P&WA FR-7175
SEPTEMBER 1975

INFLUENCE OF GASEOUS HYDROGEN ON THE MECHANICAL PROPERTIES OF INCOLOY 903

FINAL REPORT

Contract NAS8-30744
Exhibit A
National Aeronautics and Space Administration
George C. Marshall Space Flight Center

PRATT & WHITNEY AIRCRAFT
Division of UNITED TECHNOLOGIES
FLORIDA RESEARCH AND DEVELOPMENT CENTER
P. O. Box 2691 - West Palm Beach, Florida 33402

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National Aeronautics and Space Administration
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UNITED TECHNOLOGIES

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SECTION I
INTRODUCTION

This report is submitted in accordance with the requirements of Contract NAS8-30744 and represents a final report covering work performed under Exhibit A - "Influence of Gaseous Hydrogen on the Mechanical Properties of Incoloy 903" of this contract. Additional work is being performed on several nickel-base alloys under two modifications to this contract: Exhibit B - "Tensile Properties of Several Nickel Alloys in Hydrogen at Elevated Temperature" and Exhibit C - "Mechanical Properties of a Nickel Alloy in Hydrogen at Elevated Temperature." The work under these contract modifications will be reported in a subsequent final report.

Experimental efforts under Exhibit A have consisted of 156 mechanical properties tests of the iron-base alloy Incoloy 903 in various heat-treat conditions, in gaseous environments at temperatures from 297°K (75°F) to 1033°K (1400°F) and pressures from one atmosphere to 34.5 MN/m² (5000 psig).

The objective of this program was to obtain the mechanical properties of Incoloy 903 in a pure or partial hydrogen environment at different temperatures and compare with the mechanical properties in air and helium at the same conditions. The specific environments included air, helium, hydrogen, and hydrogen and water vapor.

The overall test program, including types, conditions, and number of tests conducted, is outlined in table I-1. The primary goal of these tests was to document, rather than define, the hydrogen phenomenon and provide data of use in designing structures exposed to pressurized gaseous hydrogen environments.

All testing was conducted on solid specimens exposed to external gaseous pressure. Specific mechanical properties determined and the testing methods used are summarized below:

1. Tensile - Smooth and notched tensile properties were determined using ASTM tensile testing techniques.

2. Low-Cycle Fatigue - Low-cycle fatigue life was established by constant total strain testing using smooth specimens and a closed-loop test machine.

3. Creep-Rupture - Creep-rupture and notch stress-rupture lives were determined using ASTM creep-rupture techniques.

This report is arranged in sections that cover the program conclusions, material tested, and results and conclusions of the individual property tests. It includes the Incoloy 903 information covered in the monthly progress reports previously issued under the contract.

The International System of Units (SI) is used as the primary system of units for reporting specimen and test parameters and results. Customary English units are included in parenthesis following the SI units, or in separate columns in data tables. The customary system of units was used for the principal measurements and calculations and results converted to SI units for reporting purposes.

This program was conducted using the Program Manager - Project Group System by the Pratt & Whitney Aircraft, Florida Research and Development Center, Materials Development Laboratory, under the cognizance of Mr. W. B. McPherson, Metallurgy Branch, Materials & Process Laboratory, Marshall Space Flight Center.

Table I-1. Experimental Test Program for Incoloy 903

Material Form	Material Condition	Test Temperature, °K	Test Temperature, °F	Pressure, MN/m^2	Pressure, psig	Environment	Smooth Tensile (ST)	Notch Tensile (NT)	Low-Cycle Fatigue (LCF)	Creep-Rupture (C-R)	Notch-Rupture (N-R)
		Test Conditions					Type and Number of Tests				
Parent	STA[(1)]	297	75	One Atmosphere		Air	3	3	3		
		297	75	34.5	5000	Helium	1	1			
		297	75	34.5	5000	Hydrogen	2	2	3		
		700	800	34.5	5000	Helium	1	1			
		700	800	34.5	5000	Hydrogen	2	2			
		811	1000	34.5	5000	Helium	1	1			
		811	1000	34.5	5000	Hydrogen	2	2	3		
		922	1200	34.5	5000	Helium	1	1		2	
		922	1200	34.5	5000	Hydrogen	2	2		2	
		1033	1400	34.5	5000	Helium	2	1	2*	2	
		1033	1400	34.5	5000	Hydrogen	2	2	3*	2	2
		1033	1400	34.5	5000	H_2/H_2O			3*	2	2
	STA + OA[(2)]	1033	1400	34.5	5000	Helium	1	1			
		1033	1400	34.5	5000	Hydrogen	2	2			
Weld	AW[(3)]	297	75	One Atmosphere		Air	3	3	3		
		297	75	34.5	5000	Helium	1	1			
		297	75	34.5	5000	Hydrogen	2	2	3		
		811	1000	34.5	5000	Helium	1	1			
		811	1000	34.5	5000	Hydrogen	2	2	3		
		922	1200	34.5	5000	Helium	1	1		2	
		922	1200	34.5	5000	Hydrogen	2	2	3	2	
		1033	1400	34.5	5000	Helium	1	1	2*	2	
		1033	1400	34.5	5000	Hydrogen	2	2	3*	2	2
		1033	1400	34.5	5000	H_2/H_2O			3*	2	2
	AW + OA	1033	1400	34.5	5000	Helium	1	1			
		1033	1400	34.5	5000	Hydrogen	2	2			
	AW + HAZ[(4)]	297	75	One Atmosphere		Air			3		
		297	75	34.5	5000	Hydrogen			3		
		922	1200	34.5	5000	Helium			3		
		922	1200	34.5	5000	Hydrogen			3		

*LCF/dwell, 300 second-dwell or hold time at the maximum compressive strain

(1) STA - Solution heat-treated, 1750°F (1) AC, and aged, 1325°F (8) $\xrightarrow{100°F/hr}$ 1150 (8) AC

(2) OA - Overage, 1100°F (7.5) AC

(3) AW - As welded (material welded in solution heat-treated condition)

(4) HAZ - Weld heat affected zone.

Acknowledgement is given to the following personnel of the Project Group.

J. A. Doyle	-	Tensile and Creep Testing
J. Mucci	-	Technical Supervision and Report Efforts
M. W. Shiell	-	Proposal and Report Efforts
C. B. Stevens	-	Metallurgical Investigations
J. R. Warren	-	Low-Cycle Fatigue Testing
M. Zaccagnino	-	Proposal and Report Efforts

SECTION II
CONCLUSIONS

A. GENERAL

The efforts in this program have consisted of conducting various tests to determine the mechanical properties of the iron-base alloy, Incoloy 903, that is proposed for use in a pressurized gaseous hydrogen or a hydrogen-containing environment (hydrogen and water vapor). Properties determined in the hydrogen environments were compared to properties determined in a pure helium environment at the same conditions to establish environmental degradation. In some cases, properties in the hydrogen environments only were determined to establish design information.

The following system was established to determine the degree of degradation and serve as an aid in comparing the various alloy conditions:

1. Extremely Degraded (ED) - Hydrogen environment(s) reduced the property or life (in helium or air) greater than 50%.

2. Severely Degraded (SD) - Hydrogen environment(s) reduced the property or life (in helium or air) greater than 25%, but less than 50%.

3. Degraded (D) - Hydrogen environment(s) reduced the property or life (in helium or air) greater than 10%, but less than 25%.

4. Negligible Degradation (ND) - Hydrogen environment(s) reduced the property or life (in helium or air) less than 10% or had no detrimental effect.

Using this rating system, table II-1 displays the degree of degradation for Incoloy 903 in each condition tested, where a comparable test in helium or air was conducted. In the case of the tensile tests, if any property (yield strength, smooth or notch ultimate strength, elongation, and reduction of area) was degraded, the degradation rating was that of the most severely degraded property.

Detailed conclusions are presented in the various sections pertaining to types of tests. General conclusions, as pertaining to the parent and welded material, are presented below.

B. PARENT MATERIAL

The parent (STA) material tensile properties were the least degraded of all properties evaluated. In fact, with the exception of ductility at the elevated temperatures, negligible degradation, if any, was indicated due to the hydrogen environment.

Low-cycle-fatigue (LCF) life at 297°K (75°F) was severely degraded in a hydrogen environment (based on change from air tests). At 1033°K (1400°F), LCF life with dwell was not affected by the hydrogen environment. (Refer to Section V-A for dwell cycle.) However, for the same conditions, extreme degradation in LCF/dwell life was indicated due to the hydrogen and water vapor environment. It was suspected that oxidation or other reactions caused by dissociation of the water at the specimen surface at 1033°K (1400°F) caused the reduction in LCF/dwell life from the helium environment, as the pure hydrogen environment did not cause degradation at this temperature.

Table II-1. Degree of Environmental Degradation of Incoloy 903 in 34.5 MN/m² (5000 psig) Gaseous Environment

Material Form	Material Condition	Test Temperature °K	Test Temperature °F	Environment	Smooth Tensile (ST)	Notch Tensile (NT)	Low-Cycle Fatigue (LCF)	Creep Rupture (C-R)
Parent	STA	297	75	Hydrogen	ND	ND	D[1]	
		700	800	Hydrogen	D	ND		
		811	1000	Hydrogen	D	ND		
		922	1200	Hydrogen	D	ND		[3]
		1033	1400	Hydrogen	ND	ND	ND[2]	ED[4]
		1033	1400	Hydrogen and Water			ED[2]	ED[4]
	STA + OA	1033	1400	Hydrogen	SD	ND		
Weld	AW	297	75	Hydrogen	ND	ND	ED[1]	
		811	1000	Hydrogen	SD	ND		
		922	1200	Hydrogen	ND	ND		[3]
		1033	1400	Hydrogen	SD	ND	ND[2]	SD[4]
		1033	1400	Hydrogen and Water			ED[2]	ED[4]
	AW + OA	1033	1400	Hydrogen	ND	ND		
	AW-HAZ	297	75	Hydrogen			SD[1]	
		922	1200	Hydrogen			D	

[1]Degradation based on change from air
[2]Low-cycle fatigue with dwell
[3]Results inconclusive; degree of degradation could not be determined
[4]Degradation based on average of percent changes in rupture life at stress levels shown in table VI-1.

The creep-rupture life was extremely degraded at 1033°K (1400°F) in both hydrogen and hydrogen and water vapor environments. The notch stress-rupture life was also extremely degraded at 1033°K (1400°F) due to the hydrogen and water vapor environment. However, degradation was based on the change from hydrogen, as no notch stress-rupture helium tests were conducted.

C. WELDED MATERIAL

Welded AW material tensile properties were least degraded of all properties due to hydrogen envvironment. Only degradation in ductility was indicated. The degree varied from negligible to severe over the temperature range from 297°K (75°F) to 1033°K (1400°F).

Low-cycle-fatigue life at 297°K (75°F) was extremely degraded in the hydrogen environment (based on change from air tests). Like the STA material at 1033°K (1400°F), welded AW material LCF/dwell life was not affected by the hydrogen environment. In fact, a beneficial effect due to the hydrogen environment was indicaed. LCF/dwell life at 1033°K (1400°F) was extremely degraded due to the hydrogen and water vapor environment. Heat affected zone-welded material, LCF/dwell life was severely degraded due to both 297°K (75°F) and 922°K (1200°F) hydrogen environments. Degradation at 297°K (75°F) was based on air tests.

The AW material creep-rupture life at 1033°K (1400°F) was severely and extremely degraded due to hydrogen and hydrogen and water vapor environments, respectively. Based on hydrogen environment tests, notch stress-rupture life was extremely degraded due to a hydrogen and water vapor environment.

D. ENVIRONMENTS

Four gaseous environments were used in this program. They were: air, pure helium, pure hydrogen, and hydrogen and water vapor. The hydrogen and water vapor environment was obtained by usingg triple-distilled water in conjunction with pure hydrogen, such that the water was vaporized by furnace heat. (Refer to Section V-C.) The presence of water vapor in the hydrogen was very detrimental to both LCF and creep-rupture life at 1033°K (1400°F). An absolute conclusion as to the effect of water in hydrogen at all temperatures should not be made based on results of these tests at one temperature only. The presence of water vapor in hydrogen may inhibit or reduce degradation as compared to a pure hydrogen environment at lower temperatures. This beneficial effect of water vapor was observed for some nickel-base alloys in a previous program (Contract NAS8-26191) and was reported in PWA FR-5768. We believe that, at the lower temperatures, the water vapor would not dissociate into hydrogen and oxygen, with resulting oxidation of the material and, thus, decreased properties. This does not occur at lower temperatures.

E. DISCUSSION

This program was established to determine specific material properties and to enable general observations in regard to the susceptibility of Incoloy 903 to hydrogen degradation. We have observed that creep-rupture and LCF, both of which involve relatively long exposures to the environment at high strain-stress levels, are the most severe tests of a material for hydrogen degradation. Short-term tensile tests will not always indicate a material's susceptibility to hydrogen degradation.

The testing done in this effort was of necessity very limited; conclusions as to the degree of degradation may be shown to be incorrect by additional investigations. Two general observations can be made, however, which can be used to classify this material:

1. Incoloy 903 is not immune to hydrogen environment degradation. At temperatures above 811°K (1000°F), properties appear to be more severely affected by hydrogen environments than at lower temperatures.

2. The addition of water vapor to the high-preessure hydrogen can cause disastrous reductions in this material's mechanical properties.

SECTION III
MATERIALS AND SPECIMENS

A. TEST MATERIAL

The purpose of this program was to determine the susceptibility of Incoloy 903 to environmental degradation. Testing evaluated the mechanical properties of the iron-base alloy in the parent and welded material form. Table I-1 lists the material conditions and the types of tests performed.

The raw material was procured from Huntington Alloy Products Division, the International Nickel Company, in the form of hot-rolled plate processed from ingots made by the Electro Slag Remelt (ESR) process. This process provides for ingot remelting under a blanket of reactive slag. The slag blanket protects the material from atmospheric contamination and aids the refining process. Metal producers claim the ESR process results in ingot of the same quality as vacuum arc remelt.

The material was received under Huntington Order No. 094784, Lot PC-7377-1, Heat No. HH26AOUK. The chemical composition, as certified by the producer, is listed in table III-1 Spectrographic analysis upon receipt verified material as Incoloy 903.

Table III-1. Chemical Composition of Incoloy 903, Heat HH26AOUK

Element	Weight, %
Nickel	38.320
Cobalt	15.320
Columbium & Tantalum	3.130
Titanium	1.550
Aluminum	0.790
Carbon	0.020
Manganese	0.150
Silicon	0.050
Sulfur	0.009
Chromium	0.010
Copper	0.080
Boron	0.007
Phosphorus	0.004
Iron	Balance ($\approx$ 40.56)

The material was in the form of hot-rolled plate 1.22 m (4 ft) x 0.61 m (2 ft) x 12.7 mm (0.5 in.) thick. Mill solution heat-treat was 1227°K (1750°F) for 1 hour, air cool. Hardness was 87, Rockwell "B" scale. Vendor-certified room temperature tensile properties were:

Ultimate Strength	703.3 MN/m² (102.0 ksi)
0.2% Yield Strength	372.3 MN/m² (54.0 ksi)
Elongation	49.0%
Reduction of Area	63.0%

These properties were confirmed at FRDC with the following results:

	Transverse (Perpendicular to Rolling Direction)	*Longitudinal (Parallel to Rolling Direction)*
Ultimate Strength	715.7 MN/m² (103.8 ksi)	721.2 MN/m² (104.6 ksi)
0.2% Yield Strength	365.4 MN/m² (53.0 ksi)	355.8 MN/m² (51.6 ksi)
Elongation	47.5%	45.0%
Reduction of Area	60.0%	64.2%

Material was subjected to the aging heat-treat which consisted of heating the material to 993°K (1325°F) for 8 hours, furnace cooling at 311°K (100°F) per hour to 899°K (1150°F), and holding at that temperature for a total aging time of 18 hours.

The average room temperature tensile properties obtained in the transverse direction after aging were:

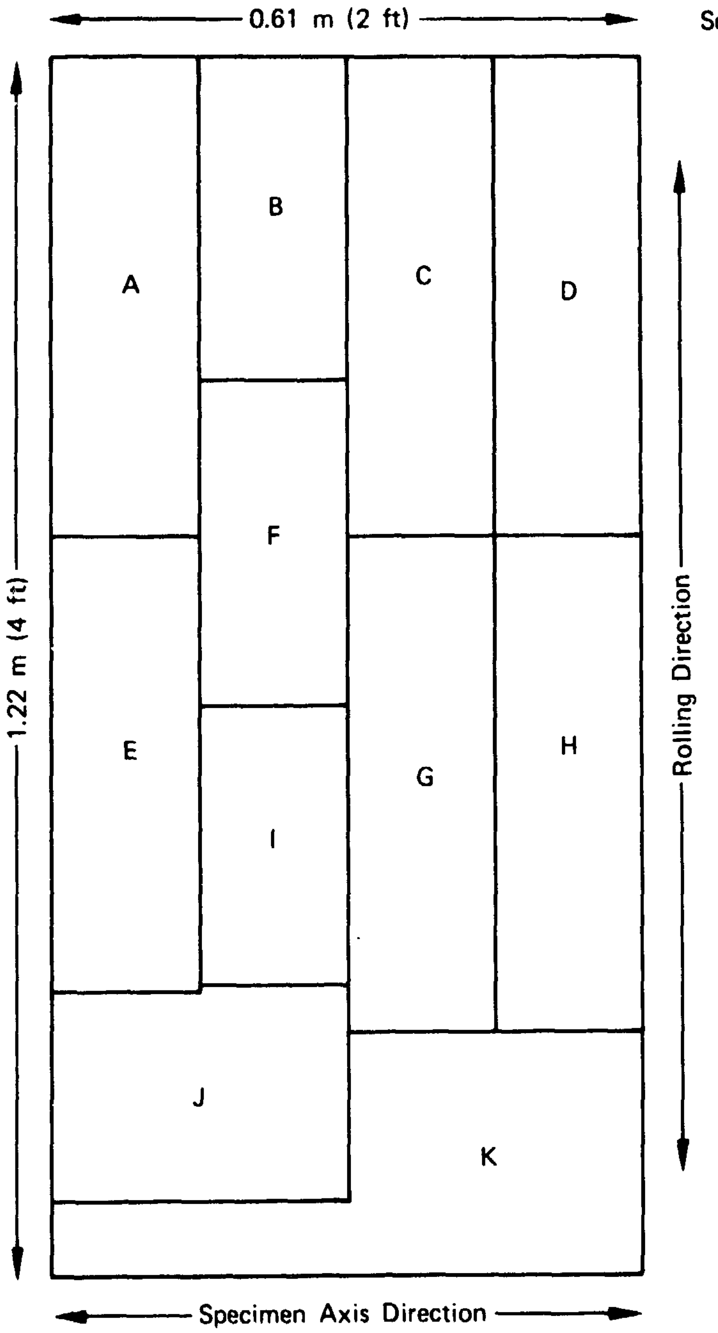
Ultimate Strength	1343.8 MN/m² (194.9 ksi)
0.2 Yield Strength	1106.6 MN/² (160.5 ksi)
Elongation	17.4%
Reduction of Area	41.4%

Based upon the results of the proceeding tests, the material was accepted as meeting the basic contract requirements.

The plate was next cut into sections as shown in figure III-1. Each section was sized to obtain the number of each type of specimens required. Plate sections were identified and heat treatments performed as required. Heat treatments applied to the Incoloy 903 material for this program are listed in table III-2. Typical microstructure of the material in each of the conditions is shown in figure III-2.

Metallographic examination of the raw material sections prior to machining verified the plate rolling direction for specimen orientation (specimen axis in transverse direction; weld joints parallel to plate rolling direction). Age and overage heat treatments were given to sufficient material for the parent material tests.

The Incoloy 903 material was tested in both the parent and welded material form. Welded specimen plates were prepared as double-vee grooves (figure III-3) parallel to the plate rolling direction. Gas Tungsten (GTA) welding was manually performed using filler material prepared from Incoloy 903 sheet. Material was in the solution-treated condition when welded. Both the root pass weld and the finished weld were X-ray inspected and judged radiographically sound. After welding, the plates were cut in 12.7 mm (0.5 in.) x 12.7 mm (0.5 in.) specimen blanks. This provided for a weld joint oriented perpendicular to the specimen test load or strain. Prior to machining, specimen blanks were given a light etch to define the weld Heat Affected Zone (HAZ) and a sufficient number of blanks were given the erage heat treatment, 1033°K (1400°F), 7.5 hours, air-cool. Test specimens were machined with the weld joint located in the center of the gage section, except for 12 LCF specimens, in which the weld HAZ was centered in the gage section.



Section ID - Type Test / Material Condition / Heat Treat

- A - LCF/Welded/As Welded
- B - Creep Rupture/Welded/ As Welded
- C - Smooth Tensile/Welded/ As Welded and Overaged
- D - Notch Tensile/Welded/ As Welded and Overaged
- E - LCF/Parent Mat'l/Aged
- F - Creep Rupture/Parent Mat'l/ Aged
- G - Smooth Tensile/Parent Mat'l Overaged
- H - Notch Tensile/Parent Mat'l/ Overaged
- I - LCF/Welded: HAZ at Ctr of Specimen/As Welded
- J - Retest, Welded Smooth Tensile
- K - Contingency and Acceptance Test Material

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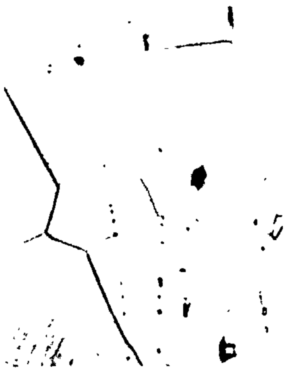
Figure III-1. Sectioning Diagram of Incoloy 903 Plate for Preparation of Specimen Blanks

Table III-2. Incoloy 903 Material Heat Treat Conditions Used in Determining Susceptibility to Environmental Degradation

Material Condition	*Condition Code*	*Heat Treatment[1] Sequence*	*Tests[2]*
Solution Treated (As-Received)	ST	1220°K (1750°F), 1 hour, air cool	Acceptance
Solution Treated and Aged	STA	Solution treatment above + 993°K (1325°F), 8 hours, furnace cool to 899°K (1150°F) hold for total age of 18 hours	LCF, ST, NT, CR
Overage	STA + OA	Solution treatment and age above + 1033°K (1400°F), 7.5 hours, air cool	ST, NT
As Weld	AW	Solution treatment above + GTA weld	LCF, CR, ST, NT
Welded and Over-aged	AW + OA	Solution treatment above + GTA weld + 1033°K (1400°F), 7.5 hours, air cool	ST, NT

[1]All heat treatment done inert (Argon) atmosphere
[2]LCF - Low-Cycle Fatigue, ST - Smooth Tensile, CR - Creep Rupture, NT - Notch Tensile.



As Received, Solution Treated (ST)

Solution Treated and Aged (STA)

Solution Treated, Aged and Overaged (STA+OA)

As Welded - Weld Zone (AW)

As Welded, Heat Affected Zone (AW-HAZ)

As Welded - Parent Metal Zone

Welded and Overaged - Weld Zone (AW+OA)

Welded and Overaged Heat Affected Zone (AW+OA-HAZ)

Welded and Overaged - Parent Metal Zone

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Figure III-2. Typical Microstructures of Incoloy 903 Material in the Conditions Tested, Magnification 500X

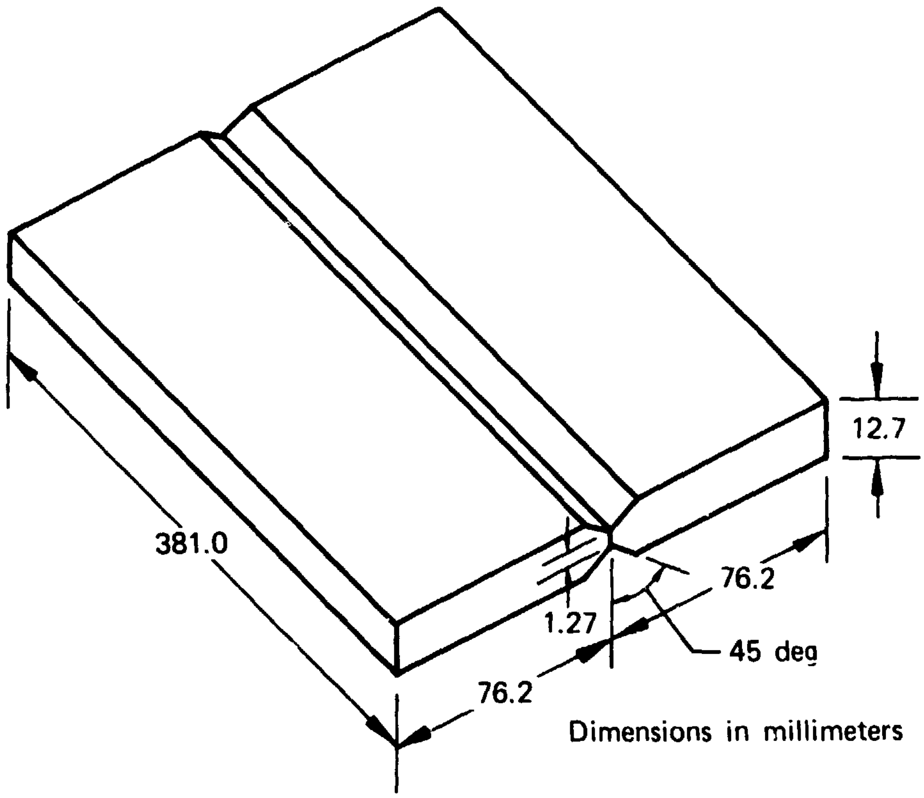

Figure III-3. Specimen Plate Weld Preparation

B. TEST GASES AND MATERIALS

Helium, hydrogen, and hydrogen and water vapor were used during the testing of specimens, and nitrogen was used as a preliminary purge gas. Propellant grade hydrogen was provided under Military Specification P-27201, which requires the gas to have an oxygen content of less than 1 part per million. Analysis verified gas to be of this purity. The helium and hydrogen gases were used directly to provide the test environments. The hydrogen and water vapor environment was obtained by utilizing triple distilled water and a retort system such that the water was vaporized by furnace heat while maintaining the specified pressure.

