NASA TECHNICAL NOTE

NASA TN D-7952

NASA TN D-7952

ENVIRONMENTAL CRACK-GROWTH BEHAVIOR OF HIGH-STRENGTH PRESSURE VESSEL ALLOYS

Royce G. Forman

Lyndon B. Johnson Space Center
Houston, Texas 77058

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1975

1. Report No. NASA TN D-7952	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ENVIRONMENTAL CRACK-GROWTH BEHAVIOR OF HIGH-STRENGTH PRESSURE VESSEL ALLOYS		5. Report Date April 1975
		6. Performing Organization Code JSC-09190
7. Author(s) Royce G. Forman		8. Performing Organization Report No. JSC S-423
9. Performing Organization Name and Address Lyndon B. Johnson Space Center Houston, Texas 77058		10. Work Unit No. 786-15-31-01-72
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Results of sustained-load environmental crack-growth threshold tests performed on six spacecraft pressure vessel alloys are presented. The alloys were Inconel 718, 6Al-4V titanium, A-286 steel, AM-350 stainless steel, cryoformed AISI 301 stainless steel, and cryoformed AISI 304L stainless steel. The test environments for the program were air; pressurized gases of hydrogen, oxygen, nitrogen, and carbon dioxide; and liquid environments of distilled water, sea water, nitrogen tetroxide, hydrazine, aerozine 50, monomethyl hydrazine, and hydrogen peroxide. Surface flaw-type specimens were used with flaws located in both base metal and weld metal.

17. Key Words (Suggested by Author(s)) · High-Strength Alloys · Environmental Tests · Crack Initiation · Metal Fatigue · Fracturing · Fracture Mechanics · Stress Functions · Flaw Detection		18. Distribution Statement STAR Subject Category: 26 (Metallic Materials)	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 43	22. Price* $3.75

*For sale by the National Technical Information Service, Springfield, Virginia 22151

CONTENTS

Section	Page
SUMMARY	1
INTRODUCTION	1
SYMBOLS	4
TEST SPECIMEN DESCRIPTION	5
TEST APPARATUS AND PROCEDURES	6
RESULTS AND DISCUSSION	8
CONCLUSIONS	11
REFERENCES	12
APPENDIX — CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS	13

TABLES

Table		Page
I	VALUES OF Φ^2	14
II	YIELD STRENGTH VALUES USED FOR K_{Ii} AND K_{IE} CALCULATIONS	15
III	FRACTURE-TOUGHNESS TEST RESULTS FOR CRYOFORMED 301 SPECIMENS AT AMBIENT TEMPERATURE	16
IV	FRACTURE-TOUGHNESS TEST RESULTS FOR CRYOFORMED 304L, A-286, AND AM-350 (SCT 1000) SPECIMENS AT AMBIENT TEMPERATURE	17
V	FRACTURE-TOUGHNESS TEST RESULTS FOR INCONEL 718 SPECIMENS FROM ALSA BOTTLE MATERIAL AT AMBIENT TEMPERATURE	18
VI	FRACTURE-TOUGHNESS TEST RESULTS FOR 6Al-4V TITANIUM (STA) PRESSURE-WELD SPECIMENS AT AMBIENT TEMPERATURE	19
VII	AVERAGE K_{IE} VALUES OF TEST MATERIALS	20
VIII	SUSTAINED-LOAD TEST RESULTS FOR CRYOFORMED 301 STAINLESS STEEL SPECIMENS WELDED WITH 308L STAINLESS STEEL WELD WIRE	21
IX	SUSTAINED-LOAD TEST RESULTS FOR CRYOFORMED 301 STAINLESS STEEL SPECIMENS WELDED WITH 301 STAINLESS STEEL WELD WIRE	24
X	SUSTAINED-LOAD TEST RESULTS FOR CRYOFORMED 304L STAINLESS STEEL SPECIMENS	25
XI	SUSTAINED-LOAD TEST RESULTS FOR INCONEL 718 SPECIMENS FROM CGSS TANK MATERIAL	26
XII	SUSTAINED-LOAD TEST RESULTS FOR INCONEL 718 SPECIMENS FROM ALSA BOTTLE MATERIAL	27

Table		Page
XIII	SUSTAINED-LOAD TEST RESULTS FOR A-286 AND AM-350 (SCT 1000) STEEL	28
XIV	SUSTAINED-LOAD TEST RESULTS FOR 6Al-4V TITANIUM (STA) PRESSURE-WELD SPECIMENS	29
XV	SUMMARY OF ENVIRONMENT INCOMPATIBILITY OF TEST MATERIALS	30

FIGURES

Figure		Page
1	Fabrication procedure for titanium pressure-weld specimens	31
2	Cryoformed 301 and 304L cross-weld and base-metal specimen configuration	31
3	Inconel 718 cross-weld and base-metal specimen configuration for CGSS tank material tests	31
4	Inconel 718 cross-weld and base-metal specimen configuration for ALSA bottle material tests	32
5	Configuration of A-286 steel specimen	32
6	Configuration of AM-350 (subcooling and tempering condition (SCT) 1000) stainless steel specimen	32
7	Configuration of 6Al-4V titanium (STA) pressure-weld specimen	33
8	Weld joint configuration and specimen processing for cryoformed 301 stainless steel specimens	33
9	Weld joint configuration and specimen processing for cryoformed 304L stainless steel specimens	33
10	Weld joint configuration and specimen processing for Inconel 718 CGSS tank material tests	33
11	Weld joint configuration and specimen processing for Inconel 718 ALSA bottle material tests	34
12	Photograph of load frame and test chamber during a cold gaseous hydrogen environment test	34
13	Photograph of cryoformed 301 stainless steel specimen and gaseous hydrogen test chamber	34

Figure		Page

14 Photograph of cryoformed 301 stainless steel specimen and high-pressure fluid chamber

(a) Test chamber and specimen 35
(b) O-ring and Teflon backup sheet 35

15 Fracture face photograph of Inconel 718 specimen 185W showing typical fatigue and sustained-load flaw-growth markings (EDM = electrical discharge machine) 35

16 Specimen geometry and stress-intensity factor analysis for deep flaws 36

17 Photomicrographs of crack growth in Inconel 718 resulting from sustained load in gaseous hydrogen

(a) Section view of fracture face 36
(b) Enlarged view of sustained-load growth in gaseous hydrogen 36

18 Sustained-load crack-growth behavior for Inconel 718 base metal in 200 K (-100° F) hydrogen at 6.9 MN/m^2 (1000 psi) . . . 36

ENVIRONMENTAL CRACK-GROWTH BEHAVIOR OF HIGH-STRENGTH PRESSURE VESSEL ALLOYS

By Royce G. Forman
Lyndon B. Johnson Space Center

SUMMARY

Crack-growth threshold tests were conducted on surface-flawed specimens of six high-strength alloys used for spacecraft pressure vessels. The alloys were Inconel 718, 6Al-4V titanium, A-286 steel, AM-350 stainless steel, cryoformed AISI 301 stainless steel, and cryoformed AISI 304L stainless steel. The test environments were air; pressurized gases of hydrogen, oxygen, nitrogen, and carbon dioxide; and liquid environments of distilled water, sea water, nitrogen tetroxide, hydrazine, aerozine 50, monomethyl hydrazine, and hydrogen peroxide. All tests were at room temperature except for those on Inconel 718, which was exposed to 200 K (-100° F) hydrogen, and 301 stainless steel, which was exposed to 322 K (120° F) nitrogen tetroxide. Both base-metal and weld-metal results were obtained for Inconel 718, 6Al-4V titanium, and 301 stainless steel. Base-metal results only were obtained for A-286 steel and AM-350 stainless steel, and weld-metal results only were obtained for 304L stainless steel.

INTRODUCTION

Starting with the Apollo Program, the application of fracture mechanics technology has become a standard requirement for preventing flaw-growth failures of manned spacecraft pressure vessels. This requirement was originated because design safety factors were reduced and because several pressure vessel test failures occurred. These failures were caused by stress-corrosion cracking from fluid-metal incompatibility. A description of these problems and the history of fracture mechanics used for the Apollo Program are discussed in reference 1. The theoretical background for the relevant technology is reported in reference 2.

To perform a fracture mechanics analysis of pressure vessels, three types of data are needed.

1. The fracture toughness of the material (critical stress-intensity factor at fracture for surface-flawed specimen (K_{IE}) or apparent stress-intensity factor conditions at failure (K_{Ic})), when obtained from surface-flaw specimens

2. The constant-stress flaw-growth threshold (K_{TH}) in the environments to which the vessel will be exposed

3. The rate of cyclic crack growth caused by fatigue

If the value of K_{IE} is known, the maximum-size flaw that would not cause failure in a proof test can be determined. This size flaw is assumed to exist at the beginning of the first operating pressure cycle. By letting K_{Ii} be the stress-intensity factor (calculated by using the initial flaw size and operating stress), it can be shown that the ratio K_{Ii}/K_{IE} at a given temperature is equal to the ratio of operating pressure to proof pressure. Also, by knowing the value of K_{TH}/K_{IE}, the possibility of sustained-stress environmental crack growth can be determined. For a specific pressure vessel design, environmental crack growth is prevented by selecting either the proof pressure ratio or the material such that $K_{Ii}/K_{IE} < K_{TH}/K_{IE}$. The greater the difference between these two ratios, the greater the number of allowable pressurizations before sustained-stress environmental flaw growth can occur.

Data for the type analysis just discussed were obtained for every pressure vessel on the Apollo and Skylab space vehicles. Part of the data was obtained from study contracts, and part of the data was obtained from in-house tests at the NASA Lyndon B. Johnson Space Center (JSC). This report presents the results of many of these in-house tests and also a number of material screening tests for application to future pressure vessels. However, the report only includes the results of fracture-toughness and environmental crack-growth tests that were performed. The following list gives specific materials and sustained-stress environments for which results are reported.

Material	Test environments
Inconel 718 base metal	Gaseous hydrogen (H_2)
Inconel 718 weld	H_2, gaseous oxygen (O_2), distilled water (DW)
6Al-4V titanium pressure weld	Laboratory air
A-286 base metal	H_2
AM-350 base metal	Hydrogen peroxide (H_2O_2)
Cryoformed 301 base metal[1]	H_2, O_2, gaseous nitrogen (N_2), DW, sea water (SW)
Cryoformed 301 weld [1] (308L wire)	O_2, N_2, carbon dioxide (CO_2), DW, SW, nitrogen tetroxide (N_2O_4), hydrazine (N_2H_4), aerozine 50 (A-50)
Cryoformed 301 weld[1] (301 wire)	N_2H_4, A-50
Cryoformed 304L weld[2] (308L wire)	Monomethyl hydrazine (MMH), N_2O_4

As an aid to the reader, where necessary the original units of measure have been converted to the quivalent value in the Systême International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

---

[1]Special controlled chemistry (not commercial grade).

[2]Commercial grade material.

SYMBOLS

The SI unit conversion factors used with these symbols are listed in the appendix.

a crack depth, centimeters (inches)

b crack half-length, centimeters (inches)

K_I stress-intensity factor, $MN/m^{3/2}$ (ksi $\sqrt{in.}$)

K_{IE} critical stress-intensity factor at fracture for surface-flawed specimen, $MN/m^{3/2}$ (ksi $\sqrt{in.}$)

K_{TH} threshold stress-intensity factor for environmental crack growth, $MN/m^{3/2}$ (ksi $\sqrt{in.}$)

M correction factor for the effect of crack shape and depth on the growth of a crack through the thickness

Q flaw-shape correction factor

t plate thickness, millimeters (inches)

w specimen width, millimeters (inches)

σ applied gross area stress, MN/m^2 (ksi)

σ_y tensile yield strength (0.2 percent offset), MN/m^2 (ksi)

θ angular coordinate

Φ complete elliptic integral of the second type

Subscripts:

c conditions at failure

i initial conditions at beginning of test

TEST SPECIMEN DESCRIPTION

The A-286 steel and AM-350 stainless steel (SS) specimens were machined from rolled plate at JSC. The 6Al-4V titanium pressure-weld specimens were cut from an Apollo high-pressure helium bottle and processed as shown in figure 1. The Inconel 718 specimens were fabricated by two different contractors. The smaller 0.28-centimeter (0.11 inch) thick Inconel 718 specimens were fabricated to simulate the thickness, welding, and heat treatment for a proposed cryogenic gas storage system (CGSS) pressure vessel for the Skylab Program. The larger 0.51-centimeter (0.20 inch) thick Inconel 718 specimens were fabricated to simulate the thickness, welding, and heat treatment for the astronaut life support assembly (ALSA) pressure vessels on Skylab. The cryoformed stainless steel specimens were also fabricated by two different contractors. The 301 stainless steel specimens were fabricated by contractor A to obtain data on the Apollo Program liferaft CO_2 bottles and for screening tests for Space Shuttle propellant tank materials. The 304L stainless steel specimens were fabricated by contractor B to also obtain screening data for Space Shuttle propellant tank materials.

The specimen design for each material is shown in figures 2 to 7. The weld joint configurations and specimen processing steps are shown in figures 8 to 11. After the specimens were fabricated, the weld beads were machined flush and the weld areas were polished and etched to show the fusion lines. Starter flaws were then machined into the specimens by an electrical discharge machine, and the specimens were degreased to prepare them for fatigue precracking. Trichlorotrifluoroethane (Freon) was used to degrease all specimens except for particular 301 stainless steel specimens that were degreased with isopropyl alcohol.

