FR-7746
JULY 1976

INFLUENCE OF GASEOUS HYDROGEN ON THE MECHANICAL PROPERTIES OF HIGH TEMPERATURE ALLOYS

FINAL REPORT

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

PRATT & WHITNEY AIRCRAFT GROUP
Government Products Division
P. O. Box 2691
West Palm Beach, Florida 33402
UNITED TECHNOLOGIES ®

29

PRATT & WHITNEY AIRCRAFT GROUP

GOVERNMENT PRODUCTS DIVISION

P. O. Box 2691
West Palm Beach, Florida 33402

31 July 1976

In reply please refer to:
GOB:lsf:Cont. Adm.

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Attention: Mr. W. B. McPherson, EH23

Subject: Contract NAS8-30744;
Final Report Exhibit B and C

Gentlemen:

In accordance with the requirements of paragraph 3, "Reports Requirements" of Contract NAS8-30744, modified, we herewith forward 25 copies of our Final Report, entitled "Influence of Gaseous Hydrogen on the Mechanical Properties of High Temperature Alloys". This report is the final report for Exhibit B and C of the subject contract. Work being performed under D of this contract will be documented in a future Final Report.

Very truly yours,

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney Aircraft Group

G. O. Bayer
Contract Administrator
Government Products Division

Enclosures (25)

cc: See attached list

UNITED TECHNOLOGIES

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812
Attention: Mr. W. B. McPherson

cc: National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812
Attention: AP13-K (1 enclosure)
AS21-D (5 enclosures)
AT01 (1 enclosure)
EM34 (1 enclosure)

Naval Plant Branch Representative Office
Pratt & Whitney Aircraft Group
West Palm Beach, Florida 33402 (1 enclosure)

FR-7746
JULY 1976

INFLUENCE OF GASEOUS HYDROGEN ON THE MECHANICAL PROPERTIES OF HIGH TEMPERATURE ALLOYS

FINAL REPORT

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

JMucci
J. Mucci
Responsible Engineer

John A. Harris Jr.
J. A. Harris, Jr.
Program Manager

PRATT & WHITNEY AIRCRAFT GROUP
Government Products Division
P. O. Box 2691
West Palm Beach, Florida 33402

UNITED TECHNOLOGIES®

Printed in the United States of America

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

TABLES

TABLES (Continued)

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 B - "Tensile Properties of Several Nickel Alloys in Hydrogen at Elevated Temperatures," and Exhibit C - "Mechanical Properties of a Nickel Alloy in Hydrogen at Elevated Temperature." Additional work is being performed on several nickel-base alloys under a modification to this contract; Exhibit D - "Mechanical Properties of Several Nickel Alloys In Hydrogen at Elevated Temperatures." The work under this modification will be discussed in a subsequent final report The Exhibit A effort of this contract, covering properties of Incoloy 903 in various heat-treat and welded conditions was documented in Pratt & Whitney Aircraft Report FR-7175, "Influence of Gaseous Hydrogen on the Mechanical Properties of Incoloy 903," September 1975.

Experimental efforts under Exhibit B have consisted of a total of 112 tensile tests of six nickel-base and one cobalt-base alloy in 34.5 MN/m² (5000 psig) helium and hydrogen environments at temperatures from 297°K (75°F) to 1088°K (1500°F). For the Exhibit C efforts 77 mechanical properties tests of the nickel-base alloy MAR M-246 (Hf modified), in two cast conditions, were conducted in gaseous environments at temperatures from 297°K (75°F) to 1144°K (1600°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 the various alloys proposed for use in space propulsion systems in a pure hydrogen environment at different temperatures and to compare with the mechanical properties in helium at the same conditions.

The overall Exhibit B and C test programs, including types, conditions, and numbers of tests conducted, are outlined in tables I-1 and I-2, respectively. The primary goal of these tests was to document, rather than define, the hydrogen phenomenon and provide limited engineering data for 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 stain and constant stress testing using smooth specimens and a closed-loop test machine.
3. Creep-Rupture - Creep-rupture life was 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 and centralizes the nickel-base alloys 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.

Table I-1. Exhibit "B" Experimental Smooth Tensile Test Program for Various Alloys in 34.5 MN/m² (5000 psig) Gaseous Environments

Material	*Form*	*Test Temp.* °K	°F	*Environment*	*Number of Tests*
TMP WASPALOY®	Forged	297	75	He	1
		297	75	H_2	3
		589	600	He	1
		589	600	H_2	3
		755	900	He	1
		755	900	H_2	3
		922	1200	He	1
		922	1200	H_2	3
MAR-M-246 (Hf Modified)	Conventionally Cast (CC)	297	75	He	1
		297	75	H_2	3
		755	900	He	1
		755	900	H_2	3
		922	1200	He	1
		922	1200	H_2	3
		1088	1500	He	1
		1088	1500	H_2	3
MAR-M-246 (Hf Modified)	Directionally Solidified Cast (DS)	297	75	He	1
		297	75	H_2	3
		755	900	He	1
		755	900	H_2	3
		922	1200	He	1
		922	1200	H_2	3
		1088	1500	He	1
		1088	1500	H_2	3
Inconel 625	Plate	297	75	He	1
		297	75	H_2	3
		589	600	He	1
		589	600	H_2	3
		755	900	He	1
		755	900	H_2	3
		922	1200	He	1
		922	1200	H_2	3
Inconel 625	Cast	297	75	He	1
		297	75	H_2	3
		589	600	He	1
		589	600	H_2	3
		755	900	He	1
		755	900	H_2	3
		922	1200	He	1
		922	1200	H_2	3
Haynes 188 (Inconel 718 STA)	Plate	297	75	He	1
		297	75	H_2	3
		589	600	He	1
		589	600	H_2	3
		755	900	He	1
		755	900	H_2	3
		922	1200	He	1
		922	1200	H_2	3
Inconel 718	Plate	297	75	He	1
		297	75	H_2	3
		589	600	He	1
		589	600	H_2	3
		755	900	He	1
		755	900	H_2	3
		922	1200	He	1
		922	1200	H_2	3

Table I-2. Exhibit "C" Experimental Test Outline for MAR-M-246 (Hf Modified) in Air and 34.5 MN/m² (5000 psig) Gaseous Environment

Material Form	Test Temperature		Test Environment	Number of Tests				
					Low-Cycle Fatigue			
	°K	°F		Creep Rupture	Strain Control	Load Control	Smooth Tensile	Notch Tensile
Directionally Solidified (DS)	297	75	Air[1]				[3]2	[3]2
	297	75	Air[2]				[3]2	[3]2
	297	75	Air[1]				[4]1	[4]1
	297	75	Air[2]				[4]1	[4]1
	1033	1400	Helium	2	2	1		
	1033	1400	Hydrogen	4	4	1		
	1144	1600	Helium	3	2	1		
	1144	1600	Hydrogen	4	4	1		
Conventionally Cast (CC)	297	75	Air[1]				[3]2	[3]2
	297	75	Air[2]				[3]2	[3]2
	297	75	Air[1]				[4]1	[4]1
	297	75	Air[2]				[4]1	[4]1
	1033	1400	Helium	2		2		
	1033	1400	Hydrogen	4		4		
	1144	1600	Helium	2		2		
	1144	1600	Hydrogen	4		4		

[1] Tested in air, one atmosphere, immediately after opening vessel.
[2] Tested in air, one atmosphere, 24 hours after opening vessel.
[3] Specimens exposed to 34.5 MN/m² (5000 psig) hydrogen at 1144°K (1600°F) for 8 hours prior to air test.
[4] Specimens exposed to 34.5 MN/m² (5000 psig) helium at 1144°K (1600°F) for 8 hours prior to air test.

This program was conducted using the Program Manager - Project Group System by the Pratt & Whitney Aircraft Group, Government Products Division, Materials Development Laboratory, under the cognizance of Mr. W. B. McPherson, Metallurgy Branch, Materials & Process Laboratory, Marshall Space Flight Center. John A. Harris, Jr. was the Pratt & Whitney Program Manager for the effort.

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

J. Mucci - Technical Supervision and Report Efforts
J. A. Doyle - Tensile and Creep Testing
A. F. Kirkpatrick - Proposal 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 one cobalt-base and six nickel-base alloys in various forms and/or heat-treat condition that are proposed for use in a high-pressure hydrogen environment. Properties determined in the hydrogen environment were compared to properties in a helium environment at the same conditions to establish environmental degradation.

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

1. Extremely Degraded (ED) - Hydrogen environment reduced the property or life (in helium) greater than 50%.
2. Severely Degraded (SD) - Hydrogen environment reduced the property or life (in helium) greater than 25%, but less than 50%.
3. Degraded (D) - Hydrogen environment reduced the property or life (in helium) greater than 10%, but less than 25%.
4. Negligible Degradation (ND) - Hydrogen environment reduced the property or life (in helium) less than 10% or had no detrimental effect.

Using this rating system, table II-1 displays the degree of degradation for the Exhibit B alloys. The degree of degradation for the MAR M-246 (Hf Modified), in both the conventionally cast (CC) and directionally solidified (DS) forms, covered under the Exhibit C effort, is shown in table II-2. In the case of the tensile tests, if any property (yield strength, smooth or notched 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 are presented below.

B. EXHIBIT B TENSILE PROPERTIES

Tested were:

TMP WASPALOY®
MAR M-246 (Hf Modified) CC
MAR M-246 (Hf Modified) DS
Inconel 625 cast
Inconel 625 plate
Haynes 188 (Inconel 718 STA heat treatment)
Inconel 718

The prime effect of hydrogen upon tensile properties was the degradation of ductility. The elongation and reduction of area were affected for most of the alloys. No alloy's yield strength was affected. The degradation ratings and the discussion below are therefore based primarily upon ductility effects.

Table II-1. Degree of Environmental Degradation on Exhibit B Smooth Tensile Properties of Various Alloys in 34.5 MN/m² (5000 psig) Hydrogen

Material	*Form*	*Test Temperature*		*Degree of Degradation*
		°K	*°F*	
TMP WASPALOY*	Forged	297	75	ED
		589	600	ED
		755	900	ED
		922	1200	SD
MAR M-246 (Hf Modified)	Conventionally Cast (CC)	297	75	ED
		755	900	ED
		922	1200	SD
		1088	1500	ED
MAR M-246 (Hf Modified)	Directionally Solidified (DS)	297	75	ED
		755	900	SD
		922	1200	ED
		1088	1500	SD
Inconel 625	Plate	297	75	D
		589	600	ND
		755	900	ND
		922	1200	ND
Inconel 625	Cast	297	75	SD
		589	600	D
		755	900	ND
		922	1200	ND
Haynes 188 (Inconel 718 STA)	Plate	297	75	ED
		589	600	SD
		755	900	ND
		922	1200	ND
Inconel 718	Plate	297	75	D
		589	600	ED
		755	900	SD
		922	1200	D

Table II-2. Degree of Environmental Degradation of Exhibit C MAR M-246 (Hf Modified) in 34.5 MN/m² (5000 psig) Gaseous Hydrogen

	Test Temperature		*Creep Rupture*[1]	*Internal Hydrogen Embrittlement*		*Low Cycle Fatigue*	
Material Form	*°K*	*°F*	*(C-R)*	*Smooth Tensile (ST)*	*Notch Tensile (NT)*	*Load Control (LCF)*	*Strain Control (LCF)*
Directionally Solidified (DS)	1033	1400	SD			ED	ND
	1144	1600	ND to ED[4]	SD[2],ED[3]	ND[2],D[3]	ED	ND
Conventionally Cast (CC)	1033	1400	ED			SD	
	1144	1600	ED	ED[2],ED[3]	SD[2],D[3]	ED	

---

[1] Degradation based on average of percent changes in rupture life at stress levels shown in table VI-1.

[2] Degradation in 297°K (75°F) air properties after 8-hour 1144°K (1600°F) hydrogen exposure (degradation based on helium exposed material).

[3] Degradation in 297°K (75°F) air properties after 8-hour 1144°K (1600°F) hydrogen exposure and subsequent 24 hour ambient air set time (degradation based on helium exposed material also with 24 hour ambient air set time).

[4] Degradation may be stress/time dependent. (See Section VI.B.)

The alloys most susceptible to hydrogen degradation were the CC and DS MAR M-246 (Hf Modified) and TMP WASPALOY. They exhibited severe to extreme degradation in tensile properties at all the temperatures evaluated.

The nickel-base alloy Inconel 625 was the least degraded alloy tested. In fact, in the wrought form (plate) relative immunity to hydrogen degradation was exhibited. The cast Inconel 625 was negligibly degraded at the higher test temperatures {755°K (900°F) and 922°K (1200°F)} and degraded up to the severe degree at the lower temperatures {297°K (75°F) and 589°K (600°F)}. A similar trend was exhibited for the cobalt-base alloy Haynes 188, except that at the lower temperatures generally greater degradation occurred.

Inconel 718 was degraded to a certain extent at all temperatures tested with the maximum reduction in tensile properties occurring at 589°K (600°F).

The materials exhibited the previously noted trend of lessening degradation with increasing temperature, with the greatest degree of degradation generally occurring at the lower test temperatures.

C. EXHIBIT C

Tested were:

MAR M-246 (Hf Modified) CC
MAR M-246 (Hf Modified) DS

1. Internal Hydrogen Embrittlement (IHE)

Severe to extreme degradation was exhibited in the 297°K (75°F) smooth tensile properties of both the CC and DS materials due to 8-hr 1144°K (1600°F) 34.5 MN/m^2 (5000 psig) hydrogen exposure. The notch tensile strength of both materials was degraded from negligible to severe due to the same exposure.

2. Low-Cycle Fatigue

The DS material did not exhibit any significant degradation in strain control LCF life at 1033°K (1400°F) and 1144°K (1600°F) due to the hydrogen environment. However, the load control LCF life was extremely degraded at both test temperatures. (See Section V.)

Load control LCF life of the CC material was severely and extremely degraded at 1033°K (1400°F) and 1144°K (1600°F), respectively, due to hydrogen environment.

3. Creep-Rupture (CR)

The CC material rupture life was extremely degraded at 1033°K (1400°F) and 1144°K (1600°F) due to 34.5 MN/m^2 (5000 psig) hydrogen environment. For the DS material, rupture life was severely degraded at 1033°K (1400°F). At 1144°K (1600°F), CR testing of the DS material indicated extreme degradation in life at the higher stress level. At the lower stress level greater rupture life in hydrogen than in helium was exhibited, indicating no degradation due to the hydrogen environment, or possibly some unique helium interaction at this temperature. It appears that at 1144°K (1600°F), degradation of this cast alloy is stress/time dependent (See Section VI).

D. DISCUSSION

This program was established to determine selected material properties and to enable general observations in regard to the susceptibility of the various alloys to hydrogen degradation. We have observed that all seven alloys were degraded in some properties to a certain extent for the test conditions evaluated. However, testing conducted was of necessity very limited, and conclusions as to the degree of degradation may be determined to be incorrect by additional investigations. These efforts were designed primarily to obtain specific information for select materials and conditions occurring in space vehicle propulsion systems. As such, the information contained herein will enable component design and evaluation with a greater degree of confidence. While answering questions concerning specific applications, many more questions, such as elevated temperature helium interactions, have been raised. Continued programs, including basic research, will be required to explain the mechanisms at work in environmental degradation of materials.

SECTION III
MATERIALS AND SPECIMENS

A. TEST MATERIAL

The purpose of this program was to determine the susceptibility of six nickel-base alloys and one cobalt-base alloy to environmental degradation. Testing evaluated the mechanical properties of the materials in various forms and heat-treat conditions. All test materials were supplied in the fully heat-treated condition, where applicable, in specimen blank configuration by the Marshall Space Flight Center. Table III-1 lists the various materials, their as-received forms and heat-treat conditions, and the types of tests performed. Chemical compositions are listed in table III-2 and typical microstructures are shown in figure III-1.

B. TEST GASES

Helium and hydrogen 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.

Gas handling systems, supplying the test vessels, were equipped to enable sampling before and after specimen tests. The hydrogen was sampled extensively. 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 Group, Materials Laboratory Machine Shop and finished to an average roughness of 16-μin. rms, or less. The notch used for the tensile specimen to obtain a stress concentration of 8.0 conforms with Peterson[1] and was machined by grinding.

A typical set of specimens is listed in table III-3 and shown in figure III-2. Specimen prints are shown in figures III-3 through III-10.

---

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

Table III-1. Government Furnished Materials Used to Determine the Susceptibility of Various Alloys to Environmental Degradation

Material	*Form*	*Vendor*	*Heat No.*	*As Tested Condition (Heat Treatment)*	*Types of Tests*[1]
TMP WASPALOY®	Forged	Special Metals	92721	1283°K (1850°F), 2 hr, WQ+ 1116°K (1550°F), 4 hr, AQ+ 1033°K (1400°F), 16 hr, AC+ 922°K (1200°F), 24 hr, AC	ST
MAR M-246 (Hf Modified)	Conventionally Cast	Austenal	167B 2649	As Cast	ST,IHE,CR
	Conventionally Cast	Austenal	L99-HPN	As Cast	LCF
	Conventionally Cast	Austenal	L99-HBE	As Cast	LCF
MAR M-246 (Hf Modified)	Directionally Solidified	Austenal	DE-002	1494°K (2230°F), 2 hr, FC+ 1144°K (1600°F), 24 hr, FC	ST
	Directionally Solidified	Austenal	DE-003	Same as DE-002	IHE,LCF,CR
Inconel 625	Plate	Picco/Teledyne	DF-2	1255°K (1800°F), 2 hr, AC	ST
Inconel 625	Cast	Reisner Metals	NX9052A	1422°K (2100°F), 2 hr, FC	ST
Haynes 188	Plate	Stellite	1880-1-0167	Same as Inconel 718	ST
Inconel 718	Plate	Special Metals	83148-1	1311°K (1900°F), 1 hr, AC+ 1033°K (1400°F), 10 hr, AC+ 922°K (1200°F), 10 hr, AC	ST

---

[1] Types of Tests:
ST - Smooth Tensile
IHE - Internal Hydrogen Embrittlement
CR - Creep Rupture
LCF - Low-Cycle Fatigue

ORIGINAL PAGE IS OF POOR QUALITY

Table III-2. Chemical Composition of Materials Used to Determine the Susceptibility of Various Alloys to Environmental Degradataion

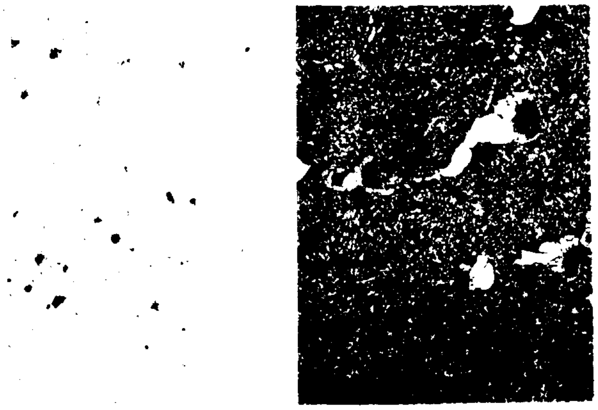
Material	Form	Heat No.	Elemental Composition - % By Weight																		
			C	*Si*	*Mn*	*P*	*S*	*Cr*	*Ni*	*Mo*	*Al*	*Ti*	*Cu*	*Fe*	*Cb*	*Ta*	*Co*	*W*	*Zr*	*B*	*Hf*	*La*
TMP WASPALOY*	Forged	92721	0.041	0.06	0.03	0.005	0.003	19.55	Bal	4.14	1.20	2.99	0.01	0.84			13.81		0.07	0.006		
MAR M-246 (Hf Modified)	Conventionally Cast	167B 2649	0.14	<0.05	0.01		0.003	8.85	Bal	2.30	5.68	1.67	<0.1	0.08		1.69	10.66	9.45	0.07	0.014	1.94	
		L99-HPN	0.14	<0.1	<0.01		0.0013	8.94	Bal	2.34	5.50	1.55	<0.1	0.13		1.36	10.64	9.30	0.07	0.014	1.80	
		L99-HBE	0.16	<0.1	<0.01		0.0018	8.90	Bal	2.60	5.50	1.68	<0.1	0.18		1.40	10.0	9.20	0.07	0.016	1.90	
MAR M-246 (Hf Modified)	Directionally Solidified	DE-002	0.14	<0.05	0.01		0.002	8.91	Bal	2.27	5.74	1.61	<0.05	0.07		1.70	10.88	9.50	0.06	0.014	1.60	
		DE-003	0.14	<0.04	0.01		0.002	8.61	Bal	2.48	5.51	1.72	0.01	0.28		1.40	10.78	9.64	0.052	0.012	1.75	
Inconel 625	Plate	DF-2	0.048	0.01	0.01	0.006	0.004	21.42	Bal	9.0	0.34	0.24	0.01	4.17	3.85		0.01					
Inconel 625	Cast	NX9052A	0.03	0.015	0.04	0.007	0.007	21.73	Bal	8.93	0.26	0.24		2.60	3.55							
Haynes 188	Plate	1880-1-0167	0.08	0.31	0.7	0.01	0.005	22.4	22.1					1.61			Bal	14.05				0.03
Inconel 718	Plate	83148-1	0.04	0.10	0.10	0.01	0.003	18.3	54.0	3.0	0.55	0.97	0.10	17.7	5.3		0.10			0.003		

Table III-3. Specimens Used to Determine the Susceptibility of Various Alloys to Environmental Degradation

Name	Print No.	Figure
Stress-Strain/Modulus Tensile	FML 96311	III-3
Notched Tensile, Variable K_T	FML 96312	III-4
Smooth Tensile	FML 95226M	III-5
Notched Tensile, $K_T = 8$	FML 96462	III-6
Creep-Rupture	FML 96470	III-7
Creep-Rupture	FML 96407	III-8
Constant Strain LCF	FML 95716C	III-9
Load Control LCF	FML 96504	III-10

Mag: 500X

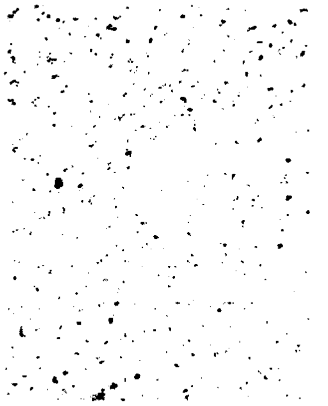
TMP Waspaloy®



Mag: 100X Mag: 500X

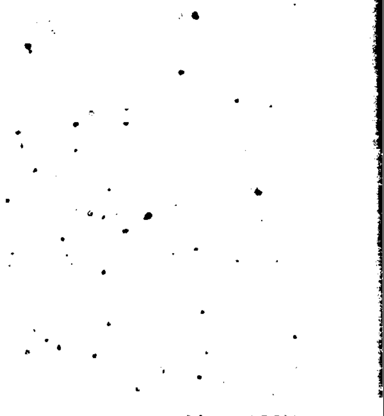
MAR M-246 (HF Modified) CC

MAR



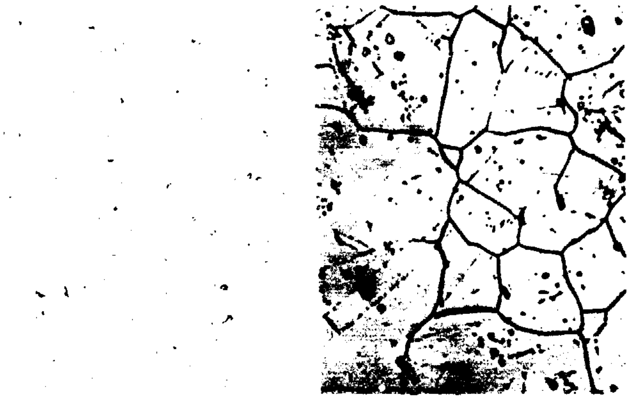
Mag: 100X Mag: 500X

Cast Inconel 625



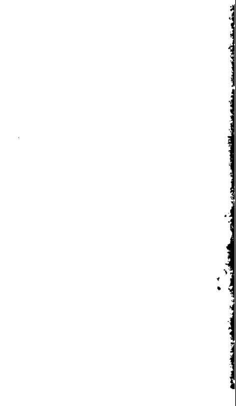
Mag: 100X

Inconel 625 Pla



Mag: 100X Mag: 500X

Haynes 188 (Inconel 718 STA)



Mag: 100X

Inconel 718

Figure III-1. Typical Microstructure of Materials Used to Determine the Susceptibility of Various Alloys to En Degradation (Magnifications indicated are prior to a 50% reduction for printing purposes)

FOLDOUT FRAME /

X

(HF Modified) CC

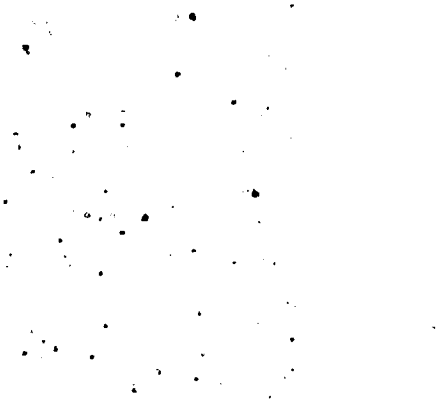
Mag: 500X

Mag: 75X

Mag: 500X

MAR M-246 (HF Modified) DS

500X



Mag: 100X

Mag: 500X

Inconel 625 Plate

500X

Mag: 100X

Mag: 500X

Inconel 718

Determine the Susceptibility of Various Alloys to Environmental
to a 50% reduction for printing purposes)

FOLDOUT FRAME 2

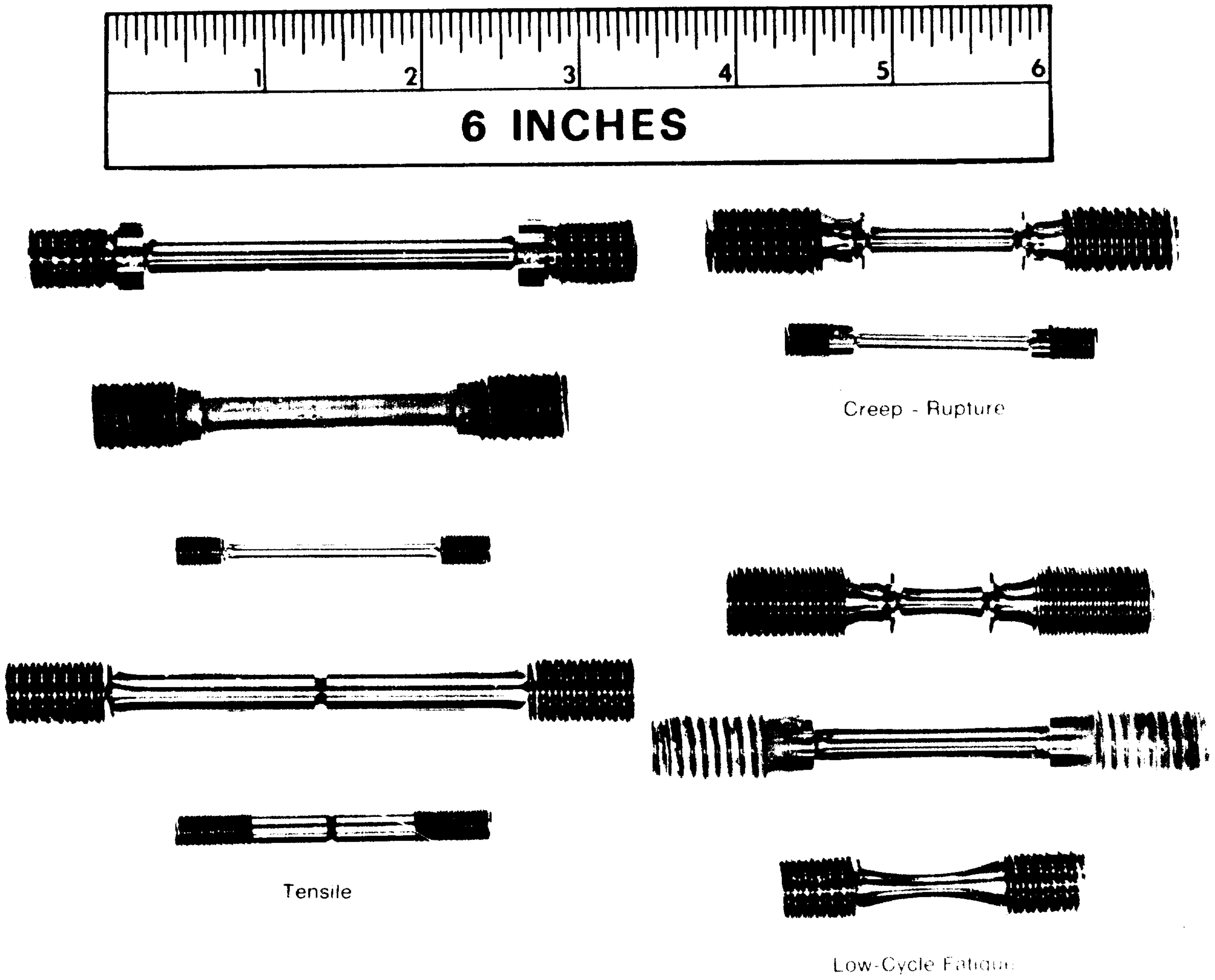


Figure III-2 Typical Test Specimens Used to Determine the Effect of High-Pressure Gaseous Environments on Mechanical Properties of Materials

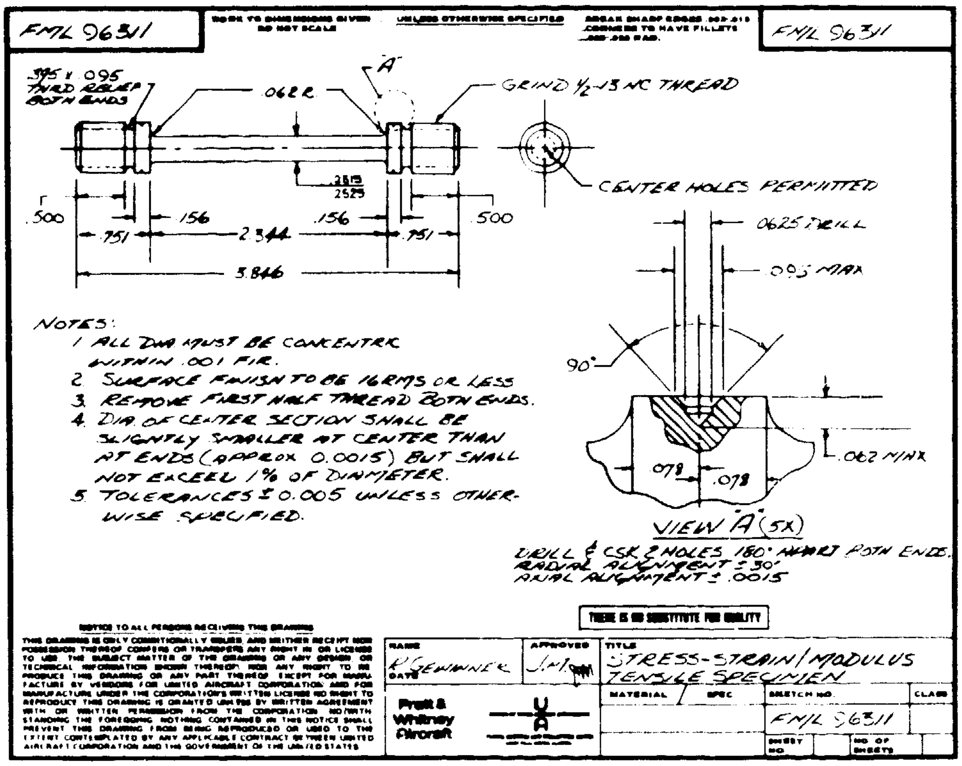


Figure III-3. Stress-Strain/Modulus Tensile Specimen

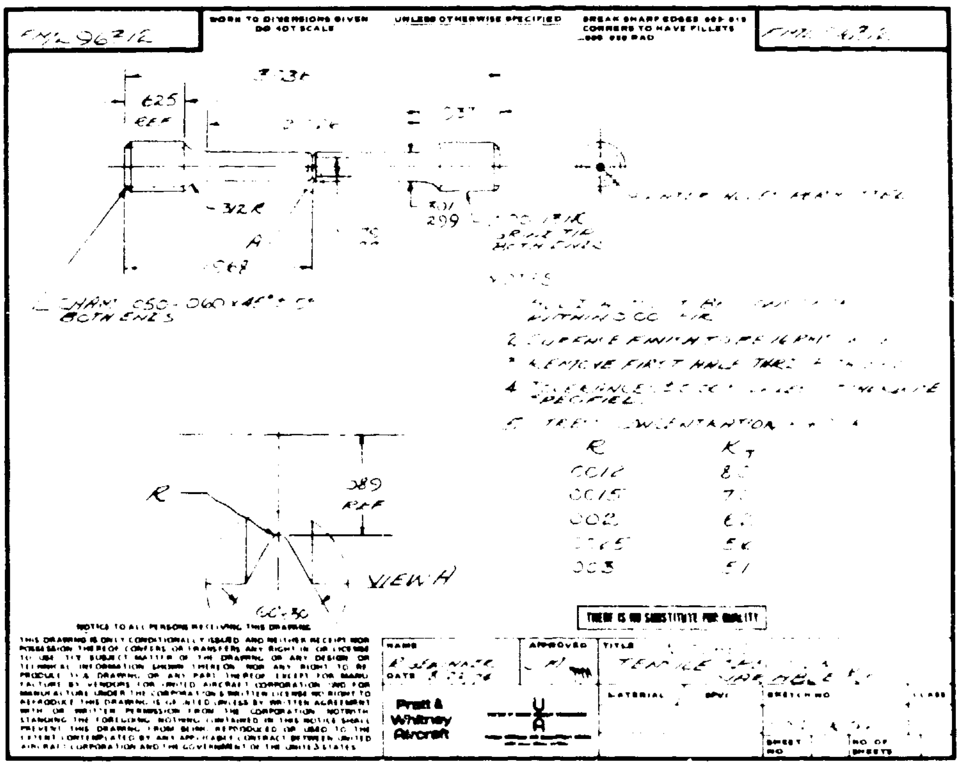


Figure III-4. Notched Tensile Specimen

ORIGINAL PAGE IS
OF POOR QUALITY

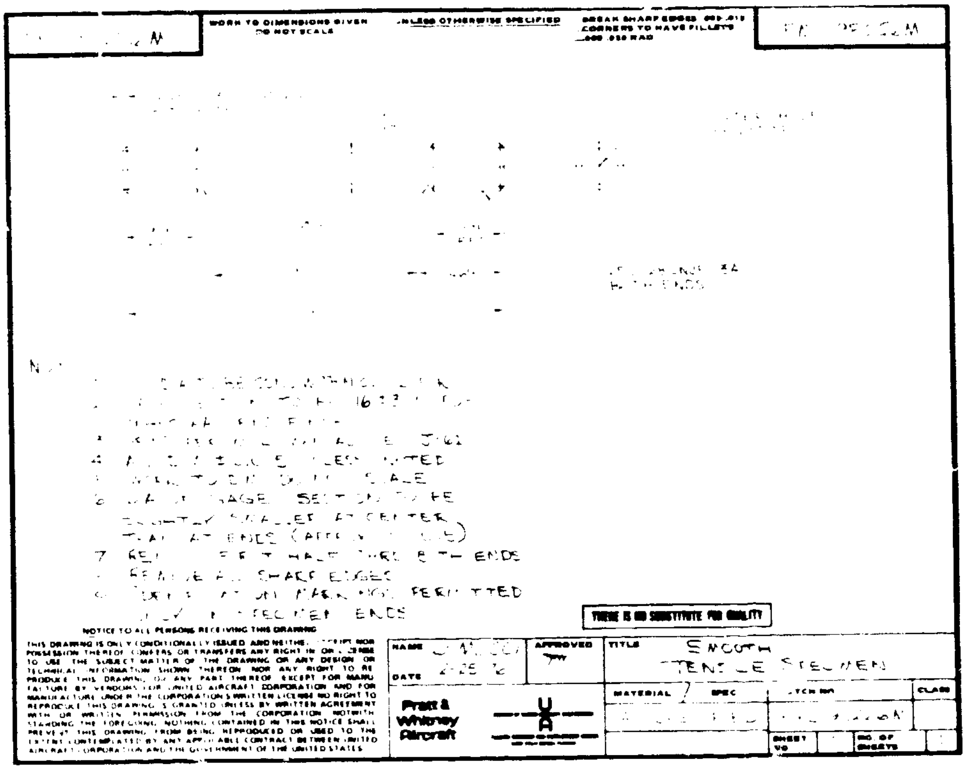


Figure III-5. Smooth Tensile Specimen

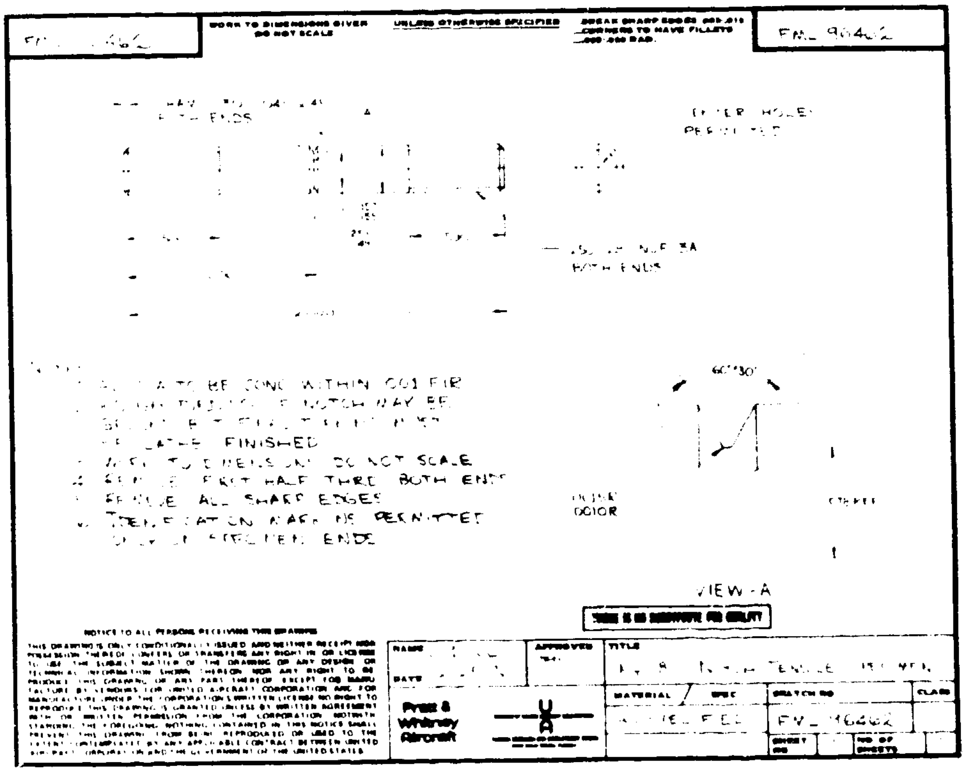
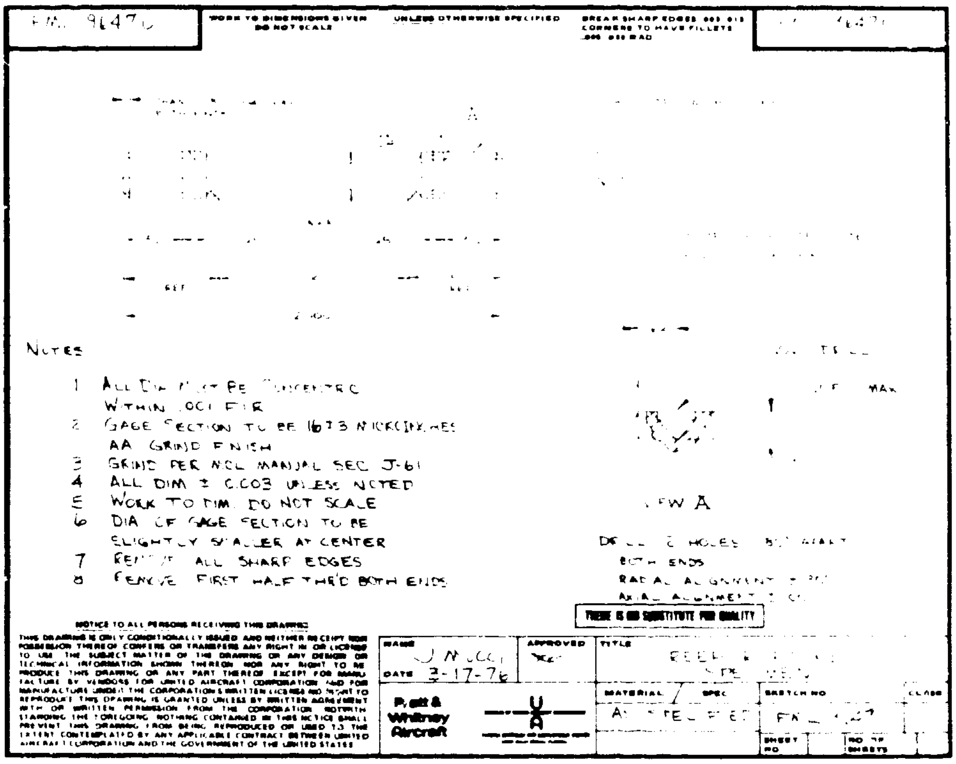


