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EVALUATION OF LASER WELDING TECHNIQUES FOR
HYDROGEN TRANSMISSION

Final Report for the Period September 30, 1977—November 30, 1979

By
J. Mucci

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Pratt & Whitney Aircraft Group
Government Products Division
West Palm Beach, Florida

U. S. DEPARTMENT OF ENERGY

Division of Energy Storage Systems

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EVALUATION OF LASER WELDING TECHNIQUES FOR HYDROGEN TRANSMISSION

FINAL REPORT

PERIOD SEPTEMBER 1977 - NOVEMBER 1979

J. Mucci

**Pratt & Whitney Aircraft Group
Government Products Division
West Palm Beach, Florida 33402**

May 1980

**PREPARED FOR
U.S. DEPARTMENT OF ENERGY
Under Contract No. EC-77-C-02-4355**

ABSTRACT

This program was established to determine the feasibility of laser beam welding as a fabrication method for hydrogen transmission and is a precursor in the effort to systematically provide the technological base necessary for large-scale, economic pipeline transmission of fuel for a hydrogen energy system. The study contributes to the technology base by establishing the effect of conventional weld processes and laser beam welding on the mechanical properties of two classes of steels in an air and high pressure gaseous hydrogen environment.

Screening evaluation of the tensile, low-cycle fatigue and fracture toughness properties and metallurgical analyses provide the basis for concluding that laser beam welding of AISI 304L stainless steel and ASTM A106B carbon steel can produce weldments of comparable quality to those produced by gas-tungsten arc and electron beam welding and is at least equally compatible with 13.8 MPa (2000 psig) gaseous hydrogen environment.

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SECTION I INTRODUCTION

The evolution of an hydrogen energy system requires major technology development programs. Regardless of the means of production, transmission and storage of hydrogen will be required. Current gas transmission pipeline technology forms the base from which hydrogen transmission will grow. However, unlike natural or hydrocarbon gases, hydrogen has a unique effect upon many metals in that it embrittles or degrades properties. This effect upon material properties has been studied most extensively in the development of hydrogen-fueled rocket engines. For space applications, use of expensive, highly alloyed materials and very stringent processing is justified. The economics of gas transmission systems, however, require the use of lower cost, more plentiful structural materials.

Mild and low alloy steels are being considered because of the economic factor. A problem exists, however, in that most ferritic steels are susceptible to degradation of structural properties resulting from hydrogen exposure over a wide range of conditions. Since numerous welded joints are required in the fabrication of transmission pipelines and storage systems, an additional problem exists: weldments appear more susceptible to hydrogen degradation (embrittlement) than the parent alloys. Moreover, various welding processes may yield different degrees of susceptibility. In general, welding processes that minimize fusion and heat-affected zones tend to produce high integrity welds that are less susceptible to hydrogen degradation and also produce joints that maintain many of the characteristics of the parent material. Preliminary research by United Technologies Research Center indicated that laser weldments possess these desired qualities.

This program was established to determine the feasibility of laser welding as a fabrication method for hydrogen transmission and is a precursor in the effort to systematically provide the technological base necessary for large-scale, economic pipeline transmission of fuel for a hydrogen energy system. The study contributes to the technology base by establishing the sensitivity of two classes of steels to gaseous hydrogen environment effects and determining the effect of gas tungsten arc welding (GTAW), electron beam welding (EBW), and laser beam welding (LBW) on properties. Screening evaluation of the important mechanical and metallurgical properties of the materials provided the basis for conclusions concerning the feasibility of LBW. The logic upon which this program was structured is diagramed in Figure 1.

Experimental efforts in this program include a total of 173 mechanical properties tests of AISI 304L stainless steel and A106B carbon steel in ambient pressure air and gaseous hydrogen. This program was initially structured to include 136 tests. However, a contract modification increased the total number of required tests to 154 for purposes of gaining a better understanding of the effect of hydrogen environment on properties. In addition to the required tests, 19 more were conducted to confirm degradation trends which were greater than anticipated. Also, because of the extreme data scatter, the additional tests were needed to provide greater confidence in the conclusions. The hydrogen environment tests were conducted at a pressure of 13.8 MPa (2000 psig), the pressure projected for economical transmission of hydrogen.¹ Testing involved going directly to the anticipated operating pressure and establishing the sensitivity of the materials and weldments to hydrogen environment. The effects of potential hydrogen pickup during welding or evaluation of thermally charged specimens were not investigated since they were not within the scope of work included in this program.

¹ Gray, H. R., and H. G. Nelson, et.al., "Potential Structural Materials Problems in a Hydrogen Energy System," NASA TM X-71752 NASA-Lewis Research Center, Cleveland, Ohio, June 1975.

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Figure 1. Process for Obtaining Program Results and Conclusions from the Laser-Welded Hydrogen Transmission Pipeline Evaluation

The primary goal of these tests was to document, rather than define, the hydrogen phenomenon and provide preliminary data for use in designing a hydrogen energy system. The overall test program is diagramed in Figure 2 and outlined in Table I. The specific mechanical properties tests and metallurgical analyses are:

1. Tensile Properties — Smooth and notched tensile properties were determined using ASTM E-8 procedures.
2. Low-Cycle Fatigue — Low-cycle fatigue life was established using constant total strain testing techniques.
3. Fracture Toughness — Fracture toughness parameters were established using ASTM E 399 procedures, where applicable, and J-Integral techniques.
4. Metallography — Metallurgical evaluation was conducted to characterize the parent and welded materials. Also, fractographic evaluation was conducted on representative samples of failed test specimens to aid in explaining test result abnormalities.

This report is arranged in sections that cover the program conclusions, materials and welding, and results and conclusions of the individual property tests. It includes all information covered in eight monthly progress reports issued under this contract.

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

This report is submitted in accordance with the requirements of Department of Energy Contract EC-77-C-02-4355 "Evaluation of Laser Welding Techniques for Hydrogen Transmission," and represents the final report covering work performed from 30 September 1977 to 31 August 1978 for the original program and from 1 September 1979 to 30 November 1979 for the contract modification. This program was sponsored by Dr. James H. Swisher, Assistant Director, Physical Storage Systems, Department of Energy, Washington, D. C., under the technical cognizance of Dr. Howard G. Nelson, NASA-Ames Research Center, Moffett Field California.

This program was conducted using the Program Manager — Project Group System by the Pratt & Whitney Aircraft Group, Government Products Division (GPD), Materials and Mechanics Technology Laboratory, and the United Technologies Research Center. Mr. J. Mucci was the Program Manager for the effort.

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Figure 2. Program Outline for the Evaluation of Laser-Welded Hydrogen Transmission Pipelines

TABLE I. EXPERIMENTAL TEST OUTLINE TO DETERMINE THE EFFECTS OF WELDING AND SUSCEPTIBILITY OF WELDED PIPELINE MATERIALS TO HYDROGEN DEGRADATION

Material	Weld Type	Environment ¹	Mechanical Properties Tests			
			Smooth Tensile	Notch Tensile ²	Low-Cycle Fatigue ³	Fracture Toughness
AISI 304L	Parent Material	Air	2	2	3	2
		Hydrogen	2	2	2	
	GTAW	Air	2	2	3	2
		Hydrogen	2	2	3	
	GTAW (HAZ)	Air		2		2
		Hydrogen		2		
	EBW	Air	2	2	4	2
		Hydrogen	2	2	6	
	EBW (HAZ)	Air		2		2
		Hydrogen		2		
	LBW	Air	2	2	3	2
		Hydrogen	2	2	3	
	LBW (HAZ)	Air		2		2
		Hydrogen		2		
ASTM A106B	Parent Mateial	Air	2	2	3	2
		Hydrogen	2	2	4	
	GTAW	Air	2	2	3	2
		Hydrogen	2	2	4	
	GTAW (HAZ)	Air		2		2
		Hydrogen		2		
	EBW	Air	2	2	3	2
		Hydrogen	2	3	4	
	EBW (HAZ)	Air		2		2
		Hydrogen		2		
	LBW	Air	2	2	4	2
		Hydrogen	2	2	4	
	LBW (HAZ)	Air		2		2
		Hydrogen		2		
Total Specimen Tests — 173			32	57	56	28

¹ Air Tests at 24°C (75°F), 1 atmosphere

Hydrogen Tests at 24°C (75°F); 13.8 MPa (2000 psig)

² Stress Concentration Factor, $K_T = 8.0$

³ Welded material tests conducted in air were added per the contract modification

SECTION II CONCLUSIONS

A. GENERAL

The test efforts in this program consisted of conducting parent and welded material mechanical properties tests of two classes of pipeline steels, AISI 304L stainless steel and A106B carbon steel, proposed for use in a hydrogen energy system. Properties determined in the hydrogen environment were compared to properties determined in air at the same conditions to establish environmental degradation. The effect of gas tungsten arc, electron beam and laser beam welding on the mechanical and metallurgical properties of the two steels was also determined.

The following rating system was established to determine the degree of degradation due to 13.8 MPa (2000 psig) gaseous hydrogen environment and served as an aid in making alloy comparisons:

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

This is the same rating system used in previous P&WA Group hydrogen environmental degradation investigations, several of which are indicated in References 1, 2, and 3. Using this rating system, Table II displays the degree of degradation based on test result averages, for the AISI 304L and A106B materials in the parent and welded conditions tested, where a comparable test in air was conducted. In the case of the smooth tensile tests, if any property (yield strength, ultimate strength, elongation or reduction of area) was degraded, the degradation rating is that of the most severely degraded property.

Use of these degradation conclusions must be tempered by the fact that very limited numbers of tests were conducted for each condition and normal data scatter could influence or change the degradation rating.

Detailed conclusions are presented in the following sections pertaining to the individual types of tests. General conclusions pertaining to the parent and welded materials are discussed in the following paragraphs.

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, Contract NAS8-30744, Exhibit A, September 1975 and Exhibits B and C, July 1976.

TABLE II. DEGREE OF DEGRADATION OF
AISI 304L AND A106B IN 13.8 MPa
(2000 psig) GASEOUS HYDROGEN
AT 24°C (75°F)

Material	Weld Type	Smooth Tensile	Notch Tensile	Low-Cycle Fatigue
AISI 304L	Parent Material	ND	ND	ED
	GTAW	ND	ND	ED
	GTAW (HAZ)		ND	
	EBW	D	ND	ED
	EBW (HAZ)		ND	
	LBW	ND	ND	SD
	LBW (HAZ)		ND	
A106B	Parent Material	SD	D	ED
	GTAW	D	D	ED
	GTAW (HAZ)		D	
	EBW	SD	D	ED
	EBW (HAZ)		D	
	LBW	D	D	ED
	LBW (HZA)		D	

B. EFFECT OF HYDROGEN

The most prominent effect of hydrogen environment on the mechanical properties evaluated in this program occurred in the low-cycle fatigue (LCF) tests. The LCF lives were *extremely* degraded for both materials in the parent material condition, due to 13.8 MPa (2000 psig) gaseous hydrogen. Reductions in mean lives of approximately 60 and 88% were indicated for the AISI 304L and A106B parent materials, respectively. The LCF lives were also *extremely* degraded for both materials in the welded conditions, with the exception of the AISI 304L laser beam weld (LBW) where degradation to the *severe* degree was indicated.

