensile data by the following approach:

- (1) The tensile properties were used to develop design fatigue data by use of the Universal Slopes Equation^[1]

$$\Delta\epsilon_t = \frac{3.5 F_{tu} N_f^{-0.12}}{E} + \left(\frac{D}{N_f}\right)^{0.6} \quad (1)$$

where

F_{tu} = the ultimate tensile strength

N_f = number of cycles to failure

E = Young's Modulus

D = a constant

$\Delta\epsilon_t$ = total strain.

- (2) The total strain ($\Delta\epsilon_t$) was converted to stress amplitude (S_A , in MPa and ksi) by Hooke's Law:

$$S_A = \frac{\Delta\epsilon_t}{2} E \quad (2)$$

- (3) The fatigue data are based on a mean stress, S_m , equal to zero and the fatigue design curve must be corrected to account for S_m . Several methods for accommodating S_m are available. The Modified Goodman Equation^[2] has been selected as the method most useful for Alloy 718^[3]. The fatigue design curve correction used to account for mean stresses is based on the Modified Goodman Equation, as follows:

$$S^1 = S_A \left(\frac{F_{tu} - F_p}{F_{tu} - S_A} \right) \quad (3)$$

where

S^1 = mean-stress-corrected value of S_A

F_p = proportional limit.

- (4) Safety Factor--The design fatigue curves were developed from the equations described earlier in this section, using either $S^1/2$ vs N_f or S^1 vs $N_f/20$, depending on which relationship produced the lower value^[4].

2. CHARPY SPECIMENS

The two types of Charpy impact testing used in this program were the same with the exception of the notch configuration. The notch configuration for the Charpy V-notch (CVN) specimens conformed to Type A, Figure 4 of ASTM E23 which requires a 0.025-cm (0.010-in.) root radius at the tip of the notch. The precracked-Charpy impact (PCI) specimens have the same root radius configuration and also have received a fatigue precracking treatment to initiate and grow a natural crack.

The CVN and PCI specimens were evaluated as instrumented-impact tests at ARA-I, using the procedure in Reference 5.

The two types of specimens were used to obtain the following information:

- (1) CVN data for comparison with other Charpy test results (qualitative)
- (2) PCI data for estimating the dynamic fracture toughness (quantitative)
- (3) CVN and PCI data collectively to seek a possible correlation between the two as a basis for estimating dynamic fracture toughness from CVN energy absorption values.

2.1 Base Metal

Charpy specimens were machined from the 1.3-cm (1/2-in.) thick rolled plate identified as 6-16. The location and orientation of specimen numbers 6-16-27, -28, -29, -34, and -55 through -62 are shown in Figure 6. These specimens were oriented in the transverse/short (TS) direction so that a crack starting at the bottom of the notch would propagate through the plate thickness. The specimens were fatigue precracked and instrumented Charpy impact tests conducted.

2.2 Weld Metal

The location and orientation of the weld metal Charpy specimens are as follows:

- (1) Heat treated transverse (TS) specimens 6-C-6-16, -17, -20, -21, -22, and -42 are shown in Figure 4

- (2) As-welded (not heat treated) transverse (TS) specimens 6-C-6-127 through -132 are shown in Figure 5
- (3) Heat treated longitudinal (LS) specimens 6-C-6-79, -83, -87, -91, 95, and -99 are shown in Figure 7.

Fig. 6 Schematic showing location and orientation of Alloy 718 base-metal specimens from plates 6-16 and -17.

EGG-A-936

Fig. 7 Schematic showing location of longitudinal-oriented Alloy 718 weld Charpy specimens 6-C-6-79 through -102.

3. FRACTURE TOUGHNESS

Earlier results indicated that instrumented Charpy test data were conservative for predicting the fracture toughness of Alloy 718^[6]. These data were obtained from nominally 2.5-cm (1-in.) thick plate. For the 0.6-cm (1/4-in.) thick-wall IPT, it appears that the fracture toughness values based on part-through-crack (PTC) test specimens could be considerably less than the values developed by compact or instrumented Charpy specimens. Such behavior was observed by Aerojet Solid Propulsion Co. and The Boeing Co. in test results shown in Figure 8. This behavior was substantiated specifically for Alloy 718 by Rock-
etdyne^[8].

Because of the possibility that the fracture toughness values based on PTC specimens might be low, four specimens were machined according to Figure 9, fatigue precracked, and tested in straight rising load to failure. A crack-opening-displacement (COD) gage was used to bridge the crack and measure crack growth as a function of load. The analytical approach used to calculate the critical stress intensity factor (K) was that shown in Reference 9. The specimens were all from the transverse orientation of Heat 3 (see Table I), and Figure 10 shows the location of specimens 3-1-12, -16, -18 and -19.

EGG-A-1426

Fig. 8 Thickness required for valid plane-strain crack toughness measurements-grade-200 18% nickel maraging steel heat 3920556^[7].

EGG-B-(935)

Fig. 9 Schematic showing configuration of part-through-crack (PTC) tensile specimens fabricated from Heat 3 of Alloy 718.

Fig. 10 Schematic showing location of transverse-oriented PTC tensile specimens from Heat 3 (Alloy 718).

4. THERMAL EXCURSION

The Alloy 718 specimens were heat treated per the INEL thermal cycle identified in Table II and placed in a furnace at 1090 K (1500°F) for 20 minutes and then water quenched.

4.1 Tensile Specimens

Tensile specimens were fabricated according to ANC Dwg 403351-1 from 1.3-cm (1/2-in.) thick rolled plate. Figure 11 shows the location for base metal specimens 6-15-47 through -52. All were oriented in the longitudinal direction. Tensile tests were conducted at 616 K (650°F).

4.2 Charpy Specimens

Charpy specimens were fabricated according to Type A, Figure 4 of ASTM E23. Figure 6 shows the location for base metal specimens 6-16-68, through -74, all from the transverse orientation. Instrumented pre-cracked Charpy specimens were tested at room temperature under impact loading.

Fig. 11 Schematic showing location and orientation of Alloy 718 base-metal specimens from plates 6-14 and -15.

EGG-A-933

V. RESULTS

1. DESIGN DATA

1.1 Tensile Tests

The tensile test results are shown in Table IV, and the ultimate tensile strength (F_{tu}), and yield strength (F_{ty}) values are plotted in Figure 12.

1.2 Fatigue Curves

The tensile test results obtained in Section V-1.1 were used to develop design fatigue data by use of the Universal Slopes Equation^[1]. The design values for the fatigue curve are shown in Figures 13, 14, and 15. Figures 13 and 14 are applicable to the base metal and Figure 15 to the weld metal. The weld data consisted of transverse and longitudinally oriented weld tensile specimens. Figures 13 and 14 are based on the lower tensile strength values of two sets of tensile test data as well as some experimental fatigue data. The approach used to develop the fatigue curves is presented in Appendix A.

TABLE IV
TENSILE TEST RESULTS FOR ALLOY 718

PROJECT: Tensile Testing of (12) Base Metal Bar Specimens Supplied by
Idaho National Engineering Laboratory
Nominal Gage Section: 0.35" dia. x 1.4" long
Strain Rate through 0.2% Yield: 0.005 in./in./min.
Head Rate thence to Failure: 0.05 in./min.

MRAI No.	Spec. Ident.	Temp. (°F)	U. T. S. (ksi)	Proportional Limit (ksi)	0.2% Y. S. (ksi)	Elong. (%)	R. A. (%)
T-15200	Trans. 6-18-20	R. T.	190.1	69.2	133.2	26.4	38.2
T-15201	Trans. 6-18-21	R. T.	189.9	100.7	136.6	27.2	37.6
T-15202	Trans. 6-18-22	R. T.	189.6	79.6	133.1	25.9	38.5
T-15141	Trans. 6-18-23	650	175.7	----	128.1	22.2	38.7
T-15144	Trans. 6-18-24	650	177.2	98.9	128.8	23.9	38.8
T-15145	Trans. 6-18-25	650	175.3	66.0	125.0	22.5	37.9
T-15150	Trans. 6-18-26	800	174.2	104.7	132.0	17.7	30.2
T-15170	Trans. 6-18-27	800	168.9	59.1	122.8	22.3	36.6
T-15175	Trans. 6-18-28	800	169.6	57.2	122.1	22.2	38.4
T-15179	Trans. 6-18-29	1000	168.1	50.9	117.2	21.5	34.1
T-15182	Trans. 6-18-30	1000	168.5	53.6	117.5	20.6	35.3
T-15185	Trans. 6-18-31	1000	168.5	51.1	117.5	20.8	36.2

PROJECT: Tensile Testing of (18) Weld-Metal Bar Specimens Supplied by
Idaho National Engineering Laboratory
Nominal Gage Section: 0.35" dia. x 1.4" long
Strain Rate through 0.2% Yield: 0.005 in./in./min.
Head Rate thence to Failure: 0.05 in./min.

