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Effect of High-Pressure Oxygen on the Mechanical Properties of Alloys

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EFFECT OF HIGH-PRESSURE OXYGEN ON THE MECHANICAL PROPERTIES OF ALLOYS

Authors

Fred R. Schwartzberg
John A. Shepic

MARTIN MARIETTA CORPORATION
P.O. Box 179
Denver, Colorado 80201

FOREWORD

The work described in this report was performed by Martin Marietta Corporation under Contract NAS8-31956 for the Marshall Space Flight Center (MSFC) of the National Aeronautics and Space Administration. Mr. W. B. MacPherson acted as Program Technical Monitor at MSFC; at Martin Marietta, Mr. F. R. Schwartzberg acted as Program Manager and Mr. John A. Shepic was Principal Investigator.

This report is submitted in accordance with the reports requirements list, Item II-B: Final Report, of the Operations Directive for Contract NAS8-31956 and covers work performed during the period of May 17, 1976 through February 17, 1977.

ABSTRACT

An experimental program was performed to determine the effect of 30-day high-pressure [69 MN/m^2 (10,000 psi)] oxygen exposure on the unnotched and notched tensile properties of stressed $\left(80\% \text{ of } \sigma_{ys}\right)$ and unstressed specimens of wrought 316 stainless steel, Incoloy 903, Monel K-500, and cast specimens of Inconel 718. As a control, tests were also performed in atmospheric pressure air and 69 MN/m^2 (10,000 psi) nitrogen.

Data showed that oxygen did not alter the tensile properties of any of the alloys studied.

CONTENTS

I. INTRODUCTION

The objective of this program was to determine the effect of high pressure oxygen exposure on the mechanical properties of four materials used in the Space Shuttle main engine. These materials are:

1) 316L stainless steel;

2) Incoloy 903;

3) Monel K-500;

4) Inconel 718.

The effect of environment on the behavior of metals continues to be a concern in the prediction of performance for service conditions. Numerous materials considered to be immune from certain environmental influences have been involved in premature and often catastrophic failures. A typical example is the titanium-methanol compatibility problem. Titanium was reputed to be the "wonder" metal. Early claims that it had excellent corrosion resistance qualities have now been tarnished by the hot salt corrosion failures and its low threshold in methanol. With each succeeding failure, the technical community continues to reevaluate its ability to predict materials compatibility based on factors such as similitude, general description, engineering judgment, and the like. A greater reliance is being placed on good, simulated service testing.

During the past decade, much research has been conducted in the area of "environmentally induced embrittlement." This descriptor is used to differentiate from embrittlement that results from the deleterious species inherent in the metal, such as hydrogen in solid solution, that can result in delayed failure. A significant portion of the environmentally induced embrittlement data obtained during recent years has dealt with the effect of hydrogen. The increased uses of hydrogen at high pressures and temperatures have resulted in the embrittlement in materials previously thought to be immune from embrittlement. A significant amount of data is currently available to characterize the effect of hydrogen on the mechanical propert behavior of metals. Data for gaseous oxygen, particularly at high pressures, are relatively scarce.

The effects of oxygen and nitrogen are anticipated to be somewhat different than those described above for hydrogen. Because of greater atomic size, nitrogen and oxygen effects are generally manifested by a diffusion-controlled chemical reaction.

Tiffany, et al.* studied the effect of high pressure gaseous oxygen on the crack growth threshold of Inconel 718 and found no effect at 1000 psi. No attempts were made to evaluate tensile behavior or the effect of higher pressure. A similar program was performed by Bixler and Engstron† on D6 steel at 3000 psi gaseous oxygen pressure. No effect on threshold was observed.

An effect of high pressure oxygen on mechanical properties is more likely to be manifested as a change in the crack growth threshold. However, preliminary investigation to determine the effect on tensile properties is a low cost, simple approach to assessing the magnitude of a potential problem.

The specific tests performed in this work consisted of determining the unnotched and notched tensile properties in air at atmospheric pressure and room temperature of the four subject alloys after stressed and unstressed exposure to the following environments and conditions:

Environment	Temperature	Pressure
Air	Ambient	Atmospheric
Oxygen	Ambient	69 MN/m^2 (10,000 psi)
Nitrogen	Ambient	69 MN/m^2 (10,000 psi)

This report gives the findings of the test program.

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*C. F. Tiffany, J. N. Masters, and W. D. Bixler: *Investigation of Crack Growth Threshold of Inconel 718 Exposed to High Pressure Oxygen*. NASA CR-108485, August 1970.

†W. D. Bixler and W. L. Engstron: *Crack Growth of D6 Steel in Air and High Pressure Oxygen*. NASA CR-114860, July 1971.

II. MATERIAL AND PROCESSING

Alloys 316L, Incoloy 903, and Monel K-500 were procured as 1.27-cm (½ in.) diameter wrought bar stock. The 316L was purchased in the annealed condition and was reannealed by Martin Marietta. The 903 and K-500 alloys were procured in the solution treated condition and then precipitation hardened by Martin Marietta.

The Inconel 718 was evaluated in the cast form in order to simulate application in the Shuttle engine. Unnotched specimens were procured as standard cast ICI 6.4-mm (¼ in.) diameter test bars. The material for preparation of the notched specimens was obtained as 1.27-cm (½ in.) diameter by 15-cm (6 in.) long cast rods. The 718 material was purchased from Teledyne Cast Products, El Monte Division, in the fully heat treated condition in accordance with specification RBO 170-155.

Heat number identification, source, and chemical composition data for the four alloys is given in Table II-1.

Data for thermal processing is given in Table II-2.