All specimens were fatigue precracked in laboratory air by either three-point or cantilever beam bending except for the specimens (Inconel 718 and cryoformed 301 stainless steel) tested in hydrogen, which were precracked by tension-fatigue loading. Also, with the exception of the hydrogen-tested specimens, the maximum precracking stress was less than the sustained-load stress. Precracking for Inconel 718 and cryoformed 301 stainless steel would not have been possible at stresses as low as those required to obtain the K_{TH} value in hydrogen gas.

After precracking, all specimens were cleaned and sealed in plastic bags until the time of test. The titanium specimens and a few cryoformed 301 stainless steel specimens tested in prepellant fluids were ultrasonically cleaned with Freon. All other specimens and test chambers were cleaned to a level-3 cleanliness and vacuum bake dried according to requirements for aerospace oxygen-type service. Because residuals of chlorinated solvents like Freon in the presence of N_2H_4 mixtures were of concern, the specific cleaning procedures for specimens tested in N_2H_4, A-50, and MMH are noted in the test results.

TEST APPARATUS AND PROCEDURES

The sustained-load tests were conducted using either dead-weight creep machines or specially fabricated load frames with nitrogen-powered load cylinders. All hydrogen testing was conducted using the load frame and test chamber shown in figure 12. A disassembled view of the hydrogen test chamber is shown in figure 13. Not shown in the disassembled view is the insulated outer chamber jacket that liquid nitrogen passed through to cool the hydrogen gas.

The test chamber used for all other environments except ambient air is shown in the photograph in figure 14(a). These chambers were machined from stainless steel and were made especially thick to withstand the high gas pressures. Although the pressure chambers were clamped on the specimens, the frictional forces were small because the nuts on the clamping bolts were torqued only a little more than finger tight. Also, the O-ring seal and Teflon backup sheet, shown in figure 14(b), prevented metal-to-metal friction between the specimen and chamber.

All pressurized gases in the test program were obtained from K-bottles. Except for the CO_2 supply, all K-bottles were purchased to a 0.99995 purity requirement for fuel-cell grade gases. The purity was maintained during the tests by evacuating the chambers before filling them with the test gases. The hydrogen gas was purified further to a maximum 15 ppm total impurities by using a molecular sieve and liquid nitrogen cold trap. A sample of the hydrogen gas was drawn from the test chamber before each test, and a chemical analysis was performed to check the purity. The 41-MN/m^2 (6000 psi) oxygen was also obtained from a K-bottle, but the high pressure was attained with a self-pumping 10-to-1 pressure intensifier unit.

The propellant fluids were purchased according to the following specifications and had the following chemical analysis after delivery:

Nitrogen tetroxide — Specification: JSC-PPD-2B
(Nitric oxide and water percent weights analyzed only)

Before environmental tests:

Nitric oxide, percent	0.63
Water, percent	0.01

After 500-hour test:

Nitric oxide, percent	0.59
Water, percent	0.02

Hydrazine — Specification: MIL-P-26536, Revision B

Hydrazine, percent	98.0
Density, g/cm^3	1.003
Water, percent	2.0
Particulate count, mg/liter	1.0

Aerozine 50 — Specification: MIL-P-27402, Revision B

Hydrazine, percent	51.3
Unsymmetrical dimethyl hydrazine, percent	47.5
Water, percent	1.2
Particulate count, mg/liter	0.1

Monomethyl hydrazine — Specification: MIL-P-27404

Monomethyl hydrazine, percent	97.4
Water, percent	1.8
Balance not identified, percent	0.8
Particulate count, mg/liter	1.6

Hydrogen peroxide

(No chemical analysis available)

Before each propellant fluid test, the test chambers were recleaned, placed on the specimens as shown in figure 14(a), and filled with the propellant fluids in a clean room at the thermochemical test laboratory. To remove fluid contaminated with air, the propellant fluids were allowed to flow through the chambers before the inlet and outlet ports were capped. In the sea water tests, the test fluid was obtained from the Gulf of Mexico approximately 16 kilometers (10 miles) offshore from Galveston, Texas.

After each sustained-load test, if the specimen had not failed, the specimen was tension fatigue cycled in ambient air to mark the sustained-load-flaw growth and then statically loaded to failure. The fracture face photograph in figure 15 of an Inconel 718 specimen shows the test sequence and appearance of the different types of flaw growth for fatigue, sustained load, and static load to fracture.

In addition to the sustained-load tests, static-fracture toughness tests were also conducted on at least two specimens for each type of material. These tests were conducted in ambient air, and the specimen geometry and initial flaw sizes were the same as for the sustained-load specimens.

RESULTS AND DISCUSSION

The sustained-load and fracture test results were analyzed using the stress-intensity factor method. The calculations were made by using the following equation for the stress-intensity factor at the minor axis of a semielliptical surface-type flaw.

$$K_I = 1.12\sigma \sqrt{\frac{\pi a}{Q}} M \tag{1}$$

where Q is a flaw-shape correction factor given by the equation

$$Q = \Phi^2 - 0.212 \left(\frac{\sigma}{\sigma_y}\right)^2 \tag{2}$$

In equation (2), Φ is an elliptic integral of the second kind with the values listed in table I.

Equation (1) is basically Irwin's expression (ref. 2) for a semielliptical surface crack with correction factor M applied to account for the finite thickness of the specimens. Correction factor M is a function of a/t and a/b and was determined by a linear interpolation of Kobayashi's solution for $a/b = 0$ and Smith's solution for $a/b = 1$ (also discussed in ref. 2). The linear interpolation procedure is shown in figure 16.

To determine the fracture toughness values, equation (1) was written in the following form.

$$K_{IE} = 1.12\sigma_c \sqrt{\frac{\pi a}{Q}} M \tag{3}$$

where Q is determined using the values of σ_y listed in table II. These calculations were made on the specimens tested, and the fracture toughness results for each specimen are listed in tables III to VI. Average K_{IE} values for each material are listed in table VII.

For the sustained-load tests, the stress-intensity factors were calculated for the conditions at the time of initial load application. The equation for this condition is

$$K_{Ii} = 1.12\sigma\sqrt{\frac{\pi a_i}{Q}}M \tag{4}$$

where Q is calculated as in equation (3). The results of these calculations for all specimens tested are listed in tables VIII to XIV. Also listed in the tables are the environmental conditions, time at load, amount of crack growth, and the ratio K_{Ii}/K_{IE}.

A listing of the estimated K_{TH}/K_{IE} values for each material and environment is given in table XV where K_{TH} is the estimated maximum value of K_{Ii} for which crack growth will not occur. By assuming the following grading system, a summarization can be made of all materials and environments tested.

K_{TH}/K_{IE}, percent	Incompatibility
≥ 85	Negligible
≥ 75, <85	Slight
≥ 60, <75	Moderate
<60	Severe

For Inconel 718, the test results showed slight or negligible incompatibility in air, water, and high-pressure oxygen. In gaseous hydrogen between room temperature and 200 K (-100° F), Inconel 718 was found to have severe incompatibility. Not enough testing was performed to determine accurately the effects of temperature and pressure on hydrogen-environment crack growth, but the difference in K_{TH} between room temperature and 200 K (-100° F) was not significant. Apparently, the lower temperature decreased the environmental crack-growth rate, but a decrease in crack-growth rate did not necessarily signify a decrease in K_{TH}.

A photomicrograph of the crack growth for an Inconel 718 specimen is shown in figure 17. Also, the results of K_{Ii} as a function of time at load for base-metal specimens tested in 200 K (-100° F) hydrogen are shown in figure 18.

For cryoformed 301 stainless steel, the test results showed slight or negligible incompatibility in high-pressure O_2, N_2, CO_2, distilled water, sea water, and N_2O_4. The N_2H_4 test results showed slight incompatibility with base-metal specimens but moderate incompatibility with weld specimens. Severe incompatibility occurred for gaseous hydrogen and A-50 environments. The specimens that were aged after cryostretching did not have lower crack-growth threshold values compared to the unaged specimens. The specimens tested in 322 K (120° F) N_2O_4 had the same slight or negligible incompatibility as the ones tested at ambient temperature.

The cryoformed 304L stainless steel showed slight incompatibility with N_2O_4 and moderate incompatibility with MMH. These results are similar to those obtained for cryoformed 301 stainless steel. The 6Al-4V titanium base metal and pressure welds showed slight incompatibility with air. The A-286 steel showed negligible incompatibility with gaseous hydrogen, and the AM-350 stainless steel showed negligible incompatibility with H_2O_2.

The occurrence of moderate incompatibility for cryoformed 301 stainless steel welds tested in N_2H_4 is significant because the material is extensively used for N_2H_4 storage vessels in spacecraft. The test results in table VIII show that the value of K_{TH}/K_{IE} is between 60 and 70 percent for the material in N_2H_4. For specimen 486A-2-E, which had a K_{Ii}/K_{IE} ratio of 60 percent and a flaw depth of 71 percent through the thickness, the flaw growth was zero after 750 hours. The sustained-load stress level was similar to that in spacecraft pressure vessels of the same material, and the value of K_{Ii} was 55.3 $MN/m^{3/2}$ (50.3 ksi$\sqrt{in.}$). The possibility of a cryoformed 301 stainless steel pressure vessel having a crack-growth problem caused by N_2H_4 would depend on the maximum size flaw that could occur. The approximate 13- to 14-percent wall-thickness reduction of the vessel during cryoforming should certainly screen out flaws smaller than halfway through the thickness of the pressure vessel wall. Also, since the cryoformed N_2H_4 storage vessels all have wall thicknesses less than 0.076 centimeter (0.03 inch), flaw sizes could not possibly be large enough to produce stress-intensity factors approaching K_{TH} at operating pressures.

In summarizing the results, it should be stated that many of the environmental tests were performed for screening purposes only, and the results should not be considered entirely conclusive. This situation was particularly true for the cryoformed stainless steel tested in hydrazine-type mixtures where contamination may have been relevant. The tests were not planned to study effects of CO_2 impurities in hydrazine that has been reported to cause environmental crack growth or to use ultrapure or buffered hydrazine mixtures that are being investigated in other programs. Concerning the cleaning problem for hydrazine environment specimens, no significant difference was found in the results between specimens cleaned with Freon and specimens cleaned with isopropyl alcohol, which is now required for cleaning spacecraft hydrazine tanks.

Finally, for many of the specimens tested at K_{Ii}/K_{IE} ratios of approximately 85 percent or higher, the small amount of crack growth indicated may not have been caused by environmental incompatibility. The reason is that most precracked metal specimens when monotonically loaded have a certain amount of stable crack growth preceding instability. This growth on loading could have happened for most of the specimens tested in which a trace of growth was found after sustained loading close to K_{IE}. To verify this, specimen 504A (made from 301 stainless steel) was monotonically loaded in approximately 1 minute to 84 percent of K_{IE} in air, and the load then immediately dropped to zero. After fatigue loading the specimen to mark the crack and then pulling to failure, a crack growth of 0.015 centimeter (0.006 inch) was found on the fracture face that occurred during the initial monotonic loading. These data are listed in table IX and indicate that the crack growth for some specimens did occur during the initial application of load. The only significance of this is that some combinations of materials and fluids rated as having slight incompatibility actually may have no incompatibility.

CONCLUSIONS

The results of the test program to investigate environmental crack behavior of high-strength pressure vessel alloys can be summarized as follows.

1. The only severe environmental crack-growth problem found in the materials tested was in cryoformed 301 stainless steel exposed to gaseous hydrogen and aerozine 50 and in Inconel 718 exposed to gaseous hydrogen.

2. The cryoformed 301 stainless steel weld had a crack-growth threshold ratio K_{TH}/K_{IE} of between 60 and 70 percent for exposure to hydrazine, but this should not be low enough to cause incompatibility problems in the very thin walled hydrazine tanks currently in use in space vehicles.

3. The cryoformed 301 stainless steel had no incompatibility problems when tested in 322 K (120° F) nitrogen tetroxide, the same as when tested at ambient temperature.

4. Unlike Inconel 718, the A-286 steel had no incompatibility with high-pressure gaseous hydrogen.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, November 22, 1974
786-15-31-01-72

REFERENCES

1. Ecord, Glenn M.: Apollo Experience Report — Pressure Vessels. NASA TN D-6975, 1972.

2. Tiffany, C. F.: Fracture Control of Metallic Pressure Vessels. NASA SP-8040, 1970.

3. Pettit, D. E.; Feddersen, C. E.; and Mindlin, H.: Flaw Growth Behavior of Inconel 718 at Room and Cryogenic Temperature. NASA CR-101942, 1969.

4. Anon.: Aerospace Structural Metals Handbook. Vol. 1, AFML-TR-68-115, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, 1971.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The Système International d'Unités (SI) was adopted by the Eleventh General Conference on Weights and Measures in Paris during October 1960, in Resolution Number 12. The factors required for conversion of U.S. customary units used in this report to SI units and the prefixes and symbols used to indicate multiples of units are presented in the following tables.