MRAI No.	Spec. Ident.	Temp. (°F)	U. T. S. (ksi)	Proportional Limit (ksi)	0.2% Y. S. (ksi)	Elong. (%)	R. A. (%)
T-15136	Long. 6C6 - 104	R. T.	191.6	111.2	140.9	20.5	26.4
T-15196	Long. 6C6 - 105	R. T.	192.1	78.7	138.5	18.8	19.8
T-15199	Long. 6C6 - 106	R. T.	192.2	100.2	142.8	21.5	26.6
T-15197	Trans. 6C6 - 26	R. T.	190.6	76.9	132.4	26.3	37.4
T-15198	Trans. 6C6 - 50	R. T.	192.1	82.0	137.3	15.5	20.2
T-15243	Trans. 6C6 - 133	R. T.	188.9	98.3	147.5	25.6	40.3
T-15137	Long. 6C6 - 108	650	177.2	98.7	130.5	17.9	20.6
T-15138	Long. 6C6 - 109	650	176.8	84.8	131.8	19.3	32.1
T-15139	Long. 6C6 - 110	650	176.2	82.9	130.1	19.7	29.6
T-15140	Trans. 6C6 - 51	650	176.1	60.1	133.2	17.3	24.1
T-15246	Trans. 6C6 - 134	650	168.9	109.1	135.6	21.7	42.7
T-15247	Trans. 6C6 - 135	650	168.9	107.8	137.2	22.9	41.4
T-15146	Long. 6C6 - 111	800	171.1	79.4	126.8	12.9	18.1
T-15147	Long. 6C6 - 112	800	169.7	--	126.1	11.3	17.0
T-15148	Long. 6C6 - 114	800	173.7	79.0	127.4	15.4	20.6
T-15149	Trans. 6C6 - 52	800	173.6	76.6	129.5	18.3	30.6
T-15249	Trans. 6C6 - 136	800	161.8	84.8	133.6	22.0	43.8
T-15250	Trans. 6C6 - 137	800	163.3	87.8	128.7	22.8	42.6

Fig. 12 Plot of yield and ultimate tensile strength versus test temperature. (See Table IV and X for ductility data).

Fig. 13 Design fatigue curve for Alloy 718 base-metal given the INEL heat treat (Heats 3 and 6).

Fig. 14 Design fatigue curve at 811 K (1000°F) for Alloy 718 base-metal given the INEL heat treat (Heats 3 and 6).

Fig. 15 Design fatigue curve for Alloy 718 weld metal given the INEL heat treat (Heats 3 and 6).

2. CHARPY TESTING

The data for tests of Charpy V-notch (CVN) impact specimens and precracked-instrumented impact (PCI) specimens are shown in Table V and VI, respectively.

3. FRACTURE TOUGHNESS

These specimens have been fatigue precracked and tested at RT. The fatigue precracking data are shown in Table VII. The plot of COD versus load curve for each specimen is shown in Figure 16. The test results are summarized in Table VIII.

4. THERMAL EXCURSION

Tensile and Charpy-impact testing of INEL heat treated Alloy 718 samples which had been subsequently exposed for 20 minutes at 1090 K (1500°F) and then water-quenched, resulted in the data shown in Table IX.

TABLE V

INSTRUMENTED CHARPY V-NOTCH IMPACT TEST RESULTS FOR ALLOY 718

Specimen Identification	Test Temperature		Dial Impact Energy		Notch Depth(a) cm (in.)	Fracture Toughness		Stress Intensity Rate ($\times 10^5$)	
	K	(°F)	J	(ft-lb)		MPa-m ^{1/2}	ksi-in ^{1/2}	MPa-m ^{1/2} per sec	ksi-in ^{1/2} per sec
6-16-30 ^{(1)*}	297	(75)	39.3	(29)	0.201 (0.079)	291.5	(219.5)	15.00	(13.64)
6-16-31 ⁽¹⁾	297	(75)	36.6	(27)	0.201 (0.079)	244.6	(222.4)	13.37	(12.15)
6-16-32 ⁽¹⁾	297	(75)	38.0	(28)	0.201 (0.079)	245.1	(222.3)	10.18	(9.25)
6-16-36 ⁽¹⁾	616	(650)	46.1	(34)	0.201 (0.079)	275.1	(250.1)	12.90	(11.73)
6-16-37 ⁽¹⁾	616	(650)	44.7	(33)	0.201 (0.079)	242.7	(220.6)	13.07	(11.88)
6-16-38 ⁽¹⁾	616	(650)	46.8	(34.5)	0.201 (0.079)	258.6	(235.1)	12.65	(11.50)
6-16-54 ⁽²⁾	297	(75)	56.9	(42.0)	0.201 (0.079)	300.2	(272.9)	13.49	(12.26)
6-16-52 ⁽²⁾	616	(650)	63.7	(47.0)	0.201 (0.079)	273.5	(248.6)	10.31	(9.37)
6-16-53 ⁽²⁾	700	(800)	66.4	(49.0)	0.201 (0.079)	295.1	(268.3)	10.26	(9.33)
6-16-63 ⁽²⁾	811	(1000)	69.8	(51.5)	0.201 (0.079)	295.5	(268.6)	10.26	(9.33)
3-19-72 ⁽³⁾	297	(75)	47.5	(35.0)	0.201 (0.079)	257.4	(234.0)	16.59	(15.08)
3-19-74 ⁽³⁾	297	(75)	43.4	(32.0)	0.201 (0.079)	234.5	(213.2)	14.47	(13.15)

(1) Transverse-oriented (TS) base metal specimens heat treated per Table IIb

(2) Transverse-oriented (TS) base metal specimens heat treated per Table IIc

(3) Transverse-oriented (TS) base metal specimens heat treated per Table IIc

* The first number in the series denotes the heat identification, i.e. 6 denotes Heat 6 of Table I.

TABLE VI

INSTRUMENTED PRECRACKED-CHARPY IMPACT TEST RESULTS FOR ALLOY 718

Specimen Identification	Test Temperature		Dial Impact Energy		Crack Depth ^[a]		Fracture Toughness		Stress Intensity Rate ($\times 10^5$)	
	K	(°F)	J	(ft-lb)	cm	(in.)	MPa-m ^{1/2}	ksi-in. ^{1/2}	MPa-m ^{1/2} per sec	ksi-in. ^{1/2} per sec
6-C-6-16 ^{(1)*}	297	(75)	12.2	(9.0)	0.50	(0.197)	179.4	(163.1)	6.00	(5.45)
6-C-6-17 ⁽¹⁾	297	(75)	10.8	(8.0)	0.51	(0.201)	170.3	(154.8)	6.16	(5.60)
6-C-6-20 ⁽¹⁾	297	(75)	10.8	(8.0)	0.50	(0.197)	167.8	(152.5)	5.18	(4.71)
6-C-6-21 ⁽¹⁾	616	(650)	12.9	(9.5)	0.51	(0.201)	168.6	(153.3)	4.98	(4.53)
6-C-6-22 ⁽¹⁾	616	(650)	12.2	(9.0)	0.54	(0.213)	177.0	(160.9)	8.04	(7.31)
6-C-6-42 ⁽¹⁾	616	(650)	12.9	(9.5)	0.49	(0.193)	177.5	(161.4)	5.62	(5.11)
6-C-6-79 ⁽²⁾	297	(75)	11.5	(8.5)	0.49	(0.193)	169.6	(154.2)	5.94	(5.40)
6-C-6-83 ⁽²⁾	297	(75)	12.2	(9.0)	0.52	(0.205)	190.0	(172.7)	5.61	(5.10)
6-C-6-87 ⁽²⁾	297	(75)	10.8	(8.0)	0.55	(0.217)	177.4	(161.3)	4.87	(4.43)
6-C-6-91 ⁽²⁾	616	(650)	13.6	(10.0)	0.52	(0.213)	180.5	(164.1)	5.80	(5.27)
6-C-6-95 ⁽²⁾	616	(650)	16.3	(12.0)	0.48	(0.189)	177.9	(161.7)	5.37	(4.88)
6-C-6-99 ⁽²⁾	616	(650)	16.3	(12.0)	0.48	(0.189)	170.9	(155.4)	5.82	(5.29)
5-C-6-129 ⁽³⁾	297	(75)	23.0	(17.0)	0.51	(0.201)	206.3	(187.5)	5.30	(4.82)
5-C-6-130 ⁽³⁾	297	(75)	21.7	(16.0)	0.53	(0.209)	201.6	(183.3)	4.86	(4.42)
5-C-6-131 ⁽³⁾	297	(75)	23.0	(17.0)	0.52	(0.205)	183.9	(167.2)	3.74	(3.40)
5-C-6-132 ⁽³⁾	297	(75)	21.7	(16.0)	0.54	(0.213)	198.9	(180.8)	4.61	(4.19)
6-C-6-127 ⁽³⁾	516	(650)	27.1	(20.0)	0.54	(0.213)	246.0	(223.6)	4.06	(3.69)
6-C-6-128 ⁽³⁾	516	(650)	24.4	(18.0)	0.52	(0.205)	202.7	(184.3)	4.68	(4.25)

TABLE VI (Continued)

Specimen Identification	Test Temperature		Dial Impact Energy		Crack Depth ^[a]		Fracture Toughness		Stress Intensity Rate ($\times 10^5$)	
	K	(°F)	J	(ft-lb)	cm	(in.)	MPa-m ^{1/2}	(ksi-in. ^{1/2})	MPa-m ^{1/2} per sec	ksi-in. ^{1/2} per sec
6-16-27 ⁽⁴⁾	297	(75)	15.6	(11.5)	0.50	(0.197)	203.5	(185.0)	7.24	(6.58)
6-16-28 ⁽⁴⁾	297	(75)	14.2	(10.5)	0.51	(0.201)	196.8	(178.9)	7.39	(6.72)
6-16-29 ⁽⁴⁾	297	(75)	12.2	(9.0)	0.54	(0.213)	188.1	(171.0)	7.37	(6.70)
6-16-34 ⁽⁴⁾	616	(650)	18.3	(13.5)	0.51	(0.201)	175.0	(159.1)	6.04	(5.49)
6-16-55 ⁽⁵⁾	297	(75)	23.7	(17.5)	0.50	(0.197)	249.8	(227.1)	6.86	(6.24)
6-16-58 ⁽⁵⁾	297	(75)	28.5	(21.0)	0.43	(0.170)	228.4	(207.6)	7.00	(6.36)
6-16-56 ⁽⁵⁾	616	(650)	21.7	(16.0)	0.55	(0.217)	225.0	(204.5)	5.10	(4.64)
6-16-57 ⁽⁵⁾	616	(650)	27.1	(20.0)	0.47	(0.185)	225.2	(204.7)	6.26	(5.69)
6-16-59 ⁽⁵⁾	700	(800)	24.4	(18.0)	0.52	(0.205)	230.3	(209.4)	6.00	(5.45)
6-16-60 ⁽⁵⁾	700	(800)	25.8	(19.0)	0.51	(0.201)	247.8	(225.3)	5.73	(5.21)
6-16-61 ⁽⁵⁾	811	(1000)	27.1	(20.0)	0.49	(0.193)	230.7	(203.7)	5.69	(5.17)
6-16-62 ⁽⁵⁾	811	(1000)	21.7	(16.0)	0.52	(0.205)	222.5	(202.3)	5.71	(5.19)
3-19-65 ⁽⁶⁾	297	(75)	20.3	(15.0)	0.50	(0.197)	236.8	(215.3)	10.60	(9.64)
3-19-66 ⁽⁶⁾	297	(75)	21.7	(16.0)	0.50	(0.197)	202.0	(183.5)	11.61	(10.55)
3-19-67 ⁽⁶⁾	297	(75)	19.0	(14.0)	0.53	(0.209)	216.0	(195.4)	14.07	(12.79)

(1) Transverse-oriented (TS) weld specimens heat treated per Table IIa.