Table II-1 Certification and Composition Data

Alloy	Heat Number	Mill Source	Composition, Weight Percent
316L	4840	Jones and Laughlin	17.28 Cr, 13.03 Ni, 2.07 Mo, 0.02 C, 1.29 Mn, 0.22 Si, Balance Fe
Incoloy 903	HH24A80Y	Huntington Alloys	41.62 Fe, 37.62 Ni, 15.29 Co, 2.8 Cb + Ta, 1.4 Ti, 0.03 C, 0.15 Mn, 0.07 Si
Monel K-500	M14A8K	Huntington Alloys	65.08 Ni, 29.29 Cu, 3.13 Aℓ, 0.48 Ti, 1.08 Fe, 0.16 C, 0.73 Mn, 0.03 Si
Inconel 718	CV-37	Certified Alloy	53.16 Ni, 18.77 Cr, 3.16 Mo, 5.41 Cb + Ta, 0.97 Ti, 0.70 Aℓ, 0.12 Co, 0.04 C, 0.07 Mn, 0.2 Si, Balance Fe

Table II-2 Thermal Processing Data

Alloy	Thermal Process
316L	Anneal 1339K (1950°F), 30 min, Water Quench
Incoloy 903	Solution Treat 1227K (1750°F), 1 hr, Air Cool
	Age 922K (1325°F), 8 hr, Furnace Cool at 56K (100°F)/hr to 894K (1150°F), Hold 8 hr, Air Cool
Monel K-500	Solution Treat 1255K (1800°F), 30 min Water Quench
	Age 866K (1100°F) 16 hr, Furnace Cool at 14K (25°F)/hr to 755K (900°F), Air Cool
Inconel 718	Homogenize 1408K (2075°F) 10 hr, Cool to 1311K (1900°F) and Solution Treat for 2 hr, Cool
	Age at 1005K (1350°F), 8 hr, Furnace Cool at 56K (100°F)/hr to 894K (1150°F), Hold for 8 hr, Air Cool

III. EXPERIMENTAL PROCEDURES

This chapter describes the specimen design, specimen stressing scheme, high-pressure environmental system, and test procedure used in conduct of the work performed.

A. SPECIMEN DESIGN

Unnotched and notched tensile specimens were designed in accordance with ASTM Specification E8 requirements. The unnotched specimen, shown in Figure III-1 contains a 6.4-mm (¼ in.) gage diameter and 2.54-cm (1 in.) gage length. The notched specimen utilizes a standard 60 deg vee-notch, 50% notched area, to give an elastic stress concentration factor $\left(K_t\right)$ of 8 (Figure III-2).

B. SPECIMEN STRESSING

A simple scheme for stressing specimens in high-pressure oxygen and nitrogen was used. Triplicate specimens of the same alloy and specimen type were joined by threaded couplers and loaded into a simple stressing cylinder (Figure III-3) consisting of a cylindrical body, end plates with a centering shoulder, and loading nuts. Figure III-4 shows the stressing cylinder installed in a testing machine.

One specimen of each set of three was strain gaged with a bonded resistance gage. The specimen was loaded in a testing machine to determine the strain level at the desired force. The cylinder was then assembled and the train reloaded to the desired level. The loading nuts were then tightened as the machine was permitted to slowly unload. Tightening of the nuts was performed in a manner that did not permit the strain to exceed the desired level during machine unloading. After loading, the strain gage leads were pulled off the specimen through the pressure equalizing hole in the cylindrical body.

All specimens were stressed to a nominal 80% of the unnotched yield strength of the respective alloy. Actual data, Table III-1, show that the stress levels were in good agreement with the desired values.