To convert from U.S. customary units	Multiply by —	To obtain SI units
lbf	4.448222	newtons (N)
in.	2.54×10^{-2}	meters (m)
kips per square inch (ksi)	6.894757×10^{6}	N/m^2
ksi $\sqrt{\text{in.}}$	1.0988	$MN/m^{3/2}$
lbf per square inch (psi)	6.894757×10^{3}	MN/m^2
°F	$K = (5/9)(F + 459.67)$	Kelvin (K)

Multiple	Prefix	Symbol
10^{-3}	milli	m
10^{-2}	centi	c
10^{6}	mega	M

TABLE I.- VALUES OF Φ^2 AS A FUNCTION OF

$$\Phi = \int_0^{\pi/2} \left[1 - \left(\frac{b^2 - a^2}{b^2}\right)\sin^2\theta\right]^{1/2} d\theta$$

a/b	Φ^2	a/b	Φ^2
0.00000	1.000000	0.74162	1.891730
.22361	1.124605	.77459	1.958297
.31622	1.220527	.80622	2.024049
.38729	1.307354	.83666	2.089074
.44721	1.388838	.86602	2.153444
.50000	1.466656	.89443	2.217225
.54772	1.541746	.92195	2.280468
.59161	1.614772	.94868	2.343220
.63245	1.685915	.97468	2.405517
.67082	1.755688	1.00000	2.467400
.70710	1.824239		

TABLE II.- YIELD STRENGTH VALUES USED FOR K_{Ii} AND K_{IE} CALCULATIONS

Type material	σ_y, MN/m^2 (ksi)	Source of σ_y values
Cryoformed 301, heat 50726, 308L weld wire:		
Unaged weld metal	1206 (175)	Contractor test
Unaged HAZ metal	1413 (205)	Estimate
Unaged base metal	1482 (215)	Contractor test
Aged weld metal	1620 (235)	Contractor test
Aged HAZ metal	1751 (254)	Estimate
Aged base metal	1765 (256)	Contractor test
Cryoformed 301, heat 53087, 308L weld wire:		
Aged weld metal	1620 (235)	Contractor test
Cryoformed 301, heat 53087, 301 weld wire:		
Aged weld metal	1620 (235)	Contractor test
Cryoformed 304L, 308L weld wire:		
Aged weld metal	1620 (235)	Estimate
Aged HAZ metal	1820 (264)	Contractor test
Inconel 718 CGSS tank material:		
Weld metal	1179 (171)	Reference 3
Base metal	1213 (176)	Reference 3
Inconel 718 ALSA bottle material:		
Weld metal	1117 (162)	Contractor test
HAZ metal	1206 (175)	Estimate
Base metal	1206 (175)	Contractor test
A-286 steel	724 (105)	Reference 4
AM-350 (SCT 1000) steel	1048 (152)	Reference 4
6Al-4V titanium (STA)[a] pressure weld:		
Weld metal	1062 (154)	Contractor test
HAZ metal	1062 (154)	Estimate
Base metal	1062 (154)	Contractor test

[a]STA = solution treated and aged.

TABLE III.- FRACTURE-TOUGHNESS TEST RESULTS FOR CRYOFORMED 301 SPECIMENS AT AMBIENT TEMPERATURE

Material description	Specimen no. (a)	t, cm (in.)	w, cm (in.)	a, cm (in.)	2b, cm (in.)	σ, MN/m^2 (ksi)	K_{IE}, $MN/m^{3/2}$ (ksi $\sqrt{in.}$)
Weld	464-1	0.145 (0.057)	2.735 (1.077)	0.089 (0.035)	0.569 (0.224)	1255 (182)	96.6 (87.9)
Weld	446-1	.142 (.056)	2.779 (1.094)	.102 (.040)	.737 (.290)	1124 (163)	92.1 (83.8)
Weld	447-1	.142 (.056)	2.769 (1.090)	.094 (.037)	.574 (.226)	1296 (188)	96.6 (87.9)
HAZ	469-1	.147 (.058)	2.729 (1.074)	.094 (.037)	.584 (.230)	1275 (185)	90.9 (82.7)
HAZ	431-1	.145 (.057)	2.738 (1.078)	.091 (.036)	.559 (.220)	1365 (198)	96.2 (87.6)
HAZ	434-1	.142 (.056)	2.718 (1.070)	.094 (.037)	.561 (.221)	1365 (198)	98.9 (90.0)
Base	441-1	.145 (.057)	2.748 (1.082)	.102 (.040)	.582 (.229)	1393 (202)	105.9 (96.4)
Base	442-1	.142 (.056)	2.743 (1.080)	.094 (.037)	.610 (.240)	1930 (280)	106.0 (96.5)
Weld	421A-1	.142 (.056)	2.713 (1.068)	.089 (.035)	.559 (.220)	1441 (209)	99.0 (90.1)
Weld	423A-1	.145 (.057)	2.735 (1.077)	.094 (.037)	.582 (.229)	1468 (213)	105.4 (95.9)
HAZ	427A-1	.142 (.056)	2.733 (1.076)	.089 (.035)	.589 (.232)	1579 (229)	110.1 (100.2)
HAZ	428A-1	.145 (.057)	2.756 (1.085)	.086 (.034)	.554 (.218)	1551 (225)	103.6 (94.3)
Base	404A-1	.140 (.055)	2.748 (1.082)	.089 (.035)	.549 (.216)	1634 (237)	113.4 (132.2)
Base	405A-1	.142 (.056)	2.738 (1.078)	.089 (.035)	.582 (.229)	1613 (234)	112.4 (102.3)
Weld[b]	478A-2	.147 (.058)	2.761 (1.087)	.096 (.038)	.554 (.218)	1310 (190)	92.2 (83.9)
Weld[b]	479A-2	.145 (.057)	2.758 (1.086)	.094 (.037)	.569 (.224)	1296 (188)	90.9 (82.7)
Weld	481A-2	.150 (.059)	2.776 (1.093)	.109 (.043)	.549 (.216)	1234 (179)	92.4 (84.1)
Weld (301)[b]	496A-2	.150 (.059)	2.764 (1.088)	.099 (.039)	.566 (.223)	1275 (185)	91.0 (82.8)
Weld (301)[b]	497A-2	.147 (.058)	2.761 (1.087)	.099 (.039)	.579 (.228)	1303 (189)	94.4 (85.9)
Weld (301)[b]	502A-2	.152 (.060)	2.781 (1.095)	.102 (.040)	.602 (.237)	1262 (183)	92.2 (83.9)
Weld (301)[b]	503A-2	.147 (.058)	2.769 (1.090)	.096 (.038)	.538 (.212)	1262 (183)	87.8 (79.9)

[a]Specimen number symbols: A = aged heat treatment; -1 = heat 50726 base metal; -2 = heat 53087 base metal.

[b]Weld bead removed before cryostretching; (301) signifies 301 weld wire used; all other samples used 308 weld wire.

TABLE IV.- FRACTURE-TOUGHNESS TEST RESULTS FOR CRYOFORMED 304L, A-286, AND AM-350 (SCT 1000) SPECIMENS AT AMBIENT TEMPERATURE

Material description	Specimen no.	t, cm (in.)	w, cm (in.)	a, cm (in.)	$2b$, cm (in.)	σ, MN/m^2 (ksi)	K_{IE}, $MN/m^{3/2}$ (ksi $\sqrt{in.}$)
304L CRES[a]							
Weld	2	0.140 (0.055)	2.273 (0.894)	0.084 (0.033)	0.549 (0.216)	1096 (159)	70.3 (64.0)
Weld	4	.142 (.056)	2.263 (.891)	.094 (.037)	.582 (.229)	1069 (155)	74.1 (67.4)
HAZ	1	.137 (.054)	2.278 (.897)	.099 (.039)	.549 (.216)	1227 (178)	89.2 (81.2)
HAZ	3	.140 (.055)	2.288 (.901)	.089 (.035)	.549 (.216)	1269 (184)	85.4 (77.7)
A-286							
Base	1	0.315 (0.124)	2.54 (1.000)	0.180 (0.071)	0.452 (0.178)	834 (121)	56.3 (51.2)
AM-350 (SCT 1000)							
Base	P-1	0.328 (0.129)	2.55 (1.002)	0.122 (0.048)	0.376 (0.148)	1020 (148)	58.9 (53.6)
Base	P-2	.328 (.129)	2.55 (1.002)	.127 (.050	.394 (.155)	1030 (150)	61.3 (55.8)

[a]CRES = corrosion-resistant steel.

TABLE V.- FRACTURE-TOUGHNESS TEST RESULTS FOR INCONEL 718 SPECIMENS FROM ALSA BOTTLE MATERIAL

AT AMBIENT TEMPERATURE

Material description	Specimen no.	t, cm (in.)	w, cm (in.)	a, cm (in.)	2b, cm (in.)	σ, MN/m^2 (ksi)	K_{IE}, $MN/m^{3/2}$ (ksi $\sqrt{in.}$)
Weld	5	0.572 (0.225)	5.080 (2.000)	0.335 (0.132)	1.89 (0.745)	503 (73)	58.8 (53.5)
Weld	[a]1-5	.510 (.201)	4.064 (1.600)	.277 (.109)	1.00 (.395)	745 (108)	69.9 (63.6)
Weld	2-4	.523 (.206)	4.059 (1.598)	.267 (.105)	1.04 (.409)	765 (111)	71.6 (65.2)
Weld	[a]2-8	.505 (.199)	4.059 (1.598)	.275 (.108)	1.00 (.394)	772 (112)	72.5 (66.0)
Weld	1-7	.513 (.202)	4.064 (1.600)	.350 (.138)	1.10 (.435)	814 (118)	86.0 (78.3)
Weld	[b]3-5	.518 (.204)	4.064 (1.600)	.297 (.117)	1.10 (.434)	862 (125)	87.0 (79.2)
Weld	1-8	.516 (.203)	4.064 (1.600)	.310 (.122)	1.03 (.407)	896 (130)	89.6 (81.5)
Weld	[c]2-1	.523 (.206)	4.066 (1.601)	.401 (.158)	1.30 (.511)	745 (108)	84.3 (76.7)
Weld	[c]2-2	.518 (.204)	4.061 (1.599)	.262 (.103)	1.05 (.413)	869 (126)	82.1 (74.7)
HAZ	3-6	.508 (.200)	4.064 (1.600)	.256 (.101)	1.04 (.409)	1096 (159)	106.0 (96.5)
HAZ	2-5	.518 (.204)	4.064 (1.600)	.234 (.092)	1.02 (.402)	1138 (165)	106.2 (96.7)
HAZ	3-7	.516 (.203)	4.064 (1.600)	.348 (.137)	1.08 (.427)	1062 (154)	112.8 (102.7)
HAZ	[c]2-6	.523 (.206)	4.069 (1.602)	.229 (.090)	1.02 (.402)	1131 (164)	103.7 (94.4)
HAZ	[c]2-7	.513 (.202)	4.054 (1.596)	.244 (.096)	1.05 (.415)	1117 (162)	106.6 (97.0)
HAZ	9	.518 (.204)	5.080 (2.000)	.386 (.152)	1.46 (.574)	745 (108)	93.7 (85.3)
HAZ	8	.526 (.207)	5.080 (2.000)	.302 (.119)	1.91 (.750)	793 (115)	94.6 (86.1)
Base	P-1	.518 (.204)	4.064 (1.600)	.221 (.087)	.99 (.391)	1105 (160)	99.3 (90.4)
Base	P-3	.516 (.203)	4.064 (1.600)	.305 (.120)	1.11 (.436)	1027 (149)	106.5 (96.9)

[a]Tie-off and repair weld specimen.
[b]Tie-off weld specimen.
[c]Specimen previously sustain load tested and fatigue marked.