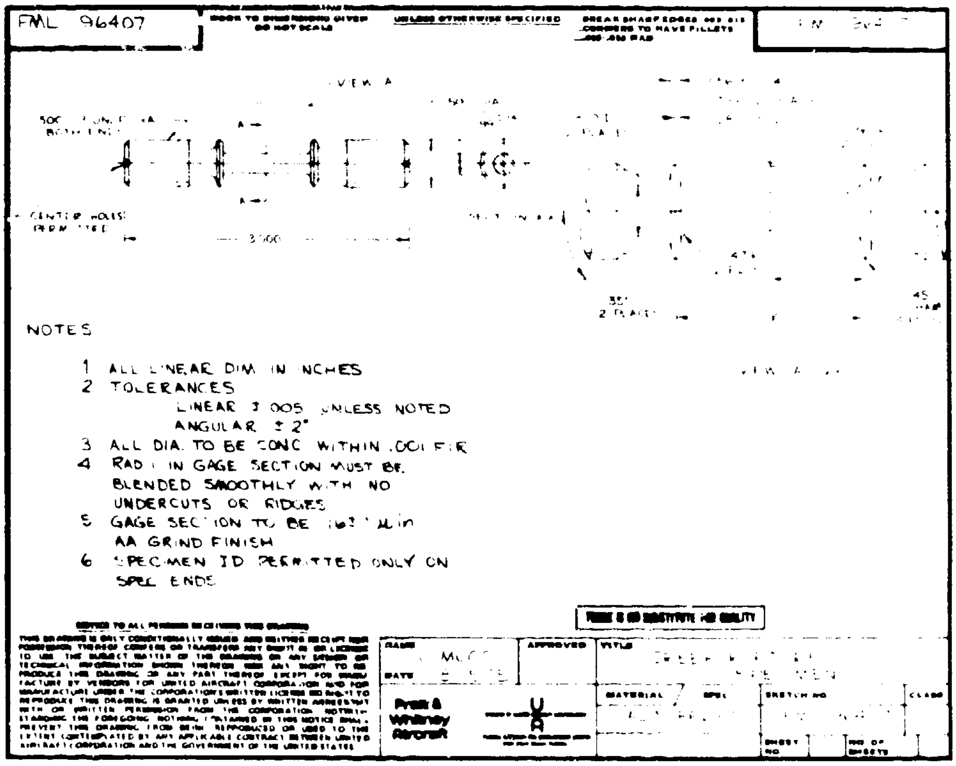
Figure III-6. Notched Tensile Specimen



NOTES

1 ALL DIA MUST BE CONCENTRIC WITHIN .001 FIR
2 GAGE SECTION TO BE 16 ± 3 MICROINCHES AA GRIND FINISH
3 GRIND PER MCL MANUAL SEC J-61
4 ALL DIM ± 0.003 UNLESS NOTED
5 WORK TO DIM. DO NOT SCALE
6 DIA OF GAGE SECTION TO BE SLIGHTLY SMALLER AT CENTER
7 REMOVE ALL SHARP EDGES
8 REMOVE FIRST HALF THR'D BOTH ENDS

Figure III-7. Creep-Rupture Specimen



NOTES

1 ALL LINEAR DIM IN INCHES
2 TOLERANCES
LINEAR ±.005 UNLESS NOTED
ANGULAR ± 2°
3 ALL DIA. TO BE CONC WITHIN .001 FIR
4 RADII IN GAGE SECTION MUST BE BLENDED SMOOTHLY WITH NO UNDERCUTS OR RIDGES
5 GAGE SECTION TO BE 16±3 μin AA GRIND FINISH
6 SPECIMEN ID PERMITTED ONLY ON SPEC ENDS

Figure III-8. Creep-Rupture Specimen

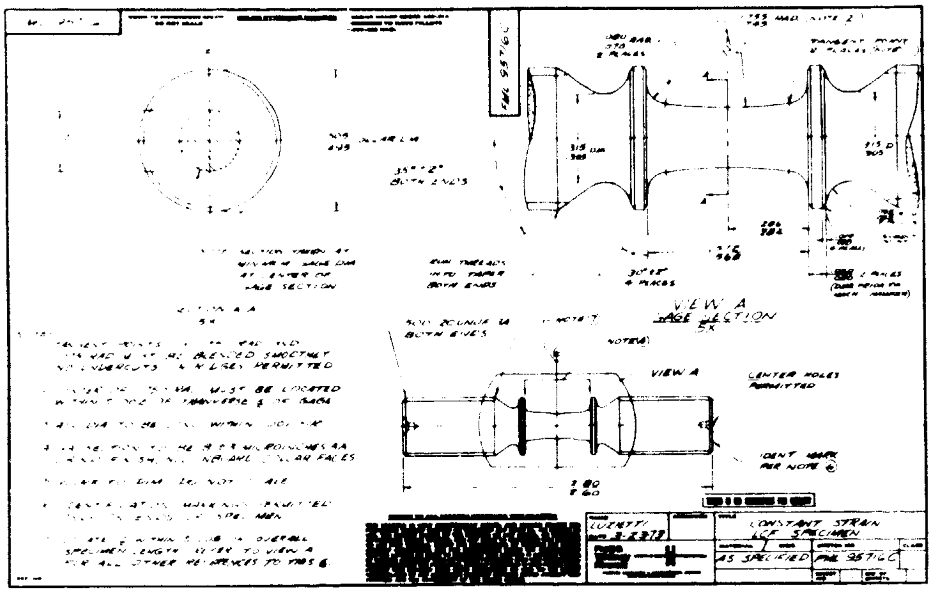


Figure III-9. Constant Strain Low-Cycle Fatigue Specimen

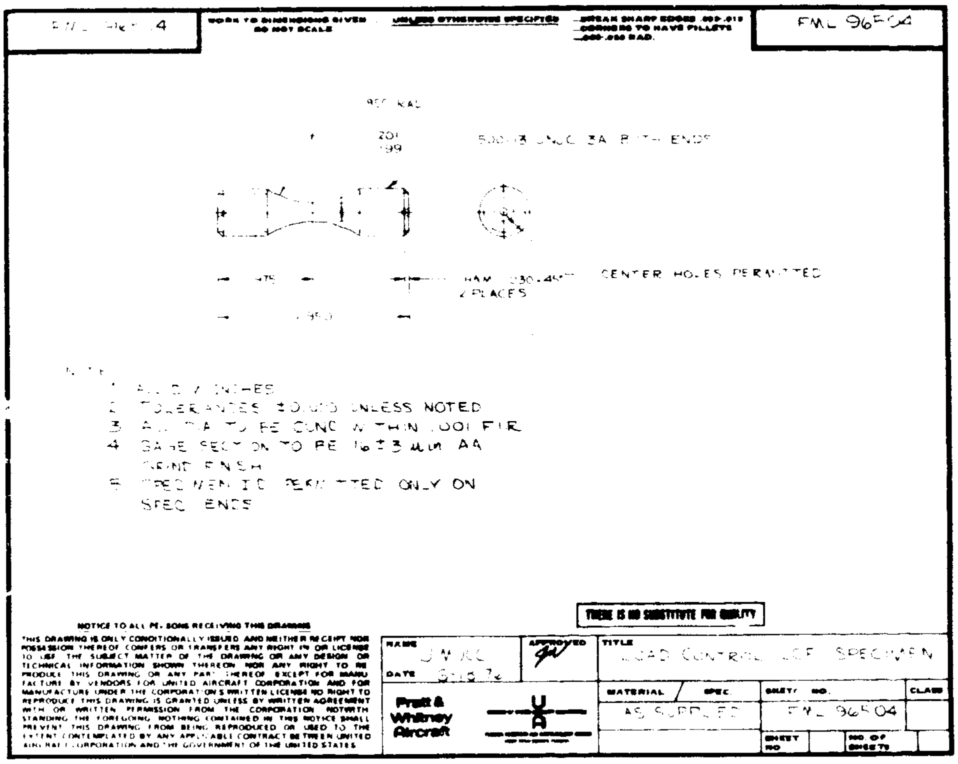


Figure III-10. Load-Control Low-Cycle Fatigue Specimens

ORIGINAL PAGE IS
OF POOR QUALITY

SECTION IV
TENSILE PROPERTIES

A. INTRODUCTION

The smooth tensile properties of six nickel-base alloys and one cobalt-base alloy were investigated in 34.5 MN/m² (5000 psig) helium and hydrogen at temperatures of 297°K (75°F) to 1088°K (1500°F) under Exhibit B of this contract. Tensile tests established stress-strain parameters, 0.2% yield and ultimate strengths, elongation, reduction of area, and modulus of elasticity. Results of tests in hydrogen were compared to those in helium to determine property degradation.

In the Exhibit C effort, tensile properties of the nickel-base alloy MAR M-246 (Hf Modified), in two cast conditions, directionally solidified (DS) and conventionally cast (CC), were determined in ambient temperature and pressure air for helium and hydrogen exposed (34.5 MN/m² [5000 psig] at 1144°K [1600°F] for 8 hours) specimens to determine the materials susceptibility to internal hydrogen embrittlement (IHE). Testing was conducted both immediately after exposure and 24 hours later to determine the extent of material internal hydrogen charging and possible property degradation. Smooth tensile tests established 0.2% yield and ultimate strengths, elongation, reduction of area, and modulus of elasticity. Notched ($K_T = 8.0$) tests established the ultimate strength.

B. RESULTS AND CONCLUSIONS

The tensile test data were subjected to a statistical analysis to determine if the measured mechanical properties of the various alloys reflected true environmental degradation or simply data scatter. The results of these analyses were used as the basis for the conclusions herein. In some cases, the experimental test matrix did not have sufficient tests to enable determination of degradation on a statistical basis. This does not mean that there was no degradation; only that it could not be established from a statistical approach.

1. Exhibit B Tensile

The individual tensile properties (0.2% yield and ultimate strengths, elongation and reduction of area) of the alloys tested did not reflect the influence of hydrogen environment to the same degree. The relative degree of environment degradation is summarized in table IV-1. None of the alloys tested exhibited degradation in the 0.2% yield strength. Differences in yield strengths obtained in the two environments did occur. However, with the limited number of tests conducted, one in helium and three in hydrogen for each test condition per alloy, normal specimen-to-specimen scatter, especially for the cast materials, precludes drawing any firm conclusions when the property differences were less than 10%.

The effects of temperature and environment upon the tensile properties of the one cobalt-base alloy, Haynes 188, and six nickel-base alloys are shown in figures IV-1 through IV-7. The mean values for three tests conducted in hydrogen environment at each temperature are plotted.

Degradation in ultimate strength for the wrought materials - TMP WASPALOY®, Haynes 188 (Inconel 718 STA) and Inconel 718 - over the temperature range investigated was less than 10% with the exception of the Haynes 188 at 297°K (75°F) where degradation of 19.7% was indicated (figure IV-8). For the CC and DS MAR M-246 (Hf Modified), and the plate and cast Inconel 625 materials, ultimate strength degradation of less than 25% over the temperature ranges investigated was indicated. Degradation vs temperature curves for the MAR M-246 and Inconel 625 materials are shown in figures IV-9 and IV-10, respectively.

Table IV-1. Degradation of Smooth Tensile Properties of Various Alloys in 34.5 MN/m^2 (5000 psig) Hydrogen

Material	Form	Temperature °K	Temperature °F	Degradation (Decrease from Helium, %) Strength 0.2% Yield	Degradation (Decrease from Helium, %) Strength Ultimate	Degradation (Decrease from Helium, %) Ductility EL	Degradation (Decrease from Helium, %) Ductility RA	Ratio of Ultimate Strength H_2/He
TMP WASPALOY®	Forged	297	75	ND	ND	27.5	59.0	0.97
		589	600	ND	ND	14.3	67.9	0.91
		755	900	ND	ND	36.5	50.1	0.95
		922	1200	ND	ND	19.7	45.1	0.98
MAR M-246 (Hf Modified)	Conventionally Cast (CC)	297	75	ND	15.4	63.3	39.1	0.85
		755	900	ND	ND	64.3	54.6	0.91
		922	1200	ND	ND	ND	38.7	1.05
		1088	1500	ND	ND	54.2	38.7	0.96
MAR M-246 (Hf Modified)	Directionally Solidified (DS)	297	75	ND	13.8	83.3	59.7	0.86
		755	900	ND	12.5	43.3	31.8	0.87
		922	1200	ND	ND	44.4	58.1	0.99
		1088	1500	ND	ND	46.7	42.6	0.95
Inconel 625	Plate	297	75	ND	ND	ND	13.1	0.94
		589	600	ND	ND	ND	ND	0.97
		755	900	ND	ND	ND	ND	0.94
		922	1200	ND	ND	ND	ND	0.98
Inconel 625	Cast	297	75	ND	22.1	32.5	11.6	0.78
		589	600	ND	10.7	ND	ND	0.89
		755	900	ND	ND	ND	ND	0.98
		922	1200	ND	ND	ND	ND	0.96
Haynes 188 (Inconel 718 STA)	Plate	297	75	ND	19.7	62.8	39.7	0.80
		589	600	ND	ND	26.3	25.3	0.93
		755	900	ND	ND	ND	ND	0.99
		922	1200	ND	ND	ND	ND	0.94
Inconel 718	Plate	297	75	ND	ND	ND	18.8	0.99
		589	600	ND	ND	53.5	58.8	0.97
		755	900	ND	ND	19.3	43.8	0.99
		922	1200	ND	ND	ND	11.9	0.99

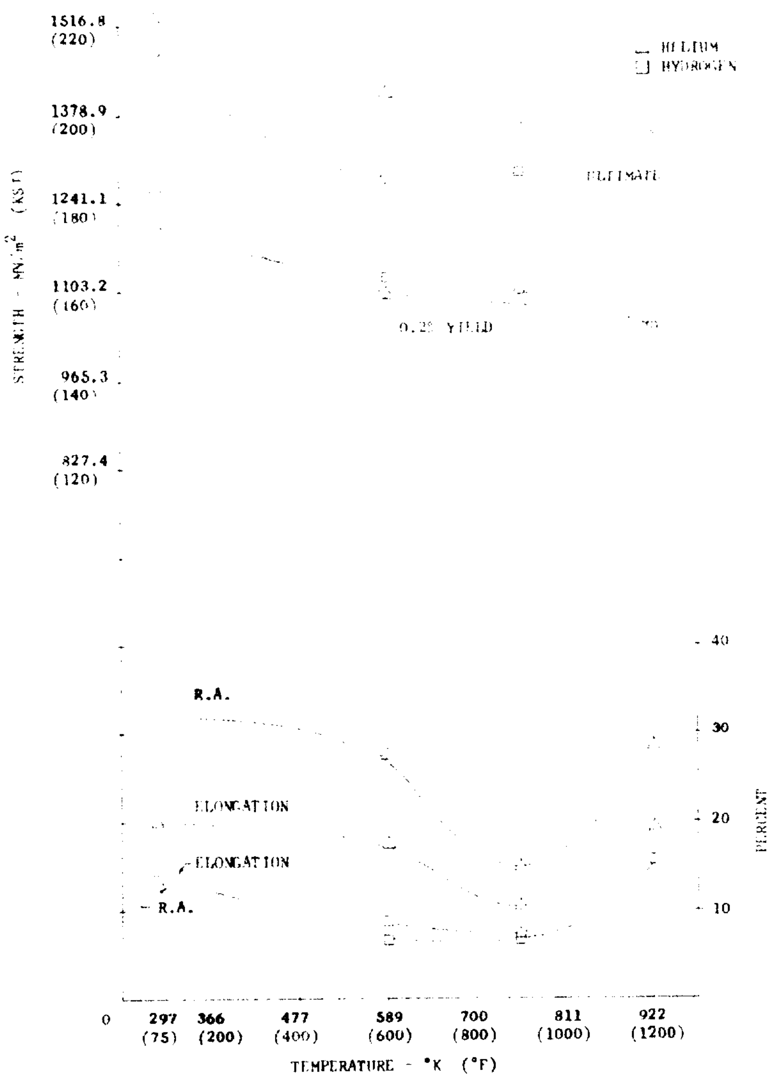


Figure IV-1. Effect of Temperature and Environment on the Tensile Properties of Forged TMP WASPALOY® at 34.5 MN/m² (5000 psig)

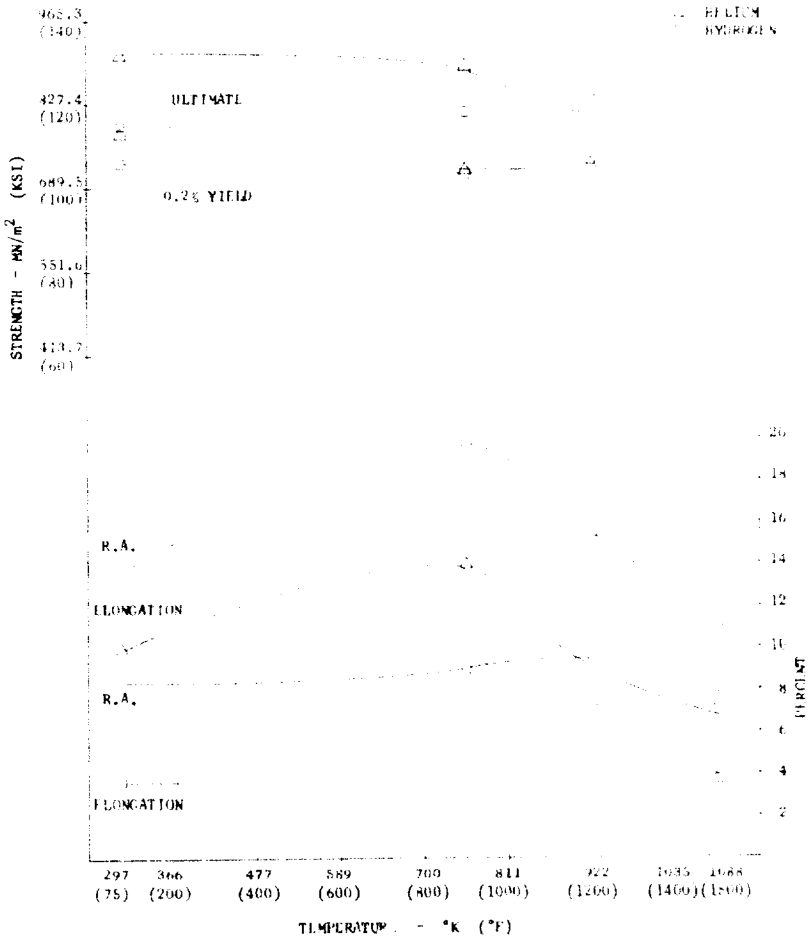


Figure IV-2. Effect of Temperature and Environment on the Tensile Properties of Conventionally Cast (CC) MAR M-246 (Hf Modified) at 34.5 MN/m² (5000 psig)

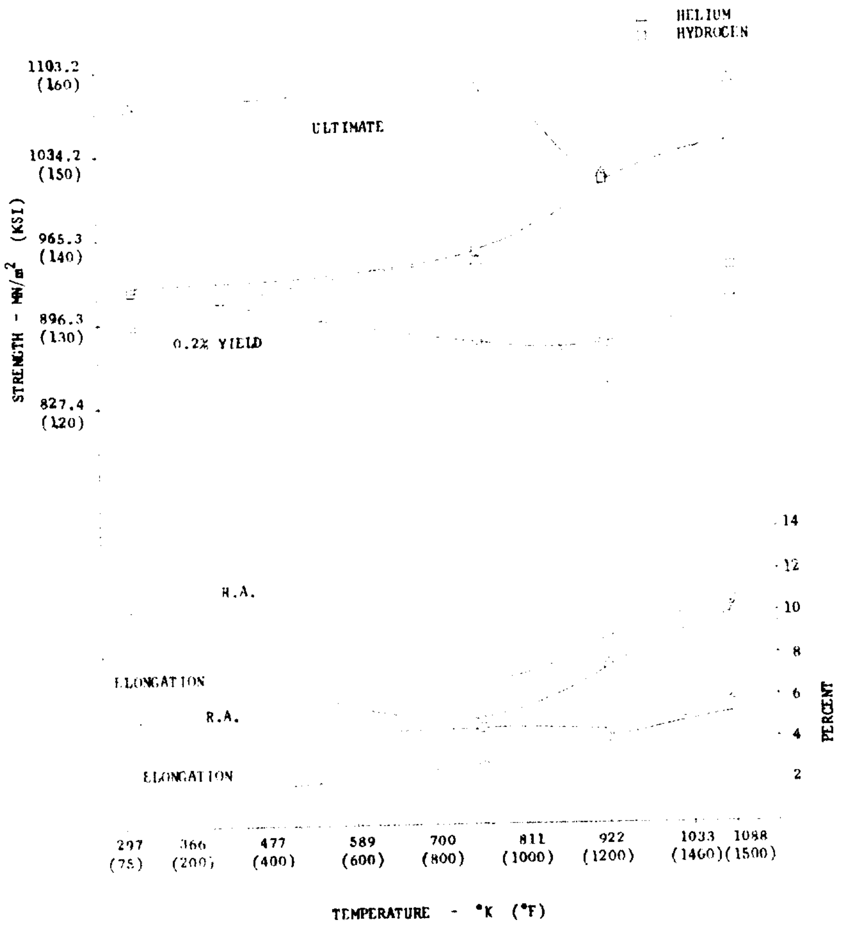


Figure IV-3. *Effect of Temperature and Environment on the Tensile Properties of Directionally Solidified (DS) MAR M-246 (Hf Modified) at 34.5 MN/m² (5000 psig)*

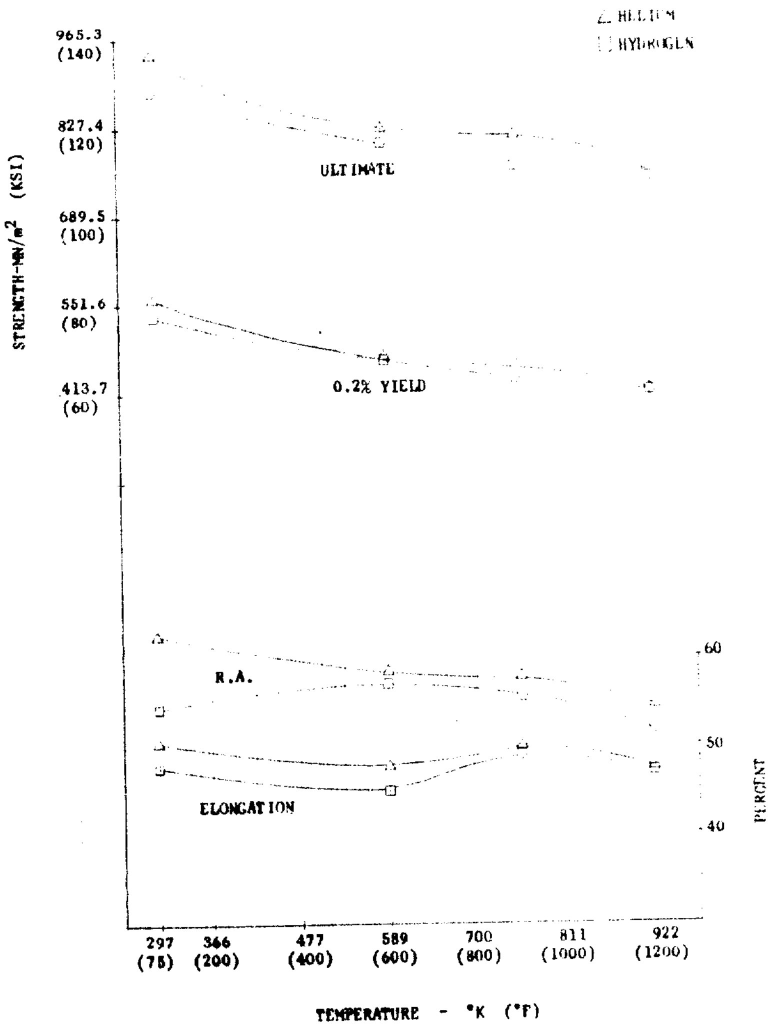


Figure IV-4. *Effect of Temperature and Environment on the Tensile Properties of Inconel 625 Plate at 34.5 MN/m² (5000 psig)*

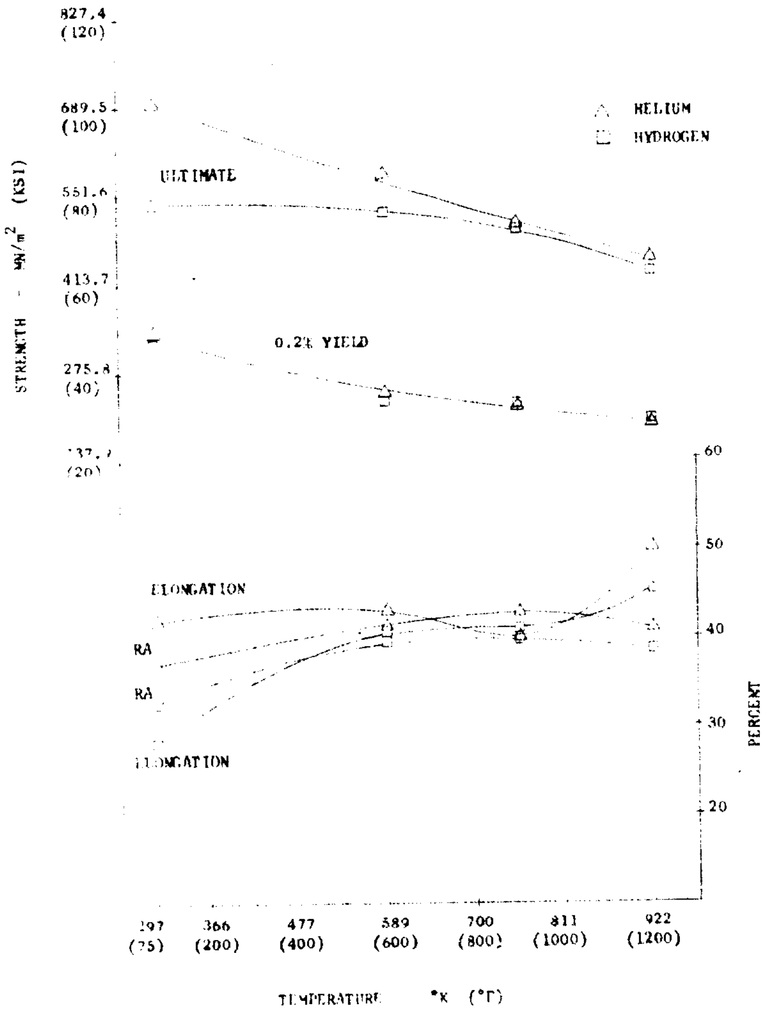


Figure IV-5. *Effect of Temperature and Environment on the Tensile Properties of Cast Inconel 625 at 34.5 MN/m² (5000 psig)*

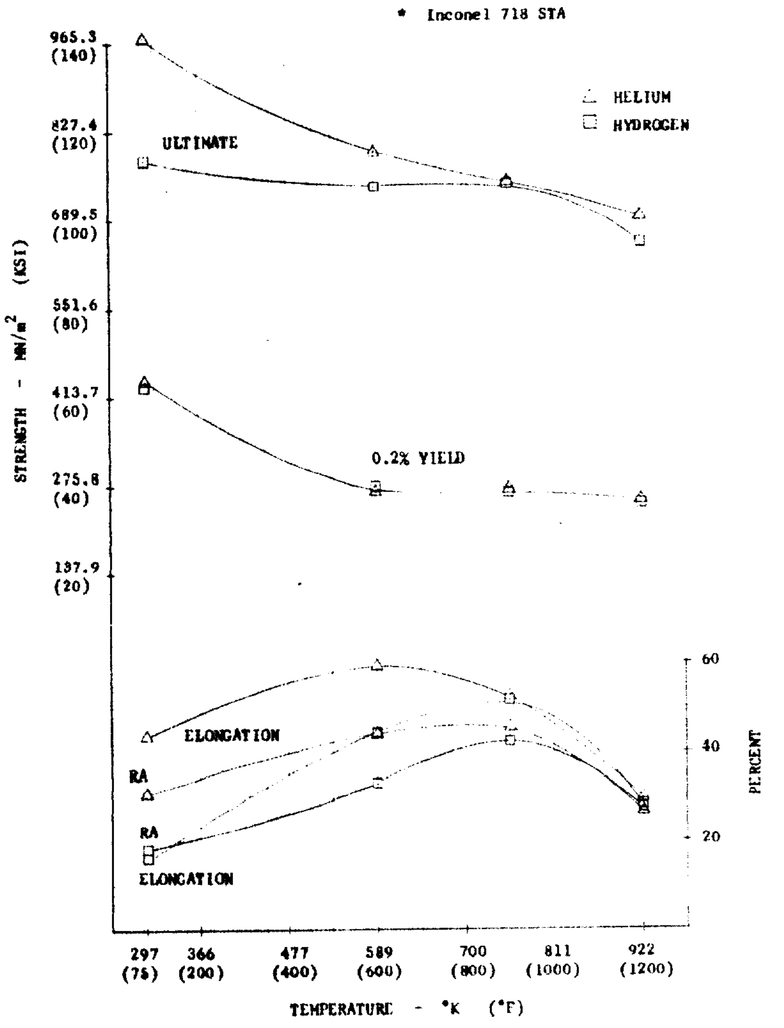


Figure IV-6. *Effect of Temperature and Environment on the Tensile Properties of Haynes 188 Plate, With Inconel 718 STA Heat Treatment, at 34.5 MN/m² (5000 psig)*

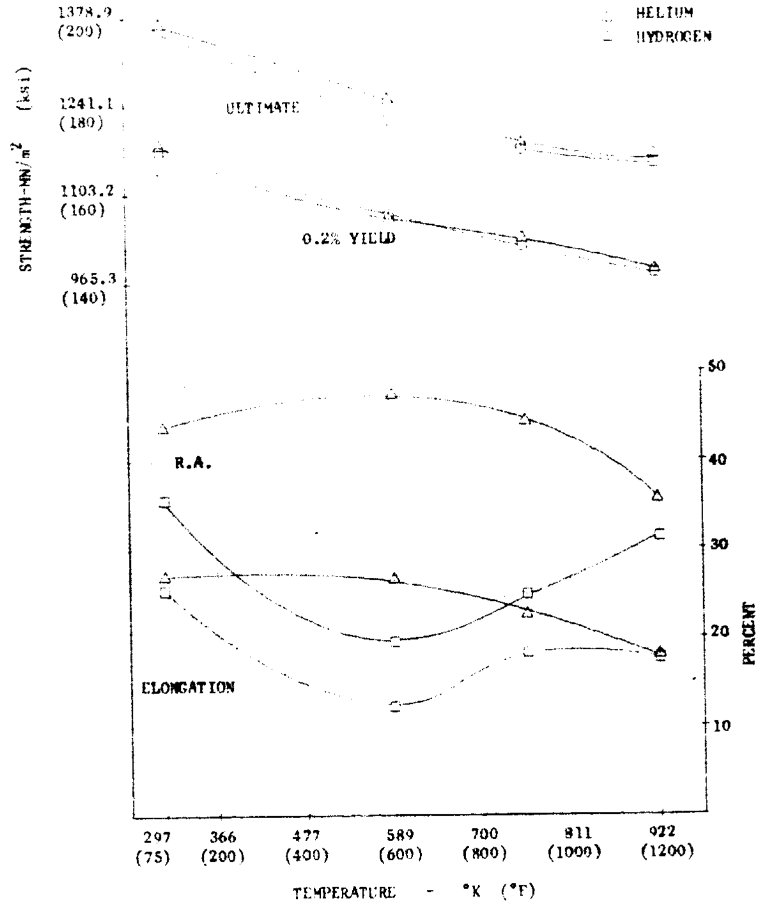
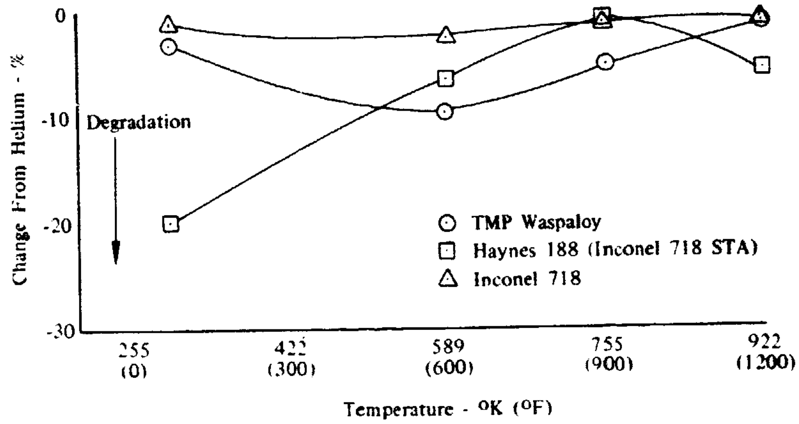
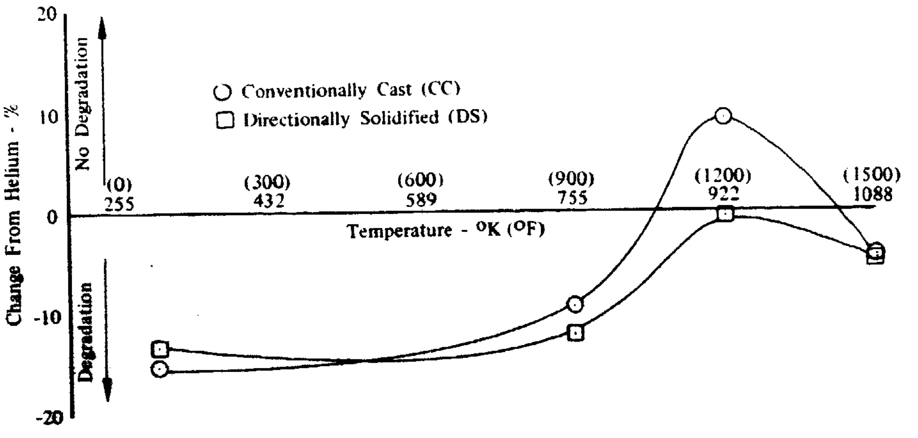


Figure IV-7. Effect of Temperature and Environment on the Tensile Properties of Inconel 718 Plate at 34.5 MN/m² (5000 psig)



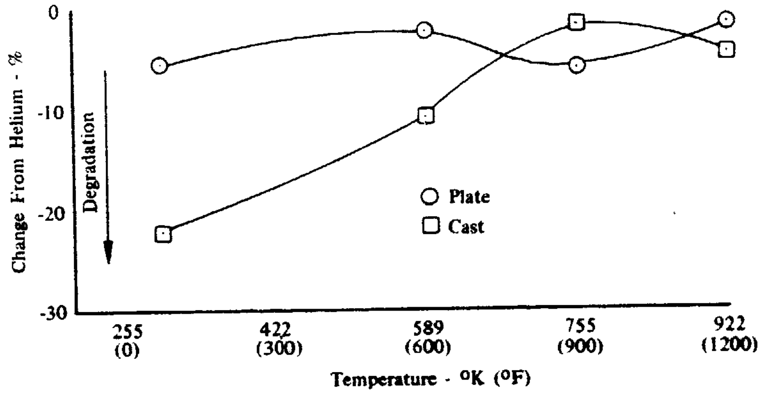
DF [illegible]

Figure IV-8. Effect of Temperature Upon Environmental Degradation of TMP WASPALOY®, Haynes 188 (Inconel 718 STA) and Inconel 718 Tensile Ultimate Strength



DF 102385

Figure IV-9. Effect of Temperature Upon Environmental Degradation of MAR M-246 (Hf Modified) Tensile Ultimate Strength



DF 102386

Figure IV-10. Effect of Temperature Upon Environmental Degradation of Inconel 625 Tensile Ultimate Strength

As previously reported in PWA FR-5768[1], FR-6709[2] and FR-7175[3], loss of ductility (elongation and/or reduction of area) was the most prominent indicator of hydrogen degradation. In the case of some alloys, ductility was extremely degraded, while the ultimate strength showed negligible degradation, if any. The elongation and reduction of area were degraded for most of the alloys, with the Inconel 625 (both cast and plate conditions) the alloy least degraded by the hydrogen environment. With the exception of elongation at 297°K (75°F) for the cast material, degradation in ductility of less than 15% up to 922°K (1200°F) was indicated for the Inconel 625 alloy (figure IV-11).

For the wrought alloys, TMP WASPALOY, Hyanes 188 and Inconel 718, degradation in ductility up to approximately 70% was indicated. Elongation and reduction of area degradation vs temperature curves are shown in figures IV-12 and IV-13.