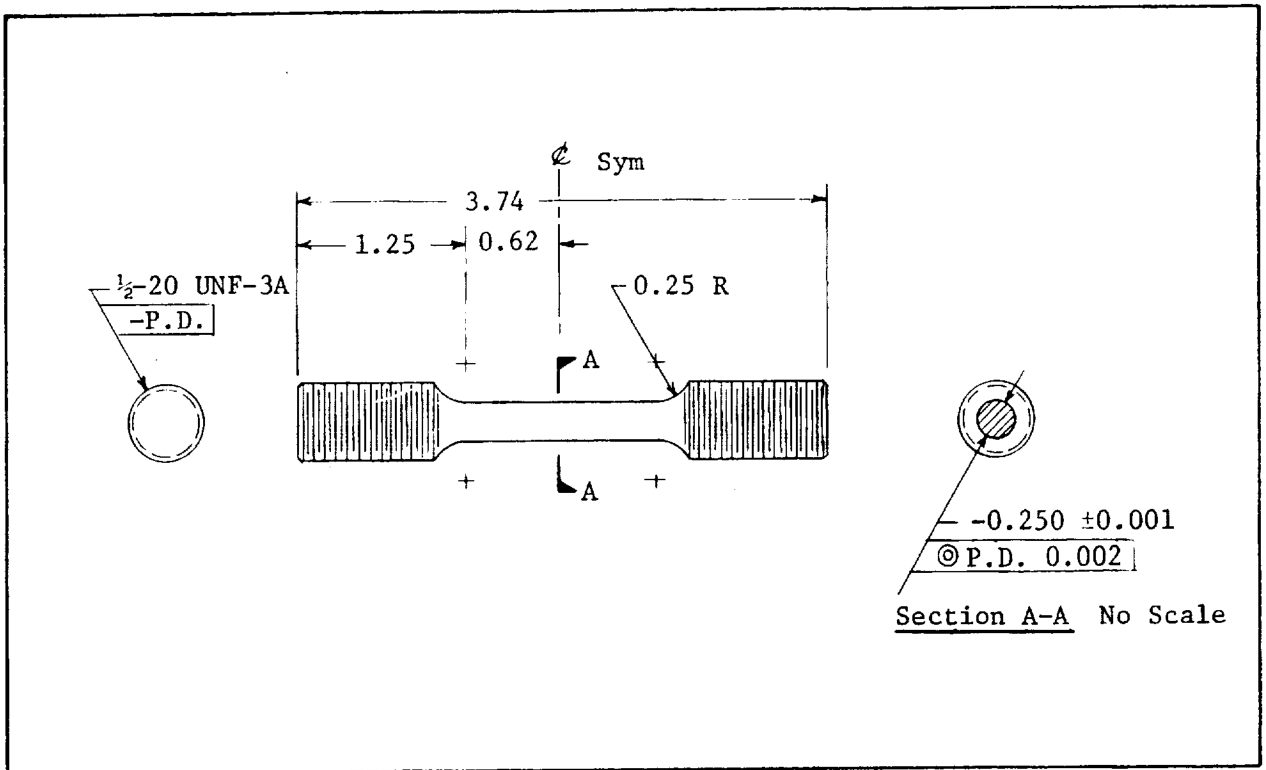

Figure III-1 Specifications for Unnotched Tensile Specimen

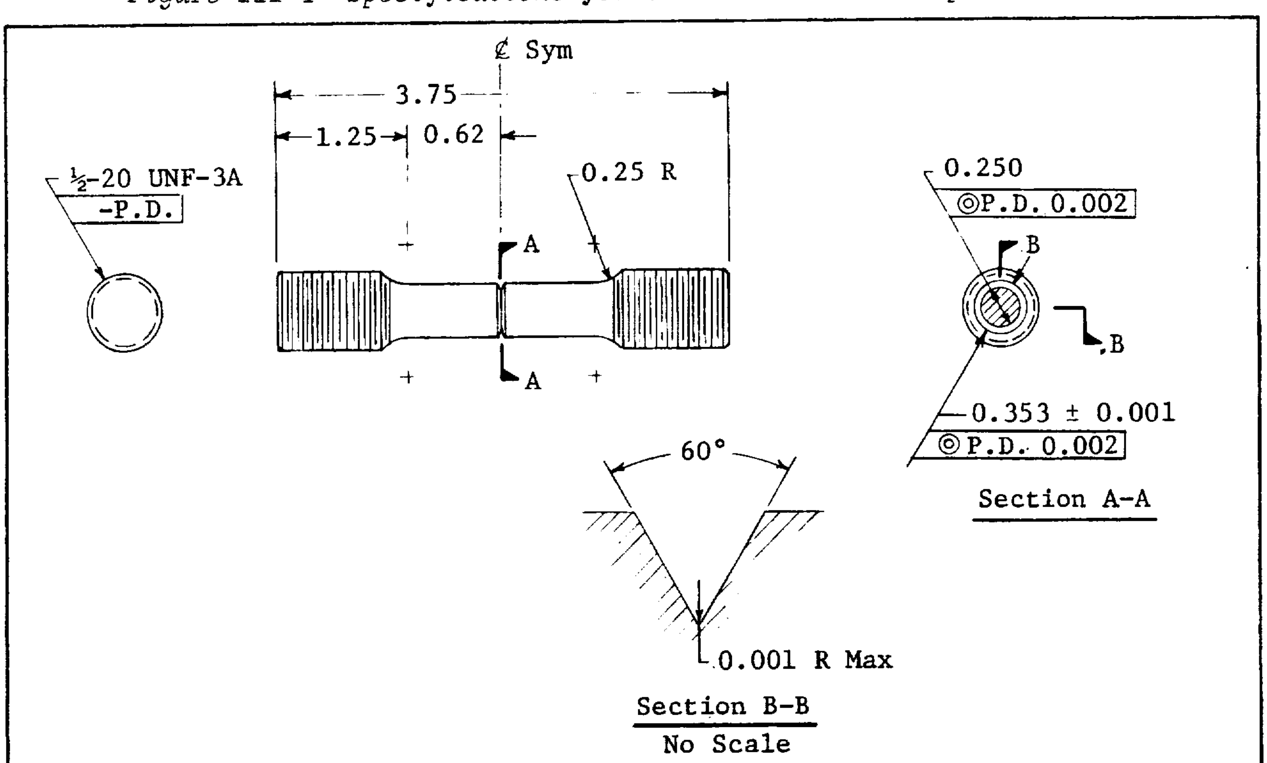

Figure III-2 Specifications for Notched Tensile Specimen

Figure III-3
Disassembled Stressing Cylinder

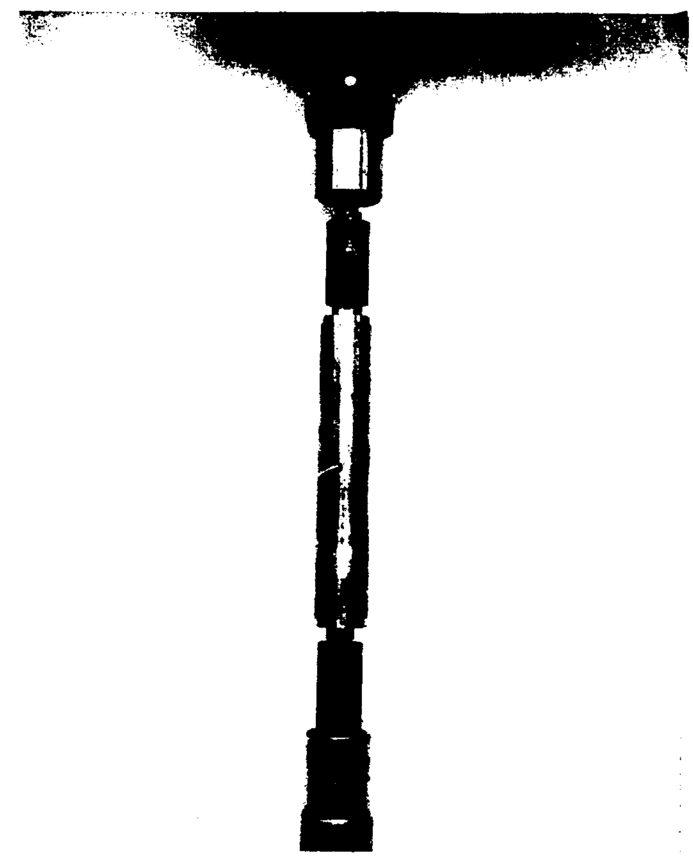

Figure III-4
Stressing Cylinder Installed in Testing Machine

Table III-1 Loading Data for Stressing Cylinders

Alloy	Specimen Type	Stress Level (% σ_{ys}) for Indicated Environment	
		Oxygen	Nitrogen
316L	Unnotched	77.1	81.2
	Notched	80.0	80.0
Incoloy 903	Unnotched	79.2	80.4
	Notched	77.4	73.9
Monel K-500	Unnotched	80.0	78.2
	Notched	76.6	78.1
Inconel 718	Unnotched	80.7	82.8
	Notched	77.9	81.0

