Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

WSRC-STI-2008-00043

HYDROGEN EFFECTS ON THE MECHANICAL PROPERTIES OF AUSTENITIC STAINLESS STEELS - a Compendium of Data from Testing at the Savannah River Laboratory in Support of High Pressure Hydrogen Service (U)

P. S. Lam

Savannah River National Laboratory
Materials Science & Technology Directorate

Publication Date: July 2008

[redacted]

Washington Savannah River Company
Savannah River Site
Aiken, SC 29808

This document was prepared in connection with work done under Contract No. DE-AC09-96SR18500 with the U. S. Department of Energy. Distribution authorized to the Department of Energy only; other requests shall be approved by the cognizant DOE Departmental Element.

DOCUMENT: WSRC-STI-2008-00043

TITLE: Hydrogen Effects on the Mechanical Properties of Austenitic Stainless Steels - a Compendium of Data from Testing at the Savannah River Laboratory in Support of High Pressure Hydrogen Service (U)

APPROVALS

[redacted] Date: July 10, 2008

Poh-Sang Lam, Author
Materials Compatibility & Welding Technology Group
SRNL-MATERIALS SCIENCE & TECHNOLOGY

[redacted] Date: 10 July 2008

Robert L. Sindelar, Technical Review
SRNL-MATERIALS SCIENCE & TECHNOLOGY

[redacted] Date: 7/10/08

Thad M. Adams, Manager
Materials Compatibility & Welding Technology Group
SRNL-MATERIALS SCIENCE & TECHNOLOGY

[redacted] Date: 7/11/08

Natraj C. Iyer, Director
SRNL-MATERIALS SCIENCE & TECHNOLOGY

WSRC-STI-2008-00043

Table of Contents

EXECUTIVE SUMMARY ………… 1
INTRODUCTION ………… 2
TENSILE PROPERTIES ………… 11
Hydrogen Effects on Tensile Ductility ………… 18
Hydrogen Concentration ………… 18
Effect of Grain Size ………… 19
Effect of Nickel Content ………… 19
FRACTURE PROPERTIES ………… 21
Fracture Data for Forged Alloys ………… 22
J-integral Testing (J_m) ………… 24
Thickness and Notch Effect (HERF 21-6-9) ………… 28
Stress Intensity Factor (K) Testing ………… 29
CONCLUDING REMARKS ………… 32
REFERENCES ………… 33
APPENDIX Savannah River Laboratory Data Sheets ………… 36
Appendix A Alloy Data Sheets ………… 37
Appendix B Definitions of the Measured Properties in SRL data Sheets ………… 83
Appendix C Mechanical Test Specimens ………… 85
Appendix D Heat Analyses ………… 93

List of Tables

Table 1 Test data and references for iron-chromium-nickel alloy ………… 3
Table 2 Test data and references for iron-chromium-nickel-manganese alloys ………… 7
Table 3 Test data and references for precipitation hardenable alloys ………… 9
Table 4 Test data and references for high purity alloys ………… 11
Table 5 Tensile properties for Fe-Cr-Ni Alloys ………… 14
Table 6 Tensile properties for Fe-Cr-Ni-Mn Alloys ………… 16
Table 7 Precipitation Hardenable Alloys ………… 17
Table 8 High Purity Alloys ………… 17
Table 9 Hydrogen Concentration in Austenitic Stainless Steel Tensile Specimens ………… 18
Table 10 Summary of SRL fracture test results up to June 1982 ………… 27
Table 11 Fracture toughness (K) for Tenelon® ………… 30
Table 12 Fracture toughness (K) for HERF Nitronic® 40 (21-6-9) ………… 30
Table 13 Fracture toughness (K) for HERF A-286 ………… 31
Table 14 Fracture toughness (K) for HERF JBK-75 ………… 32
Table 15 Fracture toughness (K) for17-4 PH ………… 32

List of Figures

Figure 1 SRL tensile test specimens …………………………………………………… 13
Figure 2 Ductility loss in 69 MPa hydrogen environment for 304L with various grain sizes ……………………………………………………………………….. 19
Figure 3 Correlation between retained ductility and nickel content for Fe-Cr-Ni and high purity alloys ……..……………………………………………………… 20
Figure 4 Reduction of area and retained ductility for Fe-Cr-Ni, precipitation hardenable, and high purity alloys ……………………………………………..……. 21
Figure 5 SRL Fracture test specimens …………………………………………………. 22
Figure 6 Notch orientation and the forging flow lines ……………………………….. 23
Figure 7 Forging flow lines as shown by scanning electron microscope (SEM). The actual dimension was not labeled …………………...……………….......... 23
Figure 8 J-integral test results for HERF 304L under various test environments and specimen conditions …..…………………………………………..……. 24
Figure 9 J-integral test results for HERF Nitronic 40® (21-6-9) under various test environments and specimen conditions …………..……………..………... 25
Figure 10 J-integral test results for HERF Nitronic 50® (22-13-5) under various test environments and specimen conditions (based on Data Sheet IIC-3 in Ref. [1]) ……………………………………………………………………..... 25
Figure 11 J-integral test results for HERF A-286 under various test environments and specimen conditions ….……………………………………………………... 26
Figure 12 J-integral test results for HERF 316 under various test environments and specimen conditions …...…………………………………………..…… 26
Figure 13 Fracture toughness (J_m) for various types of stainless steel. Note that the values for HERF materials were averaged by the number of orientations that were tested …………………………………………………………….…... 28
Figure 14 Thickness and notch effects on fracture toughness (J_m) of HERF 21-6-9 in hydrogen environment ……………………………………..……………… 29

EXECUTIVE SUMMARY

Archival materials test data on austenitic stainless steels for service in high pressure hydrogen gas has been reviewed. The bulk of the data were from tests conducted prior to 1983 at the Savannah River Laboratory, the predecessor to the Savannah River National Laboratory, for pressures up to 69 MPa (10,000 psi) and at temperatures within the range from 78 to 400 K (-195 to 127 °C). The data showed several prominent effects and correlations with test conditions:

- There was a significant reduction in tensile ductility as measured by reduction of area or by the total elongation with hydrogen. Hydrogen effects were observed when the specimens were tested in the hydrogen environment, or the specimens were precharged in high pressure hydrogen and tested in air or helium.
- There was a significant reduction in fracture toughness with hydrogen (and sometimes in tearing modulus which is proportional to the slope of the crack resistance curve).
- The effects of hydrogen can be correlated to the nickel content of the iron-chromium-nickel steels. The optimal nickel content to retain the tensile ductility in wrought Fe-Cr-Ni alloys was 10 to at least 20 wt.%.
- The effects of hydrogen can be correlated to the grain size. Large grain sizes exhibited a greater loss of ductility compared to small grain sizes.

The Savannah River Laboratory test data, especially those not readily available in the open literature, along with the sources of the data, are documented in this report.

INTRODUCTION

The Savannah River Laboratory (SRL), the predecessor to the Savannah River National Laboratory (SRNL), had carried out decades of research on the effects of hydrogen and hydrogen isotopes on the mechanical properties of materials in support of high pressure hydrogen and hydrogen isotope systems materials selection and design. Caskey [1] in 1983 provided the most comprehensive SRL database, in which the stainless steels were categorized into four major groups or alloy types:

Type I) Iron-Chromium-Nickel Alloys – 304L, 304N, 309S, 310, 316, Carpenter 20 Cb-3, Incoloy® 800H (Huntington Alloys Inc.), Nickel 200, Nickel 301, and 440 C;

Type II) Iron-Chromium-Nickel-Manganese Alloys – Tenelon® (U. S. Steel Corp.), Nitronic®- 40 or 21-6-9 (Armco, Inc.), Nitronic®-50 or 22-13-5 (Armco, Inc.), 18-18 Plus® (Carpenter Technology), X18-3 Mn, 18-2 Mn, and 216;

Type III) Precipitation Hardenable Alloys – A-286, JBK-75 (a modified form of A-286), 17-4PH, AM-363, CG-27, and Ni-SPAN-C (Alloy 902); and

Type IV) High purity alloys – Alloy A (18Cr-10Ni), Alloy B (18Cr-14Ni), and Alloy C (18Cr-19Ni).

The type of tests and test conditions of the database in Reference [1], excluding the tritium results, is provided in Tables 1 to 4, corresponding to each of the four alloy categories as described above. Tables 1 to 4 contain the alloy composition, test environment, material treatment, data type, and the location of the datasheets in Reference [1], which were reproduced in Appendix A of this report. In addition, Caskey and Ratliff [2] reported materials considerations in developing onboard hydrogen storage systems (and options) for vehicular use in an early initiative (1970s) for hydrogen as a replacement for hydrocarbon fuel with a key date set to 2015. The hydrogen effects on structural materials including austenitic stainless steels, embrittlement mechanisms, and fracture modes, etc. were thoroughly discussed. The stainless steel test data in Reference [2], and those published in the public domain, such as Caskey, et al. [3,4], Louthan, et al. [5,6], and Somerday, et al. [7], were carefully compared with those in Reference [1]. The data generated at SRL and relevant to mechanical properties for hydrogen systems materials selection and design are reported collectively in this report.

Some already-published results are included for completeness, or included after corrections were made. All the data included in this report will be consistent with the datasheets in Reference [1] from pp. 81-123. In particular, the ultimate tensile strength (UTS) has been converted, as possible, to the quantity that is commonly defined as the engineering stress at the peak load. The true (plastic) strain at failure has been converted to a more familiar parameter, Reduction of Area (RA). These results are listed in Tables 5-8. The original definitions of the measured quantities in Appendix A were listed in Appendix B. The Appendices C and D are, respectively, the test specimen geometries and the actual heats of the specimens, as were referenced by the datasheets in Appendix A.

The updated tensile properties of stainless steels are tabulated in this report. The dependence of iron-chromium-nickel alloys on the nickel content is emphasized. The grain size effect is discussed with 304L stainless steel test data. Following the tensile data, the fracture testing is discussed. Both J_m (J-integral at the maximum load) and stress intensity factor (K) were reported for stainless steels under various test environments and exposure conditions. The orientation effect of the high energy rate forging (HERF) is discussed. A limited amount of specimen sensitivity study on the effect of thickness and notch/precrack was conducted.

A review of the test methods and results summarized in this report demonstrates the importance of standardized testing. A large deviation of test data may be expected for material testing with material precharged hydrogen versus material tested in high pressure hydrogen gas.

Table 1 Test data and references for iron-chromium-nickel alloys

I. Iron-Chromium-Nickel Alloys					
Type and composition (wt.%)	Test Environment	Exposure Condition	Data Type	Remarks	Data Sheets and page numbers in Ref. [1]
304L bar stock, as received 19Cr, 10Ni	78K (LN) – 380K (air)	None & 69 MPa H_2, 470K, 1449 days	Tensile	LN: Liquid Nitrogen	IA-1 page 81
304L as received	78 (air), 298K (air)	None & 17.9 MPa H_2, 470K, 1000 hours	Charpy: Impact Energy		IA-2 page 81
304L tube	69 MPa H_2/He, RT	H_2/He, 425K, 8 and 32 days	Tensile	RT: Room Temperature	IA-3 page 82
304L HERF	200-380K air	None & 69 MPa H_2, 620K, 3 weeks	Tensile	HERF: high energy rate forged	IA-5 page 83
304L HERF	77 and 298K, air	None & 29.6 MPa H_2, 470K, 56 days	Charpy		IA-6 page 83
304L HERF	69 MPa He /H_2	None & 69 MPa D_2, 620K, 3 weeks	Fracture C-specimen (J_m)	D_2: Deuterium; J_m: J at max. load	IA-7 page 84

304L HERF	69 MPa He /H_2	None & 69 MPa D_2, 620K, 3 weeks	Fracture C-specimen (dJ/da)	dJ/da: tearing capability	IA-8 page 85
304L heat treated, GS 9.5 -340 μm	69 MPa He/H_2		Tensile	GS: grain size	IA-9 page 86
304L heat treated, GS 6.1 -290 μm	220K	None & 69 MPa (4.7cc D_2/cc)	Tensile		IA-10 page 86
304L GS 6μm	220K, Crosshead: 51 & 0.51 mm/min	None & 69 MPa, 3 weeks	Tensile		IA-11 page 87
304L heat treated, solution anneal & sensitized	69 MPa Air, He, & H_2		Tensile		IA-12 page 87
304L notched bar	Air (0.1MPa); He & H_2 (69 MPa)		Tensile		IA-13 page 88
304L notched bar		Annealed Ag, 380K, 200 days; 69 MPa H_2, 380K, 200 days	Tensile		IA-14 page 89
304L notched bar	Air, 0.1 MPa H_2, 1.03 MPa H_2, 6.89 H_2		Tensile		IA-15 page 89
304L	RT, H_2, prestress 772 MPa, Creep 325 to 614 hours		Pre-existing crack in tensile tube: Slow Crack Growth		IA-16 page 90
304N 19Cr, 9Ni, 0.13N	200-298K, air and 69 MPa He and H_2	None & 69 MPa H_2 430K, 1000 hours; 69 MPa D_2, 620K, 3 weeks	Tensile		IB-1 page 91

309S 23Cr, 13Ni	Air, 69 MPa He and H_2	None, 69 MPa H_2 430K 14 days; 28 MPa H_2, 470K, 100 hours	Tensile		IC-1 page 92
310 bar stock, as received 25Cr, 20Ni, 0.25C	78 (LN) to 380K (air)	None & 69 MPa H_2 470K 1449 days	Tensile		ID-1 page 93
310	298K, air and 69 MPa H_2, He	None & 69 MPa H_2 430K 1000 hours	Tensile		ID-2 page 93
316 bar stock, as received 17Cr, 12Ni, 2.5Mo	air	None & 69 MPa H_2 620K 3 weeks	Tensile		IE-1 page 94
Carpenter 20 Cb-3® as received 20Cr, 34Ni, 2.5Mo, 3.5Cu, 0.6Nb	Air 200 &298K; 69 MPa H_2 298K	None & 69 MPa D_2 620K, 3 weeks	Tensile		IF-1 page 95
Incoloy® 800H, hot rolled plate, solution annealed 21CR, 32Ni, 0.75Cu, 0.3Al, 0.3Ti	78 (LN) to 380 K air	None & 69 MPa H_2 620K 3 weeks	Tensile		IG-1 page 95
Nickel 200 (annealed 1090K 15 min, furnace cool); Plus additional annealed 773K 64 hours, air cooled) 99+ Ni	298K air, 69 MPa He and H_2	none	Tensile		IH-1 page 96

Nickel 200, Notched bar (annealed 1090K 15 min, furnace cool); Plus additional annealed 773K 64 hours, air cooled)	298K air, 69 MPa He and H_2	None	Tensile		IH-2 page 96
Nickel 301, (annealed 1170K 5 min, quenched); Plus additional annealed 860K 16 hours, 810K 5 hours, 755K 5 hours, furnace cooled) bal Ni, 1Si, 4.5Al, 0.6Ti	298K air, 69 MPa He and H_2	none	Tensile		IJ-1 page 97
Nickel 301, notched bar (annealed 1170K 5 min, quenched); Plus additional annealed 860K 16 hours, 810K 5 hours, 755K 5 hours, furnace cooled)	298K air, 69 MPa He and H_2	none	Tensile		IJ-2 page 97
440C 19Cr, 0.75Mo, 0.95 to 1.2C	298K air	None & 69 MPa D_2 620K, 3 weeks	Tensile		IK-1 page 98

Table 2 Test data and references for iron-chromium-nickel-manganese alloys

II. Iron-Chromium-Nickel-Manganese Alloys					
Type and composition (wt.%)	Test Condition	Exposure Condition	Data Type	Remarks	Data Sheets and page numbers in Ref. [1]
Tenelon® plate, as received, electropolished, annealed 1170K 24 hours, annealed 1270K 24 hours 18Cr, 15 Mn	78 (LN) – 350K air	None & 69 MPa H_2 620K 3 weeks	Tensile		IIA-1 page 99
Tenelon®	air, 69 MPa He, 69 MPa H_2	None & 69 MPa H_2 423K, 1000 hours	Tensile		IIA-2 page 100
Tenelon® as received, Anneal 1170K, Anneal 1270K	78 and 200K		Fracture-SENT (K)	SENT: single edge notched tension, K: fracture toughness	II-A3 page 100
Nitronic® 40 (21-6-9) bar stock, as received 21Cr, 6Ni, 9Mn, 0.15 to 0.4N	78 (LN) – 380K air	None & 69 MPa H_2 620K 3 weeks	Tensile		IIB-1 page 101
Nitronic® 40 heat treated: solution Anneal & Sensitized	200 and 230K air	None	Smooth and Notched Tensile		IIB-2 page 102
Sensitized Nitronic® 40 Solution Annealed, 920 K-2 hr, 920K-24 hr	69 MPa He, 69 MPa H2	None	Smooth and Notched Tensile		IIB-3 page 103

Sensitized Nitronic® 40 Solution Annealed, 920K-24 hr	200K	None & 69 MPa H_2 620K 3 weeks	Tensile	Crosshead: 5 and 0.5 mm/min	IIB-4 page 103
Nitronic® 40	298K air, 69 MPa He, 69 MPa H_2	None	Tensile		IIB-5 page 104
Nitronic® 40 Cold Worked 30%	298K air, 69 MPa He, 69 MPa H_2	None & 30 MPa H_2	Tensile		IIB-6 page 104
Nitronic® 40 HERF	78K (LN) – 380K air	None, 69 MPa 470K 1449 days, 69 MPa 620K 21 days	Tensile		IIB-7 page 105
Nitronic® 40 HERF	298K, air, 69 MPa He, 69 MPa H_2	None & 28 MPa H_2	Tensile		IIB-8 page 105
Nitronic® 40 HERF	77K (LN) & 298K air	None & 29.6 MPa H_2 470K 56 days	Charpy: Impact Energy		IIB-9 page 106
Nitronic® 40 HERF	298K, 69 MPa He, 69 MPa H_2	None & 0.6 MPa H_2	Fracture: C-specimen (K)		IIB-10 page 106
Nitronic ® 40 HERF	69 MPa He, 69 MPa H_2	Annealed in He, 69 MPa D_2 620K 3 weeks	Fracture: J_m		IIB-11 page 107
Nitronic ® 40 HERF	69 MPa He, 69 MPa H_2	Annealed in He, 69 MPa D_2 620K 3 weeks	Fracture: dJ/da		IIB-12 page 108
Nitronic® 50 (22-13-5) bar stock, as received 22Cr, 13Ni, 5Mn, 2Mo, 0.2 to 0.4N	78K (LN) – 380K air	None & 69 MPa H_2 620K 3 weeks	Tensile		IIC-1 page 109
Nitronic® 50 bar stock, as received	298K, air, 69 MPa He, 69 MPa H_2	None	Tensile		IIC-2

Nitronic® 50 HERF	298K, air, 69 MPa He, 69 MPa H_2	None & D2 620K 3 weeks	Fracture: J_m and dJ/da		IIC-3 page 110
18-18 Plus® 18Cr,0.5Ni, 18Mn, 1Mo, 0.4N, 1Cu, 0.1Co	298K, 69 MPa He, 69MPa H_2	None	Tensile		IID-1 page 110
X18-3 Mn Stainless Steel 18Cr, 3Ni, 12Mn, 0.3N	298K, air, 69 MPa He, 69 MPa H_2	None	Tensile		IIE-1 page 111
18-2 Mn Stainless Steel 18Cr, 2Ni, 13Mn	298K, air, 69 MPa H_2	None	Tensile		IIF-1 page 111
216 20Cr, 6Ni, 8Mn, 2Mo, 0.32N	298K, air, 69 MPa He, 69 MPa H_2	None & 69 MPa 430K 1000 hours	Tensile		IIG-1 page 112

Table 3 Test data and references for precipitation hardenable alloys

III. Precipitation Hardenable Alloys					
Type and composition (wt.%)	Test Environment	Exposure Condition	Data Type	Remarks	Data Sheets and page numbers in Ref. [1]
A286 15CR, 26Ni, 1.25Mo, 2Ti, 0.25Al, 0.3V	220 and 298K, air	None & 2.1 MPa Ar, 69 MPa D_2 620K 3 weeks	Tensile		IIIA-1 page 113
A286 HERF (Heat 1, Heat 2, R_c-11)	298K, 69 MPa He, 69 MPa H_2	None & 1.6 MPa D_2 990K 8 hours; 1.5 MPa D_2 990K 8 hours	Fracture: K		IIIA-2 page 114

A286 base metal and weld metal	298K air	0.21 MPa Ar 370K 200 days	Charpy: Impact Energy	Contains data for specimens exposed to deuterium and tritium	IIIA-3 page 115
A286	69 MPa He, 69 MPa H_2	69 MPa D_2 620K 3 weeks	Fracture C-specimen (J_m)		IIIA-4 page 116
A286	69 MPa He, 69 MPa H_2	69 MPa D_2 620K 3 weeks	Fracture C-specimen (dJ/da)		IIIA-5 page 117
JBK-75 HERF 15Cr, 30Ni, 1.25Mo, 2Ti, 0.25Al, 0.001B, 0.25V	298K, 69 MPa He, 69MPa H_2	None	Tensile		IIIB-1 page 118
JBK-75 HERF	298K, 69 MPa He, 69MPa H_2	None & 0.7 MPa D_2 625K	C-shaped Fracture: K		IIIB-2 page 118
17-4 Stainless Steel, tensile tubes 16.5Cr, 4Ni, 4Cu, 0.3Nb	298K, air, 69 MPa He	69 MPa He	Tensile	Contains data for specimens exposed to deuterium and tritium	IIIC-1 page 119
17-4 PH Stainless Steel Solution annealed 2 hrs 1339K, aged 1 hour 709-866K	69 MPa He, 3.5 MPa H_2, 69 MPa H_2	None	C-shaped Fracture: K	Hardness; R_c data available	IIIC-2 page 119
AM-350, Condition H – annealed 1310 to 1350K air cool or water quench 16.5Cr, 4.3Ni, 2.8Mo, 0.1N	298K, air, 69 MPa He, 69 MPa D_2, 6.9 MPa D_2, 0.69 MPa D_2	None & 69 MPa 570K 26 days (test in air only)	Tensile		IIID-1 page 120
AM-363 11.5Cr, 4.5Ni, 0.5Ti	298K air	None & 0.21 MPa D_2 630K 5 days	Smooth and Notched Tensile		IIIE-1 page 120

CG-27 (also CG-27 HERF) 13Cr, 38Ni, 6Mo, 2.5Ti, 1.6Al, 0.6Nb	298K air, 69 MPa He, 69 MPa H_2	None & 69 MPa H_2 425K 72 hours	Tensile		IIIF-1 page 121
Ni-SPAN-C (Alloy 902) Sheet specimens 0.25 & 19 mm gage length 5Cr, 42Ni, 0.5Al, 2.5Ti	298K, air, 69 MPa He, 69 MPa H_2, 6.9 MPa H_2	None	Tensile		IIIG-1 page 121

Table 4 Test data and references for high purity alloys

IV. High Purity Alloys					
Type and composition (wt.%)	Test Environment	Exposure Condition	Data Type	Remarks	Data Sheets and page numbers in Ref. [1]
Alloy A 18Cr, 10Ni, N<0.01	78 (LN) – 370K air	None & 69 MPa H_2 620K 3 weeks	Tensile		IVA-1 page 122
Alloy B 18Cr, 14Ni, N<0.01	78 (LN) – 370K air	None & 69 MPa H_2 620K 3 weeks	Tensile		IVB-1 page 123
Alloy C 18Cr, 19Ni, N<0.01	78 (LN) – 370K air	None & 69 MPa H_2 620K 3 weeks	Tensile		IVC-1 page 123

TENSILE PROPERTIES

Most of the tensile tests referenced in Tables 1 to 4 above were carried out with smooth bar specimens as shown in Figure 1 with gage lengths 12.7, 25.4, and 50.8 mm (or ½, 1, and 2 inches), respectively. The test temperature ranged from 4 K (liquid helium) [8], 78 K (liquid nitrogen) to 380 K in air [1]. The test pressure was up to 69 MPa (10,00 psi) in helium or hydrogen. The test specimens included the unexposed and the hydrogen or deuterium charged at various temperatures, lengths of time, and pressures. The test data were reported as 0.2% offset yield stress, stress at 5% strain, UTS or UTS in true stress, uniform elongation (elongation at UTS), elongation at break or total elongation, reduction of area, and/or true failure strain. Occasionally, there were tests conducted with thin sheet specimens and tube specimens [1]. The data from circumferentially notched tensile bars were not included in this report, since they were used to enhance the hydrogen effect by stress concentration and therefore do not represent standard tensile properties. Most of the tensile tests were carried out with a crosshead speed of 0.5mm/min for specimens with 25.4 mm gage (Tensile Specimen B in Fig. 1) [1,4,9-12].