LBW resulted in the least degraded weld joint for both materials. LBW AISI 304L was degraded approximately 30% less than both gas-tungsten arc (GTA) and electron beam (EB) welded material. For the A106B material, LBW resulted in approximately 10% less degradation than GTA and EBW.

The AISI 304L material tensile properties were the least degraded of all properties evaluated. In fact, with the exception of electron beam welded (EBW) material, negligible degradation, if any, was exhibited in the AISI 304L parent and welded material conditions. For the A106B material, degradation from the *degraded* to *severe* degree was exhibited for all conditions evaluated.

The prime effect of hydrogen on the tensile properties of the A106B material was the degradation of ductility. The degradation ratings, for the most part, are therefore based primarily upon ductility effects.

The effect of hydrogen environment on the fracture toughness properties was not established in this program since all tests were conducted in air. Testing did not result in valid K_{IC} numbers per ASTM E-399; therefore, J-Integral and strength ratio analyses were conducted and are discussed in Section VI.

C. EFFECT OF WELDING

The most prominent effects of welding also occurred in the LCF tests. Generally, welding of both the AISI 304L and A106B materials, whether conventionally welded or laser beam welded, substantially reduced the LCF lives. When evaluated in ambient pressure air, no beneficial effects due to LBW were observed in terms of LCF life. However, in 13.8 MPa (2000 psig)

hydrogen, the environment these materials would be subjected to in a transmission pipeline system, distinct advantages were observed due to LBW of both materials. LBW reduced the LCF life from that of the parent material only 23%, as compared to almost 60% for the conventional weld processes. For the A106B material, no detrimental effect on LCF life was indicated due to LBW, clearly demonstrating the potential of this means of joining materials.

The GTAW, EBW and LBW of the AISI 304L and A106B materials resulted in reduced tensile ductility. No significant differences between any of the welding processes could be established in terms of tensile strength properties. Also, in terms of fracture toughness parameters, no significant differences between the welding processes could be established.

The testing done in this program was of necessity very limited; as mentioned in sections covering the individual mechanical properties tests, conclusions as to the degree of degradation and the effects of welding may be shown to be incorrect by additional, statistically significant, investigations. General observations can be made, however, to classify the subject materials and establish the merits of laser beam welding:

1. Properties of both AISI 304L stainless steel and A106B carbon steel are extremely affected by hydrogen environment.
2. The LBW process is at least comparable to conventional weld processes in terms of LCF life, where the effects of welding were most prominent.
3. Laser beam welding of pipe to ASME boiler and pressure vessel code specifications is possible. However, due to excessive variation in pipe wall thickness which is considered typical for this application, additional weld process development is required. Over and under penetration is directly attributable to pipe wall thickness variation and the resultant porosity.

We conclude, therefore, that LBW is feasible for fabricating systems for transmission and storage of high-pressure gaseous hydrogen. It has the potential to improve weldment integrity and performance and subsequently, the safety of those systems.

D. DISCUSSION

The mechanical properties evaluation of LBW materials was encouraging and additional development is indicated. We feel that LBW is certainly feasible for pipeline fabrication. Much of the optimism is based on the performance of the LBW material in the LCF tests. We have observed that tests which involve relatively long-term exposure to hydrogen environments at high strain/stress levels, such as LCF or creep-rupture, are the most severe tests of a material for hydrogen degradation. Short-term tensile tests will not always indicate a material's long-term susceptibility to hydrogen degradation. Creep-rupture is not a consideration for a pipeline since the operating temperatures are ambient and nowhere near the creep regime for these materials. Low-cycle fatigue could become an increasing concern for hydrogen pipelines because of their long expected life and the potential consequences of failure. Fortunately, however, most pipelines are designed for operating stresses below the level where LCF is a concern.

Regardless of the material employed, the quality of the weldments must be considerably improved. Aerospace welding standards, significantly more rigid than current pipeline standards, may be required. Experience with high-pressure hydrogen aerospace systems indicates weld defects, of the type encountered during this program, could lead to pipeline or vessel failure. Ultimately, only actual pipeline testing, of representative size materials and pressures, will establish final weldment quality and design criteria.

E. RECOMMENDATIONS

Additional weld parameter development for LBW of the materials in the configuration evaluated in this program is recommended. Such parameter development should include provisions for centerless drive of the pipe to maintain the outer surface at a fixed point relative to the beam focus, and means for variation of welding speed with circumferential position in proportion to pipe wall thickness.

In addition to the optimization of process parameters, the use of weld filler materials and postweld treatments (LASERGLAZE®*) to prevent hydrogen degradation of weldments are logical extensions of this program.

These and other areas of recommended activity to develop LBW as a viable fabrication method for hydrogen transmission and storage systems are outlined in Figure 3. These activities are outlined in a step-by-step sequence with allowances after each step for decisions regarding the merit of continued development. The end goal is to have a reliable and safe means for fabrication of systems ready, when the widespread use of hydrogen fuel becomes economically possible.

*Breinan, E. M. and C. M. Banas et al, "Physics Today" November 1976

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Figure 3. Recommended Areas of Activity To Enhance This Program for Developing Laser Beam Welding as a Viable Fabrication Method for Hydrogen Transmission/Storage Systems

SECTION III MATERIALS AND WELDING

A. TEST MATERIAL

The test materials, AISI 304L stainless steel and ASTM A106B carbon steel, were procured from Ducommun Metals Corporation (Miami, Florida) and Tubesales (Forest Park, Georgia), respectively, in the form of No. 5 Schedule 160 seamless pipe [(141.3-mm (5.562-in.) outside dia, 15.9-mm (0.625-in.) wall thickness]. The materials were received under Ducommun Order No. 29903801, Heat No. SX1137 and Tubesales Order No. 131638, Heat No. L21847.

The chemical composition of each material, as determined by P&WA/Florida, is listed in Table III. Vendor-certified room temperature tensile properties are listed in Table IV. Based on the vendor certifications and P&WA evaluations, the materials were accepted as meeting basic contract requirements.

TABLE III. CHEMICAL COM-
POSITION OF AISI
304L AND A106B
STEELS

<i>Element</i>	<i>Weight (%)</i>	
	<i>AISI 304L</i>	<i>A106B</i>
Chromium	18.400	0.013
Manganese	1.350	0.600
Nickel	10.250	0.020
Copper	0.095	<0.020
Silicon	0.460	0.170
Molybdenum	0.130	0.015
Carbon	0.021	0.250
Tin		0.002
Lead		0.012
Iron	Bal	Bal

TABLE IV. VENDOR-CERTIFIED ROOM TEM-
PERATURE TENSILE PROPERTIES OF
AISI 304L AND A106B STEELS

	<i>AISI 304L</i>	<i>A106B</i>
Ultimate Strength	560.5 MPa (81.3 ksi)	497.8 MPa (72.2 ksi)
0.2% Yield Strength	287.5 MPa (41.7 ksi)	291.6 MPa (42.3 ksi)
Elongation	60%	41%

The as-received materials were subjected to metallurgical review to characterize the base metals prior to welding. The AISI 304L material consisted of γ (austenite) grains with particles of chromium-containing carbides (CrC) in the grain boundaries as shown in Figure 4. The CrC precipitation was relatively heavy indicating that the material was heated to, or slowly cooled through, the carbide precipitation or "sensitizing" range of 427 to 817°C (800 to 1600°F). The base metal may be susceptible or "sensitive" to intergranular corrosion in the presence of certain corrosive media. This sensitivity could have influenced the properties obtained in this program. Stringers of entrapped oxides were also observed. The A106B material consisted of α (ferrite) grains with pearlite colonies (Figure 4). Chromatographic analysis was also conducted to establish the oxygen levels in the as-received materials. The O₂ content of the AISI 304L and A106B material was determined to be 94 and 48 ppm, respectively.

Both the AISI 304L and A106B pipe materials were received with variations in circumferential thickness up to 1.91-mm (0.075-in.) from nominal. This condition resulted in laser beam weld penetration problems detailed later in the laser beam welding discussion in this section. Also, fracture toughness specimens in some cases, were slightly less than 12.7-mm (0.50-in.) thick due to the unanticipated pipe thickness variation.

Mag: 100x
As-Received AISI 304L
Etchant: Oxalic Electrolytic

Austenite Grains With Chromium-Containing Carbides in the Grain Boundaries

Mag: 100x
As-Received ASTM A106B
Etchant: Nital

Ferrite Grains (Light Areas) With Pearlite Colonies (Dark Area)

FD 144672

Figure 4. Typical Microstructure of the As-Received AISI 304L and ASTM A106B Materials

B. WELD PROCEDURES

Weld joints were produced in the AISI 304L and A106B materials by gas tungsten arc welding (GTAW), electron beam welding (EBW), and laser beam welding (LBW) processes. Weld schedules were established for each material prior to the joining of the pipe segments. Weld joints were produced using current process specifications or, in the absence of specifications, state-of-the-art procedures. No post-weld heat treatment was performed.

Welded pipe segments were fabricated by joining two 50.8-mm (2.0-in.) lengths of pipe as illustrated in Figures 5 through 7. Radiographic and fluorescent penetrant inspection was performed on all weld joints to ensure soundness. The weld joints were inspected using the Radiographic Inspection Sections of the ASME Boiler and Pressure Vessel Code: Section V Article 2; Section VIII, Subsection B, Part UW; Section VIII, Subsection C, Part UCS; and Mandatory Appendix IV. Portions of Mandatory Appendix IV are included as Appendix A at the end of this report for reference.

Some areas of the welded segments had unacceptable weld joints per the above requirements: these areas were avoided when fabricating test specimens.

1. Gas Tungsten Arc Welding

Gas Tungsten Arc Welded segments were prepared by machining "J"-shaped grooves into mating end sections of each pipe segment (Figure 5). The specimens were degreased, cleaned in methanol, and assembled in an alignment fixture within a welding chamber. The chamber was purged with high-purity argon gas for 15 min prior to the initiation of welding. A slight positive pressure of argon was maintained throughout the welding cycle. Tack welds, ~25.4-mm (1.0-in.) long, were made at the following locations and in the following sequence to maintain alignment: 0, 180, 90 and 270 deg. After a root pass weld was made, the segments were removed from the chamber, and the welds were examined radiographically. Any weld defects were routed out, and the welds were re-examined radiographically. The segments were refixedured in the chamber (which was then purged), and the welding was completed.