(2) Longitudinal-oriented (LS) weld specimens heat treated per Table IIa.

(3) Transverse weld specimens in the as-welded condition.

(4) Transverse-oriented (TS) base metal specimens heat treated per Table IIb.

(5) Transverse-oriented (TS) base metal specimens heat treated per Table IIa.

(6) Transverse-Oriented (TS) base metal specimens treated per Table IIa.

* The first number in the series denotes the heat identification, i.e. 6 denotes Heat 6 of Table I.

TABLE VII

FATIGUE PRECRACKING DATA FOR THE PTC TENSILE SPECIMENS
FROM BASE-METAL ALLOY 718 (HEAT 3, INEL HEAT TREAT)

PROJECT

To precrack (4) IN 718 Part-Through-Crack (PTC) Tensile Specimens

Test Equipment: BLH IV-20 fitted with a 3-point bending
fixture having 1.5 in. diameter rollers

Test Conditions: Temperature: 75°F
Relative Humidity: 54-65%
Fixture Span: S = 13.00 in.
Machine Frequency: 20 Hz
Surface Stress: Approx. 1/2 yield strength

Spec. No.	Surface Stress (ksi)	Approx. Surface K (ksi-in. ^{1/2})	Fatigue Cycles (x 10 ³)	Spec. Gage Section Size (in.)		Nom. EDM Notch Size (in.)		Final Crack Length, 2a (in.)		
				Width	Depth	Width	Length	Total	S-1	S-2
3B	93.6	50	14	3.990	0.245	0.600	0.120	0.712	0.065	0.047
3D	92.0	50	14	3.994	0.247	0.600	0.120	0.703	0.046	0.062
3E	89.9	60	16	3.996	0.250	0.993	0.080	1.100	0.056	0.050
3F	89.8	60	15	3.994	0.250	0.999	0.080	1.131	0.052	0.073

Fig. 16 Plot of load versus strain, as functions of voltage, for room temperature PTC tensile test of Alloy 718 (Heat 3 given the INEL heat treat).

TABLE VIII

PART-THROUGH-CRACK TENSILE TEST RESULTS^[a]

Specimen Numbers	Peak Load (kip)	Crack Depth ^[a]		Crack Length (2c)		a/2c	a/t	K _{max} ^[b]	
		cm	(in.)	cm	(in.)			MPa-m ^{1/2}	(ksi-in. ^{1/2})
3-1-12	(128.8)	0.343	(0.135)	1.821	(0.717)	0.19	0.54	125.4	(114.0)
3-1-16	(130.3)	0.343	(0.135)	1.806	(0.711)	0.19	0.54	126.7	(115.2)
3-1-18	(120.3)	0.414	(0.163)	2.819	(1.110)	0.15	0.65	180.3	(163.9)
3-1-19	(118.6)	0.401	(0.158)	2.850	(1.122)	0.14	0.63	171.6	(156.0)

^[a]Specimens were tested at RT at a load rate corresponding to 4.6 MPa (670 psi) per sec. Specimen physical dimensions are essentially 0.635 cm (0.250 in.) thick by 10.16 cm (4.000 in.) wide.

^[b]The stress intensity factor K_{max} was calculated on the basis of the maximum load using the equation in Appendix A, Section XI, of the ASME Boiler and Pressure Vessel Code.

TABLE IX
MECHANICAL PROPERTY TEST RESULTS - CABOT
STELLITE HEAT NO. 2180-4-9478 (VIM-ESR)

[a] Tensile specimens tested @ 616 K (650°F) (Longitudinal Orientation)

Specimen	Yield Strength		Ultimate Tensile Strength		Total Elong.	Reduction of Area
	MPa	(ksi)	MPa	(ksi)	(%)	(%)
6-15-47	912	(132.2)	1279	(185.3)	23.2	29.4
6-15-48	905	(131.2)	1259	(182.5)	23.4	28.7
6-15-49	887	(128.5)	1269	(183.9)	25.7	32.8
AVERAGE	901	(130.6)	1269	(183.9)	24.1	30.3
6-15-50*	690	(100)	1099	(159.3)	30.5	39.5
6-15-51*	717	(103.9)	1124	(162.9)	31.7	40.7
6-15-52*	702	(101.8)	1124	(162.9)	31.0	45.2
AVERAGE	703	(101.9)	1116	(161.7)	31.3	41.8

*Thermal excursion simulation: INEL heat treat plus 1089 K (1500°F) for 20 minutes and water-quenched.

[b] Instrumented precracked Charpy specimens tested at RT (Transverse Orientation, TS)

Specimen Number	Dynamic Yield Strength		Dynamic Fracture Toughness		Load Rate ($\times 10^5$)	
	MPa	(ksi)	MPa	(ksi-in. ^{1/2})	MPa-m ^{1/2} per sec	(ksi-in. ^{1/2} per sec)
6-16-68	1104	(160)	168	(153)	4.0	(3.6)
6-16-69	1076	(156)	215	(197)	6.7	(6.1)
6-16-71	1083	(157)	214	(195)	7.3	(6.6)
AVERAGE	1090	(158)	199	(182)		
6-16-72*	945	(137)	200	(257)	6.6	(6.0)
6-16-73*	1056	(153)	288	(262)	6.5	(5.9)
6-16-74*	1097	(159)	206	(269)	6.0	(5.5)
AVERAGE	1035	(150)	289	(263)		

*Thermal excursion simulation - INEL heat treat plus 1089 K (1500°F) for 20 minutes and water-quenched.

VI. DISCUSSION

1. DESIGN DATA

1.1 Tensile Strength Design Curves

The tensile test results in Table IV showed that Heat 6 did not respond as well as expected to the INEL heat treatment. The yield strength at room temperature was 910-924 Mpa (132-134 ksi) instead of the anticipated value of 980-1020 Mpa (142-148 ksi). As the temperature of testing increased, the actual test results approached or equalled the expected values. Subsequent tensile tests conducted at the INEL on specimens 6-18-34 and -39 showed an average RT yield strength of 973 Mpa (141 ksi). The schematic in Figure 2 shows that the two sets of specimens (6-18-20, -21, and -22 versus 6-18-34 and -39) came from the same general location (central portion of piece 6-18), which reduces the possibility that the difference in yield strength was due to material variability. In discussions with an individual at the original test laboratory no reasonable explanations were obtained^[10]. Therefore, the lower yield strength values were used to establish conservative design curves for both tensile and fatigue properties.

It is recognized that the tensile curves in Figure 12 were not developed on the basis of test results, for the complete temperature range, for five commercial heats with test temperature intervals no greater than 56 K (100°F) as required in Reference 11. Additional test data from other heats of Alloy 718, given the INEL heat treat, are listed in Table X. These additional test data show reasonable agreement with the results in Table IV for Heat 6. The primary differences between the results in Table IV and X are that the ultimate and yield tensile strength values are conservatively low and the ductility values (% El and % RA) are greater for Heat 6. The addition of data from Table X fulfilled the requirement for a second heat, but there were not sufficient data from other heats.

TABLE X

TENSILE TEST RESULTS FOR ALLOY 718 GIVEN THE INEL HEAT TREAT^[a]

Heat No.	Test Temperature		Ultimate Tensile Strength		0.2 % Yield Strength		Elong.	R.A.	Reference
	K	°F	MPa	(ksi)	MPa	(ksi)	%	%	
83C2EK	RT	RT	1352	(196)	994	(144)	16	15	12
87C0EK1	RT	RT	1380	(200)	1000	(145)	20	30	12
3	RT	RT	1359	(197)	1035	(150)	14	28	13
3	505	(450)	1297	(188)	959	(139)	12	20	13
3	589	(600)	1270	(184)	945	(137)	13	19	13
3	700	(800)	1228	(178)	9925	(134)	12	24	13
3	811	(1000)	1208	(175)	897	(130)	13	29	13
-	RT	RT	1311	(190)	1159	(168)	13	22	14
-	RT	RT	1304	(189)	1056	(153)	24	35	14

^[a]Excludes the data collected from Heat 5.

Reference 14 indicated that a particular forging did not respond to the INEL heat treat with the expected tensile test results. The deviation from the expected tensile test results was identified as a low RT yield strength. Because the ultimate tensile strength is the limiting design requirement and it showed reasonable stability for the several heats of Alloy 718 tested, it was assumed that the curves in Figure 12 were applicable for the 0.64-cm (1/4-in.) thick IPT. Additional verification will be obtained in that a number of specimens from the forging will be heat treated with the IPT and then tested in order to establish the tensile properties from the actual heat of Alloy 718.