Specimens for evaluation in atmospheric pressure air were deadweight loaded as triplicate specimens joined by threaded couplers in Satec creep racks. Eight racks were used for the 30-day exposure period.

C. HIGH-PRESSURE ENVIRONMENTAL SYSTEM

The high pressure oxygen system was designed for simplicity, safety, and a high degree of cleanliness. Because of the safety hazards associated with pumping oxygen to 69 MN/m^2 (10,000 psi), we elected to use a liquification-vaporization pressure intensification approach. Basically, we charged a pressure vessel submerged in a liquid nitrogen bath with gaseous oxygen. The oxygen liquified. We then pressurized the liquid oxygen, drained the LN_2 bath and permitted the LO_2 to vaporize and provide pressurization for the test chamber. Figure III-5 is a schematic diagram of the system. All of the high-pressure apparatus was contained in a high-pressure test cell. As shown by the diagram, the valves between the LO_2 supply/pressurization system and the specimen vessel and oxygen supply bottles are remotely operated. The pressure gage was observed through a safety window.

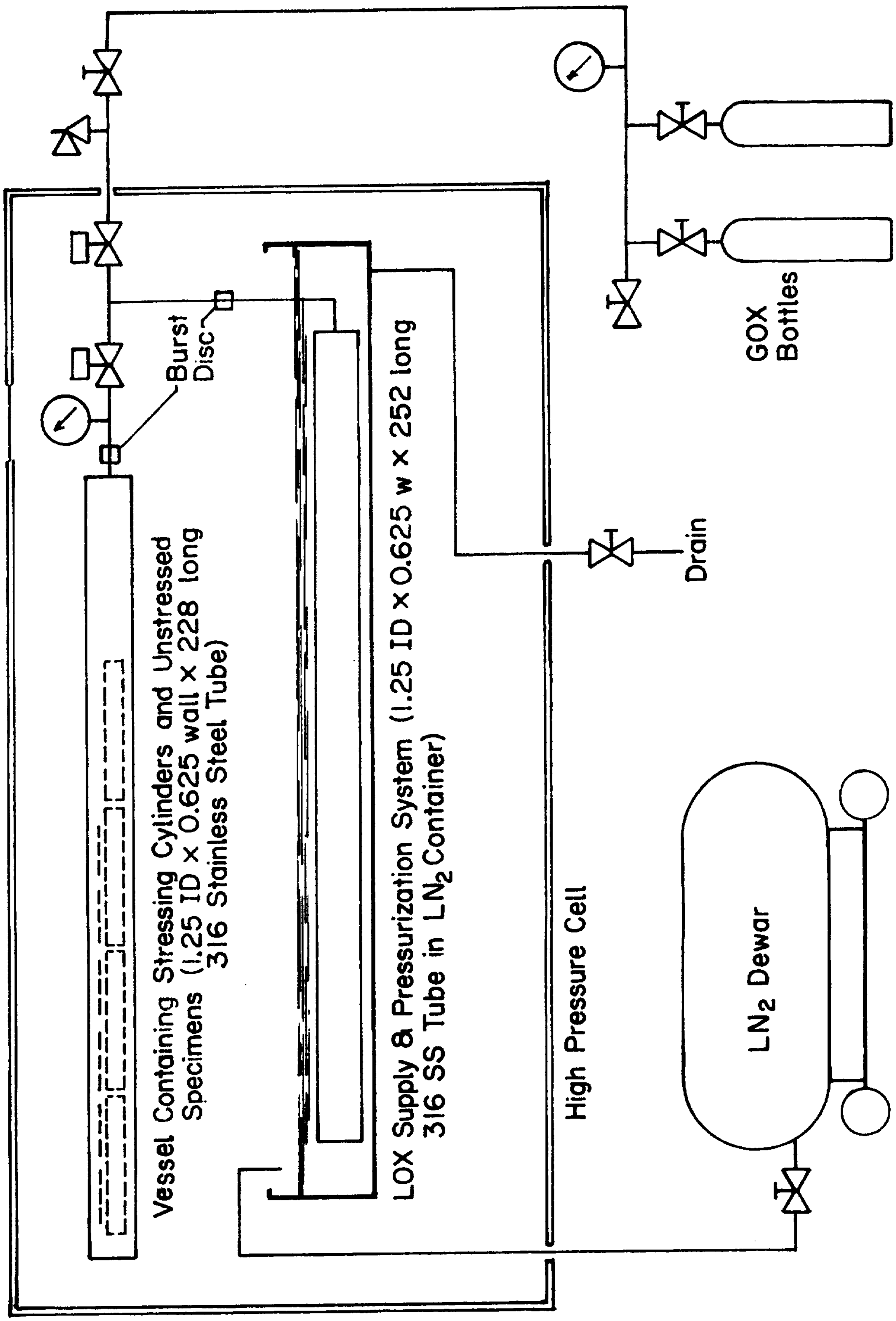

Figure III-5 Schematic Diagram for High Pressure Oxygen System

Figure III-5

The specimen and supply vessels were fabricated from 6.4 cm (2.5 in.) O.D. by 1.59 cm (5/8 in.) wall 304 stainless steel pipe. To avoid nonmetallic seals and gaskets, the pressure vessels were fabricated by welding stainless steel plugs in each end. One end of each vessel contained a welded-in pressure tubing connector. Each vessel was radiographically inspected to assure conformity to ASME Code UW51 and pressure tested to 103 MN/m^2 (15,000 psi). The specimen vessel was then cut near the end to permit loading of the specimens. After loading the vessel was welded shut and the new weld joint radiographically inspected.