Welding was accomplished using a P&H Model No. DCR-200 HFGW DC arc welder equipped with a Linde HW-20 torch and bare tungsten electrode. The torch utilized high-purity argon shielding gas. The medium amperage range (10 to 250 amps) in the DC straight polarity mode was used. CMS 32 (Fe-0.3Cr-1.1Mn-0.25Si-0.01S-0.015K-0.12C), an AWS A5.2 class RG-65 filler metal in the form of 1.6-mm (1/16-in.) dia bare wire was used for both the AISI 304L and A106B steels. Between 4 and 8 welding passes were made depending upon filler metal deposition rate and travel speed, which were both controlled by the welding operator. A completed pipe segment is shown in Figure 5.

2. Electron Beam Welding

The EBW segments were prepared by machining pipe mating end sections flat and perpendicular to the pipe axis (Figure 6). The segments were assembled into alignment fixtures within the weld chamber, and the chamber atmosphere was evacuated to a vacuum level of 10^{-4} mm Hg or greater. Welding was accomplished with a Hamilton Standard Model EBW (25) 108-60-72 electron beam welder rated at 150 kv and 167 ma. Weld parameters were 150 kv and 30 ma with a travel speed of 508 linear mm (20 linear in.)/min and a focal distance of 357 mm (14 in.). No filler metal was added. A low-energy finish cosmetic pass was used to reduce weld metal undercutting. A completed segment is shown in Figure 6.

FE 163088

Before Welding

FE 165296

After Welding

FD 144673

Figure 5. Typical GTAW Pipe Segment Before and After Welding

Before Welding

FE 163089

After Welding

FE 165297

FD 144674

Figure 6. Typical EBW Pipe Segment Before and After Welding

FE 163089

Before Welding

FE 169155

After Welding

FD 144675

Figure 7. Typical LBW Pipe Segment Before and After Welding

3. Laser Beam Welding

The LBW for this program was performed by the United Technologies Research Center using a multikilowatt, cross-beam, CO₂, convection laser shown in Figure 8. This experimental laser system operates as an oscillator-amplifier, with a 57.2 mm (2.25-in.) dia, 10.6 μ -wavelength, infrared output beam exhibiting a Gaussian energy intensity distribution.

FD 144676

Figure 8. Multikilowatt, Cross-Beam, CO₂ Convection Laser

The output laser beam was directed into focusing optics as shown in Figure 9. The welding optics were formed of polished aluminum and comprised a 25.4-mm (1.0-in.) thick by 152.4-mm (6.0-in.) dia flat and a 25.4-mm (1.0-in.) thick by 152.4-mm (6-in.) dia, 609.6-mm (24-in.) focal-length spherical focusing mirror. These mirrors were positioned as shown to provide downhand welding. Some initial welds were also produced using an 457.2-mm (18.0-in.) focal-length mirror; however, all weld segments for this program were joined using the 609.6-mm (24-in.) focal-length mirror.

The pipe segments were positioned for welding in a rotary fixture as shown in Figure 10. Rotary motion was imparted by a cantilevered-driven, 25.4-mm (1.0-in.) dia shaft supported by two pillow-block-mounted bearings. One pipe segment was located on its ID by four pins mounted in a locating plate fixed at the bearing end of the shaft as shown. The second pipe segment was positioned on a similar locating plate which was free to slide on the shaft. The mating pipe segments were then clamped together with a knurled nut threaded onto the end of the shaft; appropriate spacers were used as shown. A small-dia, thick wall pipe segment was positioned under the weld joint to protect the driven shaft from weld spatter and heat from excess laser beam energy.

Initial welds in the stainless steel pipe were produced using a sprocket and chain drive system and a servomotor. It was observed, however, that this drive system produced uneven motion which could be detrimental to the welding process. Therefore, the system was modified for direct drive as shown previously in Figure 10.

Deep-penetration welding with a multikilowatt laser beam usually requires a gas-shield device to prevent atmospheric contamination within the molten pool and also to control the detrimental effects on penetration which can be caused by interaction of the focused high-intensity laser beam and atmospheric gas. Specifically, a plasma is formed when a focused, sufficiently-high-intensity, 10.6μ laser beam interacts with air at atmospheric pressure. The plasma can absorb or defocus a major portion of the high-power beam, resulting in a significant reduction in penetration and weld capability. Plasma formation can be suppressed by purging the weld region with inert gas. In the tests reported herein, plasma suppression was achieved with a 12.7-mm (0.25 in.) OD copper tube positioned to flow helium gas over the laser beam material interaction point (Figure 10). Flowrates in the range of 2832 to 4248 l/hr (100 to 150 ft³/hr) were found to produce optimum results.

Since the molten pool exists beyond the beam interaction point, inert gas-shielding is also required to prevent oxidation of molten and recently solidified hot metal. Inert gas-shielding in this program was provided by enclosing the fixtured pipe segment assembly in a cylindrical plenum as shown in Figure 11. The plenum was purged with helium for several seconds prior to welding to the time when the weld metal temperature was low enough to prevent visible surface oxidation. To ensure inert gas coverage at both the face and root of the weld bead, gas inlets were provided to the plenum at both the OD and ID of the fixtured pipe segments.

The top of the plenum contained a 9.5-mm (0.375-in.) dia, countersunk laser beam inlet port. In addition, several louvered holes were provided near the bottom of the plenum to facilitate controlled outflow of the inert gas and prevent buildup of contaminants during welding.

The weld joint was aligned with a HeNe laser beam which was coincident with the CO₂ laser beam. During alignment, the workpiece was rotated and adjusted with respect to the alignment laser beam so that accurate tracking of the weld joint was obtained.

FD 144677

Figure 9. Laser Beam Focusing Optics

FD 144678

Figure 10. Rotary Pipe Welding Fixture (Plenum Removed)

FD 144679

Figure 11. Rotary Pipe Welding Fixture Ready for Welding

The rotary fixture was mounted on the bed of a three-axis machine tool base. The x- and y-axes were used for positioning the workpiece with respect to the laser beam and to align the seam. The z-axis was used to position the work surface at the optimum focal plane for welding. Minor seam alignment adjustments were also made using focus mirror angular adjustments in the mirror mount; such adjustments were minimized to maintain parallelism of the laser beam center line with the weld joint and to maintain clearance of the laser beam through the plenum port.

Weld parameters were developed with bead-on-plate passes in pipe segments provided for that purpose. Multiple passes were made in each sample to conserve material. The processing parameters which were varied included: laser beam power, weld speed, work distance (i.e., distance from center of focusing mirror to workpiece surface), plasma suppression, jet and shield location, and flowrates.

Parameters selected for the stainless steel pipe were:

Beam Power:	12.5 kw
Weld Speed:	1016 to 1143-mm/min (40 to 45 in./min)
Gas Flow	
— Jet:	2832 l/hr (100 ft ³ /hr)
— Plenum:	2832 l/hr (100 ft ³ /hr)
Work Distance:	637.5-mm (25.1-in.)

Prior to welding, the mating surfaces of the pipe sections were cleaned with acetone, then rinsed with alcohol and forced-air-dried. After fixturing and alignment, the specimens were tack-welded at four locations, 90 deg apart, with approximately 25.4-mm (1-in.) long running tack welds to prevent splitting apart of the pipe during the penetration pass. The tacks were formed at 12.5 kw at approximately 3302-mm/min (130-in./min). The penetration pass was generated with a full revolution of the workpiece under the laser beam under the conditions listed above, followed by a "taper out" formed by increasing the welding speed to the order of 5080-mm/min (200-in./min) before shutting off the beam. This procedure effectively eliminated the weld termination defect which occurs if the beam is turned-off at normal welding conditions.

Welds produced in stainless steel at the above parameters exhibited smooth, reinforced face and root conditions in regions in which the wall thickness was approximately 15.9-mm (0.625-in.). However, the stainless steel pipe wall thickness varied from the nominal 15.9-mm (0.625-in.) by more than ± 1.3 -mm (0.05-in.), and this wall thickness variation resulted in underbead globules in thinner regions due to overpenetration and in lack of complete penetration in thicker regions.

Parameters selected for welding the A106B carbon steel pipe were:

Power:	13.5 kw
Weld Speed:	1016 to 1270-mm/min (40 to 50 in./min)
Gas Flow	
— Jet:	2832-l/hr (100-ft ³ /hr)
— Plenum:	4248-l/hr (150-ft ³ /hr)
— Underbead:	1416-l/hr (50-ft ³ /hr)
Work Distance:	635-mm (25.0 in.)
Final Pass:	Power: 8 kw
	Weld Speed: 635-mm (25.0-in.)

The weld preprocedures for the first two specimens were identical to those employed for stainless steel. However, for the remaining carbon steel specimens, the cleaned components were blown dry with dry nitrogen instead of air, and four stationary tack-welds spaced 90 deg apart were made instead of running tack-welds. These tacks were made in the sequence 0, 180, 90 and 270 deg, respectively.

It is noted that the initial penetration pass for all the carbon steel welds was followed by a final pass to eliminate top bead underfill which could not consistently be eliminated by a single pass. Welds produced with the above-noted parameters contained smooth face and root characteristics in regions of constant wall thickness but, again, were prone to over- and under-penetration defects in regions in which the wall thickness was substantially different from the average.

A typical LBW segment was shown previously in Figure 7.

C. WELD CHARACTERIZATION

1. Gas Tungsten Arc Welds

Weld metal in the AISI 304L material welded by the GTAW process consisted entirely of γ (austenite) grains and metal carbides. Varying grain sizes were observed corresponding to the multipass nature of the weld. For the A106B material, the weld metal consisted of a layered structure caused by the multipass nature of the weld. Subsequent weld passes transformed initially-deposited material back to austenite and refined the grain size. The lower weld passes contained fully tempered martensite, whereas the upper passes contain untempered martensite. The last weld pass consisted of coarse grains of untempered martensite. The microstructures are in agreement with the microhardness values obtained (Table V). The higher values were associated with untempered martensite and the lower values with fully tempered martensite. Phase identification photomicrographs of typical AISI 304L and A106B GTAW joints are presented in Figures 12 and 13, respectively.

2. Electron Beam Welds

Weld metal in the AISI 304L material welded by the EBW process also consisted entirely of austenite grains and metal carbides. An austenite dendritic structure was more pronounced near the face of the weld. For the A106B EBW material, weld metal consisted of ferrite at prior austenite grain boundaries and within grains in a plate-like morphology, all in a matrix of pearlite. Metal carbide dispersions were also observed. Phase identification photomicrographs of typical AISI 304L and A106B EBW joints are presented in Figures 14 and 15, respectively.

3. Laser Beam Welds

Nonuniform penetration was generally evident in the sample welds, especially in A106B material, and incomplete penetration was evident in some cases. The weld nonuniformity was attributed to the variation in the pipe wall thickness. Not only did the thickness variation lead to variation in penetration requirements, but it also resulted in an out-of-roundness condition which caused change in beam focus at the surface as the pipe was rotated. Since penetration is strongly dependent on beam focus, the change in weld surface location was felt to be a principal cause for penetration variation. Selected welding parameters represented a compromise between higher power, which resulted in local drop-through, formation of bottom bead globules and top bead underfill in these regions and lower power which provided inadequate penetration in thicker sections.