TABLE VI.- FRACTURE-TOUGHNESS TEST RESULTS FOR 6Al-4V TITANIUM (STA) PRESSURE-WELD SPECIMENS

AT AMBIENT TEMPERATURE

Material description	Specimen no.	t, cm (in.)	w, cm (in.)	a, cm (in.)	2b, cm (in.)	σ, MN/m^2 (ksi)	K_{IE}, $MN/m^{3/2}$ (ksi $\sqrt{in.}$)
Weld	12	0.333 (0.131)	1.86 (0.732)	0.135 (0.053)	0.434 (0.171)	927 (134)	56.6 (51.5)
Weld	13	.348 (.137)	1.92 (.756)	.160 (.063)	.485 (.191)	865 (125)	56.5 (51.4)
Weld	14	.317 (.125)	1.88 (.742)	.164 (.064)	.467 (.184)	866 (125)	56.6 (51.5)
Weld	15	.348 (.137)	1.92 (.758)	.226 (.089)	.544 (.214)	787 (114)	56.4 (51.3)
HAZ	1	.343 (.135)	1.88 (.741)	.117 (.046)	.399 (.157)	858 (124)	48.8 (44.4)
HAZ	2	.323 (.127)	1.91 (.752)	.145 (.057)	.450 (.177)	858 (124)	53.6 (48.8)
HAZ	4	.320 (.126)	1.89 (.746)	.173 (.068)	.500 (.197)	801 (116)	54.2 (49.3)
Base	7	.317 (.125)	1.89 (.743)	.114 (.045)	.447 (.176)	831 (120)	49.1 (44.7)
Base	8	.300 (.118)	1.89 (.746)	.132 (.052)	.483 (.190)	855 (124)	54.2 (49.4)
Base	9	.312 (.123)	1.90 (.748)	.180 (.071)	.541 (.213)	761 (110)	53.9 (49.1)
Base	11	.310 (.122)	1.90 (.748)	.117 (.046)	.434 (.171)	831 (120)	49.0 (44.6)

TABLE VII.- AVERAGE K_{IE} VALUES OF TEST MATERIALS

Type material	Average K_{IE}, $MN/m^{3/2}$ (ksi $\sqrt{in.}$)
Cryoformed 301 CRES, heat 50726, 308L weld wire:	
Unaged weld metal	95.0 (86.5)
Unaged HAZ metal	95.4 (86.8)
Unaged base metal	106.0 (96.5)
Aged weld metal	102.2 (93.0)
Aged HAZ metal	106.9 (97.3)
Aged base metal	113.0 (102.8)
Cryoformed 301 CRES, heat 53087, 308L weld wire:	
Aged weld metal	91.9 (83.6)
Cryoformed 301 CRES, heat 53087, 301 weld wire:	
Aged weld metal	91.3 (83.1)
Cryoformed 304L CRES, 308L weld wire:	
Aged weld metal	72.2 (65.7)
Aged HAZ metal	87.3 (79.5)
Inconel 718 CGSS tank material:	
Weld metal	54.9 (50)[a]
Base metal	109.9 (100)[a]
Inconel 718 ALSA bottle material:	
Weld metal	78.0 (71.0)
HAZ metal	103.4 (94.1)
Base metal	102.8 (93.6)
A-286 steel	56.2 (51.2)
AM-350 (SCT 1000) steel	60.1 (54.7)
6Al-4V titanium (STA) pressure weld:	
Weld metal	56.5 (51.4)
HAZ metal	52.2 (47.5)
Base metal	51.6 (47.0)

[a]Values obtained from reference 3.

TABLE VIII.- SUSTAINED-LOAD TEST RESULTS FOR CRYOFORMED 301 STAINLESS STEEL SPECIMENS WELDED WITH 308L STAINLESS STEEL WELD WIRE

Specimen no. (a)	Flaw location	t, cm (in.)	w, cm (in.)	a_i, cm (in.)	$2b_i$, cm (in.)	σ, MN/m^2 (ksi)	Test environment			Test duration, hr	K_{Ii}, $MN/m^{3/2}$ (ksi $\sqrt{in.}$)	$\frac{K_{Ii}}{K_{IE}}$	Amount of growth, cm (in.)
							Type	Temperature, K (°F)	Pressure, MN/m^2 (psi)				
9-1-B	Weld	0.140 (0.055)	2.766 (1.089)	0.102 (0.040)	0.574 (0.226)	1080 (157)	N_2H_4	Ambient	Ambient	96	82.6 (75.2)	0.87	0
12-1-B	Weld	.147 (.058)	2.760 (1.087)	.104 (.041)	.612 (.241)	1040 (151)	N_2H_4	Ambient	Ambient	96	79.9 (72.7)	.84	<.013 (<.005)
6-1-B	Weld	.142 (.056)	2.791 (1.099)	.091 (.036)	.563 (.222)	1000 (145)	N_2H_4	Ambient	Ambient	49	69.4 (63.2)	.73	Failure
7-1-C	Weld	.137 (.054)	2.771 (1.071)	.091 (.036)	.563 (.222)	1010 (146)	N_2H_4	Ambient	Ambient	<310	71.1 (64.7)	.75	Failure
19A-1-B	Weld	.140 (.055)	2.760 (1.087)	.099 (.039)	.571 (.225)	1150 (167)	N_2H_4	Ambient	Ambient	96	83.9 (76.4)	.82	<.013 (<.005)
16A-1-C	Weld	.150 (.059)	2.776 (1.093)	.099 (.039)	.592 (.233)	1070 (155)	N_2H_4	Ambient	Ambient	310	75.7 (68.9)	.74	.013 (.005)
416A-1-B	Weld	.142 (.056)	2.743 (1.080)	.102 (.040)	.566 (.223)	1140 (166)	N_2H_4	Ambient	Ambient	48	83.9 (76.4)	.82	.041 (.016)
474A-1-E	Weld	.145 (.057)	2.763 (1.088)	.099 (.039)	.563 (.222)	1103 (160)	N_2H_4	Ambient	Ambient	98	76.6 (69.7)	.75	Failure
475A-1-E	Weld	.145 (.057)	2.766 (1.089)	.094 (.037)	.561 (.221)	1110 (161)	N_2H_4	Ambient	Ambient	296	73.7 (67.1)	.72	Failure
484A-2-E	Weld	.150 (.059)	2.769 (1.090)	.099 (.039)	.546 (.215)	965 (140)	N_2H_4	Ambient	Ambient	55	66.5 (60.5)	.73	Failure
486A-2-E	Weld	.150 (.059)	2.769 (1.090)	.107 (.042)	.587 (.231)	758 (110)	N_2H_4	Ambient	Ambient	750	55.3 (50.3)	.60	0
11-1-B	HAZ	.142 (.056)	2.769 (1.090)	.102 (.040)	.559 (.220)	1010 (146)	N_2H_4	Ambient	Ambient	165	73.6 (67.0)	.77	0
468-1-E	HAZ	.135 (.053)	2.753 (1.084)	.089 (.035)	.579 (.228)	1000 (145)	N_2H_4	Ambient	Ambient	750	68.9 (62.7)	.72	0
418A-1-B	HAZ	.147 (.058)	2.738 (1.078)	.089 (.035)	.561 (.221)	1350 (196)	N_2H_4	Ambient	Ambient	4	90.0 (81.9)	.84	Failure
17A-1-D	HAZ	.137 (.054)	2.748 (1.082)	.094 (.037)	.566 (.223)	1120 (163)	N_2H_4	Ambient	Ambient	310	78.8 (71.7)	.74	0
18A-1-D	HAZ	.147 (.058)	2.743 (1.080)	.102 (.040)	.574 (.226)	993 (144)	N_2H_4	Ambient	Ambient	310	70.9 (64.5)	.66	0
21A-1-D	HAZ	.140 (.055)	2.746 (1.081)	.096 (.038)	.576 (.227)	924 (134)	N_2H_4	Ambient	Ambient	310	64.9 (59.1)	.61	0
473A-1-E	HAZ	.147 (.058)	2.753 (1.084)	.099 (.039)	.559 (.220)	1131 (164)	N_2H_4	Ambient	Ambient	502	76.1 (69.3)	.71	0
8-1-B	Weld	.142 (.056)	2.760 (1.087)	.104 (.041)	.584 (.230)	1070 (156)	A-50	Ambient	Ambient	88	83.2 (75.7)	.87	Failure
10-1-B	Weld	.142 (.056)	2.760 (1.087)	.096 (.038)	.538 (.212)	1060 (154)	A-50	Ambient	Ambient	25	76.1 (69.3)	.80	Failure
4-1-B	Weld	.142 (.056)	2.774 (1.092)	.094 (.037)	.569 (.224)	924 (134)	A-50	Ambient	Ambient	67	64.9 (59.1)	.68	Failure
15A-1-B	Weld	.140 (.055)	2.774 (1.092)	.091 (.036)	.526 (.207)	1140 (166)	A-50	Ambient	Ambient	96	77.3 (70.4)	.76	0
477A-1-E	Weld	.132 (.052)	2.731 (1.075)	.081 (.032)	.541 (.213)	1110 (161)	A-50	Ambient	Ambient	19	71.1 (64.7)	.70	Failure
2-1-B	HAZ	.140 (.055)	2.758 (1.086)	.089 (.035)	.559 (.220)	986 (173)	A-50	Ambient	Ambient	114	66.2 (60.3)	.69	Failure
5-1-B	Weld	.142 (.056)	2.760 (1.087)	.099 (.039)	.546 (.215)	1070 (156)	N_2O_4	Ambient	Ambient	96	78.9 (71.8)	.83	0
13-1-B	Weld	.142 (.056)	2.773 (1.092)	.102 (.040)	.612 (.241)	1060 (157)	N_2O_4	Ambient	Ambient	96	81.6 (74.3)	.86	0
14A-1-B	Weld	.142 (.056)	2.769 (1.090)	.096 (.038)	.556 (.219)	1130 (164)	N_2O_4	Ambient	Ambient	96	79.7 (72.5)	.78	<.013 (<.005)
20A-1-B	Weld	.137 (.054)	2.750 (1.083)	.102 (.040)	.599 (.236)	1060 (154)	N_2O_4	Ambient	Ambient	96	64.3 (58.5)	.63	<.013 (<.005)
480A-2-E[b]	Weld	.142 (.056)	2.738 (1.078)	.094 (.037)	.544 (.214)	1075 (156)	N_2O_4	322 (120)	Ambient	500	73.6 (67.0)	.72	<.013 (<.005)
482A-2-E	Weld	.150 (.059)	2.766 (1.089)	.107 (.042)	.570 (.224)	1075 (156)	N_2O_4	322 (120)	Ambient	500	79.2 (72.1)	.77	0

[a]Specimen number symbols: A = aged heat treatment; -1 = 301 CRES, heat 50726 base material; -2 = 301 CRES, heat 53087 base material; -B = ultrasonic clean in Freon before test; -C = ultrasonic clean in Freon and flush dried with hot nitrogen gas; -D = ultrasonic clean in Freon, vacuum bake dry, and reclean with isopropyl alcohol; -E = cleaned only with isopropyl alcohol and vacuum bake dried; -F = clean for oxygen service (pickle 1 hr in 40-percent nitric acid, soak 2 hr in 20-percent ammonia hydroxide.

[b]Weld bead machined off before cryostretching.

TABLE VIII.- SUSTAINED-LOAD TEST RESULTS FOR CRYOFORMED 301 STAINLESS STEEL SPECIMENS WELDED WITH 308L STAINLESS STEEL WELD WIRE - Continued