All system components, test specimens, and stressing cylinders were GO_2-cleaned before assembly.

For evaluation of the effects of nitrogen, the testing chamber was loaded, sealed, and radiographed as described above. Pressurization was obtained by using a 110 MN/m^2 (16,000 psi) pump.

D. TEST PROCEDURE

The procedure used for the 30 day 69 MN/m^2 (10,000 psi) oxygen exposure is summarized below:

1) Test specimens and stressing cylinder components were cleaned and subsequently handled with white gloves;

2) Specimens for stressed testing were loaded into stressing cylinders;

3) Cylinders were loaded to desired levels;

4) Cylinders were then recleaned, placed in poly bags and delivered to the Propulsion Engineering Laboratory;

5) Specimens and cylinders were placed in a test container, unit was welded closed, radiographed and taken to high-pressure test cell;

6) Following assembly of test chamber in cell and verification of system integrity, test was initiated;

7) Pressure in the test chamber was monitored daily for the 30-day test period;

8) Following the exposure period, the end of the chamber was cut off, and specimens were removed and placed in poly bags ready for testing.

A similar procedure was used for the nitrogen exposure.

The oxygen specimens were delivered to the Mechanical Property Laboratory and tested within an 8-hour period following removal from the test chamber. Cylinders were unloaded and unnotched specimens gage marked for elongation measurements. All specimens had been measured for cross sectional area prior to exposure.

Unnotched specimens were evaluated with a mechanical extensometer to provide stress versus strain behavior into the plastic range. Notched specimens were tested to failure giving only the failing load.

The nitrogen specimens were placed in poly bags under a positive pressure of nitrogen and the bags were heat sealed. These specimens were tested within 2 hours after opening each bag.

IV. EXPERIMENTAL RESULTS

All exposures were completed satisfactorily. No failures occurred during the exposure periods.

Triplicate specimens were exposed and evaluated for all test conditions.

Test results are summarized by alloy in Tables IV-1 through IV-4. These tables compare the six mechanical properties determined for the stressed and unstressed conditions of the three environments. No significant effect of environment was apparent for any of the properties as a result of environment. The variation in properties was deemed normal for the triplicate specimen experiment used. Of particular significance is the good agreement between conditions for the notch/unnotch strength ratio data. Notch behavior is frequently a sensitive indicator of environmental effects.

A detailed presentation of the unnotched data for each of the exposure conditions is given in appendix Tables A-1 through A-6. Similarly, notch data are given in Tables A-7 through A-12.

Table IV-1 Data Summary for 316L Stainless Steel

	Unstressed			Stressed		
	Air	Oxygen	Nitrogen	Air	Oxygen	Nitrogen
Ultimate Tensile Strength, MN/m^2 (ksi)	551 (80.0)	552 (80.0)	549 (79.7)	553 (80.2)	557 (80.8)	544 (78.9)
Yield Strength, MN/m^2 (ksi)	212 (30.7)	221 (32.1)	227 (32.9)	236 (34.2)	236 (34.2)	250 (36.3)
Elongation, %	71.3	66.0	66.8	66.6	66.7	64.8
Reduction of Area, %	83.8	79.6	80.7	80.7	76.4	81.4
Modulus of Elasticity, GN/m^2 (10^6 psi)	193 (28.0)	142 (20.6)	160 (24.1)	146 (21.2)	206 (29.9)	182 (26.4)
Notch/Unnotch Strength Ratio	1.35	1.33	1.32	1.35	1.34	1.36

Table IV-2 Data Summary for Incoloy 903

	Unstressed			Stressed		
	Air	Oxygen	Nitrogen	Air	Oxygen	Nitrogen
Ultimate Tensile Strength, MN/m^2 (ksi)	1426 (206.9)	1428 (207.3)	1430 (207.6)	1433 (208.0)	1435 (208.1)	1430 (207.5)
Yield Strength MN/m^2 (ksi)	1201(174.3)	1204(174.8)	1207(175.2)	1188(172.5)	1224(177.5)	1215(176.4)
Elongation, %	17.3	13.1	16.8	17.2	13.8	17.1
Reduction of Area, %	45.4	43.6	45.8	45.1	40.7	46.2
Modulus of Elasticity, GN/m^2 (10^6 psi)	158 (23.0)	164 (23.8)	164 (23.8)	165 (24.0)	166 (24.1)	166 (24.1)
Notch/Unnotch Strength Ratio	1.35	1.34	1.35	1.26	1.31	1.36

Table IV-3 Data Summary for Monel K-500

	Unstressed			Stressed		
	Air	Oxygen	Nitrogen	Air	Oxygen	Nitrogen
Ultimate Tensile Strength, MN/m^2 (ksi)	1138(165.2)	1146(166.4)	1142(165.8)	1150(166.8)	1152(167.1)	1144(166.1)
Yield Strength, MN/m^2 (ksi)	750 (108.9)	757 (109.9)	757 (109.9)	750 (108.8)	772 (112.0)	758 (110.0)
Elongation, %	25.3	22.6	26.3	28.3	22.4	26.5
Reduction of Area, %	46.0	44.0	47.0	47.4	45.9	48.0
Modulus of Elasticity, GN/m^2 (10^6 psi)	180 (26.1)	182 (26.4)	191 (27.7)	187 (27.2)	185 (26.9)	183 (26.5)
Notch/Unnotch Strength, Ratio	1.12	1.13	1.14	1.14	1.08	1.16