Mag: 100X

A
Austenite Grains

Mag: 5X

FAL 48002

B
Austenite Grains

Mag: 100X

Mag: 100X

C
Austenite Grains

Mag: 100X

D
Austenite Grains

Mag: 100X

E
Austenite Grains

FD 144680

Figure 12. Phase Identification Photomicrographs of a Typical AISI 304L GTAW Joint (Etchant: Electrolytic Oxalic Acid)

FD 144681

Figure 13. Phase Identification Photomicrographs of a Typical A106B GTAW Joint (Etchant: 2% NITAL)

FD 1-4682

Figure 14. Phase Identification Photomicrographs of a Typical AISI 304L EBW Joint (Etchant: Electrolytic Oxalic Acid)

FD 144683

Figure 15. Phase Identification Photomicrographs of a Typical A106B EBW Joint (Etchant: 2% NITAL)

Visual examination of welds indicated smooth positive reinforcements of both face and root beads in sections in which wall thickness was within parameter limits. A macrograph cross section through a typical stainless steel weld shown in Figure 16, illustrates the narrowsided, deep-penetration weld obtained by the high-power laser process. This weld exhibits a relatively small crown approximately 3.8-mm (0.15-in.) wide at the surface which rapidly narrows to a parallel-sided fusion zone approximately 1.6-mm (0.063-in.) wide. Evidence of scattered fine [< 0.5 -mm (0.020-in.) dia] and medium [< 0.8 -mm (0.031-in.) dia] porosity can also be observed in the cross section. Existence of scattered porosity in the welds was evident in radiographs taken both normal to the workpiece surface and at a 30-deg angle to the surface normal. In weld regions which were visually acceptable, the porosity levels were, in general, within the acceptable limits of the ASME Boiler and Pressure Vessel Code. However, in regions in which over penetration or under penetration occurred, weld porosity levels and other weld bead characteristics did not meet code requirements. These areas of weld code nonconformance were not used for specimen fabrication.

An A106B carbon steel weld cross section is shown in Figure 17 and illustrates the positive face and root bead reinforcements produced in this material. The weld exhibits a 4.8-mm (0.19-in.) wide crown at the surface and 1.9-mm (0.075-in.) wide crown at the bottom of the weld. The depth of the final pass, approximately 10.2 mm (0.4 in.), is clearly visible in the macrograph, as is the gradual widening toward the top of the weld and the smooth contour at the weld face. These latter characteristics were the result of the slower weld speed as well as the fact that the cosmetic pass was a partial penetration weld. As evident in Figure 17, the final pass does not appear to have caused additional weld defects. However, the depth of penetration of the final pass may be excessive and could probably be substantially reduced. These results also indicate the potential of this procedure for repair welding.

The weld metal of the LBW AISI 304L material consisted solely of austenite grains and metal carbides. As in the EBW AISI 304L material, the austenite appears more dendritic in nature near the top of the weld. Figure 18 illustrates the LBW microstructure.

Nearly all of the weld metal of the LBW A106B material consisted of ferrite (light phase) both at prior austenite grain boundaries and as totally transformed austenite grains. There is a grain refined ring consisting of fine ferrite and pearlite colonies near the top of the weld. This area corresponds to the heat-affected zone of the final pass. No martensites were observed, suggesting that the laser weld cools slower than the EBW. Figure 19 illustrates the LBW microstructure.

Microhardness profiles were obtained for typical weld joints using a Zwick and Co. Model Z323 microhardness tester equipped with a stage micrometer and binocular eyepieces. A 1-kg (2.2-lb) load was used in all tests. Micrometer measurements of diamond pyramid indentation diagonals were converted directly to Vickers VPN readings. Table V lists the microhardness values for the weld configurations in both the AISI 304L and A106B materials.

Weld metal porosity was evident in all weldments of both materials. Small, egg-shaped pores were observed on the fracture surfaces of most EBW and GTAW, and to a lesser extent, LBW specimens. Similar voids are commonly found in carbon and stainless weldments and may be associated with a high, preweld oxygen level.¹ Chromatographic analysis indicated that both steels used in this program would be classified as being susceptible to weld pore formation. Figures 20 and 21 illustrate void morphology on fracture surfaces of AISI 304L welded LCF specimens, and Figures 22 and 23 illustrate the same in the welded A106B material.

¹ Nagao, T., S. Kosuge and S. Kobayashi, A Study of Electron Beam Welding — Porosity in Electron Beam Welds of Carbon Steels, *Advanced Welding Technology*, 1975, pp. 75-80.

MAG: 4.5X

FD 144684

Figure 16. Typical AISI 304L LBW Joint

MAG: 5X

FD 144685

Figure 17. Typical A106B LBW Joint

Mag: 100X A
Ferrite Grains (Light Areas)
in a Matrix of Pearlite

Mag: 5X

Mag: 100X B

Top Half: Same as A. Bottom Half: Refined Ferrite With
Some Pearlite Colonies and Dispersed Metal Carbides

Mag: 100X C
Transition Area: Lower B to A

Mag: 100X D
Transition Area: Similar to B

FD 144686

Figure 18. Phase Identification Photomicrographs of a Typical AISI 304L LBW Joint (Etchant: Picral and HCl)

Mag: 200X

A
Ferrite Grains

Mag: 6X

Mag: 200X

B
Ferrite (Light Areas) Grains and
Pearlite Colonies (Dark Areas)

Mag: 200X

C
Ferrite Grains

Mag: 200X

D
Ferrite Grains

FD 144687

Figure 19. Phase Identification Photomicrographs of a Typical A106B LBW Joint (Etchant: 2% NITAL)

TABLE V. MICROHARDNESS PROFILES FOR TYPICAL AISI 304L AND A106B, GTAW, EBW, AND LBW JOINTS

Typical GTAW Profile

Typical EBW and LBW Profile

Weld Type		Microhardness Values, Vickers VPN, at Indicated Weld Locations												
		Base Metal		HAZ		Weld Metal					HAZ		Base Metal	
		1	2	3	4	5	6	7	8	9	10	11	12	13
AISI 304L	GTAW	168	182	168	185	162	178	178	182	182	185	182	185	
	EBW	182	182	153	153	153	148	159	159	162	178	175	156	
	LBW	185	193	171	205	171	171	185	185	185	185	185	168	
A106B	GTAW	148	151	159	162	413	368	263	229	201	168	165	151	
	EBW	143	151	151	151	168	193	178	178	205	168	189	151	
	LBW	168	162	185	205	290	229	229	229	273	236	234	162

Spec S/N
SGFL-4

Spec S/N
SEFL-7

Spec S/N
SLFL-1

(Mag: 10X)

FD 144688

Figure 20. Photomicrographs of GTAW (Left), EBW (Center), and LBW (Right) AISI 304L Stainless Steel LCF Test Specimen Fracture Surfaces

Spec S/N
SGFL-4

Spec S/N
SEFL-7

Spec S/N
SLFL-1

(Mag: 50X)

FD 144689

Figure 21. Photomicrographs of Fatigue Origins on GTAW (Left), EBW (Center), and LBW (Right) AISI 304L Stainless Steel LCF Test Specimen Fracture Surfaces

Spec S/N
CGFL-2

Spec S/N
CEFL-3

Spec S/N
CLFL-3

(Mag: 10X)

Note Pores at Fatigue Origins of Specimens at Left and Center.
Laser Welded Specimen Fracture Surface Was Free of Pores

FD 144690

Figure 22. Photomacrographs of GTAW (Left), EBW (Center), and LBW (Right) ASTM A106B Carbon Steel LCF Test Specimen Fracture Surfaces

Spec S/N
CGFL-2

Spec S/N
CEFL-3

Spec S/N
CLFL-3

(Mag: 100X)

FD 144691

Figure 23. Photomicrographs of Fatigue Origins on GTAW (Left), EBW (Center), and LBW (Right) ASTM A106B Carbon Steel LCF Test Specimen Fracture Surfaces

D. TEST SPECIMENS

All specimens were machined by the P&WA/Florida tool room test specimen machine shop. Solid, externally pressurized specimens were used in this program and are illustrated in Figure 24. These specimens were machined from the pipe sections, as illustrated in Figure 25, and cleaned and packaged prior to testing to protect them from surface contamination. Test specimens are described briefly in the following paragraphs.

FD 44743A

Figure 24. Typical Test Specimens Used To Determine the Effect of Welding and High-Pressure Hydrogen Environment on the Mechanical Properties of Materials

Figure 25. Pipe Weldment Showing Specimen Orientation

1. Tensile Specimens

Smooth and notched specimens were used for this testing. Smooth specimens had a 6.40-mm (0.252-in.) gage dia and a reduced section length of 27.0 mm (1.062 in.). Notch specimens ($K_t = 8.0$) had a larger dia of 9.5 mm (0.375 in.) and a notch dia of 5.9 mm (0.234 in.) machined in the center of the specimen reduced section at a 60-deg angle, with a 0.038-mm (0.0015-in.) radius at the apex of the notch. The welded materials specimen blanks were given a light etch and the gage section oriented such that the notch was positioned in the center of the fusion or heat affected zone (HAZ) areas. The smooth and notched tensile specimens are detailed in Figures 26 (Spec. No. 6) and 27 (Spec. No. 8), respectively.

2. Fracture Toughness Specimen

A 1W, 12.7-mm (0.50-in.) thick, compact tensile specimen, conforming to ASTM E-399-74 specifications, was used for the fracture toughness tests (Figure 28, Spec. No. 3). The welded specimen starter notch was oriented so that the fatigue precrack was located in the fusion or HAZ areas.

3. Low-Cycle Fatigue Specimen

The LCF specimen incorporates integral machined extensometer collars. A calibration procedure has been established to relate the maximum strain-to-collar deflection during both the elastic and plastic portion of the strain cycle. The specimen design and calibration procedure were verified both experimentally and analytically. This specimen is detailed in Figure 29.