1.2 Fatigue Design Curves

Figures 13 through 15 were developed as design fatigue curves for Alloy 718 given the INEL heat treat cycle identified in Table II. The fatigue values determined analytically from tensile test results for Heat 6 were augmented by actual fatigue test data. In addition, fatigue values were determined analytically from tensile test results for Heat 3 which were also augmented by actual fatigue test data. This went beyond the initial scope of effort in that the design values were to have been based on Heat 6. The use of the additional data would result in more meaningful design curves for both fatigue and tensile properties. The design fatigue curves in Figures 13 through 15 were based on the lower of the results obtained from Heats 3 and 6.

Two analytical techniques were used to convert from tensile test results to design fatigue data and they were separated on the basis of test temperature. One technique was used for data collected at test temperatures less than or equal to 700 K (800°F), and the other for test temperatures greater than 700 K (800°F). A more detailed description of the tensile test and fatigue data plus the analytical techniques used to develop the design fatigue curves in Figures 13 through 15 are presented in Appendix A.

These results in Figures 13 through 15 are compared with those in Figures 17 through 19 which were developed analytically for Alloy 718 (base metal and weld metal) given the same heat treat as the first 2.5-cm (1.0-in) thick IPT for PBF^[15]. The chemistry for the 2.5-cm (1.0-in.) thick alloy 718 is 0.05 C, 0.06 Mn, 0.006 P, 0.007 S, 0.20 Si, 17.82 Cr, 54.48 Ni, 0.95 Ti, 2.86 Mo, 0.48 Al, 0.04 Co, 4.96 Nb, 18.40 Fe, and 0.06 Cu. The specific heat treatment for Alloy 718 used to collect the data for Figures 17 through 19 is identified on the applicable figures. The results in Figures 13 through 15 were compared with those in Figures 17 through 19.

For the base metal design fatigue curves in Figures 13 and 17 there is general agreement in S^1 for N_f ranging from 10^1 to 10^3 cycles. Beyond $N_f = 10^3$ cycles the values of S^1 decrease more rapidly in Figure 17 than in Figure 13 for the same N_f . The curves in Figure 17 were determined analytically using tensile test data, whereas the curves in Figure 13 were based upon analytical as well as experimental results.

The base metal design fatigue curves for 811 K (1000°F) in Figures 14 and 18 showed good agreement.

The weld design fatigue curves in Figure 15 were based on the lower values of data collected from both longitudinal- and transverse-oriented specimens from Heat C weld metal. The data were modified to reflect the differences observed in base metal behavior between Heats 3 and 6, and the differences observed between analytical and experimental results.

Figure 15 is a composite of longitudinal and transverse test results. The composite was obtained from Figures A-6 and A-10 (see Appendix A) and the lowest data points were used to develop the curves.

For weld metal design fatigue curves, from RT to 700 K (800°F) in Figures 15 and 19 there is general agreement in S^1 for N_f ranging

Fig. 17 Design fatigue curves, with and without mean stress correction, for the base-metal of PBF-IPT Alloy 718 forging^[15].

Fig. 18 Design fatigue curve (ϵ_A versus N_f) for the base-metal of PBF-IPT Alloy 718 forging at 811 K (1000°F)^[15].

Fig. 19 Design fatigue curves, with and without mean stress correction, for the weldments of PBF-IPT Alloy 718 forging^[15].

from 10^1 to 10^3 cycles. For N_f ranging between 10^1 and 10^3 cycles the corresponding values of S^1 in Figure 15 are the same as those shown in Figure 19. Beyond $N_f = 10^3$ cycles the values of S^1 decrease more rapidly in Figure 19 for the same N_f . Heat C filler metal was used to develop the data for Figures 15 and 19.

The comparisons between Figures 13 through 15 and Figures 17 through 19 showed that heat treat had little effect on the design fatigue curves for N_f ranging from 10^1 to 10^3 cycles. For N_f greater than 10^3 cycles the INEL heat treat produced higher values of S^1 for the same N_f .

2. CHARPY SPECIMENS

The information requirement pertinent to the IPT is to establish the nominal range of dynamic fracture toughness (K_{Id}) for the Alloy 718 base metal and weld metal. This discussion will deal solely with the adequacy of the K_{Id} results. Information of potential use for verifying the structural adequacy of the IPT is included in Appendix B. Appendix B discusses observations pertaining to the INEL versus a standard heat treat, heat-to-heat variability, potential correlation between CVN test results and K_{Id} , notch acuity (sharpness) effect, and the need for thermal cycling of weldments to improve ductility.

A summary of Table VI shows the following values for K_{Id} :

<u>Specimen Location</u>	<u>Test Temperature</u>		<u>K_{Id}</u>	
	K	(F)	MPa-m ^{1/2}	(ksi-in. ^{1/2})
Transverse Weld	RT	(RT)	172	(156)
	616	(650)	172	(156)
Longitudinal Weld	RT	(RT)	178	(162)
	616	(650)	176	(160)
Transverse Base Metal	RT	(RT)	239	(217)

616	(650)	224	(204)
700	(800)	217	(217)
811	(1000)	227	(206)

The above summary shows that on the basis of test data for instrumented PCI specimens the dynamic fracture toughness for both base metal and weldments is quite adequate. The effectiveness of the instrumented PCI test in determining fracture toughness has been evaluated twice at the INEL for Alloy 718.

The first evaluation was conducted for the PBF acoustic filters^[6]. These test results established that the instrumented precracked Charpy specimens tested at slow strain rates exhibited lower values than compact specimens tested at the same strain rate.

The second evaluation was conducted for this study and will be discussed in Section VI-3.

3. FRACTURE TOUGHNESS TEST RESULTS

The test results in Table VIII showed that K_{max} varied from 132 to 176 MPa-m^{1/2} (120 to 160 ksi-in.^{1/2}). There was excellent agreement between duplicate specimens having the same crack depth but a considerable variation existed as a function of crack depth. Two possible explanations exist for this dependence and are identified as follows:

- (1) The analytical technique used may be too conservative for the deeper flaws. The correction factor M_m varied from 1.44 to 1.87, depending upon the crack itself. This fluctuation in M_m explains the major portion of the variation in K_{max} . Since the analytical technique has been developed to include many materials and test conditions it would not be expected that the analytical technique would contribute much to the observed differences.

- (2) $K_{\max}$ was calculated on the basis of the maximum load and the original defect size. This is frequently done because it is assumed that the crack does not move until failure suddenly occurs at maximum load. Figure 16 shows that some crack growth and/or plastic deformation had occurred, since there is considerable deviation from the initial straight line. The specimens containing the deeper cracks (3-1-18 and -19) had less deviation from the straight line than the other two.

Although the COD measurement in Figure 16 showed a deviation from linearity, it cannot provide quantitative results of the actual crack size. When failure does not occur under elastic conditions (for nonelastic failure, as shown in Figure 16), the two events of interest are crack initiation and the onset of instability. The stress-intensity factor at crack initiation should be comparable to K_{IC} . Calculated values of the stress-intensity factor at crack initiation (taken from 5% secant offset) are less than the K_{Id} values of $125 \text{ MPa}\cdot\text{m}^{1/2}$ ($114 \text{ ksi}\cdot\text{in.}^{1/2}$). This shows that K_{Id} values from PCI tests provided a nonconservative estimate of K_{IC} for the PTC specimen.

The purpose of this investigation was not to estimate K_{IC} for the 0.64-cm (1/4-in) thick IPT but was two-fold:

- (1) To provide some understanding of the requirements for failure with 0.64-cm (1/4-in.) thick Alloy 718 material
- (2) To compare K_{Id} (instrumented PCI) values with $K_{\max}$.

Therefore, the onset of instability was the area of interest and was used in the investigation. The difficulty in using instability as a failure criterion arises from the problems associated with defining the critical defect size. Obviously, from Figure 16 there has been real and/or pseudo crack growth but the use of the initial fatigue crack size to calculate $K_{\max}$ is a conservative approach. Previously it was indicated that the K_{Id} values, from the transverse orientation,

were $125 \text{ MPa}\cdot\text{m}^{1/2}$ ($114 \text{ ksi}\cdot\text{in.}^{1/2}$) which was greater than the potential K_{IC} (from the PTC specimens) but less than K_{max} . Since failure of the IPT would be based on K_{max} (as opposed to K_{IC}) the use of K_{Id} from PCI testing appears to be conservative for the 0.64-cm (1/4-in) thick Alloy 718.

4. THERMAL EXCURSION

Exposing INEL heat treated Alloy 718 (Heat 6) for 20 minutes to a 1090 K (1500°F) temperature and then water-quenching resulted in changes in mechanical properties. Tensile tests were conducted at 616 K (650°F) and instrumented PCI specimens were tested at RT. The results are shown in Table IX.

The tensile test at 616 K (650°F) indicated a reduction of 10 to 20% of yield and tensile strength and a substantial increase (30 to 38%) in ductility as a result of the thermal excursion.

The instrumented PCI test at 297 K (75°F) indicated an increase of 45% in the K_{Id} value and a 5% decrease in the dynamic yield strength.

The above data were collected for a specific problem. Since the data in Table IX completed the requested work, the situation was not evaluated any further.