Specimen no. (a)	Flaw location	t, cm (in.)	w, cm (in.)	a_i, cm (in.)	$2b_i$, cm (in.)	σ, MN/m^2 (ksi)	Test environment			Test duration, hr	K_{Ii}, $MN/m^{3/2}$ (ksi $\sqrt{in.}$)	$\frac{K_{Ii}}{K_{IE}}$	Amount of growth, cm (in.)
							Type	Temperature, K (°F)	Pressure, MN/m^2 (psi)				
483A-2-E	Weld	0.147 (0.058)	2.769 (1.090)	0.094 (0.037)	0.597 (0.235)	1075 (156)	N_2O_4	322 (120)	Ambient	500	74.3 (67.6)	0.73	<0.013 (0.005)
485A-2-E	Weld	.147 (.058)	2.750 (1.083)	.107 (.042)	.561 (.221)	1075 (156)	N_2O_4	322 (120)	Ambient	500	79.5 (72.4)	.78	.015 (.006)
1-1-B	HAZ	.137 (.054)	2.750 (1.083)	.094 (.037)	.589 (.232)	1010 (147)	N_2O_4	Ambient	Ambient	165	72.4 (65.9)	.71	.013 (<.005)
412A-1-F	Weld	.142 (.056)	2.712 (1.068)	.094 (.037)	.566 (.223)	1160 (168)	N_2	Ambient	13.79 (2000)	70	80.6 (73.4)	.79	.041 (.016)
425A-1-F	HAZ	.140 (.055)	2.738 (1.078)	.094 (.037)	.587 (.231)	1290 (187)	N_2	Ambient	13.79 (2000)	70	91.5 (83.3)	.86	0
430A-1-F	HAZ	.140 (.055)	2.723 (1.072)	.089 (.035)	.559 (.220)	1320 (192)	N_2	Ambient	.69 (100)	88	89.7 (81.6)	.84	0
403A-1-F	Base	.147 (.058)	2.766 (1.089)	.102 (.040)	.561 (.221)	1310 (190)	N_2	Ambient	.69 (100)	88	79.0 (71.9)	.70	0
424A-1-F	Weld	.140 (.055)	2.730 (1.075)	.099 (.039)	.612 (.241)	1190 (173)	CO_2	Ambient	6.89 (1000)	42	88.8 (80.8)	.87	.015 (.006)
429A-1-F	HAZ	.140 (.055)	2.748 (1.082)	.091 (.036)	.566 (.223)	1350 (196)	CO_2	Ambient	6.89 (1000)	88	93.8 (85.4)	.88	0
34-1-F	Base	.142 (.056)	2.789 (1.098)	.071 (.028)	.282 (.111)	607 (88)	H_2	Ambient	6.89 (1000)	<.1	29.1 (26.5)	.27	Failure
35-1-F	Base	.145 (.057)	2.756 (1.085)	.086 (.034)	.284 (.112)	275 (40)	H_2	Ambient	6.89 (1000)	21	13.9 (12.7)	.13	0
36-1-F	Base	.142 (.056)	2.794 (1.100)	.086 (.034)	.279 (.110)	393 (57)	H_2	Ambient	6.89 (1000)	<.1	19.9 (18.1)	.19	Failure
37-1-F	Base	.145 (.057)	2.786 (1.097)	.086 (.034)	.284 (.112)	338 (49)	H_2	Ambient	6.89 (1000)	<.1	17.1 (15.6)	.16	Failure
435-1-F	Weld	.145 (.057)	2.718 (1.070)	.091 (.036)	.579 (.228)	1200 (174)	O_2	Ambient	.69 (100)	64	85.8 (78.1)	.90	.015 (.006)
458-1-F	Weld	.145 (.057)	2.730 (1.075)	.096 (.038)	.566 (.223)	1080 (157)	O_2	Ambient	10.34 (1500)	40	78.3 (71.3)	.82	0
452-1-F	HAZ	.147 (.058)	2.761 (1.087)	.099 (.039)	.574 (.226)	1210 (176)	O_2	Ambient	10.34 (1500)	18	88.4 (80.5)	.93	Failure
454-1-1	HAZ	.142 (.056)	2.723 (1.072)	.099 (.039)	.632 (.249)	1090 (158)	O_2	Ambient	10.34 (1500)	40	81.5 (74.2)	.86	0
411-1-1	Base	.142 (.056)	2.748 (1.082)	.091 (.036)	.566 (.223)	1300 (189)	O_2	Ambient	10.34 (1500)	18	91.4 (83.2)	.86	0
448-1-F	Weld	.145 (.057)	2.733 (1.076)	.099 (.039)	.574 (.226)	1110 (161)	DW	Ambient	9.65 (1400)	70	82.4 (75.0)	.87	0
450-1-F	Weld	.145 (.057)	2.725 (1.073)	.089 (.035)	.566 (.223)	979 (142)	DW	Ambient	10.34 (1500)	90	66.1 (60.2)	.70	0
432-1-F	Weld	.147 (.058)	2.735 (1.077)	.089 (.035)	.533 (.210)	945 (137)	DW	Ambient	8.96 (1300)	18	62.3 (56.7)	.66	0
413A-1-F	Weld	.142 (.056)	2.708 (1.066)	.089 (.035)	.574 (.226)	1150 (167)	DW	Ambient	7.58 (1100)	64	77.3 (70.4)	.76	.033 (.013)
422A-1-F	Weld	.140 (.055)	2.740 (1.079)	.089 (.035)	.533 (.210)	1096 (159)	DW	Ambient	Ambient	63	72.6 (66.1)	.71	0
449-1-F	HAZ	.145 (.057)	2.725 (1.073)	.094 (.037)	.559 (.220)	1170 (170)	DW	Ambient	10.34 (1500)	70	82.2 (74.8)	.86	0
453-1-F	HAZ	.150 (.059)	2.753 (1.084)	.094 (.037)	.561 (.221)	1030 (149)	DW	Ambient	10.69 (1550)	90	70.2 (63.7)	.73	0
456-1-F	HAZ	.140 (.055)	2.713 (1.068)	.091 (.036)	.569 (.224)	1240 (180)	DW	Ambient	10.69 (1550)	41	87.8 (79.9)	.92	0
426A-1-F	HAZ	.140 (.055)	2.735 (1.077)	.089 (.035)	.561 (.221)	1220 (177)	DW	Ambient	7.93 (1150)	64	82.1 (74.7)	.77	0
437-1-F	Base	.147 (.058)	2.753 (1.084)	.094 (.037)	.553 (.218)	1280 (186)	DW	Ambient	10.13 (1470)	30	89.6 (81.5)	.84	0
410-1-F	Base	.145 (.057)	2.753 (1.084)	.086 (.034)	.541 (.213)	1160 (169)	DW	Ambient	10.00 (1450)	18	76.1 (69.3)	.72	0
438-1-F	Base	.145 (.057)	2.730 (1.075)	.094 (.037)	.569 (.224)	1280 (186)	DW	Ambient	10.34 (1500)	41	90.9 (80.7)	.86	0
467-1-F	Weld	.145 (.057)	2.730 (1.075)	.091 (.036)	.569 (.224)	1010 (146)	SW	Ambient	Ambient	144	69.7 (63.4)	.73	0
463-1-F	Weld	.142 (.056)	2.761 (1.087)	.091 (.036)	.561 (.221)	1120 (163)	SW	Ambient	Ambient	145	79.3 (72.2)	.83	0
455-1-F	Weld	.145 (.057)	2.702 (1.064)	.096 (.038)	.564 (.222)	1190 (173)	SW	Ambient	Ambient	290	87.8 (79.9)	.92	<.013 (<.005)
462-1-F	Weld	.147 (.058)	2.713 (1.068)	.096 (.038)	.559 (.220)	1230 (178)	SW	Ambient	Ambient	480	89.9 (81.8)	.95	<.013 (<.005)
415A-1-F	Weld	.140 (.055)	2.738 (1.078)	.099 (.039)	.566 (.223)	965 (140)	SW	Ambient	Ambient	68	69.2 (63.0)	.68	0

[a]See footnote "a" on page 21.

TABLE VIII.- SUSTAINED-LOAD TEST RESULTS FOR CRYOFORMED 301 STAINLESS STEEL SPECIMENS WELDED WITH 308L STAINLESS STEEL WELD WIRE - Concluded

Specimen no. (a)	Flaw location	t, cm (in.)	w, cm (in.)	a_i, cm (in.)	$2b_i$, cm (in.)	σ, MN/m^2 (ksi)	Test environment			Test duration, hr	K_{Ii}, MN/m$^{3/2}$ (ksi $\sqrt{in.}$)	$\frac{K_{Ii}}{K_{IE}}$	Amount of growth, cm (in.)
							Type	Temperature, K (°F)	Pressure, MN/m^2 (psi)				
465-1-F	HAZ	0.142 (0.056)	2.753 (1.084)	0.089 (0.035)	0.564 (0.222)	1130 (164)	SW	Ambient	Ambient	146	76.7 (69.8)	0.80	0
451-1-F	HAZ	.147 (.058)	2.735 (1.077)	.094 (.037)	.587 (.231)	1220 (177)	SW	Ambient	Ambient	290	86.5 (78.7)	.91	0
459-1-F	HAZ	.142 (.056)	2.725 (1.073)	.091 (.036)	.546 (.215)	1240 (180)	SW	Ambient	Ambient	480	86.2 (78.5)	.90	<.013 (<.005)
417A-1-F	HAZ	.150 (.059)	2.687 (1.058)	.089 (.035)	.574 (.226)	993 (144)	SW	Ambient	Ambient	68	64.3 (58.5)	.60	0
409A-1-F	Base	.137 (.054)	2.750 (1.083)	.089 (.035)	.569 (.224)	1070 (156)	SW	Ambient	Ambient	68	72.3 (65.8)	.58	0
406A-1-F	Base	.140 (.055)	2.735 (1.077)	.089 (.035)	.571 (.225)	1330 (193)	SW	Ambient	Ambient	144	90.5 (82.4)	.73	0

[a] See footnote "a" on page 21.

TABLE IX.- SUSTAINED-LOAD TEST RESULTS FOR CRYOFORMED 301 STAINLESS STEEL SPECIMENS WELDED WITH 301 STAINLESS STEEL WELD WIRE

Specimen no. (a)	Flaw location	t, cm (in.)	w, cm (in.)	a_i, cm (in.)	$2b_i$, cm (in.)	σ, MN/m^2 (ksi)	Test environment			Test duration, hr	K_{Ii}, $MN/m^{3/2}$ (ksi $\sqrt{in.}$)	$\frac{K_{Ii}}{K_{IE}}$	Amount of growth, cm (in.)
							Type	Temperature, K (°F)	Pressure, MN/m^2 (psi)				
498A[b]	Weld	0.147 (0.058)	2.776 (1.093)	0.102 (0.040)	0.579 (0.228)	965 (140)	N_2H_4	Ambient	Ambient	192.4	69.2 (63.0)	0.76	Failure
499A	Weld	.150 (.059)	2.771 (1.091)	.091 (.036)	.561 (.221)	758 (110)	N_2H_4	Ambient	Ambient	750.0	49.3 (44.9)	.54	0
505A	Weld	.155 (.061)	2.776 (1.093)	.109 (.043)	.612 (.241)	965 (140)	N_2H_4	Ambient	Ambient	421.5	72.1 (65.6)	.79	Failure
506A	Weld	.147 (.058)	2.776 (1.093)	.097 (.038)	.528 (.208)	896 (130)	N_2H_4	Ambient	Ambient	210.7	60.4 (55.0)	.66	Failure
508A	Weld	.145 (.057)	2.774 (1.092)	.102 (.040)	.597 (.235)	896 (130)	N_2H_4	Ambient	Ambient	143.5	64.9 (59.1)	.71	Failure
500A	Weld	.150 (.059)	2.771 (1.091)	.099 (.039)	.594 (.234)	758 (110)	A-50	Ambient	Ambient	528.9	52.7 (48.0)	.58	Failure
501A	Weld	.150 (.059)	2.771 (1.091)	.097 (.038)	.572 (.225)	758 (110)	A-50	Ambient	Ambient	149.7	51.3 (46.7)	.56	Failure
504A	Weld	.145 (.057)	2.761 (1.087)	.094 (.037)	.582 (.229)	1110 (161)	Air	Ambient	Ambient	0	76.9 (70.0)	.84	.015 (.006)

[a] All specimens cleaned only with isopropyl alcohol and vacuum bake dried.

[b] Weld bead machined off before cryostretching.

TABLE X.- SUSTAINED-LOAD TEST RESULTS FOR CRYOFORMED 304L STAINLESS STEEL SPECIMENS

Specimen no.	Flaw location	t, cm (in.)	w, cm (in.)	a_i, cm (in.)	$2b_i$, cm (in.)	σ, MN/m^2 (ksi)	Test environment			Test duration, hr	K_{Ii}, $MN/m^{3/2}$ (ksi $\sqrt{in.}$)	$\frac{K_{Ii}}{K_{IE}}$	Amount of growth, cm (in.),
							Type	Temperature, K (°F)	Pressure, MN/m^2 (psi)				
5	Weld	0.140 (0.055)	2.278 (0.897)	0.091 (0.036)	0.549 (0.216)	758 (110)	MMH	Ambient	Ambient	500	50.4 (45.9)	0.70	0
8	Weld	.142 (.056)	2.268 (.893)	.094 (.037)	.541 (.213)	814 (118)	MMH	Ambient	Ambient	500	54.7 (49.8)	.76	0
10	Weld	.142 (.056)	2.255 (.888)	.097 (.038)	.554 (.218)	758 (110)	MMH	Ambient	Ambient	500	52.1 (47.4)	.72	>t
7	HAZ	.142 (.056)	2.278 (.897)	.091 (.036)	.564 (.222)	876 (127)	MMH	Ambient	Ambient	500	58.4 (53.2)	.67	0
9	HAZ	.140 (.055)	2.278 (.897)	.094 (.037)	.549 (.216)	931 (135)	MMH	Ambient	Ambient	500	63.5 (57.8)	.73	>t
13	HAZ	.137 (.054)	2.271 (.894)	.094 (.037)	.551 (.217)	896 (130)	MMH	Ambient	Ambient	500	61.6 (56.1)	.70	.028 (.011)
6	Weld	.142 (.056)	2.283 (.899)	.099 (.039)	.604 (.238)	869 (126)	N_2O_4	Ambient	Ambient	500	62.4 (56.8)	.86	>t
12	Weld	.145 (.057)	2.288 (.901)	.097 (.038)	.564 (.222)	827 (120)	N_2O_4	Ambient	Ambient	500	56.8 (51.7)	.79	0
15	Weld	.140 (.055)	2.255 (.888)	.097 (.038)	.566 (.223)	848 (123)	N_2O_4	Ambient	Ambient	500	59.3 (54.0)	.92	0
11	HAZ	.145 (.057)	2.276 (.896)	.094 (.037)	.546 (.215)	1000 (145)	N_2O_4	Ambient	Ambient	500	67.5 (61.4)	.77	0
14	HAZ	.142 (.056)	2.273 (.895)	.094 (.037)	.554 (.218)	1034 (150)	N_2O_4	Ambient	Ambient	500	70.6 (64.3)	.81	0