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Notes:

1. All Dimensions in Inches
2. Tolerance ± 0.010 Unless Noted
3. All Dia To Be Conc to Within 0.001 F.I.R.
4. Reduced Section To Be $16 \pm 3 \mu\text{inch}$
AA Grind Finish Using 320 Grit Wheel
5. Identification Markings Permitted Only on
Specimen Ends

Spec No.	± 0.001 D	G	L	N	P	Q	R	T
1	0.095	0.562	1.000	0.156	0.219	0.025	0.062	8 -32 UNJC-3A
2	0.095	1.062	2.000	0.375	0.469	0.035	0.125	10 -32 UNJC-3A
3	0.125	1.062	2.000	0.375	0.469	0.035	0.125	0.250 -28 UNJC-3A
4	0.188	1.062	2.000	0.375	0.469	0.035	0.175	0.375 -16 UNJC-3A
5	0.188	1.062	2.375	0.500	0.656	0.045	0.190	0.375 -16 UNJC-3A
6*	0.252	1.062	2.750	0.625	0.844	0.055	0.250	0.500 -13 UNJC-3A
7	0.313	1.562	3.500	0.750	0.969	0.055	0.325	0.500 -13 UNJC-3A
8	0.375	1.812	3.812	0.750	1.000	0.065	0.375	0.5625-12 UNJC-3A
9	0.438	2.062	4.125	0.750	1.031	0.065	0.450	0.625 -11 UNJC-3A
10	0.500	2.062	4.500	0.812	1.219	0.075	0.500	0.750 -10 UNJC-3A

*MMT Preferred Standard Specimen

FD 139861

Figure 26. Smooth Tensile Specimen

Notes:

1. All Dimensions in Inches
2. Tolerance ± 0.000 Unless Noted
3. All Dia To Ee Conc to Within 0.001 F.I.R.
4. Reduced Section To Be 16 ± 3 Microinch AA Grind Finish (Notch 8 ± 3) Using 320 Grit Wheel
5. Identification Markings Permitted Only on Specimen Ends

Spec No.	± 0.001		$+0.0000$ -0.0005	K_t^*
	D	d	NR	
X				
2	0.252	0.168	0.0250	2.0
3	0.324	0.243	0.0120	3.0
4	0.315	0.228	0.0060	4.0
5	0.347	0.246	0.0040	5.0
6	0.333	0.233	0.0025	6.0
7	0.363	0.246	0.0020	7.0
8	0.375	0.234	0.0015	8.0

* K_t per Peterson, "Stress Concentration Factors"

Figure 27. Notch Tensile Specimen

Spec No.	A ± 0.005	B ± 0.005	C ± 0.005	D ± 0.002	E ± 0.005	F ± 0.002	G ± 0.004	H -0.000	J ± 0.002	K ± 0.005
1	0.625	0.600	0.250	0.500	0.325	0.137	0.275	0.125	0.300	0.031
2	0.937	0.900	0.375	0.750	0.512	0.206	0.412	0.187	0.450	0.046
3	1.250	1.200	0.500	1.000	0.700	0.275	0.550	0.250	0.600	0.062
4	1.875	1.800	0.750	1.500	1.075	0.412	0.825	0.375	0.900	0.094
5	2.500	2.400	1.000	2.000	1.450	0.550	1.100	0.500	1.200	0.125
6	3.125	3.000	1.250	2.500	1.825	0.687	1.375	0.625	1.500	0.156
7	3.750	3.600	1.500	3.000	2.200	0.825	1.650	0.750	1.800	0.187

Figure 28. Fracture Toughness Specimen

Figure 29. LCF Specimen

SECTION IV TENSILE TESTING

A. INTRODUCTION

Smooth and notched tensile properties were established for the subject materials in the parent and welded (GTAW, EBW and LBW) conditions in ambient pressure air and 13.8 MPa (2000 psig) gaseous hydrogen at 24°C (75°F). The tensile tests established 0.2% yield strength, ultimate strength, elongation and reduction of area. Notched ($K_T = 8.0$) tests established the ultimate strength. Results of the welded material tests were compared to those of the parent materials to determine the effect of the various weldments on tensile properties. Also, test results in hydrogen were compared to those in air to establish property degradation.

B. RESULTS AND CONCLUSIONS

The individual tensile properties (0.2% yield and ultimate strengths, elongation, reduction of area, and notch tensile ultimate strength) of AISI 304L stainless steel and A106B carbon steel did not reflect the influence of hydrogen environment or the effect of the various weldments to the same extent. The relative extent of environmental degradation, and the effect of GTAW, EBW and LBW are summarized in Tables VI and VII, respectively. Pictorial representations of the data presented in these tables are illustrated in Figures 30 and 31 for the AISI 304L and A106B materials, respectively.

Tensile data for each individual specimen tested are listed in Table VIII.

TABLE VI. DEGRADATION OF TENSILE PROPERTIES OF AISI 304L AND A106B
IN 13.8 MPa (2000 psig) GASEOUS HYDROGEN AT 24°C (75°F)

Material	Weld Type	Notch Factor	Degradation ⁽¹⁾				Ratio of Ultimate Strength H ₂ /Air	Ratio of Notch/Smooth Ultimate Strength	
			Strength		Ductility			Air	H ₂
			0.2% Yield	Ultimate	El	RA			
AISI 304L	Parent Material	Smooth 8.0	(2)	5.0	(2)	2.5	1.05 0.95	1.36	1.23
	GTAW	Smooth 8.0	(2)	(2) 2.5	(2)	(2)	1.09 0.97	1.43	1.28
	GTAW (HAZ)	8.0		2.3			0.98	1.51	1.36
	ERW	Smooth 8.0	(2)	(2) 3.3	1.7	13.0	1.04 0.97	1.44	1.34
	EBW (HAZ)	8.0		4.1			0.96	1.44	1.33
	LBW	Smooth 8.0	(2)	(2) 6.6	(2)	2.1	1.02 0.93	1.42	1.30
	LBW (HAZ)	8.0		5.0			0.95	1.43	1.33
A106B	Parent Material	Smooth 8.0	(2)	(2) 13.3	12.9	29.2	1.05 0.87	1.64	1.35
	GTAW	Smooth 8.0	(2)	1.0 11.0	17.6	7.5	0.99 0.89	2.01	1.81
	GTAW (HAZ)	8.0		22.8			0.77	1.68	1.30
	EBW	Smooth 8.0	(2)	1.1 11.9	18.8	30.2	0.99 0.88	1.63	1.45
	EBW (HAZ)	8.0		21.2			0.79	1.62	1.29
	LBW	Smooth 8.0	(2)	(2) 15.0	13.3	22.2	1.01 0.85	1.76	1.40
	LDW (HAZ)	8.0		20.3			0.80	1.05	1.47

⁽¹⁾ Degradation calculated using average values of air and hydrogen tests.

⁽²⁾ Average value in hydrogen approximately equal to, or greater than, that in air.

TABLE VII. EFFECT OF WELDING ON THE TENSILE PROPERTIES
OF AISI 304L AND A106B STEELS

Material	Weld Type	Notch Factor	Environment ⁽¹⁾	Ratio of Weld/Parent Material			
				Strength		Ductility	
				0.2% Yield	Ultimate	El	RA
AISI 304L	GTAW	Smooth	Air	1.36	0.99	0.48	0.35
		Smooth	H ₂	1.24	1.03	0.84	0.91
	GTAW (HAZ)	8.0	Air		1.05		
		8.0	H ₂		1.07		
		8.0	Air		1.10		
		8.0	H ₂		1.14		
	EBW	Smooth	Air	1.24	0.98	0.66	0.97
		Smooth	H ₂	1.19	0.97	0.60	0.87
	EBW (HAZ)	8.0	Air		1.04		
		8.0	H ₂		1.06		
		8.0	Air		1.04		
		8.0	H ₂		1.05		
	LBW	Smooth	Air	1.21	0.99	0.69	0.93
		Smooth	H ₂	1.12	0.96	0.65	0.94
	LBW (HAZ)	8.0	Air		1.04		
		8.0	H ₂		1.02		
		8.0	Air		1.04		
		8.0	H ₂		1.04		
A106B	GTAW	Smooth	Air	0.95	1.04	0.75	0.99
		Smooth	H ₂	0.91	0.98	0.71	1.22
	GTAW (HAZ)	8.0	Air		1.28		
		8.0	H ₂		1.32		
		8.0	Air		1.06		
		8.0	H ₂		0.95		
	EBW	Smooth	Air	0.96	1.03	0.86	0.98
		Smooth	H ₂	0.92	0.97	0.80	0.97
	EBW (HAZ)	8.0	Air		1.03		
		8.0	H ₂		1.04		
		8.0	Air		1.02		
		8.0	H ₂		0.92		
	LBW	Smooth	Air	1.10	1.05	0.81	0.96
		Smooth	H ₂	1.07	1.00	0.80	1.06
	LBW (HAZ)	8.0	Air		1.13		
		8.0	H ₂		1.11		
		8.0	Air		1.19		
		8.0	H ₂		1.09		

⁽¹⁾ Air tests at 1 atmosphere, hydrogen tests at 13.8 MPa (2000 psig)

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Figure 30. Tensile Property Comparison of AISI 304L Parent and Welded Materials in Air and 13.8 MPa (2000 psig) Hydrogen Environment at 24°C (75°F)

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Figure 31. Tensile Property Comparison of A106B Parent and Welded Materials in Air and 13.8 MPa (2000 psig) Hydrogen Environment at 24°C (75°F)

TABLE VIII. TENSILE PROPERTIES OF AISI 304L AND A106B IN AIR AND HIGH-PRESSURE GASEOUS HYDROGEN ENVIRONMENT AT 24°C (75°F)

Material	Weld Type	Spec. S/N	Test Conditions		Test Results					
			Notch Factor	Environment ⁽¹⁾	Strength		Ductility			
					0.2% Yield	Ultimate	0.2% Yield	Ultimate	El ^(a)	RA
					(MPa)	(ksi)	(MPa)	(ksi)	(%)	(%)
AISI 304L	Parent Material	SPMS-1	Smooth	Air	215.8	31.3	598.5	86.8	64.0	83.2
		SPMS-2	Smooth	Air	226.8	32.9	592.3	85.9	61.0	83.1
		SPMS-3	Smooth	H ₂	245.5	35.6	622.6	90.3	66.3	81.1
		SPMS-4	Smooth	H ₂	245.5	35.6	626.7	90.9	68.0	81.1
		SPMN-1	8.0	Air			801.2	116.2		
		SPMN-2	8.0	Air			814.3	118.1		
		SPMN-3	8.0	H ₂			771.5	111.9		
		SPMN-4	8.0	H ₂			762.6	110.6		
	GTAW	SGFS-1	Smooth	Air	300.6	43.6	613.6	89.0	35.0	27.5 ^(a)
		SGFS-2	Smooth	Air	299.9	43.5	564.7	81.9	25.5	30.4 ^(a)
		SGFS-3	Smooth	H ₂	291.6	42.3	619.1	89.8	52.0	72.4 ^(a)
		SGFS-4	Smooth	H ₂	316.5	45.9	663.3	96.2	61.0	75.2 ^(a)
		SGFN-1	8.0	Air			846.7	122.8		
		SGFN-2	8.0	Air			843.9	122.4		
		SGFN-3	8.0	H ₂			817.7	118.6		
		SGFN-4	8.0	H ₂			829.4	120.3		
	GTAW (HAZ)	SGHN-1	8.0	Air			922.5	133.8		
		SGHN-2	8.0	Air			861.2	124.9		
		SGHN-3	8.0	H ₂			870.8	126.3		
		SGHN-4	8.0	H ₂			872.2	126.5		
	EBW	SEFS-1	Smooth	Air	268.2	38.9	580.5	84.2	40.0	77.5 ^(a)
		SEFS-2	Smooth	Air	280.6	40.7	584.0	84.7	42.0	84.2 ^(a)
		SEFS-3	Smooth	H ₂	289.6	42.0	607.4	88.1	40.0	69.6 ^(a)
		SEFS-4	Smooth	H ₂	296.5	43.0	606.0	87.9	40.5	71.2 ^(a)
		SEFN-1	8.0	Air			834.3	121.0		
		SEFN-2	8.0	Air			848.1	123.0		
		SEFN-3	8.0	H ₂			831.5	120.6		
		SEFN-4	8.0	H ₂			795.7	115.4		
	EBW (HAZ)	SEHN-1	8.0	Air			820.5	119.0		
		SEHN-2	8.0	Air			861.2	124.9		
		SEHN-3	8.0	H ₂			813.6	118.0		
		SEHN-4	8.0	H ₂			799.8	116.0		