With all test temperatures considered for a given material, the alloy most severely degraded in ductility was the MAR M-246 (Hf Modified). For both the CC and DS material forms, degradation generally ranged from 30 to 70% for the temperatures investigated (figure IV-14).

Test results of each specimen tested for the seven alloys are listed in table IV-2.

The effects of temperature upon the stress-strain parameters and modulus of elasticity for the various materials are shown in figures IV-15 through IV-28. Data analyses indicated that stress-strain parameters and modulus of elasticity were not affected by environment (helium or hydrogen). Therefore, for each material, the mean values for all tests conducted at each temperature were plotted. The stress-strain parameters of each individual test for the seven alloys are listed in tables IV-3 through IV-9. In the case of the CC and DS MAR M-246 materials where low ductility occurred (low strain values at failure), not all tests at each temperature were used to plot their respective stress-strain curves. Test data used in plotting the CC and DS material curves for each test temperature are indicated by an underscored specimen number in tables IV-4 and IV-5, respectively.

A comparison of modulus of elasticity for seven alloys over the temperature ranges investigated is illustrated in figure IV-29.

2. Exhibit C Internal Hydrogen Embrittlement (IHE)

This test effort was designed to determine the effect of internal hydrogen charging upon property degradation (IHE) of CC and DS MAR M-246 (Hf Modified), that is, the effect of hydrogen within the material's metal lattice as opposed to external hydrogen environment embrittlement (HEE).

The effect of 8-hour 34.5 MN/m^2 (5000 psig) hydrogen exposure at 1144°K (1600°F) on the ambient air smooth and notched tensile properties is summarized in table IV-10.

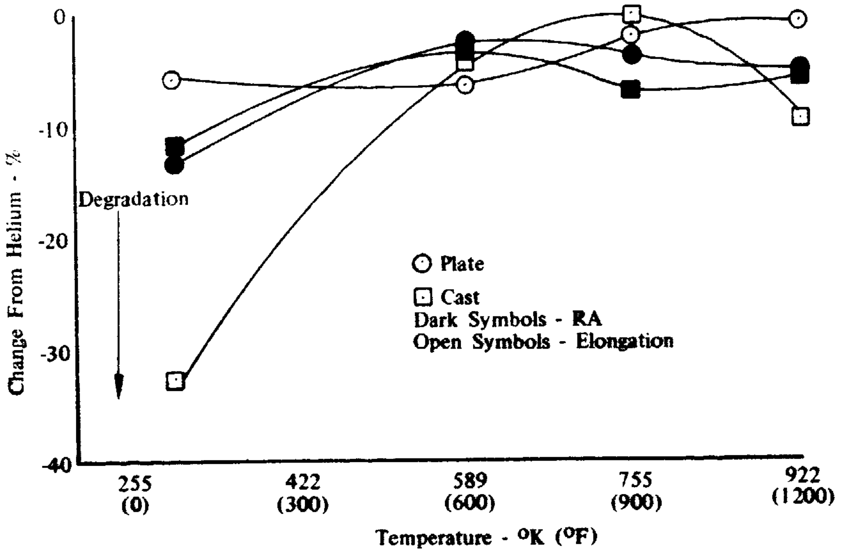
Testing of both the CC and DS materials at 297°K (75°F) indicated considerable degradation in smooth and notched strength and ductility, due to the 8-hour exposure. The effect of air set time on the properties of the hydrogen exposed CC material was minimal, if any.

---

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

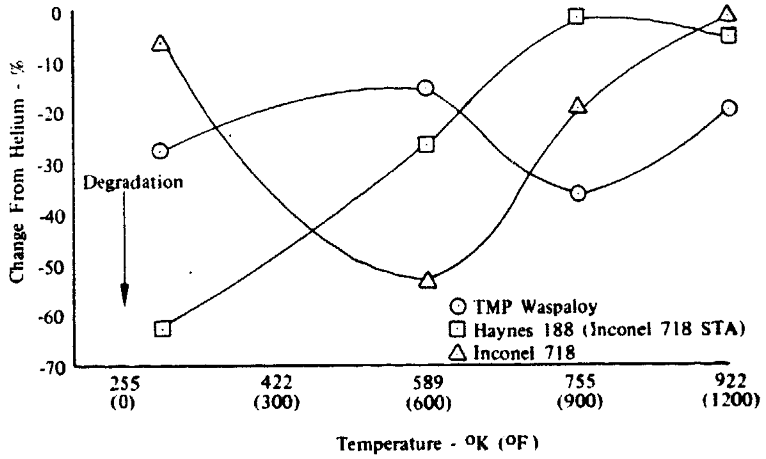
[2] "Influence of Gaseous Hydrogen on the Mechanical Properties of AISI 304 Stainless Steel," Final Report, Contract NAS8-29883.

[3] "Influence of Gaseous Hydrogen on the Mechanical Properties of Incoloy 903," Final Report Exhibit A, Contract NAS8-30744, September 1975.



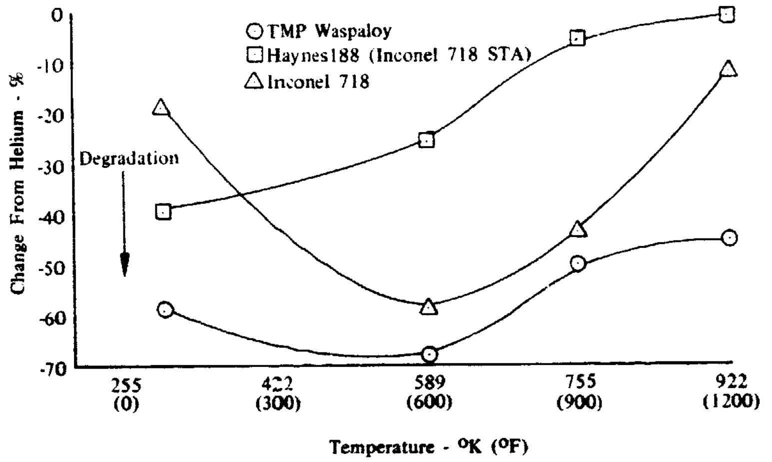
DF 102387

Figure IV-11. Effect of Temperature Upon Environmental Degradation of Inconel 625 Tensile Ductility



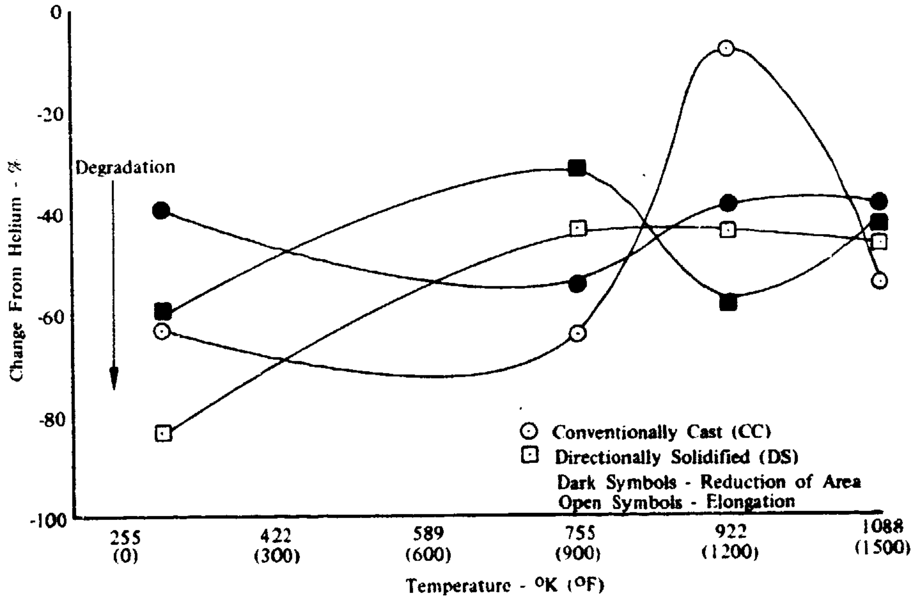
DF 102388

Figure IV-12. Effect of Temperature Upon Environmental Degradation of TMP WASPALOY, Haynes 188 (Inconel 718 STA) and Inconel 718 Tensile Elongation



DF 102389

Figure IV-13. Effect of Temperature Upon Environmental Degradation of TMP WASPALOY, Haynes 188 (Inconel 718 STA) and Inconel 718 Tensile Reduction of Area



DF 102390

Figure IV-14. Effect of Temperature Upon Environmental Degradation of MAR M-246 (Hf Modified) Tensile Ductility

ORIGINAL PAGE IS
OF POOR QUALITY

OUT FRAM /

Table IV-2. Tensile Properties of Various Alloys in 34.5 MN/m² (5000 psig) Gaseous Environments

			Test Conditions			Test Results						
			Test Temperature			Strength				Ductility		Modulus of Elasticity
						0.2% Yield		Ultimate		EL[5]	RA	
Material	Form	Spec S/N	°K	°F	Environment	MN/m²	ksi	MN/m²	ksi	%	%	psi×10⁶
TMP WASPALOY®	Forged	WF1	297	75	Helium	1266.6	183.9	1530.6	222.0	20.0	32.1	30.1
		WF2	297	75	Hydrogen	1126.6	163.4	1431.3	207.6	13.5	12.6	[1]29.2
		WF3	297	75	Hydrogen	1232.1	178.7	1517.5	220.1	15.0	13.1	[1]29.3
		WF17	297	75	Hydrogen	1181.1	171.3	1492.0	216.4	15.0	13.8	[1]29.4
		WF5	589	600	Helium	1097.6	159.2	1412.7	204.9	17.5	27.6	28.3
		WF6	589	600	Hydrogen	1161.1	168.4	1370.7	198.8	10.0	9.0	[1]28.2
		WF7	589	600	Hydrogen	1161.1	168.4	1277.6	185.3	5.0	9.7	[1]28.3
		WF8	589	600	Hydrogen	1052.8	152.7	1188.0	172.3	5.0	7.9	[1]28.0
		WF9	755	900	Helium	1088.7	157.9	1359.6	197.2	10.5	14.9	[1]27.0
		WF10	755	900	Hydrogen	1130.7	164.0	1320.3	191.5	7.5	7.9	[1]26.5
		WF11	755	900	Hydrogen	1092.1	158.4	1281.7	185.9	6.5	6.6	[1]26.7
		WF12	755	900	Hydrogen	1095.6	158.9	1270.7	184.3	6.0	7.8	[1]27.0
		WF13	922	1200	Helium	1050.1	152.3	1340.3	194.4	19.5	28.7	24.5
		WF14	922	1200	Hydrogen	1053.5	152.8	1334.1	193.5	17.0	16.1	24.0
		WF15	922	1200	Hydrogen	1065.2	154.5	1365.2	198.0	11.0	11.6	24.2
		WF16	922	1200	Hydrogen	1017.0	147.5	1252.1	181.6	19.0	19.6	24.0
MAR M-246 Hf Modified)	Conventionally Cast (CC)	MC4	297	75	Helium	779.1	113.0	908.0	131.7	10.0	13.9	27.3
		MC2	297	75	Hydrogen	762.6	110.6	790.1	114.6	3.0	9.3	25.1
		MC3	297	75	Hydrogen	726.7	105.4	769.5	111.6	4.0	11.0	25.6
		MC1	297	75	Hydrogen	700.5	101.6	745.3	108.1	4.0	5.0	25.3
		MC5	755	900	Helium	717.7	104.1	888.7	128.9	14.0	19.9	23.9
		MC6	755	900	Hydrogen	744.6	108.0	817.0	118.5	4.0	11.2	22.4
		MC7	755	900	Hydrogen	659.8	95.7	786.0	114.0	5.0	9.4	23.2
		MC8	755	900	Hydrogen	752.9	109.2	828.7	120.2	6.0	6.5	21.0
		MC9	922	1200	Helium	728.1	105.6	807.4	117.1	8.0	15.5	18.2
		MC10	922	1200	Hydrogen	726.0	105.3	866.0	125.6	6.0	8.0	20.4
		MC11	922	1200	Hydrogen	759.8	110.2	908.0	131.7	6.0	6.5	22.4
		MC12	922	1200	Hydrogen	706.7	102.5	874.3	126.8	10.0	14.0	21.7
		MC13	1088	1500	Helium	728.8	105.7	874.3	126.8	8.0	11.2	[1]19.2
		MC14	1088	1500	Hydrogen	728.8	105.7	801.9	116.3	3.0	6.3	18.2
		MC15	1088	1500	Hydrogen	776.3	112.6	795.7	115.4	3.0	6.3	21.0
		MC16	1088	1500	Hydrogen	770.8	111.8	919.1	133.3	5.0	8.0	19.7
MAR M-246 (Hf Modified)	Directionally Solidified Cast (DS)	MD1	297	75	Helium	895.6	129.9	1072.8	155.6	10.0	12.4	[1]18.3
		MD2	297	75	Hydrogen	939.1	136.2	939.1	136.2	2.0	4.7	[1]17.7
		MD3	297	75	Hydrogen	(2)	(2)	890.8	129.2	1.0	4.0	[1]17.6
		MD4	297	75	Hydrogen	939.1	136.2	944.6	137.0	2.0	6.3	[1]17.3
		MD5	755	900	Helium	947.3	137.4	1086.6	157.6	5.0	6.7	[1]16.0
		MD6	755	900	Hydrogen	897.7	130.2	982.5	142.5	3.5	5.0	16.4
		MD7	755	900	Hydrogen	908.7	131.8	985.9	143.0	2.5	4.7	[1]16.3
		MD8	755	900	Hydrogen	835.0	122.1	881.1	127.8	2.5	4.0	16.2
		MD9	922	1200	Helium	835.0	122.1	1015.6	147.2	7.5	8.9	14.9
		MD10	922	1200	Hydrogen	874.9	126.9	14.2	147.1	4.5	4.7	[1]14.4
		MD11	922	1200	Hydrogen	868.7	126.0	954.2	138.4	3.5	3.6	14.3
		MD12	922	1200	Hydrogen	888.0	128.8	1063.2	154.2	4.5	2.9	[1]14.5
		MD13	1088	1500	Helium	917.7	133.1	1092.1	158.4	10.0	10.4	12.9
		MD14	1088	1500	Hydrogen	986.6	143.1	1023.9	148.5	4.5	5.0	12.9
		MD15	1088	1500	Hydrogen	922.5	133.8	1048.7	152.1	5.5	5.9	13.5
		MD16	1808	1500	Hydrogen	908.0	131.7	1050.1	152.3	6.0	7.0	13.3
Inconel 625	Plate	5P1	297	75	Helium	561.2	81.4	940.4	136.4	50.5	62.5	28.5
		5P2	297	75	Hydrogen	541.9	78.6	895.6	129.9	46.5	58.1	28.4
		5P3	297	75	Hydrogen	525.4	76.2	877.7	127.3	50.0	52.9	27.8
		5P4	297	75	Hydrogen	543.3	78.8	888.7	128.9	47.0	52.0	28.1
		5P5	589	600	Helium	472.3	68.5	826.0	119.8	48.0	58.5	27.0
		5P6	589	600	Hydrogen	458.5	66.5	794.3	115.2	46.5	58.1	26.3
		5P7	589	600	Hydrogen	487.5	70.7	821.9	119.2	42.0	55.8	27.5
		5P8	589	600	Hydrogen	448.8	65.1	798.4	115.8	46.5	57.7	26.4
		5P9	755	900	Helium	431.6	62.6	815.0	118.2	50.0	57.8	[1]26.2
		5P10	755	900	Hydrogen	475.0	68.9	774.3	112.3	49.5	54.7	25.0
		5P11	755	900	Hydrogen	444.7	64.5	759.8	110.2	49.5	56.1	25.8
		5P12	755	900	Hydrogen	450.9	65.4	760.5	110.3	48.0	55.9	25.6
		5P13	922	1200	Helium	415.1	60.2	760.5	110.3	47.5	54.4	22.9

Inconel 625	Plate	5P1	297	75	Helium	561.2	81.4	940.4	136.4	50.5	62.5	28.5
		5P2	297	75	Hydrogen	541.9	78.6	895.6	129.9	46.5	58.1	28.4
		5P3	297	75	Hydrogen	525.4	76.2	877.7	127.3	50.0	52.9	27.8
		5P4	297	75	Hydrogen	543.3	78.8	888.7	128.9	47.0	52.0	28.1
		5P5	589	600	Helium	472.3	68.5	826.0	119.8	48.0	58.5	27.0
		5P6	589	600	Hydrogen	458.5	66.5	794.3	115.2	46.5	58.1	26.3
		5P7	589	600	Hydrogen	487.5	70.7	821.9	119.2	42.0	55.8	27.5
		5P8	589	600	Hydrogen	448.8	65.1	798.4	115.8	46.5	57.7	26.4
		5P9	755	900	Helium	431.6	62.6	815.0	118.2	50.0	57.8	[1]26.2
		5P10	755	900	Hydrogen	475.0	68.9	774.3	112.3	49.5	54.7	25.0
		5P11	755	900	Hydrogen	444.7	64.5	759.8	110.2	49.5	56.1	25.8
		5P12	755	900	Hydrogen	450.9	65.4	760.5	110.3	48.0	55.9	25.6
		5P13	922	1200	Helium	415.1	60.2	760.5	110.3	47.5	54.4	22.9
		5P14	922	1200	Hydrogen	426.1	61.8	749.5	108.7	45.0	49.8	[1]24.4
		5P15	922	1200	Hydrogen	406.8	59.0	746.0	108.2	48.0	53.3	23.1
		5P16	922	1200	Hydrogen	406.8	59.0	742.6	107.7	48.5	52.3	24.1
Inconel 625	Cast	5C1[4]	297	75	Helium	338.5	49.1	695.0	100.8	42.0	37.1	27.5
		5C2	297	75	Hydrogen	312.3	45.3	513.7	74.5	25.0	34.4	25.5
		5C3	297	75	Hydrogen	322.7	46.8	566.1	82.1	29.0	32.2	26.5
		5C4	297	75	Hydrogen	308.9	44.8	544.7	79.0	31.0	31.8	25.7
		5C5	589	600	Helium	244.8	35.5	583.3	84.6	43.0	41.3	24.1
		5C6	589	600	Hydrogen	228.9	33.2	528.8	76.7	42.0	40.3	24.4
		5C7	589	600	Hydrogen	224.1	32.5	521.9	75.7	42.0	40.0	22.9
		5C8	589	600	Hydrogen	231.7	33.6	512.3	74.3	39.5	38.6	24.4
		5C9	755	900	Helium	221.3	32.1	505.4	73.3	40.0	43.0	23.9
		5C10	755	900	Hydrogen	224.8	32.6	519.2	75.3	45.0	42.0	23.8
		5C11	755	900	Hydrogen	230.3	33.4	497.8	72.2	41.0	39.5	25.2
		5C12	755	900	Hydrogen	221.3	32.1	472.3	68.5	37.5	38.3	23.5
		5C13	922	1200	Helium	193.7	28.1	452.3	65.6	50.0	41.0	20.1
		5C14	922	1200	Hydrogen	193.1	28.0	420.6	61.0	50.0	39.3	19.8
		5C15	922	1200	Hydrogen	219.3	31.8	488.1	70.8	43.0	39.8	18.7
		5C16	922	1200	Hydrogen	189.6	27.5	387.5	56.2	42.5	37.1	20.4
Haynes 188 (Inconel 718 STA Heat Treated)	Plate	H81	297	75	Helium	440.6	63.9	974.2	141.3	43.5	30.6	[1]32.0
		H82	297	75	Hydrogen	434.4	63.0	750.8	108.9	16.0	17.5	31.1
		H83	297	75	Hydrogen	433.0	62.8	752.2	109.1	16.5	16.1	[1]30.9
		H84	297	75	Hydrogen	429.5	62.3	842.5	122.2	16.0	21.8	31.1
		H813	589	600	Helium	264.8	38.4	794.3	115.2	59.5	44.2	29.8
		H814	589	600	Hydrogen	273.0	39.6	751.5	109.0	49.5	34.5	28.2
		H815	589	600	Hydrogen	270.3	39.2	728.8	105.7	38.5	30.1	27.5
		H816	589	600	Hydrogen	276.5	40.1	747.4	108.4	43.5	34.5	[1]30.1
		H85	755	900	Helium	269.6	39.1	750.1	108.8	52.5	45.8	26.6
		H86	755	900	Hydrogen	260.6	37.8	749.5	108.7	51.5	41.6	28.1
		H87	755	900	Hydrogen	261.3	37.9	755.7	109.6	51.5	42.2	27.7
		H88	755	900	Hydrogen	261.3	37.9	737.0	106.9	52.5	44.6	[2]
		H89	922	1200	Helium	251.0	36.4	692.2	100.4	29.5	26.8	[1]23.2
		H810	922	1200	Hydrogen	229.6	33.3	639.1	92.7	28.0	28.7	[1]24.9
		H811	922	1200	Hydrogen	239.2	34.7	657.1	95.3	27.0	26.8	[1]25.6
		H812	922	1200	Hydrogen	256.5	37.2	666.0	96.6	28.0	25.3	25.3
Inconel 718	Plate	8P1	297	75	Helium	1181.1	171.3	1370.7	198.8	27.0	43.7	27.7
		8P2	297	75	Hydrogen	1174.2	170.3	1365.2	198.0	26.5	41.3	27.8
		8P3	297	75	Hydrogen	1163.8	168.8	1348.6	195.6	23.0	28.4	27.6
		8P4	297	75	Hydrogen	1169.3	169.6	1351.4	196.0	26.5	36.8	27.3
		8P5	589	600	Helium	1065.2	154.5	1250.7	181.4	26.5	47.3	25.7
		8P6	589	600	Hydrogen	1112.8	161.4	1225.2	177.7	13.0	19.6	[1]25.6
		8P7	589	600	Hydrogen	1063.9	154.3	1213.5	176.0	12.0	19.6	[1]26.2
		8P8	589	600	Hydrogen	1066.6	154.7	1218.3	176.7	12.0	19.3	25.6
		8P9	755	900	Helium	1033.5	149.9	1182.4	171.5	22.5	44.4	24.5
		8P10	755	900	Hydrogen	1014.2	147.1	1153.5	167.3	16.5	25.2	24.4
		8P11	755	900	Hydrogen	1023.9	148.5	1167.3	169.3	18.5	24.4	24.4
		8P12	755	900	Hydrogen	1023.9	148.5	1190.7	172.7	19.5	25.2	25.1
		8P13	922	1200	Helium	985.3	142.9	1158.3	168.0	18.0	35.5	22.9
		8P14	922	1200	Hydrogen	974.9	141.4	1137.6	165.0	18.0	27.0	22.4
		8P15	922	1200	Hydrogen	979.7	142.1	1141.8	165.6	20.0	32.5	22.1
		8P16	922	1200	Hydrogen	997.7	144.7	1163.8	168.8	16.5	34.3	22.8

---

[1] Failed in gage mark.
[2] Failed before 0.2% yield.
[3] Modulus not obtained, yield strength approximate.
[4] All cast Inconel 625 specimens were substandard.
[5] Elongation based on gage length of 25.4 mm (1.000 inch) or 4D.

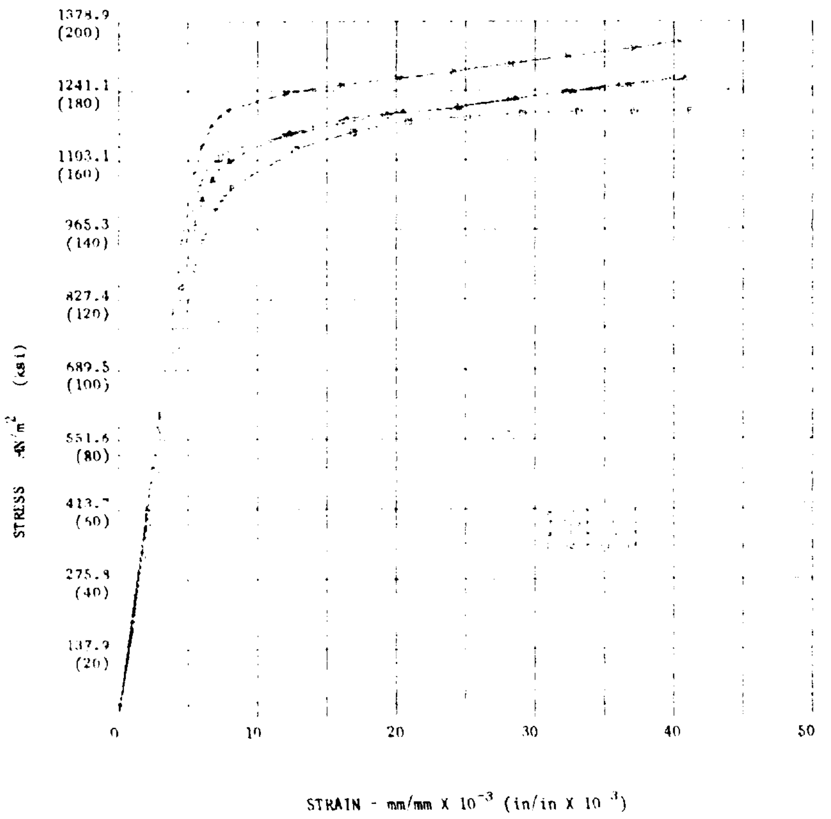


*Figure IV-15. Effect of Temperature on Tensile Stress-Strain of Forged TMP WASPALOY**

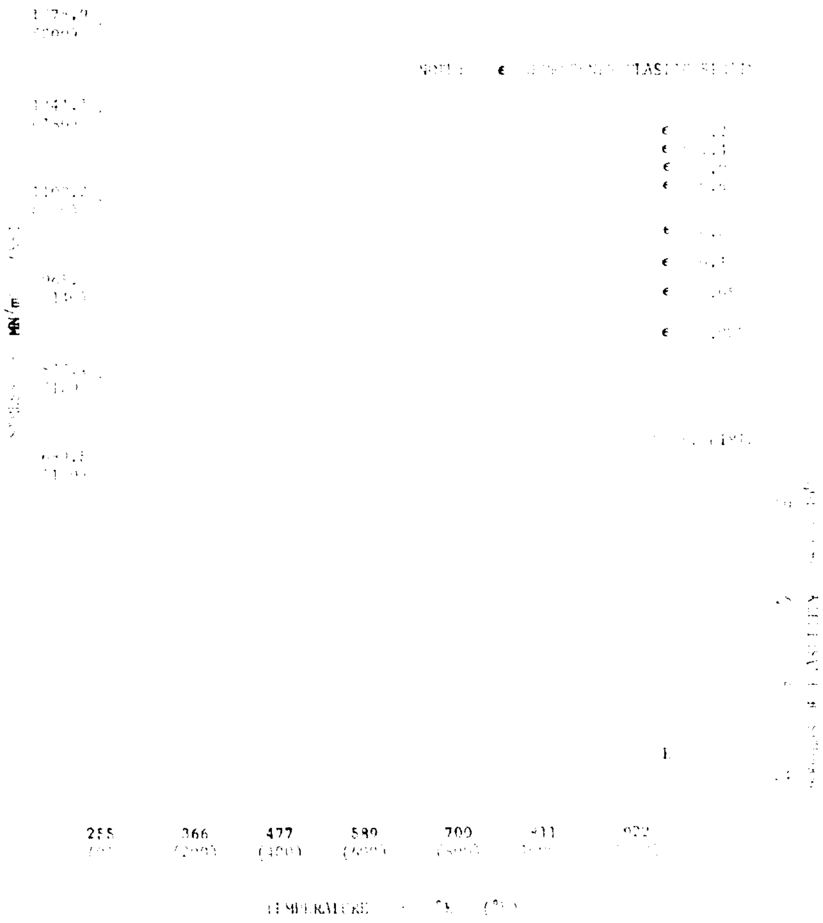


*Figure IV-16. Effect of Temperature on Tensile Stress-Strain and Modulus of Elasticity of TMP WASPALOY**

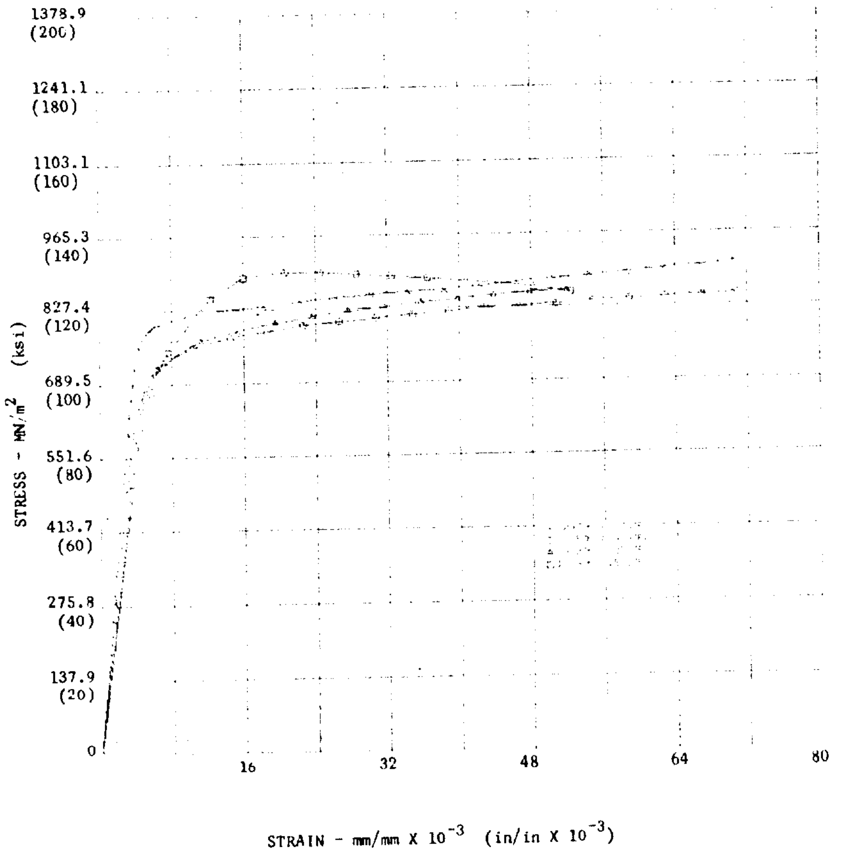


Figure IV-17. Effect of Temperature on Tensile Stress-Strain of Conventionally Cast (CC) MAR M-246 (Hf Modified)

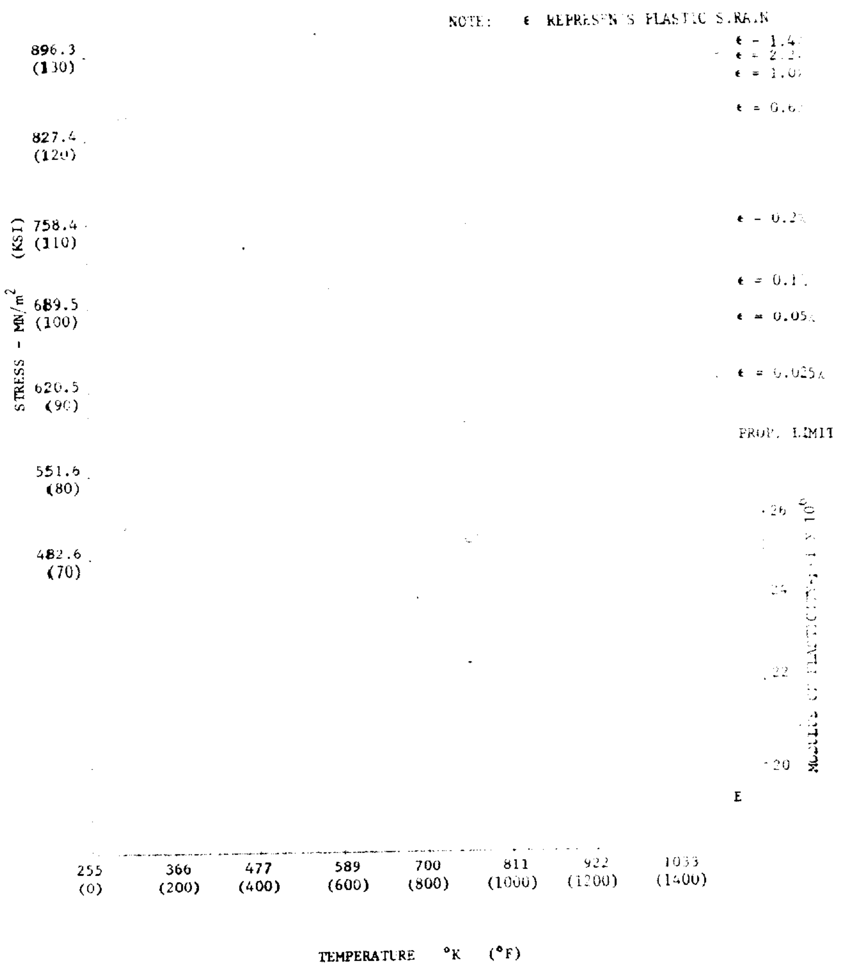


Figure IV-18. Effect of Temperature on Tensile Stress-Strain and Modulus of Elasticity of Conventionally Cast (CC) MAR M-246 (Hf Modified)

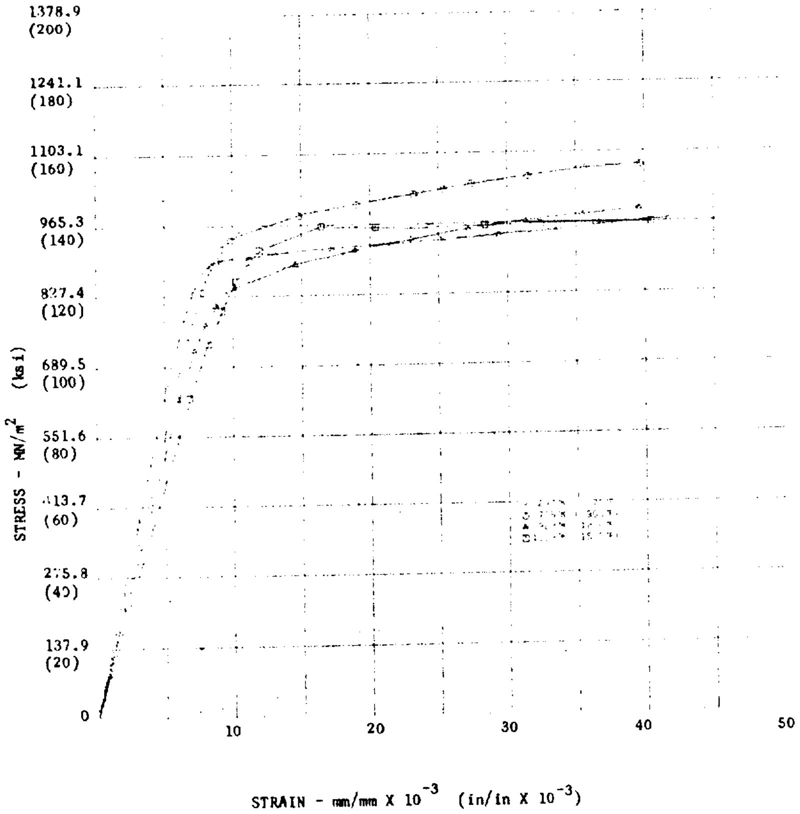


Figure IV-19. Effect of Temperature on Tensile Stress-Strain of Directionally Solidified (DS) MAR M-246 (Hf Modified)

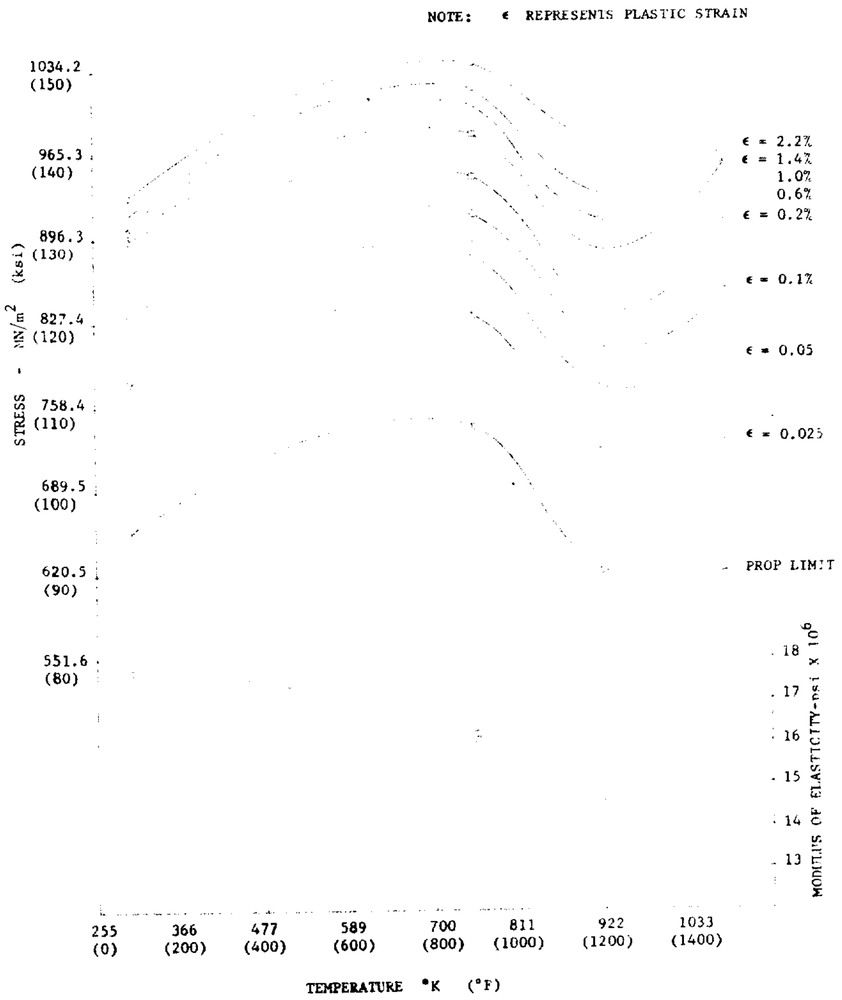


Figure IV-20. Effect of Temperature on Tensile Stress-Strain and Modulus of Elasticity of Directionally Solidified (DS) MAR M-246 (Hf Modified)