Gas handling systems, supplying the test vessels, were equipped to enable sampling before and after specimen tests. The hydrogen was sampled extensively, both dry and saturated with water vapor (wet hydrogen was dried prior to analysis). Samples were analyzed using a gas chromatograph with accuracy in the parts per billion range. No appreciable difference was noted between pretest and post-test samples, indicating no gas contamination by the test rig and/or test itself.

C. TEST SPECIMENS

All specimens were machined by the Pratt & Whitney Aircraft Materials Laboratory Machine Shop and finished to an average roughness of 16-μ in. rms, or less. The notches used for the tensile and notch stress-rupture specimens to obtain stress concentratons of 8.0 and 3.6, respectively, conform with Peterson[1] and were machined by grinding.

[1]R. E. Peterson, "Stress Concentration Design Factors," John Wiley & Sons, Inc., New York, 1974.

A typical set of specimens is listed in table III-3 and shown in figure III-4. Specimen prints are shown in figures III-5 through III-9.

Table III-3. Specimens Used to Determine the Susceptibility of Incoloy 903 to Environmental Degradations

Name	*Print Number*	*Figure*
Stress-Strain/Modulus	FML 96311	III-5
Notched Tensile, Variable K_T	FML 96312	III-6
Constant Strain Low-Cycle Fatigue	FML 95716C	III-7
Flat End Creep-Rupture	FML 95623B	III-8
Notch Stress-Rupture	FML 96175	III-9

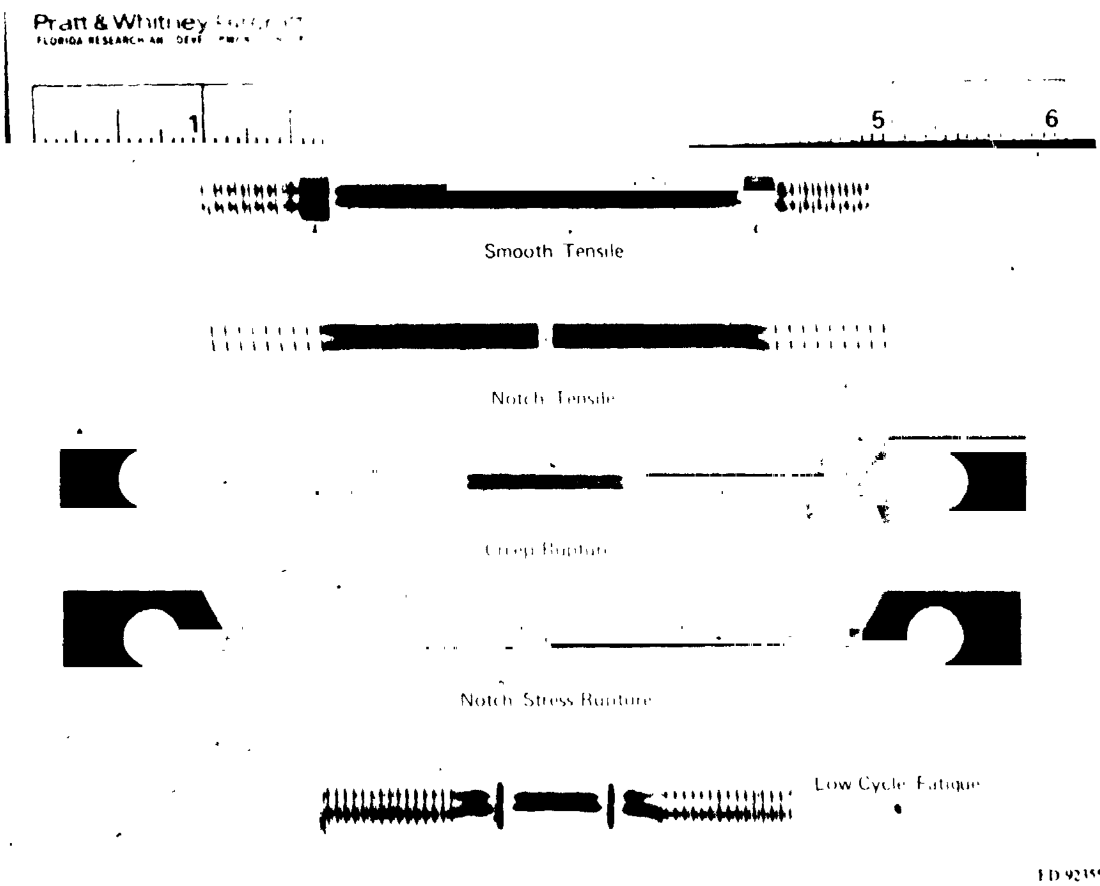

Figure III-4. Typical Test Specimens Used to Determine the Effect of High-Pressure Gaseous Environments on Mechanical Properties of Materials

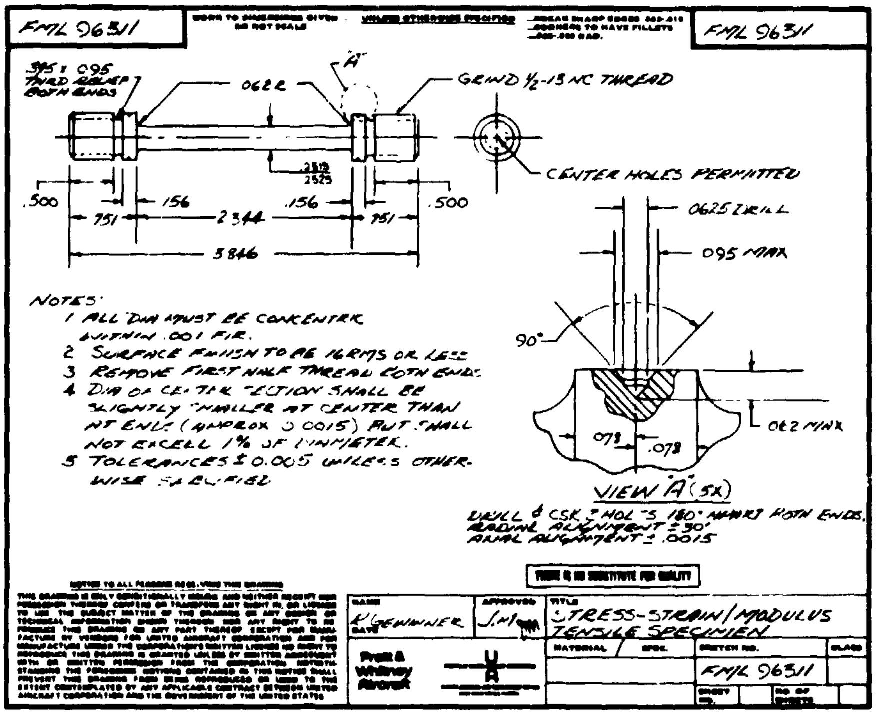

Figure III-5. Smooth Tensile Specimen

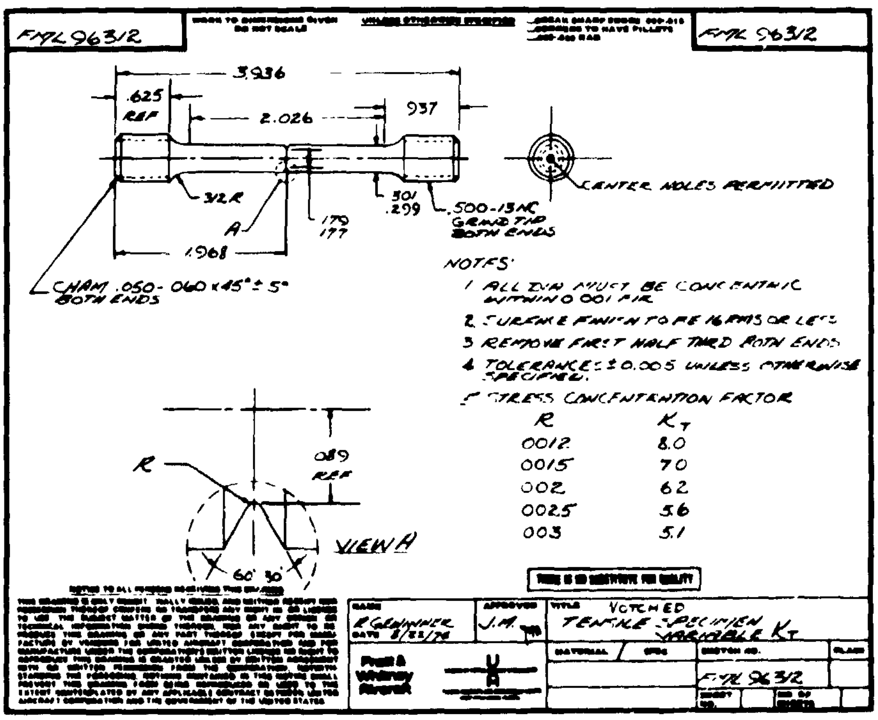

Figure III-6. Notch Tensile Specimen

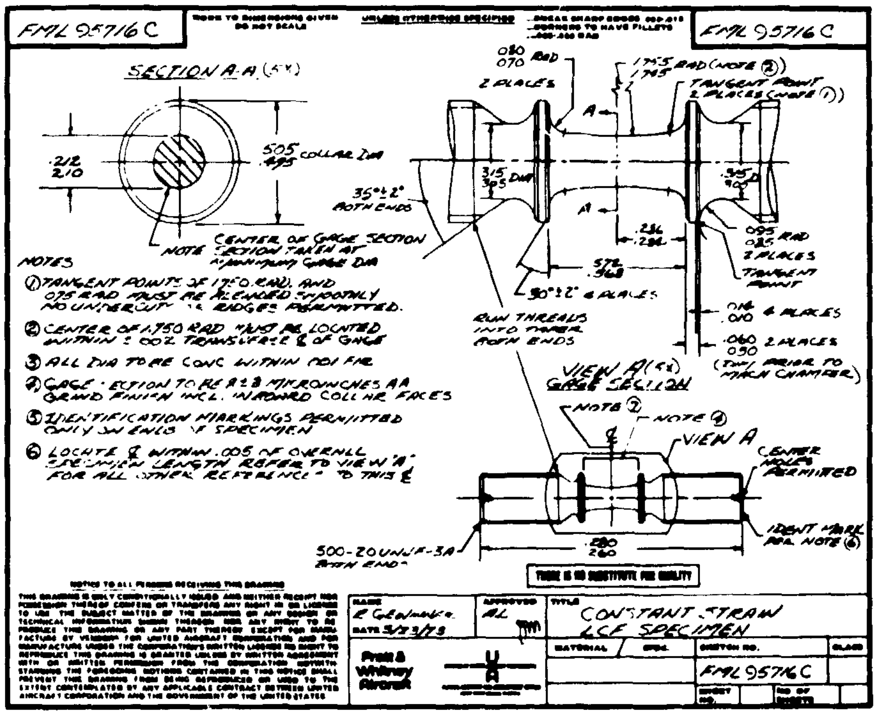

Figure III-7. Low-Cycle Fatigue Specimen

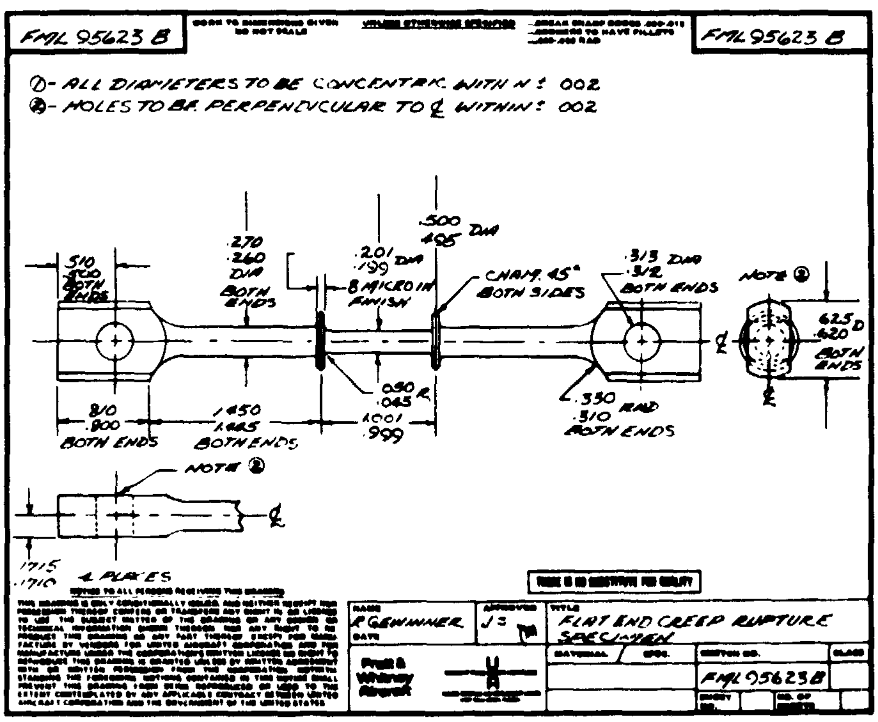

Figure III-8. Creep-Rupture Specimen

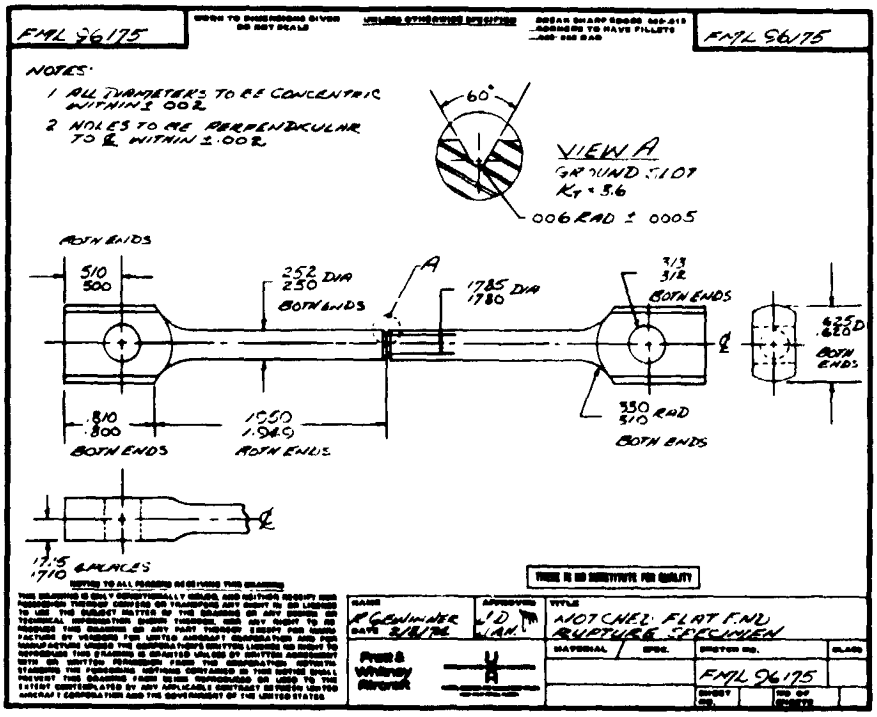

Figure III-9. Notch Stress-Rupture Specimen

SECTION IV
TENSILE PROPERTIES

A. INTRODUCTION

The tensile properties of the iron-base alloy, Incoloy 903, in the parent and welded condition were investigated in air, 34.5 MN/m² (5000 psig) helium, and hydrogen at temperatures of 297°K (75°F) to 1033°K (1400°F). Smooth tensile tests established stress-strain parameters, 0.2% yield and ultimate strengths, elongation, reduction of area, and modulus of elasticity. Notched ($K_T = 8.0$) tensile tests established ultimate strength. Results of tests in hydrogen were compared to those in helium and air to determine property degradation.

B. RESULTS AND CONCLUSIONS

The individual tensile properties (0.2% yield and ultimate strengths, elongation, reduction of area, and notch tensile ultimate) of Incoloy 903 parent and welded material did not reflect the influence of hydrogen environment to the same degree. The relative degree of environmental degradation is summarized in table IV-1. Neither the parent (STA) nor the welded (AW) material exhibited tangible degradation in the yield or ultimate strengths. Differences in the yield and ultimate strengths obtained in the three environments did occur. However, with the limited number of tests conducted, normal specimen-to-specimen scatter, especially for welded specimen tests, precludes drawing any firm conclusions when the properties differences were less than 10%.

As previously reported in PWA FR-5768[1] and PWA FR-6709[2], loss of ductility (elongation and/or reduction of area) was the most prominent indicator of hydrogen degradation. Degrees of degradation in elongation and reduction of area from "negligible" (less than 10%) to "severe" (greater than 25%) were indicated for the parent and/or welded material up to 1033°K (1400°F).

The effects of temperature and environment upon tensile properties of the STA and AW materials are shown in figures IV-1 and IV-2, respectively.

The notch strengths of both material forms were degraded less than 10%, if at all, throughout the temperature range investigated. The effects of temperature and environment upon notch strength of STA and AW material are shown in figure IV-3.

Based on helium environment tests, overaging of parent material (STA + OA) resulted in a decrease in strength and increase in ductility at 1033°K (1400°F), the only temperature investigated. The only STA + OA material tensile property affected by hydrogen environment at 1033°K (1400°F) was reduction of area, where severe degradation was indicated. For the overaged welded (AW + OA) material, no degradation in tensile properties was indicated due to the 1033°K (1400°F) hydrogen environment. Complete test results are listed in table IV-2.

The effects of temperature upon stress-strain parameters of STA and AW materials are shown in figures IV-4 and IV-5, respectively. Data analysis indicated that stress-strain parameters were not affected by environment (air, helium, hydrogen). Therefore, for each material form, the average stress-strain values for all tests conducted at each test temperature were plotted. The STA and AW material stress-strain parameters for each individual test are listed in tables IV-3 and IV-4, respectively.

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[1] "Properties of Materials in High Pressure Hydrogen at Cryogenic, Room, and Elevated Temperatures," Final Report, Contract NAS8-26191, 31 July 1973

[2] "Influence of Gaseous Hydrogen on the Mechanical Properties of AISI 304 Stainless Steel," Final Report, Contract NAS8-29883.

Table IV-1. Degradation of Tensile Properties of Incoloy 903 in 34.5 MN/m² (5000 psig) Gaseous Hydrogen

Form	Condition	Stress Concentration Factor	Temperature, °K	Temperature, °F	Degradation (Decrease from Helium, %) Strength 0.2% Yield	Strength Ultimate	Ductility EL	Ductility RA	Ratio of Ultimate Strength He/Air	Ratio of Ultimate Strength H_2/He	Ratio of Notch/Smooth Ultimate Strength Air	Helium	Hydrogen
Parent	STA	8.0	297	75					1.00		1.56	1.56	1.56
		8.0	297	75		ND				1.00			
		Smooth	297	75					1.00				
		Smooth	297	75	ND	ND	ND	ND		1.00			
		8.0	700	800		ND				0.95		1.46	1.41
		Smooth	700	800	ND	ND	ND	14		0.98			
		8.0	811	1000		ND				0.94		1.56	1.46
		Smooth	811	1000	ND	ND	16	ND		1.01			
		8.0	922	1200		ND				0.98		1.67	1.61
		Smooth	922	1200	ND	ND	21	13		1.02			
		8.0	1033	1400		ND				0.59		2.08	2.04
		Smooth	1033	1400	ND	ND	ND	ND		1.00			
	STA + OA	8.0	1033	1400		ND				0.96		2.10	1.86
		Smooth	1033	1400	ND	ND	ND	34		1.09			
Welded	AW	8.0	297	75					1.18		1.28	1.47	1.40
		8.0	297	75		ND				0.95			
		Smooth	297	75					1.02				
		Smooth	297	75	ND	ND	ND	ND		0.99			
		8.0	811	1000		ND				0.95		1.45	1.45
		Smooth	811	1000	ND	ND	24	29		1.01			
		8.0	922	1200		ND				0.93		1.88	1.76
		Smooth	922	1200	ND	ND	ND	ND		0.99			
		8.0	1033	1400		ND				0.99		2.21	1.76
		Smooth	1033	1400	ND	ND	36	26		1.24			
	AW + OA	8.0	1033	1400		ND				1.02		2.22	2.16
		Smooth	1033	1400	ND	ND	ND	ND		1.07			

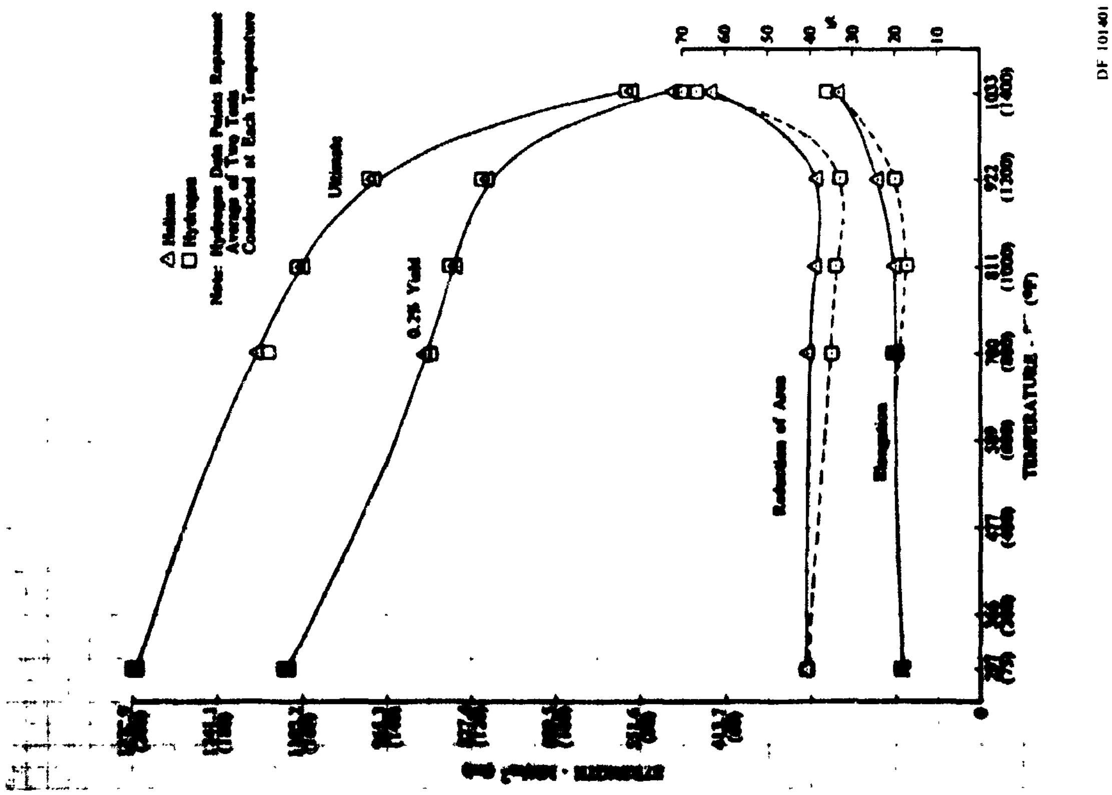

Figure IV-1. Effect of Temperature and Environment on the Tensile Properties of Incoloy 903 Parent (STA) Material at 34.5 MN/m² (5000 psig)

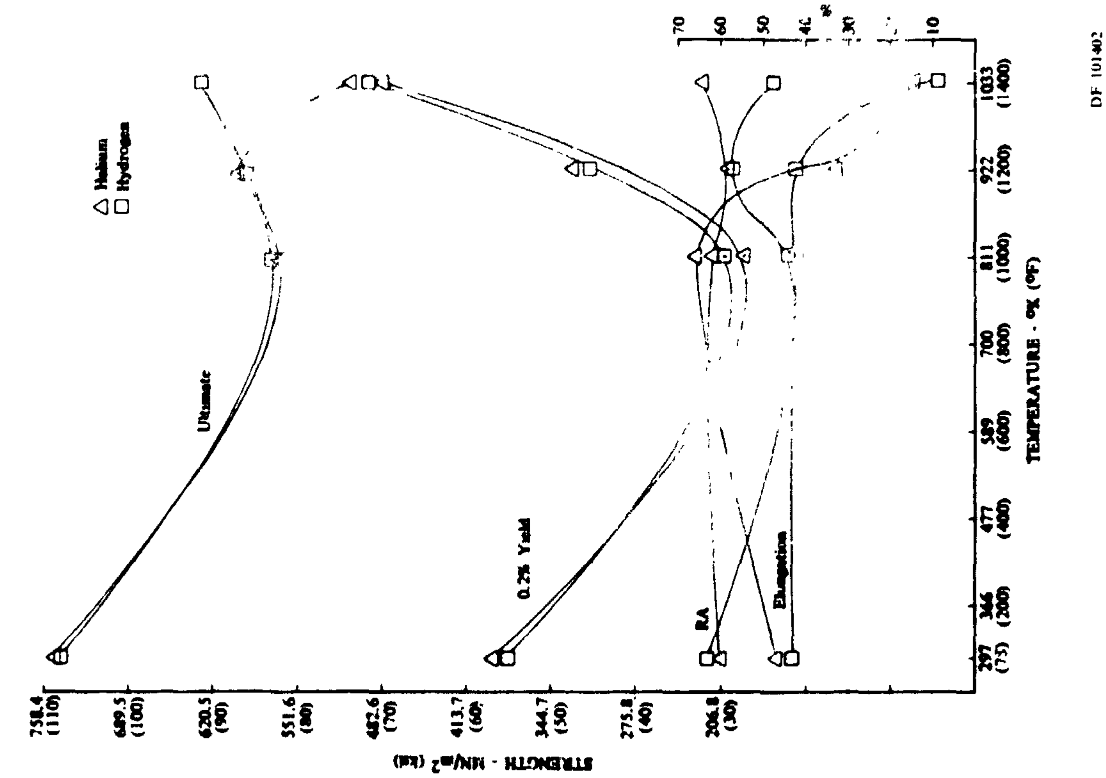

Figure IV-2. Effect of Temperature and Environment on the Tensile Properties of Welded (AW) Incoloy 903 at 34.5 MN/m² (5000 psig)