TABLE VIII. TENSILE PROPERTIES OF AISI 304L AND A106B IN AIR AND HIGH-PRESSURE GASEOUS HYDROGEN ENVIRONMENT AT 24°C (75°F) (Continued)

Material	Weld Type	Spec. S/N	Test Conditions		Test Results					
			Notch Factor	Environment ⁽¹⁾	Strength				Ductility	
					0.2% Yield	Yield	Ultimate		El ⁽²⁾	RA
					(MPa)	(ksi)	(MPa)	(ksi)	(%)	(%)
AISI 304L	LBW	SLFS-1	Smooth	Air	256.5	37.2	583.3	84.6	43.5	74.0 ⁽³⁾
		SLFS-2	Smooth	Air	279.9	40.6	595.0	86.3	42.5	81.1 ⁽³⁾
		SLFS-3	Smooth	H ₂	277.2	40.2	607.4	88.1	43.5	75.6 ⁽³⁾
		SLFS-4	Smooth	H ₂	270.3	39.2	596.4	86.5	44.5	76.4 ⁽³⁾
		SLFN-1	8.0	Air			836.3	121.3		
		SLFN-2	8.0	Air			841.2	122.0		
		SLFN-3	8.0	H ₂			772.2	112.0		
		SLFN-4	8.0	H ₂			795.7	115.4		
	LBW (HAZ)	SLHN-1	8.0	Air			852.2	123.6		
		SLHN-2	8.0	Air			834.3	121.0		
		SLHN-3	8.0	H ₂			804.6	116.7		
		SLHN-4	8.0	H ₂			797.7	115.7		
A106B	Parent Material	CPMS-1	Smooth	Air	323.4	46.9	479.2	69.5	28.5	60.5
		CPMS-2	Smooth	Air	333.0	48.3	492.3	71.4	27.3	60.6
		CPMS-3	Smooth	H ₂	349.6	50.7	513.0	74.4	24.0	40.5
		CPMS-4	Smooth	H ₂	341.3	49.5	509.5	73.9	24.5	45.2
		CPMN-1	8.0	Air			798.4	115.8		
		CPMN-2	8.0	Air			791.5	114.8		
		CPMN-3	8.0	H ₂			695.7	100.9		
		CPMN-4	8.0	H ₂			681.2	98.8		
	GTAW	CGFS-1	Smooth	Air	308.2	44.7	504.7	73.2	21.0	59.9 ⁽⁴⁾
		CGFS-2	Smooth	Air	311.6	45.2	507.5	73.6	21.0	59.6 ⁽⁴⁾
		CGFS-3	Smooth	H ₂	311.6	45.2	501.2	72.7	17.5	57.4 ⁽⁴⁾
		CGFS-4	Smooth	H ₂	319.9	46.4	502.6	72.9	17.0	47.0 ⁽⁴⁾
		CGFN-2	8.0	Air			1025.9	148.8		
		CGFN-6	8.0	Air			1012.8	146.9		
		CGFN-3	8.0	H ₂			904.6	131.2		
		CGFN-4	8.0	H ₂			910.8	132.1		
	GTAW (HAZ)	CGHN-1	8.0	Air			848.1	123.0		
		CGHN-2	8.0	Air			843.2	122.3		
		CGHN-3	8.0	H ₂			639.8	92.8		
		CGHN-4	8.0	H ₂			665.3	96.5		

TABLE VIII. TENSILE PROPERTIES OF AISI 304L AND A106B IN AIR AND HIGH-PRESSURE GASEOUS HYDROGEN ENVIRONMENT AT 24°C (75°F) (Continued)

Material	Weld Type	Spec. S/N	Test Conditions		Test Results					
			Notch Factor	Environment ⁽¹⁾	Strength				Ductility	
					0.2% Yield		Ultimate		E _L ⁽²⁾	RA
					(MPa)	(ksi)	(MPa)	(ksi)	(%)	(%)
A106B	EBW	CEFS-1	Smooth	Air	313.7	45.5	498.5	72.3	24.0	59.4 ⁽⁴⁾
		CEFS-2	Smooth	Air	319.2	46.3	500.6	72.6	24.0	59.2 ⁽⁴⁾
		CEFS-3	Smooth	H ₂	317.8	46.1	494.4	71.7	19.0	37.8 ⁽⁴⁾
		CEFS-4	Smooth	H ₂	315.8	45.8	494.4	71.7	20.0	45.0 ⁽⁴⁾
		CEFN-1	8.0	Air			804.6	116.7		
		CEFN-2	8.0	Air			824.6	119.6		
		CEFN-3	8.0	H ₂			710.2	103.0		
		CEFN-4	8.0	H ₂			758.4	110.0		
		CEFN-5	8.0	H ₂			684.6	99.3		
	EBW (HAZ)	CEHN-1	8.0	Air			804.6	116.7		
		CEHN-2	8.0	Air			810.8	117.6		
		CEHN-3	8.0	H ₂			644.7	93.5		
		CEHN-4	8.0	H ₂			628.1	91.1		
	LBW	CLFS-1	Smooth	Air	359.9	52.2	507.5	73.6	21.5	59.4 ⁽⁴⁾
		CLFS-2	Smooth	Air	363.4	52.7	510.9	74.1	23.5	57.4 ⁽⁴⁾
		CLFS-3	Smooth	H ₂	373.0	54.1	517.8	75.1	20.0	46.4 ⁽⁴⁾
		CLFS-4	Smooth	H ₂	366.1	53.1	506.8	73.5	19.0	44.4 ⁽⁴⁾
		CLFN-1	8.0	Air			836.3	121.3		
		CLFN-2	8.0	Air			958.4	139.0		
		CLFN-3	8.0	H ₂			780.5	113.2		
		CLFN-4	8.0	H ₂			746.0	108.2		
	LBW (HAZ)	CLHN-1	8.0	Air			931.5	135.1		
		CLHN-2	8.0	Air			954.9	138.5		
		CLHN-3	8.0	H ₂			712.9	103.4		
		CLHN-4	8.0	H ₂			789.4	114.5		

⁽¹⁾ Air tests at 1 atmosphere, hydrogen tests at 13.8 MPa (2000 psig).

⁽²⁾ Elongation based on gage length of 25.4 mm (1.00 in.) or 4D.

⁽³⁾ Failed in weld HAZ.

⁽⁴⁾ Failed in parent material.

⁽⁵⁾ Failed in weld.

1. Effect of Hydrogen Environment

None of the material conditions evaluated exhibited any degradation in the 0.2% yield strength due to hydrogen exposure. For the parent AISI 304L material and the GTAW, EBW and LBW configurations, negligible degradation, if any, was exhibited in the smooth and notch tensile strengths. Differences in ultimate strengths obtained in the air and hydrogen environments, in some cases, did occur. However, with the limited number of tests conducted, two each in air and hydrogen for each material condition, normal specimen-to-specimen scatter, especially pronounced in welded material tests, precludes drawing firm conclusions when the properties differences were less than 10%.

For the A106B material and its welded conditions evaluated, degradation in smooth ultimate strength was "negligible" (less than 10%). However, in all conditions there was degradation in the ultimate strength ranging from 11 to 22.8%. Of the notched specimens, those with notches in the heat-affected zones exhibited approximately twice the degradation of those notched in the fusion zone.

As previously reported in PWA FR-5768¹, FR-6709², FR-7175³, and FR-7746⁴, loss of ductility (elongation and/or reduction of area) was the most prominent indicator of hydrogen degradation. In some of the material conditions evaluated, ductility was severely degraded, while the ultimate strengths showed negligible degradation. With the exception of the EBW specimens, where 13% degradation was exhibited in reduction of area, negligible degradation, if any, occurred in all the AISI 304L welded material conditions. In contrast, degradation in ductility occurred for all the A106B material conditions evaluated. The degrees of degradation ranged from "degraded" to "severe" for the A106B materials using the grading system detailed in Section IIA. A comparison of LBW specimens tested in air (CLFS-1) and hydrogen (CLFS-3) showing typical hydrogen degradation in terms of reduced ductility and secondary cracking, is shown in Figure 32.

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Figure 32. Typical Laser Welded A106B Smooth Tensile Specimens Tested in Air (Top) and 13.8 MPa (2000 psig) Hydrogen (Bottom)

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.

⁴ "Influence of Gaseous Hydrogen on the Mechanical Properties of High Temperature Alloys." Final Report Exhibit B&C, Contract NAS8-30744, July 1976.

2. Effect of Welding

The effects of GTAW, EBW and LBW on the tensile properties of the two subject materials were summarized previously in Table VII. For comparative purposes, the effects of the various weld processes are expressed in terms of the ratio of the welded to the parent material properties.

Generally, no detrimental effects were observed on the tensile strengths (0.2% yield, smooth and notched ultimate) of both the AISI 304L and A106B material due to GTAW, EBW or LBW. However, for both materials (more so in the AISI 304L), ductility was reduced considerably in all the welded configurations evaluated.

Testing indicated that for both materials the properties of the various weldments were not influenced by the hydrogen environment. This statement appears incorrect when viewing Tables VII and VIII, specifically the AISI 304L GTAW ductility effect. However, those results must be tempered with the fact that the specimens tested in hydrogen failed in the parent material while those tested in air had failures associated with the weld and heat-affected zone. This variation in failure location and indicated lower ductility is often encountered when testing welded materials.

Generally, from the limited testing in this program, it can be concluded that welding affects the tensile properties of AISI 304L and A106B steels the same whether welded conventionally (GTAW and EBW) or by the LBW process.

C. TEST PROCEDURE

All tensile tests were conducted in accordance with ASTM E8, "Tension Testing of Metallic Materials," using the smooth and notched specimens described in Section IIID and detailed previously in Figures 26 and 27, respectively.

Smooth specimens were loaded to yield at a strain rate of 0.005 mm/mm/min (in./in./min) and at a crosshead speed of 1.27 mm/min (0.05 in./min) from yield to fracture. Notched specimens were tested at a crosshead speed of 1.27 mm/min (0.05 in./min) to fracture.