TABLE XI.- SUSTAINED-LOAD TEST RESULTS FOR INCONEL 718 SPECIMENS FROM CGSS TANK MATERIAL

Specimen no.	Flaw location	t, cm (in.)	w, cm (in.)	a_i, cm (in.)	$2b_i$, cm (in.)	σ, MN/m^2 (ksi)	Test environment			Test duration, hr	K_{Ii}, $MN/m^{3/2}$ (ksi$\sqrt{in.}$)	$\frac{K_{Ii}}{K_{IE}}$	Amount of growth, cm (in.)
							Type	Temperature K (°F)	Pressure, MN/m^2 (psi)				
153P	Base	0.287 (0.113)	2.540 (1.000)	0.147 (0.058)	0.310 (0.122)	465 (67.5)	H_2	Ambient	5.2 (750)	0.6	23.6 (21.5)	0.21	0
157P	Base	.287 (.113)	2.540 (1.000)	.137 (.054)	.373 (.147)	465 (67.5)	H_2	Ambient	5.2 (750)	20.0	26.1 (23.7)	.24	0
159P	Base	.287 (.113)	1.913 (.753)	.157 (.059)	.350 (.132)	827 (120.0)	H_2	200 (-100)	6.9 (1000)	25.8	29.8 (40.7)	.41	Failure
154P	Base	.284 (.112)	1.910 (.752)	.147 (.058)	.305 (.120)	465 (67.5)	H_2	200 (-100)	5.2 (750)	20.0	23.4 (21.3)	.21	0
156P	Base	.287 (.113)	1.910 (.752)	.157 (.062)	.350 (.138)	543 (78.7)	H_2	200 (-100)	6.0 (875)	72.0	29.8 (27.1)	.27	.010 (.004)
158P	Base	.284 (.112)	1.905 (.750)	.163 (.064)	.330 (.130)	583 (84.6)	H_2	200 (-100)	6.5 (940)	61.2	30.8 (28.0)	.28	.008 (.003)
160P	Base	.287 (.113)	1.897 (.747)	.127 (.050)	.315 (.124)	620 (90.0)	H_2	200 (-100)	6.9 (1000)	20.0	31.9 (29.0)	.29	.015 (.006)
161P	Base	.287 (.113)	1.913 (.753)	.147 (.058)	.320 (.126)	465 (67.5)	H_2	200 (-100)	5.2 (750)	20.1	24.1 (22.0)	.22	0
163P	Base	.284 (.112)	1.833 (.722)	.160 (.063)	.348 (.137)	543 (78.7)	H_2	200 (-100)	6.0 (875)	260.0	29.6 (27.0)	.27	.008 (.003)
164P	Base	.284 (.112)	1.895 (.746)	.150 (.059)	.325 (.128)	496 (72.0)	H_2	200 (-100)	5.5 (800)	231.0	26.0 (23.7)	.24	0
182W	Weld	.277 (.109)	2.479 (.976)	.168 (.066)	.394 (.155)	465 (67.5)	H_2	Ambient	5.2 (750)	4.0	27.6 (25.1)	.50	Failure
184W	Weld	.264 (.104)	2.542 (1.001)	.132 (.052)	.320 (.126)	310 (45.0)	H_2	Ambient	3.4 (500)	20.0	16.1 (14.7)	.29	0
185W	Weld	.284 (.112)	2.545 (1.002)	.150 (.059)	.343 (.135)	372 (54.0)	H_2	Ambient	4.1 (600)	20.0	20.1 (18.3)	.37	.013 (.005)
186W	Weld	.282 (.111)	2.545 (1.002)	.147 (.058)	.333 (.131)	620 (90.0)	H_2	200 (-100)	6.9 (1000)	10.0	33.4 (30.4)	.61	Failure
187W	Weld	.274 (.108)	2.545 (1.002)	.129 (.051)	.315 (.124)	465 (67.5)	H_2	200 (-100)	5.2 (750)	20.6	24.0 (21.9)	.44	0
188W	Weld	.282 (.111)	2.545 (1.002)	.137 (.057)	.335 (.132)	465 (67.5)	H_2	200 (-100)	5.2 (750)	20.3	24.9 (22.6)	.45	0
189W	Weld	.277 (.109)	2.545 (1.002)	.150 (.059)	.333 (.131)	372 (54.0)	H_2	200 (-100)	4.1 (600)	72.0	19.8 (18.0)	.36	0
190W	Weld	.284 (.112)	2.540 (1.000)	.157 (.062)	.371 (.146)	372 (54.0)	H_2	200 (-100)	4.1 (600)	183.0	21.1 (19.2)	.38	0
191W	Weld	.284 (.112)	2.540 (1.000)	.160 (.063)	.330 (.130)	372 (54.0)	H_2	200 (-100)	4.1 (600)	84.0	19.6 (17.8)	.36	0
201W	Weld	.287 (.113)	1.907 (.751)	.124 (.049)	.386 (.152)	613 (89.0)	O_2	Ambient	6.9 (1000)	23.0	34.5 (31.4)	.63	0
202W	Weld	.287 (.113)	1.907 (.751)	.201 (.079)	.411 (.162)	690 (100.0)	O_2	Ambient	6.9 (1000)	22.0	41.6 (37.9)	.76	0
203W	Weld	.285 (.112)	1.913 (.753)	.185 (.073)	.406 (.160)	693 (100.5)	O_2	Ambient	6.9 (1000)	168.0	41.8 (38.0)	.76	0

TABLE XII.- SUSTAINED-LOAD TEST RESULTS FOR INCONEL 718 SPECIMENS FROM ALSA BOTTLE MATERIAL

Specimen no.	Flaw location	t, cm (in.)	w, cm (in.)	a_i, cm (in.)	$2b_i$, cm (in.)	σ, MN/m^2 (ksi)	Test environment			Test duration, hr	K_{Ii}, $MN/m^{3/2}$ (ksi $\sqrt{in.}$)	$\frac{K_{Ii}}{K_{IE}}$	Amount of growth, cm (in.)
							Type	Temperature, K (°F)	Pressure, MN/m^2 (psi)				
2-1	Weld	0.5232 (0.2060)	4.066 (1.601)	0.234 (0.092)	1.02 (0.403)	606 (88)	O_2	Ambient	41.4 (6000)	91	53.0 (48.2)	0.66	0
2-3	Weld	.5194 (.2045)	4.066 (1.601)	.234 (.092)	1.02 (.402)	653 (94)	O_2	Ambient	41.4 (6000)	40	57.2 (52.1)	.71	0
2-2	Weld	.5169 (.2035)	4.061 (1.599)	.254 (.100)	1.02 (.401)	624 (90)	DW	Ambient	Ambient	118	56.5 (51.4)	.72	0
1-1	Weld	.5240 (.2063)	4.066 (1.601)	.277 (.109)	1.08 (.425)	679 (98)	Air	Ambient	Ambient	305	64.7 (58.9)	.80	.033 (.013)
2-6	HAZ	.5220 (.2055)	4.069 (1.602)	.229 (.090)	1.02 (.402)	858 (124)	O_2	Ambient	41.4 (6000)	91	76.0 (69.2)	.71	0
2-7	HAZ	.5118 (.2015)	4.054 (1.596)	.236 (.093)	1.05 (.412)	986 (143)	DW	Ambient	Ambient	91	90.9 (82.8)	.85	0

TABLE XIII.- SUSTAINED-LOAD TEST RESULTS FOR A-286 AND AM-350 (SCT 1000) STEEL

Specimen no.	Flaw location	t, cm (in.)	w, cm (in.)	a_i, cm (in.)	$2b_i$, cm (in.)	σ, MN/m^2 (ksi)	Test environment			Test duration, hr	K_{Ii}, $MN/m^{3/2}$ (ksi $\sqrt{in.}$)	$\frac{K_{Ii}}{K_{IE}}$	Amount of growth, cm (in.)
							Type	Temperature, K (°F)	Pressure, MN/m^2 (psi)				
A-286 steel													
4	Base	0.3094 (0.1218)	2.567 (1.010)	0.183 (0.072)	0.434 (0.171)	751 (109)	H_2	294 (70)	6.9 (1000)	78.0	48.1 (43.8)	0.85	0
8	Base	.3078 (.1212)	2.569 (1.011)	.175 (.069)	.434 (.171)	779 (113)	H_2	294 (70)	6.9 (1000)	23.0	50.1 (45.6)	.89	0
5	Base	.3104 (.1222)	2.567 (1.010)	.173 (.068)	.434 (.171)	807 (117)	H_2	294 (70)	6.9 (1000)	.3	52.0 (47.4)	.92	Failure
AM-350 (SCT 1000) steel													
P-3	Base	0.3302 (0.1300)	2.540 (1.000)	0.152 (0.060)	0.386 (0.152)	820 (119)	H_2O_2	294 (70)	Ambient	100.0	47.9 (43.6)	0.80	0
P-4	Base	.3239 (.1295)	2.540 (1.000)	.142 (.056)	.376 (.148)	917 (133)	H_2O_2	294 (70)	Ambient	100.0	53.1 (48.3)	.88	0

TABLE XIV.- SUSTAINED-LOAD TEST RESULTS FOR 6Al-4V TITANIUM (STA) PRESSURE-WELD SPECIMENS

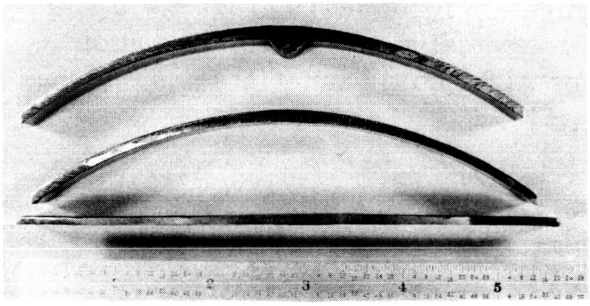
Specimen no.	Flaw location	t, cm (in.)	w, cm (in.)	a_i, cm (in.)	$2b_i$, cm (in.)	σ, MN/m^2 (ksi)	Test environment			Test duration, hr	K_{Ii}, MN/m$^{3/2}$ (ksi $\sqrt{in.}$)	$\frac{K_{Ii}}{K_{IE}}$	Amount of growth, cm (in.)
							Type	Temperature, K (°F)	Pressure, MN/m^2 (psi)				
8	Base	0.300 (0.118)	1.89 (0.746)	0.107 (0.042)	0.444 (0.175)	689 (100)	Air	294 (70)	Ambient	168	39.4 (35.9)	0.76	0
10	Base	.292 (.115)	1.88 (.740)	.145 (.057)	.645 (.254)	758 (110)	Air	294 (70)	Ambient	288	53.7 (48.9)	1.04	.020 (.008)
15	Weld	.348 (.137)	1.92 (.758)	.152 (.060)	.452 (.178)	757 (110)	Air	294 (70)	Ambient	268	47.0 (42.7)	.83	0
16	Weld	.330 (.130)	1.93 (.761)	.140 (.055)	.444 (.175)	801 (116)	Air	294 (70)	Ambient	90	48.8 (44.4)	.86	Failure
3	HAZ	.340 (.134)	1.89 (.745)	.127 (.050)	.470 (.185)	691 (100)	Air	294 (70)	Ambient	168	41.7 (38.0)	.74	0
5	HAZ	.310 (.122)	1.90 (.747)	.127 (.050)	.483 (.190)	758 (110)	Air	294 (70)	Ambient	.05	46.9 (42.7)	.90	Failure
6	HAZ	.333 (.131)	1.88 (.742)	.155 (.061)	.599 (.236)	688 (100)	Air	294 (70)	Ambient	268	47.9 (43.6)	.92	.013 (.005)

TABLE XV.- SUMMARY OF ENVIRONMENT INCOMPATIBILITY OF TEST MATERIALS

Type material	Environment	Incompatibility[a]
Cryoformed 301 welded with 308L filler wire (aged and unaged specimens)	DW, SW, O_2, N_2, and CO_2	Negligible
	N_2O_4, and N_2H_4 (base metal)	Slight
	N_2H_4 (weld metal)	Moderate
	A-50 and H_2	Severe
Cryoformed 301 welded with 301 filler wire (aged specimens)	N_2H_4	Moderate
	A-50	Severe
Cryoformed 304L welded with 308L filler wire (aged specimens)	N_2O_4	Slight
	MMH	Moderate
Inconel 718	DW, SW, O_2, and air	Slight
	H_2	Severe
A-286 steel	H_2	Negligible
AM-350 (SCT 1000) steel	H_2O_2	Negligible
6Al-4V titanium (STA) pressure weld	Air	Slight

[a]Incompatibility grading system:

K_{TH}/K_{IE}, percent	Incompatibility
≥ 85	Negligible
$\geq 75, < 85$	Slight
$\geq 60, < 75$	Moderate
< 60	Severe



Specimen fabrication procedure

1. Machine 1.9-cm (0.75 in.) wide by 12.7-cm (5.0 in.) long strips from spherical bottle.
2. Mill off weld bead from inside radius of each strip.
3. Wet sand front and back face to remove transverse curvature.
4. Flatten strips by clamping between two flat plates and heating in furnace at 755 K (900° F) for 4 hr.
5. Straighten strips final 10 percent by three-point bending at room temperature.

Figure 1.- Fabrication procedure for titanium pressure-weld specimens.

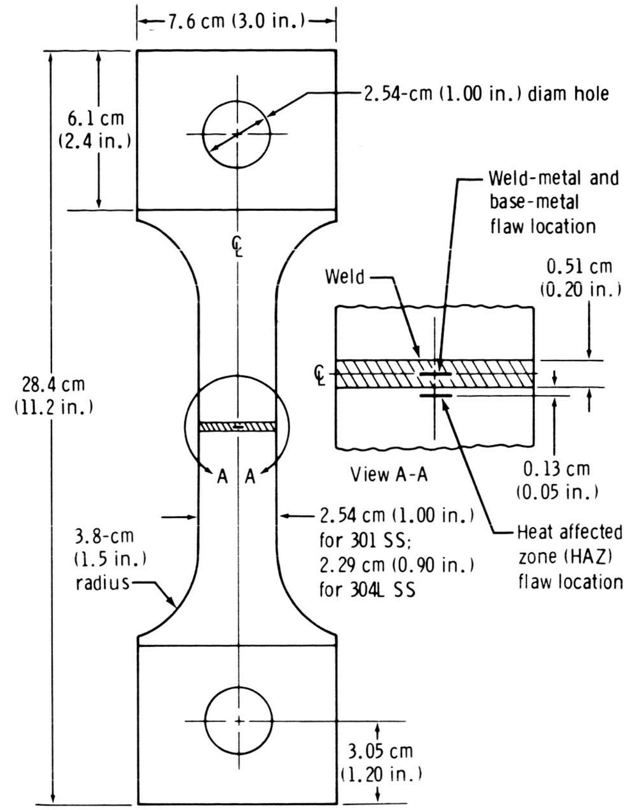


Figure 2.- Cryoformed 301 and 304L cross-weld and base-metal specimen configuration.