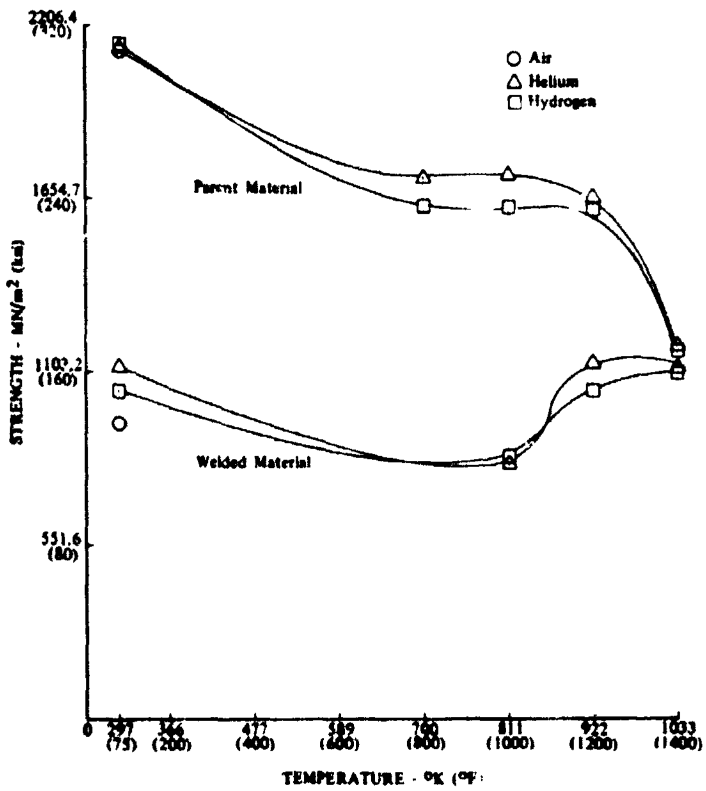

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Figure IV-3. Effect of Temperature and Environment on the Notch (K_T = 8.0) Strength of Incoloy 903 Parent (STA) and Welded (AW) Material at 34.5 MN/m^2 (5000 psig)

Table IV-2. Tensile Properties of Incoloy 903 in Air and High Pressure Gaseous Environments

Material Form	Material Condition	Spec S/N	Test Temperature °K	Test Temperature °F	Test Conditions: Stress Concentration Factor	Environment	Pressure, MN/m²	Pressure (psig)	Test Results: Strength 0.2% Yield, MN/m²	0.2% Yield, ksi	Ultimate, MN/m²	Ultimate, ksi	Ductility Elongation,* %	RA, %	Modulus of Elasticity, psi x 10⁶
Parent	STA	SPS-2	297	75	Smooth	Air	One Atmosphere		1148.0	166.5	1356.9	196.[illegible]	19.2	48.0	22.9
		SPS-3	297	75	Smooth	Air	One Atmosphere		1149.4	166.7	1365.2	198.0	19.5	37.8	23.2
		SPS-4	297	75	Smooth	Air	One Atmosphere		1128.7	163.7	1359.6	197.2	18.0	41.6	22.8
		SPS-5	297	75	Smooth	Helium	34.5	5000	1123.8	163.0	1367.9	198.4	18.0	40.8	23.9
		SPS-6	297	75	Smooth	Hydrogen	34.5	5000	1132.8	164.3	1384.5	200.8	20.0	42.0	23.0
		SPS-7	297	75	Smooth	Hydrogen	34.5	5000	1131.4	164.1	1376.2	199.6	17.5	40.8	23.4
		SPS-8	700	800	Smooth	Helium	34.5	5000	902.5	130.9	1176.2	170.6	19.5	40.6	23.8
		SPS-9	700	800	Smooth	Hydrogen	34.5	5000	890.1	129.1	1164.5	168.9	21.0	31.0	24.4
		SPS-10	700	800	Smooth	Hydrogen	34.5	5000	884.6	128.3	1152.1	167.1	20.5	35.8	23.4
		SPS-11	811	1000	Smooth	Helium	34.5	5000	853.6	123.8	1105.2	160.3	20.0	38.6	21.9
		SPS-12	811	1000	Smooth	Hydrogen	34.5	5000	866.7	125.7	1114.2	161.6	16.0	38.6	24.1
		SPS-13	811	1000	Smooth	Hydrogen	34.5	5000	863.9	125.3	1111.4	161.2	17.5	31.4	24.2
		SPS-14	922	1200	Smooth	Helium	34.5	5000	797.0	115.6	981.8	142.4	24.9	38.2	(1)
		SPS-20	922	1200	Smooth	Hydrogen	34.5	5000	808.1	117.2	989.4	143.5	20.0	31.3	21.6
		SPS-16	922	1200	Smooth	Hydrogen	34.5	5000	825.3	119.7	1007.3	146.1	18.0	35.5	22.8
		SPS-17	1033	1400	Smooth	Helium	34.5	5000	484.7	70.3	545.4	79.1	36.5	65.6	21.0
		SPS-21	1033	1400	Smooth	Helium	34.5	5000	510.9	74.1	583.3	84.6	30.0	59.8	21.0
		SPS-18	1033	1400	Smooth	Hydrogen	34.5	5000	459.2	66.6	544.0	78.9	37.5	69.7	20.9
		SPS-19	1033	1400	Smooth	Hydrogen	34.5	5000	508.1	73.7	586.1	85.0	35.0	64.6	19.8
		NPS-1	297	75	8.0	Air	One Atmosphere				2125.0	308.2			
		NPS-2	297	75	8.0	Air	One Atmosphere				2124.3	308.1			
		NPS-3	257	75	8.0	Air	One Atmosphere				2119.5	307.4			
		NPS-4	297	75	8.0	Helium	34.5	5000			2137.0	310.0			
		NPS-5	297	75	8.0	Hydrogen	34.5	5000			2144.0	311.0			
		NPS-6	297	75	8.0	Hydrogen	34.5	5000			2151.0	312.0			
		NPS-7	700	800	8.0	Helium	34.5	5000			1712.7	248.4			
		NPS-8	700	800	8.0	Hydrogen	34.5	5000			1634.7	237.1			
		NPS-9	700	800	8.0	Hydrogen	34.5	5000			1623.7	235.5			
		NPS-10	811	1000	8.0	Helium	34.5	5000			1724.4	250.1			
		NPS-11	811	1000	8.0	Hydrogen	34.5	5000			1610.6	233.6			
		NPS-12	811	1000	8.0	Hydrogen	34.5	5000			1642.3	238.2			
		NPS-13	922	1200	8.0	Helium	34.5	5000			1641.0	238.0			
		NPS-14	922	1200	8.0	Hydrogen	34.5	5000			1627.2	236.0			
		NPS-15	922	1200	8.0	Hydrogen	34.5	5000			1596.1	231.5			
		NPS-16	1033	1400	8.0	Helium	34.5	5000			1172.1	170.0			
		NPS-17	1033	1400	8.0	Hydrogen	34.5	5000			1157.6	167.9			
		NPS-18	1033	1400	8.0	Hydrogen	34.5	5000			1151.4	167.0			
	STA + OA	SPO-1	1033	1400	Smooth	Helium	34.5	5000	466.8	67.7	539.2	78.2	35.0	65.6	20.3
		SPO-2	1033	1400	Smooth	Hydrogen	34.5	5000	517.8	75.1	590.2	85.6	29.0	31.0	20.9
		SPO-3	1033	1400	Smooth	Hydrogen	34.5	5000	536.4	77.8	580.2	84.2	48.6	55.1	20.8
		NPO-1	1033	1400	8.0	Helium	34.5	5000			1132.8	164.3			
		NPO-4	1033	1400	8.0	Hydrogen	34.5	5000			1019.0	147.8			
		NPO-3	1033	1400	8.0	Hydrogen	34.5	5000			1157.6	167.9			
Weld	AW	SWW-3	297	75	Smooth	Air	One Atmosphere		399.9	58.0	724.6	105.1	57.5	52.5	22.8(2)
		SWW-20	297	75	Smooth	Air	One Atmosphere		378.5	54.9	730.2	105.9	39.0	59.8	23.4
		SWW-5	297	75	Smooth	Air	One Atmosphere		380.6	55.2	739.8	107.3	64.5	60.5	22.9
		SWW-2	297	75	Smooth	Helium	34.5	5000	390.9	56.7	749.5	108.7	47.0	60.5	22.9
		SWW-6	297	75	Smooth	Hydrogen	34.5	5000	362.0	52.5	724.6	105.1	45.0	63.5	23.5
		SWW-23	297	75	Smooth	Hydrogen	34.5	5000	397.1	57.6	763.2	110.7	41.0	62.8	23.5
		SWW-18	811	1000	Smooth	Helium	34.5	5000	188.2	27.3	564.0	81.8	56.0	62.1	25.2
		SWW-9	811	1000	Smooth	Hydrogen	34.5	5000	196.5	28.5	561.9	81.5	38.0	41.6	25.5(3)
		SWW-10	811	1000	Smooth	Hydrogen	34.5	5000	202.0	29.3	581.9	84.4	47.5	46.4	23.0
		SWW-21	922	1200	Smooth	Helium	34.5	5000	326.1	47.3	599.2	86.9	32.3	58.8	22.2(4)
		SWW-22	922	1200	Smooth	Hydrogen	34.5	5000	366.1	53.1	612.9	88.9	30.4	57.4	22.7
		SWW-14	922	1200	Smooth	Hydrogen	34.5	5000	258.6	37.5	572.3	83.0	53.9	58.1	22.4
		SWW-19	1033	1400	Smooth	Helium	34.5	5000	440.6	69.7	508.1	73.7	14.0	64.1	20.9(2)
		SWW-16	1033	1400	Smooth	Hydrogen	34.5	5000	504.0	73.1	608.1	88.2	10.0	44.9	21.5(2)
		SWW-17	1033	1400	Smooth	Hydrogen	34.5	5000	484.0	70.2	652.2	94.6	8.0	50.5	25.5
		NWW-8	297	75	8.0	Air	One Atmosphere				950.1	137.8			
		NWW-9	297	75	8.0	Air	One Atmosphere				990.8	143.7			
		NWW-10	297	75	8.0	Air	One Atmosphere				867.4	125.8			
		NWW-11	297	75	8.0	Helium	34.5	5000			1104.5	160.2			
		NWW-12	297	75	8.0	Hydrogen	34.5	5000			1056.3	153.2			
		NWW-13	297	75	8.0	Hydrogen	34.5	5000			1032.8	149.8			
		NWW-14	811	1000	8.0	Helium	34.5	5000			815.6	118.3			
		NWW-15	811	1000	8.0	Hydrogen	34.5	5000			843.9	122.4			
		NWW-16	811	1000	8.0	Hydrogen	34.5	5000			810.1	117.5			
		NWW-17	922	1200	8.0	Helium	34.5	5000			1125.2	163.2			
		NWW-18	922	1200	8.0	Hydrogen	34.5	5000			1043.2	151.3			
		NWW-19	922	1200	8.0	Hydrogen	34.5	5000			1041.1	151.0			
		NWW-20	1033	1400	8.0	Helium	34.5	5000			1121.8	162.7			
		NWW-21	1033	1400	8.0	Hydrogen	34.5	5000			1130.0	163.9			
		NWW-22	1033	1400	8.0	Hydrogen	34.5	5000			1088.0	157.8			
Weld	AW + OA	SWX-1	1033	1400	Smooth	Helium	34.5	5000	441.3	64.0	460.6	66.8	10.2	45.8	22.9
		SWX-2	1033	1400	Smooth	Hydrogen	34.5	5000	457.8	66.4	483.3	70.1	15.0	57.4	20.4
		SWX-3	1033	1400	Smooth	Hydrogen	34.5	5000	471.6	68.4	504.7	73.2	14.0	58.0	20.6
		NWX-1	1033	1400	8.0	Helium	34.5	5000			102[illegible].6	148.6			
		NWX-2	1033	1400	8.0	Hydrogen	34.5	5000			1034.2	150.0			
		NWX-3	1033	1400	8.0	Hydrogen	34.5	5000			1056.3	153.2			

*Elongation based on gage length of 25.4 mm (1.000 in.) or 4D.
(1) Malfunction of recorder, modulus not available, yield strength approximate.
(2) Failure in weld.
(3) Failed in weld with noticeable imperfection.
(4) Failed outside of gage marks.

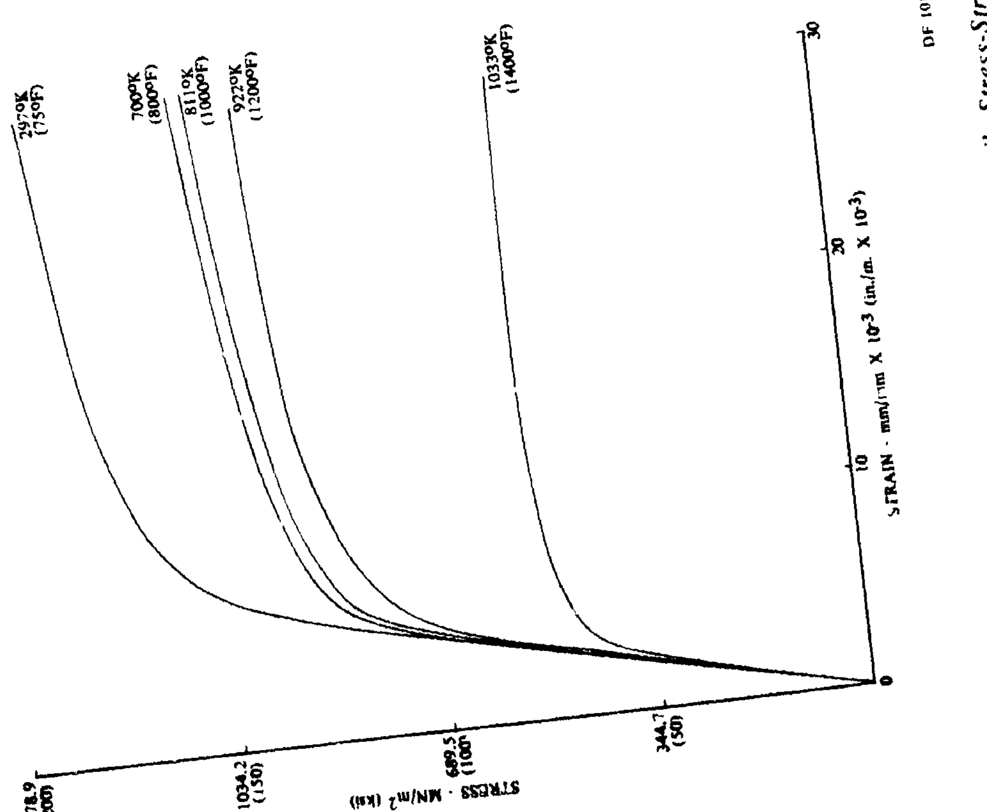


Figure IV-4. Effect of Temperature on the Tensile Stress-Strain Curves of Incoloy 903 Parent (STA) Material

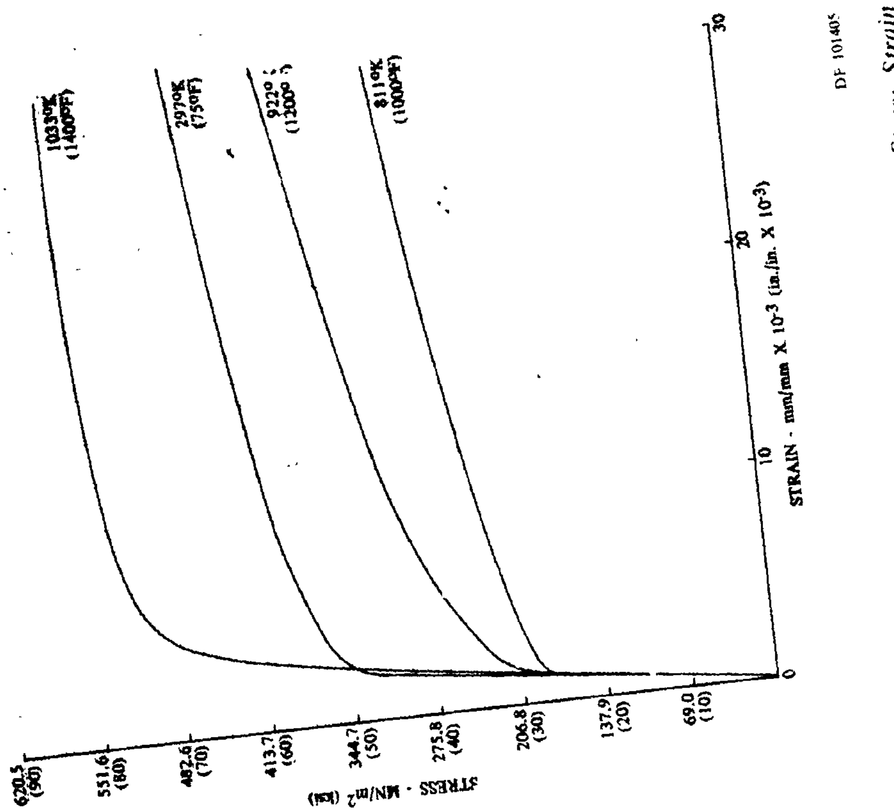


Figure IV-5. Effect of Temperature on the Tensile Stress-Strain Curves of Welded (AW) Incoloy 903

Table IV-3. Individual Specimen Stress-Strai
and 34.5 MN/m² (5000 psig) Gas

Offset, % Specimen Identity	Stress, ksi SPS-2 (STA)	Strain, in./in. x 10^{-3} 75°F Air	Stress, ksi SPS-3 (STA)	Strain, in./in. x 10^{-3} 75°F Air	Stress, ksi SPS-4 (STA)	S in./ 7
PL	128.3	5.61	123.2	5.31	120.0	
0.025	145.3	6.57	145.5	6.57	141.4	
0.05	152.3	7.11	152.5	7.11	149.3	
0.10	158.3	7.95	159.6	7.90	156.8	
0.15	163.7	8.66	163.8	8.58	160.8	
0.20	166.5	9.29	166.7	9.21	163.6	
0.40	173.3	11.55	173.7	11.51	170.5	
0.60	177.8	13.77	177.7	13.68	174.5	
0.80	181.0	15.89	181.0	15.86	177.4	
1.00	183.2	18.03	183.2	17.91	179.6	
1.20	185.0	20.08	185.1	20.00	181.4	
1.40	186.8	22.13	186.9	22.09	183.0	
1.60	188.2	24.14	188.1	24.10	184.4	
1.80	189.4	26.23	189.7	26.15	185.4	
2.00	190.4	28.24	190.5	28.24	186.7	
2.20	191.4	30.33	191.7	30.29	187.7	
Specimen Identity	SPS-8 (STA)	800°F Helium	SPS-9 (STA)	800°F Hydrogen	SPS-10 (STA)	800°
PL	92.6	3.89	91.9	3.77	93.2	
0.025	112.7	4.98	110.9	4.77	111.6	
0.05	119.1	5.52	117.2	5.27	117.2	
0.10	124.9	6.28	123.2	5.98	122.6	
0.15	128.6	6.90	126.9	6.69	126.3	
0.20	130.9	7.53	129.1	7.28	128.3	
0.40	136.8	9.75	134.9	9.50	134.1	
0.60	140.6	11.92	138.5	11.63	137.7	
0.80	143.4	14.10	141.2	13.81	140.3	
1.00	145.7	15.73	143.2	15.86	142.3	
1.20	147.3	18.24	145.3	17.95	144.1	
1.40	148.9	20.33	146.5	20.00	145.5	
1.60	150.5	22.34	147.9	21.97	146.9	
1.80	151.5	24.39	149.5	24.06	148.5	
2.00	152.7	26.44	150.5	26.11	149.3	
2.20	154.1	28.49	151.5	28.16	150.5	
2.40	155.1	30.50	152.5	30.21	151.3	

FOLDOUT FRAME

...n Stress-Strain Parameters of Incoloy 903 Parent Material in Air ...5000 psig) Gaseous Environment

...s, ...STA)	Strain, in./in. x 10^{-3} 75°F Air	Stress, ksi SPS-5 (STA)	Strain, in./in. x 10^{-3} 75°F Helium	Stress, ksi SPS-6 (STA)	Strain, in./in. x 10^{-3} 75°F Hydrogen	Stress, ksi SPS-7 (STA)	Strain, in./in. x 10^{-3} 75°F Hydrogen
	5.27	117.2	4.90	116.2	5.06	117.2	5.02
	6.44	137.8	5.98	140.1	6.28	139.5	6.19
	7.03	146.5	6.61	148.3	6.90	148.1	6.82
	7.86	155.0	7.45	156.7	7.78	156.3	7.66
	8.57	159.8	8.16	161.3	8.47	160.7	8.37
	9.20	163.0	8.83	164.3	9.10	164.1	9.04
	11.51	170.3	11.09	171.5	11.38	171.1	11.30
	13.68	174.7	13.31	176.2	13.56	175.4	13.49
	15.77	177.8	15.43	179.0	15.73	178.4	15.65
	17.95	180.2	17.53	181.4	17.85	180.8	17.74
	20.00	182.0	19.66	183.2	19.94	182.6	19.83
	22.09	183.8	21.71	184.8	21.97	184.4	21.90
	24.10	185.1	23.64	186.4	24.02	185.6	23.85
	26.10	186.3	25.77	187.6	26.05	186.8	25.90
	28.24	187.7	27.82	188.6	27.66	188.2	27.97
	30.29	188.3	29.87	189.6	30.10	189.0	30.02
...TA)	800°F Hydrogen	SPS-11 (STA)	1000°F Helium	SPS-12 (STA)	1000°F Hydrogen	SPS-13 (STA)	1000°F Hydrogen
	3.97	93.6	4.27	85.9	3.55	85.1	3.51
	5.02	107.6	5.15	106.9	4.68	106.3	4.64
	5.52	112.8	5.61	113.3	5.19	113.1	5.19
	6.19	118.6	6.36	119.6	5.94	119.2	5.98
	6.90	121.6	6.99	123.2	6.61	122.6	6.57
	7.49	123.8	7.57	125.7	7.20	125.3	7.20
	9.73	129.7	9.79	131.7	9.46	131.1	9.37
	11.88	133.3	11.97	135.6	11.59	134.7	11.55
	14.02	136.1	14.14	138.4	13.77	137.4	13.68
	16.15	138.1	16.19	140.4	15.86	139.4	15.77
	18.20	139.9	18.33	142.2	17.91	141.4	17.91
	20.25	141.5	20.38	143.8	20.00	143.0	19.96
	22.23	142.9	22.38	145.3	21.97	144.4	21.92
	24.31	144.3	24.44	146.7	24.06	145.7	24.01
	26.36	145.5	26.49	147.9	26.21	146.9	26.07
	28.41	146.7	28.58	148.9	28.16	147.9	28.11
	30.42	147.7	30.59	149.9	30.17	149.1	30.13

FOLDOUT FRAME 2

Table IV-3. Individual Specimen Stress-Strain Param...
and 34.5 MN/m² (5000 psi) Gaseous E...