VII. REFERENCES

1. G. R. Halford and S. S. Monson, Applications of a Method of Estimating High Temperature Low Cycle Fatigue Behavior of Materials, NASA TMX-52357 (October 1967).
2. B. F. Langer, "Design of Pressure Vessels for Low-Cycle Fatigue," Journal of Basic Engineering (September 1962) p 389.
3. Internal Report.
4. "Criteria of the ASME Boiler and Pressure Vessel Code for Design by Analysis," in Sections III and VIII, Division 2, of the ASME Boiler and Pressure Vessel Code, New York: The American Society of Mechanical Engineers, 1969.
5. Internal Report.
6. Internal Report.
7. Private Communication.
8. Private Communication.
9. "A Method for K_I Determination: Appendix A," Article A-3000, Section XI, of the ASME Boiler and Pressure Vessel Code, New York: The American Society of Mechanical Engineers, 1974.
10. Private Communication.
11. W. B. Hoyt, Guidelines for Required Data on New Materials Elevated Temperature Nuclear Construction, ASME Boiler and Pressure Vessel Committee.
12. Internal Report.
13. Private Communication.
14. Private Communication.
15. Internal Report.

APPENDIX A
DEVELOPMENT OF DESIGN FATIGUE CURVES FROM TENSILE
DATA FOR ALLOY 718

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APPENDIX A

DEVELOPMENT OF DESIGN FATIGUE CURVES FROM TENSILE DATA FOR ALLOY 718

This appendix sets forth the procedures used to develop the design fatigue curves from tensile test results. Two different analytical approaches were used. One method was used for data from tensile specimens tested at or below 700 K (800°F) and the other for data from those tested at 811 K (1000°F). The reason was that a single technique is not applicable for data from both temperatures. The basis for the difference is the creep consideration identified in Section A-1.2.

1. DESIGN FATIGUE CURVES FOR TEST TEMPERATURES < 700 K (800°F)

The design fatigue curves were developed using the tensile test results in Tables IV and X of the main text and the analytical approach described in References A-1 and A-2.

1.1 Conversion of Tensile Test Results to Total Strain Range

The tensile test results shown in Table IV of the main text were converted to total strain range ($\Delta\epsilon_T$) by use of the Universal Slopes Equation^[A-3]

$$\Delta\epsilon_T = \frac{3.5 F_{tu} N_f^{-0.12}}{E} + \left(\frac{D}{N_f}\right)^{0.6} \quad (A-1)$$

where

F_{tu} = the ultimate tensile strength

N_f = number of cycles to failure

E = Young's Modulus

$$D = \text{a measure of fracture ductility} = \ln \left(\frac{100}{100 - \%RA} \right)$$

%RA = percent reduction of area.

The values of $\Delta\epsilon_T$ versus N_f for base metal and weld metal specimens tested at temperatures ranging from RT to 811 K (1000°F) are listed in Table A-I.

1.2 Conversion of Total Strain Range to Stress Amplitude

The total strain range ($\Delta\epsilon_T$) was converted to stress amplitude (S_A , in MPa and ksi) by Hooke's Law:

$$S_A = \frac{\Delta\epsilon_T}{2} E \quad (A-2)$$

The values of S_A versus N_f for base metal and weld metal specimens tested at temperatures ranging from RT to 700 K (800°F) are listed in Table A-II. The use of Hooke's Law in the plastic region as well as the reason for not including the 811 K (1000°F) test results in Table A-II can best be described from Reference A-2.

"Hooke's Law is used in the plastic region (i.e., $S_A > F_p$) because the Design Engineer converts the fictitious stress amplitude, S_A , values back into strain amplitude, ϵ_A ($\epsilon_A = 1/2 \epsilon_T$), before using the design fatigue curves^[A-4,-5]. It is customary to report design fatigue data as fictitious S_A versus N_f rather than ϵ_A versus N_f .^[A-4] The ϵ_A versus N_f data is generated only for uniaxial conditions. Biaxial loading is more damaging and would result in premature failure than that indicated by the uniaxial ϵ_A versus N_f data. The ϵ_A versus N_f design fatigue curves, when given, will have to be corrected by the user for the effects of biaxial loading, torsional or shear loading, etc.

TABLE A-I

TOTAL STRAIN RANGE ($\Delta\epsilon_T$) VERSUS CYCLES TO FAILURE (N_f) FOR ALLOY 718*

N_f	BASE METAL				WELD METAL					
	Transverse Orientation				Transverse Orientation			Longitudinal Orientation		
	RT	616 K (650°F)	700 K (800°F)	811 K (1000°F)	RT	616 K (650°F)	700 K (800°F)	RT	616 K (650°F)	700 K (800°F)
1×10^2	0.053791	0.054315	0.051490	0.051907	0.049342	0.051984	0.054316	0.042629	0.045290	0.037826
2×10^2	0.038924	0.039320	0.037445	0.037807	0.036000	0.037688	0.039214	0.031598	0.033378	0.028442
3×10^2	0.032563	0.032904	0.031427	0.031763	0.030276	0.031567	0.032757	0.026841	0.028252	0.024376
5×10^2	0.026331	0.026617	0.025523	0.025830	0.024655	0.025568	0.026436	0.022146	0.023201	0.020341
1×10^3	0.020203	0.020434	0.019703	0.019977	0.019107	0.019664	0.020227	0.017474	0.018190	0.016294
5×10^3	0.012130	0.012284	0.011991	0.012208	0.011727	0.011868	0.012067	0.011140	0.011445	0.010709
1×10^4	0.01015	0.010284	0.010084	0.010282	0.009892	0.009950	0.010074	0.009522	0.009738	0.009246
5×10^4	0.007232	0.007332	0.007245	0.007406	0.007144	0.007112	0.007148	0.007029	0.007136	0.006938
1×10^5	0.006400	0.006491	0.005428	0.006576	0.006348	0.006301	0.006319	0.006285	0.006367	0.006231
5×10^5	0.004991	0.005063	0.005031	0.005152	0.004979	0.004920	0.004918	0.004975	0.005025	0.004965
1×10^6	0.004529	0.004595	0.004570	0.004681	0.004525	0.004466	0.004461	0.004532	0.004574	0.004530
5×10^6	0.003662	----	----	0.003791	0.003666	0.003613	0.003604	----	----	----
1×10^7	0.003353	0.003403	0.003389	0.003473	0.003359	0.003309	0.003300	0.003338	0.003405	0.003387
5×10^7	0.002746	----	----	----	----	----	----	----	----	----
1×10^8	0.002523	0.002561	0.002552	----	0.002530	0.002491	0.002483	----	0.002567	0.002557

*INEL heat treat, see Table II

TABLE A-II

STRESS AMPLITUDE, S_A , MPa (ksi) VERSUS CYCLES TO FAILURE (N_f) FOR ALLOY 718*

N_f	Base Metal						Weld Metal											
	Transverse Orientation						Transverse Orientation						Longitudinal Orientation					
	294 K (70°F)		616 K (650°F)		700 K (800°F)		294 K (70°F)		616 K (650°F)		700 K (800°F)		294 K (70°F)		616 K (650°F)		700 K (800°F)	
	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
1×10^2	5378	780	4961	719	4579	664	4332	715	4748	689	4331	701	4262	618	4138	600	3365	488
2×10^2	3891	564	3592	521	3331	483	3599	522	3443	499	3487	506	3159	458	3050	442	2530	367
3×10^2	3255	472	3005	436	2795	405	3027	439	2884	418	2914	423	2683	389	2581	374	2168	315
5×10^2	2632	382	2432	353	2270	329	2466	358	2681	339	2352	341	2215	321	2119	307	1809	262
1×10^3	2015	292	1864	270	1752	254	1911	277	1796	261	1800	261	1746	253	1662	241	1449	210
5×10^3	1213	176	1122	163	1067	155	1172	170	1805	157	1074	155	1114	162	1046	152	952	138
1×10^4	1015	147	939	136	896	130	989	143	909	132	896	130	952	138	890	129	823	119
5×10^4	723	105	669	97	545	94	715	104	649	94	636	92	703	102	653	95	617	90
1×10^5	540	93	593	86	572	83	635	92	576	84	562	82	629	91	582	84	555	80
5×10^5	499	72	463	67	448	65	498	72	450	65	437	63	497	72	460	67	442	64
1×10^6	453	66	420	61	407	59	453	66	408	59	397	58	453	66	418	61	403	58
5×10^6	366	53	--	-	--	-	367	53	331	48	321	47	--	-	--	-	--	-
1×10^7	335	49	311	45	302	44	336	49	302	44	294	43	334	48	311	45	302	44
5×10^7	274	40	--	-	--	-	--	-	--	-	--	-	--	-	--	-	--	-
1×10^8	252	37	234	34	227	33	253	37	228	33	221	32	--	-	235	34	228	33

*INEL heat treat, see Table I

An advantage of using Hooke's Law to convert ϵ_A into S_A is that variation of fatigue data versus temperature is similar to the decrease of E (Modulus of Elasticity) with increasing temperature up to 700 K (800°F) for Inconel 718. Thus, the effect of temperature on fatigue curves is inherently accounted for by the use of Hooke's Law.^[A-5] At temperatures higher than 700 K (800°F), Hooke's Law should not be used, as creep considerations become important.^[A-5] Lower strain rates in the creep regime [at temperatures higher than 700 K (800°F)] could result in premature failures than would be indicated by the design fatigue curves, S_A versus N_f , obtained by using Hooke's Law. Above 700 K (800°F), it is better to give design fatigue curves as ϵ_A versus N_f (rather than fictitious S_A versus N_f) and for the user to make corrections for the effects of strain rate, biaxial loading, etc."^[A-5 and -6]

1.3 Mean Stress Correction

The fatigue data are based on a mean stress (S_m) equal to zero and the fatigue design curve must be corrected to account for S_m . Several methods for accommodating S_m are available. The Modified Goodman Equation has been selected as the method most useful for Alloy 718^[A-1]. The fatigue design curve correction used to account for mean stresses is based on the Modified Goodman Equation,^[A-7] as follows:

$$S^1 = S_A \left(\frac{F_{tu} - F_p}{F_{tu} - S_A} \right) \quad (\text{for } S_A < F_p) \quad (A-3)$$

or

$$S^1 = S_A \quad (\text{for } S_A \geq F_p) \quad (A-4)$$

where

S^1 = mean-stress-corrected value of S_A

S_A = stress amplitude

F_{tu} = ultimate tensile strength

F_p = proportional limit

The mean-stress-corrected values of S_A versus N_f for base metal and weld metal specimens tested at temperatures ranging from RT to 700 K (800°F) are listed in Table A-III.