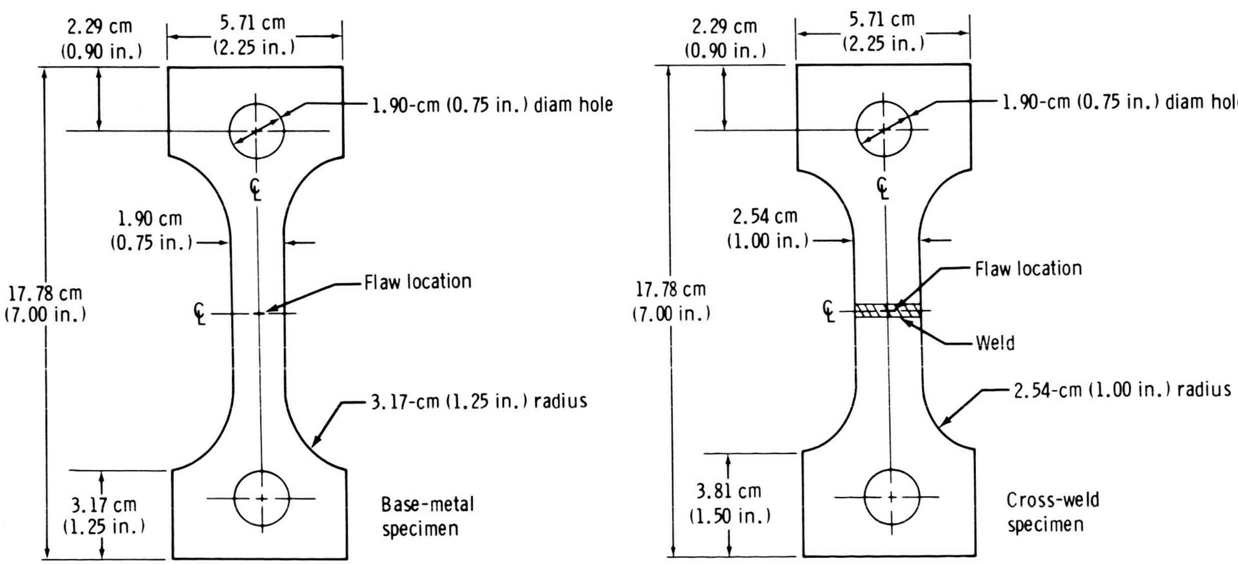


Figure 3.- Inconel 718 cross-weld and base-metal specimen configuration for CGSS tank material tests.

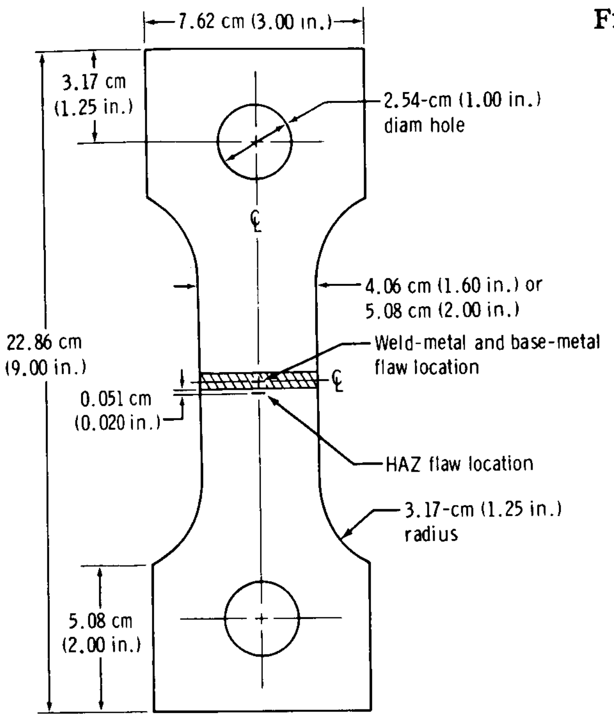


Figure 4.- Inconel 718 cross-weld and base-metal specimen configuration for ALSA bottle material tests.

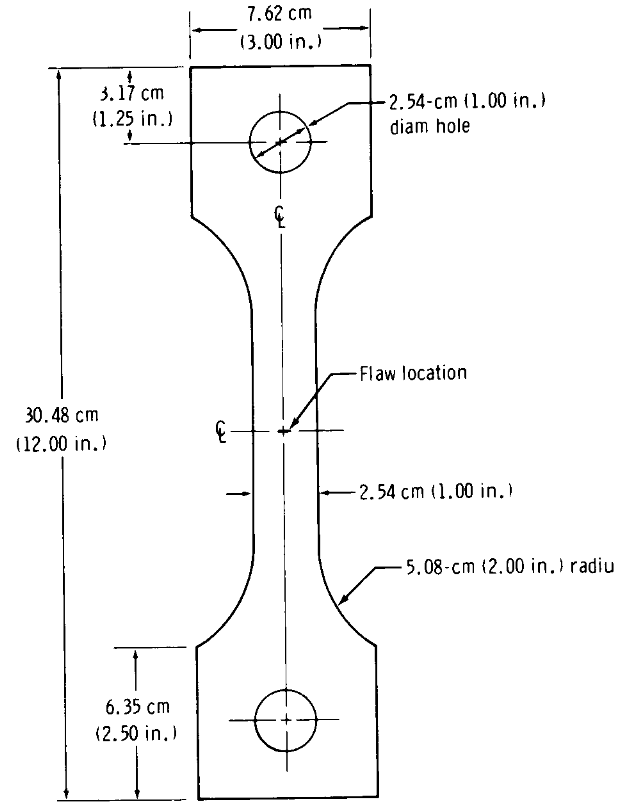


Figure 5.- Configuration of A-286 steel specimen.

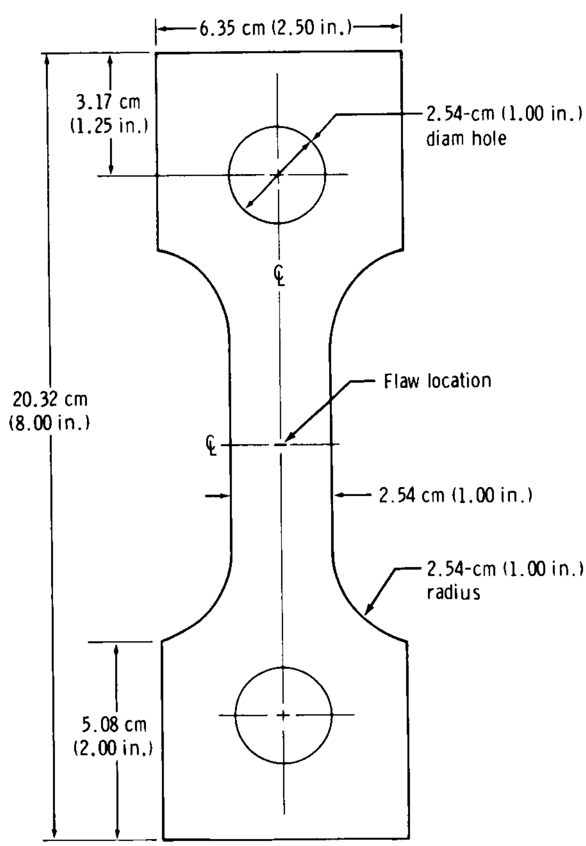


Figure 6.- Configuration of AM-350 (subcooling and tempering condition (SCT) 1000) stainless steel specimen.

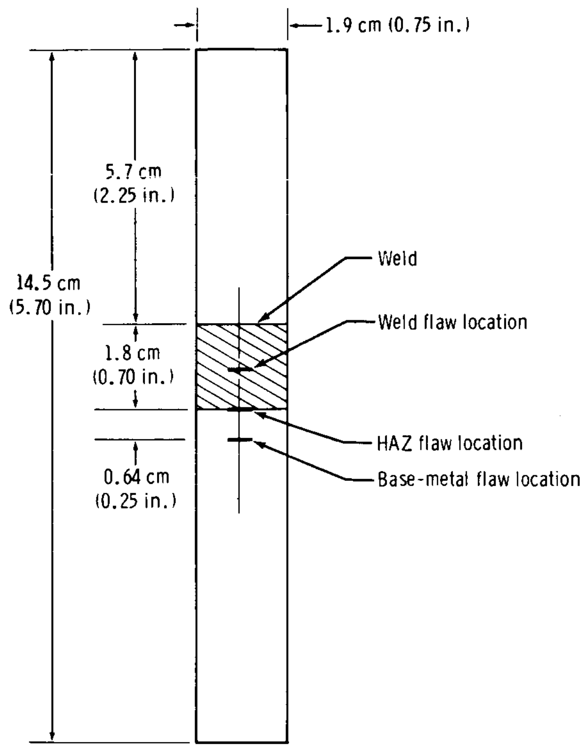
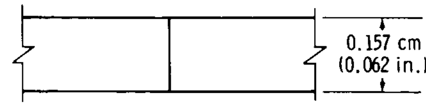


Figure 7.- Configuration of 6Al-4V titanium (STA) pressure-weld specimen.

Joint configuration



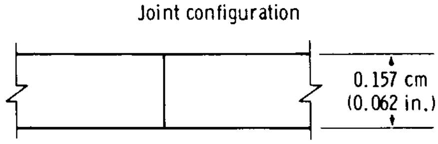
Specimen processing

1. Machine weld banks from 0.157-cm (0.062 in.) thick AISI 301 stainless steel plate.
2. Gas tungsten arc weld with single pass as follows:

   Volts: 8.5
   Amperes: 55
   Travel rate: 15 cm/min (6 in/min)
   Filler wire: 0.051-cm (0.020 in.) diam AISI 301 or AISI 308L stainless steel
   Backing gas: Argon
3. Anneal, pickle, and passivate specimen.
4. Uniaxial cryogenic stretch 16 percent in liquid nitrogen.
5. For aged specimens, heat for 20 hr at 694 K (790° F).

Figure 8.- Weld joint configuration and specimen processing for cryoformed 301 stainless steel specimens.

Joint configuration



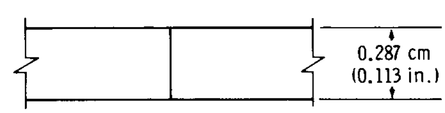
Specimen processing

1. Machine weld blanks from 0.157-cm (0.062 in.) thick AISI 304L stainless steel plate.
2. Gas tungsten arc weld with single pass as follows:

   Volts: 8
   Amperes: 93
   Travel rate: 25.4 cm/min (10 in/min)
   Filler wire: 0.114-cm (0.045 in.) diam AISI 308L stainless steel
   Wire feed: 30.5 cm/min (12 in/min)
   Shield and backup gas: Argon
3. Cryogenic stretch 28 percent in liquid nitrogen.
4. Age 20 hr at 686 K (775° F).
5. Passivate.

Figure 9.- Weld joint configuration and specimen processing for cryoformed 304L stainless steel specimens.

Joint configuration



Specimen processing

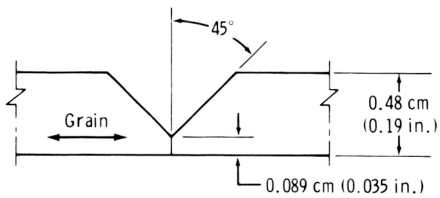
1. Machine weld blanks from 0.317-cm (0.125 in.) thick plate, mill annealed at 1283 K (1850° F).
2. Gas tungsten arc weld with single pass as follows:

   Volts: 13
   Amperes: 90
   Electrode: 0.1587-cm (0.0625 in.) diam, 1-percent thoriated tungsten, 30° included angle, 0.038 cm (0.015 in.) flat
   Travel rate: 12.7 cm/min (5 in/min)
   Filler wire: 0.089-cm (0.035 in.) diam Inconel 718
   Wire feed: 47 cm/min (18.5 in/min)
   Force gas: 75-percent helium, 25-percent argon at 0.34 m^3/hr (12 ft^3/hr)
   Backing gas: Argon with 131 p/m O_2
3. Heat treat as follows:

   Age at 1011 ± 8 K (1360 ± 15° F) for 10 hr
   Furnace cool to 922 ± 8 K (1200 ± 15° F) and hold for 10 hr to make a total aging cycle of 20 hr
   Cool to room temperature
4. Machine specimens as shown in figure 3.

Figure 10.- Weld joint configuration and specimen processing for Inconel 718 CGSS tank material tests.