Table IV-4 Data Summary for Inconel 718

	Unstressed			Stressed		
	Air	Oxygen	Nitrogen	Air	Oxygen	Nitrogen
Ultimate Tensile Strength, MN/m^2 (ksi)	978 (141.9)	1034(150.4)	1023(148.5)	1022(148.3)	1007(146.0)	1025(148.7)
Yield Strength MN/m^2 (ksi)	861 (125.0)	861 (125.0)	872 (126.5)	861 (125.0)	864 (125.3)	878 (127.5)
Elongation, %	17.8	15.7	16.7	16.4	14.6	17.7
Reduction of Area, %	20.4	17.8	24.0	22.8	21.2	25.1
Modulus of Elasticity, GN/m^2 (10^6 psi)	183 (26.6)	209 (30.3)	184(26.7)	197 (28.6)	208 (29.9)	196 (28.4)
Notch/Unnotch Strength Ratio	1.51	1.43	1.39	1.42	1.51	1.49

V. CONCLUSIONS AND RECOMMENDATIONS

The results of this investigation show that 69 MN/m^2 (10,000 psi) oxygen exposure has no effect on the unnotched or notched tensile properties of 316L, Incoloy 903, Monel K-500 and cast Inconel 718 alloys.

Although tensile properties are unaffected, it is difficult to speculate behavior in terms of crack growth threshold. If the application necessitates, a similar program using fracture mechanics specimens to evaluate threshold behavior may be warranted.

APPENDIX

Mechanical Property
Test Data

Table A-1 Room Temperature Ambient Air Tensile Properties

Alloy	Ultimate Tensile Strength, MN/m^2	(ksi)	Yield Strength, 0.2% Offset, MN/m^2	(ksi)	Elongation, %	Reduction of Area, %	Modulus of Elasticity, GN/m^2	(10^6 psi)
316L	551	(80.0)	207	(30.0)	71.0	84.0	193	(28.0)
	558	(81.0)	216	(31.4)	75.0	84.0	--	--
	550	(79.8)	211	(30.6)	68.0	83.5	--	--
	551	(80.0) Avg	212	(30.7) Avg	71.3 Avg	83.8 Avg	193	(28.0) Avg
Incoloy 903	1430	(207.6)	1201	(174.3)	16.5	42.5	159	(23.1)
	1428	(207.2)	1208	(175.3)	18.5	47.2	158	(22.9)
	1419	(206.0)	1195	(173.4)	17.0	46.6	158	(23.0)
	1426	(206.9) Avg	1201	(174.3) Avg	17.3 Avg	45.4 Avg	158	(23.0) Avg
Monel K-500	1142	(165.3)	750	(108.9)	--	45.0	185	(26.9)
	1138	(165.1)	754	(109.4)	25.5	44.7	176	(25.5)
	1134	(164.6)	747	(108.4)	25.0	48.3	178	(25.9)
	1138	(165.2) Avg	750	(108.9) Avg	25.3 Avg	46.0 Avg	180	(26.1) Avg
Inconel 718	963	(139.7)	832	(120.8)	17.0	21.0	172	(24.9)
	1003	(145.6)	857	(124.4)	21.5	23.0	163	(23.6)
	968	(140.5)	894	(129.8)	15.0	17.2	217	(31.5)
	978	(141.9) Avg	861	(125.0) Avg	17.8 Avg	20.4 Avg	183	(26.6) Avg

Table A-2 Room Temperature Tensile Properties after Stressed Exposure in Ambient Air

Alloy	Ultimate Tensile Strength, MN/m^2	(ksi)	Yield Strength, 0.2% Offset, MN/m^2	(ksi)	Elongation, %	Reduction of Area, %	Modulus of Elasticity, GN/m^2	(10^6 psi)
316L	555	(80.5)	238	(34.5)	69.7	78.5	132	(19.2)
	550	(79.8)	227	(32.9)	65.3	81.8	130	(18.9)
	553	(80.3)	241	(35.0)	64.8	81.7	176	(25.5)
	553	(80.2) Avg	236	(34.2) Avg	66.6 Avg	80.7 Avg	146	(21.2) Avg
Incoloy 903	1437	(208.6)	1193	(173.2)	17.5	45.1	170	(24.7)
	1437	(208.6)	1188	(172.4)	16.5	43.9	161	(23.4)
	1426	(207.0)	1184	(171.9)	17.5	46.2	164	(23.8)
	1433	(208.0) Avg	1188	(172.5) Avg	17.2 Avg	45.1 Avg	165	(24.0) Avg
Monel K-500	1151	(167.1)	747	(108.4)	28.1	47.1	171	(24.8)
	1148	(166.6)	743	(107.9)	28.4	47.3	202	(29.3)
	1149	(166.7)	758	(110.0)	28.5	47.7	183	(26.5)
	1150	(166.8) Avg	750	(108.8) Avg	28.3 Avg	47.4 Avg	187	(27.2) Avg
Inconel 718	996	(144.5)	852	(123.7)	--	17.1	180	(26.1)
	1052	(152.7)	858	(124.6)	17.1	27.0	183	(26.6)
	1017	(147.6)	874	(126.9)	15.8	24.2	228	(33.1)
	1022	(148.3) Avg	861	(125.0) Avg	16.4 Avg	22.8 Avg	197	(28.6) Avg

Table A-3 Room Temperature Tensile Properties after Unstressed Exposure in High Pressure Oxygen