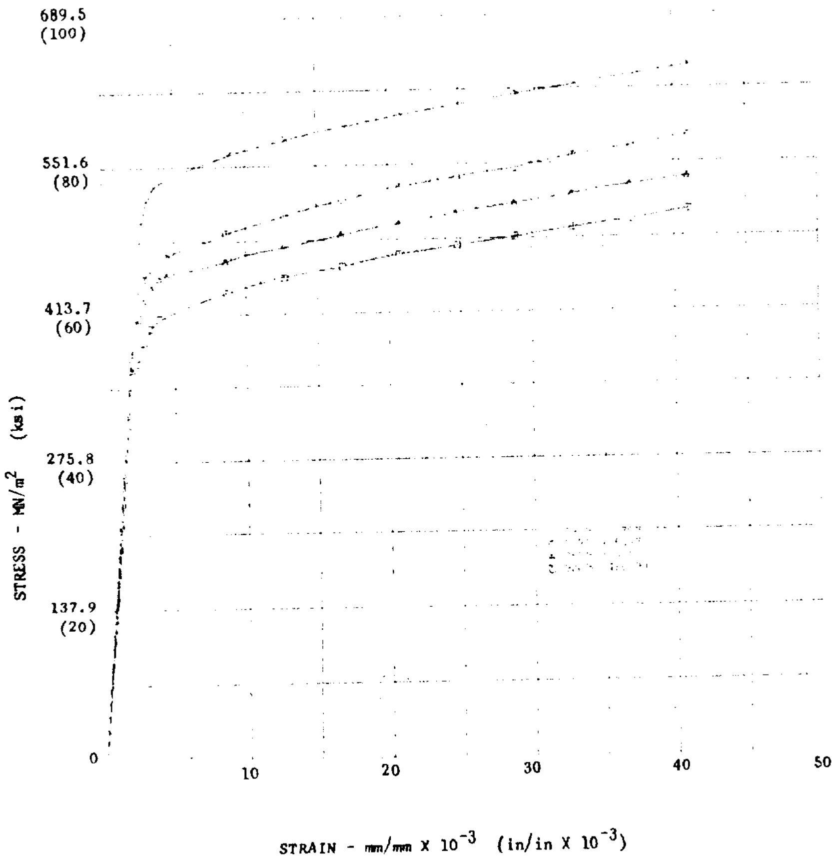


Figure IV-21. Effect of Temperature on Tensile Stress-Strain of Inconel 625 Plate

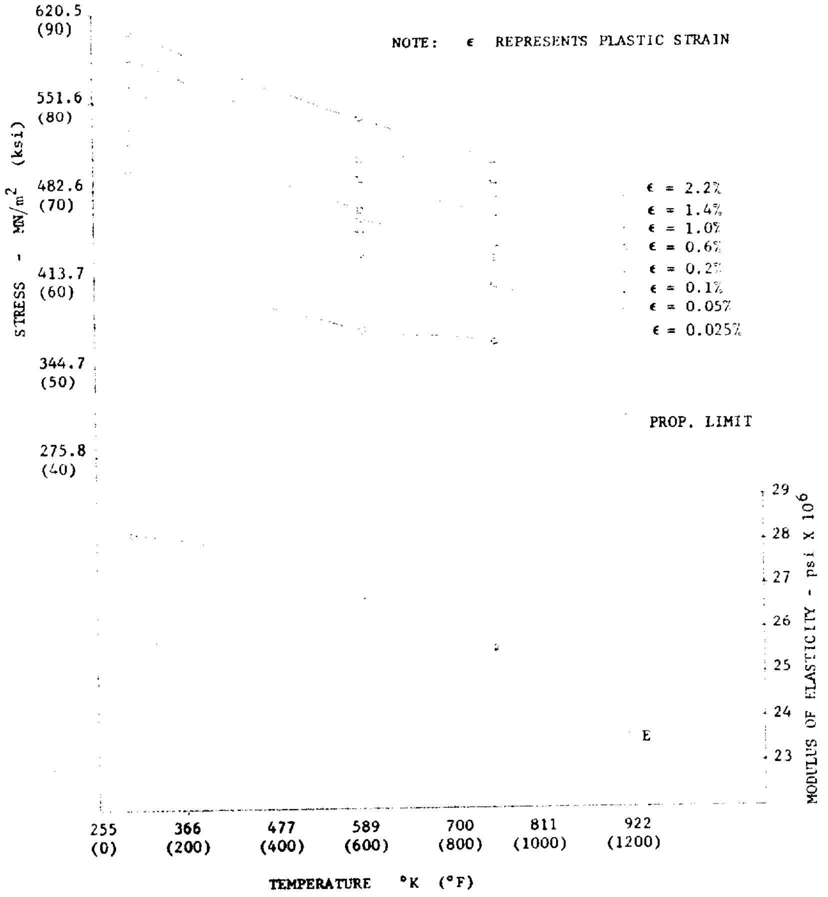


Figure IV-22. Effect of Temperature on Tensile Stress-Strain and Modulus of Elasticity of Inconel 625 Plate

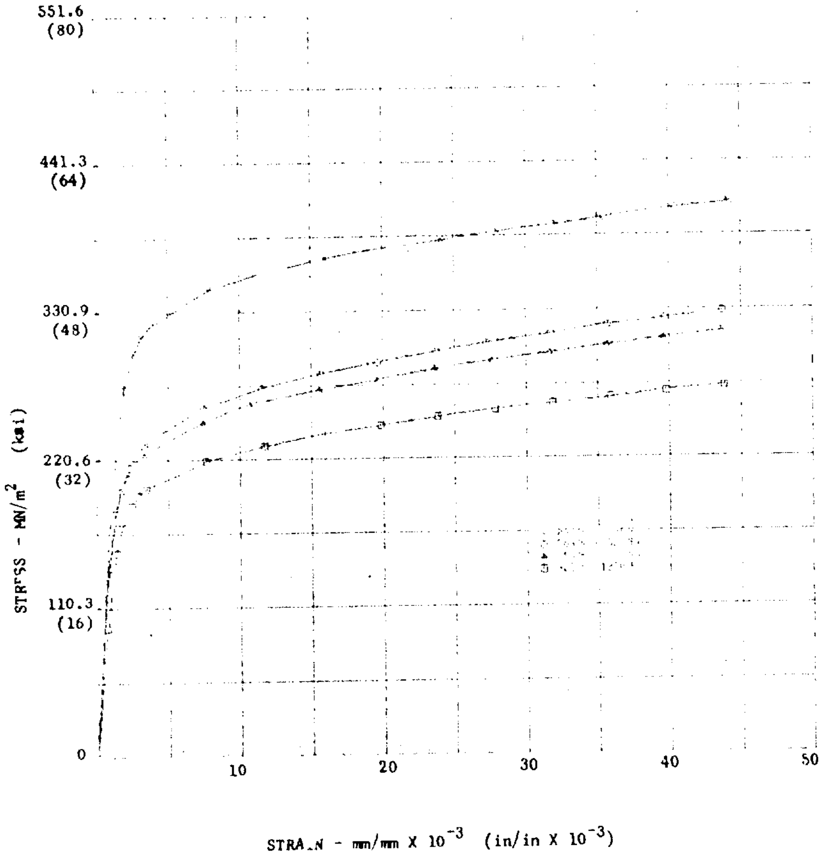


Figure IV-23. Effect of Temperature on Tensile Stress-Strain of Cast Inconel 625

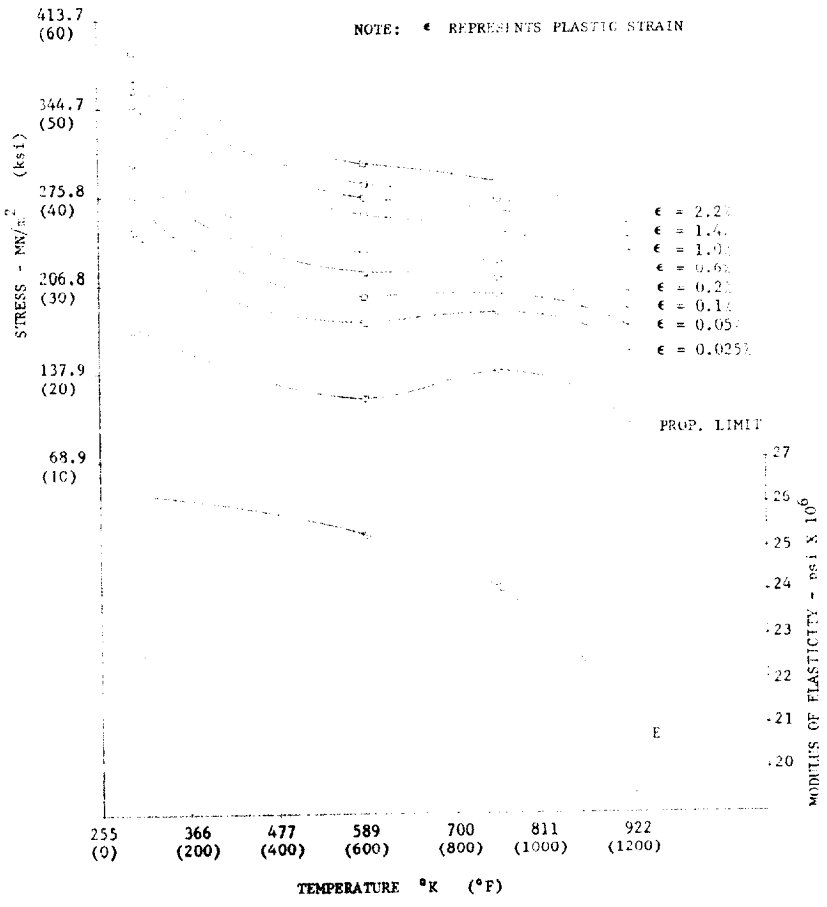


Figure IV-24. Effect of Temperature on Tensile Stress-Strain and Modulus of Elasticity of Cast Inconel 625

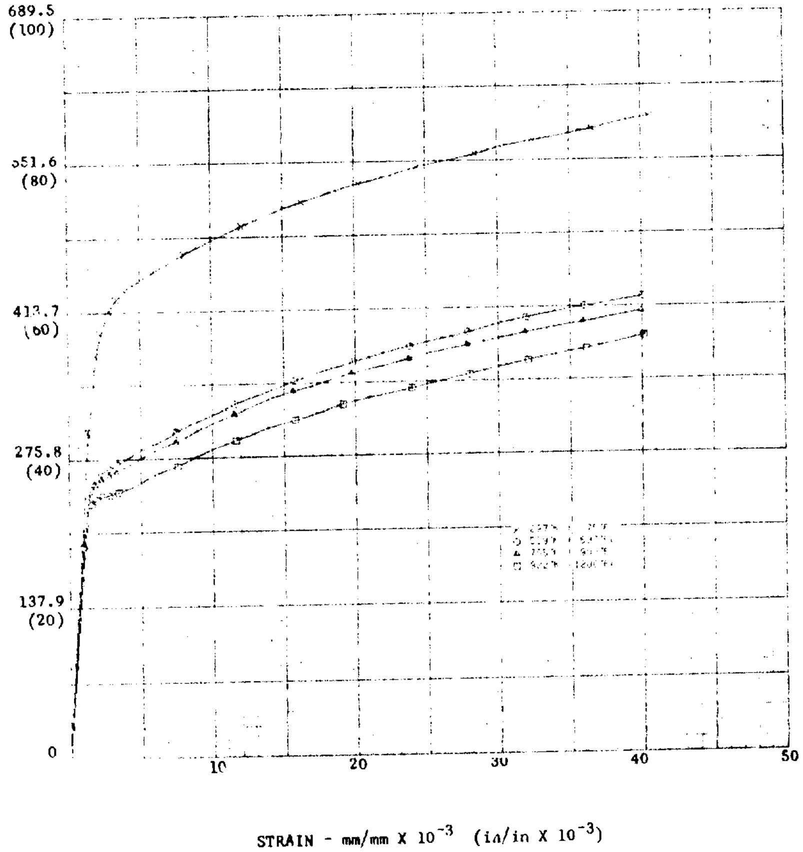


Figure IV-25. Effect of Temperature on Tensile Stress-Strain of Haynes 188 Plate With Inconel 718 STA Heat Treatment

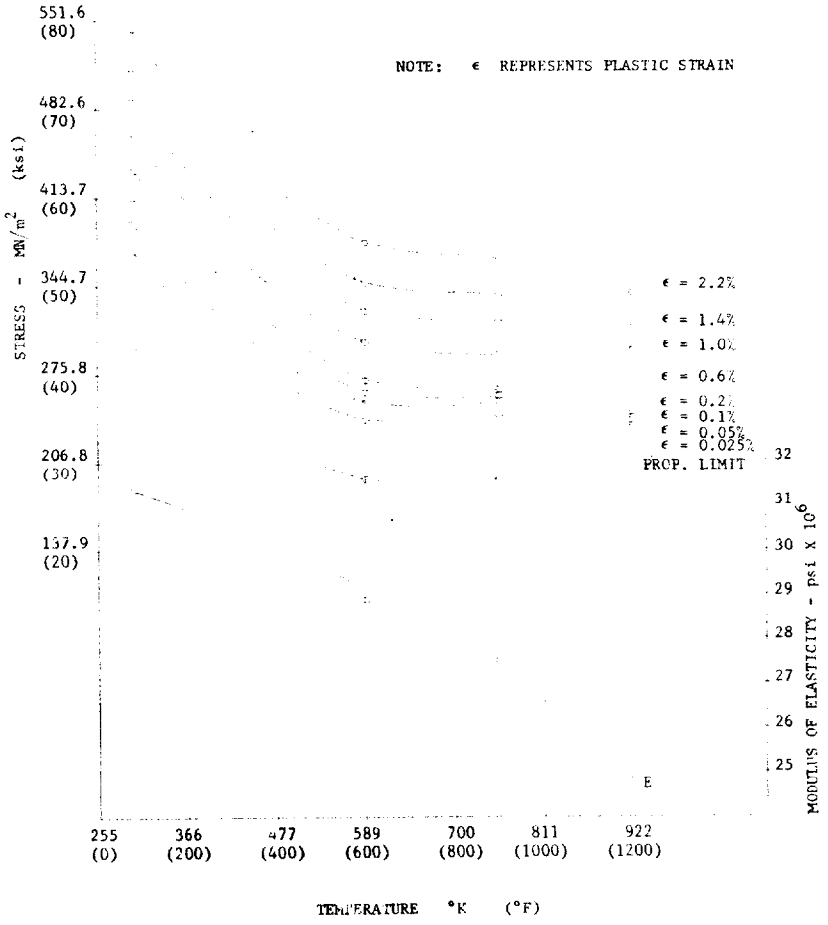


Figure IV-26. Effect of Temperature on Tensile Stress-Strain and Modulus of Elasticity of Haynes 188 Plate With Inconel 718 STA Heat Treatment

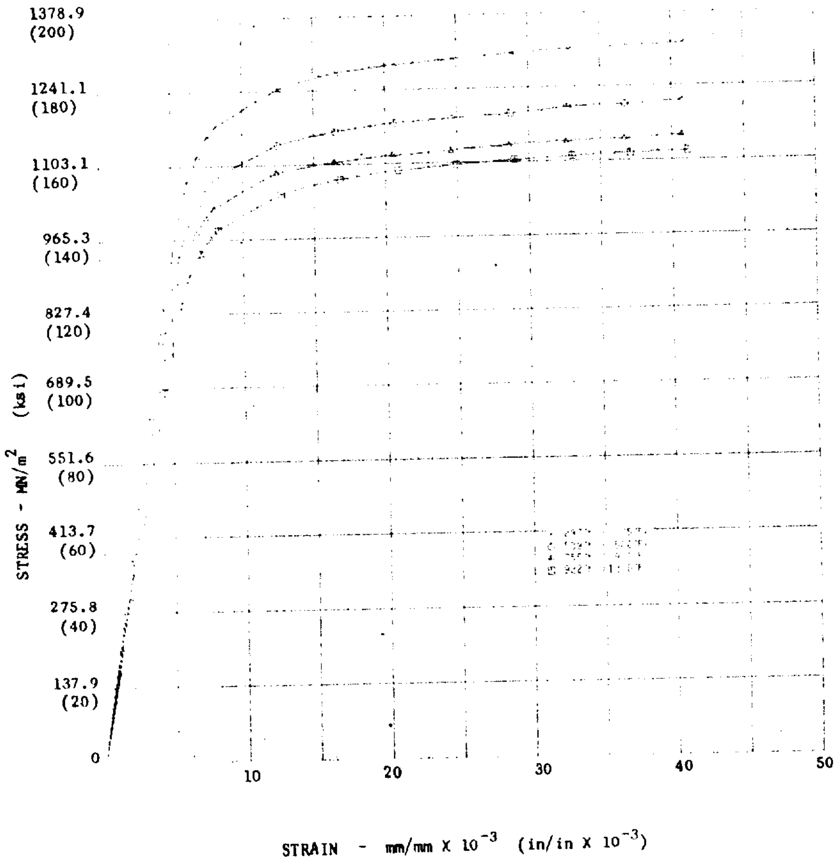


Figure IV-27. Effect of Temperature on Tensile Stress-Strain of Inconel 718 Plate

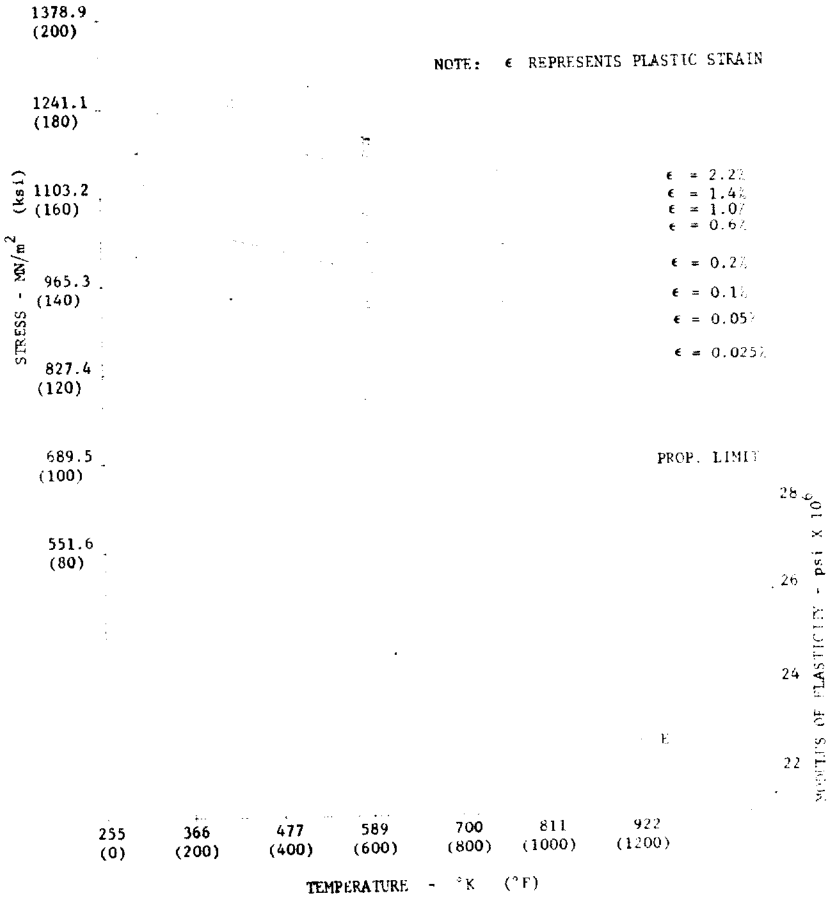


Figure IV-28. Effect of Temperature on Tensile Stress-Strain and Modulus of Elasticity of Inconel 718 Plate

Table IV-3. Individual Specimen Stress-Strain Parameters of Forged TMP WASPALOY in 34.5 MN/m² (5000 psig) Gaseous Environment

OFFSET (PCT)	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3
	SN WF1 297K (75F) 5000 PSIG HELIUM		SN WF2 297K (75F) 5000 PSIG HYDROGEN		SN WF3 297K (75F) 5000 PSIG HYDROGEN		SN WF17 297K (75F) 5000 PSIG HYDROGEN	
PL	154.8	5.14	125.2	4.29	132.4	4.51	136.8	4.63
0.025	170.3	5.89	139.2	5.09	160.6	5.66	155.9	5.49
0.050	176.4	6.34	148.3	5.66	168.6	6.17	162.0	5.94
0.100	180.9	6.97	157.3	6.46	174.6	6.86	168.0	6.63
0.150	182.9	7.54	161.4	7.14	176.7	7.49	170.0	7.14
0.200	183.9	8.11	163.4	7.66	178.7	8.00	172.0	7.71
0.600	187.4	12.23	171.4	12.00	182.7	12.11	176.1	11.94
1.000	189.4	16.23	174.4	16.06	184.7	16.23	178.1	15.94
1.400	191.4	20.29	176.5	20.11	186.7	20.23	179.5	20.00
1.800	193.5	24.40	178.5	24.17	188.7	24.34	181.7	24.06
2.200	195.7	28.46	180.5	28.23	190.7	28.40	184.1	28.17
2.600	198.0	32.57	182.5	32.29	192.8	32.46	186.1	32.23
3.000	200.4	36.63	184.5	36.34	194.8	36.51	188.1	39.14
3.400	202.6	40.63	186.5	40.34	196.8	40.57	190.1	40.34
	SN WF5 589K (600F) 5000 PSIG HELIUM		SN WF6 589K (600F) 5000 PSIG HYDROGEN		SN WF8 589K (600F) 5000 PSIG HYDROGEN		SN WF7 589K (600F) 5000 PSIG HYDROGEN	
PL	119.7	4.23	133.9	4.74	120.2	4.29	135.8	4.80
0.025	140.0	5.03	154.2	5.66	134.4	5.03	152.1	5.60
0.050	149.1	5.60	160.2	6.11	140.5	5.54	158.2	6.11
0.100	155.2	6.40	165.3	6.86	147.7	6.23	163.7	6.63
0.150	157.6	7.20	167.3	7.49	150.7	6.86	166.8	7.43
0.200	159.2	7.54	168.4	7.94	152.7	7.43	168.4	7.94
0.600	164.3	11.66	173.4	12.17	157.2	11.60	172.9	12.11
1.000	167.3	15.77	175.5	16.17	162.9	15.83	176.0	16.17
1.400	170.4	19.89	178.5	20.29	165.0	17.03	178.6	20.34
1.800	172.4	24.00	181.1	24.40	167.4	23.89	180.2	25.77
2.200	175.5	28.06	182.6	28.46	169.0	28.00	183.1	28.74
2.600	177.5	32.17	185.6	32.51	170.1	32.00	184.5	32.46
3.000	179.9	36.23	187.6	36.63	0.0	0.0	0.0	0.0
3.400	181.9	40.23	189.7	40.57	0.0	0.0	0.0	0.0

ORIGINAL PAGE IS
OF POOR QUALITY

Table IV-3. Individual Specimen Stress-Strain Parameters of Forged TMP WASPALOY in 34.5 MN/m² (5000 psig) Gaseous Environment (Continued)

OFFSET (PCT)	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3
	SN WF9 755K (900F) 5000 PSIG HELIUM		SN WF10 755K (900F) 5000 PSIG HYDROGEN		SN WF11 755K (900F) 5000 PSIG HYDROGEN		SN WF12 755K (900F) 5000 PSIG HYDROGEN	
PL	118.7	4.40	127.3	4.80	125.1	4.69	123.2	4.57
0.025	138.0	5.31	147.1	5.89	140.6	5.49	141.3	5.49
0.050	144.9	5.89	153.1	6.34	148.1	6.06	148.3	6.06
0.100	151.9	6.63	158.8	7.03	153.1	6.74	153.5	6.74
0.150	155.5	7.26	162.0	7.66	156.4	7.31	156.9	7.31
0.200	157.9	7.83	164.0	8.23	158.4	7.94	158.9	7.89
0.600	166.0	12.17	171.9	12.57	166.5	12.23	166.9	12.23
1.000	170.4	16.29	175.8	16.69	170.5	16.46	170.9	16.34
1.400	173.0	20.34	177.8	20.74	172.3	20.46	172.3	20.40
1.800	175.1	24.40	179.4	24.80	172.9	24.46	173.1	24.40
2.200	176.7	28.57	181.4	28.86	174.7	28.57	177.8	28.57
2.600	179.5	32.69	183.6	32.97	177.4	32.63	178.2	32.57
3.000	180.5	36.63	185.9	37.03	179.0	36.69	180.4	36.69
3.400	183.1	40.69	186.9	41.03	181.0	40.74	182.4	40.80
	SN WF13 922K (1200F) 5000 PSIG HELIUM		SN WF14 922K (1200F) 5000 PSIG HYDROGEN		SN WF15 922K (1200F) 5000 PSIG HYDROGEN		SN WF16 922K (1200F) 5000 PSIG HYDROGEN	
PL	98.2	4.00	106.9	4.46	117.1	4.80	100.2	4.17
0.025	129.3	5.49	129.3	5.60	134.4	5.77	123.8	5.43
0.050	139.1	6.17	137.5	6.23	143.2	6.40	132.7	6.00
0.100	146.1	6.91	145.6	7.09	149.5	7.09	140.3	6.80
0.150	149.7	7.60	149.7	7.71	153.2	7.71	144.5	7.49
0.200	152.3	8.17	152.7	8.40	155.8	8.40	147.5	8.17
0.600	163.3	12.69	163.5	12.86	166.4	12.80	158.5	12.63
1.000	169.5	16.86	167.0	16.97	172.1	17.03	164.3	16.86
1.400	174.1	21.09	168.0	20.46	175.2	21.14	167.3	20.91
1.800	176.8	25.20	167.8	25.03	176.6	25.20	168.7	24.97
2.200	178.8	29.26	167.8	28.97	177.2	29.20	169.9	29.03
2.600	180.2	33.31	168.0	32.97	177.4	33.20	170.3	33.09
3.000	180.6	37.31	167.6	36.97	177.8	37.26	170.3	37.09
3.400	180.8	41.66	167.0	40.97	178.2	41.31	170.3	41.09

Table IV-4. Individual Specimen Stress-Strain Parameters of Conventionally Cast (CC) MAR M-246 (Hf Modified) in 34.5 MN/m² (5000 psig) Gaseous Environment

OFFSET (PCT)	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3
	SN MC4 297K (75F) 5000 PSIG HELIUM		SN MC2 297K (75F) 5000 PSIG HYDROGEN		SN MC3 297K (75F) 5000 PSIG HYDROGEN		SN MC1 297K (75F) 5000 PSIG HYDROGEN	
PL	86.7	3.10	87.6	3.50	74.4	2.90	65.9	2.60
0.025	104.2	3.90	105.7	4.60	88.0	4.30	84.6	3.70
0.050	110.0	4.40	108.1	4.80	95.5	4.90	91.1	4.30
0.100	112.9	5.00	109.3	5.40	100.4	5.60	97.2	5.00
0.150	115.0	5.60	110.2	5.90	102.5	6.20	99.6	5.60
0.200	115.8	6.10	110.6	6.40	105.4	6.70	101.6	6.20
0.600	118.7	10.20	112.2	10.50	107.4	11.00	106.5	10.30
1.000	120.0	14.30	113.4	14.60	109.1	15.00	107.7	14.40
1.400	120.8	18.30	113.8	18.50	110.3	19.10	108.1	18.40
1.800	122.1	22.30	114.6	22.60	111.2	23.10	0.0	0.0
2.200	122.9	26.30	0.0	0.0	111.6	27.10	0.0	0.0
2.600	123.7	30.30	0.0	0.0	0.0	0.0	0.0	0.0
3.000	124.6	34.30	0.0	0.0	0.0	0.0	0.0	0.0
3.400	125.0	38.30	0.0	0.0	0.0	0.0	0.0	0.0
3.800	125.8	42.40	0.0	0.0	0.0	0.0	0.0	0.0
4.200	126.7	46.40	0.0	0.0	0.0	0.0	0.0	0.0
4.600	127.5	50.50	0.0	0.0	0.0	0.0	0.0	0.0
5.000	128.3	54.50	0.0	0.0	0.0	0.0	0.0	0.0
5.400	129.2	58.50	0.0	0.0	0.0	0.0	0.0	0.0
5.800	130.0	62.60	0.0	0.0	0.0	0.0	0.0	0.0
6.200	130.8	66.60	0.0	0.0	0.0	0.0	0.0	0.0
6.600	131.7	70.60	0.0	0.0	0.0	0.0	0.0	0.0
	SN MC5 755R (900F) 5000 PSIG HELIUM		SN MC6 755K (900F) 5000 PSIG HYDROGEN		SN MC7 755K (900F) 5000 PSIG HYDROGEN		SN MC8 755K (900F) 5000 PSIG HYDROGEN	
PL	71.9	3.00	80.7	3.60	62.8	2.70	84.0	4.00
0.025	86.4	3.70	94.1	4.50	80.2	3.70	95.8	4.90
0.050	95.0	4.30	100.0	5.00	86.0	4.10	100.8	5.40
0.100	99.2	5.10	104.2	5.70	90.9	4.80	105.0	6.00
0.150	102.5	5.70	106.3	6.30	94.2	5.50	108.0	6.70
0.200	104.1	6.30	108.0	6.90	95.9	6.00	109.2	7.20
0.600	109.9	10.50	113.0	11.10	102.1	10.30	115.1	11.50
1.000	112.4	14.60	115.1	15.20	104.5	14.40	117.6	15.60
1.400	114.0	18.70	116.8	19.20	106.2	18.40	119.3	19.70
1.800	115.7	22.70	118.1	23.20	107.4	22.50	120.2	23.70
2.200	116.5	26.70	116.5	27.30	108.7	26.50	0.0	0.0
2.600	117.4	30.80	0.0	0.0	109.9	30.60	0.0	0.0
3.000	118.2	34.80	0.0	0.0	110.7	34.60	0.0	0.0
3.400	119.0	38.80	0.0	0.0	111.6	38.60	0.0	0.0
3.800	119.8	42.80	0.0	0.0	112.0	42.70	0.0	0.0
4.200	120.2	46.80	0.0	0.0	112.4	46.70	0.0	0.0
4.600	120.7	50.80	0.0	0.0	114.0	50.70	0.0	0.0
5.000	121.5	54.90	0.0	0.0	114.0	54.70	0.0	0.0
5.400	121.9	58.90	0.0	0.0	0.0	0.0	0.0	0.0
5.800	122.3	62.90	0.0	0.0	0.0	0.0	0.0	0.0
6.200	122.7	66.90	0.0	0.0	0.0	0.0	0.0	0.0
6.600	123.1	70.90	0.0	0.0	0.0	0.0	0.0	0.0

Table IV-4. *Individual Specimen Stress-Strain Parameters of Conventionally Cast (CC) MAR M-246)Hf Modified) in 34.5 MN/m² (5000 psig) Gaseous Environment (Continued)*

OFFSET (PCT)	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3
	SN MC9 922K (1200F) 5000 PSIG HELIUM		SN MC10 922K (1200F) 5000 PSIG HYDROGEN		SN MC11 922K (1200F) 5000 PSIG HYDROGEN		SN MC12 922K (1200F) 5000 PSIG HYDROGEN	
PL	83.8	4.60	81.6	4.00	89.4	4.00	76.0	3.50
0.025	95.7	5.40	90.9	4.70	97.6	4.50	88.4	4.30
0.050	99.6	5.90	96.7	5.20	101.6	5.00	93.0	4.70
0.100	102.6	6.50	101.7	6.00	105.7	5.60	97.9	5.50
0.150	104.3	7.10	104.1	6.60	108.1	6.20	100.4	6.10
0.200	105.6	7.60	105.4	7.10	110.2	6.80	102.5	7.70
0.600	109.4	11.80	112.0	11.50	116.3	11.10	109.1	11.00
1.000	110.3	15.80	114.5	15.60	119.1	15.20	112.8	15.20
1.400	112.0	19.90	116.5	19.70	121.5	19.30	115.3	19.30
1.800	112.8	23.90	118.2	23.80	123.6	23.40	117.4	23.40
2.200	113.7	28.00	119.8	27.70	124.8	27.40	119.0	27.40
2.600	114.5	32.00	120.7	31.80	126.0	31.50	120.2	31.50
3.000	115.4	36.00	121.9	35.90	127.2	35.60	121.5	35.60
3.400	115.8	40.10	122.7	40.00	128.0	39.60	122.3	39.60
3.800	116.7	44.10	123.6	44.00	129.3	43.70	123.6	43.60
4.200	117.1	48.10	124.0	48.10	130.1	47.70	124.4	47.70
4.600	117.1	52.10	124.8	52.10	130.9	51.80	125.2	51.70
5.000	0.0	0.0	125.6	56.10	131.7	55.80	126.0	55.80
5.400	0.0	0.0	0.0	0.0	131.7	59.80	126.4	59.70
5.800	0.0	0.0	0.0	0.0	0.0	0.0	127.3	63.80
6.200	0.0	0.0	0.0	0.0	0.0	0.0	128.1	67.80
6.600	0.0	0.0	0.0	0.0	0.0	0.0	128.5	71.80
	SN MC13 1068K(1500F) 5000 PSIG HELIUM		SN MC14 1088K(1500F) 5000 PSIG HYDROGEN		SN MC15 1088K(1500F) 5000 PSIG HYDROGEN		SN MC16 1088K(1500F) 5000 PSIG HYDROGEN	
PL	84.6	4.40	76.4	4.20	79.7	3.80	82.9	4.20
0.025	91.5	5.20	86.2	5.00	92.7	4.30	91.5	4.80
0.050	97.2	5.80	91.5	5.50	98.4	4.80	98.8	5.50
0.100	100.4	6.40	98.4	6.30	105.7	5.60	104.5	6.20
0.150	103.7	7.10	103.3	7.10	109.8	6.30	106.1	6.90
0.200	105.7	7.60	105.7	7.80	112.6	6.90	111.4	7.60
0.600	118.7	12.30	115.4	12.30	118.7	11.20	127.2	12.40
1.000	125.2	16.60	116.3	16.30	119.5	15.20	132.1	15.50
1.400	126.8	20.70	115.0	20.20	118.7	19.20	133.3	20.60
1.800	126.8	24.60	114.2	24.10	117.1	23.10	132.4	24.60
2.200	126.0	28.60	111.4	28.00	113.8	27.00	132.5	28.60
2.600	125.6	32.60	0.0	0.0	0.0	0.0	132.1	32.60
3.000	124.4	36.60	0.0	0.0	0.0	0.0	131.7	36.50
3.400	123.2	40.60	0.0	0.0	0.0	0.0	131.3	40.60
3.800	122.0	44.50	0.0	0.0	0.0	0.0	130.9	44.50
4.200	120.3	48.40	0.0	0.0	0.0	0.0	130.5	48.40
4.600	117.9	52.30	0.0	0.0	0.0	0.0	129.7	52.50
5.000	0.0	0.0	0.0	0.0	0.0	0.0	128.9	56.40

Table IV-5. Individual Specimen Stress-Strain Parameters of Directionally Solidified (DS) MAR M-246 (Hf Modified) in 34.5 MN/m² (5000 psig) Gaseous Environment

OFFSET (PCT)	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3
	SN MD1 297K (75F) 5000 PSIG HELIUM		SN MD3 297K (75F) 5000 PSIG HYDROGEN		SN MD2 297K (75F) 5000 PSIG HYDROGEN		SN MD4 297K (75F) 5000 PSIG HYDROGEN	
PL	94.9	5.20	102.6	5.63	97.0	5.43	97.0	5.60
0.025	113.3	6.46	121.1	7.14	121.8	7.09	115.4	6.86
0.050	121.6	7.14	127.0	7.71	128.9	7.66	126.7	7.77
0.100	127.3	7.94	127.4	8.29	133.5	8.40	132.3	8.57
0.150	129.3	8.57	129.2	8.69	135.4	8.97	135.2	9.20
0.200	129.9	9.14	0.0	0.0	136.2	9.54	136.2	9.77
0.400	131.1	11.26	0.0	0.0	135.2	11.60	135.8	11.77
0.600	131.9	13.26	0.0	0.0	0.0	0.0	0.0	0.0
1.000	133.3	17.26	0.0	0.0	0.0	0.0	0.0	0.0
1.400	134.1	21.31	0.0	0.0	0.0	0.0	0.0	0.0
1.800	135.4	25.31	0.0	0.0	0.0	0.0	0.0	0.0
2.200	136.8	29.43	0.0	0.0	0.0	0.0	0.0	0.0
2.600	137.8	33.54	0.0	0.0	0.0	0.0	0.0	0.0
3.000	139.4	37.54	0.0	0.0	0.0	0.0	0.0	0.0
3.400	140.8	41.71	0.0	0.0	0.0	0.0	0.0	0.0
	SN MD5 755K (900F) 5000 PSIG HELIUM		SN MD8 755K (900F) 5000 PSIG HYDROGEN		SN MD7 755K (900F) 5000 PSIG HYDROGEN		SN MD6 755K (900F) 5000 PSIG HYDROGEN	
PL	107.1	6.69	101.4	6.23	105.5	6.46	95.6	5.83
0.025	121.2	7.77	110.3	7.03	119.5	7.54	113.1	7.09
0.050	128.5	8.51	115.2	7.60	123.7	8.00	119.7	7.71
0.100	133.3	9.31	119.5	8.29	128.0	8.80	125.8	8.57
0.150	135.8	9.89	121.7	8.97	130.0	9.43	128.6	9.26
0.200	137.4	10.51	123.1	9.60	131.8	10.00	130.2	9.64
0.600	142.6	14.66	127.8	13.89	136.3	14.29	136.0	14.29
1.000	145.7	19.03	0.0	0.0	139.9	18.46	139.0	18.40
1.400	148.5	23.20	0.0	0.0	142.0	22.57	141.2	22.51
1.600	149.7	25.43	0.0	0.0	0.0	0.0	141.9	24.69
1.800	151.1	27.43	0.0	0.0	0.0	0.0	0.0	0.0
2.200	153.1	31.54	0.0	0.0	0.0	0.0	0.0	0.0
2.600	155.2	35.60	0.0	0.0	0.0	0.0	0.0	0.0
2.800	156.2	39.71	0.0	0.0	0.0	0.0	0.0	0.0

ORIGINAL PAGE IS
OF POOR QUALITY

Table IV-5. *Individual Specimen Stress-Strain Parameters of Directionally Solidified (DS) MAR M-246 (Hf Modified) in 34.5 MN/m² (5000 psig) Gaseous Environment (Continued)*

OFFSET (PCT)	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3
	SN MD9 922K (1200F) 5000 PSIG HELIUM		SN MD11 922K (1200F) 5000 PSIG HYDROGEN		SN MD10 922K (1200F) 5000 PSIG HYDROGEN		SN MD12 922K (1200F) 5000 PSIG HYDROGEN	
PL	90.5	6.06	94.2	6.74	103.0	7.14	104.5	7.37
0.025	104.4	7.20	109.7	8.06	113.9	8.11	114.6	8.29
0.050	111.9	8.00	115.7	8.74	119.0	8.69	120.3	8.97
0.100	117.1	8.80	121.3	9.60	123.2	9.49	124.3	9.71
0.150	120.5	9.54	124.3	10.29	125.3	10.17	127.2	10.40
0.200	122.1	10.17	126.0	10.91	126.9	10.74	128.8	11.03
0.600	128.8	14.57	132.0	15.31	133.5	15.20	142.0	15.60
1.000	132.6	18.86	134.8	19.54	139.2	19.60	146.2	19.44
1.400	135.6	23.03	136.8	23.71	143.2	23.83	150.1	24.23
1.800	138.4	27.20	0.0	0.0	147.1	28.11	153.1	28.51
2.200	140.4	31.37	0.0	0.0	0.0	0.0	154.2	32.74
2.600	142.1	35.49	0.0	0.0	0.0	0.0	0.0	0.0
3.000	143.7	39.60	0.0	0.0	0.0	0.0	0.0	0.0
	SN MD13 1088K(1500F) 5000 PSIG HELIUM		SN MD14 1088K(1500F) 5000 PSIG HYDROGEN		SN MD15 1088K(1500F) 5000 PSIG HYDROGEN		SN MD16 1088K(1500F) 5000 PSIG HYDROGEN	
PL	82.8	6.40	98.6	7.83	93.6	6.91	96.2	7.26
0.025	103.0	8.17	120.9	9.77	106.4	8.00	109.4	8.46
0.050	113.1	9.20	129.0	10.63	116.1	9.03	113.2	9.43
0.100	123.2	10.46	136.6	11.71	124.7	10.11	124.4	10.34
0.150	129.1	11.43	140.8	12.57	130.8	11.04	128.9	11.20
0.200	133.1	12.23	143.1	13.26	133.8	11.83	131.7	11.84
0.600	141.0	16.80	148.5	17.66	140.8	16.29	136.9	16.29
1.000	140.4	20.74	146.9	21.54	140.0	20.23	136.7	20.23
1.400	140.0	24.74	145.9	25.49	134.6	24.17	136.7	24.29
1.800	140.6	28.74	145.7	29.43	139.4	23.23	133.1	23.29
2.200	141.4	32.86	145.7	33.43	139.2	32.17	138.5	32.40
2.600	141.8	36.86	145.7	37.37	139.0	36.11	138.7	36.40
3.000	141.3	40.86	0.0	0.0	138.9	40.17	138.7	40.40