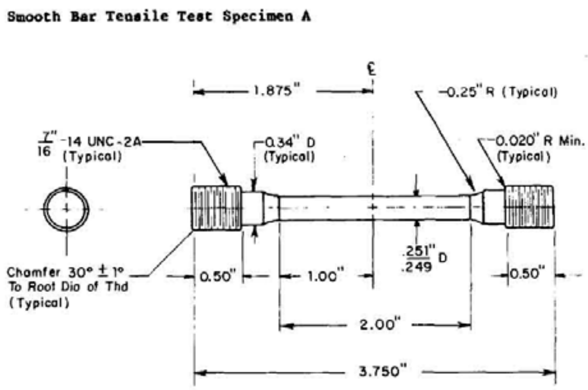
Tables 5 through 8 list the tensile properties of alloys Type I (Fe-Cr-Ni), Type II (Fe-Cr-Ni-Mn), Type III (precipitation hardenable), and Type IV (high purity), respectively. Because various hydrogen exposure conditions would result in drastic change of mechanical properties, Tables 5 to 8 contain data only from the unexposed specimens tested in air and in 69 MPa gaseous environments (hydrogen and helium) at room temperature (298 K). The yield stress refers to the stress at 0.2% strain unless otherwise specified (e.g., stress at 5% strain will be denoted as “5%”), ultimate tensile strength (UTS, or engineering stress at the peak load), uniform elongation (engineering strain at UTS before necking takes place) unless otherwise specified (denoted by “true” if only the true stress was reported), total elongation (engineering strain at failure), reduction of area (RA, defined as 1-R_f/R_o, where R_o is the original cross-sectional area of the tensile specimen, and R_f is the final cross-sectional area at break). Note that the elongation data are specimen gage length sensitive, the SRL tensile specimen types (i.e., Type A, B, and C in Fig. 1) and the gage lengths are included in Tables 5 to 8. The original (e.g., laboratory notebooks or internal reports/memoranda) data sources are provided if possible. The data attributes (such as the stress and strain measures, or the yield stress definitions) found in open literature and in the internal SRL reports may be occasionally inconsistent. If this was observed, the data information reported in the datasheets of Reference [1] was considered as accurate.

The following equations are used to convert the non-conventional data definitions in the SRL datasheets [1], unless the needed parameters are not provided:

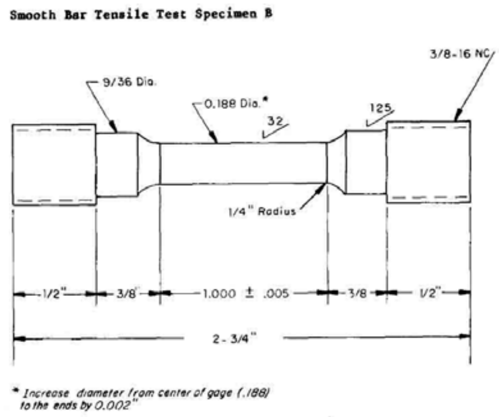
UTS = (True ultimate tensile Stress in Ref. [1])/(1 + Uniform Elongation)
$RA = 1 - \exp(-\varepsilon_p^f)$, where ε_p^f is the true strain at failure [1].

If the uniform elongation was not reported, then the conventional UTS (engineering stress) cannot be converted from the reported value of true stress. Also note that the total elongation is not easily related to RA or ε_p^f via the plastic incompressibility unless the curvature of the deformed gage section is measured, since the cross-sectional area is no longer uniform in the post-necking configuration.

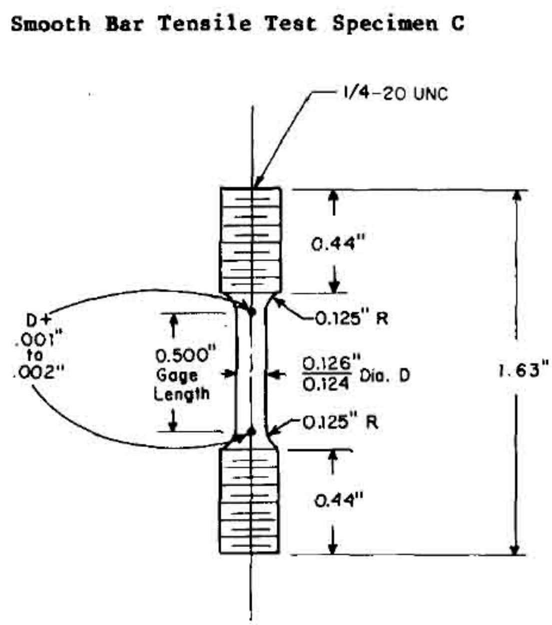
When the data or the references are not found, the entries in Tables 5 to 8 will be marked as “-”.



(a) Tensile Specimen A,
Gage length: 50.8 mm (2 in.)



(b) Tensile Specimen B,
Gage length: 25.4 mm (1 in.)



(c) Tensile Specimen C, Gage length: 12.7 mm (½ in.)

Figure 1 SRL tensile test specimens

Table 5 Tensile properties for Fe-Cr-Ni Alloys

Alloy	Test Environ-ment.	Strength (MPa)		Ductility (%)				Ref.
		Stress at 0.2% offset unless specified	Ultimate Tensile Strength (UTS) unless specified	Uniform Elonga-tion	Total Elonga-tion	Speci-men Type and Gage (mm)	Reduction of Area (RA)	
304L As received Grain Size (GS)=9.5 μm	Air He H_2	- 390 (5%) 390 (5%)	- 574 583	- 62 56	- 71 62	Type B (25.4)	- 89 76	[1] IA-9, [13]
304L Sensitized at 920K 24hrs (GSH10 μm)	Air He H_2	- 380 (5%) 380 (5%)	- 596 599	- 56 57	- 63 63	Type B (25.4)	- 82 68	[13]
304L Annealed at 1170K for 24hrs GS=30μm	Air He H_2	- 260 (5%) 240 (5%)	- 532 515	- 82 88	- 89 94	Type B (25.4)	- 90 92	[1] IA-9, [13]
304L Annealed at 1270K for 24hrs GS=55μm	Air He H_2	- 250 (5%) 240 (5%)	- 510 500	- 90 86	- 99 91	Type B (25.4)	- 90 69	[1] IA-9, [13]
304L annealed at 1470K for 24hrs GS=340μm	Air He H_2	- 190 (5%) 180 (5%)	- 458 451	- 81 84	- 88 88	Type B (25.4)	- 89 65	[1] IA-9, [13]
304L As machined	Air He H_2	- - 370 (5%)	- - 569	- - 60	- - 66	Type B (25.4)	- - 78	[13]
304L Electro- polished	Air He H_2	- 376 (5%) 370 (5%)	- 589 593	- 68 62	- 76 73	Type B (25.4)	- 91 90	[13]
304L Electro- polished * Pd plated	Air He H_2	- - 390 (5%)	- - 591	- - 64	- - 73	Type B (25.4)	- - 85	[13]
304L Annealed at 1170K , 5 min. in Argon, Quenched in 8% UCONC® Coolant	Air He H_2	- - 270 (5%)	- - 519	- - 83	- - 93	Type B (25.4)	- - 87	[13]
304L Annealed at 1170K , 5 min. in vacuum, slow cool	Air He H_2	- - 260 (5%)	- - 532	- - 86	- - 92	Type B (25.4)	- - 83	[13]
304L Solution Anneal	Air He H_2	380 (5%) 375 (5%) 370 (5%)	630 (true) 600 (true) 580 (true)	- - -	- - -	Type B (25.4)	86 89 75	[1] IA-12

304L Sensitized	Air He H_2	300 (5%) 350 (5%) 330-350 (5%)	560 (true) 670 (true) 660 (true)	- - -	- - -	Type B (25.4)	83 89 50-55	[1] IA-12
304N	Air He H_2	760 630 640	880 850 840	- - -	33 43 36	Type A (50.8)	71 74 54	[1] IB-1
309S	Air He H_2	290 276 260	600 580 586	- - -	54 60 63	Type A (50.8)	72 71 74	[1] IC-1
310	Air He H_2	210 180 186	540 480 490	- - -	61 70 67	Type A (50.8)	79 80 82	[1] ID-2
316 (unknown data source)	Air He H_2	- 186 (?) 206 (?)	- 565 (?) 503 (?)	- - -	- 74 48	(?)	- 81 33	[14]
Carpenter 20 Cb-3	Air He H_2	236 - 230	600 - 590	- - -	48 - 48	Type B (25.4)	68 - 68	[1] IF-1
Incoloy® 800H	Air He H_2	310 (5%) - -	554 - -	48 - -	55 - -	Type B (25.4)	62 - -	[1] IG-1
Nickel 200 Annealed at 1090K, 15 min, furnace cooled	Air He H_2	88 (5%) 120 (5%) 106 (5%)	506 (true) 490 (true) 470 (true)	- - -	55 55 51	Type A (50.8)	90 91 53	[1] IH-1
Nickel 200 Annealed at 1090K, 15 min, Plus annealed at 773K, 64 hrs, air cooled	Air He H_2	135 (5%) 122 (5%) 156 (5%)	480 (true) 450 (true) 460 (true)	- - -	50 48 45	Type A (50.8)	89 87 50	[1] IH-1
Nickel 301 Annealed at 1170K, 5 min, quenched	Air He H_2	451 (5%) 486 (5%) 532 (5%)	778 (true) 791 (true) 618 (true)	- - -	39 34 12	Type A (50.8)	85 74 20	[1] IJ-1
Nickel 301 Annealed at 1170K, 5 min, Plus annealed 860K 16 hrs, 810K 5 hrs, and 755K 5 hrs, furnace cooled	Air He H_2	1008 (5%) 1009 (5%) -	1380 (true) 1350 (true) 850 (true)	- - -	23 22 4	Type A (50.8)	39 34 0	[1] IJ-1

Table 6 Tensile properties for Fe-Cr-Ni-Mn Alloys

Alloy	Test Environ-ment.	Strength (MPa)		Ductility (%)				Ref.
		Stress at 0.2% offset unless specified	Ultimate Tensile Strength (UTS) unless specified	Uniform Elonga-tion	Total Elonga-tion	Speci-men Type and Gage (mm)	Reduction of Area (RA)	
Tenelon® (U.S. Steel Corp)	Air He H_2	570 500 500	930 875 900	- - -	56 65 55	Type A (50.8)	65 68 47	[1] IIA-2
Nitronic®-40 (21-6-9) (Armco, Inc)	Air He H_2	400 350 360	670 700 700	- - -	58 69 61	Type A (50.8)	78 77 76	[1] IIB-5
Nitronic®-40 (21-6-9) Cold worked 30%	Air He H_2	1240 1010 980	1290 1050 1100	- - -	26 26 26	Type A (50.8)	58 63 64	[1] IIB-6
Nitronic®-40 (21-6-9) HERF	Air He H_2	610 570 570	790 780 790	- - -	34 34 30	Type A (50.8)	74 75 73	[1] IIB-8
21-6-9 As received	Air He H_2	- 640 650	- 741 755	- 42 41	- 52 50	Type B (25.4)	- 67 70	[15] p.130
21-6-9 Heat treated at 923K 2 hrs, Argon cooled	Air He H_2	- 620 620	- 770 763	- 43 42	- 50 49	Type B (25.4)	- 78 78	[15] p.130
21-6-9 Heat treated at 923K 24 hrs, Argon cooled	Air He H_2	- 607 600	- 760 756	- 46 46	- 53 52	Type B (25.4)	- 75 67	[15] p.130
Nitronic®-50 (22-13-5) (Armco, Inc)	Air He H_2	440 400 400	710 680 680	- - -	43 47 45	Type A (50.8)	72 74 73	[1]IIC-2
18-18® Plus (carpenter Technology)	Air He H_2	- 520 506	- 910 800	- - -	- 63 42	Type A (50.8)	- 78 34	[1] IID-1 [2]
X18-3 Mn	Air He H_2	580 530 520	810 790 790	- - -	45 50 46	Type A (50.8)	71 74 73	[1] IIE-1
18-2 Mn	Air He H_2	730 - 660	1007 - 924	- - -	51 - 33	Type A (50.8)	58 - 27	[1] IIF-1
216	Air He H_2	640 590 590	810 790 780	- - -	40 45 44	Type A (50.8)	67 70 69	[1] IIG-1

Table 7 Precipitation Hardenable Alloys

Alloy	Test Environ-ment.	Strength (MPa)		Ductility (%)				Ref.
		Stress at 0.2% offset unless specified	Ultimate Tensile Strength (UTS) unless specified	Uniform Elonga-tion	Total Elonga-tion	Speci-men Type and Gage (mm)	Reduction of Area (RA)	
A286 (unknown data source)	Air He H_2	- 724 (?) 710 (?)	- 1117 (?) 1131 (?)	- - -	- 26 34	(?)	- 47 49	[14]
JBK-75 HERF	Air He H_2	- 800 809	- 1090 1160	- 10 10	- 14 13	Type C (12.7)	- 47 33	[1] IIIB-1
17-4PH (No data)								
AM350 Annealed at 1310 to 1350K, air cooled, or water quenched	Air He D_2	420 420 430	1160 1240 520	- - -	70 55 2.6	(?)	- - -	[1] IIID-1
AM363 (No data)								
CG-27	Air He H_2	- 806 855	- 1165 1117	- - -	- 29 10	Type A (50.8)	- 26 12	[1] IIIF-1 [14]
CG-27 HERF	Air He H_2	- 1070 1034	- 1385 1138	- - -	- 12 1	Type A (50.8)	- 12 3	[1] IIIF-1
Ni-SPAN-C (Alloy 902)	Air He H_2	760 750 650	1186 1160 1130	- - -	10 16 15	Sheet (19)	- - -	[1] IIIG-1

Table 8 High Purity Alloys

Alloy	Test Environ-ment.	Strength (MPa)		Ductility (%)				Ref.
		Stress at 0.2% offset unless specified	Ultimate Tensile Strength (UTS) unless specified	Uniform Elonga-tion	Total Elonga-tion	Speci-men Type and Gage (mm)	Reduction of Area (RA)	
Alloy A 18CR-10Ni	Unknown Pressure Air He H_2	 350 (5%) - -	 780 - -	 62 - -	 73 - -	Type B (25.4)	 81 82 26	[1] IVA-1 [15] p.167
Alloy B 18CR-14Ni	Unknown Pressure Air He H_2	 340 (5%) - -	 640 - -	 61 - -	 69 - -	Type B (25.4)	 79 83 91	[1] IVB-1 [15] p.167
Alloy C 18CR-19Ni	Unknown Pressure Air He H_2	 330 (5%) - -	 610 - -	 49 - -	 58 - -	Type B (25.4)	 81 82 92	[1] IVC-1 [15] p.167

Hydrogen Effects on Tensile Ductility

The ductility loss is the most pronounced hydrogen effect on tensile test results for stainless steels. This significant phenomenon is reflected by the data reported in Reference [1], which documented the mechanical testing conducted at SRL from 1970s to 1983 for unexposed (not precharged) specimens that were tested in high pressure hydrogen; and for specimens precharged with hydrogen with various conditions (duration and temperature) and then tested in air, helium, or hydrogen environments. Most of the hydrogen pressure used for precharging or for test environment was 69 MPa. No systematic studies of pressure level effect on ductility were conducted.

Hydrogen concentrations were measured for some exposed tensile specimens and the results are listed in Table 9. In addition, the grain size and nickel content were found to be related to the degree of ductility loss in hydrogen environments (Fig. 2).

Hydrogen Concentration

The hydrogen concentration in metal may be an indication of degree of hydrogen damage. Specimens were cut from the gage or the end of the post-test tensile specimens and the hydrogen concentrations were measured with a LECO RH-1 Hydrogen Determinator [4]. Table 9 which was reproduced from Reference [4] shows the hydrogen concentration when the tensile specimens were exposed to 69 MPa deuterium (D_2) at 620 K for three weeks. The compositions of the alloys can be found in Tables 1 to 4 or from Appendix A. It is believed that the high hydrogen concentrations in Tenelon®, Nitronic® 40, and Nitronic® 50 were caused by the added nitrogen as austenite strengthener, which trapped the excess hydrogen [4].

Table 9 Hydrogen Concentration in Austenitic Stainless Steel Tensile Specimens [4]

Alloy	Hydrogen Concentration (cc D_2/cc alloy)
304L (bar)	4.5
310 (plate)	6.5
316 (bar)	4.9
330 (bar)	5.1
A286 (bar)	4.4
I800H (bar)	4.0
Nitronic® 40 (bar)	8.7
Nitronic® 50 (bar)	12.8
Tenelon® (bar)	10.0
A	2.3
B	5.1
C	4.8

Effect of Grain Size

Stainless steel 304L was heat treated to achieve various grain sizes ranging from 9.5 μm (as received) to 340 μm (annealed at 1470 K for 24 hours). Unexposed tensile specimens were tested in 69 MPa helium and in 69 MPa hydrogen. It can be seen from Figure 1 that 304L with the larger gain size is more susceptible to hydrogen damage in losing ductility [13]. This is the only known study at SRL using 304L stainless steel for grain size effect.

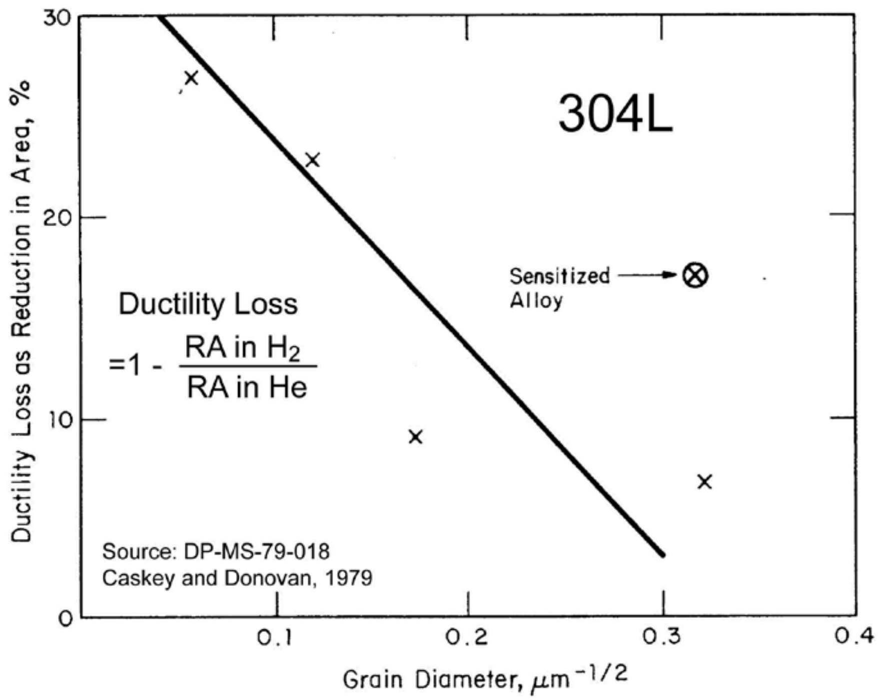


Figure 2 Ductility loss in 69 MPa hydrogen environment for 304L with various grain sizes [13]

Effect of Nickel Content

It was first pointed out by Caskey [1,3] that there is a strong correlation between the hydrogen embrittlement and the nickel content in the iron-chromium-nickel alloys based on tensile testing in 69 MPa hydrogen environment at room temperature. By plotting the retained ductility of the Fe-Cr-Ni alloys versus the nickel composition, it can be seen that the resistance of hydrogen damage in ductility begins to improve at nickel content between 8 to 14 wt.%. It is possible that the austenite stability was increased with respect to the transformation to α'-martensite at room temperature and to ε-martensite when the nickel content is increased (both α'-martensite and ε-martensite are detrimental to ductility). This correlation appeared to be valid for commercial grade and high purity alloys. The relationship between the retained ductility and the nickel content has been recently reconstructed by Morgan [12] and was modified by adding more alloy data. The resulting plot, similar to Figure 1 in Reference [1], is shown in Figure 3. Most of the data points were obtained by testing unexposed (not precharged) specimens in 69 MPa hydrogen, except A-286 and 17-4 for which hydrogen-precharged specimens were used in testing. The correlation between the resistance of hydrogen damage and nickel content was not unique for iron-chromium-nickel-manganese alloys. Therefore, they were not included in Figure 3.

Note that “Retained Ductility” in Figure 3 is defined as RA_{H2}/RA_{air} or RA_{H2}/RA_{He}, where RA_{H2}, RA_{air}, and RA_{He} are, respectively, the reduction of area (RA) for specimens tested in hydrogen, in air, and in helium. It appears that the optimal nickel content to retain the tensile ductility in wrought Fe-Cr-Ni alloys is 10 to at least 20 wt.%.