Offset, %	Stress, ksi	Strain, in./in. x 10^{-3}	Stress, ksi	Strain, in./in. x 10^{-3}	Stress, ksi	Strain, in./in. x
Specimen Identity	SPS-14 (STA)	1200°F Helium	SPS-20 (STA)	1200°F Hydrogen	SPS-16 (STA)	1200°F Hyd.
PL	88.0	4.64	85.2	3.96	78.5	3.42
0.025	101.0	5.52	101.2	5.02	101.4	4.[illegible]5
0.05	105.4	6.03	106.4	5.49	107.8	5.20
0.10	110.2	6.82	112.0	6.27	113.7	5.96
0.15	113.4	7.49	115.0	6.94	117.1	6.65
0.20	115.6	8.08	117.2	7.45	119.7	7.27
0.40	121.0	10.38	123.0	9.71	125.8	9.55
0.60	124.6	12.55	126.3	11.84	129.6	11.76
0.80	127.0	14.69	128.7	13.88	132.2	13.92
1.00	129.0	16.78	130.3	15.96	134.0	16.04
1.20	130.3	18.87	131.7	17.96	135.2	18.16
1.40	131.6	20.96	132.5	19.96	136.6	20.24
1.60	132.2	22.92	133.3	21.96	137.2	22.33
1.80	133.2	24.94	133.9	23.96	138.2	24.41
2.00	134.0	26.99	134.3	25.92	138.3	26.49
2.20	134.4	29.04	134.7	27.92	139.2	28.53
2.40	135.0	31.00			139.8	30.61
2.60						
Specimen Identity	SPS-19 (STA)	1400°F Hydrogen	SPO-1 (STA+OA)	1400°F Helium	SPO-2 (STA+OA)	1400°F Hyd...
PL	53.3	2.70	4[illegible].1	2.18	42.8	2.04
0.025	62.5	3.40	56.7	3.01	59.7	3.13
0.05	66.9	3.91	60.5	3.47	65.3	3.63
0.10	70.3	4.55	64.3	4.18	70.6	4.38
0.15	72.5	5.16	66.3	4.77	73.3	5.04
0.20	73.7	5.72	67.7	5.31	75.1	5.58
0.40	77.0	7.79	70.3	7.45	78.9	7.79
0.60	78.4	9.86	71.3	9.50	79.7	9.79
0.80	79.0	11.89	71.1	11.51	80.4	11.[illegible]
1.00	79.2	13.81	70.9	13.51	80.2	13.83
1.20	79.2	15.78	70.5	15.48	80.0	15.83
1.40	79.0	17.75	70.3	17.45	79.5	17.79
1.60	78.8	18.81	69.9	19.37	79.3	19.71
1.80	78.6	21.60	69.7	21.38	79.1	21.6[illegible]
2.00	78.4	23.52	69.5	23.35	78.9	23.61
2.20	78.4	25.49	69.3	25.36	78.7	25.[illegible]
2.40	78.2	27.42	69.3	27.32	78.3	27.[illegible]
2.60	78.0	29.90	69.3	29.37	77.9	29.5[illegible]

FOLDOUT FRAME

nen Stress-Strain Parameters of Incoloy 903 Parent Material in Air
(5000 psig Gaseous Environments (Continued)

ess, si	Strain, in./in. x 10^{-3}	Stress, ksi	Strain, in./in. x 10^{-3}	Stress, ksi	Strain, in./in. x 10^{-3}	Stress, ksi	Strain, in./in. x 10^{-3}
.6 (STA)	1200°F Hydrogen	SPS-17 (STA)	1400°F Helium	SPS-21 (STA)	1400°F Helium	SPS-18 (STA)	1400°F Hydrogen
.5	3.42	50.2	2.38	50.1	2.38	40.2	1.92
.4	4.65	61.4	3.14	64.2	3.26	56.7	2.97
.8	5.20	64.5	3.56	67.5	3.68	60.8	3.43
.7	5.96	67.3	4.18	70.7	4.35	64.0	4.06
.1	6.65	69.1	4.73	72.7	4.93	65.6	4.69
.7	7.27	70.3	5.31	74.1	5.52	66.6	5.19
.8	9.55	73.3	7.45	77.4	7.68	69.6	7.32
.6	11.76	75.3	9.54	79.0	9.75	71.0	9.39
.2	13.92	76.3	11.63	80.2	11.80	71.8	11.46
.0	16.04	76.7	13.64	80.4	13.85	72.2	13.47
.2	18.16	77.3	15.69	80.8	15.44	72.4	15.52
.6	20.24	77.5	17.70	80.8	17.89	72.2	17.49
.2	22.33	77.5	19.58	80.8	19.77	72.0	19.41
.2	24.41	77.3	21.59	80.6	21.80	71.8	21.42
.8	26.49	77.1	23.60	80.4	23.74	71.6	22.97
.2	28.53	76.9	25.61	80.2	25.79	71.4	25.40
.8	30.61	76.7	27.57	80.0	27.74	71.2	27.37
		76.5	29.58	79.9	29.75	71.0	29.37
A+OA)	1400°F Hydrogen	SPO-3 (STA+OA)	1400°F Hydrogen				
8	2.04	44.1	2.13				
7	3.13	64.1	3.29				
3	3.63	69.7	3.83				
6	4.38	74.0	4.54				
3	5.04	76.2	5.17				
1	5.58	77.8	5.71				
9	7.79	81.4	7.88				
7	9.79	82.6	9.92				
4	11.88	83.0	11.96				
2	13.83	83.0	13.96				
0	15.83	82.8	15.92				
5	17.79	82.4	17.92				
3	19.71	82.2	19.79				
1	21.67	81.8	21.79				
9	23.69	81.4	23.75				
7	25.63	81.2	25.75				
3	27.58	80.8	27.71				
9	29.58	80.4	29.71				

FOLDOUT FRAME 2

Table IV-4. Individual Specimen Stress-Strain Parame
Air and 34.5 MN m² (5000 psig) Gaseous

Offset, % / Specimen Identity	Stress, ksi SWW-3 (AW)	Strain, in./in. x 10^{-3} 75°F Air	Stress, ksi SWW-20 (AW)	Strain, in./in. x 10^{-3} 75°F Air	Stress, ksi SWW-5 (AW)	Strain, in./in. x 10^{-3} 75°F Air
PL	41.8	1.83	34.3	1.46	36.7	1.60
0.025	52.1	2.38	47.3	2.22	40.4	2.25
0.05	55.1	2.80	51.5	2.72	50.7	2.72
0.10	57.0	3.34	53.5	3.22	53.4	3.35
0.15	57.6	3.89	54.5	3.81	54.8	3.89
0.20	58.0	4.44	54.9	4.31	55.2	4.45
0.40	59.8	6.53	57.0	6.40	57.2	6.53
0.60	61.2	8.58	58.9	8.49	59.1	8.58
0.80	62.4	10.62	59.8	10.59	60.3	10.67
1.00	63.4	12.72	61.0	12.59	61.3	12.72
1.20	64.2	14.77	61.8	14.69	62.3	14.77
1.40	65.1	16.82	62.6	16.69	63.1	16.82
1.60	65.9	18.74	63.2	18.66	63.7	18.79
1.80	66.5	20.79	64.0	20.63	64.8	20.84
2.00	67.2	22.85	64.6	22.72	65.2	22.85
2.20	67.9	24.85	65.1	24.73	65.8	24.90
2.40	68.5	26.90	65.9	26.74	66.6	26.90
2.60	69.1	28.91	66.7	28.79	67.2	29.00
2.80	69.7	30.92	67.1	30.59	67.6	30.96
Specimen Identity	SWW-18 (AW)	1000°F Helium	SWW-9 (AW)	1000°F Hydrogen	SWW-10 (AW)	1000°F Hydroge
PL	20.0	0.79	20.4	0.79	21.2	0.92
0.025	24.0	1.17	26.1	1.25	26.9	1.33
0.05	25.7	1.51	26.9	1.55	27.9	1.67
0.10	26.3	2.01	27.7	2.05	28.3	2.18
0.15	27.1	2.55	27.9	2.59	28.7	2.72
0.20	27.3	3.05	28.5	3.10	29.3	3.22
0.40	28.5	5.10	30.4	5.15	30.7	5.27
0.60	30.1	7.20	31.2	7.20	32.3	7.36
0.80	31.3	9.25	32.6	9.25	33.7	9.41
1.00	32.5	11.30	33.8	11.34	34.3	11.46
1.20	33.5	13.39	34.6	13.35	34.7	13.51
1.40	34.1	15.36	35.2	15.36	36.0	15.52
1.60	34.9	17.32	35.8	17.32	36.6	17.49
1.80	35.5	19.37	36.9	19.33	37.4	19.54
2.00	36.3	21.38	37.5	21.38	38.4	21.59
2.20	37.1	23.39	38.3	23.43	38.8	23.56
2.40	37.9	25.44	38.9	25.43	39.4	25.56
2.60	38.3	27.45	39.5	27.49	40.4	27.62
2.80	39.5	29.50	40.3	29.54	40.8	29.66

FOLDOUT FRAME 1

ress-Strain Parameters of Incoloy 903 Welded Material in
5000 psig) Gaseous Environments

Strain, in./in. x 10^{-3} 75°F Air	Stress, ksi SWW-2 (AW)	Strain, in./in. x 10^{-3} 75°F Helium	Stress, ksi SWW-6 (AW)	Strain, in./in. x 10^{-3} 75°F Hydrogen	Stress, ksi SWW-20 (AW)	Strain, in./in. x 10^{-3} 75°F Hydrogen
1.60	37.4	1.63	33.5	1.42	37.4	1.38
2.25	53.7	2.57	44.8	2.09	49.5	2.09
2.72	55.4	2.89	48.9	2.55	53.9	2.51
3.35	55.8	3.43	51.1	3.14	56.2	3.10
3.89	56.3	3.93	51.9	3.68	56.8	3.68
4.45	56.7	4.46	52.5	4.18	57.6	4.14
6.53	57.7	6.49	54.5	6.28	59.8	6.28
8.58	59.0	8.58	56.2	8.28	61.4	8.33
10.67	59.9	10.63	57.4	10.38	62.6	10.42
12.72	60.9	12.68	58.4	12.47	63.8	12.47
14.77	61.6	14.71	59.4	14.48	64.6	14.27
16.82	62.4	16.74	60.4	16.53	65.5	16.52
18.79	63.3	18.70	61.0	18.45	66.5	18.45
20.84	63.7	20.75	61.8	20.50	66.9	20.50
22.85	64.5	22.76	62.4	22.51	67.7	22.55
24.90	65.2	24.81	63.2	24.60	68.5	24.60
26.90	65.8	26.78	63.8	26.57	69.1	26.61
29.00	66.2	28.87	64.6	28.62	69.7	28.62
30.96	67.1	30.88	65.1	30.67	70.5	30.67
1000°F Hydrogen	SWW-21 (AW)	1200°F Helium	SWW-22 (AW)	1200°F Hydrogen	SWW-14 (AW)	1200°F Hydrogen
0.92	35.4	1.59	40.4	1.97	26.3	1.17
1.33	42.4	2.09	47.7	2.59	31.9	1.59
1.67	44.2	2.43	48.9	2.89	33.3	1.92
2.18	44.8	2.91	50.5	3.47	35.1	2.51
2.72	46.1	3.51	51.7	4.02	36.3	3.10
3.22	47.3	4.10	53.1	4.56	37.5	3.64
5.27	51.1	6.23	57.4	6.36	40.5	5.73
7.36	53.9	8.41	59.0	8.87	43.3	7.87
9.41	56.6	10.46	61.4	11.00	46.1	10.04
11.46	59.2	12.59	62.4	13.05	47.3	12.09
13.51	59.6	14.64	63.6	15.15	49.1	14.14
15.52	61.0	16.69	64.6	17.15	50.9	16.23
17.49	62.0	18.66	66.3	19.16	52.1	18.20
19.54	63.6	20.75	67.3	21.26	53.7	20.29
21.59	64.6	22.76	68.3	23.26	54.7	22.38
23.56	65.3	24.85	69.3	25.31	55.9	24.39
25.56	66.1	26.82	70.1	27.36	57.1	26.40
27.62	66.9	28.87	71.1	29.41	58.1	28.49
29.66					58.9	30.50

FOLDOUT FRAME 7

Table IV-4. Individual Specimen Stress-Strain Param
Air and 34.5 MN/m² (5000 psig) Gaseous

Offset, % Specimen Identity	Stress, ksi SWW-19 (AW)	Strain, in./in. x 10^{-3} 1400°F Helium	Stress, ksi SWW-16 (AW)	Strain, in./in. x 10^{-3} 1400°F Hydrogen	Stress, ksi SWW-17 (AW)	Strain, in./in. x 1 1400°F Hydr
PL	34.1	1.63	36.1	1.67	34.2	1.33
0.025	50.9	2.72	58.3	2.97	50.7	2.18
0.05	57.9	3.31	65.1	3.51	60.4	2.80
0.10	64.5	4.14	69.5	4.27	66.6	3.56
0.15	67.9	4.81	71.9	4.85	68.6	4.14
0.20	69.7	5.36	73.1	5.44	70.2	4.69
0.40	72.7	7.53	76.0	7.53	73.4	6.78
0.60	73.7	9.58	77.2	9.58	76.4	8.91
0.80	73.3	11.59	78.0	11.63	78.3	10.96
1.00	72.5	13.56	78.6	13.68	79.5	13.05
1.20	71.7	15.52	79.2	15.73	80.3	15.10
1.40	70.5	17.49	79.8	17.74	80.5	17.11
1.60	69.7	19.33	80.0	19.67	81.3	19.04
1.80	68.5	21.98	80.2	21.67	82.1	21.09
2.00	67.7	23.26	80.3	23.68	82.5	23.10
2.20	66.1	25.18	80.4	25.69	82.7	25.15
2.40	65.3	27.11	80.5	27.70	83.1	27.11
2.60	63.9	29.12	80.6	29.71	83.7	29.16
2.80	62.5	31.05			83.9	31.17

FOLDOUT FRAME 1

ess-Strain Parameters of Incoloy 903 Welded Material in
psig) Gaseous Environments (Continued)

Strain, in./in. x 10^{-3} .J) 1400°F Hydrogen	Stress, ksi SWX-1 (AW+OA)	Strain, in./in. x 10^{-3} 1400°F Helium	Stress, ksi SWX-2 (AW+OA)	Strain, in./in. x 10^{-3} 1400°F Hydrogen	Stress, ksi SWX-3 (AW+OA)	Strain, in./in. x 10^{-3} 1400°F Hydrogen
1.33	34.6	1.51	37.5	1.84	36.8	1.80
2.18	48.1	2.30	51.9	2.80	53.1	2.85
2.80	54.6	2.89	57.2	3.31	59.0	3.39
3.56	59.7	3.18	62.5	4.06	64.0	4.14
4.14	62.5	4.23	65.2	4.73	67.0	4.81
4.69	64.0	4.77	66.4	5.27	68.4	5.36
6.78	66.4	6.86	69.2	7.41	71.2	7.45
8.91	66.8	8.91	70.1	9.46	72.4	9.54
10.96	66.2	10.88	69.9	11.46	72.4	11.55
13.05	65.2	12.85	69.7	13.47	72.0	13.56
15.10	64.2	14.77	69.2	15.44	71.2	15.52
17.11	62.7	16.74	68.8	17.41	70.8	17.49
19.04	61.1	18.62	68.2	19.33	70.0	19.37
21.09	59.3	20.50	67.4	21.26	69.6	21.38
23.10	57.4	22.43	66.8	23.22	68.8	23.34
25.15	55.4	24.35	66.2	25.23	67.8	25.31
27.11	53.2	26.23	65.2	27.15	67.2	27.23
29.16	50.7	28.16	64.8	29.12	66.0	29.21
31.17	47.3	30.00	63.5	31.09	65.2	31.21

FOLDOUT FRAME 7

The AW material elevated temperature tests indicated that exposure of the material for the time required to stabilize temperature (approximately 15 minutes for tensile tests) at 922°K (1200°F) and 1033°K (1400°F) aged the material sufficiently to alter its properties relative to those at 811°K (1000°F). This aging effect is shown by an increase in yield strength and change in stress-strain parameters from 811°K (1000°F) to 1033°K (1400°F).

Modulus of elasticity increased slightly from room temperature to 700°K (800°F) and then decreased with increasing temperature to 1033°K (1400°F). A dynamic modulus analysis confirmed this trend. The effect of temperature upon modulus of elasticity for both static (as determined from tensile stress-strain curves for each test) and dynamic analyses is shown in figure IV-6. Data plotted is the average of specimen test results at each temperature. Individual specimen modulus of elasticity is listed in table IV-2 and dynamic modulus vs temperature data in table IV-5.

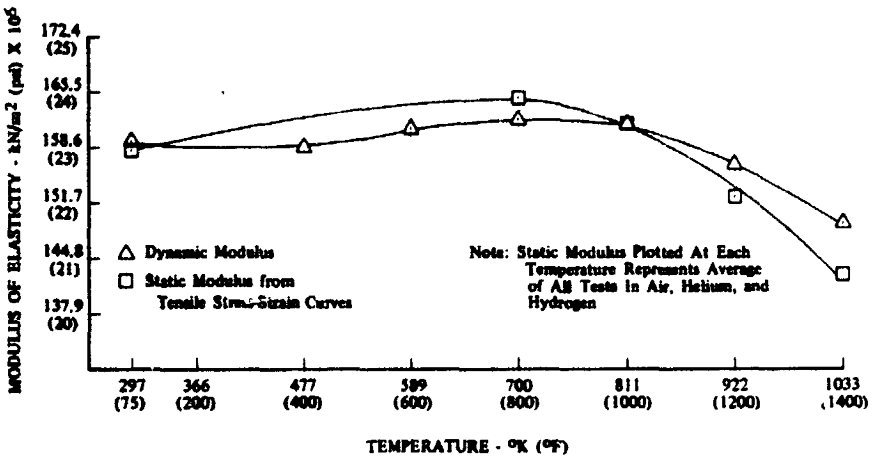


Figure IV-6. Effect of Temperature on the Modulus of Elasticity of Incoloy 903

Table IV-5. Dynamic Modulus of Incoloy 903 Material

Temperature		Dynamic Modulus	
°K	°F	$kN/m^2 \times 10^6$	psi
297	75	159.3	23.1
477	400	158.6	23.0
589	600	160.6	23.3
700	800	162.0	23.5
811	1000	161.3	23.4
922	1200	156.5	22.7
1033	1400	148.9	21.6

Generally, the air and helium test results agreed, indicating that air tests can provide a suitable and less expensive baseline for establishing environmental degradation at room temperature. It is suspected that the differences in the air and helium tests results for the welded material can be attributed to data scatter.

The values shown in table IV-1 are based upon the average of all tests conducted at a given condition. In the case of notch tensile tests of AW material, three tests were conducted in air and only one in helium at room temperature. The helium test ultimate strength was higher than the average air test strength, resulting in a strength ratio, Helium/Air, of 1.18. Metallographic examinination of the failed specimens revealed no significant reason for the difference. No anomolies in the test or data analysis were observed; therefore, at this time the strength difference must be attributed to data scatter.

C. TEST PROCEDURE

All tensile tests were conducted per ASTM Standard E8-69, "Tension Testing of Metallic Materials." Two types of tensile specimens, smooth and notched, were used for this testing. Smooth specimens had a 6.40-mm (0.252-in.) gage diameter and a reduced section length of 56.39 mm (2.220 in.). Notched specimens (K_T = 8.0) had a larger diameter of 7.62 mm (0.300 in.) and a notch diameter of 4.52 mm (0.178 in.) machined in the center of the specimen reduced section at a 60-deg angle, with a 0.051-mm (0.002-in.) radius at the apex of the notch. The test specimens are described in Section III and detailed in figures III-5 and III-6.

Smooth specimens were tested at a strain rate of 0.01 mm/mm/min (in./in./min) to yield and a crosshead speed of 0.64 mm/min (0.025 in./min) from yield to fracture. Notch specimens were tested at a crosshead speed of 0.127 mm/min (0.050 in./min) to fracture.

All tensile testing was conducted on a Tinius Olsen 266.8-kN (60,000-lb) capacity tensile machine, equipped with a P&WA-designed and developed pressure vessel. All controls and instrumentation readout equipment are located inside an adjacent blockhouse. This equipment is shown in figures IV-7 and IV-8a.

Various views of the pressure vessel showing specimen, extensometer, and furnace setup are presented in figure IV-8. The vessel is made of AISI 347 stainless steel and incorporates a high-pressure GrayLoc connector. A compensating device built into the base of the vessel eliminates the effect of loads resulting from differential specimen and adapter cross-sectional areas.

To measure specimen strain for both room temperature and elevated temperature tests an averaging-type linear variable displacement transducer (LVDT) extensometer system was used (figure IV-9). Specimen load was determined by both the tensile machine load measuring system and an internal strain-gage-type load cell; thus, absolute specimen load was known and friction at the pressure vessel seals was of no consequence. Electrical connections to the internal load cell, extensometer, thermocouples, and furnace were made through the bottom of the pressure vessel via high-pressure bulkhead connectors.

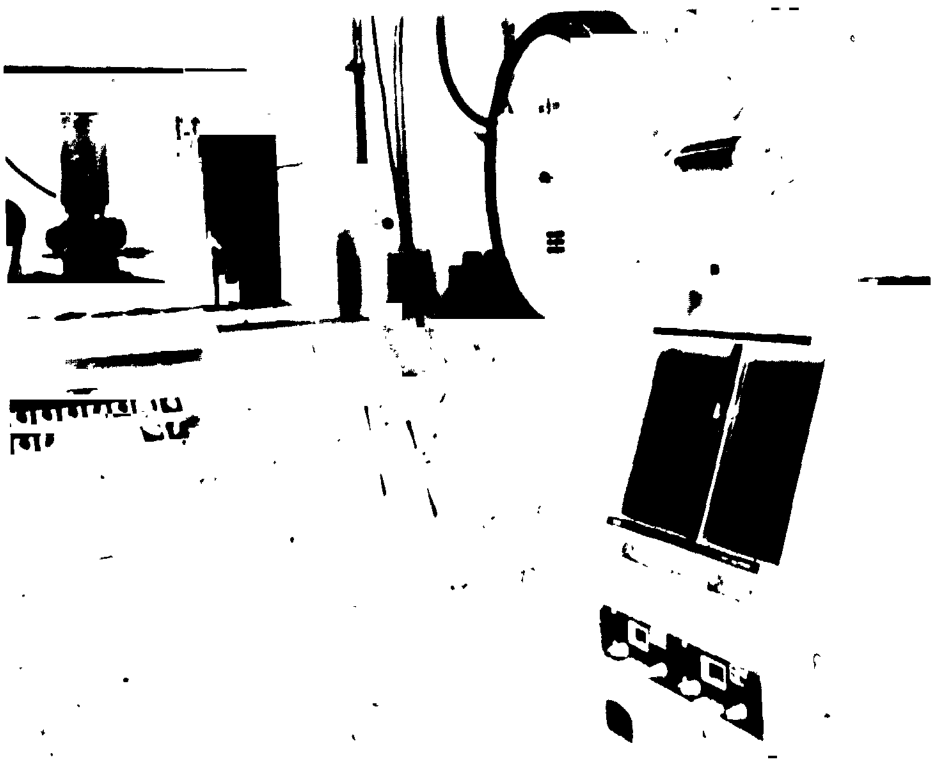


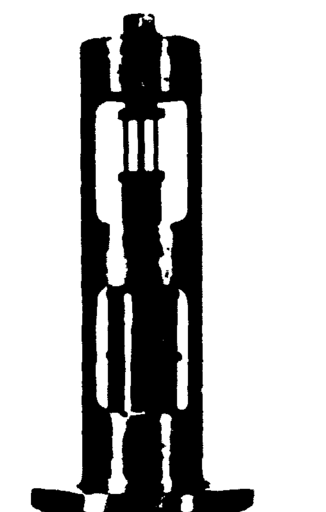
Figure IV-7 Tensile Machine, Test Environmental Controls and Data Acquisition Equipment

FC 42236

a) Test Vessel Installed on Tensile Machine Located In Remote Test Cell

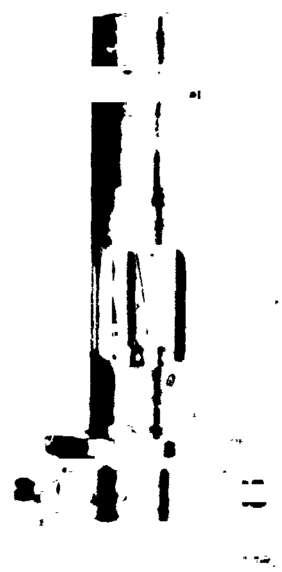
FAE 146120

b) Test Vessel Open With Notch Tensile Specimen in Place



FAE 146118

c) Test Vessel Open With Smooth Specimen In Place and Extensometer Attached

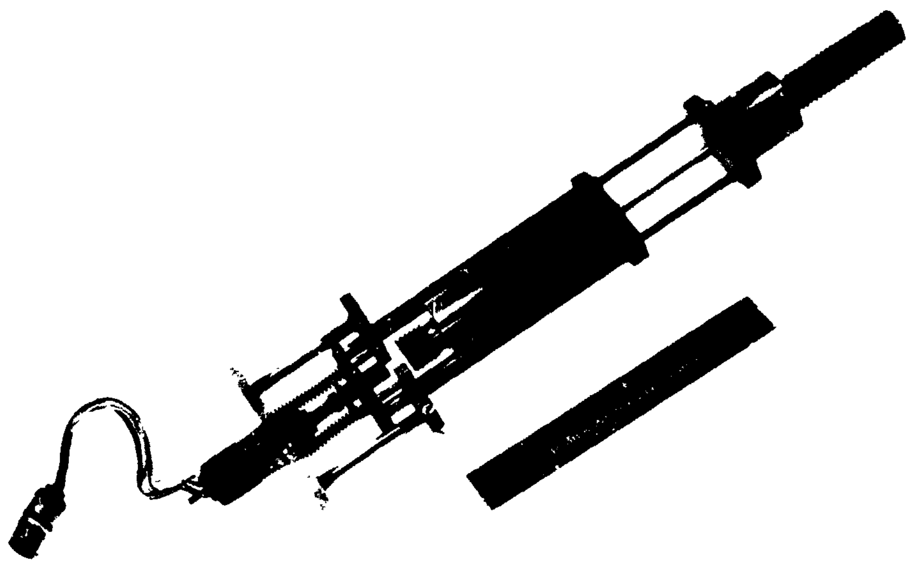


FAE 146119

d) Test Vessel Open With Furnace Attached

FD 92357

Figure IV-8. Setups of Tensile Test Vessel



FAE 146126

Figure IV-9. Averaging Type LVDT Extensometer System

To conduct elevated temperature tests, a two-zone furnace with separate control systems for each zone was used that minimized any heat gradient due to the high thermal conductivity of the gases. The furnace fits within the pressure vessel load frame (figure IV-8d). Thermocouples looped around the specimen gage section (or notch) were used to control and monitor specimen temperature during each test. Temperature variation over the gage length of the smooth specimens was minimal, less than 2%.

Prior to test, specimens were rinsed with trichlorethylene, wiped dry, rinsed with acetone, wiped dry, and inserted into the test fixture. All handling of specimens was done with clean gloves.