The air tensile tests were conducted on a Tinius Olsen 266.8-kN (60,000-lb) Deluxe Super "L" Universal Testing Machine equipped with an electronic flatbed recorder and full digital indicating system. This test machine showing the various readout modules, including crosshead speed indicator and combination strain rate/load rate indicator, is shown in Figure 33.

All high-pressure hydrogen tensile tests were conducted on a Tinius Olsen 266.8-kN (60,000-lb) capacity tensile machine, located in a remote test area and equipped with a Pratt & Whitney Aircraft Group/Florida designed and developed pressure vessel. All controls and instrumentation readout equipment are located inside an adjacent pressurized blockhouse. This equipment is shown in Figure 34.

Various views of the pressure vessel showing smooth and notched specimens in place, extensometer, and furnace setup are presented in Figure 35. The elevated temperature test setup (Figure 35d) is shown for information purposes only, as all tensile tests in this program were conducted at ambient temperature. The pressure vessel is made of AISI 347 stainless steel and incorporates a high-pressure Gray LOC connector. A compensating device built into the base of the vessel eliminates the effect of loads resulting from pressure acting over differential specimen and adapter cross-sectional areas.

FAC 38941

A. Overall View of Machine and
Readout Instrumentation

FAC 38942

B. Closeup View of Electronic Flat-Bed
Recorder and Digital Readout Modules

FD 144694

Figure 33. Tensile Machine Used for Conducting Air Tests

FC 42233

Figure 34. Tensile Machine, Test Environmental Controls and Data Acquisition Equipment

FC 42236

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

FAE 146120

b) Test Vessel Open With Notch Tensile Specimen in Place

FAE 146118

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

FAE 146119

d) Test Vessel Open With Furnace Attached

FD 92357

Figure 35. Setups of Tensile Test Vessel

An averaging-type linear variable displacement transducer (LVDT) extensometer system was used (Figure 36) to measure specimen strain for the smooth tensile tests. 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 and extensometer were made through the bottom of the pressure vessel via high-pressure bulkhead connectors.

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 level.
2. Pressurize to 0.345 MPa (50 psig) with nitrogen gas, leak check, and vent.
3. Evacuate to 0.101 MPa (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 MPa (30 in. Hg).
5. Pressure purge to 3.45 MPa (500 psig) with hydrogen gas three times, obtain pretest gas sample.
6. Pressurize to 13.8 MPa (2000 psig) with hydrogen gas and conduct test.
7. Reduce pressure, vent to atmospheric pressure, flow and pressure purge with nitrogen gas, open pressure vessel and remove failed specimen.

Tensile properties, including 0.2% offset yield strength, ultimate strength, percent elongation and reduction of area were obtained for all smooth specimen tests. For notched tests, only ultimate strength was determined. A typical tensile load-deflection curve is shown in Figure 37.

FAE 146126

Figure 36. Averaging-Type LVDT Extensometer System

FC 39839A

Figure 37. Typical Load-Deflection (Stress-Strain) Curve Generated During an Actual Tensile Test

SECTION V LOW-CYCLE FATIGUE TESTING

A. INTRODUCTION

Low-cycle fatigue tests were conducted on both the parent and welded AISI 304L and A106B materials in ambient pressure air and in 13.8 MPa (2000 psig) hydrogen. From these data, the effect of the hydrogen exposure on the LCF lives of the parent and welded materials was established and the effect of the various welds on LCF life was assessed.

The LCF tests were conducted in the strain-control mode with the material cycling through a constant total strain range (elastic plus inelastic) until complete specimen fracture. The tensile and compressive portions of the strain cycle were of equal magnitude resulting in a mean strain of zero (Figure 38). All tests were conducted on a screening basis, i.e., all specimens tested at the same total strain range, with the effect of hydrogen environment and the various weld processes established on the basis of mean cyclic life differences.

FD 102380A

Figure 38. Hysteresis Loop for an LCF Test With Mean Strain of Zero

B. RESULTS AND CONCLUSIONS

Statistical analysis of all LCF test data was made to establish the effects of hydrogen environment and welding on the lives of both materials. Analysis of variance techniques indicated that statistically significant differences do exist between air and hydrogen environment data for both materials. Also, differences exist between the welded conditions of the A106B material. However for the AISI 304L welded conditions, no statistically significant differences could be found due to the large data scatter experienced. Therefore, the following conclusions as to the relative merits of the AISI 304L weldments were made to indicate possible trends. Additional testing would be required to statistically confirm this trend.

1. Effect of Hydrogen Environment

The AISI 304L and A106B parent materials exhibited approximately 60 and 88% degradation, respectively, in mean LCF life, due to the 13.8 MPa (2000 psig) gaseous hydrogen environment. In the welded conditions, the AISI 304L welded systems exhibited lower degradation than the same welds in the A106B material. The least degraded weld in both materials was the LBW.

The effects of hydrogen environment on the AISI 304L and A106B parent and welded material LCF lives are summarized in Table IX and presented graphically in Figure 39.

Complete LCF test results for each specimen tested are listed in Table X.

2. Effects of Welding

The effects of GTAW, EBW and LBW are summarized in Table XI and presented in previously shown Figure 39.

In comparing the performance of the welded materials in air, the GTAW, EBW and LBW AISI 304L materials exhibited comparable mean LCF lives; as compared to the parent material they were all approximately 43% lower. For the A106B material, both EBW and LBW produced comparable lives, approximately 26% lower than the parent material. The LCF life of the A106B GTAW material was 44% lower.

Based on the performance of the welded materials in hydrogen, LBW material appears superior to the conventional weld processes. In the AISI 304L material, the LCF life of LBW material was only 23% lower than the parent material. In contrast, both the GTAW and EBW material lives were 58% lower. For the A106B material, no detrimental effect in LCF life was indicated due to LBW. The EBW and GTAW material exhibited 27 and 44% lower lives respectively, than the parent material.

TABLE IX. DEGRADATION OF LCF LIFE OF AISI 304L AND A106B
IN 13.8 MPa (2000 psig) GASEOUS HYDROGEN AT 24°C
(75°F)

Material	Weld Type	Environment	LCF Life, Cycles to Failure		Degradation, Decrease from Air (%)
			Log. Mean	S. Dev.	
AISI 304L	Parent Material	Air	5262	0.0611	60
		H ₂	2074	0.0595	
	GTAW	Air	2968	0.1240	72
		H ₂	842	0.1190	
	EBW	Air	3145	0.0119	73
		H ₂	865	0.1338	
	LBW	Air	2853	0.0760	44
		H ₂	1588	0.0460	
A106B	Parent Material	Air	4245	0.0275	88
		H ₂	489	0.2810	
	GTAW	Air	2372	0.1835	90
		H ₂	244	0.2950	
	EBW	Air	3104	0.1280	88
		H ₂	358	0.3090	
	LBW	Air	3180	0.1198	81
		H ₂	599	0.2180

FD 144695

Figure 39. Low-Cycle Fatigue Results of AISI 304L Stainless Steel and A106B Carbon Steel

TABLE X. LOW-CYCLE FATIGUE PROPERTIES OF AISI 304L AND A106B IN AIR AND HIGH-PRESSURE HYDROGEN ENVIRONMENT AT 24°C (75°F)

Material	Weld Type	Spec. S/N	Test Conditions		Test Results			
			Environment ⁽¹⁾	Total Strain Range ⁽²⁾	Cycles to Failure ⁽⁴⁾	Inelastic Strain Range (%)		
				(%)		Min	Max	Ave
AISI 304L	Parent Material	SPML-1	Air	1.0	4,511	0.64	0.68	0.66
		SPML-2	Air	1.0	5,943	0.65	0.67	0.66
		SPML-6	Air	1.0	5,437	0.63	0.69	0.66
		SPML-3	Hydrogen	1.0	2,285	0.58	0.65	0.62
		SPML-4	Hydrogen	1.0	1,882	0.58	0.69	0.64
	GTAW	SGFL-3	Air	1.0	4,113	0.53	0.62	0.58
		SGFL-5	Air	1.0	2,640	0.53	0.56	0.55
		SGFL-6	Air	1.0	2,407	0.53	0.59	0.56
		SGFL-1	Hydrogen	1.0	620	0.54	0.59	0.57
		SGFL-2	Hydrogen	1.0	1,054	0.50	0.62	0.56
		SGFL-4	Hydrogen	1.0	915	0.55	0.60	0.58
	EBW	SEFL-10	Air	1.0	3,073	0.53	0.57	0.55
		SEFL-11	Air	1.0	3,077	0.57	0.63	0.60
		SEFL-12	Air	1.0	3,180	0.55	0.60	0.58
		SEFL-13	Air	1.0	3,252	0.52	0.59	0.56
		SEFL-1	Hydrogen	1.0	647	0.53	0.59	0.56
		SEFL-2	Hydrogen	1.0	617	0.56	0.58	0.57
		SEFL-6	Hydrogen	1.0	1,204	0.56	0.63	0.60
		SEFL-7	Hydrogen	1.0	920	0.57	0.63	0.60
		SEFL-8	Hydrogen	1.0	745	0.50	0.60	0.55
		SEFL-9	Hydrogen	1.0	1,259	0.52	0.60	0.56
	LBW	SLFL-4	Air	1.0	2,421	0.55	0.63	0.59
		SLFL-5	Air	1.0	2,801	0.58	0.65	0.62
		SLFL-6	Air	1.0	3,425	0.55	0.63	0.59
		SLFL-1	Hydrogen	1.0	1,783	0.51	0.63	0.57
		SLFL-2	Hydrogen	1.0	1,548	0.56	0.62	0.59
		SLFL-3	Hydrogen	1.0	1,450	0.58	0.63	0.61
A106B	Parent Material	CPML-1	Air	1.0	4,555	0.67	0.77	0.72
		CPML-2	Air	1.0	4,171	0.64	0.67	0.66
		CPML-5	Air	1.0	4,027	0.65	0.69	0.67
		CPML-4	Hydrogen	1.0	283	0.54	0.62	0.58
		CPML-6	Hydrogen	1.0	1,165	0.64	0.68	0.66
		CPML-7	Hydrogen	1.0	550	0.61	0.67	0.64
		CPML-8	Hydrogen	1.0	315	0.61	0.69	0.65
	GTAW	CGFL-5	Air	1.0	2,316	0.43	0.52	0.48
		CGFL-6	Air	1.0	3,660	0.57	0.62	0.60
		CGFL-7	Air	1.0	1,574	0.50	0.61	0.56
		CGFL-1	Hydrogen	1.0	669	0.31	0.50	0.41
		CGFL-2	Hydrogen	1.0	180	0.32	0.54	0.43
		CGFL-3	Hydrogen	1.0	195	0.43	0.51	0.47
		CGFL-4	Hydrogen	1.0	152	0.42	0.51	0.47
	EBW	CEFL-5	Air	1.0	2,258	0.62	0.66	0.64
		CEFL-6	Air	1.0	3,278	0.63	0.69	0.66
		CEFL-7	Air	1.0	4,047	0.55	0.60	0.58
		CEFL-1	Hydrogen	1.0	171	0.57	0.63	0.60
		CEFL-2	Hydrogen	1.0	920	0.56	0.62	0.59
		CEFL-3	Hydrogen	1.0	386	0.53	0.53	0.53
		CEFL-4	Hydrogen	1.0	272	0.59	0.65	0.62
	LBW	CLFL-4	Air	1.0	3,679	0.55	0.64	0.60
		CLFL-5	Air	1.0	4,294	0.53	0.59	0.56
		CLFL-6	Air	1.0	2,318	0.68	0.70	0.69
		CLFL-7	Air	1.0	2,792	0.52	0.61	0.57
		CLFL-1	Hydrogen	1.0	1,028 ⁽³⁾	0.52	0.59	0.56
		CLFL-2	Hydrogen	1.0	548	0.58	0.63	0.61
		CLFL-3	Hydrogen	1.0	381	0.62	0.62	0.58

⁽¹⁾Air tests at 1 atmosphere, hydrogen tests at 13.8 MPa (2000 psig)

⁽²⁾Mean Strain = 0, cyclic frequency = 5 cycles/min.