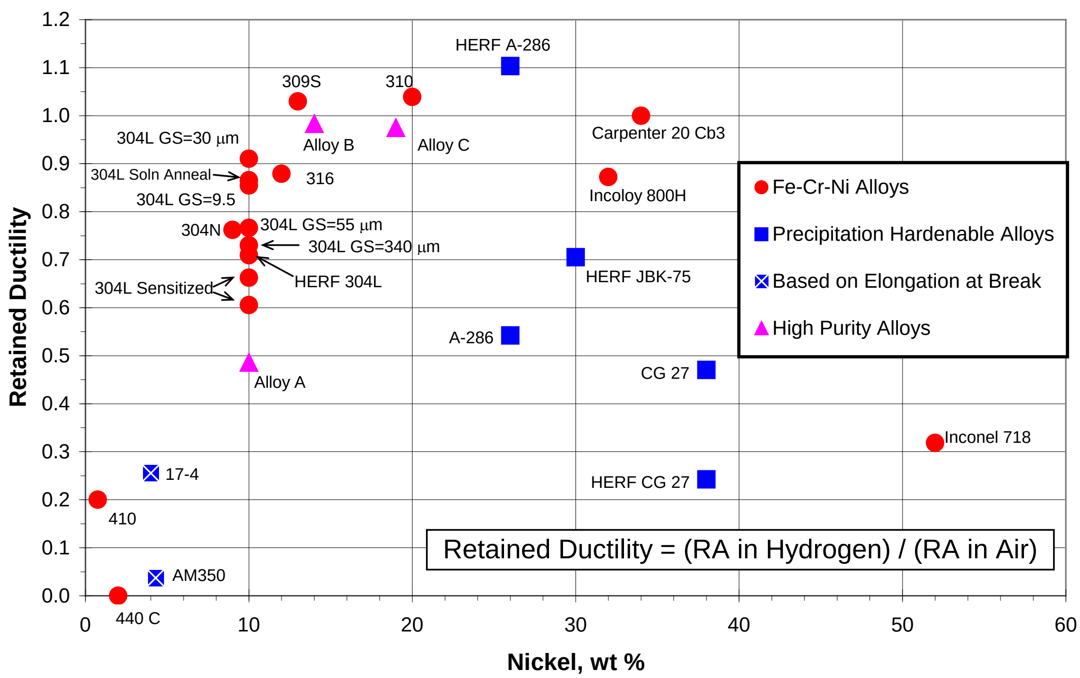


Figure 3 Correlation between retained ductility and nickel content for Fe-Cr-Ni and high purity alloys [16,1].

The actual values of the reduction of area for alloys in Figure 3 are shown in Figure 4, in which the retained ductility for each alloy was also plotted. These test results indicated that the ductility of alloys 309S, 310, and HERF A-286 was actually increased in the hydrogen environment, contrary to the common observation. It should be noted that alloy 440C contains zero nickel, and exhibited a completely brittle fracture at break (no reduction of area).

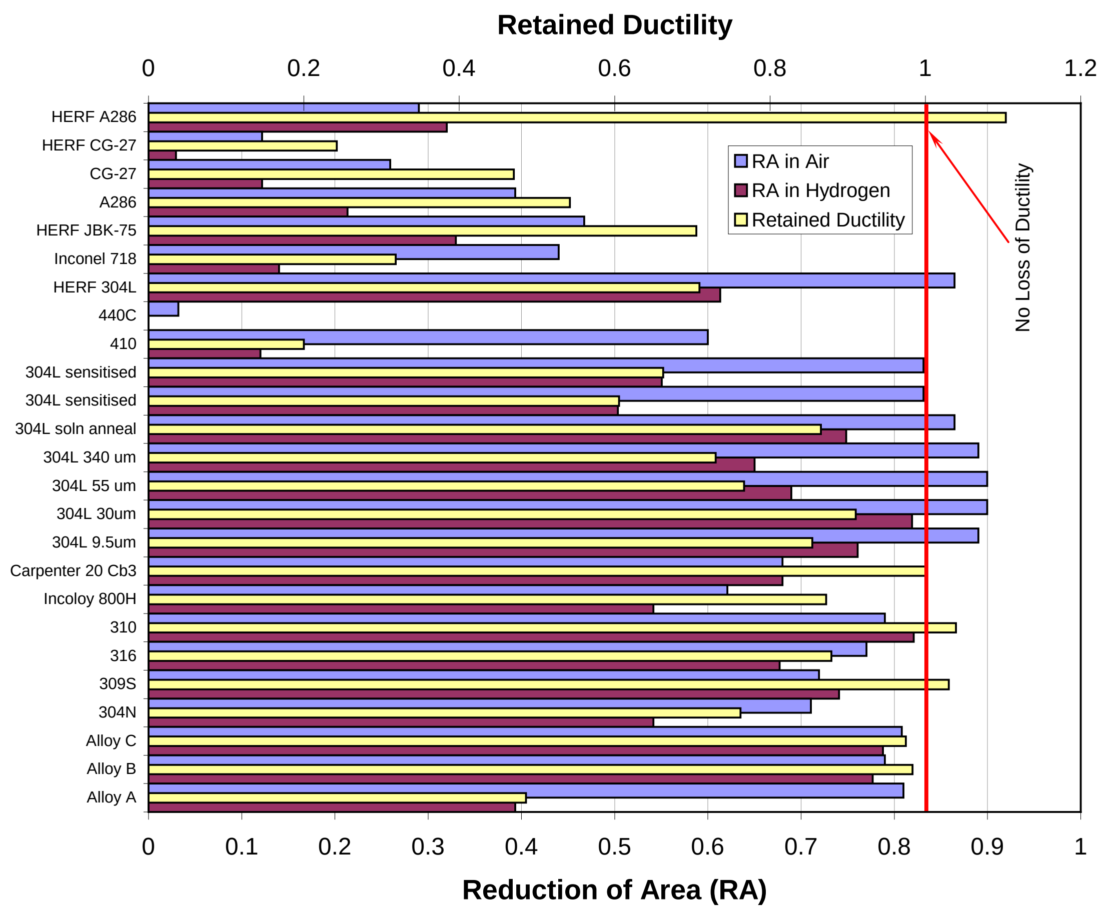
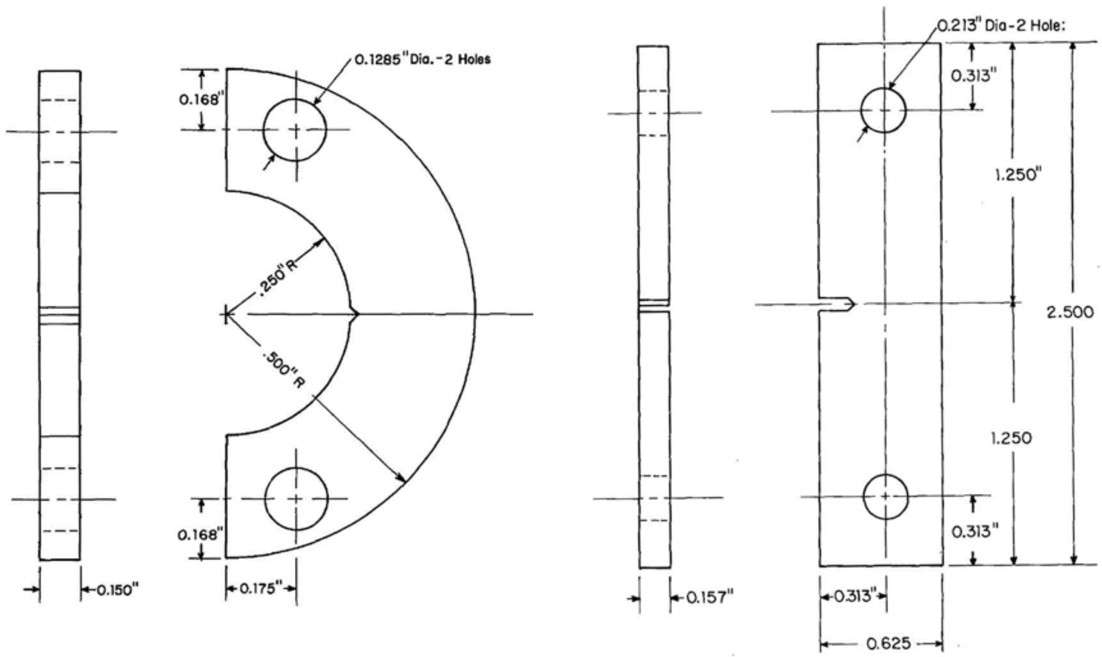


Figure 4 Reduction of area and retained ductility for Fe-Cr-Ni, precipitation hardenable, and high purity alloys.

FRACTURE PROPERTIES

The loss of fracture toughness is a pronounced hydrogen effect in stainless steels. Most of the SRL fracture testing was carried out with C-shaped specimens (Fig. 5a), which is a standard test specimen in ASTM E 399 [17] for linear elastic fracture mechanics. In addition, the single edge notched tension (SENT) specimens (Fig. 5b) were sometimes employed. The test results were summarized in Reference [1]; and for several HERF stainless steels, data can be found in Reference [18]. Because of the instrumentation difficulties for measuring fracture parameters in high pressure hydrogen environment, and the tedious test procedure for elastic-plastic fracture mechanics (ASTM E 813 [19]), SRL developed J_m approach [1] as an alternative parameter for J_{IC}. The J_m is the J-integral value calculated at the maximum load, at which the crack initiation was assumed to take place. A subsequent verification study was carried out with A-286 and 21-6-5 stainless steels [20] following ASTM E 813 procedure. It was demonstrated that the J_m is about 10% higher than J_{IC}. However, it was considered quite acceptable [20] because the J-integral testing with the same material using the same technique often times contains even higher data deviation than 10%, and that is the inherent nature of material ductile failure under elastic-plastic deformation. Furthermore, considering the data deviation resulted from different fracture toughness measurement techniques or different specimen types, the variation between J_m and ASTM J_{IC} appears to be small.



(a) C-shaped specimen (b) single edge notched tension (SENT)

Figure 5 SRL Fracture test specimens

Fracture Data for Forged Alloys

Strong orientation effects on the mechanical properties have been noted for HERF stainless steels, especially in the determination of fracture toughness. The C-shaped specimens were fabricated such that the initial machine notch was parallel (0°), 45°, or perpendicular (90°) to the forging flow lines. The schematic specimen layout [1,21] can be seen in Figure 6. The actual forging flow lines in such materials can be observed through scanning electron microscopes, as shown in Figure 7. It can be seen that the crack growth resistance is very poor when the initial notch is in parallel with the forging flow lines. A markedly higher J-integral can be obtained for notch orientation at 45° or 90° with respect to the flow lines.

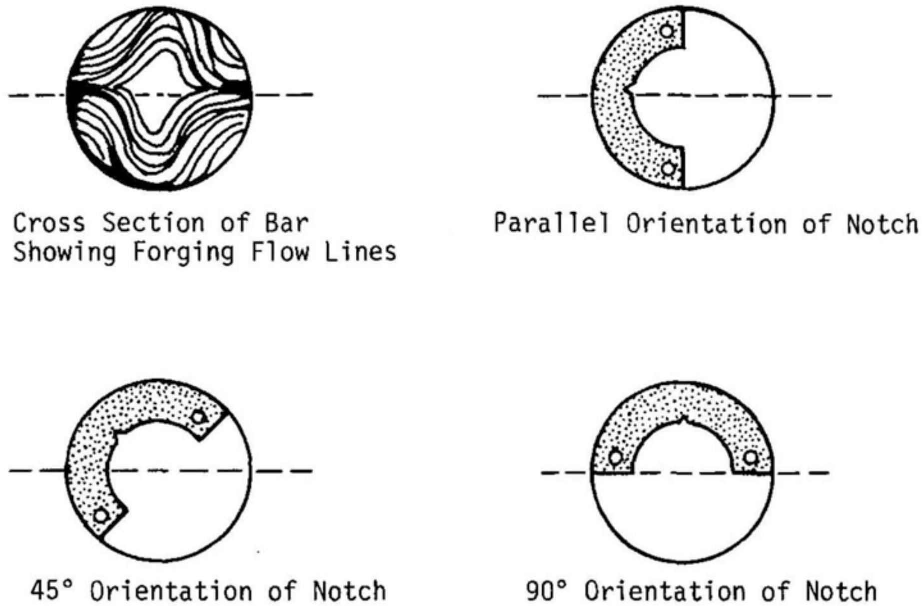
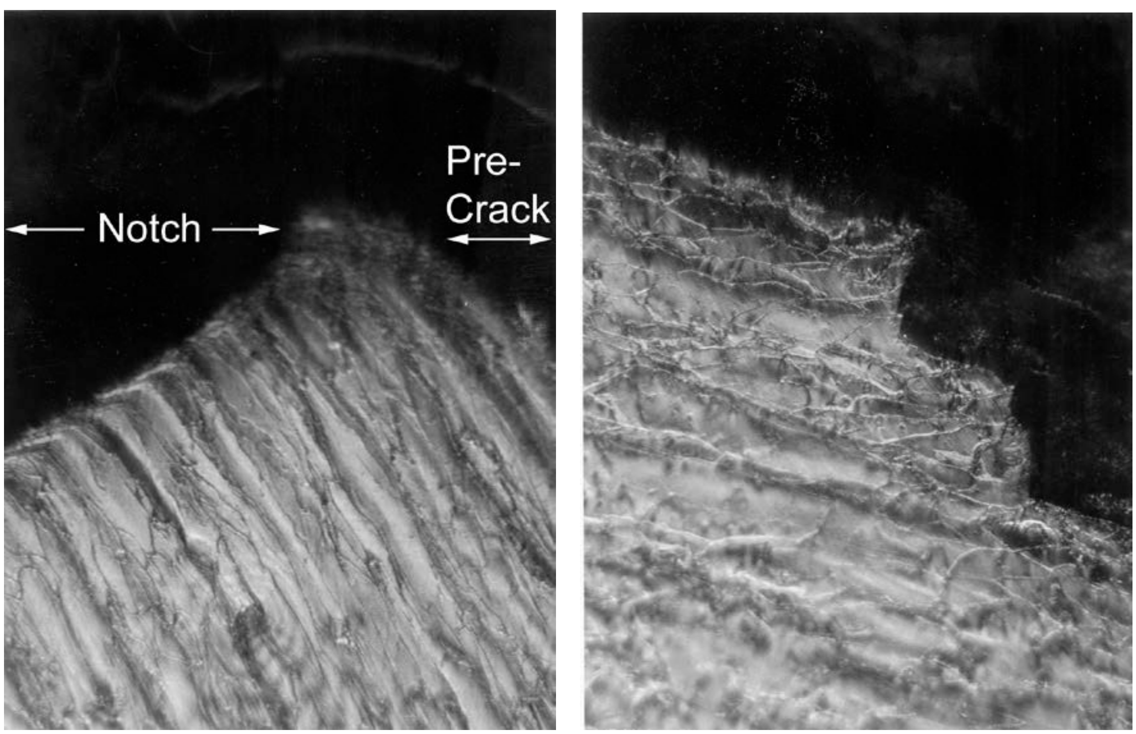


Figure 6 Notch orientation and the forging flow lines



(a) Specimen Cross-section (SEM 500X) (b) Fracture surface (SEM 500X)

Figure 7 Forging flow lines as shown by scanning electron microscope (SEM). The actual dimension was not labeled [21].

J-integral Testing (J_m)

The J-integral test data (J_m) for HERF 304L, Nitronic 40® (21-6-9), Nitronic 50® (22-13-5), A-286, and 316 are shown in Figures 8 to 12, respectively. Additional test data prior to June 1982 were summarized in Reference [21], which are reproduced in Table 10 and plotted in Figure 13. Note that the values of J_m have been corrected for combined tension and bending in the specimen, and were averaged if multiple orientations were tested.

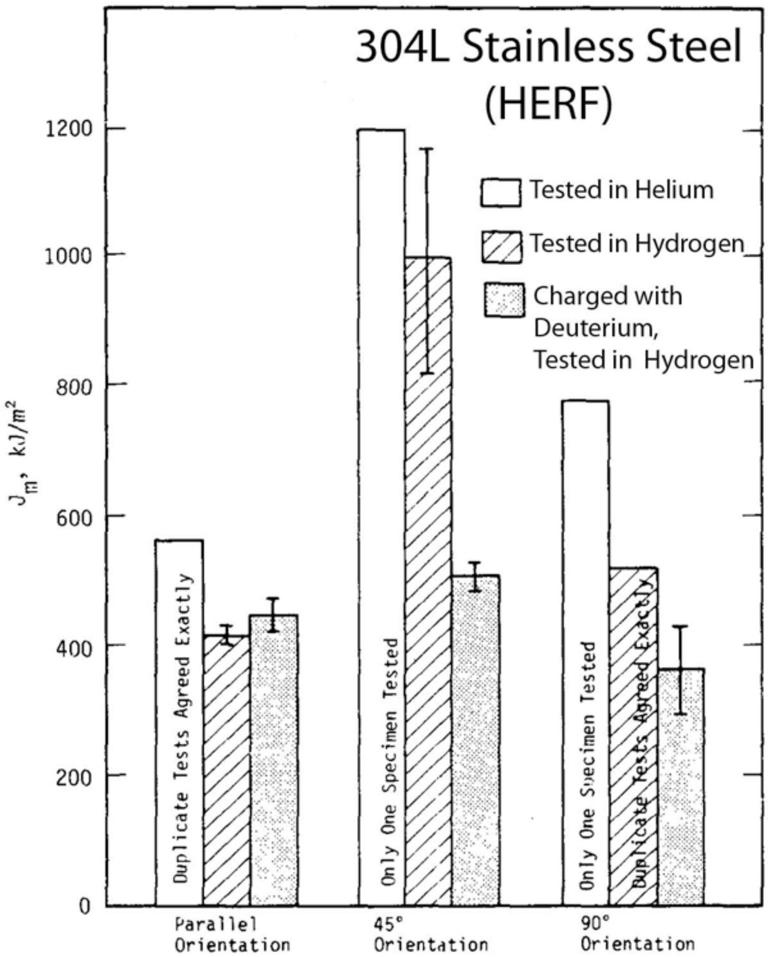


Figure 8 J-integral test results for HERF 304L under various test environments and specimen conditions [1].

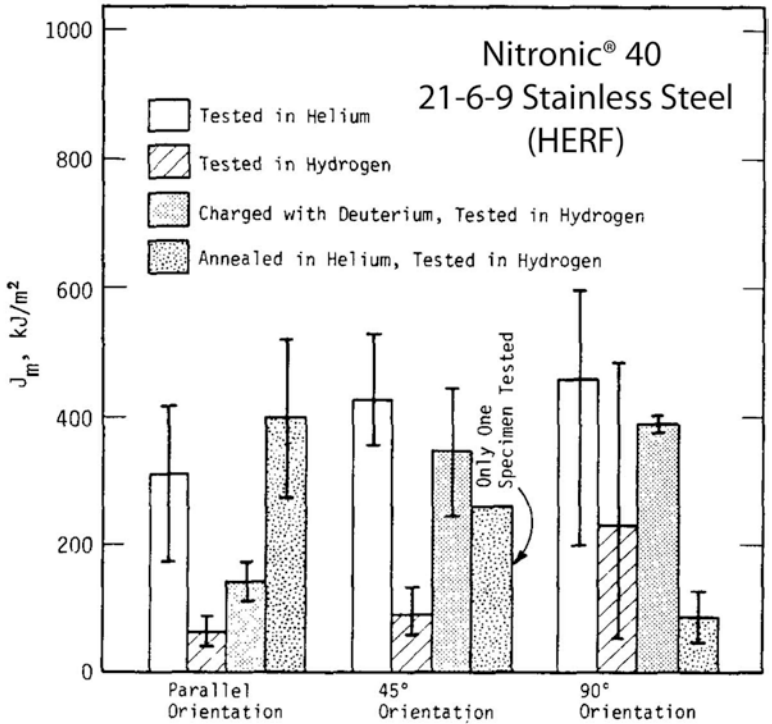


Figure 9 J-integral test results for HERF Nitronic 40® (21-6-9) under various test environments and specimen conditions. [1]

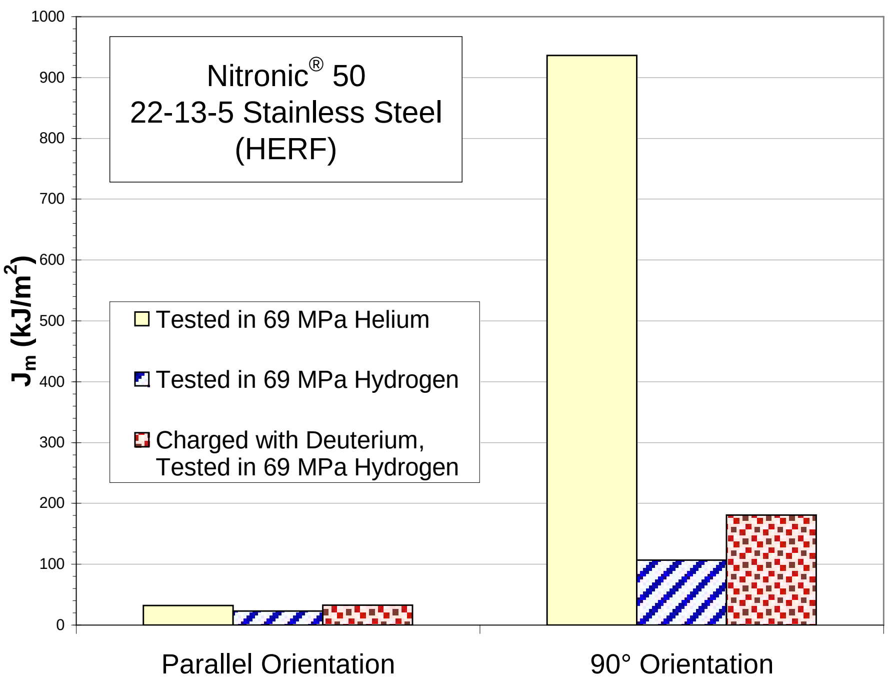


Figure 10 J-integral test results for HERF Nitronic 50® (22-13-5) under various test environments and specimen conditions (based on Data Sheet IIC-3 in Ref. [1]).

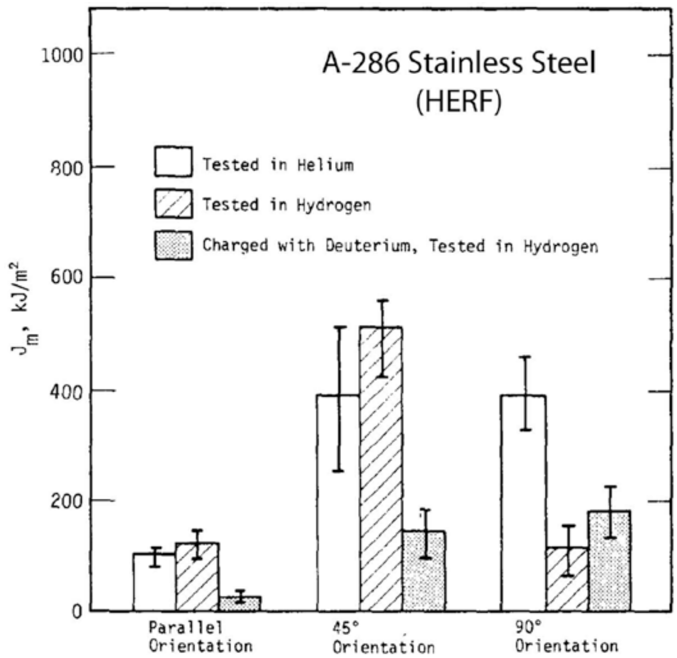


Figure 11 J-integral test results for HERF A-286 under various test environments and specimen conditions [1].