Periodic checks of hydrogen test environments revealed oxygen levels less than 1 ppm. This purity level was obtained using the following test procedure:

1. Secure pressure vessel.
2. Pressurize to 0.345 MN/m^2 (50 psig) with nitrogen gas, leak check, and vent.
3. Evacuate to 0.101 MN/m^2 (30 in. Hg) and fill with nitrogen gas two times.
4. Evacuate pressure vessel and gas supply and sampling system to an indicated vacuum of 0.101 MN/m^2 (30 in. Hg).
5. Pressure purge to 3.45 MN/m^2 (500 psig) with hydrogen gas three times, obtain pretest gas sample.
6. Pressurize to 34.5 MN/m^2 (5000 psig) with hydrogen gas and conduct test.

7. Reduce pressure to obtain post-test gas sample, vent to atmospheric pressure, flow and pressure purge with nitrogen gas, open pressure vessel and remove failed specimen.

For the helium tests, the procedure was as follows:

1. Secure pressure vessel.

2. Pressurize to 0.345 MN/m^2 (50 psig) with nitrogen gas; leak check, and vent.

3. Evacuate pressure vessel and gas supply to an indicated vacuum of 0.101 MN/m^2 (30 in. Hg).

4. Pressure purge to 3.45 MN/m^2 (500 psig) with helium three times.

5. Pressurize to 34.5 MN/m^2 (5000 psig) with helium and conduct test.

6. Vent to atmospheric pressure, open pressure vessel and remove failed specimen.

Tensile properties, including 0.2% offset yield strength, ultimate strength, percent elongation, reduction of area, modulus of elasticity and stress-strain parmeters were obtained for all smooth specimen tests. For notched tests, only ultimate strength was determined. For smooth tensile tests, the stress-strain and static modulus of elasticity information was obtained from the load-deflection curves. A typical test curve is shown in figure IV-10.

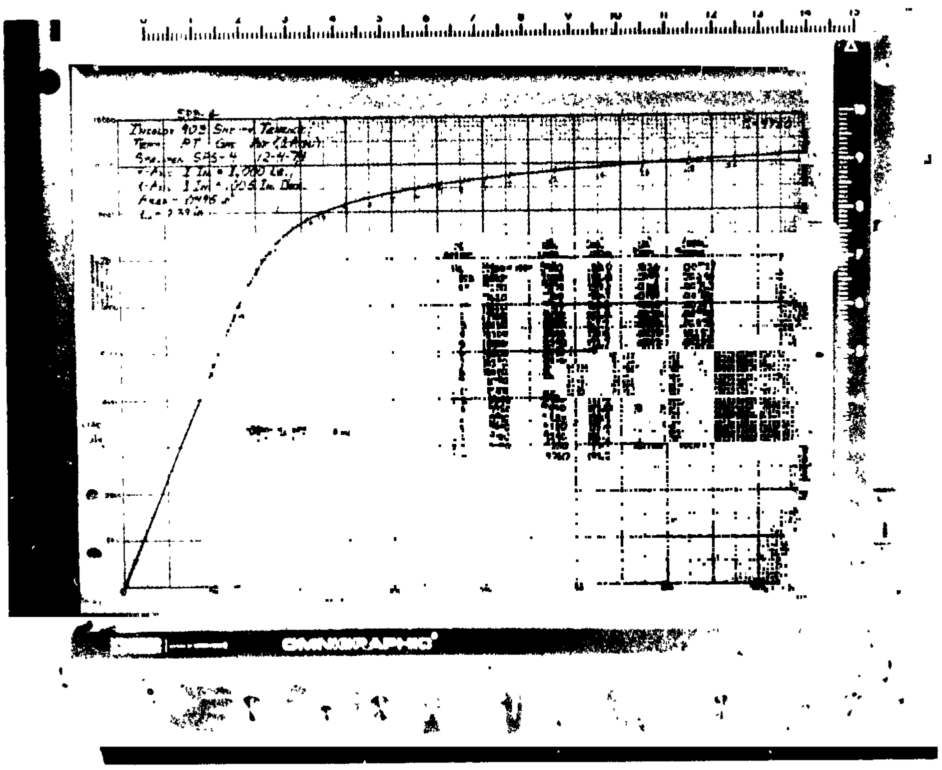


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Figure IV-10. Typical Load/Deflection (Stress-Strain) Curve

To confirm the modulus of elasticity obtained from the tensile test curves, a dynamic modulus analysis was conducted. It involved determining the free-free fundamental mode frequency of vibration of a 6.35 mm (0.250 in.) diameter 101.6 mm (4.00 in.) long bar at progressively increasing temperatures. The dynamic modulus was established at each temperature from the empirical formulas:

$$E_{RT} = (9.16 \times 10^{-6})(f^2 L^3 W / d^4)$$

and

$$E_{ET} = E_{RT} \times (f_{ET} / f_{RT})^2$$

where:

E_{RT} = Modulus of Elasticity at Room Temperature.
E_{ET} = Modulus of Elasticity at Elevated Temperature.
f = Natural Frequency (Hz)
W = Weight
d = Diameter
L = Length

SECTION V
LOW-CYCLE FATIGUE

A. INTRODUCTION

Low-cycle fatigue (LCF) tests were conducted to establish LCF life of Incoloy 903 material in parent and welded forms in various environments including air, helium, hydrogen or hydrogen and 50% by weight water vapor. Where comparable conditions were evaluated, comparison of results of axial strain tests in high-pressure hydrogen environments to results of similar tests in helium or air environments established degradation in cyclic life due to the hydrogen environments. In some cases, comparable conditions were not evaluated; therefore, test results are presented for engineering use.

The LCF tests were the strain-controlled type. This is a compressive start with the material cycling through a (elastic plus plastic) constant total strain range until specimen fracture. The tensile and compressive portions of the strain cycle were of equal magnitude, resulting in a mean strain of zero. This cycle is shown in figure V-1.

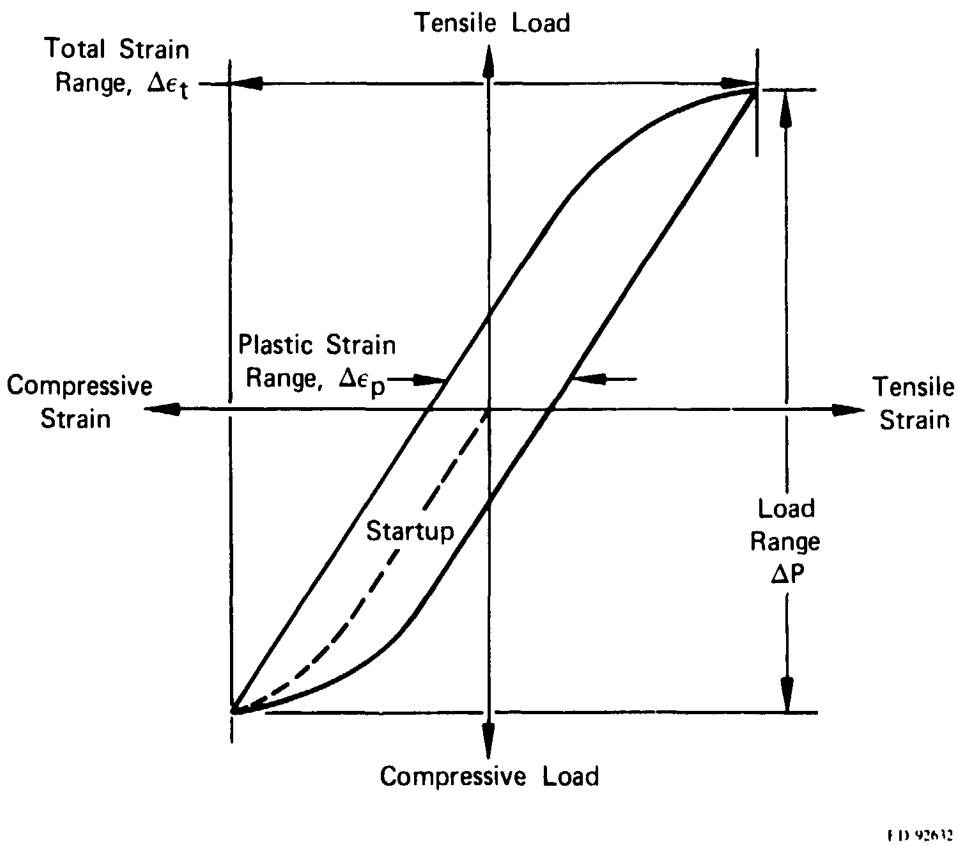

Figure V-1. Typical Load-Strain Hysteresis Curve Obtained During a Specimen Low-Cycle Fatigue Test

Sixteen low-cycle fatigue tests were conducted with a 300 sec dwell or hold time at the maximum compressive strain. In these tests, the first strain cycle was zero, compression, dwell, and tension through zero to compression, et. al.

A typical cycle with strain dwell is shown in figure V-2. This cycle is an actual recorder plot of the 245th cycle of welded material test specimen number LWW-15.

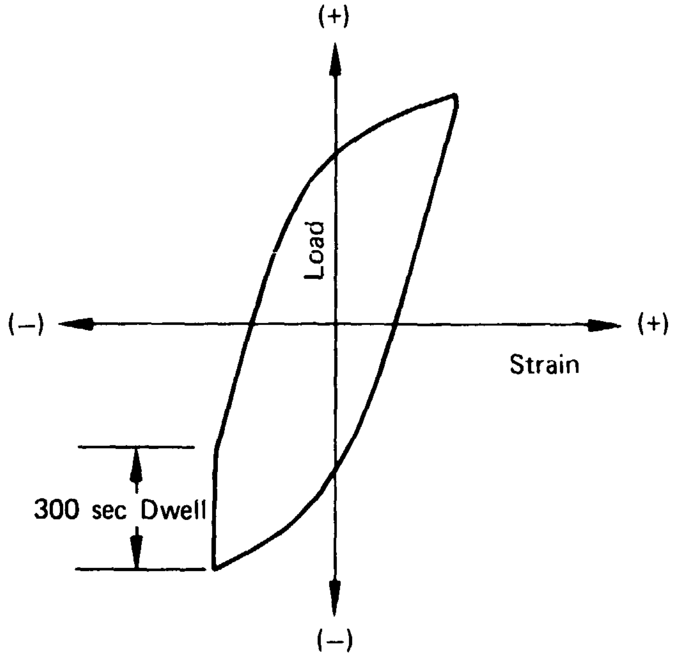

Figure V-2. Low-Cycle Fatigue/Dwell Load vs Strain Curve, Specimen LWW-15, Cycle 245

B. RESULTS AND CONCLUSIONS

The Incoloy 903 material exhibited degradation in LCF life in each of the conditions tested: (1) parent (STA), (2) welded (AW), and (3) welded Heat Affected Zone (AW-HAZ). The conditions evaluated and degradations observed are listed in table V-1.

The AW material exhibited the greatest degradation in cyclic life at room temperature followed by the AW-HAZ material with the STA material the least degraded at this condition. At 922°K (1200°F), AW-HAZ material was degraded 21 vs 36% at 297°K (75°F), indicating that the previous observation of decreasing hydrogen degradation with increasing temperature holds for this material up to 922°K (1200°F).

The STA and AW materials were tested at 1033°K (1400°F) with a 300 sec compressive strain dwell. No degradation in life compared to life in helium, occurred when tested in a pure hydrogen environment. Under some of the dwell conditions, life in hydrogen was greater than in helium. However, in hydrogen and water vapor both materials exhibited very extreme degradation (90% or greater) in LCF/dwell lives at 1033°K (1400°F). It must be emphasized that the conclusions made were based on limited numbers of tests; in some cases only two tests for a particular condition. Therefore, these conclusions must be viewed in a qualitative rather than quantitative manner.

Table V-1. Incoloy 903 Low-Cycle Fatigue Test Conditions and Degradation Due to 34.5 MN/m² (5000 psig) Hydrogen Environments

Form	Condition	Temperature, °K	°F	Environment/ Conditions	Degradation in Life at Mean of H_2 Ranges Tested
Parent	STA	297	75	Air/Cyclic[1]	-
		297	75	H_2/Cyclic	25%
		811	1000	H_2/Cyclic	-
		1033	1400	He/Dwell[2]	-
		1033	1400	H_2/Dwell	ND
		1033	1400	H_2+H_2O/Dwell	95%
Welded	AW	297	75	Air/Cyclic	-
		297	75	H_2/Cyclic	53%
		811	1000	H_2/Cyclic	-
		922	1200	H_2/Cyclic	-
		1033	1400	He/Dwell	-
		1033	1400	H_2/Dwell	ND
		1033	1400	H_2+H_2O/Dwell	90%
Welded	AW-HAZ	297	75	Air/Cyclic	-
		297	75	H_2/Cyclic	36%
		922	1200	He/Cyclic	-
		922	1200	H_2/Cyclic	21%

[1]Cyclic strain waveform at 2-4 cycles per minute
[2]Dwell of 300 sec at maximum compressive strain

Based on air tests, STA material LCF life was severely degraded at 297°K (75°F) due to the hydrogen environment. Curves of LCF life vs cycles to failure in air (one atmosphere) and high-pressure hydrogen are shown in figure V-3. The effect of strain range upon degradation is also illustrated in figure V-4. At 811°K (1000°F), STA material LCF tests were conducted in hydrogen only (figure V-5); therefore, no conclusions as to the effect of hydrogen at that temperature were made. Comparison of test results at 297°K (75°F) and 811°K (1000°F) in hydrogen indicates a reduction in LCF life with increased temperature.

At 1033°K (1400°F), STA material LCF/dwell life in hydrogen, over the strain range investigated was at least equal to that in helium, indicating no detrimental effect on life due to the hydrogen environment. However, the addition of water to the hydrogen environment resulted in extreme degradation of 1033°K (1400°F) LCF/dwell life (figures V-6 and V-7).

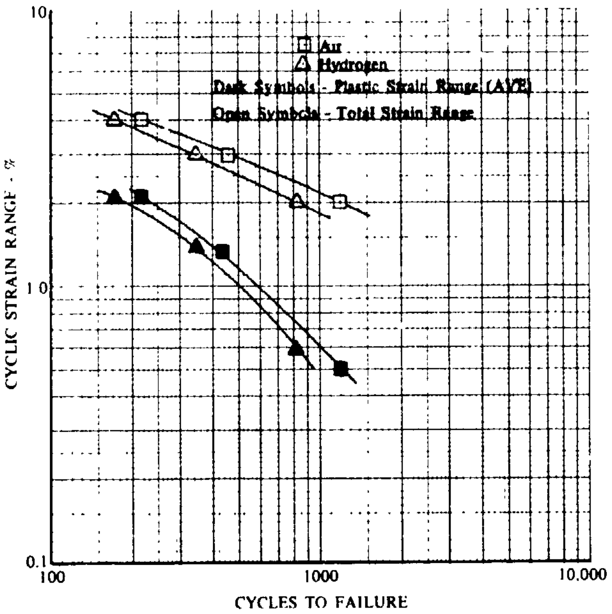

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Figure V-3. Low-Cycle-Fatigue Life of Incoloy 903 Parent (STA) Material in Air and 34.5 MN/m² (5000 psig) Hydrogen at 297°K (75°F)

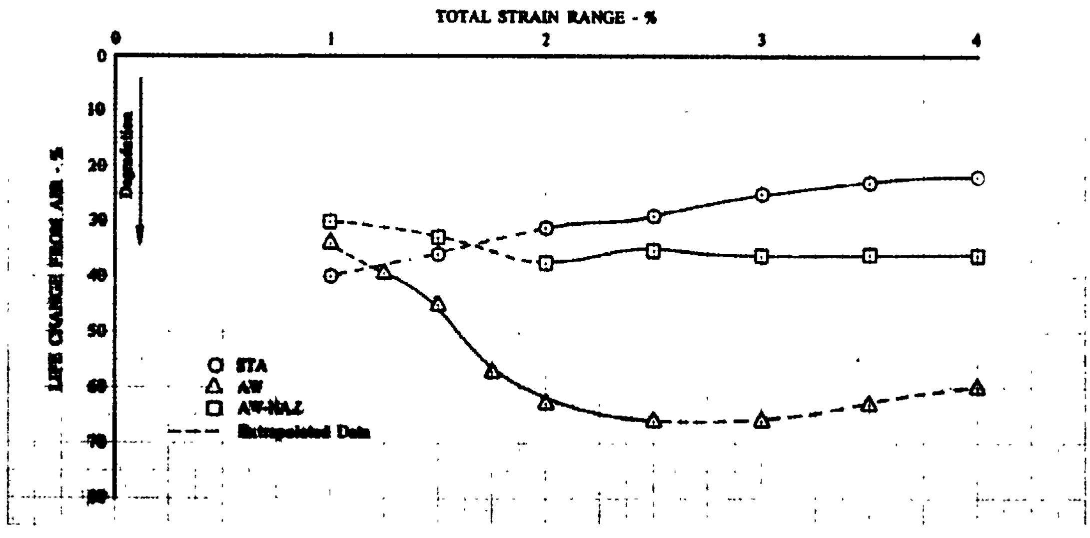

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Figure V-4. Effect of Material Condition and Strain-Range on Hydrogen Degradation of Incoloy 903 at 297°K (75°F) and 34.5 MN/m² (5000 psig)

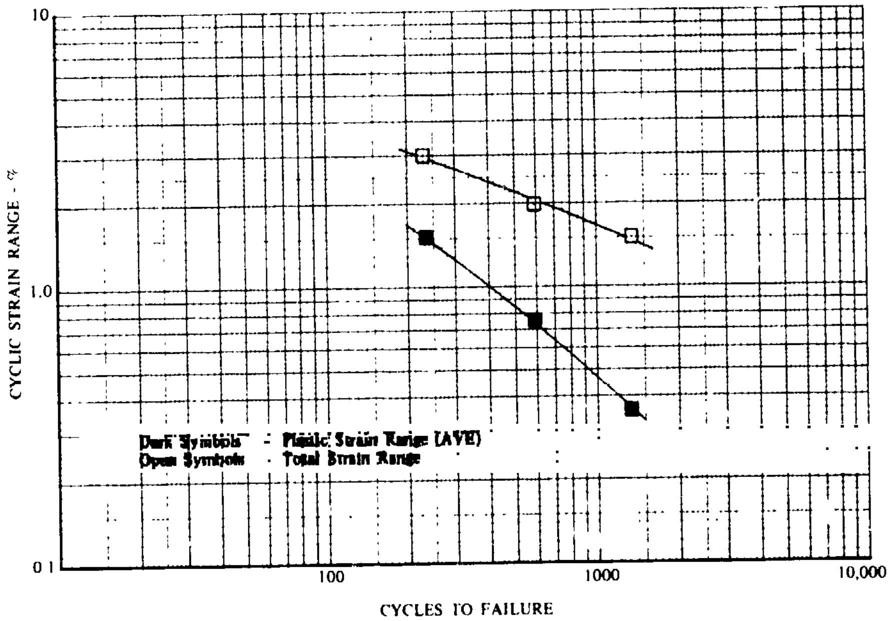

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Figure V-5. Low-Cycle-Fatigue Life of Incoloy 903 Parent (STA) Material in 34.5 MN/m² (5000 psig) Hydrogen at 811°K (1000°F)

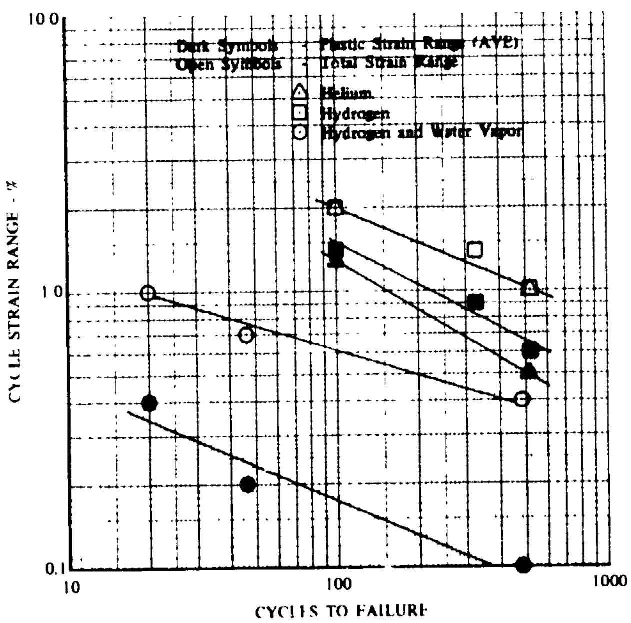

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Figure V-6. Low-Cycle-Fatigue/Dwell Life of Incoloy 903 Parent (STA) Material in 34.5 MN/m² (5000 psig) Helium, Hydrogen, and Hydrogen and Water Vapor at 1033°K (1400°F)

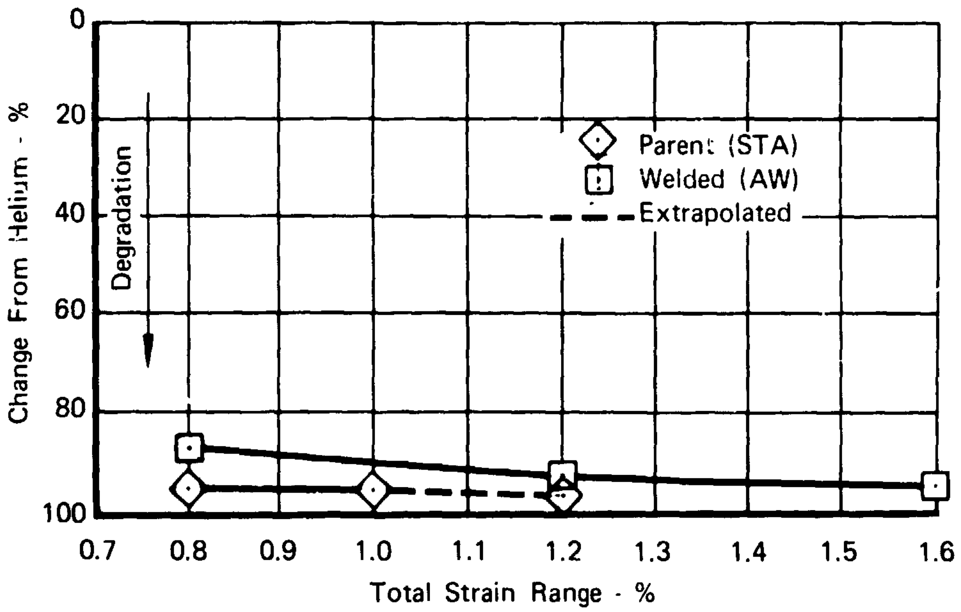

Figure V-7. Effect of Material Condition and Strain-Range on Hydrogen Degradation of Low-Cycle-Fatigue/Dwell Life of Incoloy 903 at 1033°K (1400°F) in 34.5 MN/m² (5000 psig) Hydrogen and Water Vapor

Based on air tests, AW material LCF life was extremely degraded at 297°K (75°F) due to the hydrogen environment (figure V-8, and previously shown figure V-4). At 811°K (1000°F) and 922°K (1200°F), AW material LCF tests were conducted in hydrogen only (figures V-9 and V-10). Over the strain ranges investigated, comparison of LCF test results at 297°K (75°F), 811°K (1000°F), and 922°K (1200°F) in hydrogen indicates greater LCF life at 811°K (1000°F) and 922°K (1200°F) than 297°K (75°F). This trend in AW material LCF life with increased temperature is attributed to the material aging effect discussed in Section IV.

The effects of hydrogen and hydrogen and water vapor environments upon the 1033°K (1400°F) LCF/dwell life of AW material were the same as those for the STA material, i.e., some increase in life in hydrogen environment and extreme degradation in the hydrogen and water vapor environment as shown in figure V-11 and previously shown figure V-7. For both the STA and AW materials this increase in degradation in the hydrogen and water vapor environment at 1033°K (1400°F) can be attributed in part to the occurrence of oxides on the metal. At 1033°K (1400°F), the water vapor partially dissociates at the specimen surface into hydrogen and oxygen. The oxygen immediately reacts with the metal to form oxides, and the hydrogen remains in the environment.

Based on air tests, AW-HAZ material was severely degraded at 297°K (75°F) due to the hydrogen environment as shown in figure V-12 and previously shown figure V-4. At 922°K (1200°F), both helium and hydrogen environment tests were conducted on AW-HAZ material. The effect of hydrogen and strain range on the LCF life of AW-HAZ material at 922°K (1200°F) is shown in figures V-13 and V-14. A comparison of AW and AW-HAZ material test results at 922°K (1200°F) indicates greater LCF life of the latter in hydrogen environment. This increase in life is attributed to the fact that the heat affected zone, located in the center of the specimen gage section where maximum strain occurs has some beneficial aging which results from the heat developed during the welding process.

Complete LCF and LCF/dwell test results are listed in table V-2.