Table IV-6. Individual Specimen Stress-Strain Parameters of Inconel 625 Plate in 34.5 MN/m² (5000 psig) Gaseous Environment

OFFSET (PCT)	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3
	SN 5P1 297K (75F) 5000 PSIG HELIUM		SN 5P2 297K (75F) 5000 PSIG HYDROGEN		SN 5P3 297K (75F) 5000 PSIG HYDROGEN		SN 5P4 297K (75F) 5000 PSIG HYDROGEN	
PL	66.7	2.34	61.7	2.17	57.1	2.06	64.2	2.29
0.025	75.2	2.86	73.[illegible]	2.80	68.5	2.63	72.7	2.80
0.050	78.8	3.26	75.8	3.14	72.3	3.09	75.6	3.14
0.100	80.2	3.77	77.2	3.71	74.5	3.66	77.4	3.71
0.150	80.8	4.29	78.0	4.23	75.4	4.17	78.4	4.29
0.200	81.4	4.86	78.6	4.74	76.2	4.74	78.8	4.80
0.600	84.4	8.97	81.4	8.86	78.8	8.80	81.6	8.86
1.000	86.9	12.97	83.4	12.91	80.6	12.86	83.4	12.97
1.400	88.7	17.03	85.0	16.97	82.2	16.91	85.1	16.97
1.800	90.1	21.09	86.6	21.03	83.8	20.97	86.5	20.97
2.200	91.5	25.14	87.8	25.03	85.2	24.74	87.7	25.03
2.600	93.1	29.20	89.0	29.09	86.4	29.03	88.9	29.09
3.000	94.5	33.26	90.2	33.14	87.4	33.09	90.1	33.14
3.400	95.8	37.31	91.4	37.20	88.8	37.14	90.9	37.14
3.800	97.0	41.31	92.4	41.14	90.0	41.14	91.9	41.14
	SN 5P5 589K (600F) 5000 PSIG HELIUM		SN 5P6 589K (600F) 5000 PSIG HYDROGEN		SN 5P7 589K (600F) 5000 PSIG HYDROGEN		SN 5P8 589K (600F) 5000 PSIG HYDROGEN	
PL	52.5	1.94	54.1	2.06	56.6	2.06	52.7	2.00
0.025	62.8	2.57	61.5	2.57	65.5	2.63	60.7	2.51
0.050	65.1	2.91	63.9	2.97	67.7	2.97	62.5	2.86
0.100	66.7	3.43	65.1	3.54	69.5	3.49	64.1	3.43
0.150	67.3	3.94	66.1	4.06	69.9	4.00	64.7	4.00
0.200	68.5	4.46	66.5	4.57	70.7	4.57	65.1	4.46
0.600	71.7	8.69	69.9	8.69	73.7	8.69	68.7	8.63
1.000	73.9	12.69	72.1	12.74	76.4	12.74	70.7	12.69
1.400	76.4	16.74	74.1	16.86	77.8	16.74	72.9	16.74
1.800	77.8	20.86	76.2	20.86	79.8	20.86	74.1	20.74
2.200	79.2	24.86	77.2	24.91	80.8	24.86	75.8	24.80
2.600	80.8	28.91	78.2	28.97	82.0	28.91	76.4	28.86
3.000	82.2	32.91	79.6	32.91	83.8	32.97	78.4	32.91
3.400	83.2	36.97	80.8	37.09	85.3	37.03	79.2	36.97
3.800	84.8	41.03	81.8	41.09	86.9	41.09	80.4	40.91

ORIGINAL PAGE IS
OF POOR QUALITY

Table IV-6. *Individual Specimen Stress-Strain Parameters of Inconel 625 Plate in 34.5 MN/m² (5000 psig) Gaseous Environment (Continued)*

OFFSET (PCT)	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3
	SN 5P9 755K (900F) 5000 PSIG HELIUM		SN 5P10 755K (900F) 5000 PSIG HYDROGEN		SN 5P11 755K (900F) 5000 PSIG HYDROGEN		SN 5P12 755K (900F) 5000 PSIG HYDROGEN	
PL	49.5	1.89	58.6	2.34	50.1	1.94	51.3	2.00
0.025	57.6	2.40	61.8	2.74	58.7	2.46	59.0	2.46
0.050	59.6	2.74	65.5	3.03	60.7	2.80	61.8	2.80
0.100	61.4	3.26	67.1	3.66	62.3	3.37	63.4	3.43
0.150	62.0	3.83	68.3	4.17	63.9	3.94	64.6	3.94
0.200	62.6	4.34	68.9	4.74	64.5	4.46	65.4	4.51
0.600	64.8	8.46	70.5	8.86	66.3	8.57	66.6	8.57
1.000	66.7	12.46	72.5	12.86	67.9	12.57	69.0	12.63
1.400	68.7	16.57	73.9	16.91	70.1	16.63	69.8	16.69
1.800	69.7	20.57	75.4	20.91	71.1	20.69	72.2	20.74
2.200	71.5	24.57	76.4	24.97	72.5	24.80	73.0	24.74
2.600	72.7	28.69	77.6	29.03	74.1	28.80	74.0	28.80
3.000	73.5	32.69	78.8	33.03	75.4	32.86	75.3	32.86
3.400	75.4	36.80	80.0	37.14	76.2	36.86	76.5	36.91
3.800	75.8	40.74	81.0	41.14	77.2	40.91	77.7	40.86
	SN 5P13 922K (1200F) 5000 PSIG HELIUM		SN 5P14 922K (1200F) 5000 PSIG HYDROGEN		SN 5P15 922K (1200F) 5000 PSIG HYDROGEN		SN 5P16 922K (1200F) 5000 PSIG HYDROGEN	
PL	48.5	2.11	47.5	1.94	42.3	1.83	38.5	1.60
0.025	54.9	2.57	55.6	2.51	52.3	2.46	50.7	2.29
0.050	57.0	2.91	58.0	2.86	55.3	2.86	54.8	2.74
0.100	58.6	3.49	59.8	3.49	57.3	3.43	57.2	3.31
0.150	59.6	4.06	61.2	4.00	58.4	4.00	58.4	3.89
0.200	60.2	4.63	61.8	4.57	59.0	4.57	59.0	4.40
0.600	63.0	8.69	64.6	8.69	61.8	8.63	62.1	8.51
1.000	65.3	12.74	66.5	12.74	63.6	12.74	64.1	12.57
1.400	66.9	16.91	68.1	16.74	65.0	16.80	65.5	16.69
1.800	68.5	20.91	69.3	20.80	66.4	20.80	66.9	20.69
2.200	69.7	24.97	70.7	24.86	67.6	24.86	68.2	24.74
2.600	70.9	29.03	71.7	28.86	68.6	28.86	69.4	28.74
3.000	72.3	33.03	72.1	32.91	70.0	32.97	70.6	32.80
3.400	73.3	37.14	73.9	37.03	70.8	37.03	71.4	36.86
3.800	74.5	41.14	74.9	41.03	72.0	40.97	72.6	40.86

Table IV-7. Individual Specimen Stress-Strain Parameters of Cast Inconel 625 MN/m² (5000 psig) Gaseous Environment

OFFSET (PCT)	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3
	SN 5C1 297K (75F) 5000 PSIG HELIUM		SN 5C2 297K (75F) 5000 PSIG HYDROGEN		SN 5C3 297K (75F) 5000 PSIG HYDROGEN		SN 5C4 297K (75F) 5000 PSIG HYDROGEN	
PL	26.5	0.96	24.4	0.96	25.1	0.95	24.4	0.95
0.025	39.1	1.60	34.6	1.66	35.7	1.58	34.4	1.58
0.050	43.2	1.99	38.9	2.10	39.8	2.03	38.7	1.96
0.100	46.6	2.56	42.7	2.74	43.5	2.66	42.2	2.59
0.150	47.9	3.14	44.3	3.31	45.6	3.23	43.8	3.16
0.200	49.1	3.72	45.3	3.89	46.8	3.80	44.8	3.61
0.600	53.2	7.82	48.7	7.96	51.1	7.85	48.7	7.78
1.000	55.2	11.92	50.3	12.04	53.2	11.96	50.5	11.84
1.400	57.0	16.09	51.6	16.11	54.6	16.01	51.7	15.89
1.800	58.2	20.45	52.4	20.19	55.6	20.00	52.7	19.87
2.200	59.1	24.23	53.4	24.20	56.7	24.05	53.4	23.92
2.600	60.1	28.21	54.0	28.22	57.5	28.04	54.2	27.91
3.000	61.1	32.37	54.9	32.29	58.1	32.03	55.0	31.96
3.400	61.9	36.41	55.7	36.31	58.7	32.09	55.4	35.95
3.800	62.9	40.45	56.3	40.32	59.8	40.06	56.2	39.94
4.200	63.7	44.55	57.1	44.33	60.4	43.99	56.8	43.92
	SN 5C5 589K (600F) 5000 PSIG HELIUM		SN 5C6 589K (600F) 5000 PSIG HYDROGEN		SN 5C7 589K (600F) 5000 PSIG HYDROGEN		SN 5C8 589K (600F) 5000 PSIG HYDROGEN	
PL	19.8	0.82	15.5	0.63	13.1	0.57	20.1	0.82
0.025	27.6	1.39	24.7	1.20	22.1	1.27	27.3	1.33
0.050	30.3	1.71	28.5	1.65	25.7	1.71	29.7	1.58
0.100	33.0	2.34	30.9	2.22	29.1	2.34	31.9	2.09
0.150	34.4	2.91	32.4	2.85	31.1	2.97	32.9	2.66
0.200	35.5	3.42	33.2	3.35	32.5	3.42	33.5	3.10
0.600	39.7	7.53	36.9	7.47	37.1	7.66	36.9	7.28
1.000	42.0	11.65	39.0	11.52	39.6	11.71	38.6	11.33
1.400	43.6	15.70	40.4	15.63	41.2	15.82	40.0	15.44
1.800	45.3	19.75	41.4	19.62	42.4	19.94	40.8	19.43
2.200	46.3	23.80	42.5	23.67	43.8	23.92	41.8	23.48
2.600	47.4	27.85	43.3	27.59	44.6	26.01	42.6	27.47
3.000	48.2	31.77	44.3	31.65	45.4	31.96	43.6	31.46
3.400	49.5	35.82	45.4	35.70	46.2	35.95	44.4	35.51
3.800	50.1	39.81	46.0	39.68	47.0	39.87	45.0	39.43
4.200	50.9	43.86	46.6	43.61	47.8	43.92	45.6	43.42

Table IV-7. *Individual Specimen Stress-Strain Parameters of Cast Inconel 625 MN/m² (5000 psig) Gaseous Environment (Continued)*

OFFSET (PCT)	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3
	SN 5C9 755K (900F) 5000 PSIG HELIUM		SN 5C10 755K (900F) 5000 PSIG HYDROGEN		SN 5C11 755K (900F) 5000 PSIG HYDROGEN		SN 5C14 755K (900F) 5000 PSIG HYDROGEN	
PL	22.6	0.95	19.6	0.82	22.3	0.89	16.4	0.70
0.025	27.3	1.33	26.4	1.39	27.2	1.33	25.8	1.39
0.050	29.0	1.71	28.5	1.71	29.1	1.65	28.2	1.71
0.100	30.4	2.28	30.5	2.41	31.5	2.28	30.3	2.34
0.150	31.4	2.78	31.5	2.85	32.6	2.72	31.5	2.85
0.200	32.0	3.29	32.6	3.35	33.4	3.29	32.3	3.35
0.600	35.5	7.41	36.3	7.47	36.9	7.34	35.6	7.47
1.000	37.4	11.46	38.4	11.58	39.0	11.39	37.6	8.42
1.400	38.8	15.57	39.8	15.63	40.4	15.51	39.1	15.63
1.800	39.8	19.68	41.0	19.75	41.4	19.49	40.1	19.68
2.200	41.1	23.67	42.1	23.73	42.7	23.54	41.1	23.67
2.600	41.9	27.59	42.9	27.66	43.5	27.47	41.9	27.66
3.000	42.5	31.71	43.9	31.77	44.3	31.52	42.7	31.71
3.400	43.5	35.63	44.7	35.76	45.2	35.57	43.4	35.76
3.800	44.1	39.62	45.6	39.68	45.8	39.49	44.0	39.68
4.200	45.0	43.67	46.2	43.67	46.6	43.54	44.8	43.67
	SN 5C13 922K (1200F) 5000 PSIG HELIUM		SN 5C12 922K (1200F) 5000 PSIG HYDROGEN		SN 5C15 922K (1200F) 5000 PSIG HYDROGEN		SN 5C16 922K (1200F) 5000 PSIG HYDROGEN	
PL	15.3	0.76	11.3	0.57	13.3	0.82	15.5	0.76
0.025	21.6	1.33	20.5	1.33	23.2	1.71	22.5	1.20
0.050	24.4	1.71	23.6	1.71	26.7	2.15	24.3	1.58
0.100	26.5	2.34	26.3	2.41	29.8	2.91	26.0	2.22
0.150	27.5	2.85	27.3	2.91	31.0	3.42	26.8	2.72
0.200	28.3	3.35	27.9	3.48	31.8	3.99	27.4	3.16
0.600	31.4	7.47	30.6	7.59	35.3	8.16	30.1	7.28
1.000	33.0	11.58	32.0	11.65	37.2	12.22	31.5	11.33
1.400	34.4	15.63	33.1	15.63	38.4	16.33	32.8	15.38
1.800	35.4	19.68	33.9	19.75	39.6	20.44	33.6	19.43
2.200	36.5	23.73	34.7	23.73	40.7	24.49	34.2	23.42
2.600	37.3	27.72	35.3	27.72	41.5	28.48	35.1	27.41
3.000	37.9	31.71	35.9	31.77	42.3	32.53	35.7	31.46
3.400	38.7	35.76	36.3	35.76	42.9	36.58	36.1	35.44
3.800	39.3	39.43	37.0	39.68	43.7	40.57	36.7	39.43
4.200	39.9	43.67	37.4	43.73	44.4	44.56	37.1	43.42

Table IV-8. Individual Specimen Stress-Strain Parameters of Haynes 188 Plate, with Inconel 718 STA Heat Treatment, in 34.5 MN/m² (5000 psig) Gaseous Environment

OFFSET (PCT)	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3
	SN H81 297K (75F) 5000 PSIG HELIUM		SN H82 297K (75F) 5000 PSIG HYDROGEN		SN H83 297K (75F) 5000PSIG HYDROGEN		SN H84 297K (75F) 5000 PSIG HYDROGEN	
PL	42.1	1.31	44.4	1.43	42.4	1.37	44.4	1.43
0.025	56.1	1.83	53.9	1.89	52.9	1.94	53.1	2.00
0.050	58.1	2.29	57.0	2.29	56.8	2.29	56.4	2.29
0.100	60.9	2.86	60.2	2.86	60.4	2.86	59.0	2.86
0.150	62.5	3.37	61.8	3.43	61.6	3.43	60.8	3.43
0.200	63.9	3.94	62.8	3.94	62.8	4.00	62.2	4.00
0.600	68.9	8.11	67.7	8.11	67.5	8.17	66.9	8.11
1.000	72.9	12.17	71.1	12.17	71.1	12.23	70.7	12.17
1.400	76.2	16.29	74.5	16.34	74.3	16.34	73.5	16.34
1.800	78.6	20.34	76.8	20.34	76.6	20.34	76.0	20.40
2.200	80.8	24.40	78.8	24.40	78.8	24.46	78.0	24.46
2.600	82.6	28.40	80.8	28.46	80.4	28.51	79.8	28.46
3.000	84.6	32.51	82.6	32.51	82.0	32.51	81.4	32.57
3.400	86.2	36.57	84.0	36.57	83.4	36.63	83.0	36.57
3.800	87.8	40.57	85.5	40.57	85.1	40.63	84.6	40.63
	SN H813 589K (600F) 5000 PSIG HELIUM		SN H814 589K (600F) 5000 PSIG HYDROGEN		SN H815 589K (600F) 5000 PSIG HYDROGEN		SN H816 589K (600F) 5000 PSIG HYDROGEN	
PL	27.2	0.91	27.3	0.97	28.3	1.03	29.2	0.97
0.025	34.0	1.37	34.9	1.49	33.9	1.43	35.5	1.43
0.050	35.6	1.71	36.6	1.83	36.4	1.83	37.4	1.71
0.100	37.2	2.23	38.2	2.34	37.8	2.34	38.6	2.29
0.150	37.8	2.80	39.0	2.91	38.6	2.91	39.5	2.80
0.200	38.4	3.31	39.6	3.43	39.2	3.43	40.1	3.31
0.600	42.5	7.37	43.8	7.60	43.4	7.60	44.1	7.49
1.000	46.3	11.54	47.5	11.66	47.1	11.71	47.8	11.54
1.400	49.3	15.60	50.5	15.77	50.5	15.83	50.7	15.71
1.800	51.9	19.71	53.1	19.89	52.9	19.89	53.2	19.77
2.200	54.1	23.77	55.2	23.89	54.9	24.00	55.1	23.77
2.600	56.3	27.83	56.8	28.00	56.6	28.06	57.0	27.77
3.000	58.1	31.89	59.2	32.06	58.4	32.11	58.7	31.89
3.400	60.0	35.94	60.6	36.11	59.4	36.17	60.1	35.94
3.800	60.8	40.00	61.6	40.11	61.0	40.17	61.8	40.00

Table IV-8. *Individual Specimen Stress-Strain Parameters of Haynes 188 Plate, with Inconel 718 STA Heat Treatment, in 34.5 MN/m² (5000 psig) Gaseous Environment (Continued)*

OFFSET (PCT)	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3
	SN H65 755K (900F) 5000 PSIG HELIUM		SN H86 755K (900F) 5000 PSIG HYDROGEN		SN H67 755K (900F) 5000 PSIG HYDROGEN		SN H68 755K (900F) 5000 PSIG HYDROGEN	
PL	28.9	1.09	28.9	1.03	28.5	1.03	28.1	0.80
0.025	34.8	1.54	35.6	1.49	35.6	1.54	35.8	1.20
0.050	36.5	1.89	36.8	1.77	36.5	1.83	36.9	1.49
0.100	37.5	2.40	37.0	2.29	37.1	2.29	37.3	2.00
0.150	38.5	2.91	37.6	2.80	37.5	2.86	37.5	2.51
0.200	39.1	3.43	38.0	3.31	37.9	3.37	37.9	3.09
0.600	43.8	7.66	41.6	7.43	41.8	7.49	42.0	7.20
1.000	47.9	11.71	44.6	11.54	45.4	11.66	45.4	11.26
1.400	50.9	15.89	47.9	15.66	48.5	15.71	46.5	15.31
1.800	53.4	20.00	49.9	19.71	50.9	19.83	50.5	19.43
2.200	55.4	24.00	51.9	23.77	52.5	23.83	52.5	23.43
2.600	57.2	28.06	53.9	27.83	54.0	27.94	54.6	27.49
3.000	58.9	32.11	55.8	31.89	55.6	31.94	56.0	31.54
3.400	60.3	36.17	56.6	35.89	57.2	36.00	57.6	35.60
3.800	61.1	40.23	58.8	40.00	58.9	40.06	58.9	39.60
	SN H89 922K (1200F) 5000 PSIG HELIUM		SN H810 922K (1200F) 5000 PSIG HYDROGEN		SN H811 922K (1200F) 5000 PSIG HYDROGEN		SN H812 922K (1200F) 5000 PSIG HYDROGEN	
PL	34.5	1.49	28.5	1.14	26.4	1.03	30.3	1.20
0.025	34.9	1.77	32.4	1.54	32.3	1.43	36.4	1.66
0.050	35.5	2.06	32.6	1.77	32.9	1.77	36.8	1.94
0.100	35.9	2.57	32.8	2.29	34.1	2.34	36.9	2.46
0.150	36.1	3.09	33.1	2.66	34.3	2.86	37.0	2.97
0.200	36.3	3.60	33.4	3.37	34.7	3.31	37.2	3.49
0.600	39.6	7.71	36.7	7.49	38.7	7.49	40.8	7.60
1.000	42.6	11.89	40.3	11.60	42.2	11.60	44.2	11.66
1.400	45.6	16.00	43.0	15.71	44.4	15.71	46.7	15.77
1.800	47.1	20.06	45.0	19.77	46.9	16.91	48.9	19.89
2.200	49.9	24.17	47.0	23.89	48.9	23.83	50.7	23.94
2.600	51.3	28.29	46.7	27.94	50.9	27.89	52.5	28.06
3.000	53.8	32.34	50.5	32.00	52.5	32.00	54.1	32.11
3.400	55.0	36.46	52.5	36.00	54.0	36.06	55.4	36.17
3.800	56.8	40.46	54.6	40.11	55.6	40.06	56.6	40.11

Table IV-9. *Individual Specimen Stress-Strain Parameters of Inconel 718 Plate in 34.5 MN/m² (5000 psig) Gaseous Environment*

OFFSET (PCT)	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3
	SN 8P1 297K (75F) 5000 PSIG HELIUM		SN 8P2 297K (75F) 5000 PSIG HYDROGEN		SN 8P3 297K (75F) 5000 PSIG HYDROGEN		SN 8P4 297K (75F) 5000 PSIG HYDROGEN	
PL	123.2	4.46	119.2	4.29	121.4	4.34	121.7	4.46
0.025	146.9	5.54	145.7	5.49	146.1	5.49	145.9	5.60
0.050	155.7	6.17	154.7	6.06	156.9	6.17	154.9	6.17
0.100	163.1	6.91	162.3	6.74	164.3	6.86	162.0	6.91
0.150	169.7	7.60	167.1	7.49	169.0	7.60	166.6	7.60
0.200	171.3	8.23	170.3	8.11	172.2	8.17	169.4	8.17
0.600	181.8	12.63	180.6	12.46	182.7	12.57	177.3	12.51
1.000	185.4	16.69	184.4	16.57	186.1	16.69	183.1	16.69
1.400	187.8	20.80	186.4	20.63	188.2	20.74	185.1	20.74
1.800	189.2	24.80	187.6	24.69	189.4	24.80	186.3	24.80
2.200	190.4	28.86	188.6	28.74	190.6	28.86	187.5	28.80
2.600	191.4	32.86	189.4	32.74	191.4	32.86	188.3	32.86
3.000	192.4	36.91	190.2	36.80	192.2	36.86	189.1	36.91
3.400	193.0	40.91	190.6	40.80	192.9	40.86	189.7	40.86
	SN 8P5 589K (600F) 5000 PSIG HELIUM		SN 8P6 589K (600F) 5000 PSIG HYDROGEN		SN 8P7 589K (600F) 5000 PSIG HYDROGEN		SN 8P8 589K (600F) 5000 PSIG HYDROGEN	
PL	116.2	4.51	121.2	4.74	109.2	4.17	111.1	4.29
0.025	135.7	5.71	140.8	5.71	131.3	5.26	132.5	5.31
0.050	143.1	6.29	148.3	6.29	140.3	5.83	140.6	5.89
0.100	149.9	7.09	154.5	6.97	147.3	6.63	147.5	6.63
0.150	154.1	7.77	158.6	7.66	151.3	7.26	152.1	7.31
0.200	156.5	8.34	161.2	8.29	154.3	7.83	154.7	8.00
0.600	165.7	12.69	169.1	12.57	163.3	12.23	163.6	12.29
1.000	169.5	16.74	171.9	16.63	167.3	16.34	167.1	16.40
1.400	171.3	20.86	173.5	20.74	169.7	20.40	169.1	20.46
1.800	172.5	24.91	173.9	24.74	170.9	24.46	170.3	24.51
2.200	173.7	28.97	174.5	28.74	172.3	28.51	171.5	28.57
2.600	176.8	32.97	175.4	32.74	173.1	32.57	172.5	32.57
3.000	177.8	37.03	175.6	36.74	173.9	36.63	172.9	36.57
3.400	178.2	41.03	175.8	40.80	174.7	40.63	173.9	40.63

Table IV-9. Individual Specimen Stress-Strain Parameters of Inconel 718 Plate in 34.5 MN/m² (5000 psig) Gaseous Environment (Continued)

OFFSET (PCT)	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3	STRESS (KSI)	STRAIN IN/IN*10-3
	SN 8P9 755K (900F) 5000 PSIG HELIUM		SN 8P10 755K (900F) 5000 PSIG HELIUM		SN 8P11 755K (900F) 5000 PSIG HYDROGEN		SN 8P12 755K (900F) 5000 PSIG HYDROGEN	
PL	107.9	4.40	107.2	4.40	107.2	4.40	106.2	4.23
0.025	129.3	5.54	125.3	5.31	127.5	5.43	128.3	5.31
0.050	137.4	6.11	133.3	5.89	135.1	6.00	136.1	5.89
0.100	143.2	6.86	140.5	6.69	141.9	6.86	142.3	6.63
0.150	147.3	7.54	144.5	7.37	145.7	7.49	146.1	7.26
0.200	149.7	8.11	147.1	8.00	148.5	8.11	148.5	7.89
0.600	159.4	12.51	156.3	12.40	157.9	12.46	158.1	12.23
1.000	162.2	16.57	158.9	16.40	160.9	16.57	160.3	16.29
1.400	163.8	20.63	160.9	20.46	162.5	20.69	162.1	20.34
1.800	165.1	24.69	161.9	24.57	163.5	24.69	162.7	24.40
2.200	166.1	28.74	163.1	28.57	164.9	28.69	163.7	28.46
2.600	167.3	32.74	163.7	32.63	165.3	32.74	164.3	32.46
3.000	168.1	36.86	164.5	36.69	165.7	36.74	164.7	36.46
3.400	168.7	40.80	165.3	40.69	166.3	40.74	166.1	40.51
	SN 8P13 922K (1200F) 5000 PSIG HELIUM		SN 8P14 922K (1200F) 5000 PSIG HYDROGEN		SN 8P15 922K (1200F) 5000 PSIG HYDROGEN		SN 8P16 922K (1200F) 5000 PSIG HYDROGEN	
PL	99.6	4.34	94.6	4.23	94.6	4.29	106.6	4.69
0.025	121.7	5.60	120.3	5.54	122.5	5.66	124.5	5.66
0.050	129.8	6.17	127.8	6.11	129.2	6.23	132.0	6.34
0.100	136.4	7.03	134.8	6.91	135.8	7.03	138.4	7.03
0.150	140.0	7.66	138.6	7.54	139.4	7.71	142.1	7.71
0.200	142.9	8.23	141.4	8.23	141.9	8.29	144.7	8.29
0.600	152.5	12.69	150.7	12.63	151.3	12.74	154.1	12.74
1.000	156.3	16.86	154.3	16.74	155.1	16.91	157.9	16.91
1.400	158.6	20.91	156.3	20.80	157.1	20.97	160.4	20.97
1.800	160.2	24.97	157.5	24.91	158.6	25.03	161.6	25.03
2.200	161.4	29.03	158.8	28.91	159.4	29.03	162.8	29.03
2.600	162.2	33.03	159.2	32.91	160.4	33.03	163.4	33.09
3.000	163.0	37.09	159.6	36.97	160.8	37.14	164.4	37.14
3.400	163.6	41.09	160.0	40.97	161.2	41.14	164.8	41.20

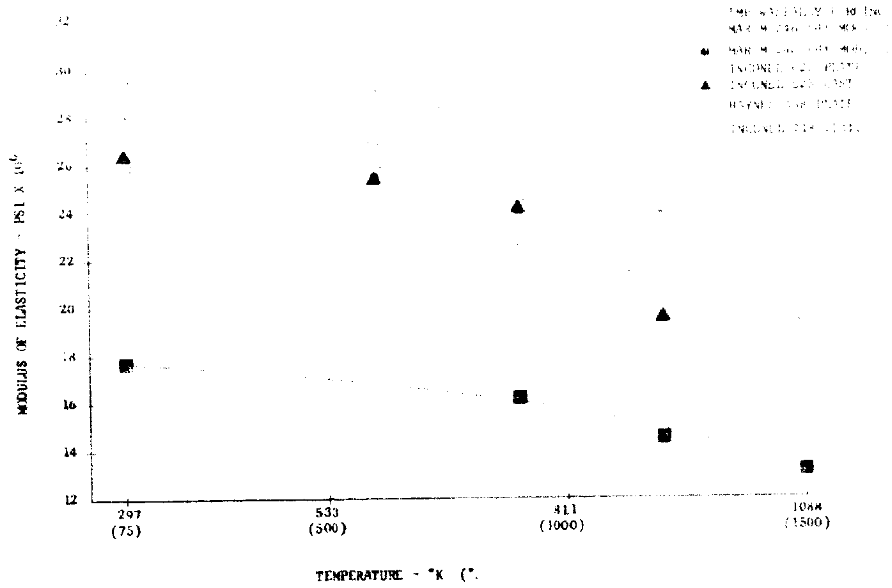


Figure IV-29. Effect of Temperature on Modulus of Elasticity of Various Alloys

Table IV-10. Degradation of Ambient Air Tensile Properties of MAR M-246 (Hf Modified) After 8-Hour 1144°K (1600°F) 34.5 MN/m² (5000 psig) Gaseous Hydrogen Exposure

		Ambient Air Set Time (hr) After Exposure		*Degradation (Decrease from Helium Exposed Material, %)*			
				Strength		*Ductility*	
Material Form	*Stress Concentration Factor*	*0*	*24*	*0.2% Yield*	*Ultimate*	*EL*	*RA*
Directionally Solidified	Smooth	X		ND[1]	ND	42	25
	Smooth		X	ND	20	68	32
	8.0	X			ND		
	8.0		X		D		
Conventionally Cast	Smooth	X		ND	12	73	ND
	Smooth		X	ND	ND	82	17
	8.0	X			27		
	8.0		X		23		

---

[1] Negligible degradation indicated (less than 10%) or property in hydrogen greater than in helium.

However, for the hydrogen exposed DS material, increased property degradation was indicated with increased air set time. To aid in explaining this behavior a metallographic investigation was conducted. Through optical and electron metallography, no correlation of test condition with fracture appearance was apparent, except for a more ductile fracture appearance evident in those specimens with higher ductility values (figure IV-30). No evidence of overtemperature or material anomalies were observed at the fracture faces. All specimens had similar microstructure with exception of SDS-4 which showed colonies of unsolutioned large γ' associated with alloy-rich areas with eutectic γ'. These colonies were not evident in the other specimens (figure IV-31). This discrepancy in microstructure of one specimen does not explain the material behavior.

Due to the limited number of specimens tested and data scatter, characteristic of cast materials, these conclusions are tenative.

Test results for each specimen tested are listed in table IV-11.

C. TEST PROCEDURE

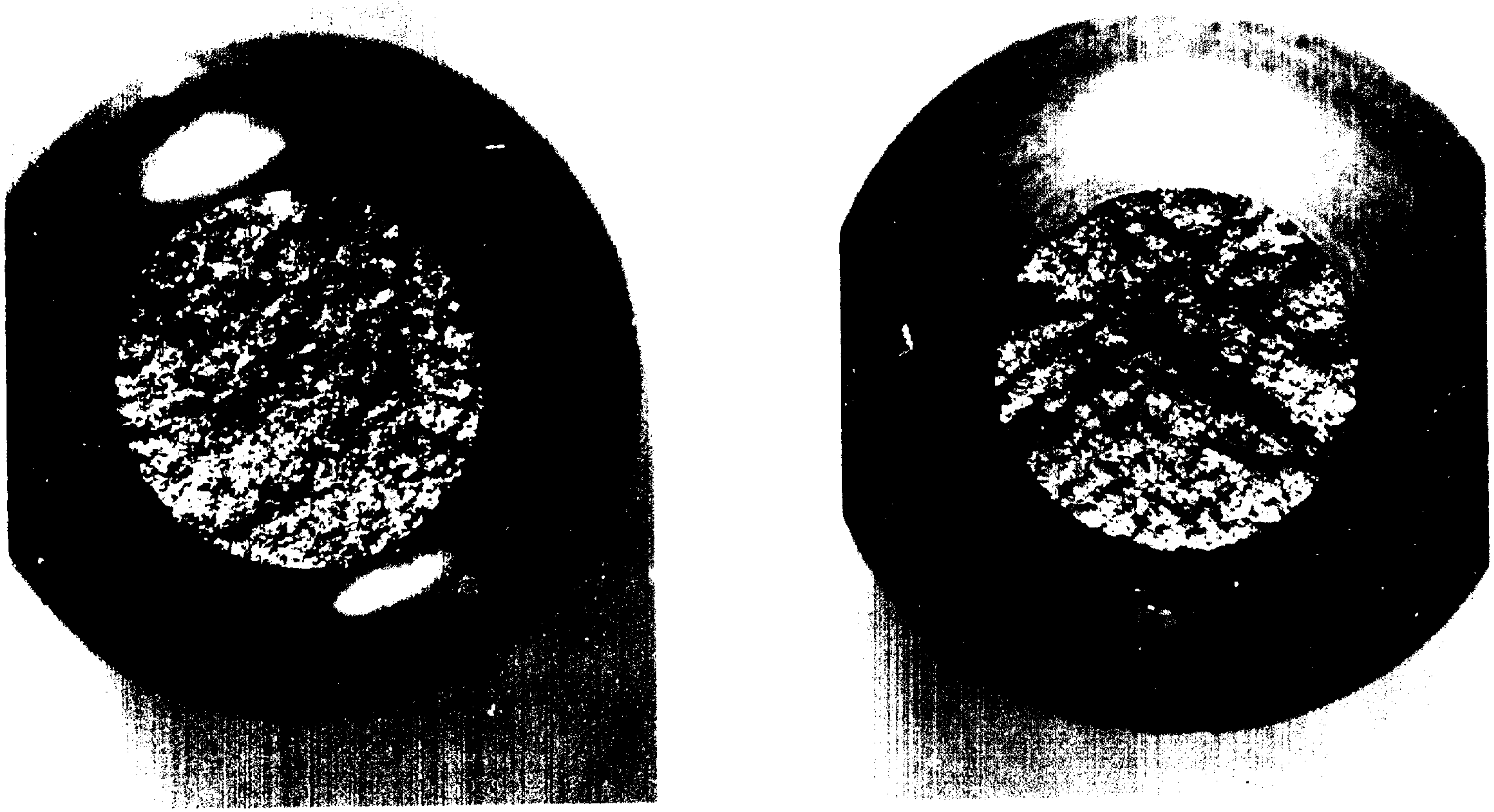
All tensile tests were conducted per ASTM E8-69, "Tension Testing of Metallic Materials," using five specimen designs. The test specimen utilized depended upon the type of test conducted (smooth or notched) and the size of the furnished raw materials. In the Exhibit B effort, only smooth tests were conducted. The test specimen (FML 96311), shown in figure III-3, was used for the majority of the materials with the exception of the cast Inconel 625 and the CC MAR M-246 (Hf Modified). A cast-to-size specimen (figure III-2) was used for the cast Inconel 625 tests and specimen FML 95226M, shown previously in figure III-5, for the CC MAR M-246 (Hf Modified). For the Exhibit C IHE tensile tests, both smooth and notched ($K_T=8.0$) specimens were tested. The DS material was evaluated utilizing FML 96311 (figure III-3) and FML 96312 (figure III-4) for smooth and notched tests, respectively. For the CC material, FML 95226M and FML 96462 (figure III-6) were used. All test specimens are described previously in Section III and shown in figure III-2.

For the IHE tensile testing all specimens were exposed to either 34.5 MN/m^2 (5000 psig) helium or hydrogen environment at 1144°K (1600°F) for 8 hours. After exposure and cooling of test specimens to 297°K (75°F), the test vessel was opened and specimens were tested in ambient air immediately and/or 24 hours later.

Smooth specimens were tested at a strain rate of 0.005 mm/mm/min (in./in./min) to yield and a crosshead speed of 1.27 mm/min (0.05 in./min) from yield to fracture. Notch specimens were tested at a crosshead speed of 1.27 mm/min (0.05 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-32 and IV-33.

Various views of the pressure vessel showing specimen, extensometer, and furnace setup are presented in figure IV-33. 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 eliminated the effect of loads resulting from differential specimen and adapter cross-sectional areas.