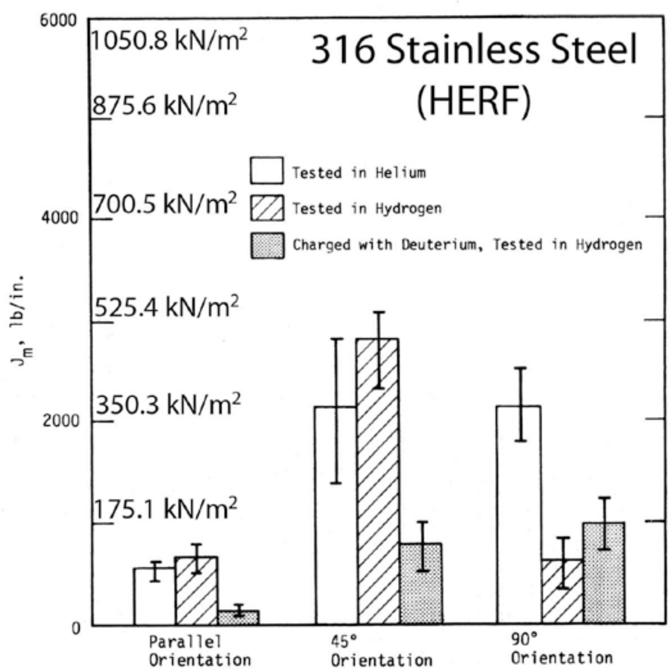


Figure 12 J-integral test results for HERF 316 under various test environments and specimen conditions [18].

Table 10 Summary of SRL fracture test results up to June 1982 [21]

Alloy	J_m[1] Tested in 69 MPa He (kJ/m^2)	J_m[1] Tested in 69 MPa H_2 (kJ/m^2)	J_m[1] Precharged in Deuterium and tested in 69 MPa H_2 (kJ/m^2)	Remarks
304L HERF	701	573	489	-
316 HERF	792	880	-	-
316 WR[2]	312	268	-	1 orientation
310S HERF	537	417	291	6J Forging
21-6-9 HERF[5]	686	475	695	-
21-6-9 HERF[5]		468	158	2 orientations
21-6-9 CRP[3]	1409	1158	-	Forging Step 7, 2 orientations
21-6-9 WR[2]	281	259	-	1 orientation
JBK-75 HERF	560	377	201	-
A-286 HERF	539	497	132	-
22-13-5 HERF	289	72	116	2 orientations
17-4PH STA[4]	80	4	-	-
17-4PH Annealed	995	85	-	-

1. J_m: with Merkle-Corten correction [22] for the combined tension and bending in specimens. The values were averaged if multiple orientations were tested.
2. WR: Warm Rolled
3. CRP: Cross-Rolled Plate
4. STA: solution treated/annealed
5. Alloys from different sources.

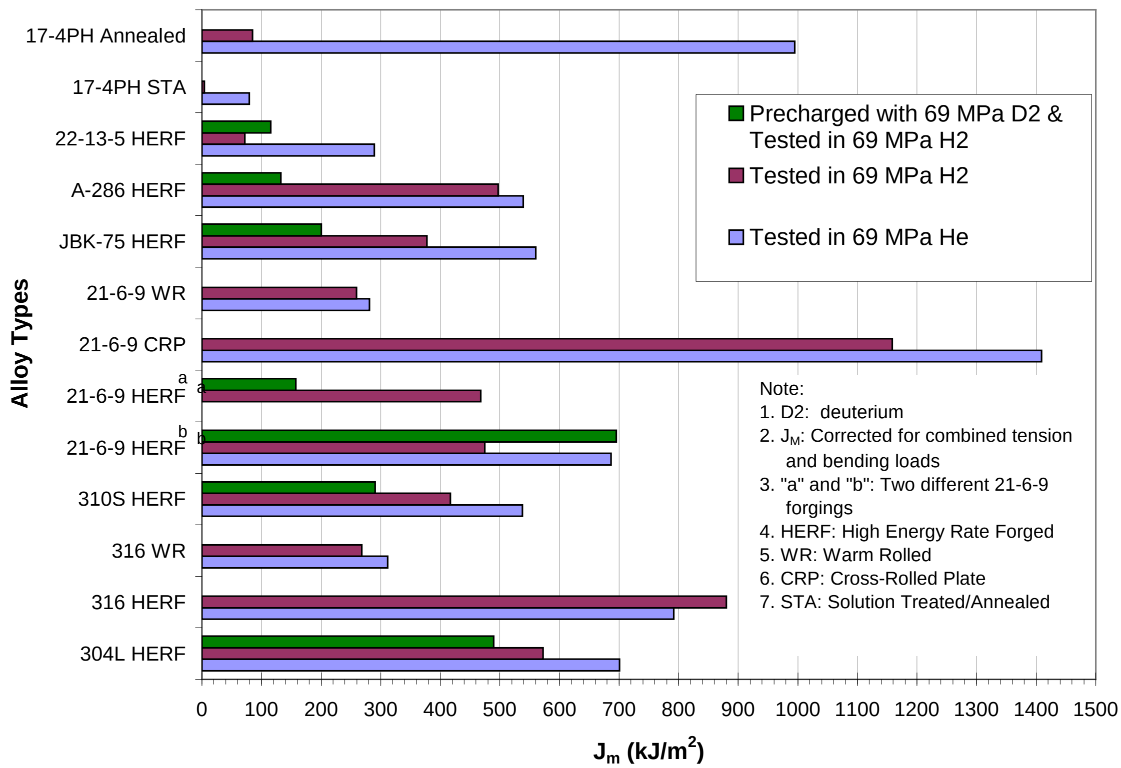


Figure 13 Fracture toughness (J_m) for various types of stainless steel. Note that the values for HERF materials were averaged by the number of orientations that were tested.

Thickness and Notch Effects (HERF 21-6-9)

Thickness and notch effects on fracture properties with C-specimens were investigated with HERF MP35N (nickel-cobalt based alloy) and HERF 21-6-9 in 69 MPa helium and in 69 MPa hydrogen [21]. In addition to the SRL standard C-specimen thickness (3.81 mm or ½ in.), another thickness of 6.35 mm (0.25 in.) was chosen. The initial machine notch length was 1.27 mm. Two specimens with 6.35 mm thick were not precracked (tested respectively in helium and in hydrogen). The test results for 21-6-9 are plotted in Figure 14. The data scatter is less for the standard thickness (thinner specimens).

The averaged J_m values for testing in helium are higher than that in hydrogen, which is consistent with the data trend of hydrogen damage. However, the overall data scattering leads to inconclusiveness for the thickness and the notch effects. In fact, the higher averaged values of J_m for thicker specimens seem to contradict the constraint theory in fracture mechanics, which predicts that, qualitatively, thinner specimens tend to have higher fracture toughness [23] because it allows much larger plastic zone to develop around the crack tip. All the discrepancies may be resulted from the anisotropy of the HERF materials (see Fig. 9 for alloy 21-6-9). A refined experiment with a carefully designed test matrix could resolve the discrepancies.

Two additional sets of test data found in Reference [21] are included in Figure 14: 1) Two specimens with different orientations precharged with deuterium in 69 MPa at 190 °C for six weeks and then tested in 69 MPa hydrogen environment; and 2) Two specimens tested in 69 MPa hydrogen in a separate experiment. These data further suggested that the testing for HERF materials be conducted with careful planning and characterization.

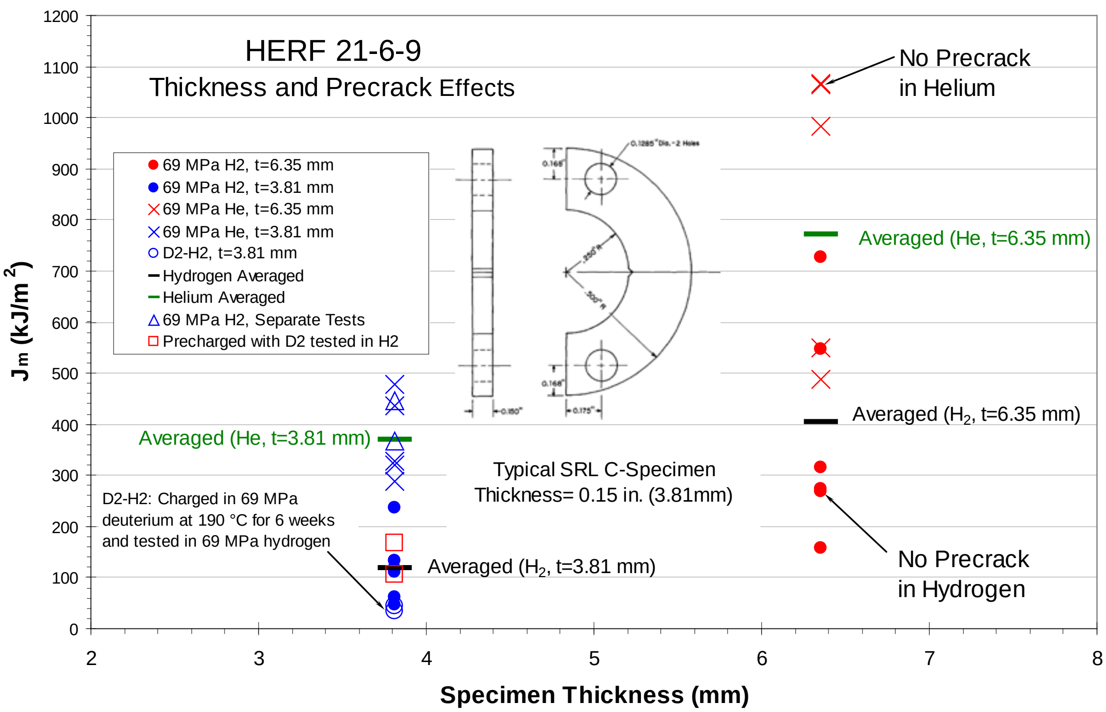


Figure 14 Thickness and notch effects on fracture toughness (J_m) of HERF 21-6-9 in hydrogen environment

Stress Intensity Factor (K) Testing

Alloys Tenelon®, HERF Nitronic® 40 (21-6-9), HERF A-286, HERF JBK-75, and 17-4 PH were tested for fracture toughness in terms of stress intensity factors under various test environments (temperatures or high pressure gases) and specimen preparations (aged, annealed, or exposed to hydrogen at difference pressures). The tests were conducted with either C-shaped (Fig. 4a) or SENT (Fig. 4b) specimens. The results are listed in Tables 10 to 14.

Table 11 Fracture toughness (K) for Tenelon®

Tenelon® (Ref.: Data Sheet IIA-3, Ref. [1], page 100)				
Test Specimen: SENT (Fig. 4b)				
Test Temperature (kelvin)	Test Environment	Specimen Condition	Specimen Exposure	Fracture Toughness ($MPa\sqrt{m}$)
78	-	As received	-	68.6
78	-	Annealed 1170 K	-	36.5
78	-	Annealed 1270 K	-	71.4
200	-	As received	-	127.8
200	-	Annealed 1170 K	-	99.6
200	-	Annealed 1270 K	-	120.5

Table 12 Fracture toughness (K) for HERF Nitronic® 40 (21-6-9)

Nitronic® 40 (Alloy 21-6-9) HERF (Ref.: Data Sheet IIB-10, Ref. [1], page 106)				
Test Specimen: C-specimen (Fig. 4a)				
Test Temperature (kelvin)	Test Environment	Specimen Condition	Hydrogen Exposure	Fracture Toughness ($MPa\sqrt{m}$)
298	69 MPa He	-	None	79
298	69 MPa H_2	-	none	81
298	69 MPa H_2	-	0.6 MPa H_2	62

Note: For independent test results for J_m, see Figure 9.

Table 13 Fracture toughness (K) for HERF A-286

A-286 HERF (Ref.: Data Sheet IIIA-2, Ref. [1], page 114)				
Test Specimen: SENT (Fig. 4b)				
Test Temperature (kelvin)	Test Environment	Specimen Condition	Hydrogen Exposure	Fracture Toughness ($MPa\sqrt{m}$)
298	69 MPa He	Aged 4 hrs 990 K (Heat 1)	none	76
298	69 MPa H_2	Aged 4 hrs 990 K (Heat 1)	(ditto)	89
298	69 MPa He	Aged 8 hrs 990 K (Heat 1)	none	71
298	69 MPa H_2	Aged 8 hrs 990 K (Heat 1)	(ditto)	90
298	69 MPa He	Aged 16 hrs 990 K (Heat 1)	none	81
298	69 MPa H_2	Aged 16 hrs 990 K (Heat 1)	(ditto)	82
298	69 MPa He	Aged 8 hrs 990 K (Heat 2)	none	93
298	69 MPa H_2	Aged 8 hrs 990 K (Heat 2)	none	89
298	69 MPa He	Aged 8 hrs 990 K (Heat 2)	1.6 MPa Deuterium	88
298	69 MPa H_2	Aged 8 hrs 990 K (Heat 2)	1.6 MPa Deuterium	97
298	69 MPa He	HERF, not aged, R_c-11	none	52
298	69 MPa H_2	HERF, not aged, R_c-11	none	56
298	69 MPa H_2	HERF, not aged, R_c-11	1.5 MPa Deuterium	59
298	69 MPa He	Aged 8 hrs 990 K R_c-11	none	93
298	69 MPa H_2	Aged 8 hrs 990 K R_c-11	none	90
298	69 MPa H_2	Aged 8 hrs 990 K R_c-11	1.5 MPa Deuterium	97

Table 14 Fracture toughness (K) for HERF JBK-75

JBK-75 HERF (Ref.: Data Sheet IIIB-2, Ref. [1], page 118)				
Test Specimen: C-specimen (Fig. 4a)				
Test Temperature (kelvin)	Test Environment	Specimen Condition	Hydrogen Exposure	Fracture Toughness ($MPa\sqrt{m}$)
298	69 MPa He	-	none	80
298	69 MPa H_2	-	none	80
298	69 MPa H_2		0.7 MPa Deuterium at 625 K	81

Table 15 Fracture toughness (K) for17-4 PH

17-4 PH (Ref.: Data Sheet IIIC-2, Ref. [1], page 119)				
Test Specimen: C-specimen (Fig. 4a)				
Test Temperature (kelvin)	Test Environment	Specimen Condition	Hydrogen Exposure	Fracture Toughness ($MPa\sqrt{m}$)
-	69 MPa He	Underaged[1]	-	104
-	3.5 MPa H_2	(ditto)	-	31
-	69 MPa H_2	(ditto)	-	20
-	69 MPa He	Peak aged[2]	-	97
-	3.5 MPa H_2	(ditto)	-	29
-	69 MPa H_2	(ditto)	-	13
-	69 MPa He	Overaged[3]	-	-
-	3.5 MPa H_2	(ditto)	-	57
-	69 MPa H_2	(ditto)	-	34
-	69 MPa He	Solution annealed[4]	-	97
-	3.5 MPa H_2	(ditto)	-	71
-	69 MPa H_2	(ditto)	-	31

Condition of Heat Treatments:
1 Solution annealed 2 hours at 1339 K and aged at 709 K, Hardness R_c= 38
2. Solution annealed 2 hours at 1339 K and aged at 783 K, Hardness R_c= 42
3. Solution annealed 2 hours at 1339 K and aged at 866 K, Hardness R_c= 35
4. Hardness R_c= 28

CONCLUDING REMARKS

A range of austenitic stainless steels were tested for hydrogen compatibility for service condition up to 69 MPa (10,000 psi) hydrogen and temperatures from 78 to 400 K (some tests were carried out at 4 K in liquid helium) at the Savannah River Laboratory to support materials selections and designs for systems in high pressure hydrogen service. These steels included the iron-chromium-nickel alloys (304L, 304N, 309S, 310, 316, Carpenter 20 Cb-3, Incoloy® 800H, Nickel 200, Nickel 301, and 440 C), iron-chromium-nickel-manganese alloys (Tenelon®, Nitronic®- 40 or 21-6-9, Nitronic®-50 or 22-13-5, 18-18 Plus®, X18-3 Mn, 18-2 Mn, and 216), precipitation hardenable alloys (A-286, JBK-75, 17-4PH, AM-363, CG-27, and Ni-SPAN-C or Alloy 902), and high purity alloys (18Cr-10Ni, 18Cr-14Ni, and 18Cr-19Ni). An in-depth summary of the hydrogen transport in these alloys (permeation) and the hydrogen effects on the mechanical properties (tensile and fracture) was provided by Caskey [1]. This present report reviewed the SRL test data which are in general not readily available in the open literature. The following conclusions can be made:

- Hydrogen has a minor influence on the yield stress and the ultimate tensile strength of the austenitic stainless steels. However, the tensile ductility suffers significant loss when the hydrogen is present, either externally as the service environment, or internally resulting from extended exposure or precharging. This material behavior (hydrogen embrittlement) is similar in carbon steels [24,25].
- The ductility loss increases as the grain size increases, as shown by 304L testing on the heat treatment effects [13] (Fig. 2).
- The retain ductility [1,16], defined by the ratio of reduction of area in hydrogen to the reduction of area in helium, correlates well with the nickel content in Fe-Cr-Ni alloys. The optimal nickel content to retain the tensile ductility in wrought Fe-Cr-Ni alloys is 10 to at least 20 wt.% (Fig. 3).
- The fracture toughness testing shows a strong orientation effect with respect to the forging flow lines in the high energy rate forged (HERF) stainless steels (Figs. 8-12).
- The fracture toughness (J-integral or stress intensity factor) is reduced significantly when the hydrogen is present in the test environment or internally in the metal by extended exposure to hydrogen (Figs. 8-13). Similar behavior has been observed for carbon steels [24].

The SRL test data also indicated that the specimen condition has significant influence on the mechanical property measurement, such as the surface polishing or plating, and the orientations in the HERF stainless steels. Previous testing attempted to explore the effects of specimen geometry (such as the sample thickness and precracking), but only inconclusive results were obtained. A refined experiment with advanced fracture mechanics analysis of the constraint effect may be employed to resolve the discrepancy and uncertainty.

More recent SRNL test data are mostly related to tritium exposure and aging, which results in helium-3, a radioactive decay product, and is a different mechanism for mechanical property degradation. Limited hydrogen effects were reported and the information is available in open literature (e.g., [26,27]). The general trend is consistent with the earlier data which have been covered in this report. The quantitative comparison is not possible because the alloy composition, specimen fabrication, exposure condition, and test environment may be different.

REFERENCES

[1] Caskey Jr., G. R., Hydrogen Compatibility Handbook for Stainless Steels, DP-1643, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, 1983.

[2] Caskey Jr., G. R. and Ratliff, J. T., Hydrogen Storage Systems, DPST-76-455, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, 1977.

[3] Caskey Jr., G. R., "Hydrogen Effects in Stainless Steel," in *Hydrogen Degradation of Ferrous Alloys*, eds. R. A. Oriani, J. P. Hirth, and M. Smialowski, Park Ridge NJ: Noyes Publications, pp. 822-862, 1985 (also DP-MS-82-090, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, 1982).

[4] Caskey Jr., G. R., "Hydrogen Damage in Stainless Steel," in *Environmental Degradation of Engineering Materials*, eds. M. R. Louthan, R. P. McNitt, and R. D. Sission, Virginia Polytechnic Institute, Blacksburg, VA, pp. 283-302, 1981 (also DP-MS-81-31, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, 1981).

[5] Louthan, M. R. and Caskey, Jr., G. R., "Hydrogen Transport and Embrittlement in Structural Metals," First World Hydrogen Energy Conference, Miami Beach, FL, March 1976 (also DPSTWD-75-156, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, 1975).

[6] Louthan, M. R., Caskey, Jr., G. R., Donovan, J. A., and Rawl, Jr., D. E., "Hydrogen Embrittlement of Metals," Materials Science and Engineering, vol. 10, pp. 357-368, 1972.

[7] Somerday, B. P. and San Marchi, C. W., "http://www.ca.sandia.gov/matlsTechRef/," Sandia National Laboratories, Livermore, California, 2008.

[8] Caskey Jr., G. R., DPSTN-2184, Laboratory Notebook, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, April 1969 to September 1971.

[9] Caskey Jr., G. R., "Fractography of Hydrogen-Embrittled Stainless Steel," Scripta Metallurgica, Vol. 11, pp. 1077-1083, 1977 (also DP-MS-77-51, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, 1977).

[10] Caskey Jr., G. R., "Fracture of Fe-Cr-Mn Austenitic Steel,", at the 108th Annual AIME Meeting, New Orleans, LA, Feb. 18-22, 1979 (also DP-MS-78-68, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, 1978).

[11] Caskey Jr., G. R., "Hydrogen Effects in High Purity Stainless Steels," in *The Third International Congress, Hydrogen and Materials*, Paris, France, June 7-11, 1982, pp. 611-616 (also DP-MS-81-80, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, 1981).

[12] Caskey Jr., G. R., "Hydrogen Effects in Austenitic Stainless Steels Based on the Fe-Cr-Mn-N System," at the Materials Research Society Symposium on Hydrogen in Metals, Boston, MA, Nov. 26-30, 1984 (also DP-MS-84-74, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, 1984).

[13] Caskey Jr., G. R. and Donovan, J. A., Effect of heat Treatment on Fracture of Type 304L Stainless Steel in a Hydrogen Environment, DP-MS-79-18, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, 1979; TMS-AIME Fall Meeting, Milwaukee, WI, Sept. 16-20, 1979.

[14] Capeletti, T. L. and Louthan Jr., M. R., "The Tensile Ductility of Austenitic Steels in Air and Hydrogen," Journal of Engineering and Technology, 99, pp. 153-158, 1977 (also DPSTWD-75-147, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, 1975).

[15] Caskey Jr., G. R., DPSTN-2357, Laboratory Notebook, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, November 1971 to September 1983.

[16] Morgan, M. J., “Effect of Nickel Content on Retained Ductility,” WSRC-STI-2007-00610, Washington Savannah River Company, Aiken, SC, October 2007.

[17] ASTM E 399, “Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{IC} of Metallic Materials,” American Society for Testing and Materials, Philadelphia.