Joint configuration



Specimen processing

1. Shear specimens from sheet.
2. Machine joint configuration.
3. Thermal cycle as follows:

   Heat to 1200 K (1700° F) in 3 hr and hold for 30 min
   Heat to 1255 K (1800° F) in 20 min and hold for 5 min
   Cool to room temperature in 3 hr

4. Weld specimens as follows:

   Process: Gas tungsten arc, dc straight polarity
   Filler wire: Inconel 718, 0.089-cm (0.035 in.) diam
   Electrode: 2-percent thoriated tungsten, 0.081-cm (0.032 in.) diam
   Shielding gas: Argon at 0.85 m^3/hr (30 ft^3/hr) flow

Weld pass	Potential, V	Current, A	Travel rate, cm/min (in/min)	Wire feed, cm/min (in/min)
1	7.5	115	6.1 (2.4)	63 (25)
2	8.0	130	10.2 (4.0)	142 (56)
3	8.5	150	10.2 (4.0)	142 (56)

5. Machine specimens as shown in figure 4.
6. Heat treat as follows in vacuum atmosphere:

   Age at 992 K (1325° F) for 8 hr
   Furnace cool at 55.5 K/hr (100° F/hr) to 894.3 ± 13.9 K (1150° ± 25° F)
   Hold at 894.3 ± 13.9 K (1150° ± 25° F) for 8 hr
   Cool to room temperature

Figure 11.- Weld joint configuration and specimen processing for Inconel 718 ALSA bottle material tests.

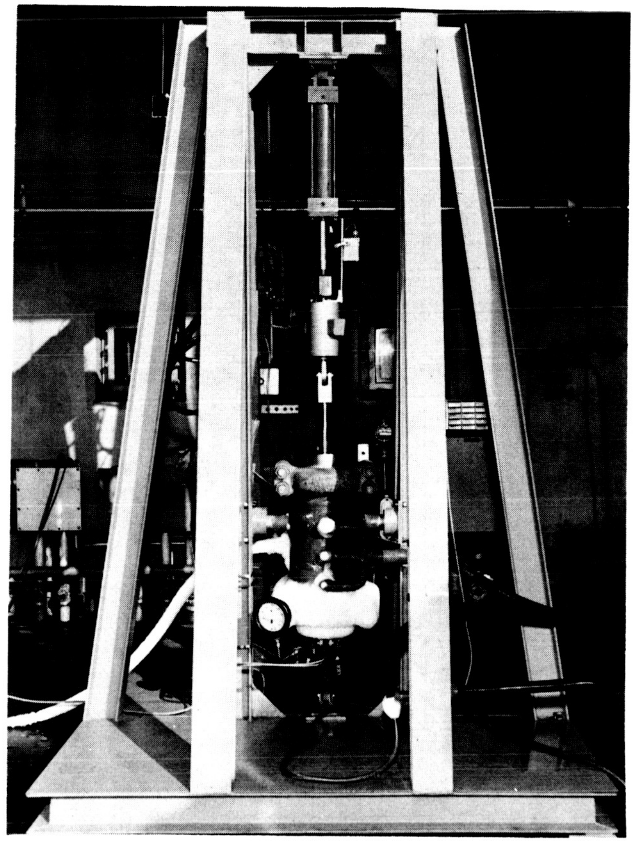


Figure 12.- Photograph of load frame and test chamber during a cold gaseous hydrogen environment test.

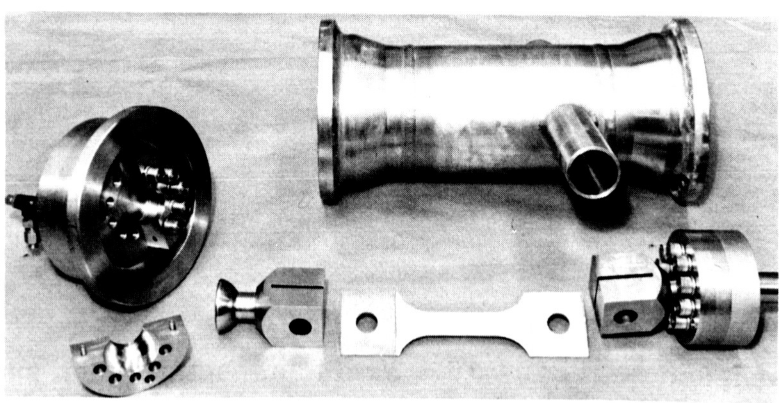
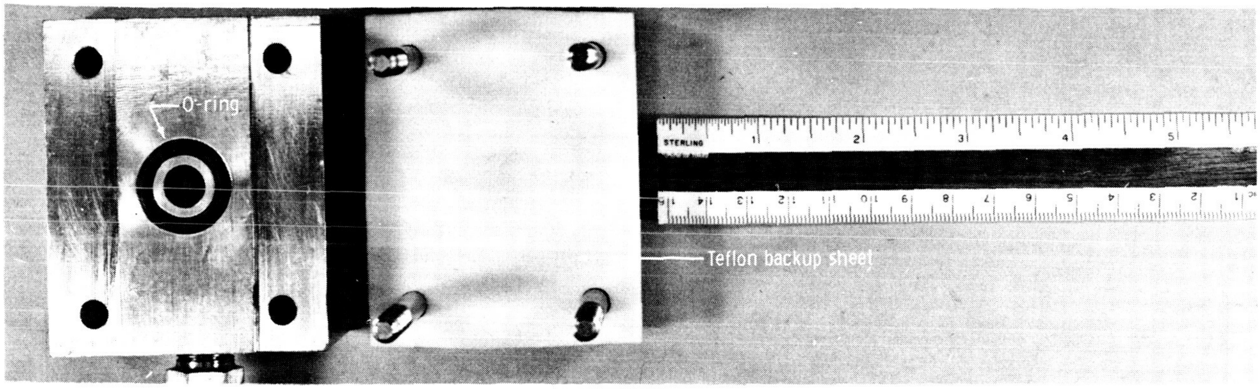
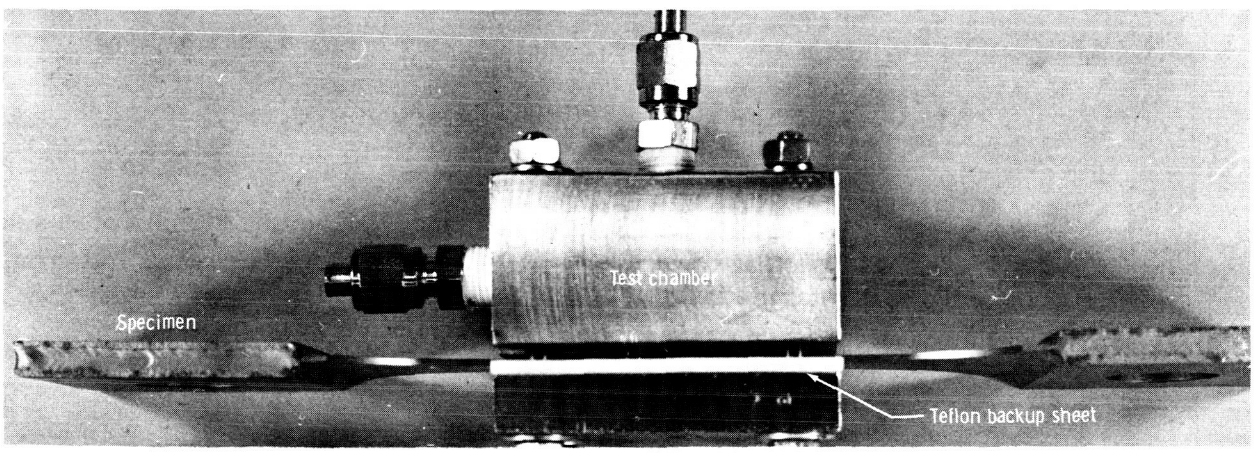


Figure 13.- Photograph of cryoformed 301 stainless steel specimen and gaseous hydrogen test chamber.



(a) Test chamber and specimen.



(b) O-ring and Teflon backup sheet.

Figure 14.- Photograph of cryoformed 301 stainless steel specimen and high-pressure fluid chamber.

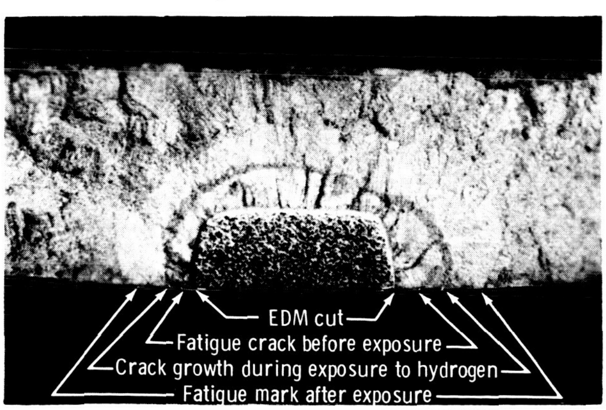


Figure 15.- Fracture face photograph of Inconel 718 specimen 185W showing typical fatigue and sustained-load flaw-growth markings (EDM = electrical discharge machine).

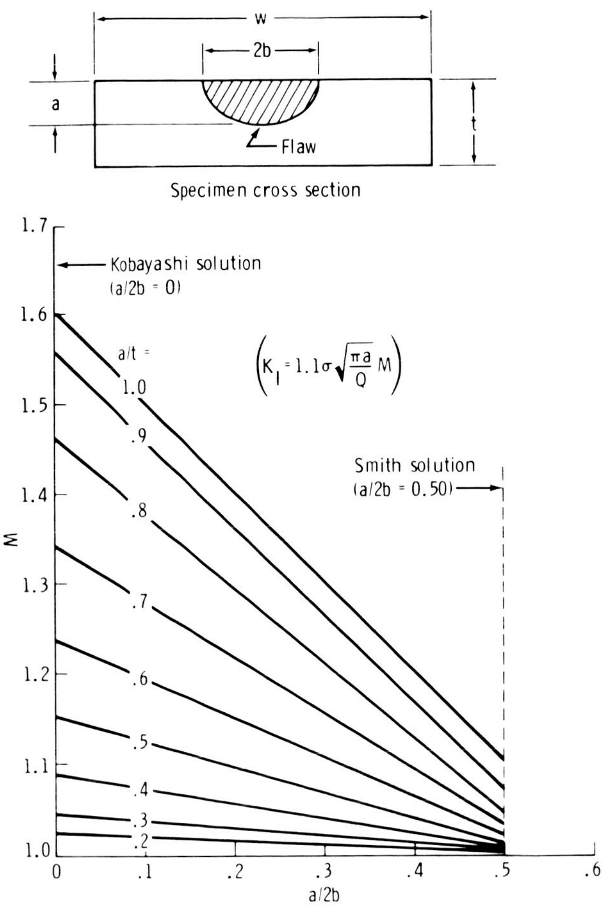
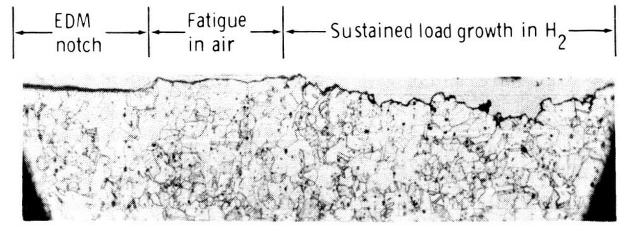
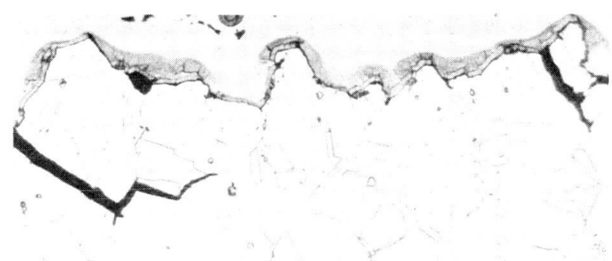


Figure 16.- Specimen geometry and stress-intensity factor analysis for deep flaws.



(a) Section view of fracture face.



(b) Enlarged view of sustained-load growth in gaseous hydrogen.

Figure 17.- Photomicrographs of crack growth in Inconel 718 resulting from sustained load in gaseous hydrogen.

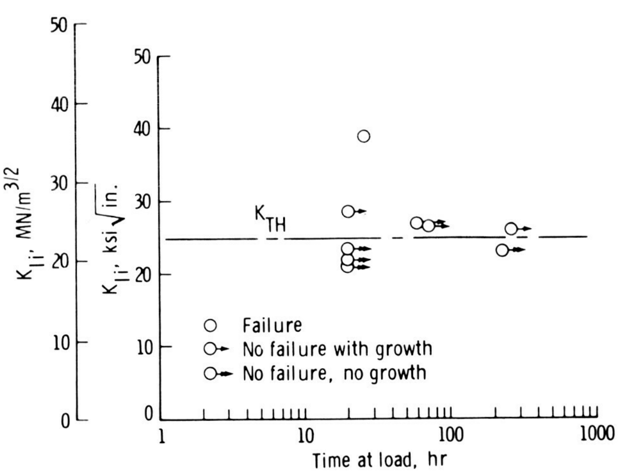


Figure 18.- Sustained-load crack-growth behavior for Inconel 718 base metal in 200 K (-100° F) hydrogen at 6.9 MN/m^2 (1000 psi).

NASA-Langley, 1975 S-423