1.4 Application of Safety Factors

In order to establish design fatigue curves it is necessary to apply a factor of two on stress or a factor of twenty on cycles, whichever is the more conservative at each point [A-4].

The results of applying the factor of two on stress or twenty on cycles are shown in Figures A-1 through A-3. The solid symbols denote the lower-valued points and a curve was drawn through them.

TABLE A-III

STRESS AMPLITUDE, S^1 , MPa (ksi) VERSUS CYCLES TO FAILURE (N_f) FOR ALLOY 718*

N_f	Base Metal						Weld Metal											
	Transverse Orientation						Transverse Orientation						Longitudinal Orientation					
	294 K		616 K		700 K		294 K		616 K		700 K		294 K		616 K		700 K	
	(70°F)		(650°F)		(800°F)		(70°F)		(650°F)		(800°F)		(70°F)		(650°F)		(800°F)	
	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
1×10^2	5378	780	4961	719	4579	664	4932	715	4748	689	4831	701	4262	618	4138	600	3365	488
2×10^2	3891	564	3592	521	3331	483	3599	522	3443	499	3487	506	3159	458	3050	442	2530	367
3×10^2	3255	472	3005	436	2795	405	3027	439	2884	418	2914	423	2683	389	2581	374	2168	315
5×10^2	2632	382	2432	353	2270	329	2466	358	2681	339	2352	341	2215	321	2119	307	1809	262
1×10^3	2015	292	1864	270	1752	254	1911	277	1796	261	1800	261	1746	253	1662	241	1449	210
5×10^3	1213	176	1122	163	1067	155	1172	170	1085	157	1074	156	1114	162	1046	152	952	138
1×10^4	1015	147	939	136	896	130	989	143	909	132	896	130	952	138	890	129	823	119
5×10^4	723	105	669	97	645	94	715	104	649	94	636	92	703	102	653	95	617	90
1×10^5	640	93	593	86	572	83	625	91	518	75	552	80	593	86	555	80	555	80
5×10^5	425	62	397	58	411	60	381	55	335	49	354	51	395	57	367	53	408	59
1×10^6	364	53	342	50	353	51	328	48	288	42	304	44	342	50	317	46	354	51
5×10^6	268	39	--	-	--	-	242	35	212	31	223	32	--	-	--	-	--	-
1×10^7	237	34	222	32	230	33	215	31	187	27	197	29	221	32	208	30	235	34
5×10^7	183	27	--	-	--	-	--	-	--	-	--	-	--	-	--	-	--	-
1×10^8	165	24	154	22	160	23	149	22	130	19	137	20	--	-	144	21	164	24

*INEL heat treat, see Table II

Fig. A-1 Plot of stress amplitude (S^1) versus cycles to failure (N_f) for Alloy 718 base-metal (Heat 6, given the INEL heat treat).

Fig. A-2 Plot of stress amplitude (S') versus cycles to failure (N_f) for transverse-oriented Alloy 718 weld metal (Heat C, given the INEL heat treat).

Fig. A-3 Plot of stress amplitude (S^1) versus cycles to failure (N_f) for longitudinal-oriented Alloy 718 weld metal (Heat C, given the INEL heat treat).

2. DESIGN FATIGUE CURVE FOR 811 K (1000°F)

In Section 1.2 the following guidelines were identified for use of tensile test data from specimens tested at 811 K (1000°F):

- (1) Hooke's Law should not be used
- (2) Curves should be developed for ϵ_A (where $\epsilon_A = 1/2 \Delta\epsilon_T$) versus N_f , the factor of two on strain or twenty on N_f applied, and the minimum points for the design curve selected. The user is then to make corrections for effects of strain rate, biaxial loading, etc. [A-5,-6]

In addition, Reference A-2 indicated that

"at temperatures higher than 700 K (800°F), no mean-stress correction needs to be applied to the design fatigue curves for Inconel 718 for constant-strain-rate fatigue tests. This is because of the gradual relaxation of mean-stress to zero. In the case of constant-load fatigue tests, the strain amplitude versus N_f (cycles to failure) follows the pattern of a creep curve. In creep regions, correction for mean-stress effects would have to be applied in the case of constant-load fatigue tests but not in the case of constant strain fatigue tests."

Therefore, on the basis of the above information, the design curve at 811 K (1000°F) for the base metal Alloy 718, given the INEL heat treatment, was developed by the following procedure:

- (1) The values of $\Delta\epsilon_T$ in Table A-I were used to obtain ϵ_A where $\epsilon_A = 1/2 \Delta\epsilon_T$
- (2) After application of a factor of two on strain (ϵ_A) or twenty on N_f the data were plotted
- (3) The design fatigue curve was drawn connecting the minimum points, see Figure A-4.

Fig. A-4 Plot of strain amplitude (ϵ_A) versus cycles to failure (N_f) for Alloy 718 base-metal at 811 K (1000°F) (Heat 6, given the INEL heat treat).

3. UTILIZATION OF EXPERIMENTALLY DETERMINED FATIGUE RESULTS

After completion of the analytical evaluation some experimental testing was conducted for comparison purposes. Comparisons of analytical and experimental results for weld specimens (Heat C) are shown in Figure A-5. The longitudinally oriented weld data points for RT and 616 K (650°F) showed that the experimental and analytical values were essentially the same. Therefore, there is no need to modify the design fatigue curves, in Figure A-3, for the longitudinally oriented weld metal.

Inspection of the transverse weld data points at 700 K (800°F) shows that the analytically determined values are greater than the experimental values for N_f varying from 10 to 2.5×10^5 cycles. Since this is a nonconservative condition the design fatigue curves identified in Figure A-2 will have to be modified. The results in Figure A-2 showed that the 616 K (650°F) and 700 K (800°F) values were the same and the general shape of the elevated temperature curve agreed with that of the RT curve. Therefore, the RT and elevated temperature curves will be modified to include the experimental values for N_f ranging from 10 to 2.5×10^5 cycles and will remain the same for N_f greater than 5×10^5 cycles.

The techniques used to modify the analytical results are as follows:

- (1) Determine the amount by which the analytical results ($\Delta\epsilon_T$) are to be reduced on the basis of experimental test data
- (2) Develop the stress amplitudes S_A and S^1
- (3) Apply safety factors and plot results as identified in Section A-1.4.

The experimental and analytical results obtained at 700 K (800°F) were compared as shown in Table A-IV.

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Fig. A-5 Plot of $\Delta \epsilon_T$ versus N_f for analytical and experimental fatigue results on weld metal Alloy 718. (Heat C given the INEL heat treat).

TABLE A-IV
COMPARISON OF ANALYTICAL AND EXPERIMENTAL
VALUES OF $\Delta\epsilon_T$ FOR TRANSVERSE-ORIENTED
WELD SPECIMENS AT 700 K (800°F)

<u>Cycles to Failure (N_f)</u>	$\Delta\epsilon_T$		<u>Ratio of Experimental to Analytical (%)</u>
	<u>Experimental</u>	<u>Analytical</u>	
1×10^5	59.5	62.5	95.2
5×10^4	65	71	91.5
1×10^4	86	100	86.0
5×10^3	100	120	83.3
1×10^3	160	195	82.1
5×10^2	215	260	82.1
3×10^2			82.1*
2×10^2			82.1*

*Since the ratio was 82.1 for $N_f = 5 \times 10^2$ and 1×10^3 it was assumed to be applicable for $N_f = 2 \times 10^2$ and 3×10^2 cycles.

The ratios in Table A-IV were used to modify the analytical results in Tables A-I, -II, and -III for transverse-oriented weld metal at RT, 616 K (650°F), and 700 K (800°F). Table A-V shows the modified values for the transverse-oriented weld metal. The results of applying the factor of two on stress or twenty on cycles are shown in Figure A-6. The solid symbols denote the lower of the points and curves were drawn for RT and elevated temperature. The curves for 616 K (650°F) and 700 K (800°F) were identical and fell on the same line.

The modified results in Figure A-6 were no lower than those values in Figure A-3. A possible explanation for the difference between the experimental and analytical data, from the transverse-oriented weld specimens, could be the heterogeneity associated with a transverse weld section. An examination of the failed specimens revealed that many of them failed in the base metal which resulted in a larger reduction of area but a smaller ultimate tensile strength than observed for weld metal failures. Therefore, the analytical results would be a composite of weld and base metal test results. The longitudinal-oriented weld specimens are much more homogeneous and there was good agreement between experimental and analytical results. It is assumed, on the basis of homogeneity, that the experimental and analytical results for the base metal specimens would also show reasonable agreement.