Alloy	Ultimate Tensile Strength, MN/m^2 (ksi)	Yield Strength, 0.2% Offset, MN/m^2 (ksi)	Elongation, %	Reduction of Area, %	Modulus of Elasticity, GN/m^2 (10^6 psi)
316L	553 (80.2)	220 (32.0)	65.4	80.5	145 (21.1)
	549 (79.6)	222 (32.2)	64.4	78.5	136 (19.8)
	553 (80.2)	220 (32.0)	68.3	79.8	144 (20.9)
	552 (80.0) Avg	221 (32.1) Avg	66.0 Avg	79.6 Avg	142 (20.6) Avg
Incoloy 903	1430 (207.6)	1206 (175.1)	12.5	44.8	162 (23.5)
	1424 (206.7)	1200 (174.1)	14.4	42.9	168 (24.4)
	1430 (207.6)	1206 (175.1)	12.5	43.0	162 (23.5)
	1428 (207.3)	1204 (174.8) Avg	13.1 Avg	43.6 Avg	164 (23.8) Avg
Monel K-500	1149 (166.8)	760 (110.3)	22.2	44.7	183 (26.5)
	1146 (166.4)	753 (109.3)	21.6	42.9	181 (26.2)
	1144 (166.1)	762 (110.6)	24.0	44.5	182 (26.4)
	1146 (166.4) Avg	757 (109.9) Avg	22.6 Avg	44.0 Avg	182 (26.4) Avg
Inconel 718	1051 (152.5)	885 (128.5)	17.3	14.4	211 (30.6)
	1029 (149.3)	820 (119.0)	19.2	23.5	185 (26.9)
	1030 (149.5)	878 (127.4)	10.5	15.7	230 (33.4)
	1034 (150.4) Avg	861 (125.0) Avg	15.7 Avg	17.8 Avg	209 (30.3) Avg

Table A-4 Room Temperature Tensile Properties after Stressed Exposure in High Pressure Oxygen

Alloy	Ultimate Tensile Strength, MN/m^2	(ksi)	Yield Strength 0.2% Offset, MN/m^2	(ksi)	Elongation, %	Reduction of Area, %	Modulus of Elasticity, GN/m^2	(10^6 psi)
316L	553	(80.2)	234	(33.9)	67.3	77.0	209	(30.3)
	552	(80.0)	232	(33.6)	67.3	72.9	209	(30.3)
	566	(82.1)	243	(35.2)	65.4	79.4	201	(29.2)
	557	(80.8) Avg	236	(34.2) Avg	66.7 Avg	76.4 Avg	206	(29.9) Avg
Incoloy 903	1438	(208.6)	1233	(178.8)	13.5	36.0	169	(24.5)
	1435	(208.2)	1231	(178.5)	13.5	44.2	160	(23.2)
	1431	(207.6)	1209	(175.3)	14.4	42.0	169	(24.6)
	1435	(208.1) Avg	1224	(177.5) Avg	13.8 Avg	40.7 Avg	166	(24.1) Avg
Monel K-500	1152	(167.1)	jj2	(112.0)	22.1	46.4	182	(26.6)
	1153	(167.3)	771	(111.8)	23.1	45.2	187	(27.2)
	1152	(167.1)	774	(112.2)	22.1	45.2	185	(26.9)
	1152	(167.1) Avg	772	(112.0) Avg	22.4 Avg	45.9 Avg	185	(26.9) Avg
Inconel 718	980	(142.1)	863	(121.3)	13.1	16.3	194	(28.1)
	1025	(148.6)	891	(129.2)	16.4	28.6	194	(28.1)
	1016	(147.4)	864	(125.3)	14.4	18.6	231	(33.5)
	1007	(146.0) Avg	864	(125.3) Avg	14.6 Avg	21.2 Avg	206	(29.9) Avg

Table A-5 Room Temperature Tensile Properties after Unstressed Exposure in High Pressure Nitrogen

Alloy	Ultimate Tensile Strength, MN/m^2	(ksi)	Yield Strength, 0.2% Offset, MN/m^2	(ksi)	Elongation, %	Reduction of Area, %	Modulus of Elasticity GN/m^2	(10^6 psi)
316L	544	(79.0)	223	(32.4)	67.4	81.0	156	(22.6)
	553	(80.2)	232	(33.6)	67.2	81.7	159	(23.1)
	550	(79.8)	226	(32.8)	65.7	79.5	183	(26.5)
	549	(79.7) Avg	227	(32.9) Avg	66.8 Avg	80.7 Avg	160	(24.1) Avg
Incoloy 903	1428	(207.2)	1201	(174.3)	183	47.2	167	(24.3)
	1433	(208.0)	1209	(175.5)	16.0	45.9	161	(23.3)
	1430	(207.6)	1212	(175.9)	16.0	44.2	165	(23.9)
	1430	(207.6) Avg	1207	(175.2) Avg	16.8 Avg	45.8 Avg	16.4	(23.8) Avg
Monel K-500	1145	(166.2)	763	(110.7)	25.0	45.5	178	(25.9)
	1138	(165.3)	757	(109.8)	27.0	47.8	199	(29.9)
	1144	(166.0)	753	(109.3)	27.0	47.7	196	(28.4)
	1142	(165.8) Avg	757	(109.9) Avg	26.3 Avg	47.0 Avg	191	(27.7) Avg
Inconel 718	1036	(150.3)	875	(127.0)	16.0	20.8	192	(27.8)
	1021	(148.2)	862	(125.1)	17.0	23.5	187	(27.1)
	1013	(147.0)	877	(127.3)	17.0	27.7	174	(25.2)
	1023	(148.5) Avg	872	(126.5) Avg	16.7 Avg	24.0 Avg	184	(26.7) Avg

Table A-5

Table A-6 Room Temperature Tensile Properties after Stressed Exposure in High Pressure Nitrogen