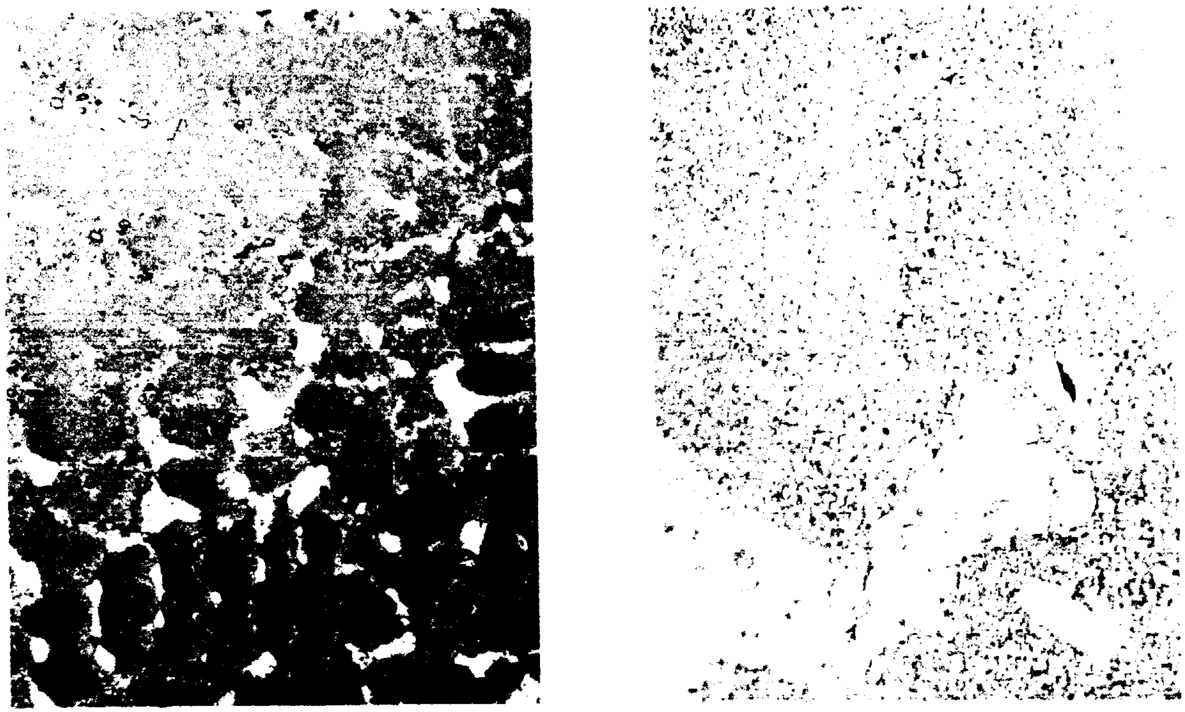
Mag: 8X FAL 37494

a. Specimen SDS-5 Showing Brittle Fracture

Mag: 8X FAL 37499

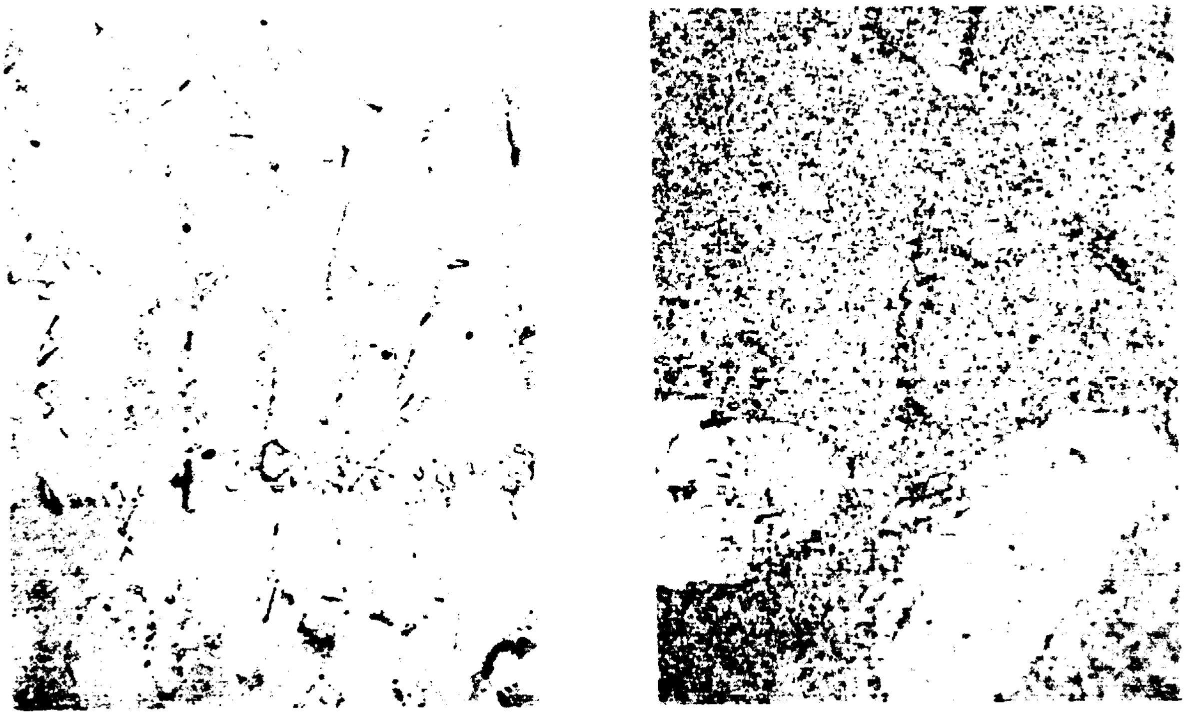
b. Specimen SDS-6 Showing Relatively Ductile Fracture

Figure IV-30. Macrographs of Failed Directionally Solidified MAR M-246 (Hf Modified) Internal Hydrogen Embrittlement Tensile Test Specimens



Mag: 100X Mag: 1000X

a. Specimen SDS-4 Showing Colonies of Unsolutioned Large δ'



Mag: 100X Mag: 1000X

b. Specimen SDS-5 Showing Typical DS Material Structure

FD 90343

Figure IV-31. Micrographs of Directionally Solidified MAR M-246 (Hf Modified) Internal Hydrogen Embrittlement Tensile Test Specimens

Table IV-11. *Tensile Properties of MAR M-246 (Hf Modified) After 8-Hour 1144°K (1600°F) 34.5 MN/m^2 (5000 psig) Gaseous Environment Exposure*

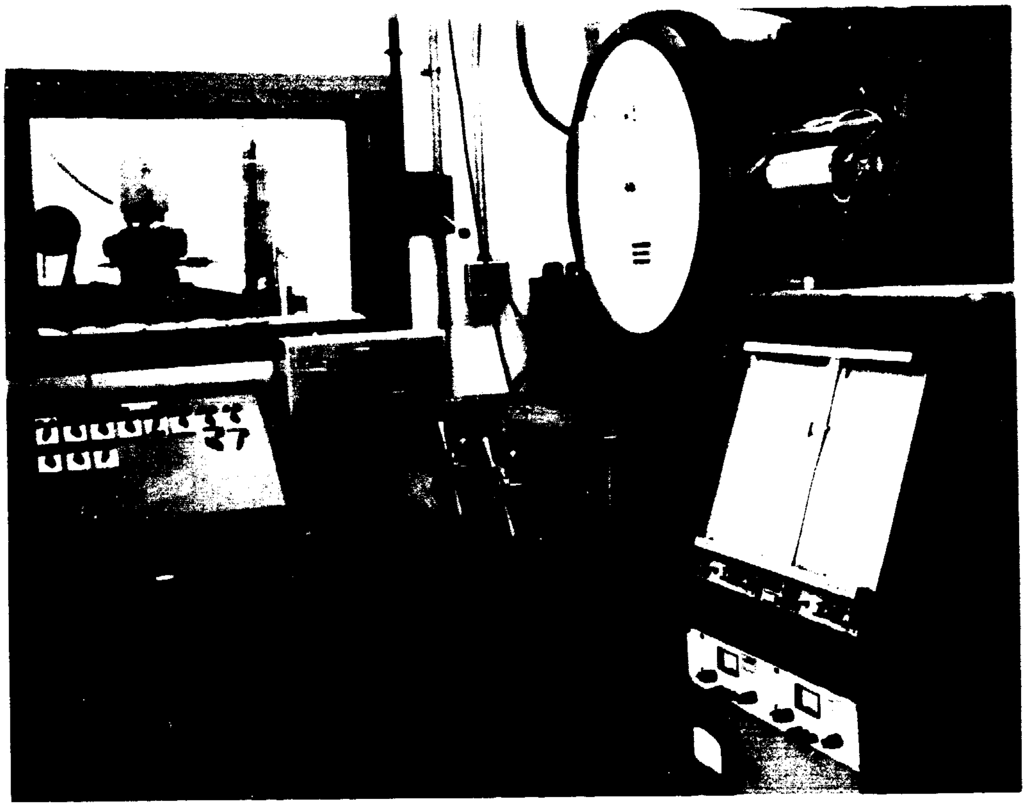
Material Form	Spec S/N[1]	Exposure Environment	Ambient Air Set Time (hr) After Exposure		Ambient Air Test Results						
					Strength				Ductility		Modulus of Elasticity
					0.2% Yield		Ultimate		EL[2]	RA	
			0	24	MN/m^2	ksi	MN/m^2	ksi	%	%	psi × 10^6
Directionally Solidified	SDS-1	Hydrogen	X		943.2	136.8	1028.0	149.1	5.3	6.7	18.6
	SDS-2	Hydrogen	X		926.0	134.3	985.9	143.0	4.5	9.4	18.4
	SDS-3	Helium	X		894.2	129.7	945.3	137.1	8.5	10.8	19.2
	SDS-4	Hydrogen		X	875.6	127.0	961.1	139.4	4.5	8.9	18.6
	SDS-5	Hydrogen		X	916.3	132.9	955.6	138.6	3.9	7.1	18.4
	SDS-6	Helium		X	894.2	129.7	1192.1	172.9	13.0	11.8	18.0
	NDS-1	Hydrogen	X				1381.7	200.4			
	NDS-2	Hydrogen	X				1289.3	187.0			
	NDS-3	Helium	X				1283.1	186.1			
	NDS-4	Hydrogen		X			1183.8	171.7			
	NDS-5	Hydrogen		X			1415.5	205.3			
	NDS-6	Helium		X			1439.6	208.8			
Conventionally Cast	SCC-1	Hydrogen	X		835.0	121.1	852.2	123.6	0.7	4.0	27.3
	SCC-2	Hydrogen	X		867.4	125.8	875.6	127.0	0.5	4.0	28.2
	SCC-3	Helium	X		920.4	133.5	983.9	142.7	2.2	4.2	29.6
	SCC-4	Hydrogen		X	868.7	126.0	887.4	128.7	0.4	4.0	27.4
	SCC-5	Hydrogen		X	834.3	121.0	852.2	123.6	0.7	4.0	29.8
	SCC-6	Helium		X	829.4	120.3	902.5	130.9	3.0	4.8	24.4
	NCC-1	Hydrogen	X				1020.4	148.0			
	NCC-2	Hydrogen	X				931.5	135.1			
	NCC-3	Helium	X				1339.6	194.3			
	NCC-4	Hydrogen		X			1008.7	146.3			
	NCC-5	Hydrogen		X			1009.4	146.4			
	NCC-6	Helium		X			1314.8	190.7			

---

[1] NDS and NCC are Notch specimens, $K_t = 8.0$

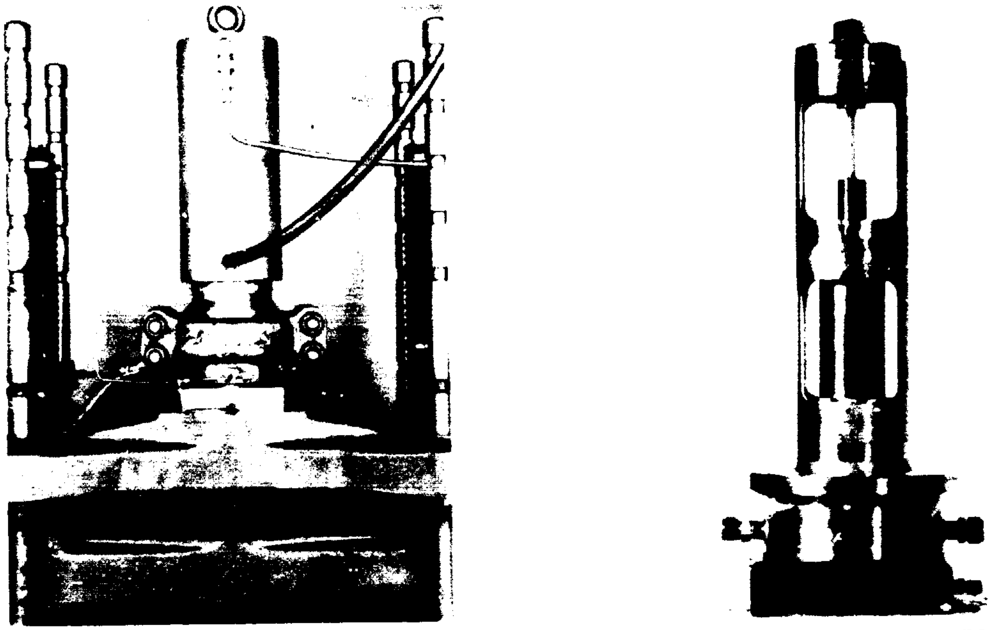
[2] Elongation based on gage length of 4D. For the CC material elongation was measured off load-deflection curve (plastic portion).

ORIGINAL PAGE IS
OF POOR QUALITY



[illegible]

Figure IV-32. Tensile Machine, Test Environmental Controls and Data Acquisition Equipment

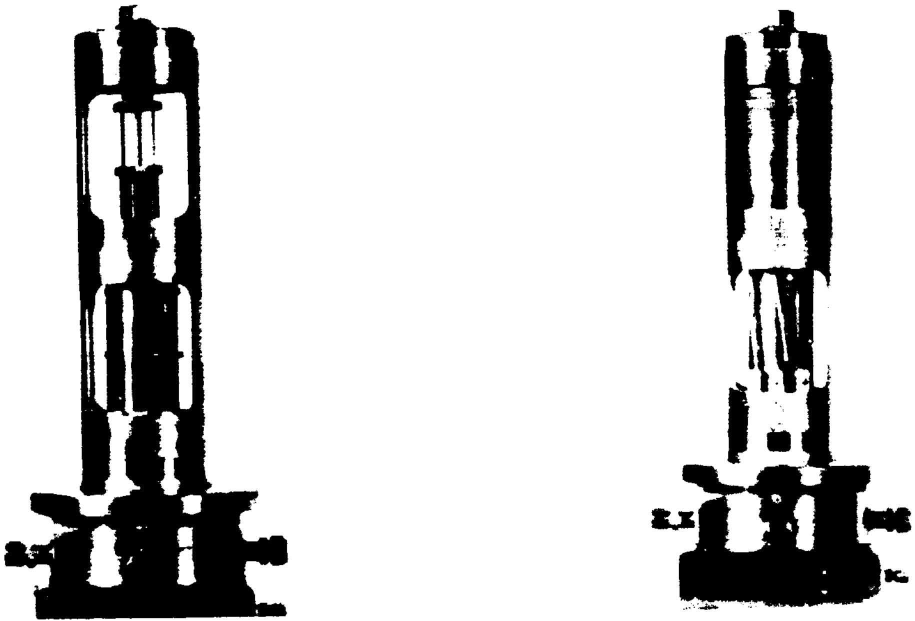


FC 42236

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

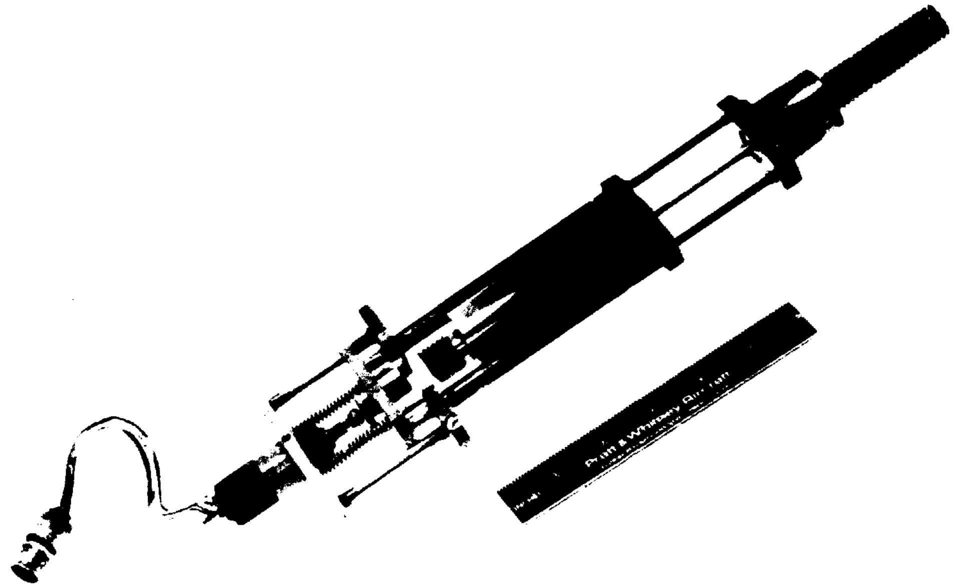
FAE 146119

d) Test Vessel Open With Furnace Attached

[illegible]

Figure IV-33. Setups of Tensile Test Vessel

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-34). 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.



FE 130126

Figure IV-34. 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-33d). 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°C.

Prior to test, specimens were rinsed with trichloroethylene, 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, gas supply and sampling system to an indicated vacuum of 0.101 MN/m^2 (30 in. Hg).

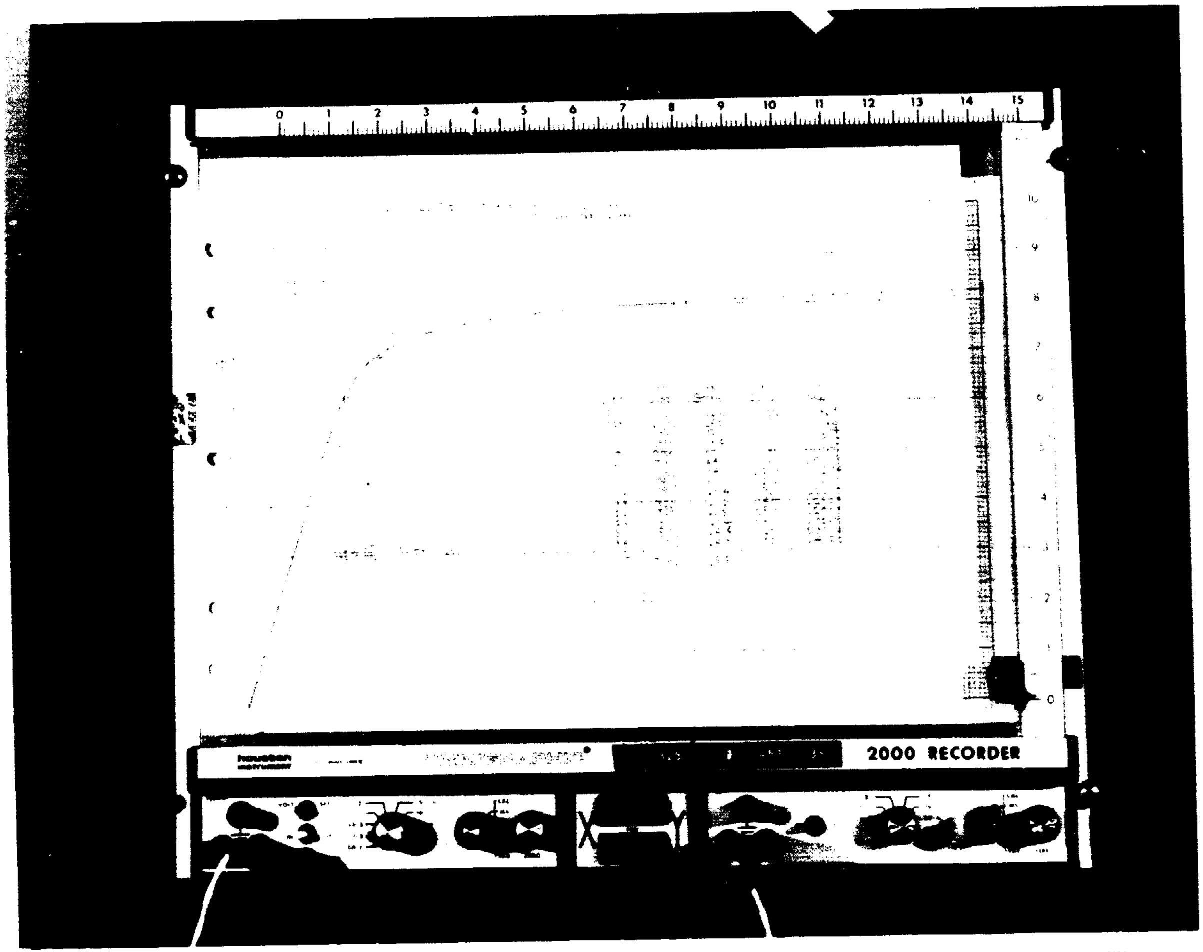
5. Pressure purge to 3.45 MN/m² (500 psig) with hydrogen gas three times, obtain pretest gas sample.
6. Pressurize to 34.5 MN/m² (5000 psig) with hydrogen gas and conduct test.
7. Reduce pressure to obtain post-test gas sample, vent to atmospheric pressure, flow and pressure purge with nitrogen gas, 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/m² (50 psig) with nitrogen gas; leak check, and vent.
3. Evacuate pressure vessel and gas supply to an indicated vacuum of 0.101 MN/m² (30 in. Hg).
4. Pressure purge to 3.45 MN/m² (500 psig) with helium three times.
5. Pressurize to 34.5 MN/m² (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 parameters 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-35.

In determining specimen elongation, the standard, most often used, method (fitting together the fractured specimen and measuring the distance between gage marks with dividers and scale) was used. However, because of the low ductility of the conventionally cast MAR M-246 (Hf Modified), and the fact that for the IHE tensile tests a substandard specimen with a short 12.7 mm (0.5 inch) 4D gage length, had to be utilized, inherent error in the standard method measuring technique precluded measurement for values of elongation less than 2%. Therefore, elongation of the CC specimens was measured from the plastic portion of the load-deflection curves. This approach yielded values less than 2% to within approximately 0.1% accuracy. Typical load-deflection curves for hydrogen and helium exposed CC material IHE tensile tests are shown in figures IV-36 and IV-37.



FE 151[illegible]

Figure IV-35. Typical Load-Deflection (Stress-Strain) Curve

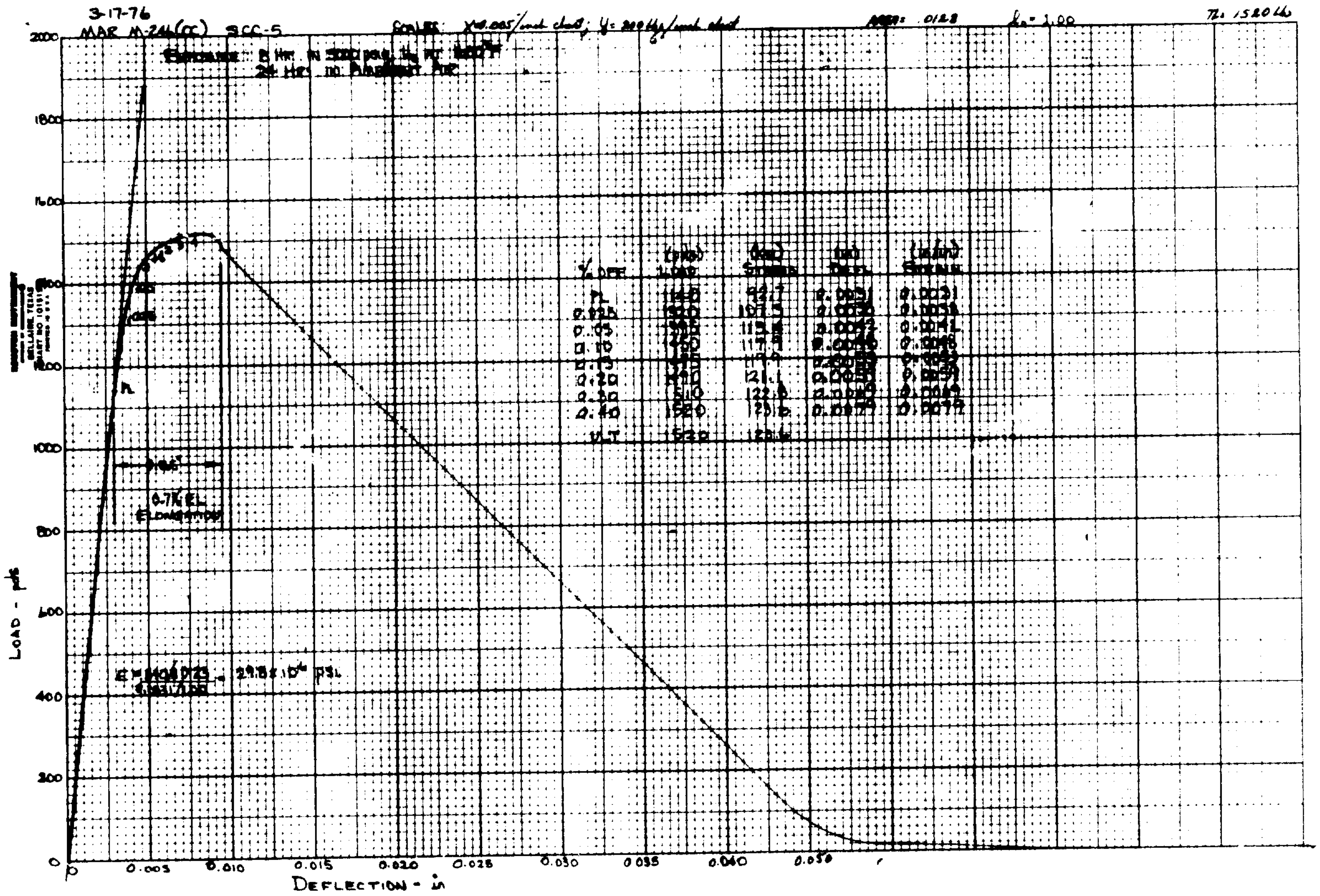


Figure IV-30. Load-Deflection (Stress-Strain) Curve for IHE Tensile Test SCC-5

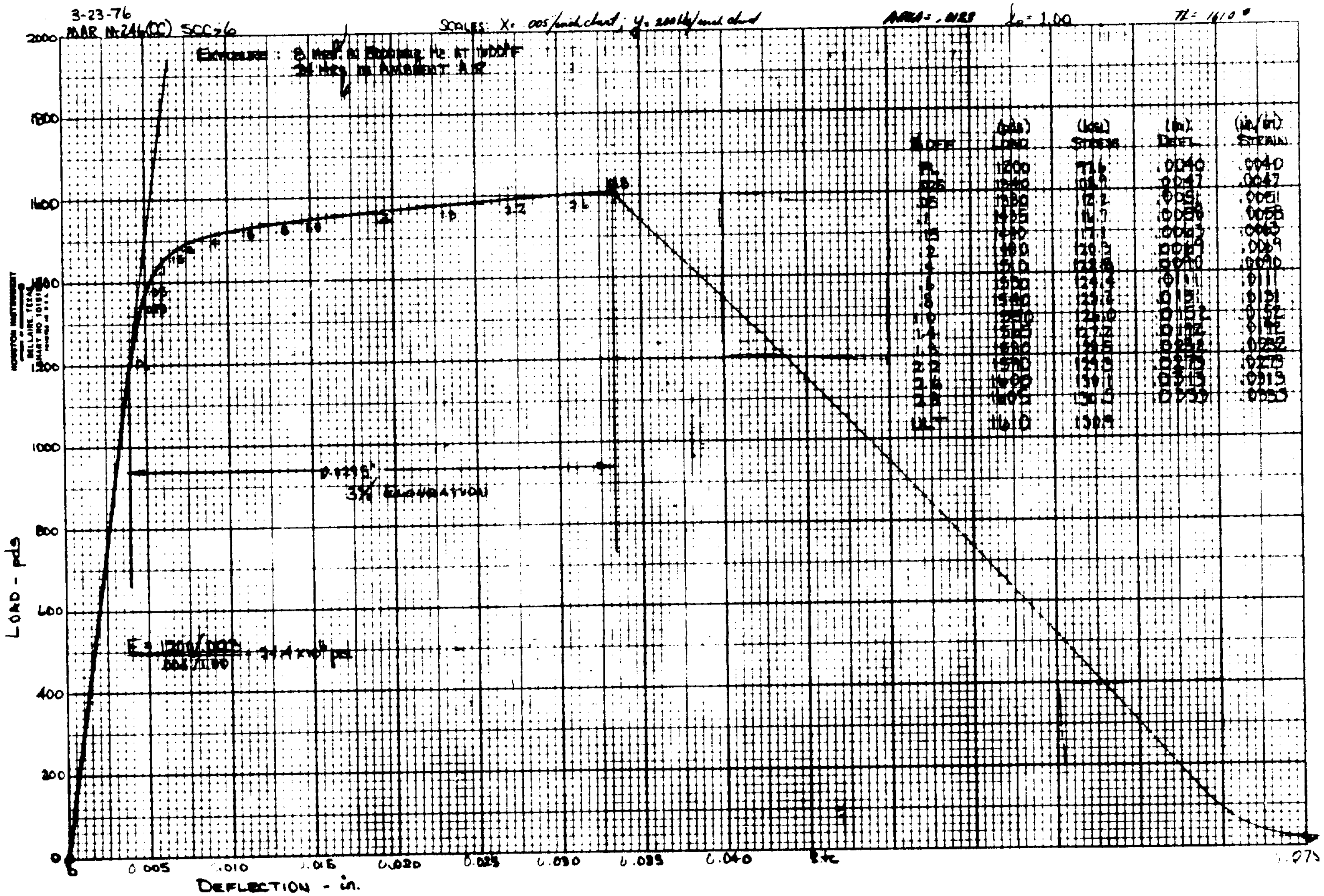


Figure IV-37. Load-Deflection (Stress-Strain) Curve for IHE Tensile Test SCC-6

SECTION V
LOW-CYCLE FATIGUE

A. INTRODUCTION

Low-cycle fatigue (LCF) tests were conducted under Exhibit C of this contract to establish the LCF life of MAR M-246 (Hf Modified) in two cast conditions, conventionally cast (CC) and directionally solidified (DS), in 34.5 MN/m² (5000 psig) helium and hydrogen environments at 1033°K (1400°F) and 1144°K (1600°F). Comparison of results in hydrogen environment to results of similar tests in helium environment established degradation in cyclic life due to the hydrogen environment.

The LCF tests were of both the strain-control and load-control type. It was intended that all LCF tests be in the strain-control mode. However, the limited size of the CC material, supplied by NASA in the form of cast-to-size specimens (figure III-2), necessitated the use of the load-control fatigue test in lieu of strain-control as used in the DS material tests. Upon completion of the CC material tests several load-control DS material tests were conducted for a material comparison.

The strain-control LCF tests consisted of a compressive start with the material cycling through a constant total strain range (elastic plus plastic) 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. Test strains were selected to establish LCF life between 100 and 1000 cycles.

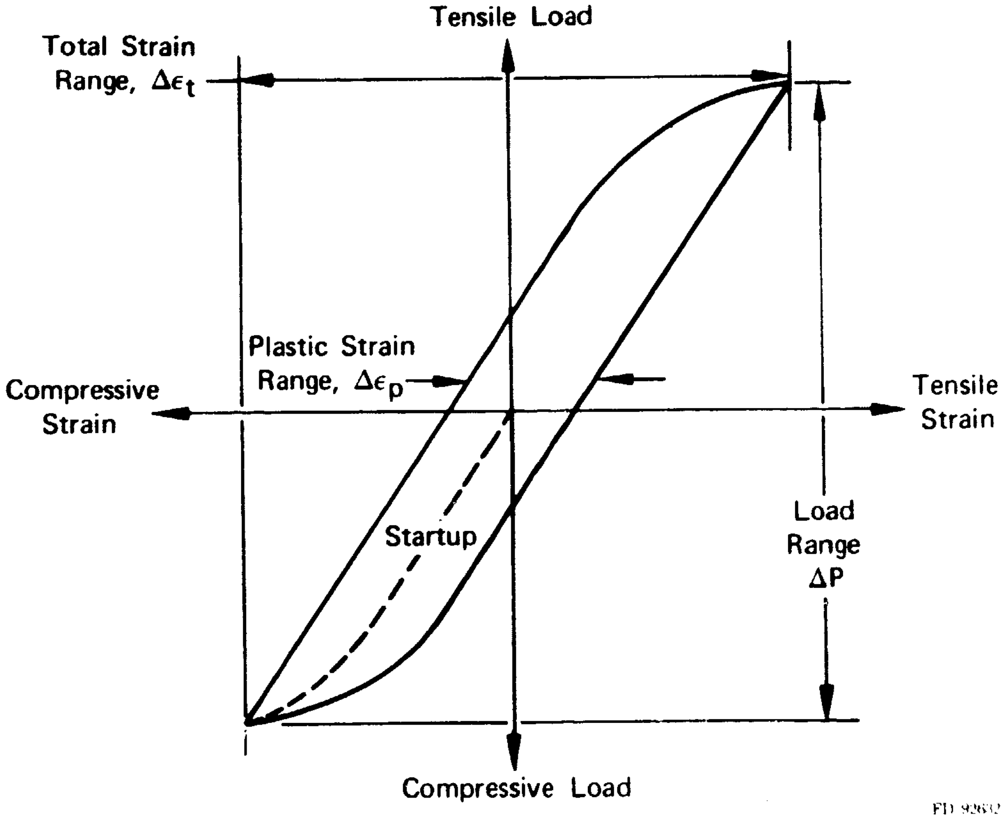
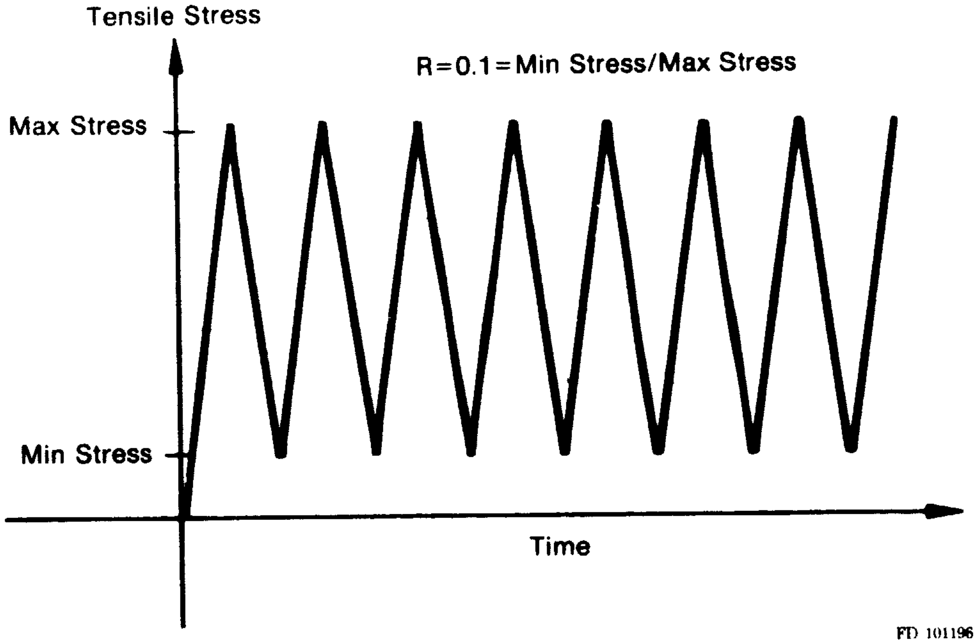


Figure V-1. Typical Load-Strain Hysteresis Curve Obtained During a Specimen Low-Cycle Fatigue Test

The load-control LCF tests, consisted of a tension-to-tension cycle with load (stress) varying about a constant tensile preload at a cyclic rate of 9 cpm. All specimens were tested at an R ratio (minimum stress/maximum stress) of 0.1 (figure V-2), with a sawtooth wave form. Test stress levels were selected to obtain specimen failure within 1000 to 10,000 cycles.



FD 101196

Figure V-2. Typical Load-Control Low-Cycle Fatigue Test Cycle

B. RESULTS AND CONCLUSIONS

The MAR M-246 (Hf Modified) material in the DS form exhibited negligible degradation, in strain-control LCF life. However, the CC material exhibited considerable degradation in load-control LCF life. The material forms evaluated, the test types and the degradations observed are listed in table V-1.

Table V-1. Degradation of MAR M-246 (Hf Modified) Low-Cycle-Fatigue Life Due to 34.5 MN/m² (5000 psig) Hydrogen Environment

Material Form	Type of Test	Test Temperature °K	Test Temperature °F	Degradation (Decrease From Helium, %) in Life at Mean of Strain Ranges or Stress Range Tested
Directionally Solidified	Strain Control	1033	1400	ND[1]
	(Mean Strain=0)	1144	1600	ND
Conventionally Cast	Load Control	1033	1400	35
	(R, min stress/max stress=0.1)	1144	1600	57
Directionally Solidified	Load Control	1033	1400	65
	(R=0.1)	1144	1600	61

---

[1] Negligible Degradation - Degradation less than 10% or hydrogen life greater than helium.

No degradation in the DS material strain-control LCF life was indicated at 1033°K (1400°F) due to the hydrogen environment. At 1144°K (1600°F) a slight reduction of 12% in life was indicated at the higher strain range of 2.8%. Strain-control LCF cyclic strain vs cycles to failure curves for the DS material in 34.5 MN/m^2 (5000 psig) helium and hydrogen at 1033°K (1400°F) and 1144°K (1600°F) are shown in figures V-3 and V-4, respectively. The effect of temperature and strain range upon degradation is illustrated in figure V-5. The strain-control LCF test results for each specimen tested are listed in table V-2.

The CC material exhibited considerable degradation in load-control LCF life at 1033°K (1400°F) and 1144°K (1600°F) due to the hydrogen environment. Maximum stress vs cycles to failure curves in helium and hydrogen at 1033°K (1400°F) and 1144°K (1600°F) are shown in figures V-6 and V-7, respectively, which also show approximate strain range scales. At both test temperatures, increased hydrogen degradation resulted with increased maximum stress. The effect of temperature and maximum stress on hydrogen degradation of the CC material load-control LCF life are illustrated in figure V-8. Complete load-control LCF test results are listed in table V-3.

Four DS material load-control LCF tests were conducted to enable a comparison between the two cast materials in 34.5 MN/m^2 (5000 psig) hydrogen. Based on minimal testing, a single helium and hydrogen test at each temperature, the DS material load-control LCF life was degraded 65 and 61%, at 1033°K (1400°F) and 1144°K (1600°F) respectively, due to the hydrogen environment. This reduction in load-control LCF life was greater than that of the CC material as shown previously in table V-1.

The extreme degree of degradation obtained in the DS material load-control LCF test results is contrary to that obtained for the strain-control tests. In the strain-control mode negligible degradation, if any, resulted due to the hydrogen environment. This occurrence was similar to that noted for MAR M-200 DS material reported in PWA FR 5768, (Contract NAS8-26191) where strain-control tests indicated negligible degradation and load-control tests indicated extreme degradation in fatigue life. A CC material, IN-100, tested at that same time indicated more consistant degradation results between the two types of test. The initial inclination, based upon the limited number of DS material tests was to attribute this difference in degradation to data scatter associated with the load-control test. However, it has occurred for two different DS materials and it appears there may be some mechanism unique to the DS material that is influencing degradation results.

Metallurgical examination of the failed specimens indicated no significant differences which could account for the variations in degradation between tests. One specimen, LLDS-3, did have an internal origin from a hafnium rich carbide inclusion, shown in figure V-9. This alone will not account for the difference in degradation between the two tests, and further mechanistic studies are required to explain that occurrence.

C. TEST PROCEDURE

Smooth, round, solid specimens were used for the LCF tests conducted under this contract. The strain-control test specimen used is described in Section III and detailed in figure III-9. The specimen configuration incorporates integral machined extensometer collars (figure V-10). 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. Two load-control specimens were used in this program. The CC material load-control specimens were furnished by NASA in the cast-to-size configuration shown previously in figure III-2. The DS material load-control specimen is also shown previously in figure III-2 and detailed in figure III-10.