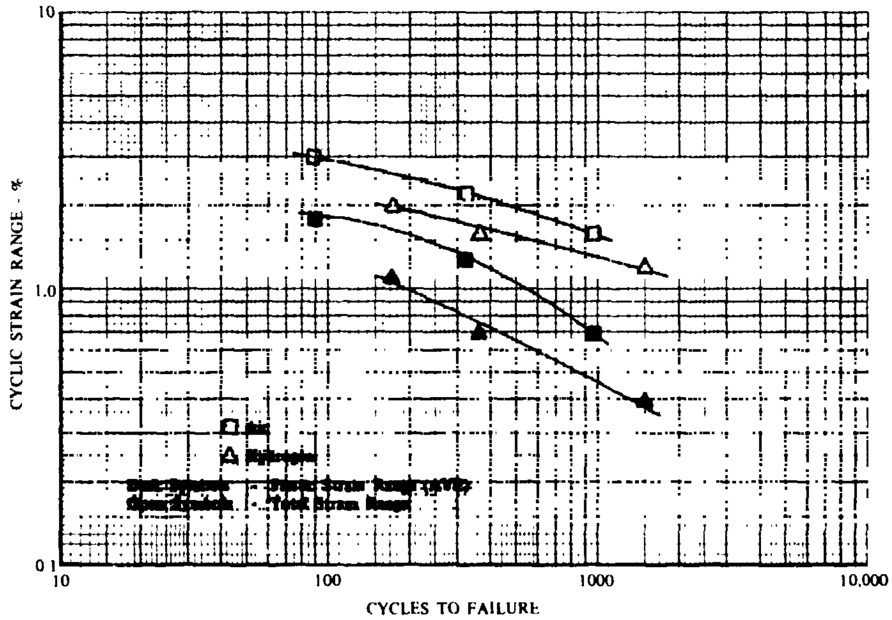

Figure V-8. Low-Cycle-Fatigue Life of Incoloy 903 Welded (AW) Material in Air and 34.5 MN/m² (5000 psig) Hydrogen at 297°K (75°F)

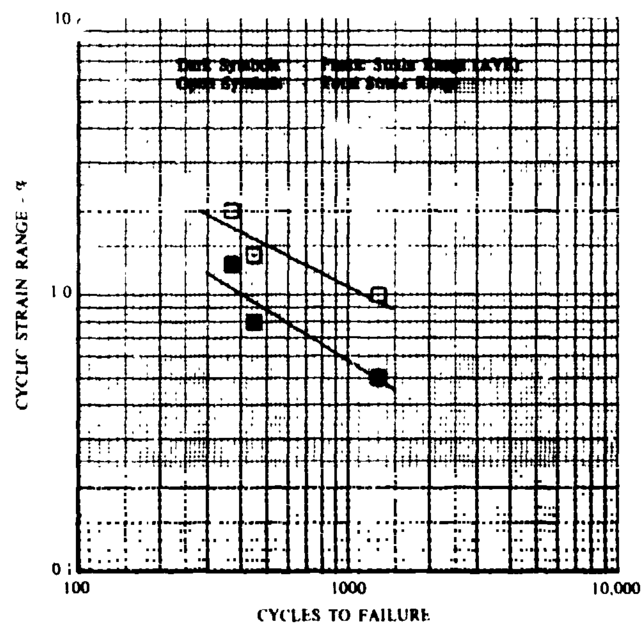

Figure V-9. Low-Cycle-Fatigue Life of Incoloy 903 Welded (AW) Material in 34.5 MN/m² (5000 psig) Hydrogen at 811°K (1000°F)

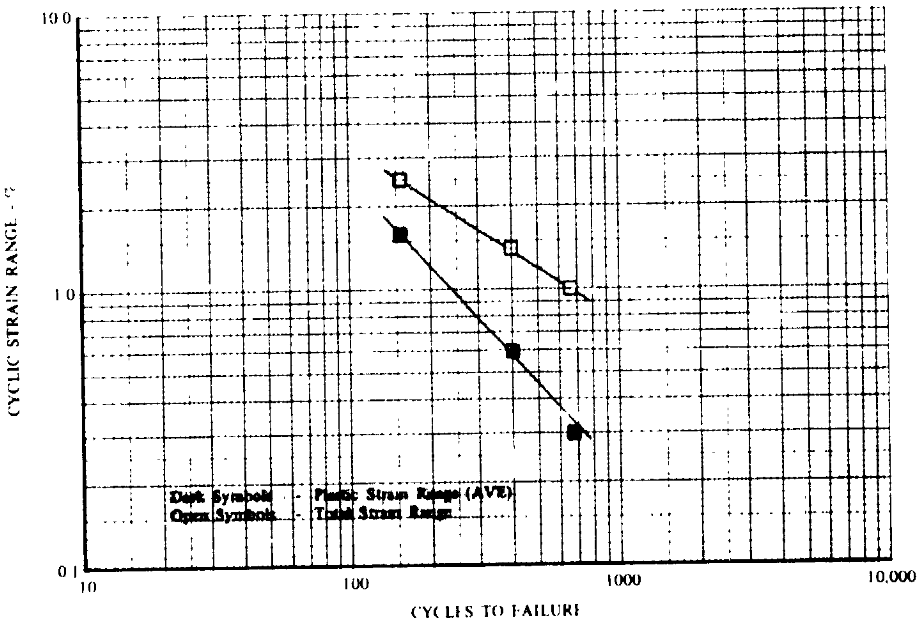

Figure V-10. Low-Cycle-Fatigue Life of Incoloy 903 Welded (AW) Material in 34.5 MN/m² (5000 psig) Hydrogen at 922°K (1200°F)

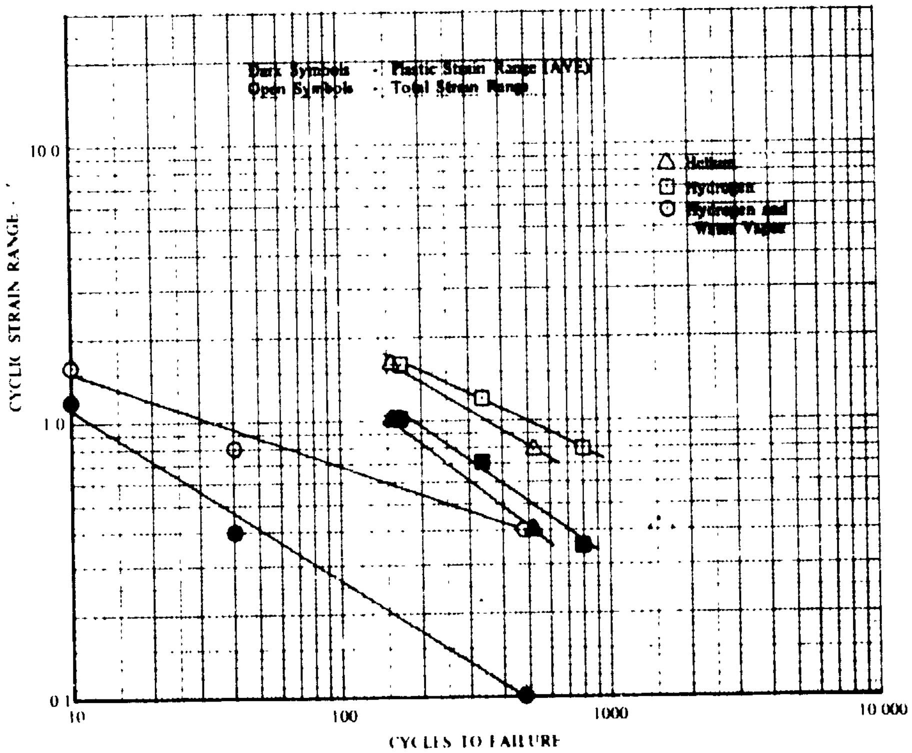

Figure V-11. Low-Cycle-Fatigue/Dwell Life of Incoloy 903 Welded (AW) Material in 34.5 MN/m² (5000 psig) Helium, Hydrogen, and Hydrogen and Water Vapor at 1033°K (1400°F)

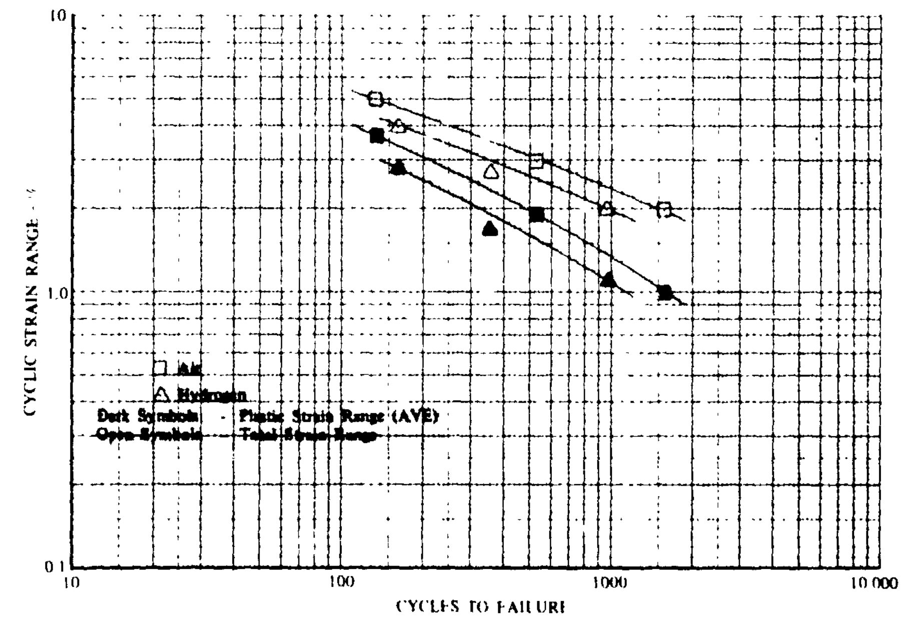

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Figure V-12. Low-Cycle-Fatigue Life of Incoloy 903 Welded (AW-HAZ) in Air and 34.5 MN/m² (5000 psig) Hydrogen at 297°K (75°F)

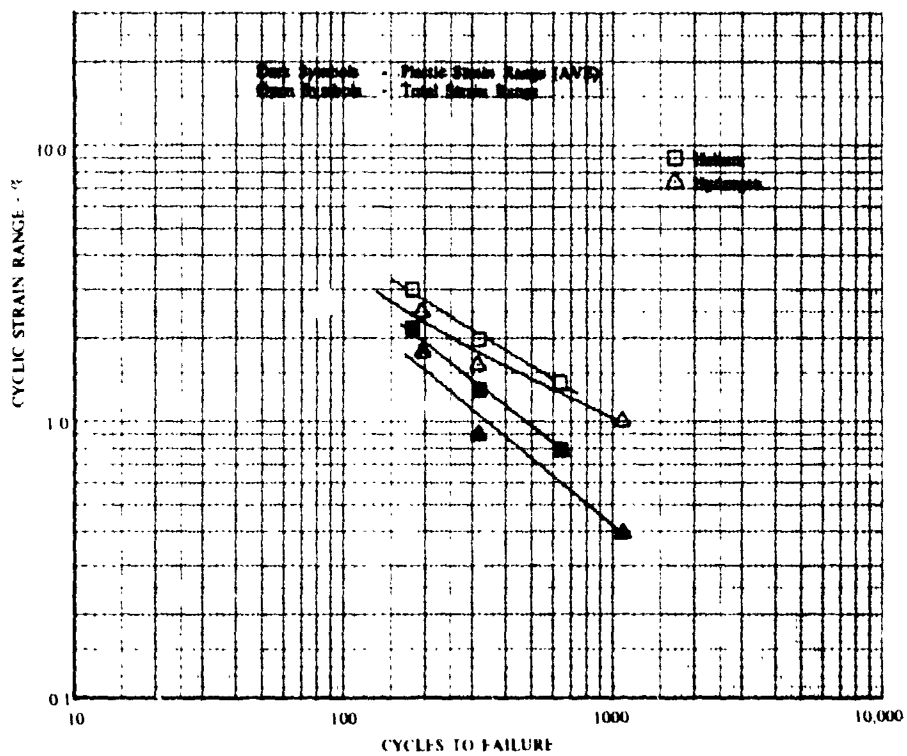

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Figure V-13. Low-Cycle-Fatigue Life of Incoloy 903 Welded (AW-HAZ) Material in 34.5 MN/m² (5000 psig) Helium and Hydrogen at 922°K (1200°F)

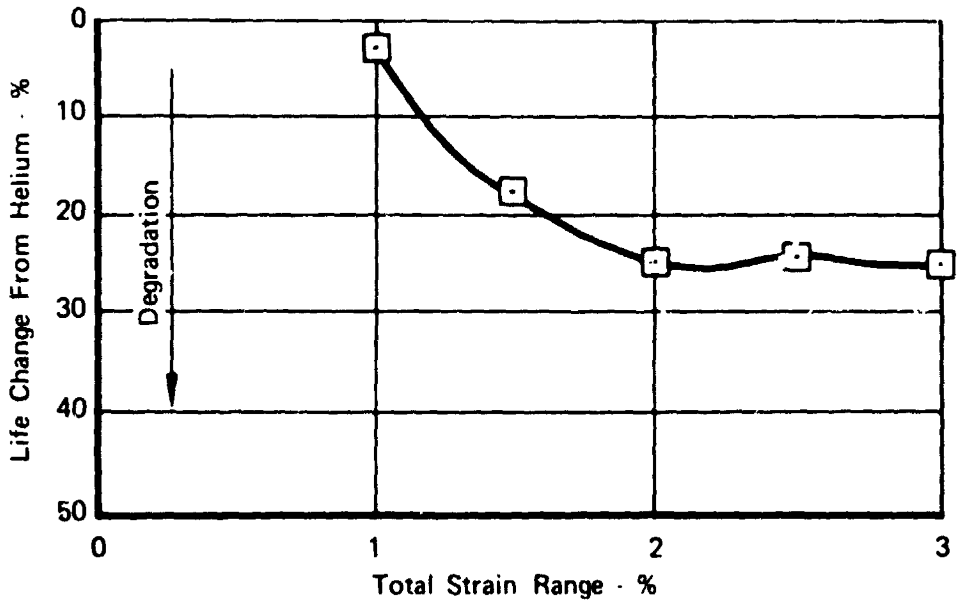

Figure V-14. Effect of Strain Range on Hydrogen Degradation of Low-Cycle Fatigue Life at 922°K (1200°F) of Incoloy 903 Welded (AW-HAZ) Material

Table V-2. Low-Cycle Fatigue Properties of Incoloy 903 in Air and High Pressure Gaseous Environments

Material			Test Conditions							Test Results			
Form	Condition	Spec. S/N	Test Temperature °K	°F	Environment	Pressure MN/m²	(psig)	Total Strain Range**, %	Cyclic Rate Cycles/Min	Cycles to Failure	Plastic Strain Range, % Minimum	Maximum	Average
Parent	STA	LPS-3	297	75	Air	One Atmosphere		4.00	3	224	1.9	2.3	2.1
		LPS-2	297	75	Air	One Atmosphere		3.00	3	461	1.0	1.5	1.3
		LPS-1	297	75	Air	One Atmosphere		2.00	3	1203	0.3	0.6	0.5
		LPS-4	297	75	Hydrogen	34.5	5000	3.00	2	348	1.1	1.7	1.4
		LPS-5	297	75	Hydrogen	34.5	5000	4.00	2	174	1.8	2.3	2.1
		LPS-6	297	75	Hydrogen	34.5	5000	2.00	4	822	0.4	0.7	0.6
		LPS-7	811	1000	Hydrogen	34.5	5000	2.00	4	590	0.6	0.9	0.8
		LPS-8	811	1000	Hydrogen	34.5	5000	3.00	3	231	1.2	1.7	1.5
		LPS-9	811	1000	Hydrogen	34.5	5000	1.50	4	1310	0.3	0.4	0.4
		LPS-13*	1033	1400	Helium	34.5	5000	2.00	*	99	1.2	1.4	1.3
		LPS-14*	1033	1400	Helium	34.5	5000	1.00	*	510	0.3	0.7	0.5
		LPS-10*	1033	1400	Hydrogen	34.5	5000	2.00	*	98	1.3	1.4	1.4
		LPS-11*	1033	1400	Hydrogen	34.5	5000	1.40	*	329	0.6	1.1	0.9
		LPS-12*	1033	1400	Hydrogen	34.5	5000	1.00	*	520	0.3	0.9	0.6
		LPS-18*	1033	1400	Hydrogen Water	34.5	5000	1.00	*	20	0.3	0.5	0.4
		LPS-19*	1033	1400	Hydrogen Water	34.5	5000	0.40	*	479	0	0.2	0.1
		LPS-20*	1033	1400	Hydrogen Water	34.5	5000	0.70	*	46	0.1	0.2	0.2
Weld	AW	LWW-1	297	75	Air	One Atmosphere		2.24	4	327	1.2	1.4	1.3
		LWW-2	297	75	Air	One Atmosphere		3.00	4	89	1.7	1.9	1.8
		LWW-3	297	75	Air	One Atmosphere		1.60	4	957	0.5	0.8	0.7
		LWW-4	297	75	Hydrogen	34.5	5000	2.00	3	172	1.0	1.2	1.1
		LWW-5	297	75	Hydrogen	34.5	5000	1.60	3	363	0.6	0.8	0.7
		LWW-6	297	75	Hydrogen	34.5	5000	1.20	4	1504	0.3	0.5	0.4
		LWW-7	811	1000	Hydrogen	34.5	5000	1.40	3	444	0.7	0.9	0.8
		LWW-8	811	1000	Hydrogen	34.5	5000	2.00	2	369	1.2	1.3	1.3
		LWW-10	811	1000	Hydrogen	34.5	5000	1.00	4	1306	0.4	0.5	0.5
		LWW-11	922	1200	Hydrogen	34.5	5000	1.40	3	396	0.4	0.7	0.6
		LWW-12	922	1200	Hydrogen	34.5	5000	2.50	2	156	1.4	1.7	1.6
		LWW-13	922	1200	Hydrogen	34.5	5000	1.00	4	666	0.2	0.4	0.3
		LWW-17*	1033	1400	Helium	34.5	5000	1.60	*	158	0.9	1.1	1.0
		LWW-18*	1033	1400	Helium	34.5	5000	0.80	*	524	0.2	0.6	0.4
		LWW-14*	1033	1400	Hydrogen	34.5	5000	1.60	*	169	0.9	1.0	1.0
		LWW-15*	1033	1400	Hydrogen	34.5	5000	1.20	*	339	0.5	0.9	0.7
		LWW-16*	1033	1400	Hydrogen	34.5	5000	0.80	*	795	0.2	0.5	0.4
		LWW-19*	1033	1400	Hydrogen Water	34.5	5000	[illegible]	*	10	1.0	1.4	1.2
		LWW-20*	1033	1400	Hydrogen Water	34.5	5000	0.80	*	41	0.2	0.5	0.4
		LWW-21*	1033	1400	Hydrogen Water	34.5	5000	0.40	*	481	0.1	0.1	0.1
Weld	AW-HAZ	LWZ-1	297	75	Air	One Atmosphere		2.00	3	1581	0.8	1.2	1.0
		LWZ-2	297	75	Air	One Atmosphere		4.00	3	536	1.7	2.0	1.9
		LWZ-3	297	75	Air	One Atmosphere		5.00	2	135	3.6	3.8	3.7
		LWZ-4	297	75	Hydrogen	34.5	5000	[illegible]	2	361	1.6	1.9	1.8
		LWZ-5	297	75	Hydrogen	34.5	5000	4.00	[illegible]	163	2.7	3.0	2.9
		LWZ-6	297	75	Hydrogen	34.5	5000	2.00	4	976	0.9	1.2	1.1
		LWZ-10	922	1200	Helium	34.5	5000	2.00	4	314	1.2	1.4	1.3
		LWZ-11	922	1200	Helium	34.5	5000	1.00	2	180	2.1	2.2	2.2
		LWZ-12	922	1200	Helium	34.5	5000	1.40	4	636	0.7	0.8	0.8
		LWZ-7	922	1200	Hydrogen	34.5	5000	2.50	2	195	1.7	1.8	1.8
		LWZ-8	922	1200	Hydrogen	34.5	5000	1.00	4	1186	0.4	0.4	0.4
		LWZ-9	922	1200	Hydrogen	34.5	5000	1.60	3	413	0.8	0.9	0.9

*LCF dwell, 300 second-dwell or hold time at the maximum compressive strain
**Mean Strain = 0

C. TEST PROCEDURE

Smooth, round, solid specimens were used for the strain-controlled LCF tests conducted under this contract. The test specimen used is described in Section III and detailed in figure III-7. The specimen configuration incorporates integral machined extensometer collars. A calibration procedure has been established to relate the maximum strain-to-collar-deflection during both the elastic and plastic portion of the strain cycle. The specimen design and calibration procedure were verified both experimentally and analytically.

All tests were conducted on P&WA-designed and fabricated, closed-loop-type, hydraulically actuated test machines utilizing the strain-control mode. The machine, controls, and readout instrumentation used for the air tests are shown in figure V-15. Specimen axial strain was measured and controlled by means of a dual proximity probe extensometer system (figure V-16). An open extensometer head, showing the attachment of the extensometer to the specimen integral collars, is shown in figure V-17. Specimen load was recorded using commercial tension-compression flat-load cells.

High-pressure environmental tests were conducted on a closed-loop-type hydraulically activated test machine, similar to the one used for the air tests. The test machine is located in an isolated test cell with all controls and instrumentation located in an adjacent blockhouse (figure V-18). A pressure vessel similar to the one used for tensile testing (Section IV-C) was mounted on the upper platen of the test machine. The vessel also incorporated a GrayLoc-type high-pressure flange connector, however, unlike the tensile vessel where a compensating piston device was used to counteract load in the specimen due to pressure acting over differential specimen/adapter areas, this test system compensated for that load through the servosystem. A pressure transducer provided a feedback signal, proportional to chamber pressure, to the servocontroller. This signal was used in controlling a mean load applied to the linkage so zero strain in the specimen gage was maintained when the vessel assembly was pressurized. This same load was then superimposed on the cyclic load during testing.

Both internal (to the pressure vessel) and external load cells were used to obtain cyclic load; thus, the effect of friction at the load rod seals was known and accounted for. Electrical connections to the load cell, extensometer system, furnace (for elevated temperature tests), and thermocouples were made through the vessel wall via high-pressure bulkhead connectors. Setups of the pressure vessel showing the extensometer system and furnace arrangement are shown in figure V-19.

For elevated temperature testing, a two-zone resistance furnace with separate control systems for each zone was used. The furnace surrounds the specimen and fits within the frame of the pressure vessel (figure V-19c). Thermocouples attached to the specimen gage section were used to monitor and control temperature during test.

Hydrogen and water vapor environment was obtained utilizing triple-distilled water in a pure hydrogen-containing retort system so the water was vaporized by furnace heat. The retort system, containing the test specimen and water, fits within the furnace and consists of a piston /tube type arrangement (figure V-20). The piston, attached to the lower pull rod, incorporates an O-ring which provides a seal against the inner surface of a tube (cylinder), which is attached to the upper pull rod. During test the tube remains basically stationary relative to the piston. The base of the piston incorporates O-ring holes for passage of the extensometer tubes, and check valves which allow hydrogen to enter the retort and prevent water from escaping. Pressure inside the retort and vessel was equalized; therefore, the retort contained the hydrogen and water vapor environment and did not withstand any pressure loading. Thermocouples also exit the retort via connectors installed in the base of the piston. They monitor and control specimen and water vapor temperature. By controlling the lower zone of the furnace, water was vaporized at a temperature which assured 500,000-ppm water vapor (50% by weight).