[18] Dietrich, M. R., Caskey Jr., G. R., and Donovan, J. A., “J-Controlled Crack Growth as an Indicator of Hydrogen-Stainless Steel Compatibility,” in *Proceedings of the International Conference on Effect of Hydrogen on Behavior of Materials: Hydrogen Effects in Metals*, Moran WY., The Metallurgical Society of AIME, pp. 637-643,1980.

[19] ASTM E 813, "Standard Test Method for J_{IC}, a Measure of Fracture Toughness" American Society for Testing and Materials, Philadelphia.

[20] Wheeler, D. A., “Experimental Verification of the J_{max} Technique for Fracture Toughness Measurements,” Memorandum DPST 87-836, Technical Division, Savannah River Laboratory, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, November 1987.

[21] Mezzanotte, D. A., Laboratory Notebook, DPSTN-3305, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, June 1981 to August 1983.

[22] Merkle, J. G. and Corten, H. T., “A J-integral Analysis for the Compact Tension Specimen, Considering Axial Force as well as Bending Effects,” Transactions of American Society of Mechanical Engineers, Journal of Pressure Vessel Technology, vol. 96, pp. 286-292, 1974.

[23] Roos, E., Eisele, U., and Silcher, H., “Effect of Stress State on Ductile Fracture Behavior of Large-scale Specimens,” in *Constraint Effects in Fracture*, ASTM STP 1171, eds. E. M. Hackett, K. H. Schwalbe, and R. H. Dodds, American Society for Testing and Materials, Philadelphia, pp. 41-63, 1993.

[24] Lam, P.-S., Sindelar, R. L., and Adams, T. M., “Literature Survey of Gaseous Hydrogen Effects on the Mechanical Properties of Carbon and Low Alloy Steels,” Paper No. PVP2007-26730, Proceedings of ASME Pressure Vessels and Piping Conference, San Antonio, Texas, July 2007.

[25] Duncan, A. J., Lam, P.-S., Adams, T. M., “Tensile Testing of Carbon Steel in High Pressure Hydrogen,”, Paper No. PVP2007-26736, Proceedings of ASME Pressure Vessels and Piping Conference, San Antonio, Texas, July 2007

[26] Morgan, M. J., “The Effects of Hydrogen Isotopes and Helium on the Flow and Fracture properties of 21-6-9 Stainless Steel,” in Morris E. Fine Symposium, eds. P. K. Liaw, J. R. Weertman, H. L. Marcus, and J. S. Santner, The Minerals, Metals& Materials Society, pp. 105-111, 1991.

[27] Morgan, M. J., “Hydrogen Effects on the Fracture Toughness Properties of Forged Stainless Steels,” PVP2008-61390, Proceedings ASME Pressure vessels and Piping Conference, Chicago, Illinois, July 27-31, 2008.

APPENDIX

Savannah River Laboratory Data Sheets

(Reference [1])

The original data source which is referenced in Tables 1 through 4 of this report is included in **Appendix A**.

The measured properties in the data sheets may be differently from the customary definitions. The original definitions for these data sheets are reproduced from Reference [1] and are listed in **Appendix B**.

Mechanical test specimen types and dimensions for the data sheets are included in **Appendix C**.

Some of the data sheets referenced the actual heats of the alloys that were tested. These heats are summarized in **Appendix D**.

Appendix A

Alloy Data Sheets

	Data Sheet
I. Iron-Chromium-Nickel Alloys	
304L	IA-1 to IA-16
304N	IB-1
309S	IC-1
310	ID-1 to ID-2
316	IE-1
Carpenter 20 Cb-3	IF-1
Incoloy® 800H (Huntington Alloys, Inc)	IG-1
Nickel 200	IH-1 to IH-2
Nickel 301	IJ-1 to IJ-2
440 C	IK-1
II. Iron-Chromium-Nickel-Manganese Alloys	
Tenelon® (U.S. Steel Corp)	IIA-1 to IIA-3
Nitronic®-40 (21-6-9)(Armco, Inc)	IIB-1 to IIB-12
Nitronic®-50 (22-13-5)(Armco, Inc)	IIC-1 to IIC-3
18-18 Plus® (Carpenter Technology)	IID-1
X18-3 Mn	IIE-1
18-2 Mn	IIF-1
216	IIG-1
III. Precipitation Hardenable Alloys	
A-286	IIIA-1 to IIIA-5
JBK-75	IIIB-1 to IIIB-2
17-4PH	IIIC-1 to IIIC-2
AM-350	IIID-1
AM-363	IIIE-1
CG-27	IIIF-1
Ni-SPAN-C (Alloy 902)	IIIG-1
IV. High Purity Alloys	
A - 18Cr-10Ni	IVA-1
B - 18Cr-14Ni	IVB-1
C - 18Cr-19Ni	IVC-1

<u>Nominal</u> Alloy Composition (wt.%)

Alloy	Cr	Ni	Mn	Mo	Other
Fe-Cr-Ni-Alloys					
304L	19	10	-	-	
304N	19	9	-	-	0.13 N
309S	23	13	-	-	
310	25	20	-	-	0.25 C
316	17	12	-	2.5	
440C	19	-	-	0.75	0.95 to 1.20 C
Carpenter 20 Cb-3	20	34	-	2.5	3.5 Cu, 06 Nb
I800H	21	32	-	-	0.75 Cu, 0.3 Al, 0.3 Ti
I718	19	52	-	13	5 (Nb + Ta), 1 Ti, 0.5 A
Ni200	-	99+	-	-	
Ni301	-	bal	-	-	1 Si, 4.5 Al, 0.6 Ti
Fe-Cr-Ni-Mn-N Alloys					
216	20	6	8	2	0.32 N
Tenelon®	18	-	15	-	**(see Note below)**
Nitronic®-40	21	6	9	-	0.15 to 0.4 N
Nitronic®-50	22	13	5	2	0.2 to 0.4 N
18-18 Plus®	18	0.5	18	1	0.4 N, 1 Cu, 0.1 Co
X 18-3 Mn	18	3	12	-	0.3 N
18-2 Mn	18	2	13	-	
Precipitation-Hardenable Alloys					
17-4 PH	16.5	4	-	-	4 Cu, 0.3 Nb
A-286	15	26	-	1.25	2 Ti, 0.25 Al, 0.3 V
JBK-75	15	30	-	1.25	2 Ti, 0.25 Al, 0.001 B, 0.25 V
AM363	11.5	4.5	-	-	0.5 Ti
CG27	13	38	-	6	2.5 Ti, 1.6 Al, 0.6 Nb
AM350	16.5	4.3	-	2.8	0.1 N
Ni-SPAN-C Alloy 902	5	42	-	-	0.5 Al, 2.5 Ti
High-Purity Alloys					
A	18	10	-	-	N <0.01 in all
B	18	14	-	-	three alloys
C	18	19	-	-	

Note: The nitrogen content in Tenelon® was 0.40 to 0.60 wt.% as listed in Ref. [10]: "Fracture of Fe-Cr-Mn Austenitic Steel," by G. R. Caskey, Jr., DP-MS-78-68, E. I. du Pont de Nemours & Co, Savannah River Laboratory, Aiken, SC, 1978; presented at the 108th Annual AIME Meeting, New Orleans, LA, Feb. 18-22, 1979.

<u>Nominal</u> Tensile Properties for Annealed Materials (unless otherwise noted)

Alloy	Strength, MPa Yield*	Tensile	Elongation, %
304L	230–270	540–560	55–60
304N	290–330	620	50–55
309S	275–310	620–650	45
310	310	650	45–50
316	207–290	550–585	45–50
440C	450–1890	760–1965	2–14
Carpenter 20 Cb-3	250	600	50
I800H	140–345	450–650	30–50
I718	1180–1250	1350–1400	16
Ni 200	103–207	380–550	40–55
Ni 301	210–1200	620–1450	15–55
216	428	745	50
Tenelon®	570	930	56
Nitronic®-40	414	690	40
Nitronic®-50	448	828	45
18-18 Plus®	520	900	60
X 18-3 Mn	580	810	45
18-2 Mn	730	1000	51
17-4 PH	940	980	5
A-286	760	1100	25
JBK-75**	800	1090	14
AM 350	420	1160	70
AM 363	890	890	7
CG 27	810	1160	29
Ni-SPAN-C Alloy 902	760–870	900–1200	6–25

* 0.2% offset.

** HERF & Age.

Measured Mechanical Properties at Savannah River Laboratory

IRON-CHROMIUM-NICKEL ALLOYS

DATA SHEET IA-1

Type 304L Stainless Steel Bar Stock, As Received*

Test Condition		Hydrogen**	Strength, MPa		Elongation, %		Fracture
Temp, K	Environ.	Exposure	Yield	Ultimate	Uniform	Total	Strain
380	AIR	NONE	240	680	58	69	1.78
		69 MPa	260	730	60	70	1.27
273	AIR	NONE	310	1160	80	89	1.56
		69 MPa	330	870	44	44	0.45
200	AIR	NONE	360	1500	61	70	1.27
		69 MPa	390	1210	44	44	0.25
78	LN	NONE	390	2200	60	64	1.27
		69 MPa	430	2100	59	65	1.27

* Heat Analysis, Appendix D-1; Tensile B, Appendix C-2.

** Exposure conditions: 69 MPa at 470 K for 1449 days.

DATA SHEET IA-2

Type 304L Stainless Steel, As Received

Test Conditions		Hydrogen	Impact
Temp, K	Environ.	Exposure	Energy, J
298	AIR	NONE	194
		17.9 MPa*	185
78	AIR	NONE	165
		17.9 MPa*	110

* 17.9 MPa hydrogen pressure at 470 K for 1000 hours.

DATA SHEET IA-3

Effect of Test Environment on Tensile Properties of Type 304L Stainless Steel Tubes*

Exposure Conditions			Tensile Properties		
Gas	Temp, K	Time, days	σ_y, MN/m^2	σ_{ult}, MN/m^2	% Elong.
He	425	32	270	560	59
H_2	425	32	320	480	19
T_2	425	32	300	490	22
H_2	425	8	260	490	26
T_2	425	8	250	490	22

* All tensile tubes tested at room temperature with 69 MPa gas; data reported are averages of at least two samples.

DATA SHEET IA-4

Tensile Properties of Type 304L Stainless Steels Containing Hydrogen and Helium

Test Condition		Hydrogen	Strength, MPa		Elong
Temp, K	Environment	Exposure	Yield	Ultimate	%
300	Air	none	327	734	49-56
300*	Air	**	400	733	28-32
300*	Air	**	434	744	28
973†	Air	none	152	237	31
973†	Air	**	179	190	1.5

* Specimens contained tritium and Helium-3.

** 328 mol hydrogen isotopes and 6.2 mol helium per m^3 metal.

† 146 mol hydrogen isotopes and 25 mol helium per m^3 metal. Held 1/2 hour at 973 K before testing.

DATA SHEET IA-5

Type 304L Stainless Steel, High Energy Rate Forged*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environ.	Exposure**	Yield	Ultimate	Uniform	Total	Strain
380	Air	None	440	630	32	44	1.72
		69 MPa	440	650	32	43	1.63
298	Air	None	480	930	57	68	2.00
		69 MPa	510	990	55	62	0.95
250	Air	None	490	1100	52	61	1.65
		69 MPa	610	1120	41	41	0.40
200	Air	None	660	1390	46	55	1.37
		69 MPa	620	1300	43	44	0.38

* Tensile B, Appendix C-2.

** Exposed at 620 K for 3 weeks.

DATA SHEET IA-6

Type 304L Stainless Steel, High Energy Rate Forged*

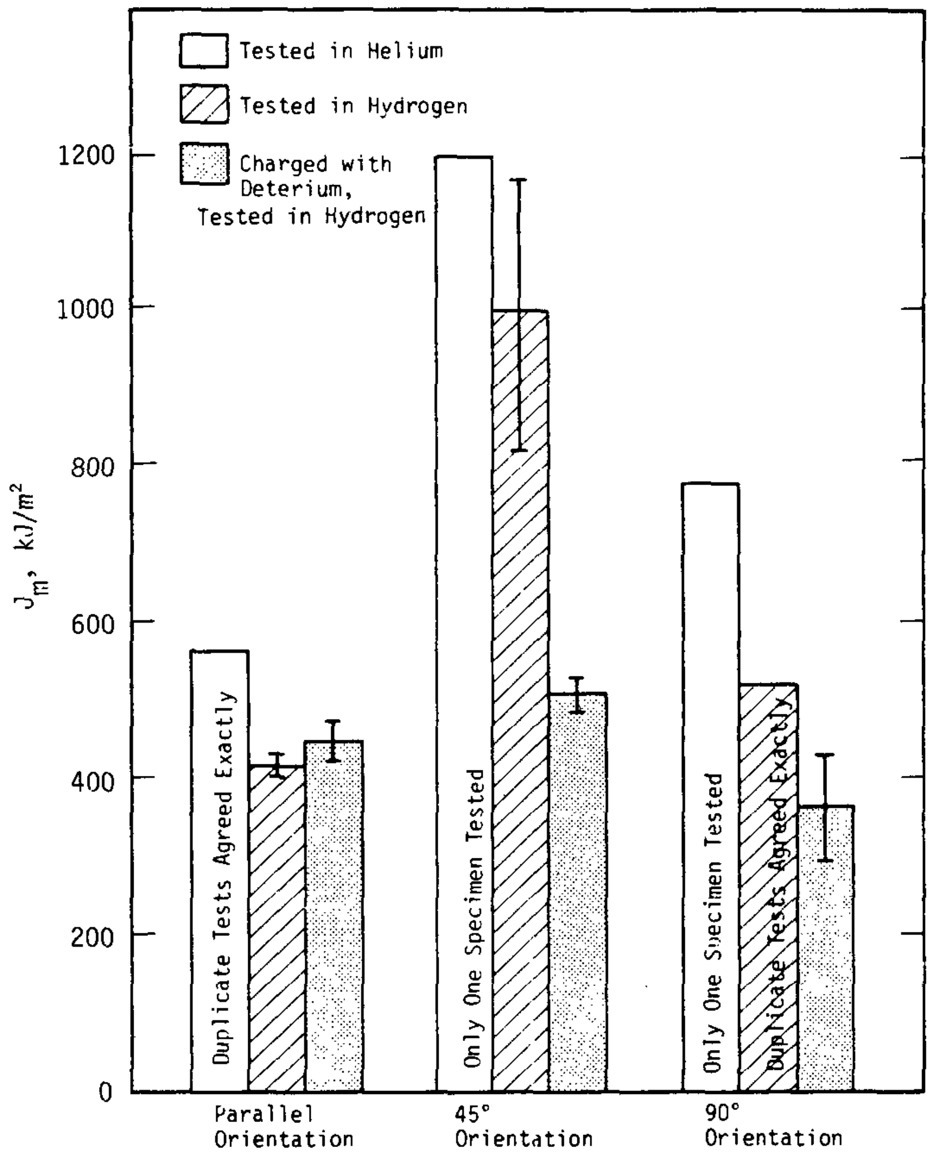
Test Condition		Hydrogen	Impact
Temp, K	Environ.	Exposure	Energy, J
298	Air	None	199
298	Air	29.6 MPa H_2**	152
77	Air	None	160
77	Air	29.6 MPa H_2**	95

* Impact, Appendix C-8.

** Exposure of 56 days at 470 K.

DATA SHEET IA-7

Fracture Parameters for Type 304L Stainless Steel, High Energy Rate Forged*

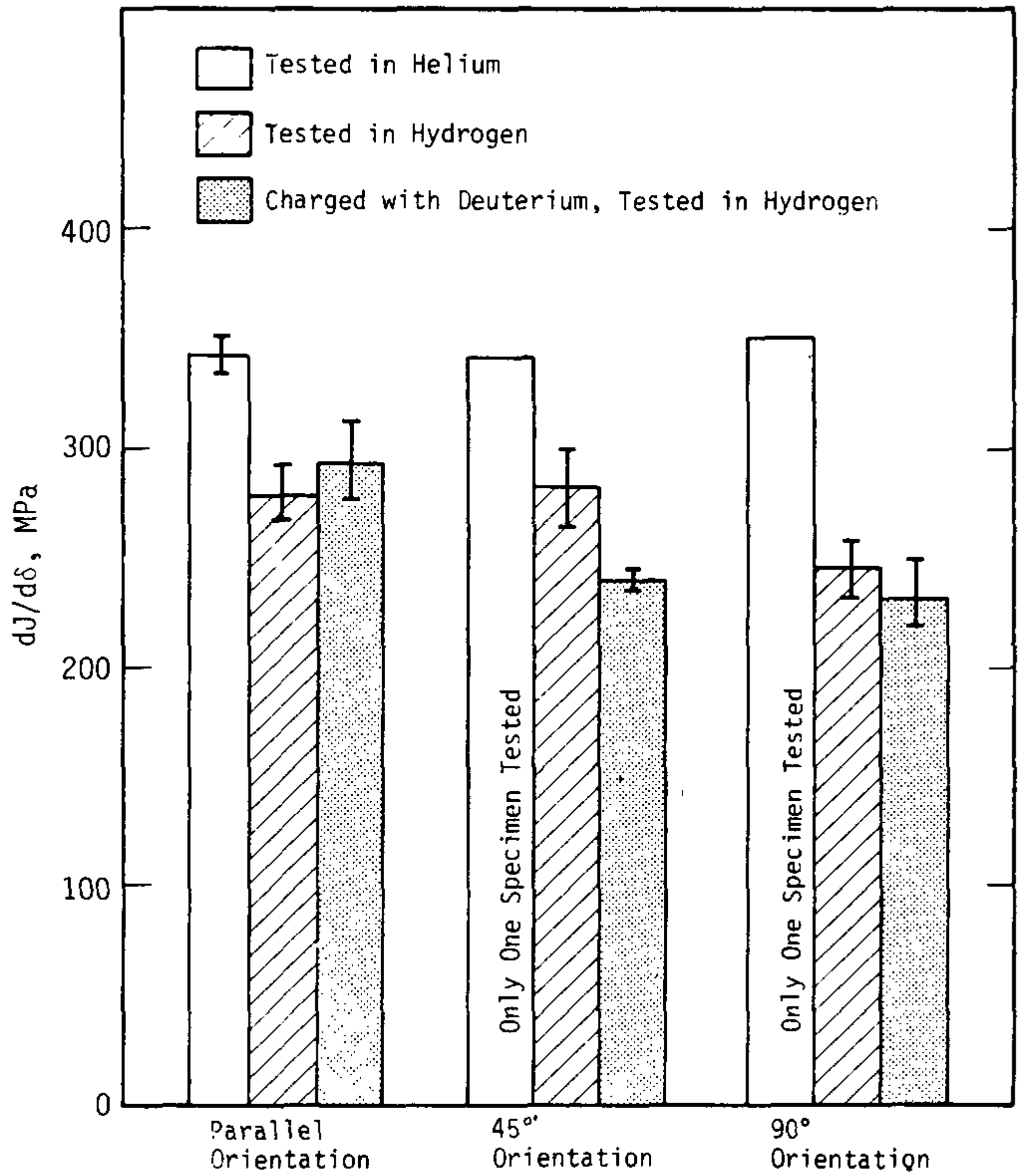


---

* C-shaped tensile, Appendix C-7. Test in 69 MPa He or H_2. Deuterium charge at 69 MPa at 620 K for 3 weeks.

DATA SHEET IA-8

Fracture Parameters for Type 304L Stainless Steel*



* C-shaped tensile, Appendix C-7. Test in 69 MPa He or H_2. Deuterium charge at 69 MPa at 620 K for 3 weeks.

DATA SHEET IA-9

Effect of Heat Treatment on Mechanical Properties of Type 304L Stainless Steel*

Heat Treatment	Test Environment	Strength, MPa		Elongation, %		Fracture Strain
		Yield	Ultimate	Uniform	Total	
As-received	69 MPa He	390	930	62	71	2.21
GS = 9.5 μm	69 MPa H_2	390	910	56	62	1.43
1170 K-24 hrs	69 MPa He	260	970	82	89	2.30
GS = 30 μm	69 MPa H_2	240	970	88	94	1.71
1270 K-24 hrs	69 MPa He	250	970	90	99	2.30
GS = 55 μm	69 MPa H_2	240	930	86	91	1.17
1470 K-24 hrs	69 MPa He	190	830	81	88	2.21
GS = 340 μm	69 MPa H_2	180	830	84	88	1.05

* Heat analysis; Appendix D-1; Tensile B, Appendix C-2.

DATA SHEET IA-10

Grain Size Dependence of Mechanical Properties - Test at 220 K*

Hydrogen Exposure	Grain Size, μm	Strength, MPa		Elongation, %		Fracture Strain
		Yield	Ultimate	Unit	Total	
None	6.4	520	1310	56	63	1.71
	42.0	340	1210	60	72	1.70
	290	250	1130	55	63	1.64
69 MPa**	6.1	630	1040	35	35	0.27
	26	400	1020	47	47	1.10
	50	370	860	37	37	0.40
	260	270	690	31	31	0.39

* Heat analysis, Appendix D-1; Tensile B, Appendix C-2.

** Average deuterium contents measured on samples from the tensile specimens were 4.7 ccD_2/cc (69 MPa).

DATA SHEET IA-11

Effect of Deformation Rate on Hydrogen Damage*

TYPE 304L Stainless Steel
T = 220 K
Grain Size: 6 m

Hydrogen Exposure**	Cross Headspeed, mm/min	Strength, MPa		Elongation, %		Fracture Strain
		Yield	Ultimate	Uniform	Total	
None	51	570	1170	50	60	1.68
	0.51	5.20	1310	56	63	1.70
69 MPa	51	675	1210	52	52	0.92
	0.51	630	1040	35	35	0.27

* Heat analysis, Appendix D-1; Tensile B, Appendix C-2.

** Exposed at 620 K for 3 weeks.

DATA SHEET IA-12

Mechanical Properties of Sensitized Type 304L Stainless Steel*
(Smooth Bar Tensile Specimens)

Treatment	Test Environment**	Strength, MPa		Fracture Strain
		Yield	Ultimate	
Solution Anneal	Air	380	630	2.00
	Helium	375	600	2.20
	Hydrogen	370	580	1.38
Sensitized	Air	300	560	1.78
	Helium	350	670	1.90
	Hydrogen†	330	660	0.70
	Hydrogen††	350	660	0.80

* Heat analysis, Appendix D-1; Tensile B, Appendix C-2.

** 69 MPa gas pressure.

† Nearly continuous carbide network on some grain boundaries.

†† Isolated carbides.

DATA SHEET IA-13

Mechanical Properties of Notch Bar Tensile Specimens of Type 304L Stainless Steel*

Treatment	Test Environment**	Strength, MPa Yield	Ultimate	Fracture Strain
Solution Anneal	Air†	700	750	0.41
Sensitized	Air††	350	590	1.26
	Helium††	410	740	1.10
	Hydrogen††,¶	430	590	0.35
	Hydrogen ¶¶	480	620	0.38
	Air†	510	680	1.17
	Helium†	540	790	1.00
	Hydrogen†,¶	730	750	0.30
	Hydrogen ¶¶	-	690	0.20

* Heat analysis, Appendix D-1 and Appendix C-2.