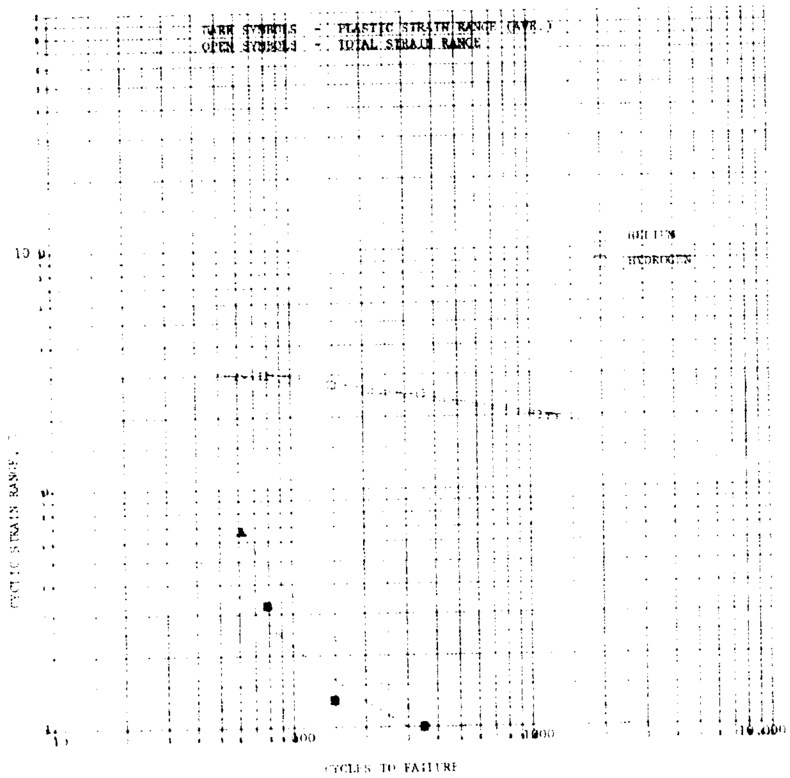


Figure V-3. Low-Cycle Fatigue Life of Directionally Solidified (DS) MAR M-246 (Hf Modified) in 34.5 MN/m² (5000 psig) Helium and Hydrogen at 1033°K (1400°F)

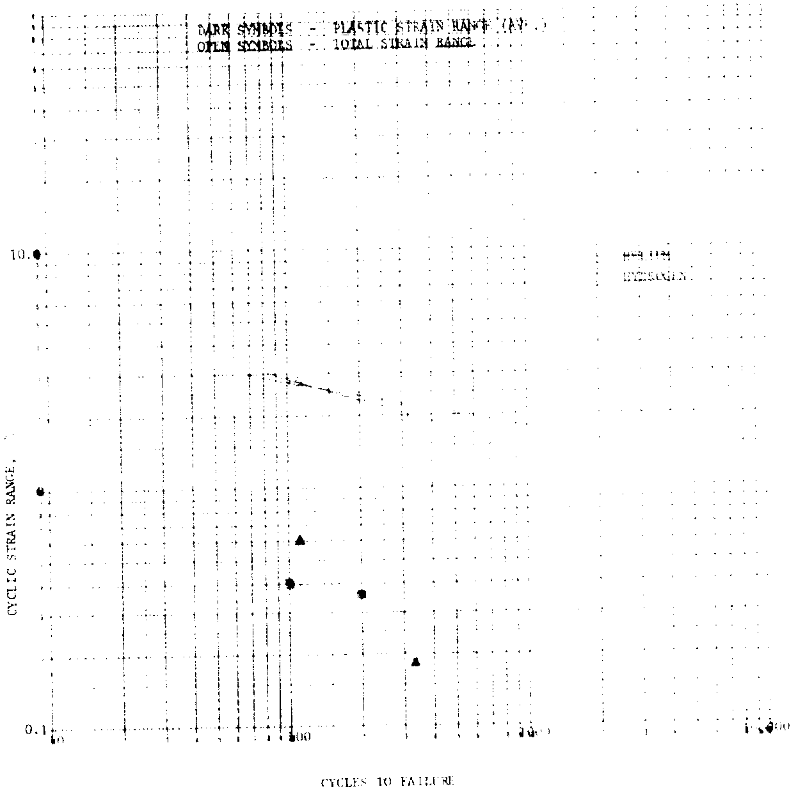


Figure V-4. Low-Cycle Fatigue Life of Directionally Solidified (DS) MAR M-246 (Hf Modified) in 34.5 MN/m² (5000 psig) Helium and Hydrogen at 1144°K (1600°F)

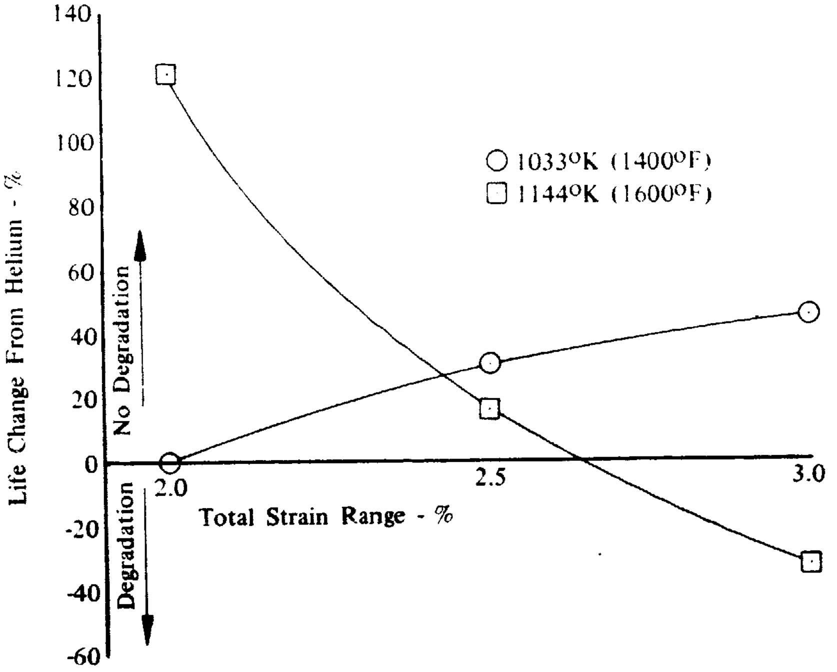


Figure V-5. Effect of Temperature and Strain-Range on Hydrogen Degradation of Directionally Solidified (DS) MAR M-246 (Hf Modified) Strain-Control Low-Cycle Fatigue Life

Table V-2. Strain-Control Low-Cycle Fatigue Properties of Directionally Solidified (DS) MAR M-246 (Hf Modified) in 34.5 MN/m² (5000 psig) Helium and Hydrogen

	Test Conditions				*Test Results*			
Specimen	*Test Temperature*			*Total Strain Range*[1]	*Cycles to*	*Plastic Strain Range, %*		
S/N	*°K*	*°F*	*Environment*	*%*	*Failure*[2]	*Min*	*Max*	*Ave*
LDS-1	1033	1400	Hydrogen	3.00	78	0.27	0.39	0.33
LDS-2	1033	1400	Hydrogen	2.00	1074	0.06	0.08	0.07
LDS-3	1033	1400	Hydrogen	2.50	352	0.08	0.11	0.10
LDS-4	1033	1400	Hydrogen	2.75	148	0.08	0.17	0.13
LDS-5	1033	1400	Helium	3.00	62	0.51	0.82	0.67
LDS-6	1033	1400	Helium	2.00	1249	0.03	0.04	0.04
LDS-7	1144	1600	Hydrogen	2.00	[3]220	0.30	0.30	0.30
LDS-8	1144	1600	Hydrogen	2.40	201	0.31	0.34	0.33
LDS-9	1144	1600	Hydrogen	1.60	1861	0.03	0.04	0.03
LDS-10	1144	1600	Hydrogen	2.80	98	0.38	0.41	0.40
LDS-11	1144	1600	Helium	2.80	111	0.53	0.67	0.60
LDS-12	1144	1600	Helium	2.00	331	0.15	0.22	0.18

---

[1] Mean Strain 0
[2] Cyclic Rate, 4 cycles/min
[3] Test rig malfunction, specimen overloaded.

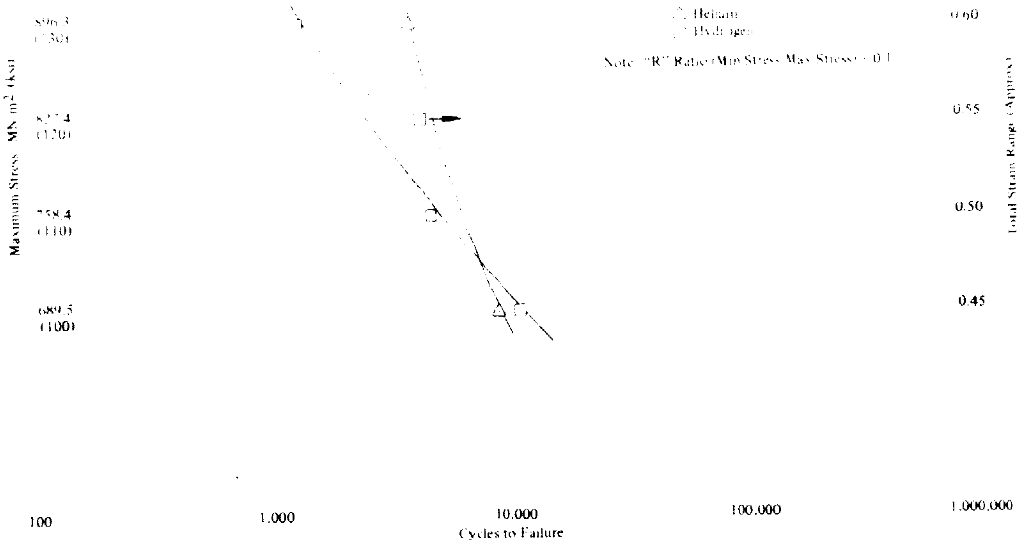


Figure V-6. Load-Control Low-Cycle Fatigue Life of Conventionally Cast (CC) MAR M-246 (Hf Modified) in 34.5 MN/m² (5000 psig) Helium and Hydrogen at 1033°K (1400°F)

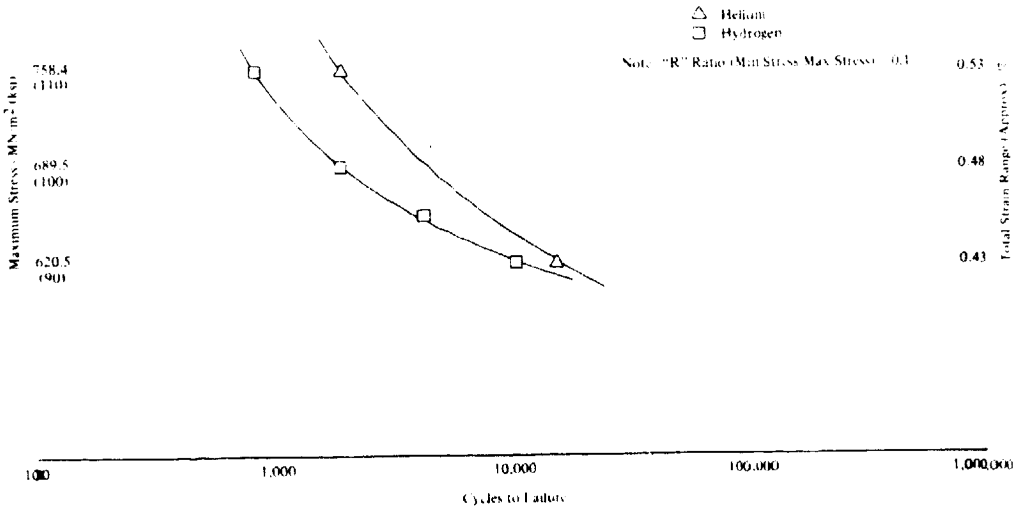
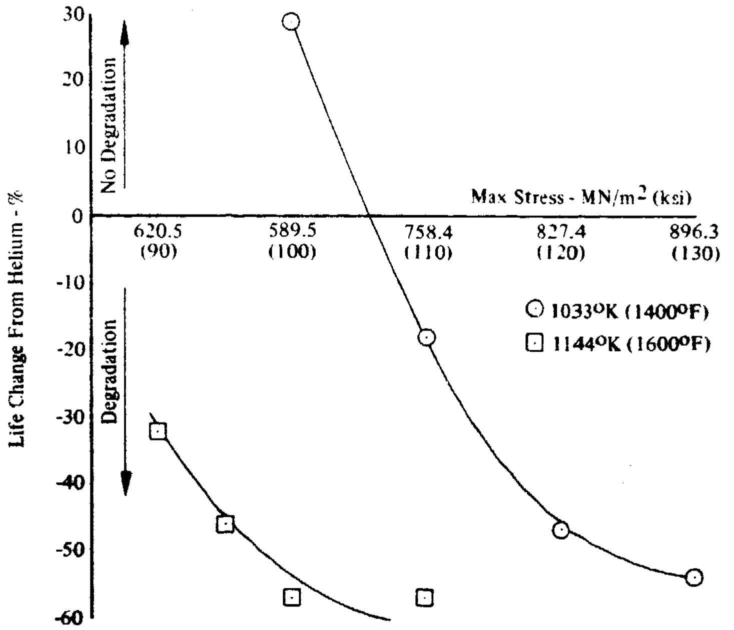


Figure V-7. Load-Control Low-Cycle Fatigue Life of Conventionally Cast (CC) MAR M-246 (Hf Modified) in 34.5 MN/m² (5000 psig) Helium and Hydrogen at 1144°K (1600°F)



DF 102400

Figure V-8. Effect of Temperature and Maximum Stress on Hydrogen Degradation of Conventionally Cast MAR M-246 (Hf Modified) Load-Control Low-Cycle Fatigue Life

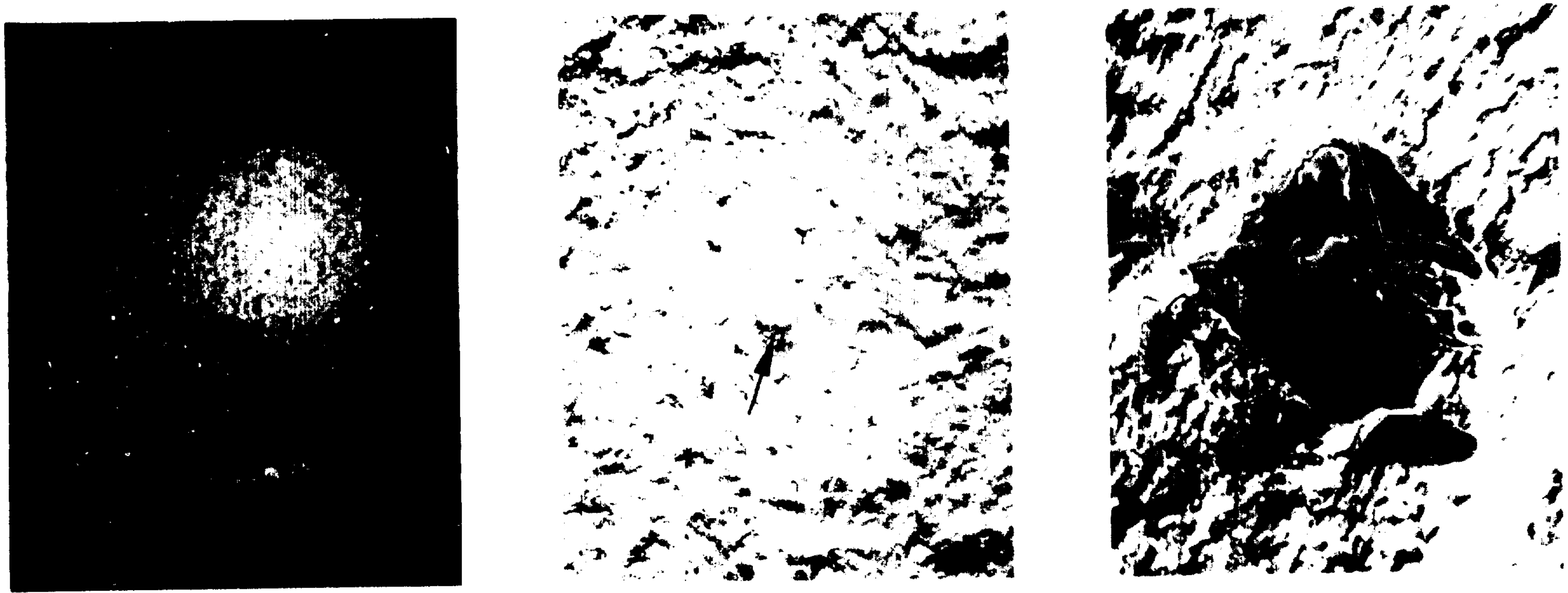
Table V-3. Load-Control LCF[1] Properties of MAR M-246 (Hf Modified) in 34.5 MN/m^2 (5000 psig) Helium and Hydrogen

		Test Conditions					Test Results	
		Test Temperature			Maximum Stress		Approximate Total Strain Range	
Material Form	Specimen S/N	°K	°F	Environment	MN/m^2	ksi	%	Cycles to Failure
Conventionally Cast	LCC-2	1033	1400	Hydrogen	758.4	110	0.50	4,631
	LCC-3	1033	1400	Hydrogen	827.4	120	0.54	[2]4,230
	LCC-4	1033	1400	Hydrogen	896.3	130	0.59	1,341
	LCC-5	1033	1400	Hydrogen	689.5	100	0.45	10,661
	LCC-11	1033	1400	Helium	896.3	130	0.59	3,904
	LCC-12	1033	1400	Helium	689.5	100	0.45	8,698
	LCC-6	1144	1600	Hydrogen	689.5	100	0.48	1,935
	LCC-7	1144	1600	Hydrogen	620.5	90	0.43	10,450
	LCC-8	1144	1600	Hydrogen	758.4	110	0.53	863
	LCC-10	1144	1600	Hydrogen	655.0	95	0.4[illegible]	4,283
	LCC-13	1144	1600	Helium	620.5	90	0.43	15,398
	LCC-14	1144	1600	Helium	758.4	110	0.53	1,989
Directionally Solidified	LLDS-3	1033	1400	Helium	896.3	130	0.87	40,375
	LLDS-1	1033	1400	Hydrogen	896.3	130	0.87	14,022
	LLDS-4	1144	1600	Helium	758.4	110	0.83	32,958
	LLDS-2	1144	1600	Hydrogen	758.4	110	0.83	12,993

---

[1] "R" ratio (min stress/max stress) of 0.1, cyclic frequency 9 cpm

[2] Premature specimen fracture due to power failure.



Mag: 10X

(a) Fracture Face

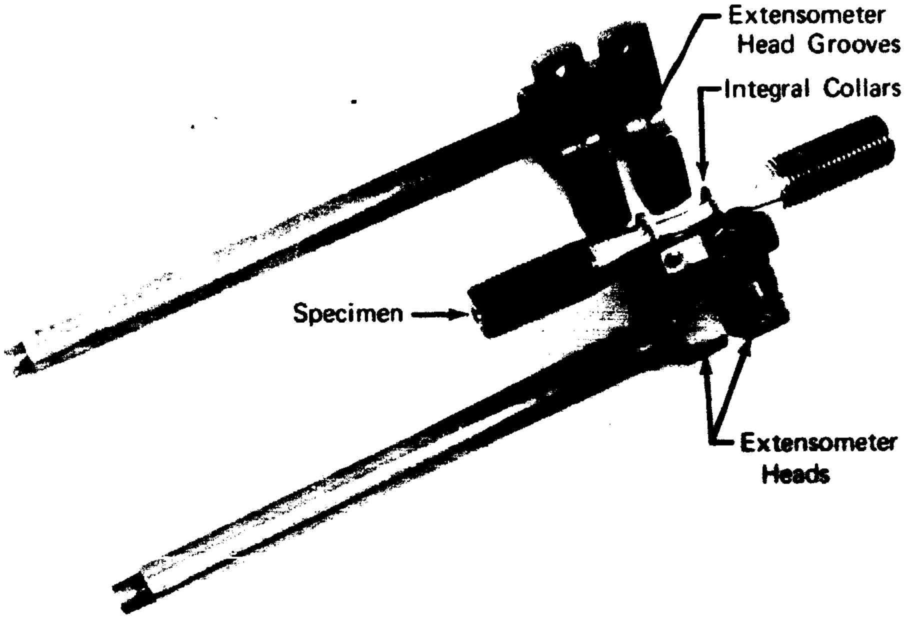
Mag: 40X

(b) Fracture Face Showing Fatigue Origin (Arrow)

Mag: 500X

(c) Hafnium Rich Carbide Inclusion at Fatigue Origin

Figure V-9. Macrographs and Micrograph of Fractured Load-Control LCF Specimen LLDS-3, Tested in Helium, Which Has an Internal Fatigue Origin



FD 92638

Figure V-10. Open Extensometer Head Assembly and Strain-Control Low-Cycle Fatigue Specimen

All tests were conducted on a P&WA/Florida designed and fabricated, closed-loop type, hydraulically actuated test machine capable of operation in both the strain-and load-control mode. The test machine is located in an isolated test cell with all controls and instrumentation located in an adjacent blockhouse (figure V-11). 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 (for strain control tests), 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 for the strain-control tests and furnace arrangement are shown in figure V-12.

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-12c). Thermocouples looped around the specimen gage section were used to monitor and control temperature during test.

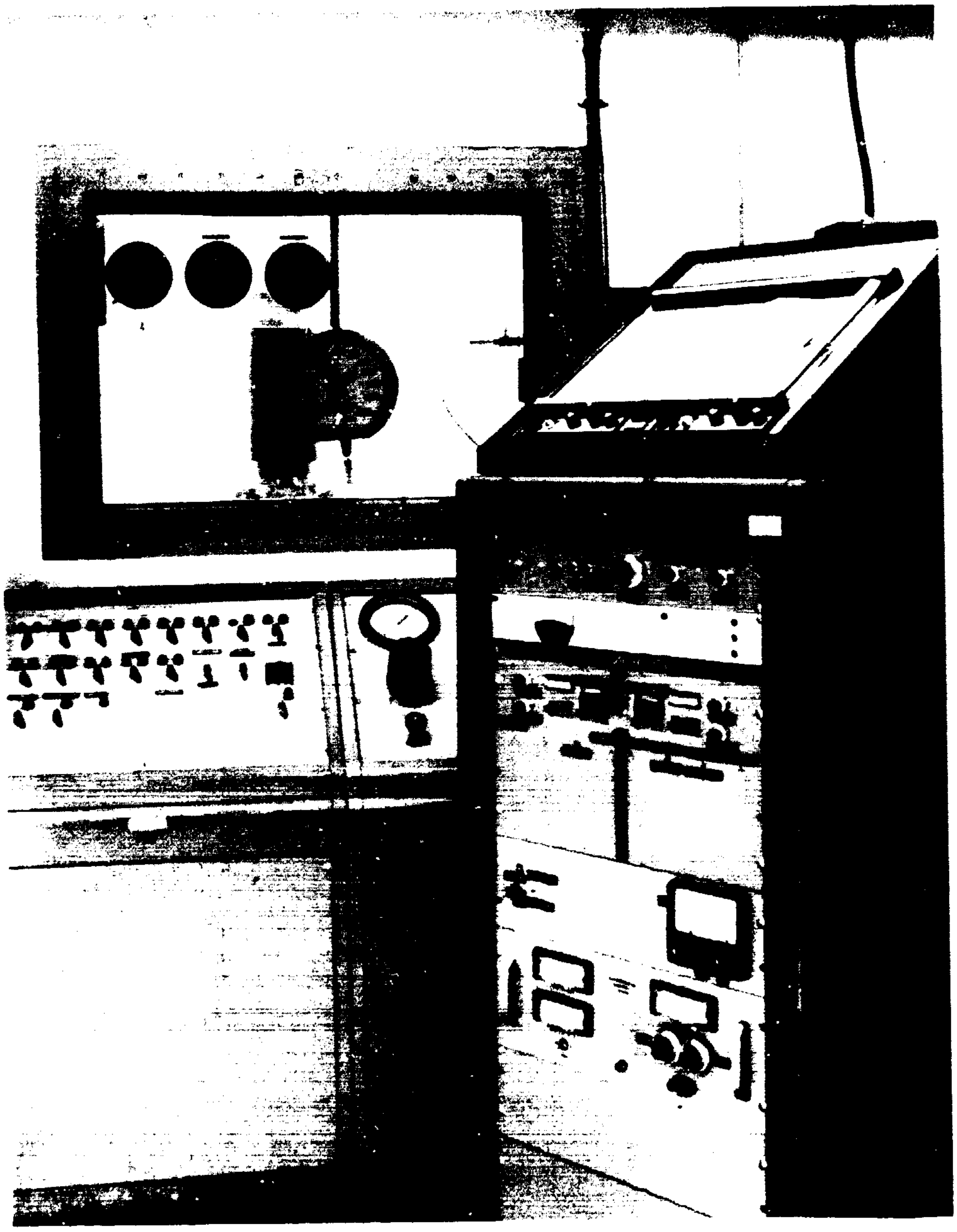
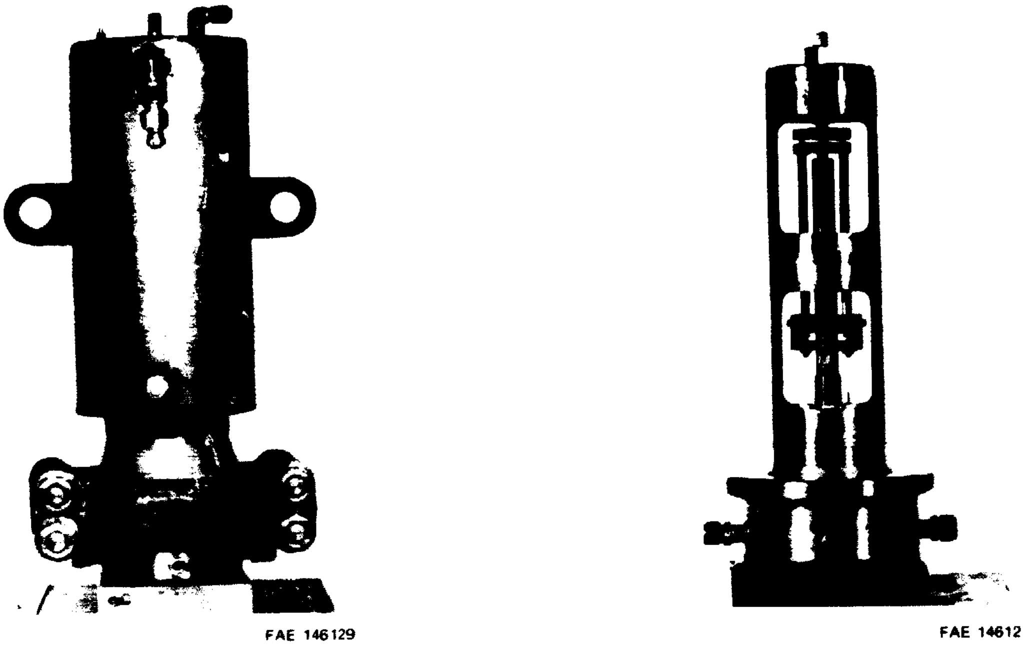
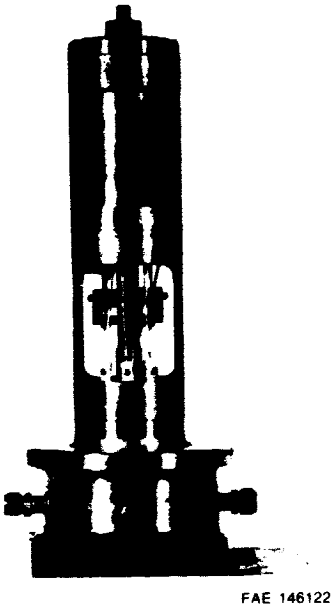


Figure V-11. Low-Cycle Fatigue Test Machine Environmental Controls and Data Acquisition Equipment



(a) Test Vessel Closed

(b) Test Vessel Open Showing Extensometer System Used in the Strain Control Tests



(c) Test Vessel Open Showing Furnace in Place

FD 92640A

Figure V-12. Setups of Low-Cycle Fatigue Test Vessel

For the strain-control tests, strain, as sensed by the extensometer, 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-13. In the load-control tests, load (stress) was recorded on the "Y" axis and time on the "X" axis of the "X-Y" plotter. This enabled monitoring of the load cycle at various intervals throughout the duration of all tests. A typical series of load-control LCF cycles is shown in figure V-14. During setup of each load-control test, the load cycle was monitored as the load (stress) limits were being set. They can be seen at the start of the load cycle record illustrated in figure V-14.

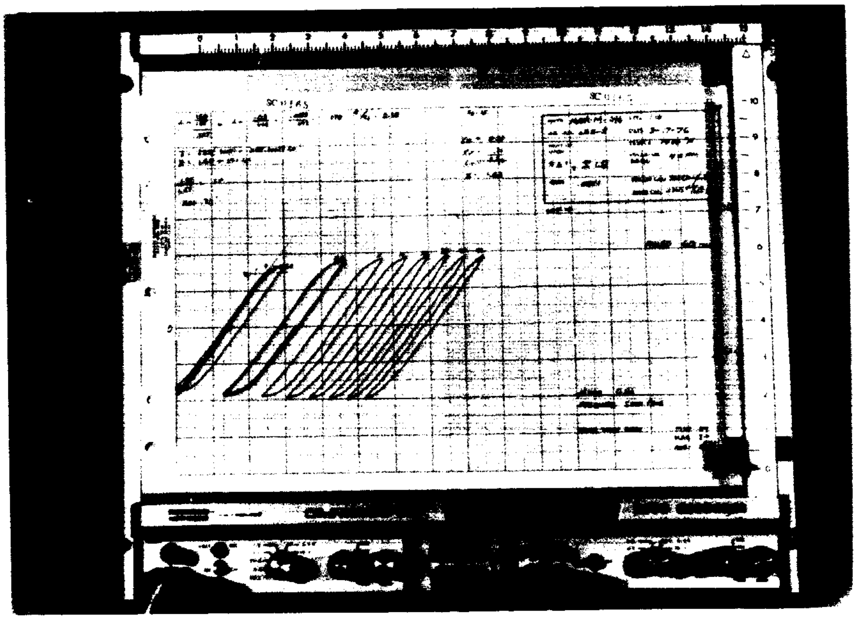
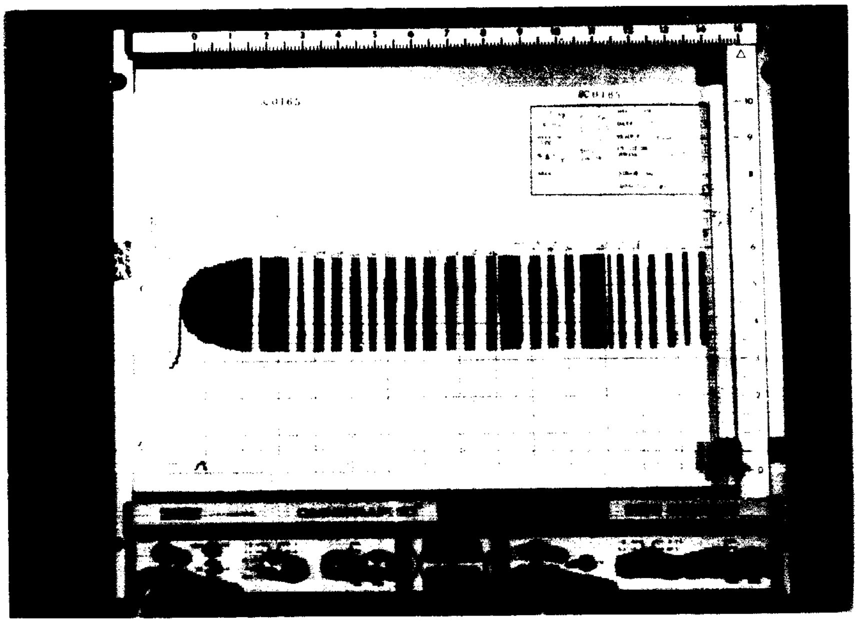

FD 101200

Figure V-13. A Typical Series of Hysteresis Loops Generated During an Actual Strain-Control Low-Cycle Fatigue Test

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 101201

Figure V-14. A Typical Series of Load-Cycles Generated During an Actual Load-Control Low-Cycle Fatigue Test

SECTION VI
CREEP-RUPTURE

A. INTRODUCTION

Under Exhibit C of this contract, creep-rupture properties of the nickel-base alloy MAR M-246 (Hf Modified), in two cast conditions, directionally solidified (DS) and conventionally cast (CC), were determined in 34.5 MN/m^2 (5000 psig) helium and hydrogen at 1033°K (1400°F) and 1144°K (1600°F). Testing established creep rate, rupture life, elongation, and reduction of area. Results of tests in hydrogen 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, 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. MAR M-246 (Hf Modified) exhibited such a range of lives in the different environments that a comparison 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.

The MAR M-246 (Hf Modified) material, in the DS and CC forms, exhibited degradation in creep-rupture life at both 1033°K (1400°F) and 1144°K (1600°F). Degradation in stress-rupture life up to 80% occurred due to the hydrogen environments. Degradations for the specific test conditions are listed in table VI-1.

Table VI-1. Degradation of Stress-Rupture Life of MAR M-246 (Hf Modified) in 34.5 MN/m^2 (5000 psig) Hydrogen Environment

	Test Temperature		*Stress Level*		*Degradation (Decrease from Helium, %) in Rupture Life at Indicated Stress Level*
Material Form	*°K*	*°F*	*MN/m^2*	*ksi*	
Directionally Solidified	1033	1400	792.9	115.0	50
	1033	1400	758.4	110.0	48
	1033	1400	723.9	105.0[1]	32
	1144	1600	586.1	85.0	66
	1144	1600	517.1	75.0	ND[2]
	1144	1600	482.6	70.0	ND[3]
Conventionally Cast	1033	1400	689.5	100.0	80
	1033	1400	620.5	90.0	ND[3]
	1144	1600	482.6	70.0	78
	1144	1600	413.7	60.0	60

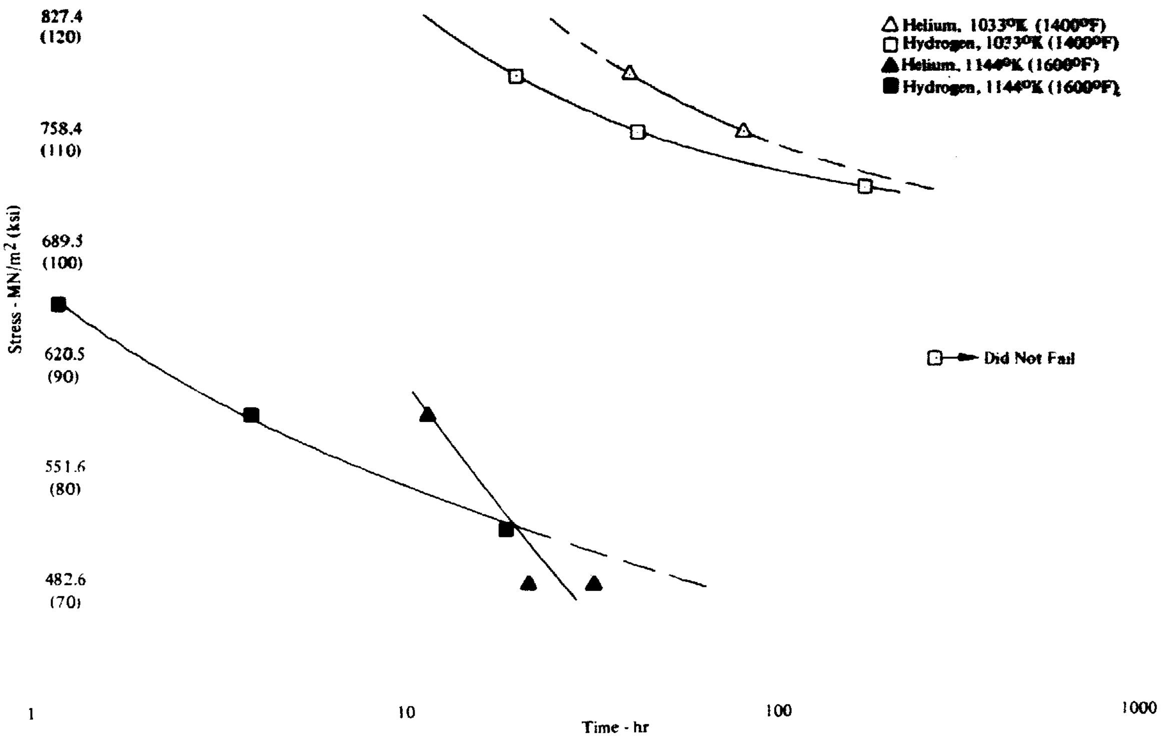
[1] Life in helium extrapolated from curve
[2] Life in helium and hydrogen approximately equal
[3] Life in hydrogen greater than helium.

---

[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.

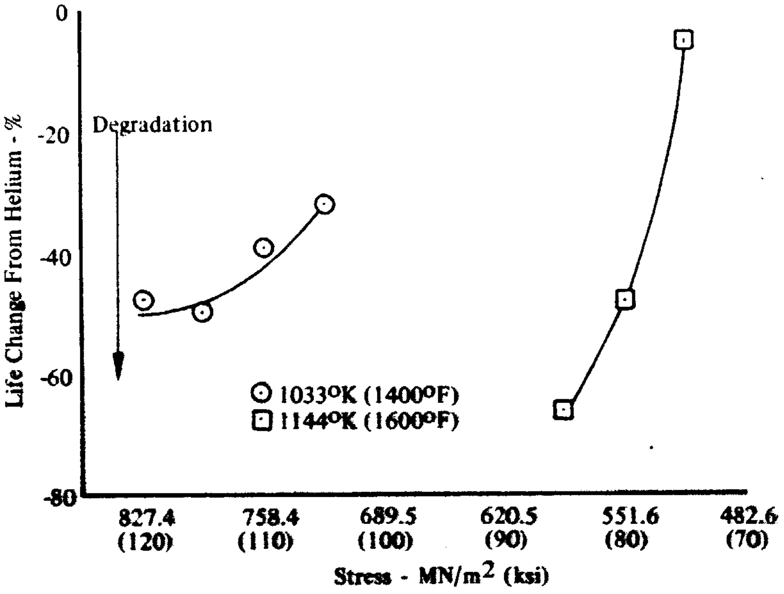
Stress vs time curves for the DS material at 1033°K (1400°F) and 1144°K (1600°F) in helium and hydrogen environments are shown in figure VI-1 . They indicate reductions in rupture life from 32 to 50% over the stress range investigated at 1033°K (1400°F) and approximately 66% at 586.1 MN/m² (85 ksi) for the 1144°K (1600°F) tests. At 1144°K (1600°F), testing at the lower stress level indicated lower rupture life in helium environment than in hydrogen. Metallographic examination of specimen CDS-12 revealed microstructure not consistant with the others (Section IV. B.2). A repeat test in helium at the same stress level was conducted and similar low rupture life resulted. Examination of this specimen (CDS-13) indicated microstructure consistant with the majority of the specimens. At the present time, no explanation can be given for the lower than anticipated helium environment rupture life.