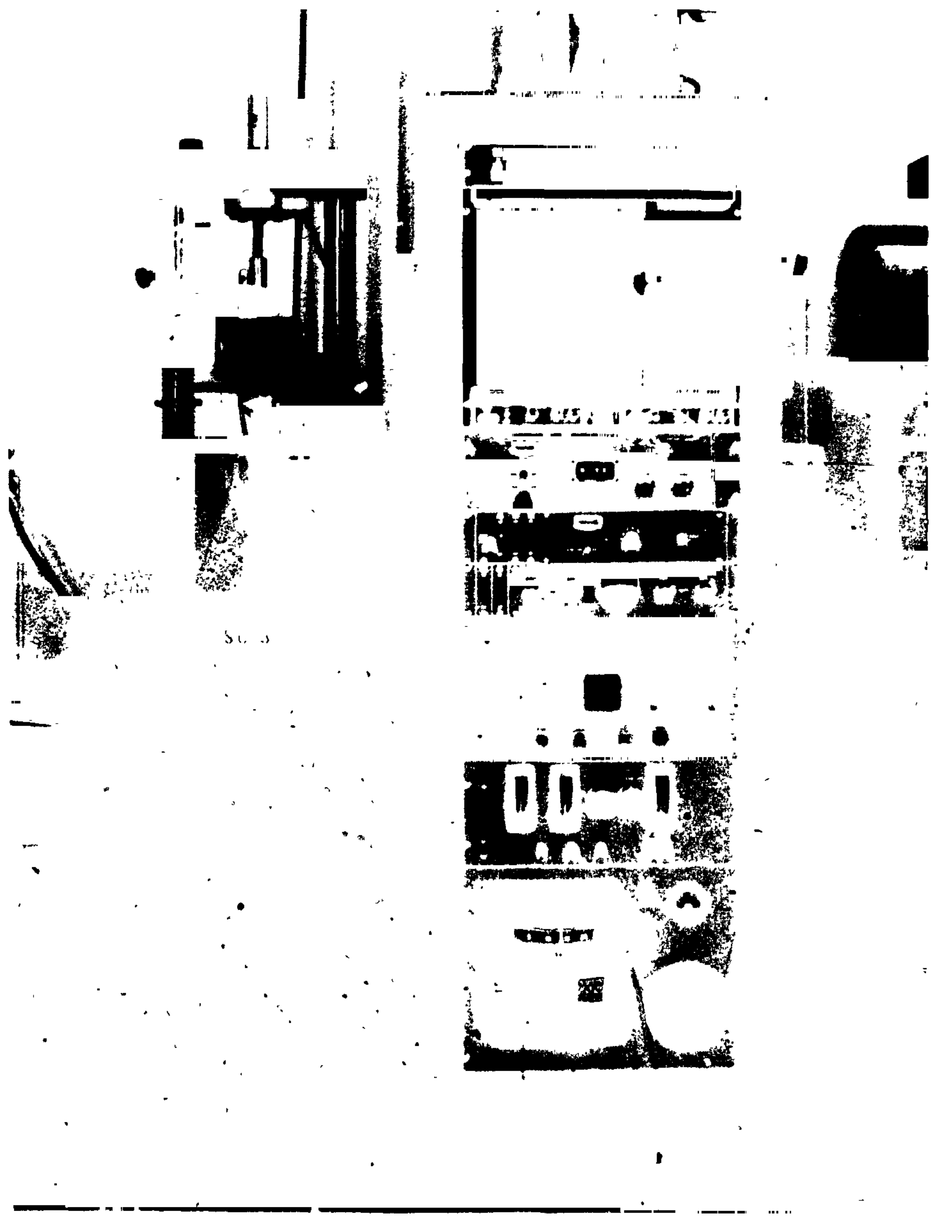

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Figure V-15. Servohydraulic Closed-Loop Low-Cycle Fatigue Testing Machine

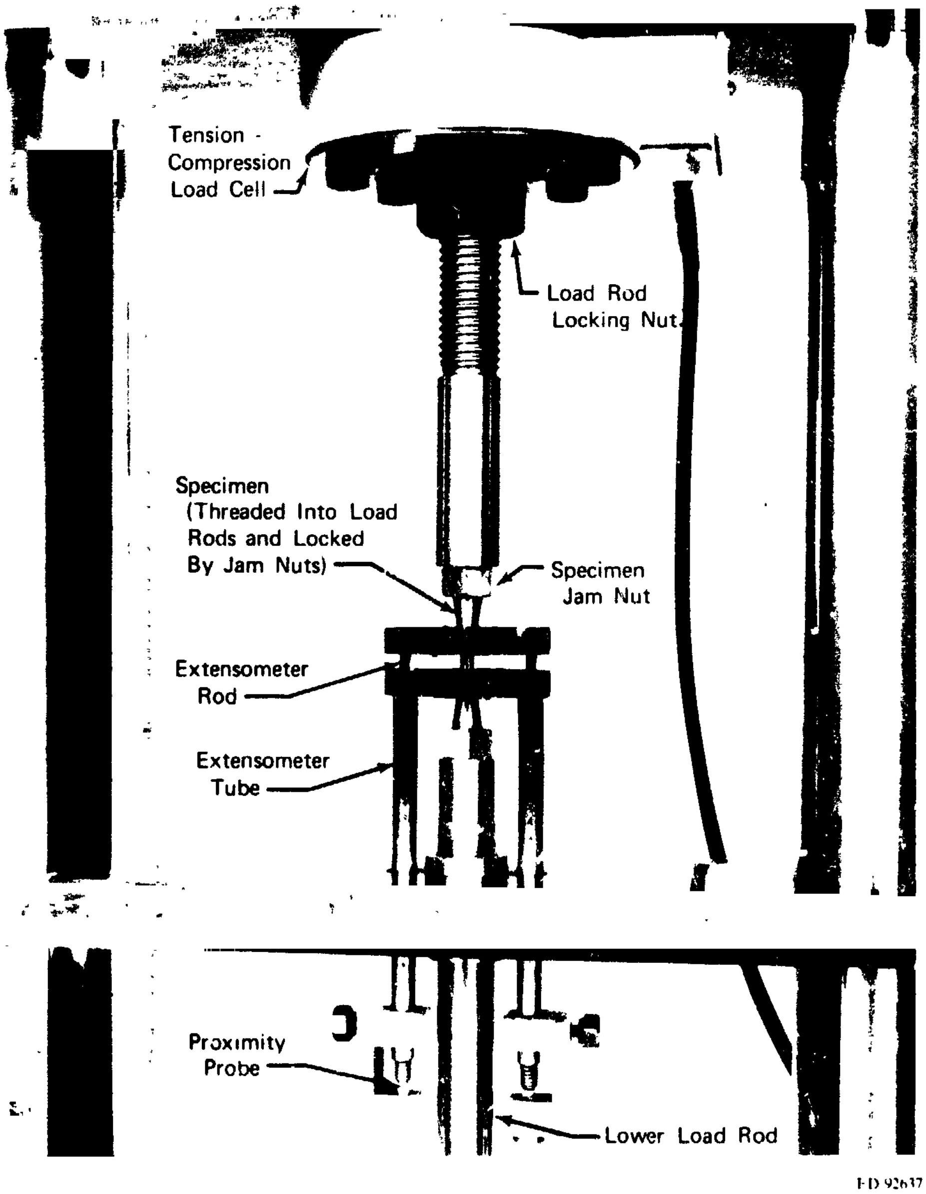


Figure V-16. Load Cell, Load Rod, Specimen, and Extensometer Assembly Mounted in Low-Cycle Fatigue Machine

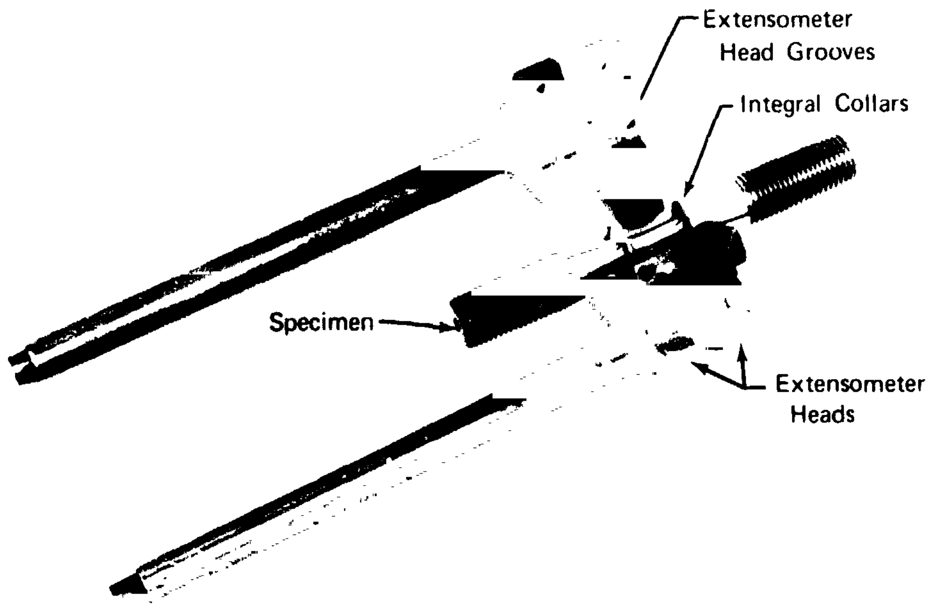
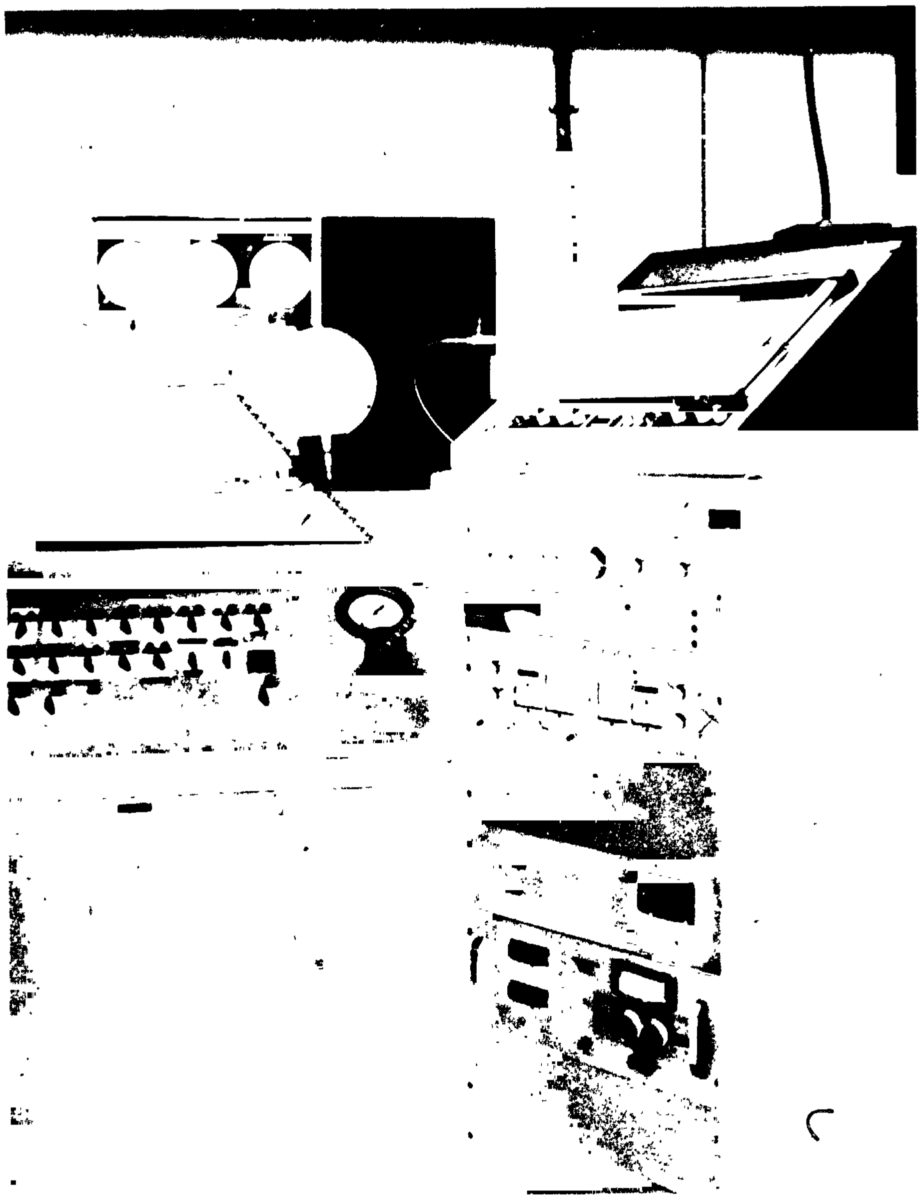
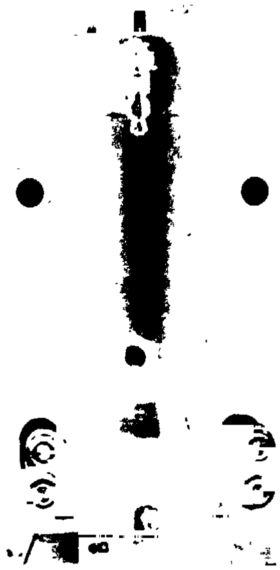


Figure V-17. Open Extensometer Head Assembly and Low-Cycle Fatigue Specimen



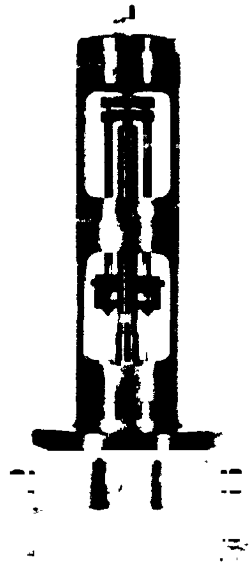
FD 97639

Figure V-18. Low-Cycle Fatigue Test Machine Environmental Controls and Data Acquisition Equipment



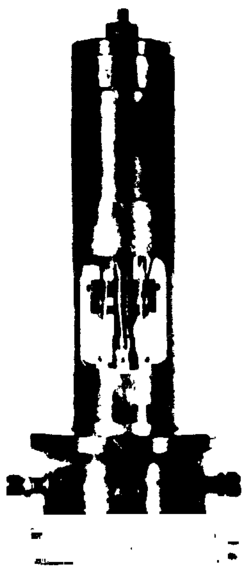
FAE 146129

a) Test Vessel Closed



FAE 146121

b) Test Vessel Open Showing Extensometer System

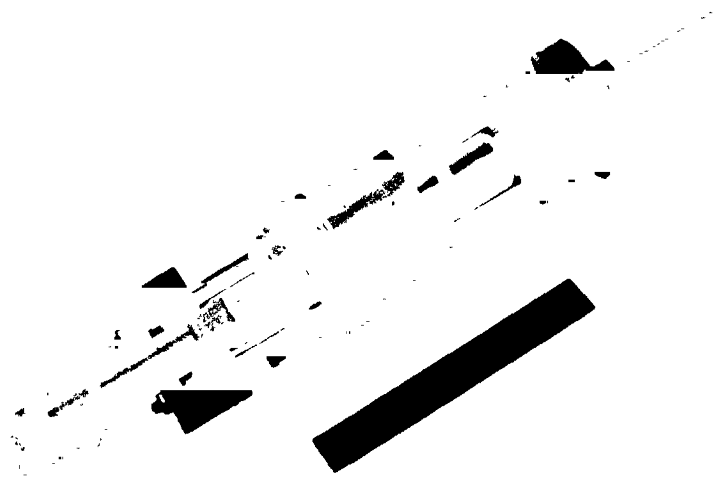


FAE 146122

c) Test Vessel Open Showing Furnace In Place

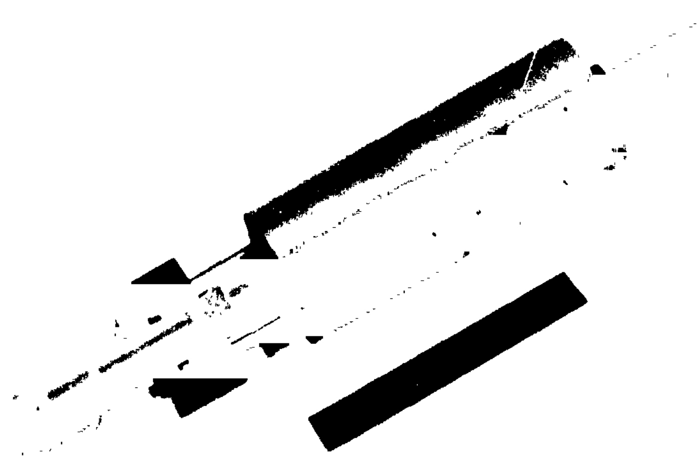
FD 92640

Figure V-19. Setups of Low-Cycle Fatigue Test Vessel



FAE 146128

a) Retort With Cylinder Removed Showing Piston, Extensometer System and Thermocouple Leads



FAE 146132

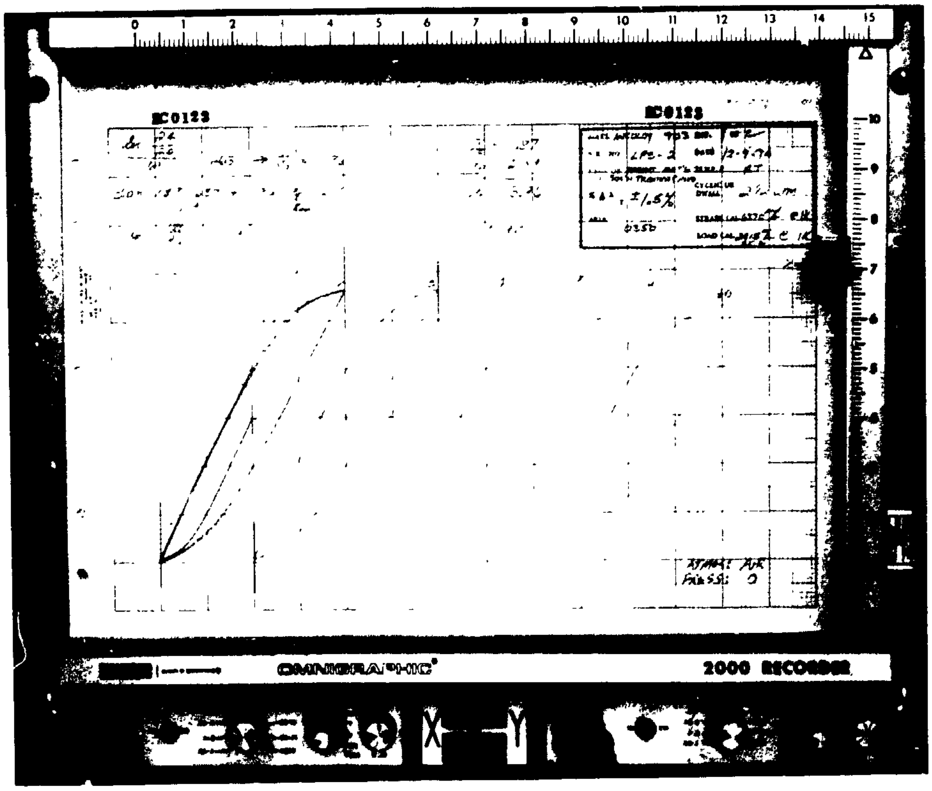
b) Retort System With Cylinder In Place

FD 92641

Figure V-20. Low-Cycle Fatigue Test Retort System

Strain, as sensed by the extensometer system, was recorded on the "X" axis of an "X-Y" recorder, and load (sensed by the internal load cell) was recorded on the "Y" axis, thus providing hysteresis loops, as desired, during the cyclic life of all tests. A typical series of LCF hysteresis loops is shown in figure V-21.

The test and gas handling procedures used for the LCF tests were similar to those used for the tensile tests performed under this contract (Section IV-C).



FD 92642

Figure V-21. A Typical Series of Hysteresis Loops Generated During an Actual Low-Cycle Fatigue Test

SECTION VI
CREEP-RUPTURE

A. INTRODUCTION

Creep-rupture properties of Incoloy 903 in the parent (STA) and welded (AW) material conditions were determined in 34.5 MN/m² (5000 psig) helium, hydrogen, and hydrogen and water vapor at 922°K (1200°F) and 1033°K (1400°F). Eight tests (4 STA and 4 AW material) were notch stress-rupture (K_T = 3.6) at 1033°K (1400°F). Testing established creep rate, rupture life, percent elongation, and percent reduction of area. Results of tests in hydrogen and hydrogen and water vapor were compared to those in helium to determine property degradation.

B. RESULTS AND CONCLUSIONS

Degradation was determined at given stress levels from the percentage reduction in life for hydrogen and hydrogen and water vapor environments, compared to the helium environment. Using this method, some extrapolation of the stress vs time curves was necessary to obtain equivalent stress levels. In previous work[1], degradation was based upon stress for a given life. Incoloy 903 exhibited such a range of lives in the different environments that a comparision of this nature would require extensive extrapolation. With the limited amount of data, extrapolations of this type would be unrealistic. Because of the limited data, the degradation values should be considered as indicators of a trend, not absolute.

At the lowest temperature tested, 922°K (1200°F) life in helium was greater than in hydrogen. At 1033°K (1400°F), life was degraded by the hydrogen environments. The most pronounced degradation occurred in the hydrogen and water vapor environment. Degradations in excess of 90% occurred when water was introduced. In the case of notch-rupture life, degradation in excess of 80% occurred between the life in a pure hydrogen environment and a hydrogen and water vapor environment. Degradations for specific conditions are listed in table VI-1.

Results of STA material tests at 922°K (1200°F) were inconclusive; failure location and/or lack of failure precluded degradation determination. However, comparative tests at two stress levels indicate creep-rupture lives greater in the hydrogen environment than in helium, indicating some beneficial effect of the hydrogen environment at those conditions. Metallurgical evaluation of the failed specimens revealed intergranular fractures with helium specimens indicating brittle characteristics to a much greater degree than the hydrogen speci. iens (figure VI-1). Additional work is required to define the environmental degradation me hanism and to explain this occurrence; unfortunately that work was beyond the scope of this program.

At 1033°K (1400°F), STA material was extremely degraded in both smooth- and notch-rupture lives due to hydrogen, and/or hydrogen and water vapor environments (figures VI-2 and VI-3). Average degradation in excess of 90% was indicated due to the hydrogen and water vapor environment. Individual specimen plots of creep vs time for the creep-rupture tests at 1033°K (1400°F) are shown in figure VI-4.

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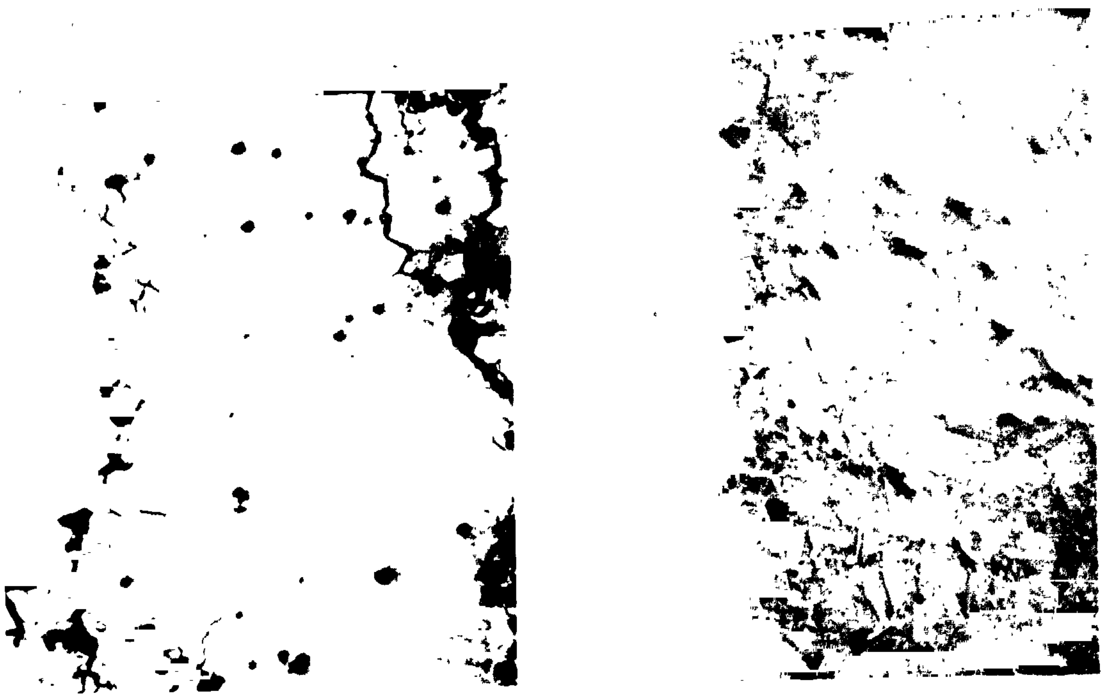
[1] "Properties of Materials in High Pressure Hydrogen at Cryogenic, Room and Elevated Temperatures," PWA FR-5768, Final Report, Contract NAS8-26191, 31 July 1973.

Table VI-1. Degradation of Stress-Rupture Life of Incoloy 903 in 34.5 MN/m^2 (5000 psig) Gaseous Environments

Material Form	Material Condition	Test Temperature °K	Test Temperature °F	Stress Concentration Factor	Environment	Stress Level MN/m^2	Stress Level ksi	Degradation (% Decrease) In Rupture Life at Indicated Stress Level From Helium	Degradation (% Decrease) In Rupture Life at Indicated Stress Level From Hydrogen
Parent	STA	922	1200	Smooth	Hydrogen	(1)	(1)	(1)	
		1033	1400	Smooth	Hydrogen	310.3	45.0	85	
		1033	1400	Smooth	Hydrogen	258.6	37.5	57	
		1033	1400	Smooth	Hydrogen and Water	310.3	45.0	95	66
		1033	1400	Smooth	Hydrogen and Water	258.6	37.5	65	20
		1033	1400	3.6	Hydrogen and Water	275.8	40.0		99
		1033	1400	3.6	Hydrogen and Water	206.8	30.0		91
Weld	AW	922	1200	Smooth	Hydrogen	(1)	(1)	(1)	
		1033	1400	Smooth	Hydrogen	275.8	40.0	15	
		1033	1400	Smooth	Hydrogen	206.8	30.0	48	
		1033	1400	Smooth	Hydrogen and Water	275.8	40.0	73	68
		1033	1400	Smooth	Hydrogen and Water	206.8	30.0	67	67
		1033	1400	3.6	Hydrogen and Water	206.8	30.0		81

(1) Results inconclusive; failure location, lack of failure or excessive stress level precluded degradation determination.