** He and H_2 at 69 MPa. Air at 0.1 MPa.

† Deep notch.

†† Shallow notch.

¶ Nearly continuous carbide network on some grain boundaries.

¶¶ Isolated carbides.

DATA SHEET IA-14

Effect of Hydrogen Charging on Notch Bar Tensile Properties of Type 304L Stainless Steel*

Condition	Specimen	Nominal Tensile Strength, MPa	Fracture Strain
As received	Smooth	600	1.50
	Notch	770	0.30
Annealed**	Smooth	600	1.43
	Notch	710	0.24
Hydrogen charged†	Smooth	530	0.37
	Notch	580	0.13

* Tensile C, Appendix C-4.

** Annealed 200 days at 380 K in argon.

† Exposed to hydrogen gas at 69 MPa for 200 days at 380 K.

DATA SHEET IA-15

Type 304L Stainless Steel Notch Tensile Strength*

Test Environment	Notch Tensile Strength, MPa
Air	896
H_2, 0.1 MPa	786
H_2, 1.03 MPa	703
H_2, 6.89 MPa	662

* Tensile C, Appendix C-4.

DATA SHEET IA-16

Stress Necessary for Slow Crack Growth in Type 304L Stainless Steel*

Net Section Stress, MN/m^2	Time, hrs Incremental	Time, hrs Accumulated	Crack Growth
600	325	325	No
641	72	397	No
682	72	469	No
724	72	541	No
765	72	613	No
786	1.4 (failed)	614.4	Yes

* Crack developed during room temperature tensile test in hydrogen environment; net section stress when tensile test was stopped was 772 MN/m^2. Specimen then loaded in creep frame at indicated stresses without removal from the hydrogen environment.

Tensile E, Appendix C-5.

DATA SHEET IB-1
Type 304N Stainless Steel*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield†	Tensile	Uniform	Total	Strain
298	Air	none	760	880	–	33	1.24
	Air	69 MPa H_2**	740	830	–	31	1.05
	69 MPa H_2	none	640	840	–	36	0.78
	69 MPa H_2	69 MPa H_2**	550	790	–	37	0.62
	69 MPa He	none	630	850	–	43	1.35
375	Air	none	820	950	11	26	1.31
		69 MPa D_2††	820	970	11	22	1.20
298	Air	none	906	1110	16	28	1.47
		69 MPa D_2††	950	1185	16	28	0.95
245	Air	none	975	1340	27	37	1.82
		69 MPa D_2††	1063	1420	22	27	0.49
220	Air	none	1026	1450	26	35	1.67
		69 MPa D_2††	1093	1480	21	24	0.33
200	Air	none	1096	1810	47	56	1.44
		69 MPa D_2††	1160	1510	19	23	0.38

* Tensile A, Appendix C-1; Heat Analysis, Appendix D-10.

** 69 MPa H_2 at 430 K for 1000 hours.

† 0.2% offset.

†† 69 MPa D_2 at 620 K for 3 weeks.

DATA SHEET IC-1

Type 309S Stainless Steel*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	Air	none	290	600	-	54	1.27
	69 MPa He	none	276	580	-	60	1.24
	69 MPa H2	none	260	586	-	63	1.35
	Air	69 MPa H_2-430K 14d	255	615	-	43	0.92
	Air	28 MPa H_2-470K 100 hr	330	615	-	57	1.17

* Tensile A, Appendix C-1.

** 0.2% offset.

DATA SHEET IC-2

Tensile Properties of Type 309S Stainless Steels Containing Hydrogen and Helium

Test Condition		Hydrogen	Strength, MPa		Elongation,
Temp, K	Environment	Exposure	Yield	Ultimate	%
300	Air	none	243	612	56
300*	Air	**	301	618	48-57
300*	Air	†	382	658	45-53
973††	Air	none	131	296	27
973††	Air	†	227	196	<1

* Specimens contained tritium and Helium-3.

** 328 mol hydrogen isotopes and 6.2 mol helium per m^3 metal.

† 146 mol hydrogen isotopes and 2.5 mol helium per m^3 metal.

†† Held 1/2 hour at 973 K before testing.

DATA SHEET ID-1

Type 310 Stainless Steel Bar Stock, As Received*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure**	Yield	Ultimate	Uniform	Total	Strain
380	Air	none	440	670	25	36	1.35
		69 MPa	440	700	27	40	1.71
273	Air	none	510	860	44	53	1.71
		69 MPa	510	900	46	53	1.47
200	Air	none	560	1200	60	66	1.20
		69 MPa	590	1280	62	73	1.24
78	LN	none	570	1720	74	78	1.05
		69 MPa	570	1790	71	76	1.35

* Tensile B, Appendix C-2.

** Exposed at 470 K for 1449 days.

DATA SHEET ID-2

Type 310 Stainless Steel*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	Air	none	210	540	-	61	1.56
	Air	69 MPa H_2†	200	500	-	63	1.42
	69 MPa H_2	none	186	490	-	67	1.72
	69 MPa H_2	69 MPa H_2†	180	440	-	66	1.56
	69 MPa He	none	180	480	-	70	1.61

* Tensile A, Appendix C-1.

** 0.2% offset.

† 69 MPa H_2 at 430 K for 1000 hours.

DATA SHEET IE-1

Type 316 Stainless Steel; Bar Stock, As Received*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure**	Yield	Ultimate	Uniform	Total	Strain
380	Air	none	810	830	7	20	1.61
		69 MPa	880	930	11	22	1.19
273	Air	none	890	1040	21	33	1.47
		69 MPa	990	1160	20	32	1.13
250	Air	none	900	1150	27	40	1.51
		69 MPa	1030	1280	24	35	1.07
200	Air	none	960	1210	24	43	1.56
		69 MPa	1100	1410	26	37	1.06

* Tensile B, Appendix C-2.

** Exposed at 620 K for 3 weeks.

DATA SHEET IF-1

Carpenter 20 Cb-3® Stainless Steel As-Received*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure**	Yield†	Ultimate	Uniform	Total	Strain
298	Air	none	236	600	-	48	1.14
	69 MPa H_2	none	230	590	-	48	1.14
	69 MPa H_2	69 MPa D_2	262	610	-	48	1.14
200	Air	none	320	1100	60	66	1.01
	Air	69 MPa D_2	348	1177	55	62	1.08

* Tensile B, Appendix C-2; heat analysis, Appendix D-11.

** Exposed at 620 K for 3 weeks.

† 0.2% offset.

DATA SHEET IG-1

Incoloy® Alloy 800H, Hot Rolled Plate, Solution Annealed*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure**	Yield	Ultimate	Uniform	Total	Strain
380	Air	none	270	750	47	52	0.92
		69 MPa	290	770	48	53	0.82
298	Air	none	310	820	48	55	0.97
		69 MPa	330	840	48	53	0.78
250	Air	none	340	870	48	56	1.20
		69 MPa	360	900	49	55	0.92
200	Air	none	360	930	49	56	1.11
		69 MPa	380	990	54	63	0.94
78	LN	none	530	1520	80	84	0.78
		69 MPa	540	1490	74	76	0.69

* Tensile B, Appendix C-2; heat analysis, Appendix D-3.

** Exposed at 620 K for 3 weeks.

DATA SHEET IH-1

Nickel 200*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield	Ultimate	Uniform	Total	Strain
298	Air**	none	88	506	-	55	2.30
	69 MPa He**	none	120	490	-	55	2.41
	69 MPa H_2**	none	106	470	-	51	0.76
298	Air†	none	135	480	-	50	2.21
	69 MPa He†	none	122	450	-	48	2.04
	69 MPa H_2†	none	156	460	-	45	0.69

* Tensile A, Appendix C-1.

** Annealed 1090 K 15 minutes and furnace cooled.

† As in **, plus annealed 773 K for 64 hours and air cooled.

DATA SHEET IH-2

Nickel 200, Notch-Bar Tensile Properties*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield	Ultimate	Uniform	Total	Strain
298	Air**	none	-	660	-	-	0.35
	69MPa He**	none	-	810	-	-	0.37
	69 MPa H_2**	none	-	560	-	-	0.11
	Air†	none	-	635	-	-	0.44
	69 MPa He†	none	-	710	-	-	0.34
	69 MPa H_2†	none	-	580	-	-	0.20

* Tensile A, Appendix C-1 with notch.

** Annealed 1090 K 15 minutes and furnace cooled.

† As in **, plus annealed 773 K for 64 hours and air cooled.

DATA SHEET IJ-1

Nickel 301*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield	Ultimate	Uniform	Total	Strain
298	Air**	none	451	778	-	39	1.89
	69 MPa He**	none	486	791	-	34	1.35
	69 MPa H_2**	none	532	618	-	12	0.22
298	Air†	none	1008	1380	-	23	0.49
	69 MPa He†	none	1009	1350	-	22	0.42
	69 MPa H_2†	none	-	850	-	4	0

* Tensile A, Appendix C-1.

** Annealed 1170 K for 5 min and quenched.

† Annealed as in **, plus annealed 860 K for 16 hours, 810 K for 5 hours and 755 K for 5 hours and furnace cooled.

DATA SHEET IJ-2

Nickel 301, Notch Bar Tensile Properties*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield	Ultimate	Uniform	Total	Strain
298	Air**	none	-	985	-	-	0.30
	69 MPa He**	none	-	995	-	-	0.30
	69 MPa H2**	none	-	690	-	-	0.01
	Air†	none	-	1630	-	-	0.19
	69 MPa He†	none	-	1600	-	-	0.10
	69 MPa H2†	none	-	840	-	-	0.04

* Tensile A, Appendix C-1 plus notch.

** Annealed 1170 K for 5 min and quenched.

† Annealed as in **, plus annealed 860 K for 16 hours, 810 K for 5 hours and 755 K for 5 hours and furnace cooled.

DATA SHEET IK-1

Type 440C Stainless Steel*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure**	Yield	Ultimate	Uniform	Total	Strain
298	Air	none	377	620	-	7.1	0.010
		69 MPa D_2	377	575	-	4.6	0.006
200	Air	none	406	670	-	7.7	0.013
		69 MPa D_2	450	570	-	4.2	0.009

* Tensile B, Appendix C-2.

** Exposure at 620 K for 3 weeks.

IRON-CHROMIUM-NICKEL-MANGANESE ALLOYS

DATA SHEET IIA-1

Tenelon® Plate, As Received*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure**	Yield	Ultimate	Uniform	Total	Strain
350	Air	none	675	1270	48	59	1.43
		69 MPa	700	1300	53	60	0.94
273	Air	none	830	1480	50	58	1.14
		69 MPa	920	1540	48	50	0.51
200	Air	none	1050	1960	59	66	0.69
		69 MPa	1020	1620	40	40	0.36
78	LN	none	1740	1780	19	19	0.08
		none†	1730	2040	22	22	0.07
		none††	1670	2120	25	25	0.13
		none¶	1450	1730	21	21	0.14
		69 MPa	1720	1780	20	20	0.06

* Tensile B, Appendix C-2; heat analysis, Appendix D-4

** Exposed at 620 K for 3 weeks.

† Electropolished.

†† Annealed 1170 K for 24 hours.

¶ Annealed 1270 K for 24 hours.

DATA SHEET IIA-2

Tenelon®*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	Air	none	570	930	-	56	1.05
	69 MPa He	none	500	875	-	65	1.14
	69 MPa H_2	none	500	900	-	55	0.63
	Air	69 MPa H_2†	550	840	-	41	0.45
	69 MPa H_2	69 MPa H_2†	470	760	-	24	0.26

* Tensile A, Appendix C-1.

** 0.2% offset.

† 69 MPa H_2 for 1000 hours at 423 K.

DATA SHEET IIA-3

Fracture Toughness of Tenelon®*

Test Temp, K	Specimen Condition	Fracture Toughness, MPa $\sqrt{m}$
78	As received	68.6
	Anneal 1170 K	36.5
	Anneal 1270 K	71.4
200	As received	127.8
	Anneal 1170 K	99.6
	Anneal 1270 K	120.5

* Heat analysis, Appendix D-4; single edge notched, Appendix C-6.

DATA SHEET IIB-1

Nitronic® 40 Stainless Steel Bar Stock, As Received*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure**	Yield	Ultimate	Uniform	Total	Strain
380	Air	none	680	940	30	39	1.66
		69 MPa	690	1020	36	46	1.02
298	Air	none	770	1170	41	51	1.61
		69 MPa	800	1270	46	56	0.92
250	Air	none	860	1360	46	57	1.51
		69 MPa	-	1380	41	46	0.45
200	Air	none	970	1550	48	58	1.56
		69 MPa	1060	1650	44	48	0.65
78	LN	none	1580	2140	45	49	0.64
		69 MPa	1600	2060	36	36	0.38

* Tensile B, Appendix C-2; heat analysis, Appendix D-5.

** Exposed at 620 K for 3 weeks.

DATA SHEET IIB-2

Mechanical Properties of Nitronic® 40 Alloy: Heat Treatment and Notch Effects*

Test Temp, K**	Treatment	Specimen	Strength, MPa Yield	Strength, MPa Ultimate	Elongation, % Uniform	Elongation, % Total	Fracture Strain
300	Solution Anneal	Smooth bar	700	1170	41	51	1.59
		Notch bar	800	1160	24	27	0.74
	Sensitize	Notch bar	750	1070	18	18	0.53
200	Solution	Smooth bar	880	1550	48	58	1.57
		Notch bar	1130	1500	19	19	0.72
	Sensitize	Smooth bar	720	1490	51	60	1.03
		Notch bar	1120	1250	10	10	0.17

* Heat analysis, Appendix D-5; Tensile B, Appendix C-2.

** Air environment.

DATA SHEET IIB-3

Mechanical Properties of Sensitized Nitronic® 40 Stainless Steel Tested in a High-Pressure Hydrogen Environment at Room Temperature*

Specimen Condition	Test Atmosphere	Strength, MPa Yield	Strength, MPa Ultimate	Elongation, % Uniform	Elongation, % Total	Fracture Strain
Solution Annealed	69 MPa He	650	1050	42	52	1.11
	69 MPa H_2	670	1060	41	50	1.22
920 K-2 hr	69 MPa He	640	1100	43	50	1.51
	69 MPa H_2	640	1080	42	49	1.50
920 K-24 hr	69 MPa He	625	1110	46	53	1.38
	69 MPa H_2	620	1100	46	52	1.10
920 K-24 hr	69 MPa He**	760	1060	16	16	0.32
	60 MPa H_2**	700	760	9	9	0.06

* Heat analysis, Appendix D-5; Tensile B, Appendix C-2.
** Notch bar specimen.

DATA SHEET IIB-4

Mechanical Properties of Sensitized Nitronic® 40 Stainless Steel Saturated with Hydrogen*

Temp, K	Treatment**	Hydrogen Exposure	Strength, MPa Yield	Strength, MPa Ultimate	Elongation, % Uniform	Elongation, % Total	Fracture Strain
200	Solution Anneal	none	970	1550	48	58	1.57
	Solution Anneal	69 MPa H_2†	1060	1650	44	48	0.66
	920 K-24 hr	none	790	1490	51	60	1.03
	920 K-24 hr	69 MPa H_2	920	1470	37	37	0.33
	920 K-24 hr	69 MPa H_2††	900	1350	35	40	0.45

* Heat analysis, Appendix D-5; Tensile B, Appendix C-2.
** Smooth bar tensile specimens.
† Exposed at 620 K for 3 weeks.
§ †† Crosshead speed, 5 mm/sec; all others, 0.5 mm/sec.

Note: Typographic errors were made on the original Data Sheet IIB-4 in Ref. [1]. The crosshead speeds (denoted by § above) should be 5 mm/min and 0.5 mm/min, respectively.

DATA SHEET IIB-5

Nitronic® 40*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	Air	none	400	670	-	58	1.51
	69 MPa He	none	350	700	-	59	1.47
	69 MPa H_2	none	360	700	-	61	1.43

* Tensile A, Appendix C-1.

** 0.2% offset.

DATA SHEET IIB-6

Nitronic® 40; Cold Worked 30%*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	Air	none	1240	1290	-	26	0.87
		30 MPa H_2	1075	1150	-	32	0.43
	69 MPa He	none	1010	1050	-	26	0.99
	69 MPa H_2	none	980	1100	-	26	1.02
	69 MPa H_2	30 MPa H_2	1060	1130	-	36	0.44

* Tensile A, Appendix C-1.

** 0.2% offset.

DATA SHEET IIB-7

Nitronic® 40 Stainless Steel, High Energy Rate Forged*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield	Ultimate	Uniform	Total	Strain
380	Air	none	540	1040	47	59	1.81
		69 MPa**	570	1070	50	68	1.26
		none	780	970	21	31	1.17
		69 MPa†	690	930	26	33	0.67
298	Air	none	780	1140	32	44	1.24
		69 MPa†	890	1220	30	42	0.96
273	Air	none	640	1300	57	69	1.81
		69 MPa**	690	1430	67	78	1.06
220	Air	none	900	1320	33	45	1.31
		69 MPa†	960	1420	37	47	0.80
200	Air	none	930	1700	51	59	1.26
		69 MPa**	1050	1830	49	54	0.90
		none	1020	1610	42	54	1.26
		69 MPa†	990	1740	53	60	0.66
78	LN	none	1450	2840	46	56	0.83
		69 MPa**	1400	2600	46	46	0.53

* Tensile B, Appendix C-2.
** 69 MPa at 470 K for 1449 days.
† 69 MPa at 620 K for 21 days.

DATA SHEET IIB-8

Nitronic® 40 Stainless Steel, High Energy Rate Forged*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	Air	none	610	790	–	34	1.35
		28 MPa H_2	660	820	–	31	0.89
	69 MPa He	none	570	780	–	34	1.39
	69 MPa H_2	none	570	790	–	30	1.31
		28 MPa H_2	630	830	–	31	0.78

* Tensile A, Appendix C-1.
** 0.2% offset.

DATA SHEET IIB-9

Nitronic® 40 Stainless Steel, High Energy Rate Forged*

Test Condition		Hydrogen	Impact
Temp, K	Environment	Exposure	Energy, J
298	Air	none	110
		29.6 MPa H_2**	91
77	LN	none	37
		29.6 MPa H_2**	35

* Impact, Appendix C-8.

** 470 K - 56 days.

DATA SHEET IIB-10

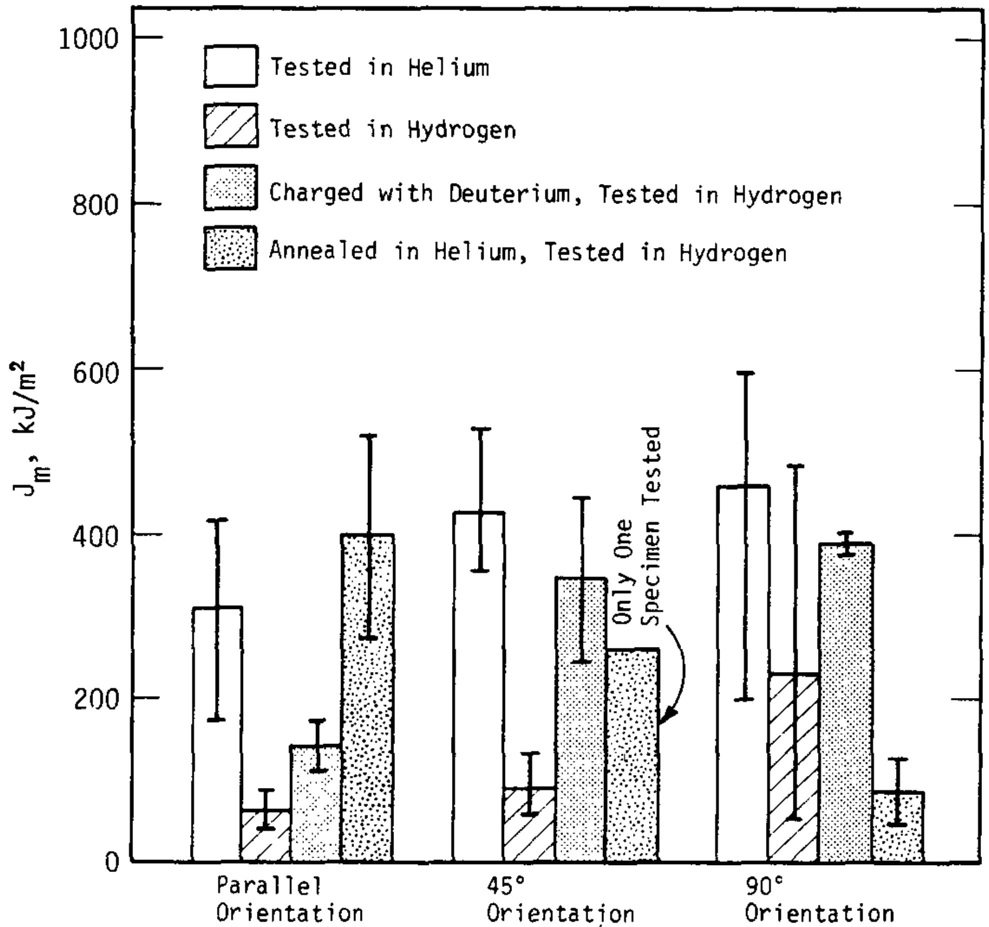
Nitronic® 40 Stainless Steel, High Energy Rate Forged*

Test Condition		Hydrogen	Fracture Toughness, MPa $\sqrt{m}$	
Temp, K	Environment	Exposure	Long	Trans
298	69 MPa He	none	79	74
	69 MPa H_2	none	81	68
	69 MPa H_2	0.6 MPa H_2	76	62

* C-shaped tensile, Appendix C-7.