TABLE A-V

TOTAL STRAIN RANGE VERSUS MODIFIED STRESS AMPLITUDE VALUES FOR TRANSVERSE-ORIENTED ALLOY 718 WELD METAL^[c]

N_f	$\Delta\epsilon_T$			Stress Amplitude, S_A , MPa (ksi) ^[b]					
	RT	616 K (650°F)	700 K (800°F)	294 K (70°F)		616 K (650°F)		700 K (800°F)	
				MPa	(ksi)	MPa	(ksi)	MPa	(ksi)
2×10^2	0.029556	0.030942	0.032195	2955	429	2827	410	2863	415
3×10^2	0.024857	0.025917	0.026893	2485	360	2368	343	2392	347
5×10^2	0.020242	0.020991	0.021704	2025	294	2201	278	1931	280
1×10^3	0.015687	0.16144	0.016606	1569	227	1478	214	1478	214
5×10^3	0.009769	0.009886	0.010052	976	142	904	131	895	130
1×10^4	0.008507	0.008557	0.008664	851	123	782	114	771	112
5×10^4	0.006537	0.006507	0.006540	654	95	594	86	582	84
1×10^5 [a]	0.005043	0.006000	0.006016	605 (600)	88 (87)	548 (490)	80 (71)	535 (524)	78 (76)

[a] For $N_f > 1 \times 10^5$ use S^1 from Table A-III.[b] $S_A = S^1$ down to the values in parentheses at 1×10^5 cycles. The values in parentheses are for S^1 .

[c] Heat C given the INEL heat treat.

Fig. A-6 Plot of corrected amplitude (S^1) versus cycles to failure (N_f) for transverse-oriented Alloy 718 weld metal (Heat 6, given the INEL heat treat).

4. UTILIZATION OF DATA FROM OTHER HEATS OF ALLOY 718

In an attempt to conform with the requirements of collecting data from more than one heat of Alloy 718 the results in Table X and Reference A-9 were used to compare with those in Table A-I. Figure A-7 was developed for making the comparisons somewhat easier. A summary of the comparisons are as follows:

- (1) There was good agreement between the experimentally and analytically determined fatigue values for Heat 3 tested at 700 K (800°F)
- (2) The analytically determined fatigue values for Heat 3 at RT and 700 K (800°F) are essentially the same
- (3) The analytically determined fatigue values for Heat 6 at RT, 700 K (800°F), and 811 K (1000°F) are essentially the same
- (4) The analytically determined fatigue values for Heat 3 have a lower $\Delta\epsilon_T$ for the same N_f than observed for Heat 6. This was observed for fatigue values at RT, 700 K (800°F), and 811 K (1000°F).

The above comparisons suggest that the fatigue design curves for Heat 6 in Figures A-1 and A-4 be reduced to take into consideration heat-to-heat variabilities. There were no additional data from longitudinally oriented weld metal specimens, but the same modifications identified for Alloy 718 base metal will be used for weld metal. The ratios in Table A-VI were used to modify the analytical results in Tables A-I, -II, and -III for transverse-oriented base metal and longitudinally oriented weld metal. Table A-VII shows the modified values of S_A for transverse-oriented base metal and longitudinally oriented weld metal.

As the modifications for the fatigue results, obtained at temperatures ranging from RT to 700 K (800°F), took place at stress levels greater than the proportional limit there was no need to take into

consideration the mean stress correction. Therefore, the values of S_A in Table A-VII, plus S^1 in Table A-III for N_f greater than 5×10^3 cycles, were used to develop the design fatigue curves in Figure A-8 through A-10.

5. REFERENCES

- A-1. Internal Report.
- A-2. Internal Report.
- A-3. G. R. Halford and S. S. Monson, Applications of a Method of Estimating High Temperature Low Cycle Fatigue Behavior of Materials, NASA TMX-52357 (October 1967).
- A-4. "Criteria of the ASME Boiler and Pressure Vessel Code for Design by Analysis," in Sections III and VIII, Division 2, of the ASME Boiler and Pressure Vessel Code, New York: The American Society of Mechanical Engineers, 1969.
- A-5. Private Communication.
- A-6. Private Communication.
- A-7. B. F. Langer, "Design of Pressure Vessels for Low-Cycle Fatigue," Journal of Basic Engineering (September 1962) p 389.
- A-8. Private Communication.
- A-9. Mechanical Properties Test Data for Structural Materials Quarterly Progress Report for Period Ending January 31, 1976, ORNL-5112 (1976).

Fig. A-7 Plot of $\Delta\epsilon_T$ versus N_f for analytical and experimental fatigue results on base-metal Alloy 718 (INEL heat treat).

TABLE A-VI

COMPARISON OF ANALYTICAL VALUES OF $\Delta\epsilon_T$ FOR ALLOY 718 BASE-METAL GIVEN THE INEL HEAT TREAT

Cycles to Failure (N_f)	$\Delta\epsilon_T$		Ratio of $\Delta\epsilon_T$ for Heat 6 to Heat 3		
	Heat 3		Heat 6		
	RT to 700 K (800°F)	811 K (1000°F)	RT to 811 K (1000°F)	RT to 700 K (800°F)	811 K (1000°F)
1×10^5	0.00630	0.00500	0.00630	1.00	0.79
5×10^4	0.00715	0.00580	0.00715	1.00	0.81
1×10^4	0.0100	0.00835	0.0100	1.00	0.84
5×10^3	0.0117	0.0100	0.0120	0.98	0.83
1×10^3	0.0181	0.0161	0.0200	0.90	0.80
5×10^2	0.0227	0.0205	0.0253	0.90	0.81
3×10^2	0.0320	0.0297	0.0366	0.87	0.81
2×10^2	0.0445	0.0420	0.0520	0.86	0.81

TABLE A-VII

MODIFIED STRESS AMPLITUDE, S_A , MPa (ksi) VERSUS CYCLES TO FAILURE, N_f , FOR ALLOY 718

N_f	Base Metal Transverse Orientation							Weld Metal Longitudinal Orientation					
	294 K (70°F)		616 K (650°F)		700 K (800°F)		811 K* 1000°F (ϵ_A)	294 K (70°F)		616 K (650°F)		700 K (800°F)	
	MPa	(ksi)	MPa	(ksi)	MPa	(ksi)		MPa	(ksi)	MPa	(ksi)	MPa	(ksi)
2×10^2	3347	(485)	3091	(448)	2864	(415)	0.01531	2719	(394)	2622	(380)	2180	(316)
3×10^2	2836	(411)	2615	(379)	2429	(352)	0.012864	2332	(338)	2243	(325)	1891	(274)
5×10^2	2374	(344)	2194	(318)	2042	(296)	0.010461	1994	(289)	1904	(276)	1628	(236)
1×10^3	1815	(263)	1677	(243)	1530	(229)	0.0080907	1573	(228)	1497	(217)	1304	(189)
5×10^3	1187	(172)	1104	(160)	1049	(152)	0.004944	1097	(159)	1028	(149)	932	(135)
1×10^4	Same as shown in Table A-II						0.004164	Same as shown in Table A-II					
5×10^4	" " "						0.002999	" " "					
1×10^5	" " "						0.002663	" " "					
5×10^5	" " "						0.002087	" " "					
1×10^6	" " "						0.001896	" " "					
5×10^6	" " "						0.001535	" " "					
1×10^7	" " "						0.001407	" " "					
5×10^7	" " "						----	" " "					
1×10^8	" " "						----	" " "					

*For test temperature exceeding 700 K (800°F) the stress amplitude, S_A , is not determined. ϵ_A is used instead of S_A where $\epsilon_A = 1/2 \Delta\epsilon_T$.

Fig. A-8 Plot of stress amplitude (S^1) versus cycles to failure (N_f) for Alloy 718 base-metal (Heats 3 and 6 given the INEL Heat treat).

Fig. A-9 Plot of strain amplitude (ϵ_A) versus cycles to failure (N_f) for Alloy 718 base-metal at 811 K (1000°F) (Heats 3 and 6, given the INEL heat treat).

Fig. A-10 Plot of stress amplitude (S^1) versus cycles to failure (N_f) for longitudinal-oriented Alloy 718 weld metal (Heat C given the INEL heat treat).

APPENDIX B
COMPARISON OF CHARPY IMPACT TEST RESULTS

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APPENDIX B

COMPARISON OF CHARPY IMPACT TEST RESULTS

The Charpy specimen, because of its small size, is frequently used to estimate (qualitatively) the toughness of various sections in a weld joint, effects of heat-treat variation, heat-to-heat variation, etc. Charpy specimens were used for conducting Charpy V-notch (CVN) and instrumented precracked (PCI) testing under impact loading. The PCI results were used to estimate the dynamic fracture toughness K_{Id} . More description was given in Section IV of the report. This appendix will discuss some of the observations useful to the utilization of Alloy 718 but not required for the 0.64-cm (1/4-in.) thick IPT. This appendix will discuss the effect of the INEL heat treat as opposed to a standard thermal cycle, heat-to-heat variability, notch acuity (sharpness) effects, and the need for postweld thermal treatment of weldments, and will identify a potential correlation between CVN test results and K_{Id} .

1. EFFECT OF HEAT TREAT CYCLE

Some of the test results in Tables V and VI of the main text were used to estimate the effects of the INEL heat treat as opposed to a standard heat treat (see Table II of the main text for actual heat treat). These data are summarized in Table B-I for Heat 6 base metal. From the data, it is apparent that the INEL heat treat resulted in an approximate 50% increase in impact energy absorption for the CVN specimen and an increase in K_{Id} of about 25%. In addition to improving the impact properties of Alloy 718 base metal, as shown in Table B-I, the INEL heat treatment has beneficial effects on welds in this material. Two results have been observed:

- (1) The 2000°F solution anneal enhances the ductility of weldments as shown in Figure B-1. This increased ductility is assumed to indicate an increase in fracture toughness

TABLE B-I

EFFECT OF HEAT TREAT ON ALLOY 718 (HEAT 6 BASE-METAL)

Specimen Configuration	Heat Treat*	Test Temperature		Dial Impact Energy		Dynamic Fracture Toughness (K_{Id})	
		K	(°F)	J	(ft lb)	(MPa-m ^{1/2})	(ksi-in. ^{1/2})
CVN	INEL	RT	RT	57	42	--	--
CVN	STD	RT	RT	38	28	--	--
CVN	INEL	616	(650)	64	47	--	--
CVN	STD	616	(650)	46	34	--	--
PCI	INEL	RT	RT	35	26	239	217
PCI	STD	RT	RT	19	14	196	178
PCI	INEL	616	(650)	34	25	224	204
PCI	STD	616	(650)	24	18	175	159

*See Table II where INEL and Standard refer to specific thermal cycles.