Alloy	Ultimate Tensile Strength, MN/m^2	(ksi)	Yield Strength, 0.2% Offset, MN/m^2	(ksi)	Elongation, %	Reduction of Area, %	Modulus of Elasticity GN/m^2	(10^6 psi)
316L	544	(79.0)	247	(35.9)	65.5	82.3	192	(27.9)
	546	(79.2)	252	(36.6)	65.0	80.3	179	(26.0)
	542	(78.6)	251	(36.4)	64.0	81.7	174	(25.2)
	544	(78.9) Avg	250	(36.3) Avg	64.8 Avg	81.4 Avg	182	(26.4) Avg
Incoloy 903	1439	(208.8)	1229	(178.4)	17.0	46.1	164	(23.8)
	1421	(206.2)	1199	(174.0)	17.0	46.5	169	(24.5)
	1430	(207.5)	1219	(176.9)	17.4	45.9	166	(24.1)
	1430	(207.5) Avg	1215	(176.4) Avg	17.1 Avg	46.2 Avg	166	(24.1) Avg
Monel K-500	1148	(166.6)	763	(110.7)	27.5	48.2	184	(26.7)
	1142	(165.7)	754	(109.5)	26.0	48.0	182	(26.4)
	1144	(166.0)	757	(109.9)	26.0	47.7	183	(26.5)
	1144	(166.1) Avg	758	(110.0) Avg	26.5 Avg	48.0 Avg	183	(26.5) Avg
Inconel 718	1016	(147.5)	873	(126.7)	15.0	26.9	202	(29.3)
	1062	(154.1)	899	(130.5)	20.0	24.3	195	(28.3)
	996	(144.5)	863	(125.3)	18.0	24.2	190	(27.6)
	1025	(148.7) Avg	878	(127.5) Avg	17.7 Avg	25.1 Avg	196	(28.4) Avg

Table A-7
Room Temperature Ambient Air Notch Tensile Properties

Alloy	Notch Tensile Strength, MN/m^2	(ksi)		Notch/Unnotch Strength Ratio
316L	748	(108.6)		
	743	(107.8)		1.35
	738	(107.1)		
	743	(107.8)	Avg	
Incoloy 903	1963	(284.9)		
	1931	(280.2)		1.35
	1890	(274.3)		
	1928	(279.8)	Avg	
Monel K-500	1273	(184.8)		
	1306	(189.6)		1.12
	1257	(182.4)		
	1279	(185.6)	Avg	
Inconel 718	1479	(214.7)		
	1477	(214.4)		1.51
	1461	(212.2)		
	1472	(213.7)	Avg	

Table A-8
Room Temperature Notch Tensile Properties after Stressed Exposure in Ambient Air

Alloy	Notch Tensile Strength, MN/m²	(ksi)	Notch/Unnotch Strength Ratio
316L	741	(107.6)	
	739	(107.2)	1.35
	762	(110.6)	
	748	(108.5) Avg	
Incoloy 903	1911	(277.4)	
	1798	(261.0)	1.26
	1696	(246.1)	
	1802	(261.5) Avg	
Monel K-500	1266	(183.7)	
	1350	(196.0)	1.14
	--	--	
	1308	(189.9) Avg	
Inconel 718	1431	(207.7)	
	1497	(217.3)	1.42
	1421	(206.2)	
	1450	(210.4) Avg	

Table A-9
Room Temperature Notch Tensile Properties after Unstressed Exposure in High Pressure Oxygen

Alloy	Notch Tensile Strength, MN/m^2	(ksi)		Notch/Unnotch Strength Ratio
316L	732	(106.3)		1.33
	741	(107.6)		
	731	(106.1)		
	735	(106.7)	Avg	
Incoloy 903	1903	(276.3)		1.34
	1961	(284.6)		
	1874	(272.0)		
	1913	(277.6)	Avg	
Monel K-500	1317	(191.2)		1.13
	1268	(184.0)		
	1310	(190.2)		
	1299	(188.5)		
Inconel 718	1456	(211.3)		1.43
	1481	(215.0)		
	1497	(217.2)		
	1478	(214.5)	Avg	

Table A-10
Room Temperature Notch Tensile Properties after Stressed Exposure in High Pressure Oxygen

Alloy	Notch Tensile Strength, MN/m^2	(ksi)		Notch/Unnotch Strength Ratio
316L	783	(110.8)		1.34
	721	(104.7)		
	754	(109.4)		
	746	(108.3)	Avg	
Incoloy 903	1768	(256.6)		1.31
	1950	(283.1)		
	1917	(278.2)		
	1878	(272.6)		
Monel K-500	1255	(182.2		1.08
	1273	(184.7)		
	1217	(176.6)		
	1248	(181.2)	Avg	
Inconel 718	1550	(225.0)		1.51
	1524	(221.2)		
	1477	(214.4)		
	1517	(220.2)	Avg	

Table A-11
Room Temperature Notch Tensile Properties after Unstressed Exposure in High Pressure Nitrogen

Alloy	Notch Tensile Strength, MN/m^2	(ksi)		Notch/Unnotch Strength Ratio
316L	721	(104.7)		1.32
	730	(106.0)		
	732	(106.3)		
	728	(105.7)	Avg	
Incoloy 903	1952	(283.3)		1.35
	1937	(281.1)		
	1913	(277.6)		
	1934	(280.7)	Avg	
Monel K-500	1299	(188.5)		1.14
	1286	(186.7)		
	1311	(190.3)		
	1299	(188.5)	Avg	
Inconel 718	1405	(203.9)		1.39
	1422	(206.4)		
	1430	(207.5)		
	1419	(205.9)	Avg	

Table A-12
Room Temperature Notch Tensile Properties after Stressed Exposure in High Pressure Nitrogen

Alloy	Notch Tensile Strength, MN/m^2	(ksi)		Notch/Unnotch Strength Ratio
316L	729	(105.8)		1.36
	743	(107.9)		
	739	(107.2)		
	737	(107.0)	Avg	
Incoloy 903	1943	(282.0)		1.36
	1913	(277.6)		
	1962	(284.7)		
	1939	(281.4)	Avg	
Monel K-500	1264	(183.4)		1.16
	1370	(198.9)		
	1362	(197.7)		
	1333	(193.4)	Avg	
Inconel 718	1483	(215.3)		1.49
	1563	(226.9)		
	1530	(222.0)		
	1525	(221.4)	Avg	