DATA SHEET IIB-11

Fracture Parameters for Nitronic® 40 Stainless Steel*

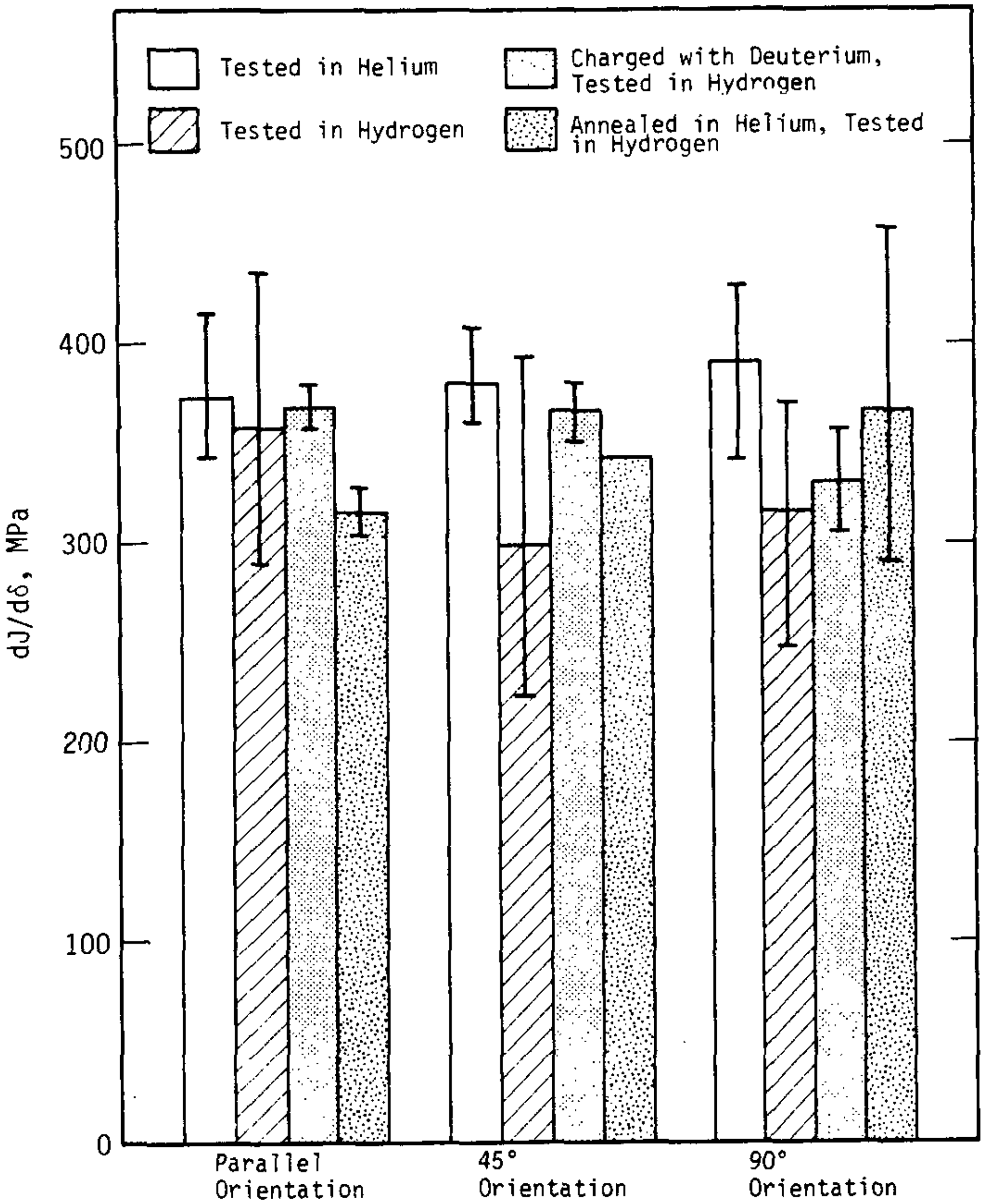


---

* C-shaped tensile, Appendix C-7. Test in 69 MPa He or H_2. Deuterium exposed at 69 MPa at 620 K for 3 weeks.

DATA SHEET IIB-12

Fracture Parameters for Nitronic® 40 Stainless Steel*



---

* C-shaped tensile, Appendix C-7. Test in 69 MPa He or H_2. Deuterium charged at 69 MPa at 620 K for 3 weeks.

DATA SHEET IIC-1

Nitronic® 50 Stainless Steel Bar Stock, As Received*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure**	Yield	Ultimate	Uniform	Total	Strain
380	Air	none	700	990	26	34	1.23
		69 MPa	720	1060	29	37	1.16
298	Air	none	800	1190	32	41	1.17
		69 MPa	820	1240	33	44	1.05
248	Air	none	870	1310	34	43	1.23
		69 MPa	900	1390	35	43	1.00
200	Air	none	1030	1550	35	44	1.08
		69 MPa	1020	1620	37	44	0.97
78	LN	none	1590	2310	38	44	0.91
		69 MPa	1590	2350	38	44	0.90

* Tensile B, Appendix C-2.

** Exposed at 620 K for 3 weeks.

DATA SHEET IIC-2

Nitronic® 50 Stainless Steel Bar Stock, As Received.*

Test Condition		Hydrogen	Strength, MPa			Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Elongation, %	Strain
298	Air	none	440	710	43	1.27
	69 MPa He	none	400	680	47	1.35
	69 MPa H_2	none	400	680	45	1.31

* Tensile A, Appendix C-1; heat analysis, Appendix D-6.

** 0.2% offset.

DATA SHEET IIC-3

Nitronic® 50 Stainless Steel, High-Energy-Rate-Forged*

Test Condition		Hydrogen	Deflection J_m	Jm	dJ/da
Temp, K	Environment	Exposure	mm	kJ/m^2	MPa
298	69 MPa He†	none	-	32	176
	69 MPa H_2	none	-	23	137
	69 MPa H_2	D_2	-	33	211
	69 MPa He††	none	-	936	360
	69 MPa H_2††	none	-	107	209
	69 MPa H_2††	D_2	-	181	264

* C-Shaped tensile, Appendix C-7.

** Exposed at 620 K for 3 weeks.

† Crack parallel to forging pattern

†† Crack perpendicular to forging patterns.

DATA SHEET IID-1

18-18 Plus® Stainless Steel*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	69 MPa He	none	520	910	-	63	1.51
	69 MPa H_2	none	506	880	-	42	0.42

* Tensile A, Appendix C-1; heat analysis, Appendix D-9.

** 0.2% offset.

DATA SHEET IIE-1

X18-3 Mn Stainless Steel*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	Air	none	580	810	-	45	1.24
	69 MPa He	none	530	790	-	50	1.35
	69 MPa H_2	none	520	790	-	46	1.31

* Tensile A, Appendix C-1; heat analysis, Appendix D-8.

** 0.2% offset.

DATA SHEET IIF-1

18-2 Mn Stainless Steel*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	Air	none	730	1007	-	51	0.87
	69 MPa H_2	none	660	924	-	33	0.31

* Tensile A, Appendix C-1.

** 0.2% offset.

DATA SHEET IIG-1

Type 216 Stainless Steel*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	Air	none	640	810	-	40	1.10
298	Air	69 MPa H_2†	630	790	-	36	1.05
298	69 MPa H_2	none	590	780	-	44	1.17
298	69 MPa H_2	69 MPa H_2†	560	760	-	45	1.02
298	69 MPa He	none	590	790	-	45	1.20

* Tensile A, Appendix C-1; heat analysis, Appendix D-7.

** 0.2% offset.

† 69 MPa H_2 at 430 K for 1000 hours.

PRECIPITATION HARDENABLE ALLOYS

DATA SHEET IIIA-1

A-286 Stainless Steel*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield	Tensile	Uniform	Total	Strain
298	Air	none	765	1098	-	25	0.77
		2.1 MPa Argon	776	1089	-	24	0.79
		69 MPa D/T**	750	1041	-	13	0.34
		none¶	-	1500	-	4	0.15
		2.1 MPa Argon¶	-	1380	-	3.6	0.11
		69 MPa D/T**,¶	-	1310	-	3	0.06
		none	1010†	1350††	23	28	0.50
		69 MPa D_2¶¶	1070†	1380††	23	24	0.24
220	Air	none	1100†	1520††	28	34	0.49
		69 MPa D_2¶¶	1130†	1530††	27	27	0.25

* Tensile A, Appendix C-1.

** 69 MPa D/T at 370 K for 200 days.

† True stress at 5% strain.

†† True stress at maximum load.

¶ Notched-bar tensile specimens, all others smooth-bar specimens.

¶¶ 69 MPa D_2 at 620 K for 3 weeks.

DATA SHEET IIIA-2

A-286 Stainless Steel High Energy, Rate Forged*

Test Condition Temp, K	Test Condition Environment	Hydrogen Exposure	Fracture Toughness, MPa $\sqrt{m}$
298	69 MPa He	none	76**
	69 MPa H_2		89**
	69 MPa He	none	71***
	69 MPa H_2		90***
	69 MPa He	none	81†
	69 MPa H_2		82†
	69 MPa He	none	93††
	69 MPa H_2		89††
	69 MPa He	1.6 MPa D_2	88††
	69 MPa H_2	1.6 MPa D_2	97††
	69 MPa He	none	52¶
	69 MPa H_2	none	56¶
	69 MPa H_2	1.5 MPa D_2	59¶
	69 MPa He	none	93¶¶
	69 MPa H_2	none	90¶¶
	69 MPa H_2	1.5 MPa D_2	97¶¶

* Single edge notched, Appendix C-6.

** Aged 4 hours at 990 K (Heat 1).

*** Aged 8 hours at 990 K (Heat 1).

† Aged 16 hours at 990 K (Heat 1).

†† Aged 8 hours at 990 K (Heat 2).

¶ HERF only not aged. R_C-11.

¶¶ Aged 8 hours at 990 K. R_C-11.

DATA SHEET IIIA-3

A-286 Stainless Steel Notch Impact Test*

Test Condition		Hydrogen	Impact
Temp, K	Environment	Exposure	Energy, J
298	Air	Base Metal	
		As Received	6.10
		Argon**	5.08
		D/T†	4.74
298	Air	Weld Metal	
		As Received	4.18
		Argon**	3.40
		D/T†	4.51

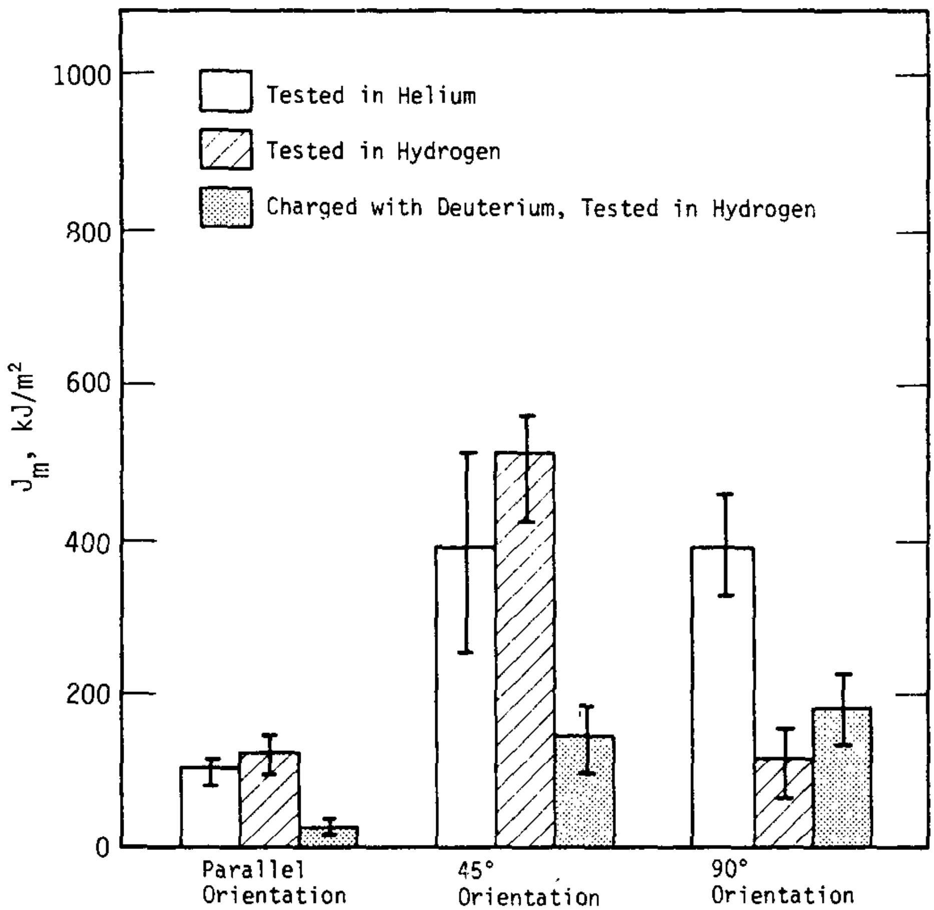
* Impact Appendix C-8.

** 0.21 MPa at 370 K for 200 days.

† 69 MPa D/T at 370 K for 200 days.

DATA SHEET IIIA-4

Fracture Parameters for A-286 Stainless Steel*

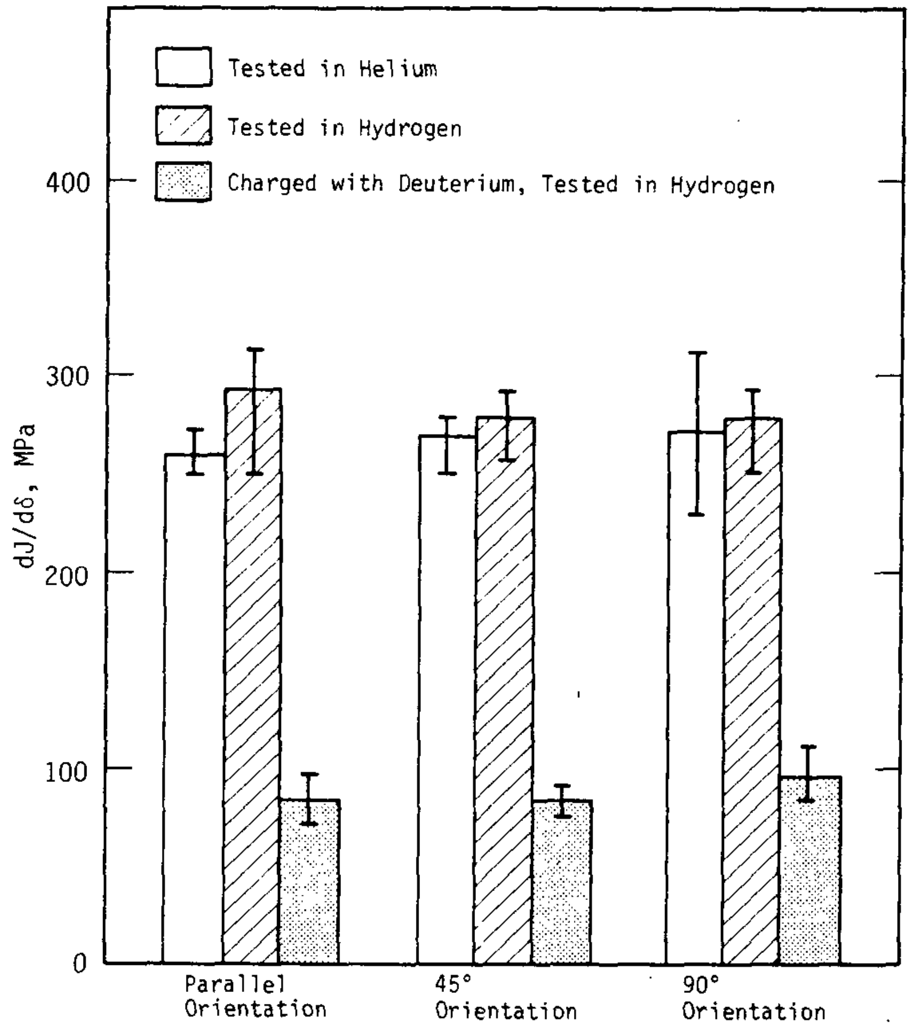


---

* C-shaped tensile, Appendix C-7. Tested in 69 MPa H_2 or He. Deuterium charged at 69 MPa at 620 K for 3 weeks.

DATA SHEET IIIA-5

Fracture Parameters for A-286 Stainless Steel*



* C-shaped Tensile, Appendix C-7. Tested in 69 MPa He or H_2. Deuterium charged at 69 MPa at 620 K for 3 weeks.

DATA SHEET IIIB-1

JBK-75 HERF and Age*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	69 MPa He	none	800	1090	10	14	0.63
	69 MPa H_2	none	890	1160	10	13	0.40

* Tensile, Appendix C-3.

** 0.2% offset.

DATA SHEET IIIB-2

JBK-75 HERF and Age*

Test Condition		Hydrogen	Stress Intensity,	Fracture Energy,
Temp, K	Environment	Exposure	MPa $\sqrt{m}$	MJ/m^2
298	69 MPa He	none	80	0.350
	69 MPa H_2	none	80	0.333
	69 MPa H_2	0.7 MPa D_2 at 625 K	81	0.294

* C-shaped tensile, Appendix C-7.

DATA SHEET IIIC-1

17-4 Stainless Steel, Tensile Tubes*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	Air	none	940	980	-	4.7	-
	69 MPa He	69 MPa He	1076	1145	-	6.4	-
	35 MPa D/T	35 MPa D/T†	1000	1000	-	0.7	-
	69 MPa D/T	69 MPa D/T††	1062	1096	-	1.2	-

* Tensile E, Appendix C-5.

** 0.2% offset.

† 8 hours at 315 K.

†† 2 hours at 370 K.

DATA SHEET IIIC-2

Fracture Toughness 17-4 PH Stainless Steel*

Fracture Toughness, MPa $\sqrt{m}$

Material	Test Environment		
Condition	69 MPa He	3.5 MPa H_2	69 MPa H_2
Underaged	104	31	20
Peak Aged	97	29	13
Overaged	-	57	34
Solution Annealed	97	71	31

Heat Treatments

Material Condition	Aging Temp, K	Hardness R_C
Underaged	709	38
Peak Aged	783	42
Overaged	866	35
Solution Annealed	-	28

* C-shaped tensile, Appendix C-7.
All specimens were solution annealed 2 hours at 1339 K and aged 1 hour at indicated temperatures.

DATA SHEET IIID-1

AM-350 Stainless Steel*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	Air	none	420	1160	-	70	-
		69 MPa†	455	580	-	3/4	-
	69 MPa He	none	420	1240	-	55	-
	6.9 MPa D_2	none	345	430	-	4	-
	69 MPa D_2	none	430	520	-	2.6	-
	0.69 MPa D_2	none	410	455	-	3	-

* Condition H - annealed at 1310 to 1350 K air cool or water quench.

** 0.2% offset.

† 26 days at 570 K.

DATA SHEET IIIE-1

AM-363 Stainless Steel

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield*	Tensile	Uniform	Total	Strain
298	Air	none	890	890	-	7	-
	Air	0.21 MPa H_2**	900	900	-	8.6	-
	Air	none	1340†	1480	-	3	-
	Air	0.21 MPa H_2**	1400†	1500	-	3	-

* 0.21 MPa D_2 at 630 K for 5 days.

** 0.2% offset.

† Notched - 45° notch. Notch diameter = 0.5X outer diameter.

DATA SHEET IIIF-1

CG-27 Stainless Steel*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	69 MPa He	none	806	1165	-	29	0.30
	69 MPa H_2	none	855	1117	-	10	0.13
298	69 MPa H_2	69 MPa H_2 at 425 K-72 hrs	855	1020	-	4	0.03
298	69 MPa He†	none	1070	1385	-	12	0.13
	69 MPa H_2†	none	1034	1138	-	1	0.03

* Tensile A, Appendix C-1.

** 0.2% offset.

† HERF specimens.

DATA SHEET IIIG-1

Ni-SPAN-C* (Alloy 902)

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure	Yield**	Tensile	Uniform	Total	Strain
298	Air	none	676	1186	-	10	-
	69 MPa He	none	750	1160	-	16	-
	6.9 MPa H_2	none	-	1170	-	14	-
	69 MPa H_2	none	650	1130	-	15	-

* Sheet specimens 0.25 mm and 19 mm gauge length.

** 0.2% offset.

HIGH PURITY ALLOYS

DATA SHEET IVA-1

Mechanical Properties (Alloy A)*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure**	Yield	Ultimate	Uniform	Total	Strain
370	Air	none	230	610	45	52	1.57
		69 MPa	270	660	50	59	1.65
298	Air	none	350	1270	62	73	1.66
		69 MPa	290	1030	60	60	0.50
235	Air	69 MPa	390	1110	38	38	0.27
200	Air	none	540	1320	36	46	1.42
		69 MPa	420	1190	33	33	0.31
78	LN	none	-	-	-	-	1.44
		69 MPa	-	1060	42	48	1.13

* Tensile B, Appendix C-2.

** Exposed at 620 K for 3 weeks.

DATA SHEET IVB-1

Mechanical Properties (Alloy B)*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure**	Yield	Ultimate	Uniform	Total	Strain
370	Air	none	240	630	45	56	1.58
		69 MPa	260	660	46	56	1.40
298	Air	none	340	1020	61	69	1.56
		69 MPa	290	870	65	72	1.50
235	Air	69 MPa	320	1170	72	79	0.44
200	Air	none	340	1170	64	74	1.57
		69 MPa	380	1250	66	71	0.89
78	LN	none	260	870	63	67	1.37
		69 MPa	270	900	66	72	1.41

* Tensile B, Appendix C-2.

** Exposed at 620 K for 3 weeks.

DATA SHEET IVC-1

Mechanical Properties (Alloy C)*

Test Condition		Hydrogen	Strength, MPa		Elongation, %		Fracture
Temp, K	Environment	Exposure**	Yield	Ultimate	Uniform	Total	Strain
370	Air	none	250	630	44	52	1.62
		69 MPa	260	660	45	53	1.45
298	Air	none	330	910	49	58	1.65
		69 MPa	290	770	52	62	1.55
200	Air	none	300	1100	78	87	1.52
		69 MPa	330	1170	78	86	1.50
78	LN	none	250	850	82	89	1.53
		69 MPa	280	890	80	86	1.43

* Tensile B, Appendix C-2.

** Exposed at 620 K for 3 weeks.

Appendix B

Definitions of the Measured Properties in SRL data Sheets

ELONGATION

Percentage increase of a gauge length, usually one inch, during plastic strain in tension. In the data presented here, crosshead motion was taken as the measure of change in length.

Total elongation is length increase at fracture.

Uniform elongation is length increase to the point where drop in load is detected which signals beginning of observable strain localization or necking.

HEAT TREATMENTS

Aging is a process of heating a previously solution-treated alloy to an intermediate temperature to cause precipitation of a finely dispersed phase which hardens the alloy.

Sensitization is a heat treatment that causes precipitation of carbides of the form M_{23} C_6 along grain boundaries and simultaneously reduces the chromium content of the grain boundary regions.

Solution annealing is a process of heating to elevated temperature to dissolve all precipitates and produce a homogeneous solid solution and quenching to retain the solid solution.

MECHANICAL PROCESSING

Ingots of stainless steel are formed into plate or bar by mechanical processes of rolling and forging.

Cross-rolled plate refers to turning plate 90° between passes through the rolling mills to minimize preferred orientation that arises during the rolling process.

High energy rate forged (HERF) alloys are hot forged at a very rapid rate and immediately quenched in water to retain deformation introduced during forging.

PLASTIC STRAIN

Irreversible or permanent strain of the test specimen measured by subtracting elastic or recoverable strain from total strain. This was usually done graphically on the load-deformation record obtained during a tensile test.