- (a) Specimen No. 3: Solution Annealed at 1900°F, Air Cooled, and Aged.
- (b) Specimen No. 4: Solution Annealed at 2000°F, Air Cooled, Aged, and Bent to 5t Radius.
- (c) Specimen No. 5: Solution Annealed at 2000°F, Air Cooled, Aged, and Bent to 3t Radius.

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Fig. B-1 Side bend specimens illustrating the effect of solution anneal temperature upon Alloy 718 weld ductility.

- (2) The slow cooling rate from the solution temperature (2000°F) reduces thermal stresses [B-1].

2. HEAT-TO-HEAT VARIATION FOR INEL HEAT TREAT

CVN and PCI data from Tables V and VI were used to show what might be expected from the standpoint of heat-to-heat variabilities (see Table B-II). Since the data are few, the RT data should be used as a starting point to establish the potential variability attributable to heat-to-heat differences.

With the exception of Heat A weld wire, the dynamic fracture toughness values are good. Heat A weld wire will be discussed in more detail in Section B-5.

TABLE B-II
HEAT-TO-HEAT VARIATION FOR ALLOY 718 (INEL HEAT TREAT)^[a]

<u>Specimen Type</u>	<u>Material Identification</u>	<u>Dial Impact Energy</u>		<u>Dynamic Fracture Toughness (K_{Id})</u>	
		J	(ft lb)	(MPa-m ^{1/2})	(ksi-in. ^{1/2})
CVN	Heat 6, base metal	57	42	--	--
	Heat 3, base metal	45	33.5	--	--
PCI	Heat 6, base metal		--	239	217
	Heat 3, base metal		--	218	198
	Heat C, weld metal		--	173	157
	Heat A, weld wire (HT 60C 7 E)		--	95	86 ^[b]
	Heat 87 [COEK1]		--	190	173 ^[b]
^[a] RT Test Results.					
^[b] See Reference B-2.					

3. CORRELATION BETWEEN CVN AND K_{Id}

The correlation between CVN and K_{Id} is often used when trying to estimate the fracture toughness of components for which only CVN data were collected. Figure B-2 is a plot of CVN versus K_{Id} for Alloy 718, and sufficient data are not available for a useful correlation. Additional data, when obtained, should be added to Figure B-2 so that a possible correlation may be developed.

Fig. B-2 Plot of Dynamic Fracture Toughness (K_{ID}) versus Charpy Impact Value for Alloy 718.

4. NOTCH ACUITY SENSITIVITY

Notch acuity (sharpness) sensitivity, as discussed here, will compare the instrumented test results obtained from the 0.025-cm (0.010-in.) radius and from the infinitely sharp fatigue crack at the root of the notch. The notch acuity effects can be estimated (for Heat 6) from Tables V and VI of the main text. The pertinent results are shown in Table B-III.

Since the above results are based on energy normalized to unflawed area, the differences in values will be due to notch acuity. This indicates that the reason the PCI results were 80% of the CVN values was due to the difference in notch root radius. This may be more simply explained by the fact that the CVN specimen requires some energy to initiate the infinitely sharp crack from the 0.025-cm (0.010-in.) root radius.

TABLE B-III
COMPARISON BETWEEN K_{Id} VALUES MEASURED BY CVN AND PCI TECHNIQUES
(ALLOY 718, HEAT 6 GIVEN THE INEL HEAT TREAT)

Test Temperature		Dynamic Fracture Toughness (K_{Id})				Ratio of PCI to CVN
		CVN		PCI		
		MPa-m ^{1/2}	(ksi-in. ^{1/2})	MPa-m ^{1/2}	(ksi-in. ^{1/2})	
K	(°F)					
RT	RT	300	(273)	239	(217)	0.79
616	(650)	274	(249)	226	(205)	0.82
700	(800)	295	(268)	238	(216)	0.81
811	(1000)	295	(268)	227	(206)	0.77

5. AS-WELDED WELD FRACTURE TOUGHNESS

Once in a while repair welds are required where it is very difficult to give a postweld thermal cycle. This section identifies data taken from two separate studies in which the results varied appreciably. The test results of interest are listed in Table B-IV for transverse-oriented weld specimens.

There is an appreciable difference in K_{Id} at RT between Heat A^[B-2] at $68.6 \text{ MPa-m}^{1/2}$ ($62.4 \text{ ksi-in.}^{1/2}$) versus Heat C at $197.7 \text{ MPa-m}^{1/2}$ ($179.7 \text{ ksi-in.}^{1/2}$). The chemistries of both heats are shown in Table B-V.

From the chemistry data, one cannot easily identify any element(s) which might be blamed for the difference in test results, although the possibility exists that trace elements might be the cause. The next step is to examine the welding procedures. The weld procedures are as follows:

- (1) Heat C - The plate of Alloy 718 was welded by the manual gas-tungsten-arc process utilizing the practices of ANC welding procedure I-20. A groove 0.8-cm (5/16-in.) deep, with 60-degree angle and 0.2-cm (1/16-in.) root radius was machined and filled with two weld passes. The opposite side was then machined with the same groove geometry to a depth of 0.6-cm (1/4-in.) and filled with three weld passes. Two final passes were then made on the first side and one final pass on the second side. Filler wire was 0.11-cm (0.045-in.) diameter Heat C wound in five strands. Amperage utilized was 140 to 150.
- (2) Heat A - See Table B-VI.

The weld procedures do not positively identify any reasonable explanation for the difference in K_{Id} values for the two sets of data.

TABLE B-IV
K_{Id} VALUES FOR AS-WELDED ALLOY 718

<u>Weld Wire Identification</u>	<u>Test Temperature</u>		<u>Dynamic Fracture Toughness (K_{Id})</u>	
	K	(°F)	MPa-m ^{1/2}	(ksi-in. ^{1/2})
Heat C	RT	RT	206.3	(187.5)
Heat C	RT	RT	201.6	(183.3)
Heat C	RT	RT	183.9	(167.2)
Heat C	RT	RT	198.9	(180.8)
Heat C	616	(650)	246.0	(223.6)
Heat C	616	(650)	202.7	(184.3)
Heat A	RT	RT	60.5	(55.0)
Heat A	RT	RT	62.5	(56.8)
Heat A	RT	RT	82.9	(75.4)
Heat A	616	(650)	154.3	(140.3)
Heat A	616	(650)	217.1	(197.4)
Heat A	616	(650)	168.1	(152.8)

TABLE B-V
CHEMICAL ANALYSIS FOR TWO HEATS OF ALLOY 718

<u>Elements</u>	<u>Heat A (60C7C)</u>	<u>Heat C (52B0E)</u>
Cr	18.04	17.91
Fe	17.97	17.60
C	0.04	0.04
Si	0.18	0.19
Co	0.03	0.04
Ni	53.84	54.58
Mn	0.09	0.04
Cb	5.11	5.07
Ta	0.01	0.01
Mo	3.00	2.96
P	0.01	0.011
S	0.007	0.007
Al	0.55	0.49
Ti	1.01	0.99
B	0.0042	0.0031
Cu	0.10	0.05

TABLE B-VI

WELDING INSTRUCTION SHEET FOR INEL HEAT TREATED
ALLOY 718 MOCKUP AND IMPACT TEST PIECES

JOB IDENTITY: PBF Acoustic Filter Repair Test

NO. 070

WELD JOINT/APPLICABLE PROCEDURE		GTAW Process					
PASS NUMBER		All					
POSITION		1G					
TORCH ANGLE (Leading)		70°-90°					
ARC INITIATION		HF					
WELDING ROD/WIRE (TYPE)		Inco 718 (AMS 5832)					
FILLER METAL DIAMETER		1/16"					
CURRENT (AMPS)		120-130					
VOLTS (ARC LENGTH)		~18V					
ELECTRODE POLARITY		DCSP					
TORCH GAS CFH		30 CFH 75% Helium/25% argon					
PURGE GAS CFH		N/A					
INTERPASS TEMP.		250° max.					
CUP SIZE (ORFICE DIA.)		3/8"-1/2"					
ELECTRODE EXTENSION		1/2" max.					
TUNGSTEN DIAMETER		3/32"					
TRAVEL SPEED IN MIN.		N/A					
AUTOMATIC/MANUAL		Manual					
HEAT MEASUREMENT (METHOD)		T.C.					
FIXTURING		N/A					
RESTRAINTS		None					
TORCH SIZE		200 amp					
INSERT SIZE		N/A					
INSERT (TYPE)		N/A					
CONTACT TUBE TO WORK DISTANCE		N/A					
PREHEAT TEMPERATURE		>60°F					
POST HEAT TEMPERATURE		None					
RADIOGRAPHY		Steps 3, 7, 9, & 11 COAS 17-1-2					
DYE PENETRANT		Steps 2, 6, 7, 9, & 11 COAS 17-3-2					
MAG. PARTICLE		N/A					
VISUAL		At completion of steps 6, 8, & 10 COAS 17-17					

The procedure for Heat A used a stringer bead technique which should result in a finer grain size than the procedure for Heat C. To establish the reason(s) for obtaining low fracture toughness welds (in the as-welded condition) would require additional study. Therefore, in order to eliminate the possibility of a brittle weld joint it is recommended that all welds be given the INEL heat treat.

6. REFERENCES

B-1. G. R. Smolik, Analysis of Failures Which Occurred During Heat Treatments of the Inconel 718 PBF Acoustic Filters, ANCR-1178 (October 1974).

B-2. Internal Report.

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