(2) Degradation based on change from hydrogen.



a) Typical Specimen Tested in Helium at 922°K (1200°F)

b) Typical Specimen Tested in Hydrogen at 922°K (1200°F)

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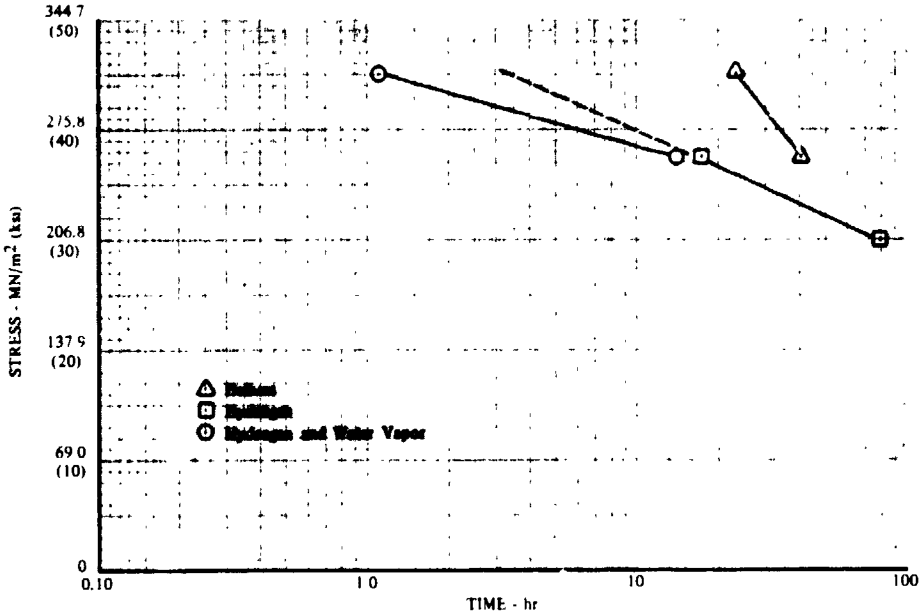
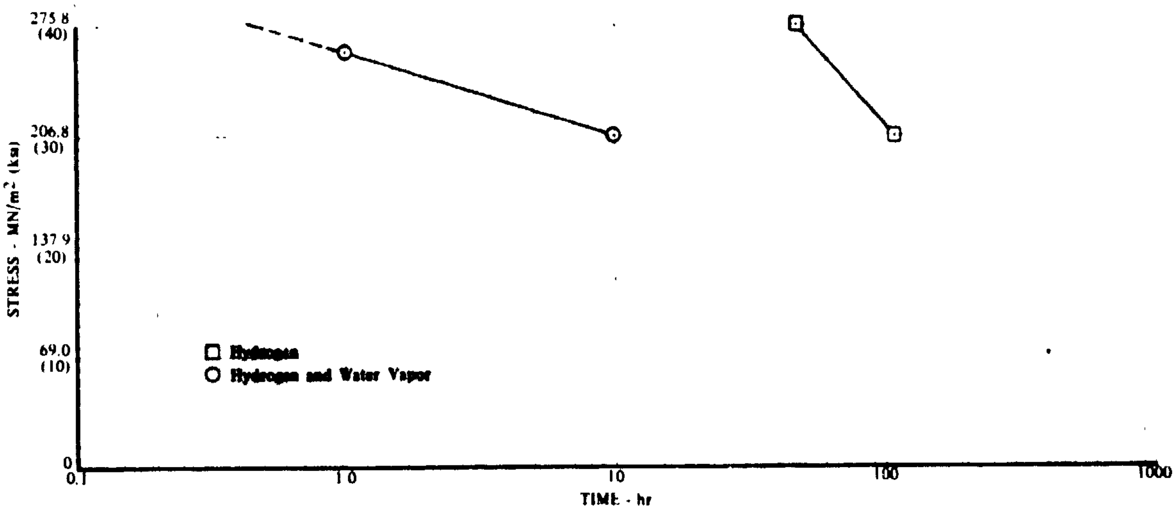
Figure VI-1. Incoloy 903 Parent (STA) Material Fracture Faces Showing Intergranular Fracture



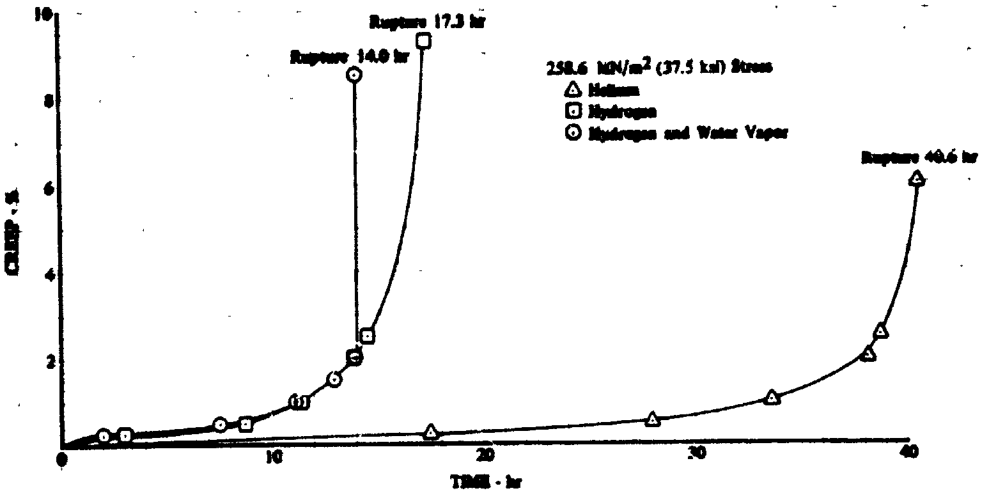
DF 101434

Figure VI-2. Stress-Rupture of Incoloy 903 Parent (STA) Material at 1033°K) (1400°F) and 34.5 MN/m² (5000 psig) Pressure



DF 101435

Figure VI-3. Notch Stress-Rupture of Incoloy 903 Parent (STA) Material at 1000°K (1400°F) and 34.5 MN/m² (5000 psig) Pressure



DF 101436

Figure VI-4. Creep Stress-Rupture of Incoloy 903 Parent (STA) Material at 1033°K (1400°F) and 34.5 MN/m² (5000 psig) Pressure

Welded material tests at 922°K (1200°F) were also inconclusive. Results indicate the same apparent beneficial effect of the hydrogen environment as seen in the STA material tests. At 1033°K (1400°F), AW material was severely to extremely degraded in both average smooth- and notched-rupture lives due to hydrogen, and/or hydrogen and water vapor environments (figures VI-5 and VI-6). All test results are listed in table VI-2.

C. TEST PROCEDURE

Creep- and notch-rupture tests were conducted per ASTM E139-70, "Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials," where applicable, using round, smooth, and notched ($K_T = 3.6$) specimens. The test specimens are described in Section III and detailed in figures III-8 and III-9.

All tests were conducted on a modified 53.4-kN (12,000-lb) capacity Arcweld Model JE creep-rupture machine. The test machine was explosion-proofed and located in a test cell open to the atmosphere (figure VI-7). Controls and data recording equipment were located in an adjacent blockhouse. A high-pressure test vessel (figures VI-7 and VI-8), similar in design and operation to the vessels used for the tensile and LCF tests, was suspended in the test machine and counter-balanced to maintain the load lever arm in a level position.

The design of the test specimen included integral collars for positive location and gripping of creep-measuring extensometer heads. The ends of the specimen were flat pin joints rather than conventionally threaded joints, and acted as part of a two-pin joint. Load rods and adapters also incorporated pin joints, which, in effect, formed universal joints at the ends of the specimen to eliminate alignment errors and resulting bending stresses upon the specimen.

The extensometer system was a dual LVDT averaging type and was located inside the high-pressure vessel. The extensometer output was recorded in the adjacent blockhouse as elongation vs time records for all creep-rupture tests. The extensometer system is shown in figures VI-8c and VI-9. A typical chart record is shown in figure VI-10. This record is for specimen CPS-4, tested in 34.5 MN/m² (5000 psig) helium at 1033°K (1400°F).

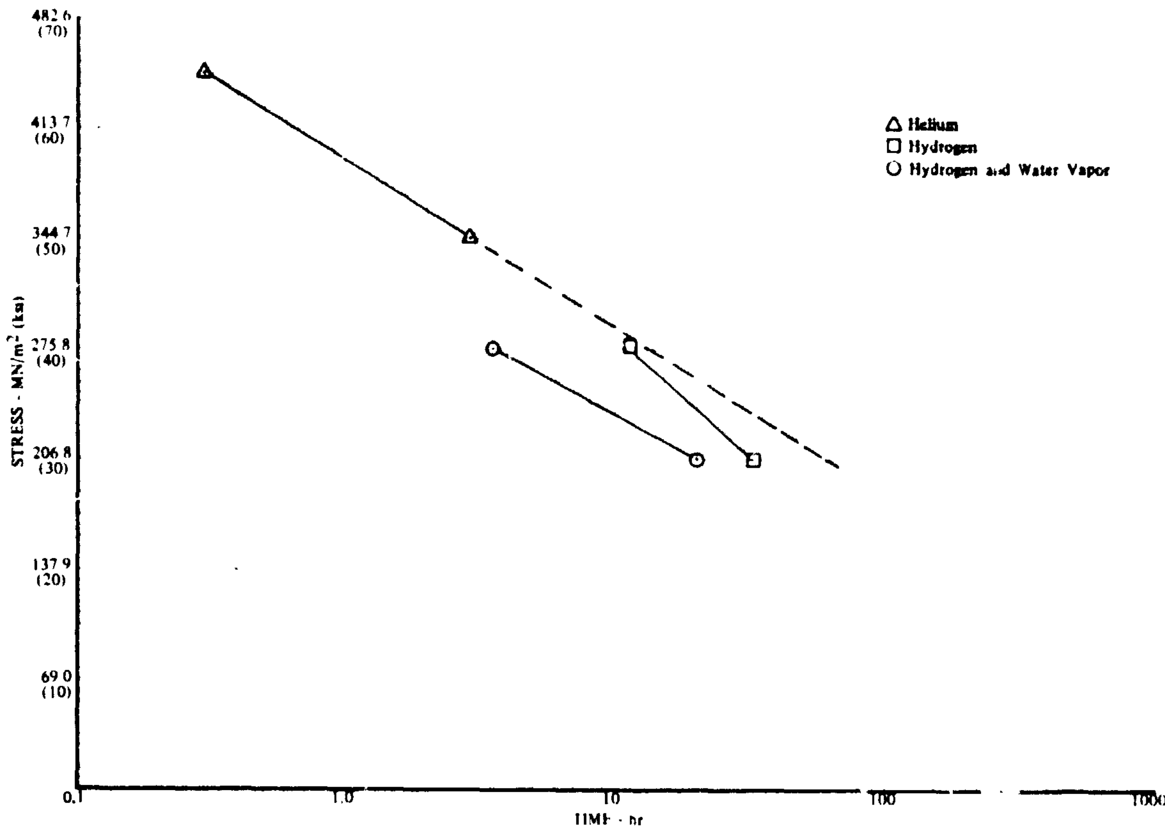


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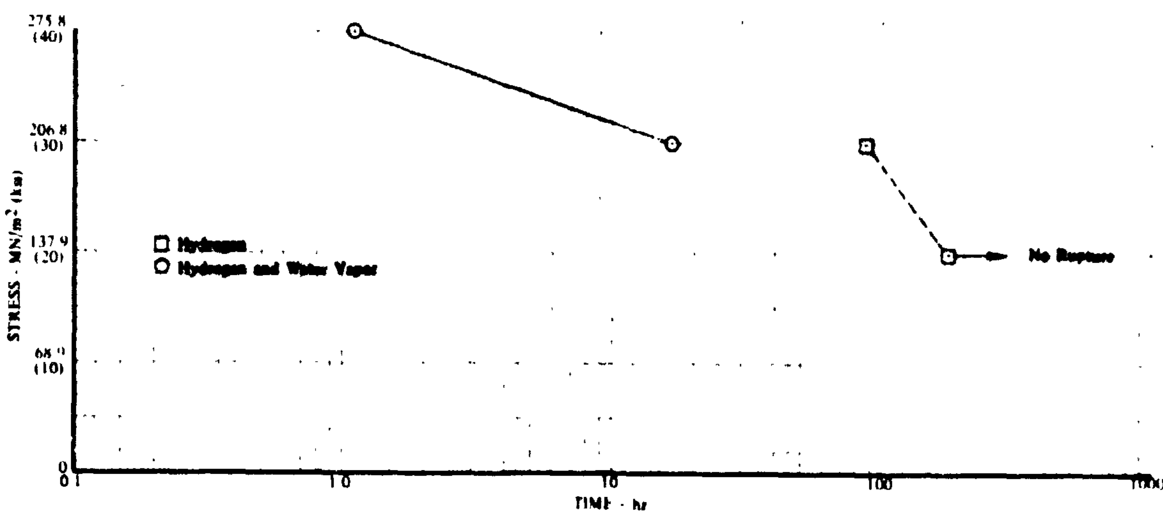
Figure VI-5. Stress-Rupture of Incoloy 903 Welded (AW) Material at 1033°K (1400°F) and 34.5 MN/m² **(5000 psig) Pressure**



DF 101438

Figure VI-6. Notch Stress-Rupture of Incoloy 903 Welded (AW) Material at1033°K (1400°F) and 34.5 MN/m² **(5000 psig) Pressure**

Table VI-2. Creep-Rupture Properties of Incoloy 903 in 34.5 MN/m² (5000 psig) Gaseous Environments

Material Form	Material Condition	Spec. S/N	Test Temperature °K	Test Temperature °F	Stress Concentration Factor	Environment	Stress Level MN/m²	Stress Level ksi	Time (hr) to Creep 0.5%	Time (hr) to Creep 1.0%	Time (hr) to Creep 2.0%	Time to Rupture, hr	EL, %	RA, %
			Test Conditions						Test Results					
Parent	STA	CPS-1	922	1200	Smooth	Helium	482.6	70.0	4.3	4.3		4.3(1)	1.7	0
		CPS-11	922	1200	Smooth	Helium	344.7	50.0	85.3			90.3(1)	0.7	0
		CPS-2	922	1200	Smooth	Hydrogen	344.7	50.0	(2)			136.5(3)	0	0
		CPS-3	922	1200	Smooth	Hydrogen	482.6	70.0	60.3	60.3	60.3	60.3	2.0	5.0
		CPS-4	1033	1400	Smooth	Helium	310.3	45.0	16.1	20.2	23.0	23.3	6.7	19.5
		CPS-6	1033	1400	Smooth	Helium	258.6	37.5	28.0	33.6	38.2	40.6	6.0	18.2
		CPS-7	1033	1400	Smooth	Hydrogen	258.6	37.5	8.7	11.4	13.9	17.3	9.3	22.1
		CPS-9	1033	1400	Smooth	Hydrogen	206.8	30.0	43.3	52.8	61.2	79.9	13.5	25.0
		CPS-13	1033	1400	Smooth	Hydrogen and Water	258.6	37.5	7.5	13.2	14.0	14.0	8.5	17.4
		CPS-14	1033	1400	Smooth	Hydrogen and Water	310.3	45.0	(2)			1.1(1)	0	0
		KPS-1	1033	1400	3.6	Hydrogen	206.8	30.0				109.2		
		KPS-2	1033	1400	3.6	Hydrogen	275.8	40.0				47.0		
		KPS-3	1033	1400	3.6	Hydrogen and Water	258.6	37.5				1.0		
		KPS-4	1033	1400	3.6	Hydrogen and Water	206.8	30.0				9.8		
Weld	AW	CWW-1	922	1200	Smooth	Helium	172.4	25.0	(2)			162.5(3)	0	0
		CWW-11	922	1200	Smooth	Helium	413.7	60.0	4.8	4.8	4.8	4.8	3.0	13.5
		CWW-10	922	1200	Smooth	Hydrogen	241.3	35.0	(2)			149.0(3)	0	0
		CWW-3	922	1200	Smooth	Hydrogen	413.7	60.0	19.6	19.6	19.6	19.6	14.3	48.9
		CWW-4	1033	1400	Smooth	Helium	448.2	65.0	0.1	0.2	0.3	0.3(4)	6.4	14.6
		CWW-5	1033	1400	Smooth	Helium	344.7	50.0	1.6	2.5	2.9	[illegible]	3.4	13.0
		CWW-7	1033	1400	Smooth	Hydrogen	275.8	40.0	5.1	7.1	8.8	11.1	7.8	4.4
		CWW-6	1033	1400	Smooth	Hydrogen	206.8	30.0	26.6	30.3	31.1	32.0	5.3	19.9
		CWW-8	1033	1400	Smooth	Hydrogen and Water	275.8	40.0	(2)			3.5	0	0
		CWW-9	1033	1400	Smooth	Hydrogen and Water	206.8	30.0	16.3	19.1	20.0	20.0	3.4	5.0
		KWW-1	1033	1400	3.6	Hydrogen	137.9	20.0				178.5(3)		
		KWW-2	1033	1400	3.6	Hydrogen	206.8	30.0				87.4		
		KWW-3	1033	1400	3.6	Hydrogen and Water	275.8	40.0				1.1		
		KWW-4	1033	1400	3.6	Hydrogen and Water	206.8	30.0				16.5		

(1) Failed in radius
(2) Negligible creep
(3) Did not fail; test discontinued
(4) Plastic deflection of 0.025 mm (0.001 in.) or 0.1% creep occurred on loading.

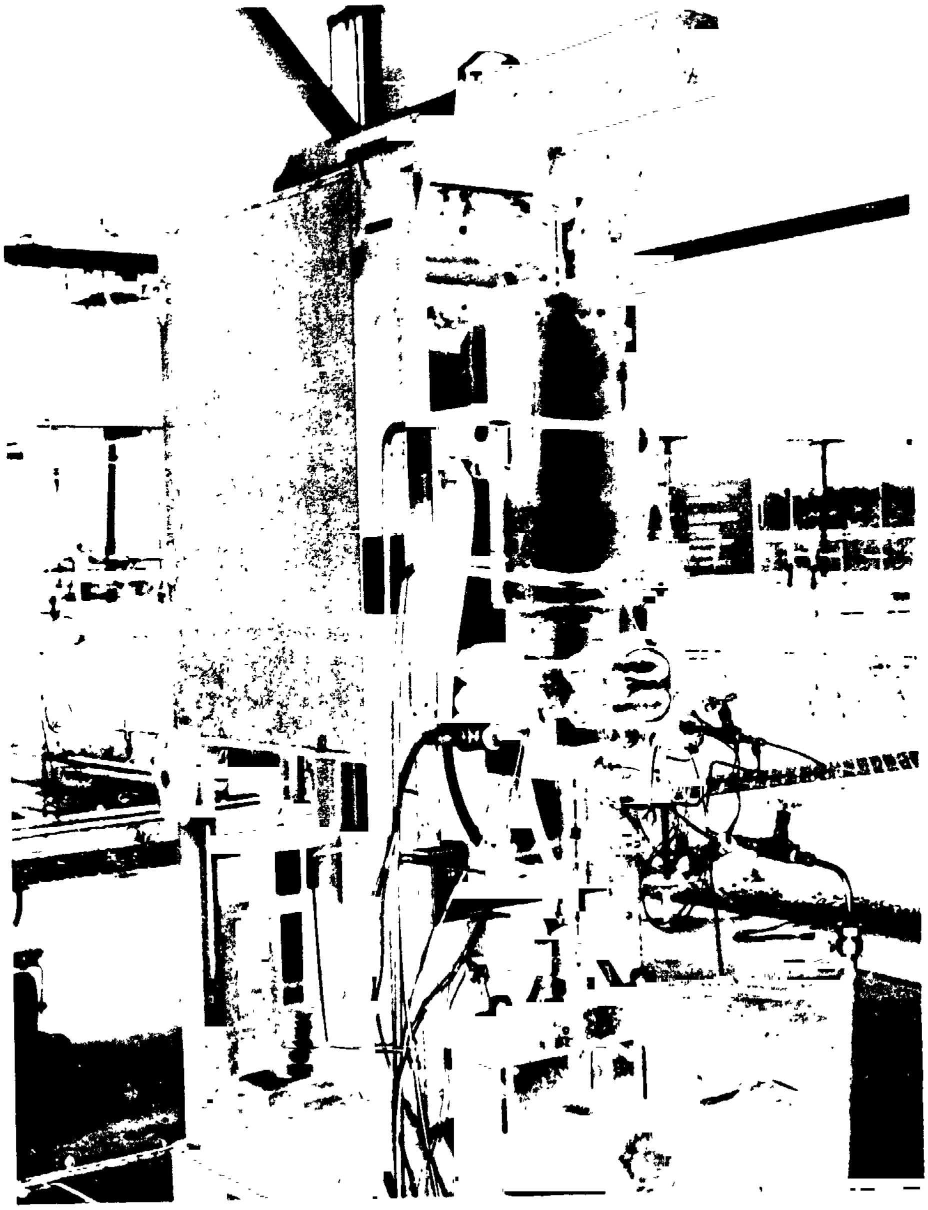
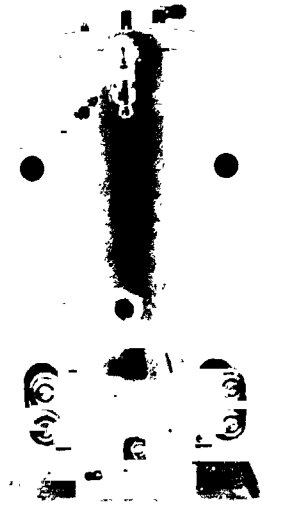
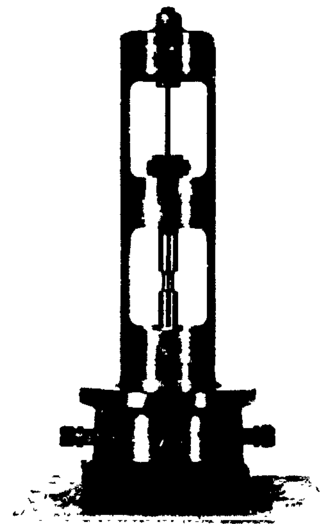

FD 92653

Figure VI-7. Creep-Rupture Machine, With Pressure Vessel Installed, Located in Test cell



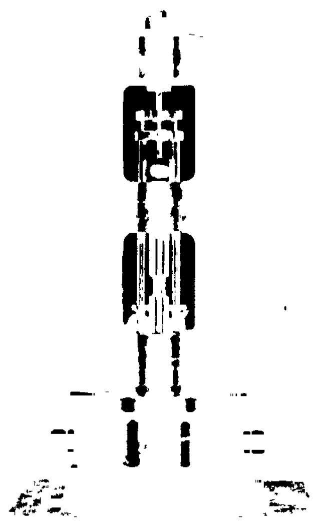
FAE 146129

a) Vessel Closed



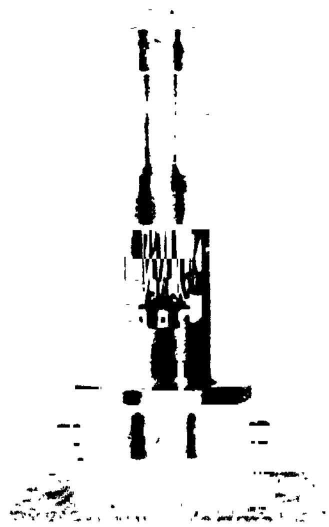
FAE 146125

b) Vessel Open Showing Notch Stress-Rupture Specimen



FAE 146123

c) Vessel Open Showing Creep-Rupture Specimen and Extensometer System



FAE 146124

d) Vessel Open with Furnace Installed

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Figure VI-8. Setups of Creep-Rupture Pressure Vessel

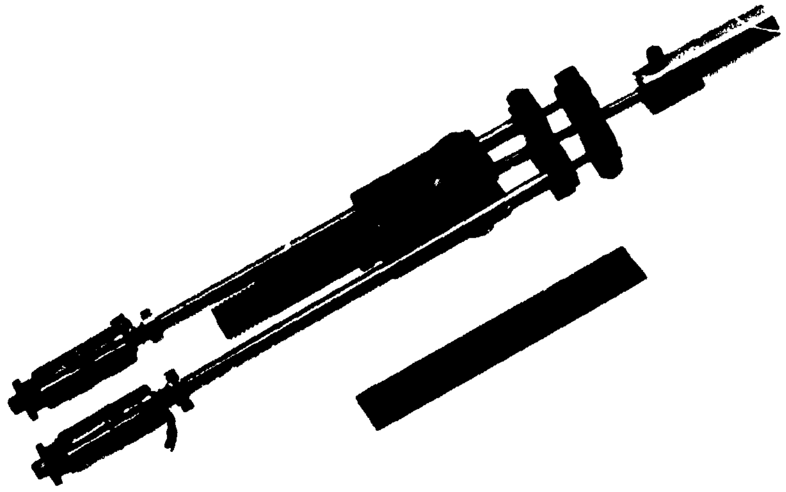

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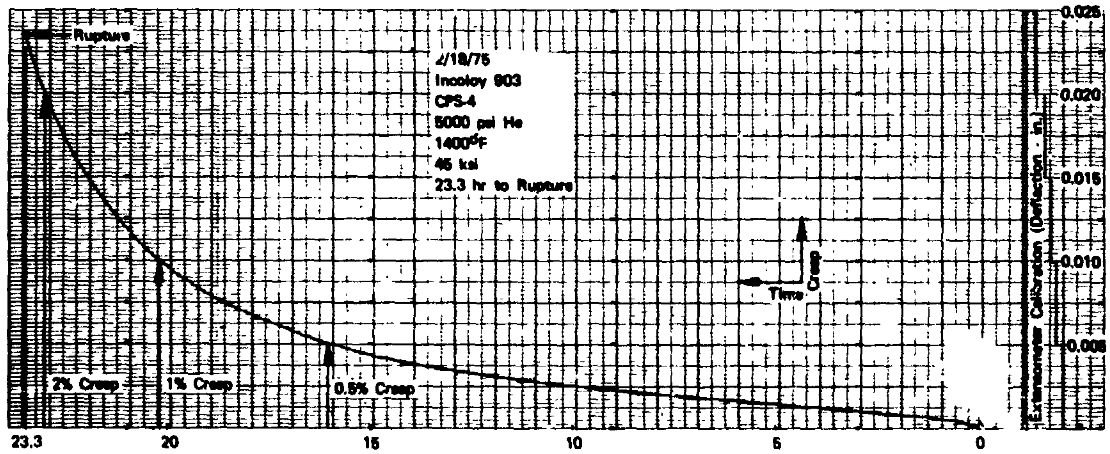
Figure VI-9. Creep Extensometer System



FD 92656

Figure VI-10. Creep vs Time Chart Record for an Incoloy 903 Specimen in a High-Pressure Environment

Elevated temperatures were obtained using a two-zone resistance-type furnace with individual zone temperature control and monitoring. The independent zone control provided even temperature over the specimen gage length. Temperature was monitored and controlled by three thermocouples looped around the specimen gage section. The furnace system was contained within the pressure vessel (figure VI-8d). In figure VI-8d, the thermocouples and furnace leads can be seen extending into the base of the furnace.

Hydrogen and water vapor tests were accomplished in a retort system containing the test specimen and distilled water. The retort consists of a piston/tube-type arrangement and is identical in design and operation as the one used for the LCF tests (Section V-C).

The test and gas handling procedures used for the low-cycle fatigue and tensile tests were also used for the creep-rupture tests.