Plastic strain to failure (ε_p) is calculated from the measured change in cross sectional area from the original (A_0) to the final area (A_f) at the fracture.

$$\varepsilon_p = \ln A_0/A_f$$

Reduction in area (RA) is a measure of plasticity calculated from the original (A_0) and final (A_f) cross sectional areas.

$$RA = 100 \frac{A_0 - A_f}{A_0}$$

STRESS

Stress or force per unit area may be defined with respect to an initial area (engineering stress) or the instantaneous area (true stress). Both definitions have been utilized in data presented here and are distinguished in each table.

Yield strength is the stress corresponding to a plastic strain of 5% unless otherwise noted.

Ultimate strength is the true stress corresponding at maximum load.

Tensile strength is the engineering stress at maximum load.

STRESS INTENSITY

The stress intensity factor (K) relates the stress field (σ_{ij}) around a crack tip to the crack dimensions (a) and specimen dimensions (width = w), where the function f(a,W) depends on specimen shape, crack location and loading mode.

The stress intensity corresponding to the critical value for crack extension is the Fracture Toughness (K_c). Fracture toughness is a measure of the ability of a material to resist crack propagation.

Under sustained load, cracks will propagate in hydrogen at stress intensities greater than a threshold or K_{TH}.

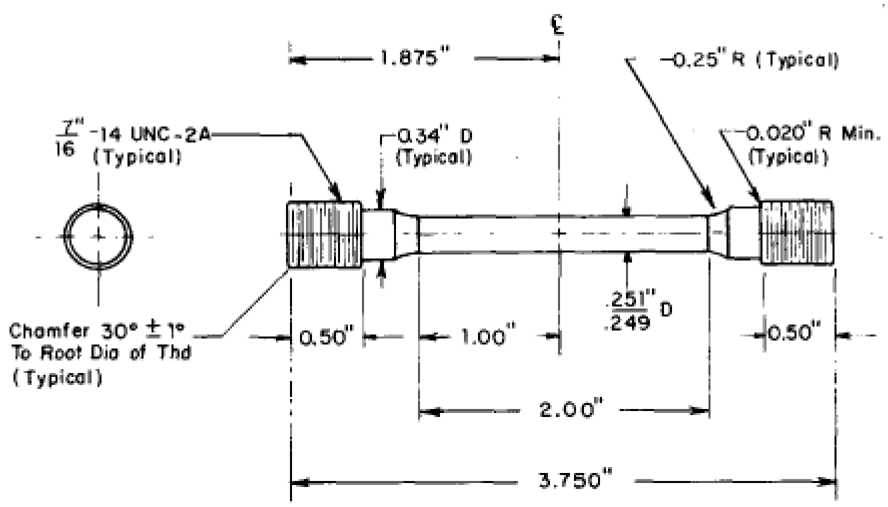
Appendix C

Mechanical Test Specimens

C-1 to C-3: Tensile Specimens
C-4: Notched Tensile Specimen
C-5: Tensile Tube Specimen
C-6 and C-6a: Single Edge Notched Specimen
C-7 and C-7a: C-shaped Fracture mechanics Specimen
C-8: Impact Specimen

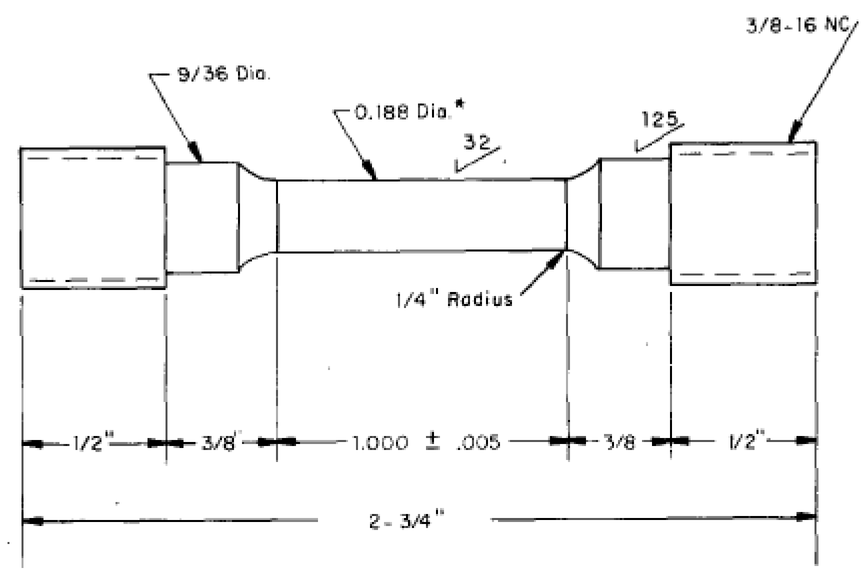
APPENDIX C-1

Smooth Bar Tensile Test Specimen A



APPENDIX C-2

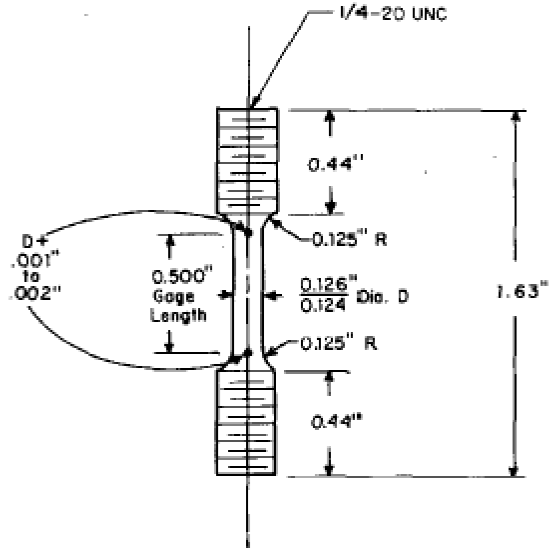
Smooth Bar Tensile Test Specimen B



** Increase diameter from center of gage (.188) to the ends by 0.002".*

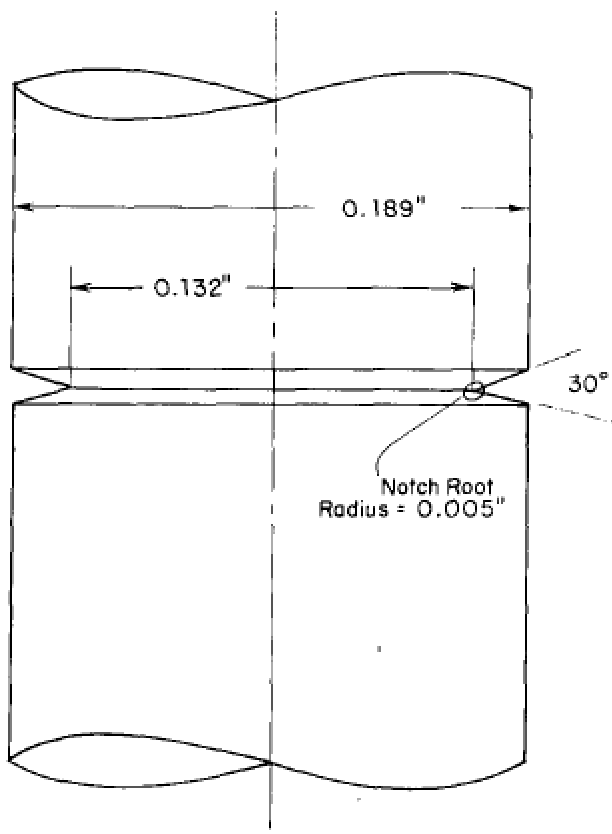
APPENDIX C-3

Smooth Bar Tensile Test Specimen C



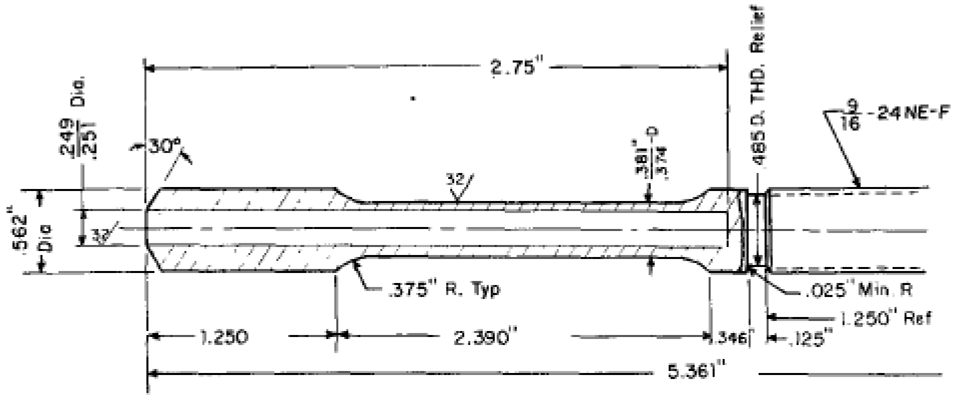
APPENDIX C-4

Circumferential Notch at Center of Specimen
for Notched Tensile Specimens



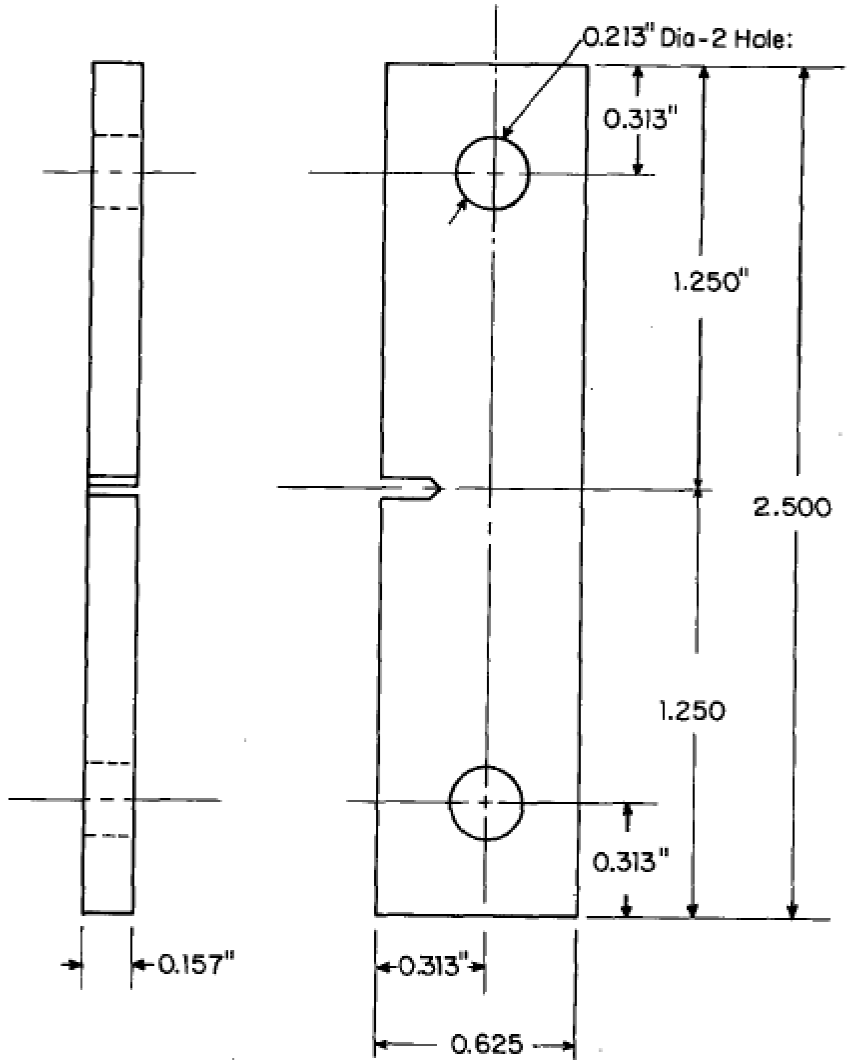
APPENDIX C-5

Tensile Tube Specimen



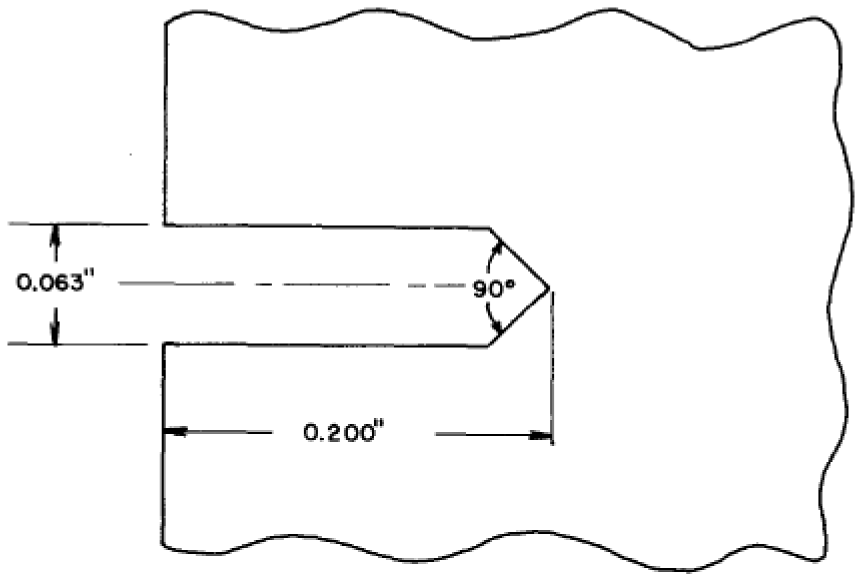
APPENDIX C-6

Single Edge Notched Tensile Specimen



APPENDIX C-6a

Detail of Notch in Single Edge Notched Tensile Specimen



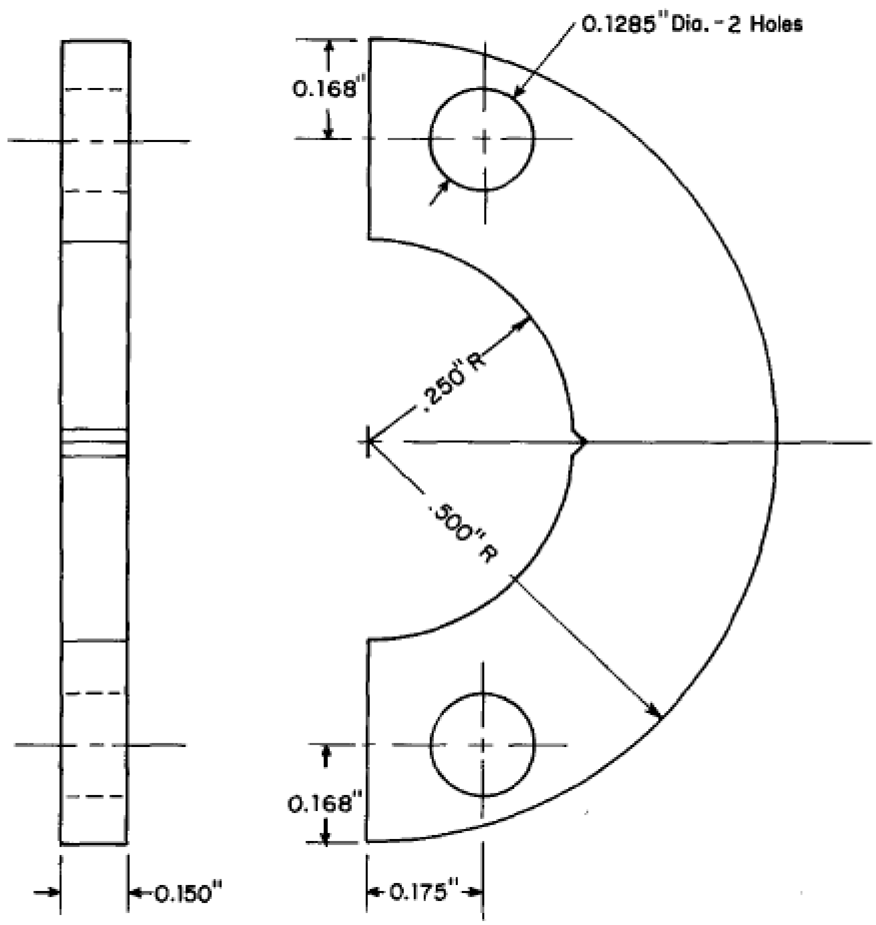
Notes: 1) All demensions ± 0.001"

2) Notch root radius = 0.005"

3) To prevent excessive hardening in notch area, machine final 0.040" of notch in five cuts (0.010" on first cut, 0.010" on 2nd cut, 0.010" on 3rd cut, 0.005" on 4th cut and 0.005" on 5th cut).

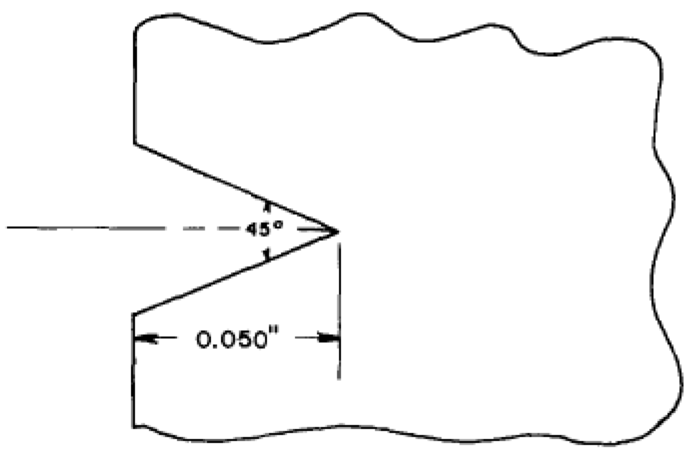
APPENDIX C-7

C-Shaped Fracture Mechanics Specimen



APPENDIX C-7a

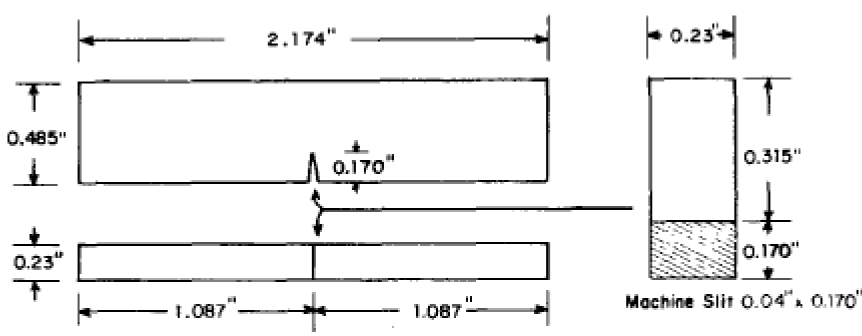
Detail of Notch in C-Shaped Fracture Mechanics Specimen



Notes: 1) All demensions ± 0.001"
2) Notch root radius = 0.005"

APPENDIX C-8

Impact Specimen: Modified Naval Research Laboratory Dynamic Tear Specimen



Appendix D

Heat Analyses

D-1: Type 304L Stainless Steel
D-2: Type 330 Stainless Steel
D-3: Incoloy® 800H
D-4 Tenelon®
D-5: Nitronic 40® Stainless Steel
D-6: Nitronic 50® Stainless Steel
D-7: Type 316 Stainless Steel
D-8: X18-3 Mn Stainless Steel
D-9: 18-18 Plus®
D-10: 304N
D-11: Carpenter 20 Cb-3®

DATA SHEET D-2

Heat Analysis Type 330 Stainless Steel

Element	Weight Percent
C	0.049
Mn	1.40
P	–
S	0.005
Si	1.46
Cr	18.40
Ni	35.00
Mo	0.18
N	–
Al	–
Ti	0.45
Nb	–
Cu	0.20

DATA SHEET D-3

Heat Analysis Incoloy® 800H

Element	Weight Percent
C	0.08
Mn	0.84
P	–
S	0.002
Si	0.51
Cr	19.19
Ni	34.04
Mo	–
N	–
Al	0.36
Ti	0.41
Nb	–
Cu	0.52

DATA SHEET D-4

Heat Analysis Tenelon®

Element	Weight Percent
C	–
Mn	15.3
P	–
S	–
Si	0.53
Cr	17.4
Ni	0.22
Mo	–
N	0.4-0.6
Al	–
Ti	–
Nb	–
Cu	–

DATA SHEET D-5

Heat Analysis Nitronic® 40 Stainless Steel

Element	Weight Percent
C	0.015
Mn	9.01
P	0.018
S	0.016
Si	0.24
Cr	20.32
Ni	6.71
Mo	–
N	0.35
Al	–
Ti	–
Nb	–
Cu	–

DATA SHEET D-6

Heat Analysis Nitronic® 50 Stainless Steel

Element	Weight Percent
C	0.05
Mn	5.44
P	0.015
S	0.010
Si	0.42
Cr	21.48
Ni	12.36
Mo	2.12
N	0.25
Al	-
Ti	-
Nb	0.19
Cu	-
V	0.2

DATA SHEET D-7

Heat Analysis Type 316 Stainless Steel

Element	Weight Percent
C	0.07
Mn	8.08
P	0.015
S	0.023
Si	0.69
Cr	19.57
Ni	5.67
Mo	2.13
N	0.32
Al	-
Ti	-
Nb	-
Cu	-

DATA SHEET D-8

Heat Analysis X18-3 Mn Stainless Steel

Element	Weight Percent
C	0.067
Mn	12.4
P	0.013
S	0.013
Si	0.43
Cr	18.55
Ni	3.17
Mo	–
N	0.33
Al	–
Ti	–
Nb	–
Cu	–
B	0.0015

DATA SHEET D-9

Heat Analysis 18-18 Plus®

Element	Weight Percent
C	0.11
Mn	17.80
P	0.020
S	0.004
Si	0.56
Cr	17.78
Ni	0.46
Mo	1.09
N	0.45
Al	–
Ti	–
Nb	–
Cu	0.95
Co	0.01

DATA SHEET D-10

Heat Analysis 304N

Element	Weight Percent
C	0.06
Mn	1.66
P	0.30
S	0.025
Si	0.19
Cr	18.37
Ni	8.43
Mo	0.10
N	0.250
Al	–
Ti	–
Nb	–
Cu	0.15

DATA SHEET D-11

Heat Analysis Carpenter 20 Cb-3®

Element	Weight Percent
C	0.018
Mn	1.60
P	0.028
S	0.007
Si	0.44
Cr	20.60
Ni	34.90
Mo	4.33
N	–
Al	–
Ti	–
Nb	0.39
Cu	0.20

REPORT WSRC-STI-2008-00043

DISTRIBUTION

SAVANNAH RIVER SITE

N. C. Iyer, 773-41A
R. L. Sindelar, 773-41A
T. M. Adams, 773-41A
T. Motyka, 719-18A
S. L. West, 773-A
M. J. Morgan, 773-A
P. S. Lam, 773-41A

EXTERNAL

Rana Mohtadi, Toyota Motor Engineering & Manufacturing North America TEMA
Kazuo Kawahara, Toyota Motor Engineering & Manufacturing North America TEMA
Taisuke Miyamoto**,** Toyota Motor Corporation