The effect of temperature and stress level on hydrogen degradation of the DS material stress-rupture life is shown in figure VI-2. Creep-to-rupture data are plotted for the DS material tests in figures VI-3 through VI-6.



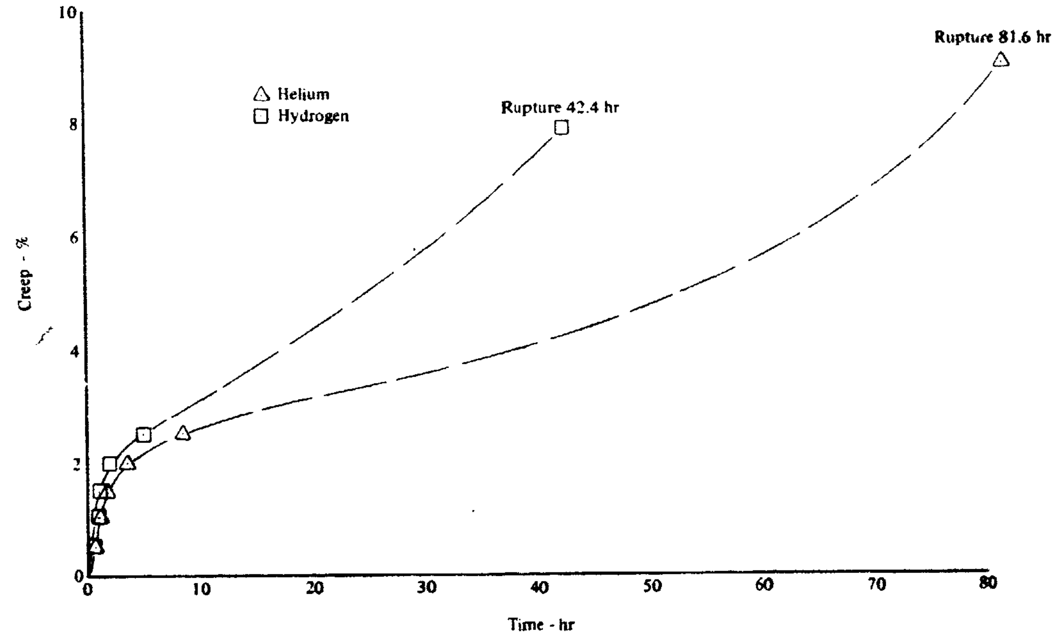
DF 102401

Figure VI-1. Stress-Rupture of Directionally Solidified (DS) MAR M-246 (Hf Modified) in 34.5 MN/m² (5000 psig) Helium and Hydrogen at 1033°K (1400°F) and 1144°K (1600°F)



DF 102402

Figure VI-2. Effect of Temperature on Hydrogen Degradation of Directionally Solidified (DS) MAR M-246 (Hf Modified) Stress-Rupture Life



DF 102403

Figure VI-3. Creep Stress-Rupture of Directionally Solidified (DS) MAR M-246 (Hf Modified) in 1033°K (1400°F) 34.5 MN/m² (5000 psig) Gaseous Environment at 758.4 MN/m² (110 ksi) Stress

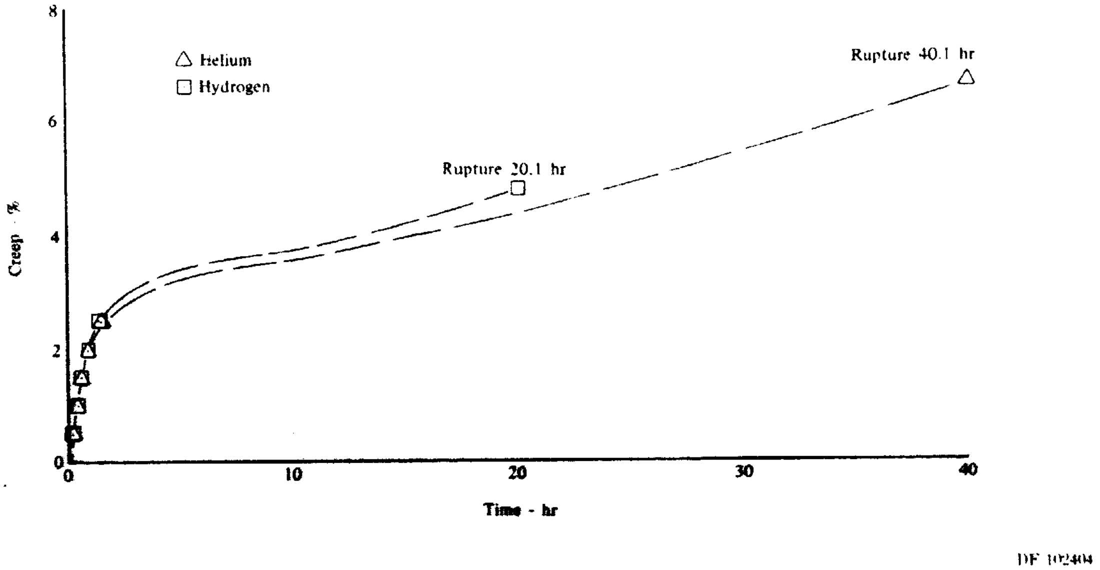


Figure VI-4. *Creep Stress-Rupture of Directionally Solidified (DS) MAR M-246 (Hf Modified) in 1033°K (1400°F) 34.5 MN/m² (5000 psig) Gaseous Environment at 792.9 MN/m² (115 ksi) Stress*

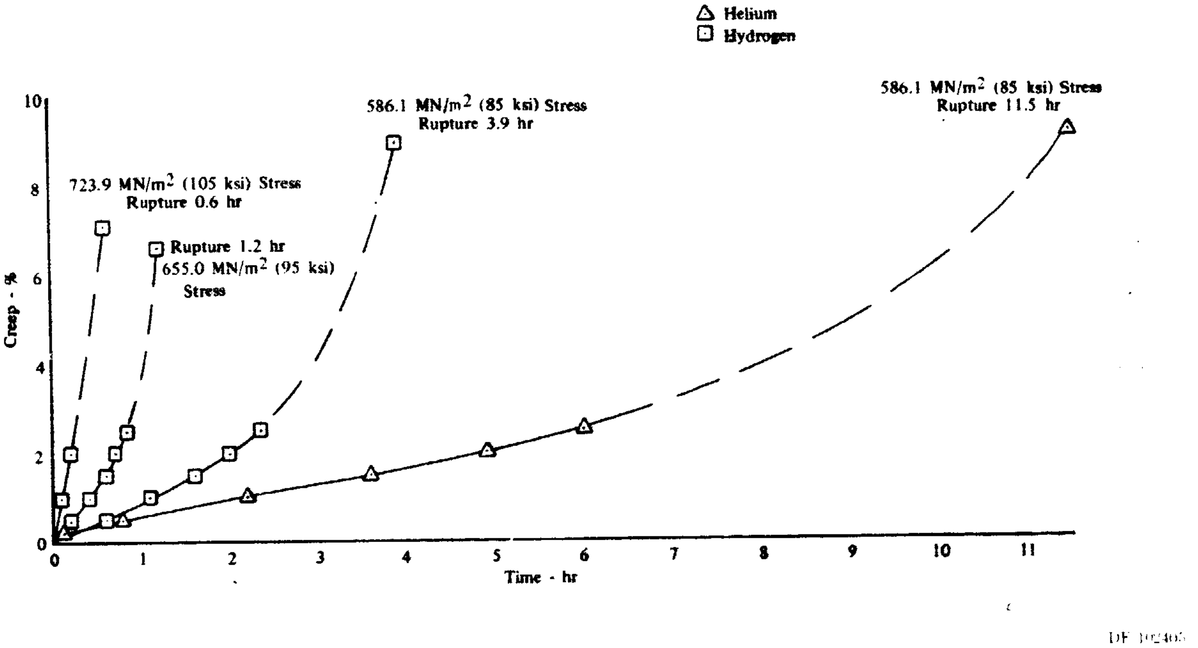
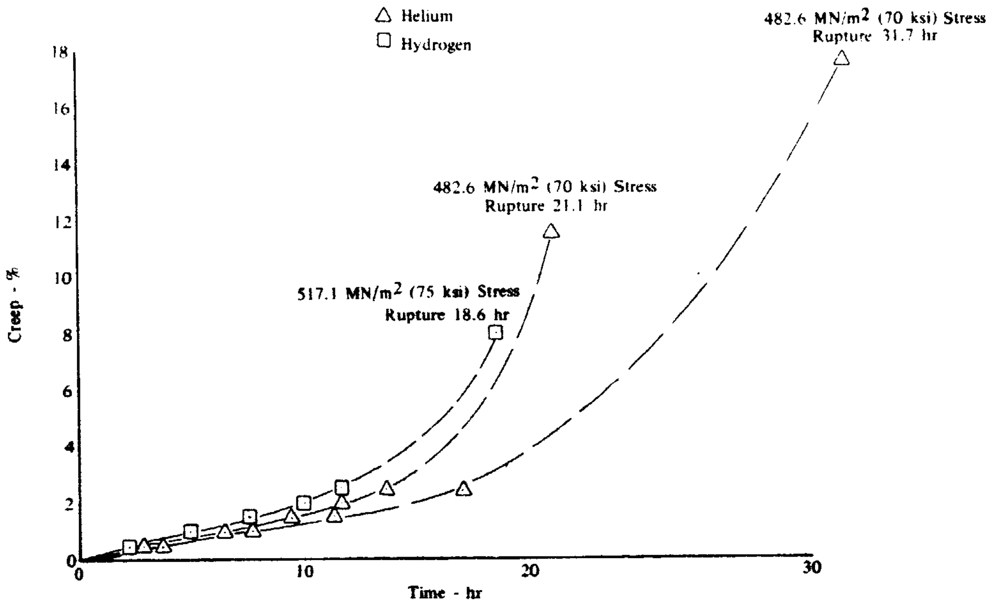


Figure VI-5. *Creep Stress-Rupture of Directionally Solidified (DS) MAR M-246 (Hf Modified) in 1144°K (1600°F) 34.5 MN/m² (5000 psig) Gaseous Environment*



DF 102496

Figure VI-6. Creep Stress-Rupture of Directionally Solidified (DS) MAR M-246 (Hf Modified) at 1144°K (1600°F) in 34.5 MN/m² (5000 psig) Gaseous Environment

Stress vs time curves for the CC material at both 1033°K (1400°F) and 1144°K (1600*0F) are illustrated in figure VI-7. They indicate degradation in rupture life up to approximately 80% for both test temperatures. As stated previously, these degradation figures must be viewed as trends. The somewhat erratic behavior of the helium tests at 1033°K (1400°F), and the slope of the helium stress-rupture curves at 1144°K (1600°F) (figures VI-1 and VI-7) make comparisons difficult. The distinct change of slopes between the helium and hydrogen stress-rupture curves at 1144°K (1600°F) reinforces the observation from earlier programs that there may be some mechanism unique to helium atmospheres at elevated temperatures. Studies of materials exposed to nuclear radiation in helium at elevated temperatures have observed an effect on materials peculiar to helium environments. An extensive study comparing properties in vacuum and helium at temperatures above 1144°K (1600°F) would be required to establish and document this phenomena.

Creep-to-rupture data plots for the CC material tests are illustrated in figures VI-8 through VI-10.

Individual creep-rupture test data for each DS and CC specimen tested are listed in table VI-2.

C. TEST PROCEDURE

Creep-rupture tests were conducted per ASTM E139-70, "Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials," were applicable, using round externally pressurized specimens. The test specimens used for the CC and DS materials are described in Section III and detailed in figures III-7 and III-8, respectively.

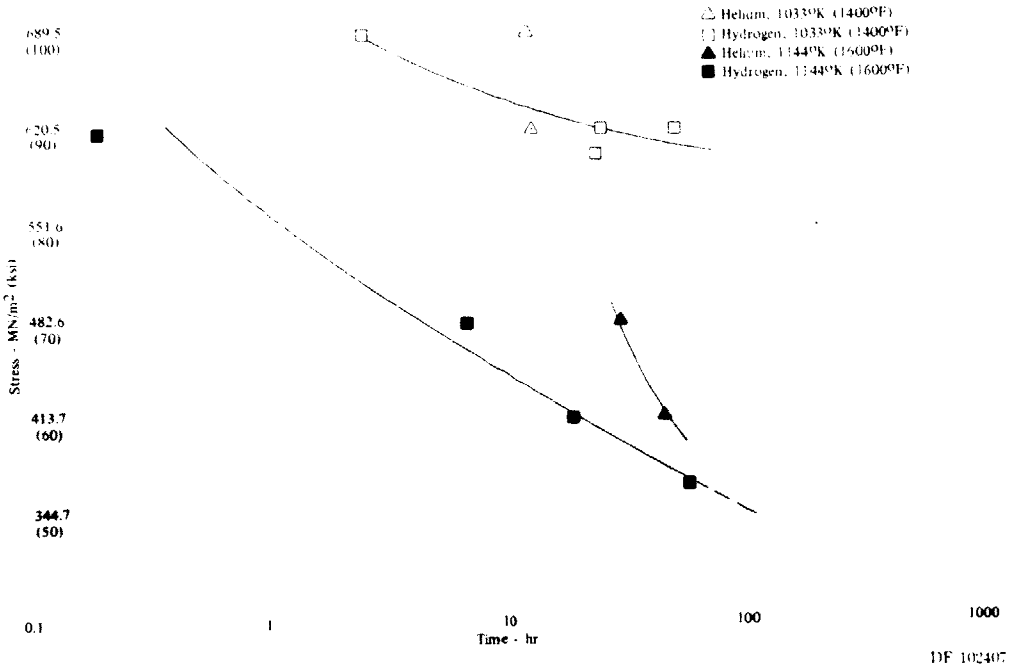


Figure VI-7. Stress-Rupture of Conventionally Cast (CC) MAR M-246 (Hf Modified) in 34.5 MN/m² (5000 psig) Helium and Hydrogen at 1033°K (1400°F) and 1144°K (1600°F)

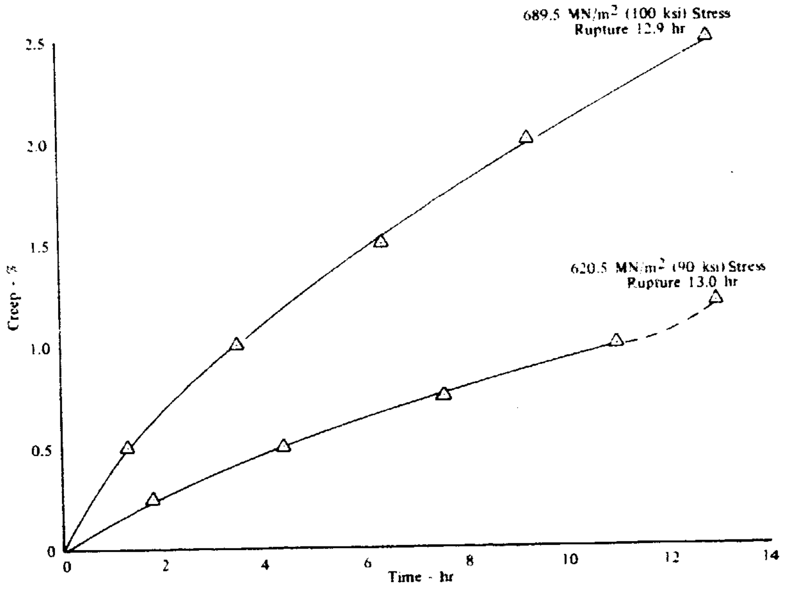
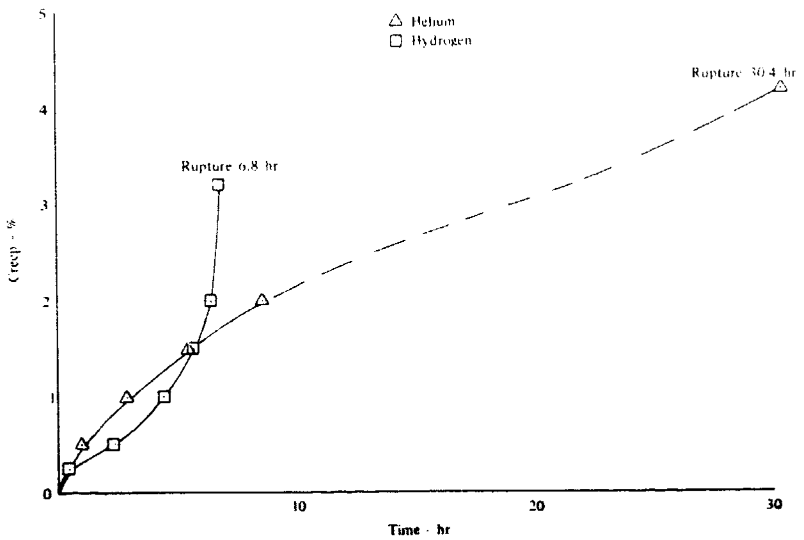
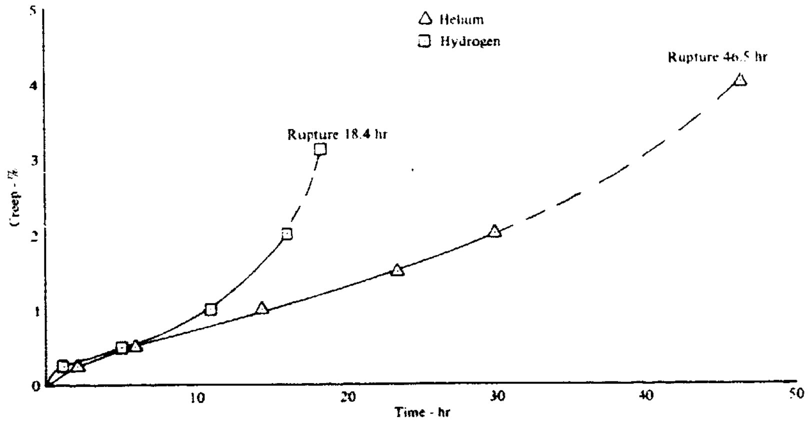


Figure VI-8. Creep Stress-Rupture of Conventionally Cast (CC) MAR M-246 (Hf Modified) in 34.5 MN/m² (5000 psig) Helium at 1033°K (1400°F)



DF 102409

Figure VI-9. Creep Stress-Rupture of Conventionally Cast (CC) MAR M-246 (Hf Modified) in 1144°K (1600°F) 34.5 MN/m² (70 ksi) Stress



DF 102410

Figure VI-10. Creep Stress-Rupture of Conventionally Cast (CC) MAR M-246 (Hf Modified) in 1144°K (1600°F) 34.5 MN/m² (5000 psig) Gaseous Environment at 413.7 MN/m² (60 ksi) Stress

Table VI-2. Creep-Rupture Properties of MAR M-246 (Hf Modified) in 34.5 MN/m² (5000 psig) Gaseous Environments

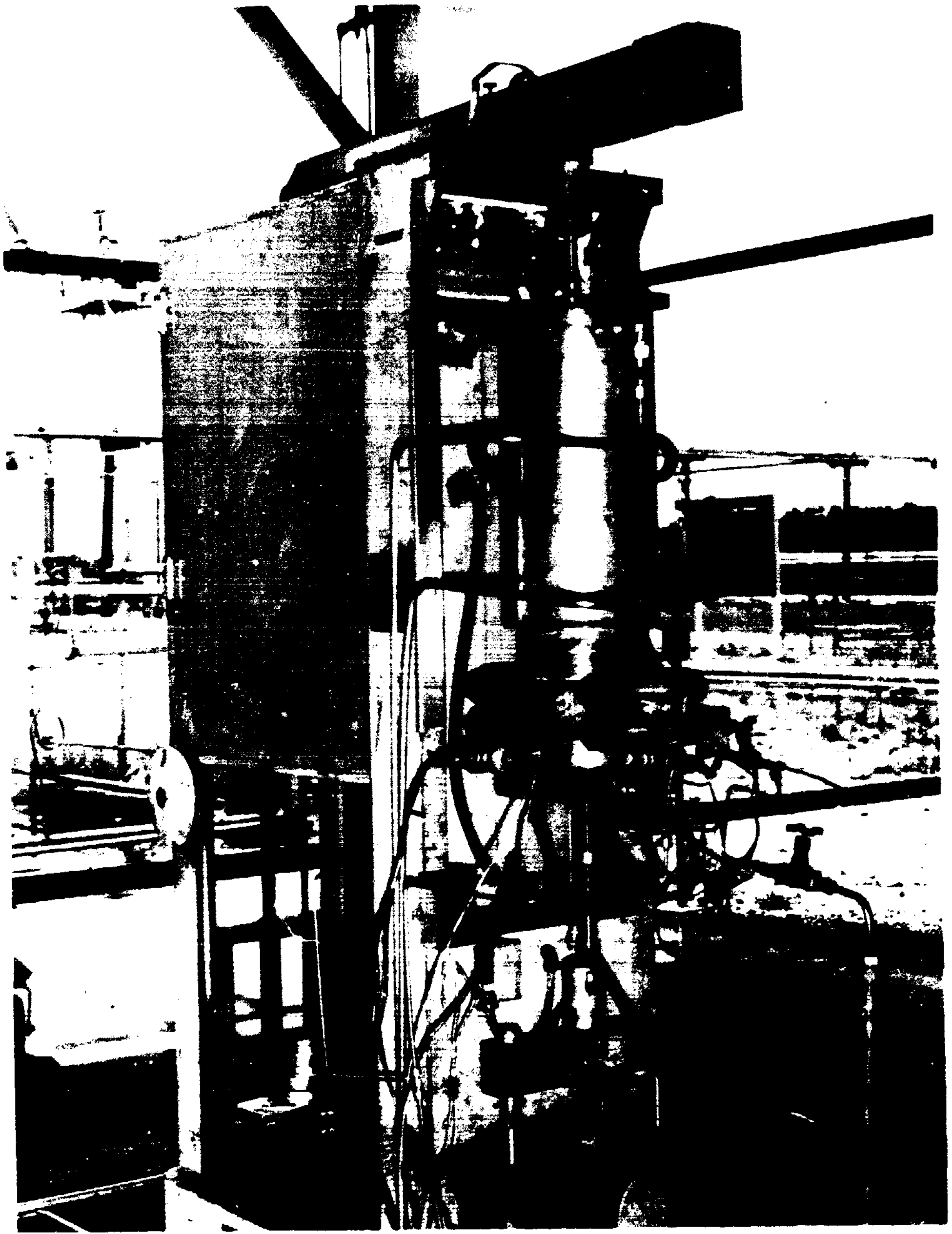
		Test Conditions					Test Results					
	Specimen	Test Temperature			Stress Level		Time to Creep (hr)			Time to Rupture	EL	RA
Material Form	S/N	°K	°F	Environment	MN/m²	ksi	0.5	1.0	2.0	hr	%	%
Directionally Solidified	CDS-1	1033	1400	Hydrogen	620.5	90.0	[1]			[2]260.2	0	0
	CDS-2	1033	1400	Hydrogen	758.4	110.0	0.3	0.6	1.9	42.4	7.8	11.8
	CDS-3	1033	1400	Hydrogen	792.9	115.0	0.2	0.4	1.0	20.1	4.8	6.5
	CDS-4	1033	1400	Hydrogen	723.9	105.0	0.6	1.2	15.9	170.0	8.4	12.2
	CDS-5	1033	1400	Helium	792.5	115.0	0.2	0.3	0.9	40.1	6.7	11.8
	CDS-6	1033	1400	Helium	758.4	110.0	0.5	1.0	3.6	81.6	9.0	10.9
	CDS-7	1144	1600	Hydrogen	723.9	105.0	<0.1	0.1	0.2	0.6	[3]7.1	13.5
	CDS-8	1144	1600	Hydrogen	655.0	95.0	0.2	0.4	0.7	1.2	[4]6.6	13.5
	CDS-9	1144	1600	Hydrogen	586.1	85.0	0.6	1.1	2.0	3.9	8.9	12.5
	CDS-10	1144	1600	Hydrogen	517.1	75.0	2.2	4.9	9.8	18.6	8.0	15.3
	CDS-11	1144	1600	Helium	586.1	85.0	0.8	2.2	4.9	11.5	9.1	13.2
	CDS-12	1144	1600	Helium	482.6	70.0	3.7	7.6	14.4	[5]31.7	17.6	39.2
	CDS-13	1144	1600	Helium	482.6	70.0	2.8	6.4	11.7	21.1	11.5	31.0
Conventionally Cast	CCC-1	1033	1400	Hydrogen	689.5	100.0	1.6	2.6		2.6	[6]1.2	4.8
	CCC-2	1033	1400	Hydrogen	620.5	90.0				26.0	0.4	1.2
	CCC-3	1033	1400	Hydrogen	620.5	90.0				52.1	0.4	1.5
	CCC-4	1033	1400	Hydrogen	603.3	87.5	23.4			24.1	0.8	1.5
	CCC-5	1033	1400	Helium	689.5	100.0	1.3	3.5	9.3	12.9	[7]2.5	3.0
	CCC-6	1033	1400	Helium	620.5	90.0	4.4	11.0		13.0	1.2	3.0
	CCC-7	1144	1600	Hydrogen	620.5	90.0	<0.1	0.1	0.2	0.2	[8]2.1	5.5
	CCC-8	1144	1600	Hydrogen	482.6	70.0	2.3	4.4	6.4	6.8	[9]3.2	7.0
	CCC-9	1144	1600	Hydrogen	413.7	60.0	5.0	10.9	16.3	18.4	3.1	4.9
	CCC-10	1144	1600	Hydrogen	365.4	53.0	17.8	[10]		57.0	3.3	4.9
	CCC-11	1144	1600	Helium	482.6	70.0	1.0	2.9	8.6	30.4	4.2	4.9
	CCC-12	1144	1600	Helium	413.6	60.0	6.0	14.4	30.0	46.5	4.0	9.2

---

[1] Negligible creep
[2] Test discontinued; did not fail
[3] 0.03175 mm (0.00125 inch) or 0.125% elongation on loading
[4] 0.01524 mm (0.00060 inch) or 0.060% elongation on loading
[5] Metallographic examination revealed microstructure not consistent with other specimens. Material appeared to be solution heat treated at a lower temperature than the other specimens or not solution heat treated at all. (See Section IV.B.2.)
[6] 0.00510 mm (0.0002 inch) or 0.02% elongation on loading
[7] 0.01524 mm (0.0006 inch) or 0.06% elongation on loading
[8] 0.01524 mm (0.0006 inch) or 0.06% elongation on loading
[9] 0.00254 mm (0.0001 inch) or 0.01% elongation on loading
[10] Extensometer readout system malfunction, time to 1.0 and 2.0% creep not obtained.

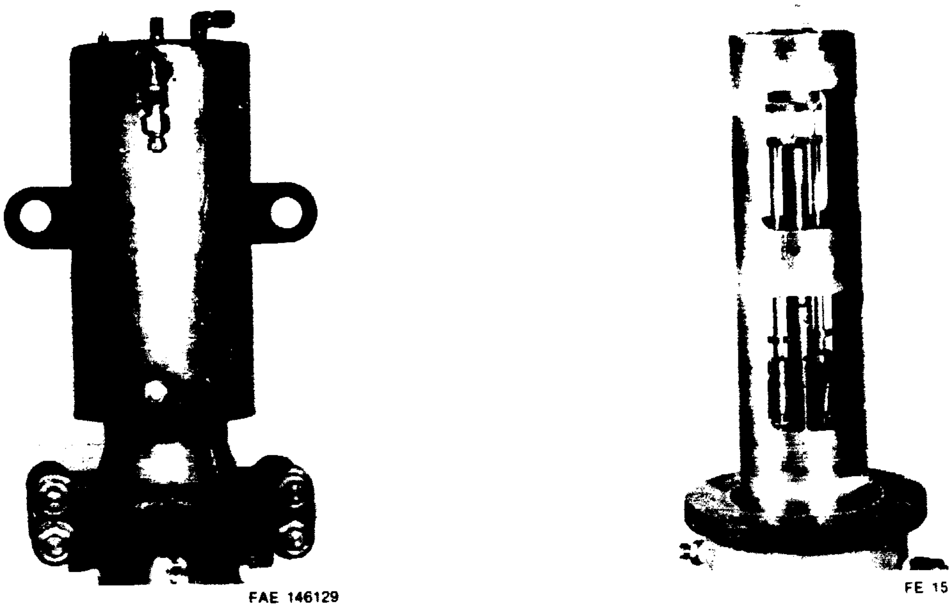
All tests were conducted on a modified 53.4-kN (12,000-lb) capacity Arcweld Model JE creep-rupture machine. The test machine was explosion-proofed and located in a test cell open to the atmosphere (figure VI-11). Controls and data recording equipment were located in an adjacent blockhouse. A high-pressure test vessel (figures VI-11 and VI-12), 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 specimens included integral collars or pin holes for positive location and gripping of creep-measuring extensometer heads. Load rods and adapters 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.



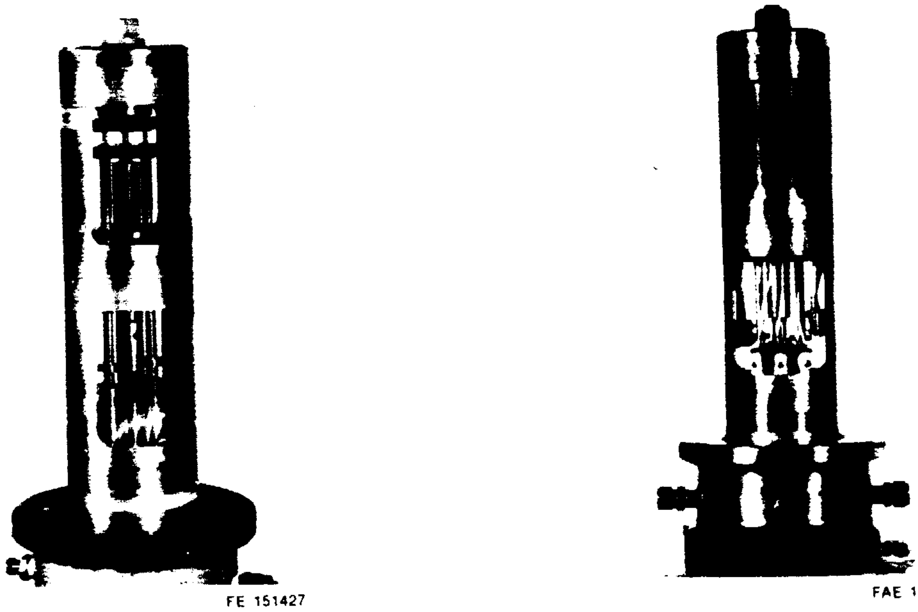
FD [illegible]

Figure VI-11. Creep-Rupture Machine, with Pressure Vessel Installed, Located in Test Cell



(a) Vessel Closed

(b) Vessel Open Showing CC Material Specimen in Place



(c) Vessel Open Showing DS Material Specimen in Place

(d) Vessel Open With Furnace Installed

FD 101197

Figure VI-12. Setups of Creep-Rupture Pressure Vessel

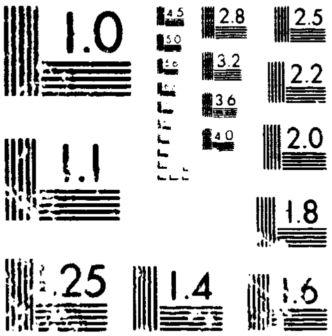
The extensometer system was a dual LVDT averaging-type and was located inside the high pressure vessel. The extensometer output was recorded in the adjacent blockhouse as elongation vs time records for all creep-rupture tests. The extensometer systems are shown in figures VI-12b&c and VI-13. A typical chart record is shown in figure VI-14. This record is for specimen CDS-13, tested in 34.5 MN/m^2 (5000 psig) helium at 1144°K (1600°F).

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-12d). In figure VI-12d, the thermocouples and furnace leads can be seen extending in to the base of the furnace.

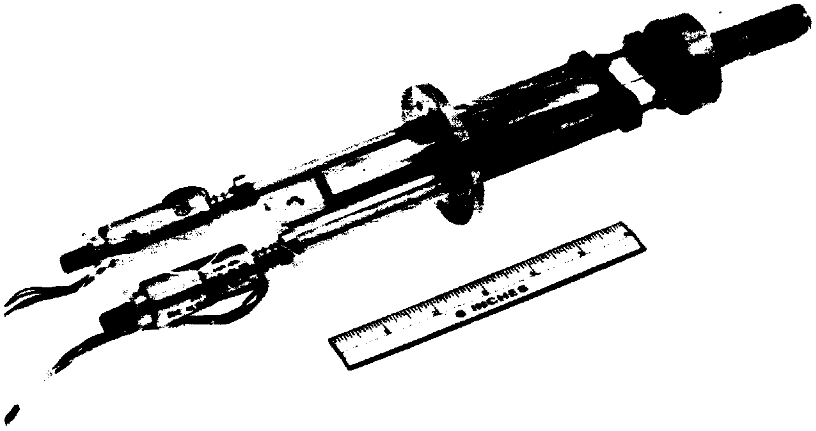
The test and gas handling procedures used for the low-cycle fatigue and tensile tests were also used for the creep-rupture tests.

OF

29400

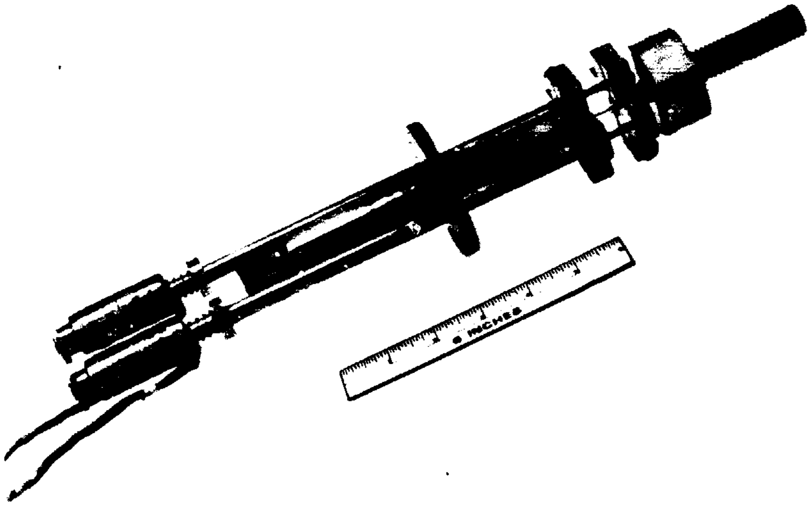


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



FE 151426

(a) Conventionally Cast Specimen Extensometry



FE 151310

(b) Directionally Solidified Specimen Extensometry

FD 101198

Figure VI-13. Creep Extensometer Systems

C.2

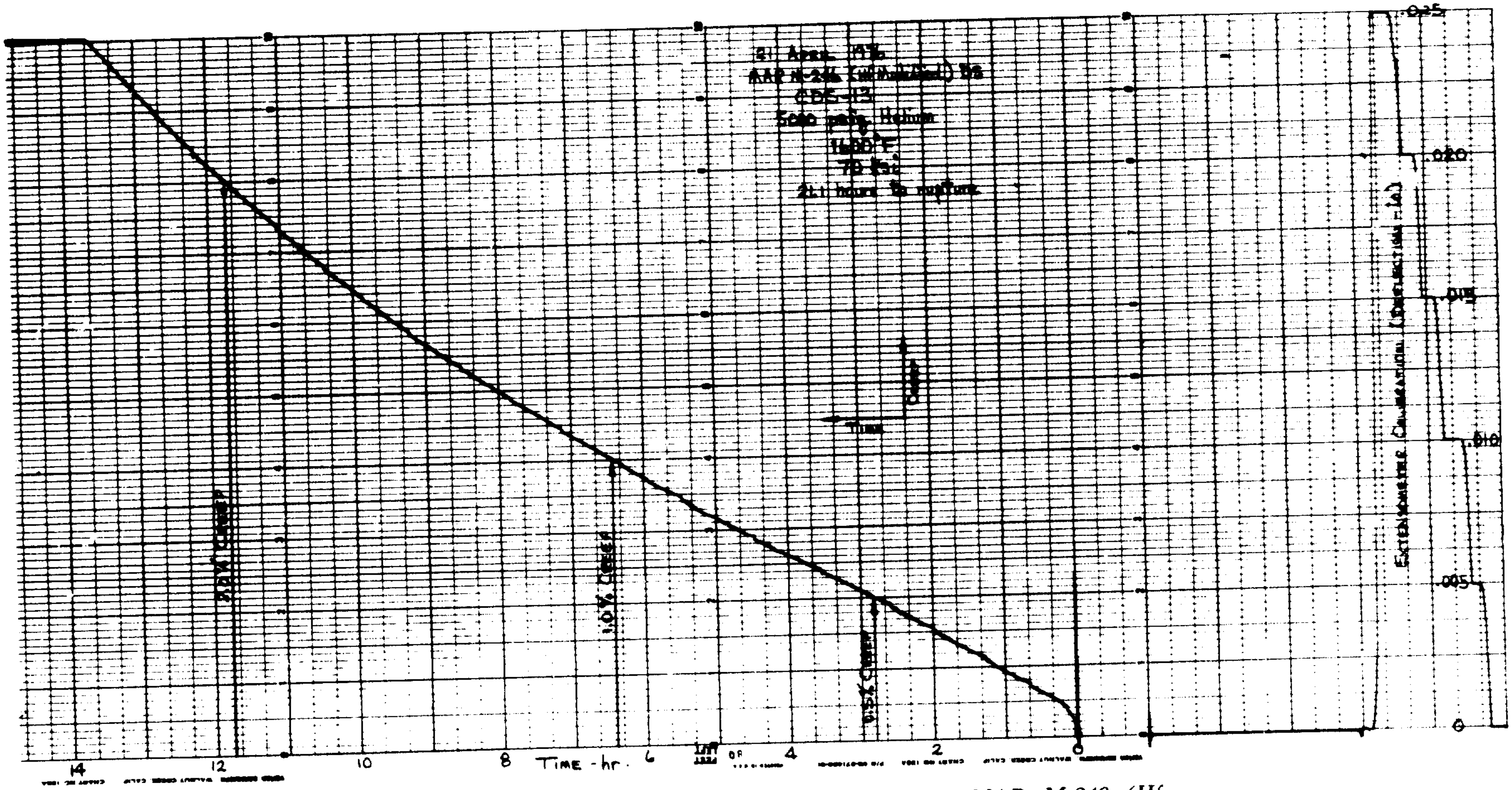


Figure VI-14. Creep vs Time Chart Record for MAR M-246 (Hf Modified) Specimen in High Pressure Environment

END

DATE

FILMED

OCT 5 1976