⁽³⁾Specimen did not fail; however, it was damaged at indicated number of cycles due to a power failure.

⁽⁴⁾Failure defined as complete specimen fracture (separation).

TABLE XI. EFFECT OF WELDING ON THE MEAN LCF
LIFE OF AISI 304L AND A106B STEELS

Material	Weld Type	Mean LCF Life Air	Mean LCF Life H ₂	Ratio of Welded/Parent Material Mean LCF Life	
				Air	H ₂
AISI 304L	Parent Material	5,262	2,074		
	GTAW	2,968	842	0.56	0.41
	EBW	3,145	865	0.60	0.42
	LBW	2,853	1,588	0.54	0.77
A106B	Parent Material	4,245	489		
	GTAW	2,372	244	0.56	0.50
	EBW	3,104	358	0.73	0.73
	LBW	3,180	599	0.75	1.22

The aforementioned conclusions regarding superiority of the LBW joints in hydrogen must be qualified in view of the porous condition of the welded materials (Section IIIC) and the small sample sizes evaluated. It is felt that additional testing could result in somewhat altered conclusions as to the effect of LBW on LCF life. Therefore, absolute conclusions as to the relative merits of the various weldments, moreso for the AISI 304L welded material as previously discussed, cannot be made without additional testing to establish statistically meaningful data.

Fracture surface photomicrographs of typical GTAW, EBW and LBW LCF specimens, showing fatigue origins at pores, are presented in Section IIIC.

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 IIID and detailed in Figure 29. The specimen configuration incorporates integral machined extensometer collars (Figure 40). A calibration procedure has been established to relate the maximum strain-to-collar deflection during both the elastic and inelastic portion of the strain cycle. The specimen design and calibration procedure were verified both experimentally and analytically.

FD 92638

Figure 40. Open Extensometer Head Assembly and Low-Cycle Fatigue Specimen

All LCF tests were conducted on P&WA/Florida designed and fabricated, closed-loop type, hydraulically actuated test machines. The test machine utilized for the air LCF tests in this program is shown in Figure 41. Specimen axial strain was measured and controlled by a dual proximity probe extensometer system (Figure 42). An open extensometer head, showing the attachment of the extensometer to the specimen integral collars, is shown previously in Figure 40. Specimen load was measured using commercial tension-compression flat-load cells.

FC 30186

Figure 41. Servohydraulic Closed-Loop, Low-Cycle Fatigue Testing Machine

FD 92637

Figure 42. Load Cell, Load Rod, Specimen, and Extensometer Assembly Mounted in Low-Cycle Fatigue Machine

For the high-pressure hydrogen tests, a closed-loop type, hydraulically actuated test machine, similar to the one used for the air tests, was utilized. The test machine is located in an isolated test cell with all controls and instrumentation located in an adjacent blockhouse (Figure 43). A pressure vessel similar to the one used for tensile testing was mounted on the upper platen of the test machine. The vessel also incorporates a Gray LOC-type high-pressure flange connector; however, unlike the tensile vessel, where a compensating piston device is used to counteract load in the specimen due to pressure acting over differential specimen/adaptor areas, this test system compensates for that load through the servosystem. A pressure transducer provides 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 is maintained when the vessel assembly is pressurized. This same load was then superimposed on the cyclic load during testing.

FD 92639

Figure 43. Low-Cycle Fatigue Test Machine, Environmental Controls and Data Acquisition Equipment

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 and extensometer system were made through the vessel wall via high-pressure bulkhead connectors. Setups of the pressure vessel showing the extensometer system are shown in Figure 44.

FAE 146129

a) Test Vessel Closed

FAE 146121

b) Test Vessel Open Showing
Extensometer System

FAE 146122

c) Test Vessel Open Showing Furnace
In Place

FD 92640

Figure 44. Setups of Low-Cycle Fatigue Test Vessel

Strain, as sensed by the extensometer system, was recorded on the "X" axis of an "X-Y" recorder, and load (sensed by the internal load cell) was recorded on the "Y" axis, thus providing hysteresis loops, as desired, during the cyclic life of all tests. A typical series of LCF hysteresis loops is shown in Figure 45.

The test and gas handling procedures used for the LCF tests were the same as those used for the tensile tests performed under this contract (Section IVC).

FC 39840A

Figure 45. A Typical Series of LCF Hysteresis Loops Generated During an Actual Test

SECTION VI FRACTURE TOUGHNESS TESTING

A. INTRODUCTION

Fracture toughness tests were conducted in 24°C (75°F) ambient pressure air in accordance with ASTM E399-74, "Plane Strain Fracture Toughness of Metallic Materials," where applicable. Results of the welded material tests were compared to those of the parent material tests to establish the effect of the various weldments on fracture toughness.

B. RESULTS AND CONCLUSIONS

As was anticipated for AISI 304L and A106B steels in the specimen configuration tested, (½-in. thick, 1W compact tension), valid K_{IC} parameters per ASTM E399 could not be met. The load ratio criterion, in ASTM E399-74, allows a maximum P_{max}/P_Q of 1.10. Tests with load ratios exceeding the allowable 1.10 are deemed invalid for subsequent K_{IC} calculations as K_Q bears no relation to K_{IC} . Testing of the AISI 304L and A106B parent material specimens resulted in average load ratios of 2.1 and 1.4, respectively. The alternate method of this procedure covers the determination of the specimen strength ratio, R_{sc} , a function of the total stress (M_c/I and P/A stresses) at the crack tip, resulting from the maximum load the specimen can sustain, and the yield strength of the material. The specimen strength ratios, established for the fracture toughness tests in this program, can be significant as a measure of material toughness when results are compared for specimens of the same form and size. This method allows a quantitative comparison to determine the effect of the various welded conditions on the subject materials.

The effects of GTAW, EBW, and LBW on the specimen strength ratio, R_{sc} , of the subject materials are summarized in Table XII. All test data are listed in Table XIII.

The R_{sc} analysis for both the AISI 304L and A106B materials indicates that for the GTAW, EBW, and LBW conditions, R_{sc} values are all comparable to that of the parent materials. On a statistical basis, no significant differences in R_{sc} could be established due to the various weldments. Moreover, firm conclusions as to the effect of the various weldments on R_{sc} could not be made due to the small sample sizes evaluated and the data scatter experienced.

TABLE XII. EFFECT OF WELDING ON THE
STRENGTH RATIO (R_{sc}) OF AISI
304L AND A106B STEELS

Material	Weld Type	Ratio of Welded/Parent Material
		Average R_{sc}
AISI 304L	GTAW	0.88
	GTAW (HAZ)	0.97
	EBW	0.97
	EBW (HAZ)	1.00
	LBW	1.02
	LBW (HAZ)	1.06
A106B	GTAW	1.11
	GTAW (HAZ)	1.08
	EBW	0.96
	EBW (HAZ)	1.00
	LBW	0.90
	LBW (HAZ)	1.20

TABLE XIII. FRACTURE TOUGHNESS OF AISI 304L AND A106B IN AIR AT 24°C (75°F)

Specimen Parameters					Test Results						
Material	Weld Type	Spec S/N	Precrack Length, <i>a</i>		$K_Q^{(1)}$		$2.5 (K_Q/ys)^{(2)}$	P_{max}/P_Q	$R_{SC}^{(3)}$	$K_{IC}(J)^{(4)}$	
			(mm)	(in.)	(MPa√m)	(ksi√in.)				MPa√m	ksi√in.
AISI 304L Parent Material		SPMF-1	14.2	0.560	47.1	42.9	4.77	2.03	6.16		
		SPMF-2	15.8	0.622	44.4	40.4	3.96	2.17	6.55		
	GTAW	SGFF-1	14.1	0.556	56.5	51.5	6.43	1.49	5.41		
		SGFF-2	15.8	0.621	58.0	52.8	6.76	1.42	5.77		
	GTAW (HAZ)	SGHF-1	13.5	0.531	59.4	54.1	7.11	1.67	6.13		
		SGHF-2	15.7	0.618	49.0	44.6	4.83	1.80	6.15		
	EBW	SEFF-1	13.6	0.536	56.1	51.1	6.31	1.72	6.01		
		SEFF-2	16.0	0.629	46.8	42.6	4.40	1.90	6.32		
	EBW (HAZ)	SEHF-1	17.0	0.670	50.8	46.2	5.18	1.79	6.86		
		SEHF-2	13.4	0.529	55.7	50.7	6.23	1.71	5.84		
	LBW	SLFF-1	14.4	0.568	59.2	53.9	7.06	1.46	5.63		
		SLFF-2	17.4	0.687	54.0	49.1	5.86	1.75	7.32		
	LBW (HAZ)	SLHF-1	14.5	0.571	50.7	46.1	5.15	2.00	6.60		
		SLHF-2	16.7	0.657	45.5	41.4	4.17	2.04	6.87		
A106B	Parent Material	CPMF-1	13.0	0.513	49.8	45.3	2.26	1.48	2.99	195.1	177.5
		CPMF-2	15.1	0.595	51.4	46.8	2.42	1.32	3.09		
	GTAW	CGFF-6	14.0	0.553	58.1	52.9	3.08	1.28	3.19	162.1	147.5
		CGFF-7	15.7	0.617	62.2	56.6	3.54	1.21	3.53		
	GTAW (HAZ)	CGHF-2	17.1	0.674	47.1	42.9	2.03	1.35	3.25	209.2	190.4
		CGHF-3	13.3	0.522	51.1	46.5	2.44	1.56	3.29		
	EBW	CEFF-1	13.9	0.546	52.0	47.3	2.47	1.31	2.85	187.8	170.9
		CEFF-2	16.7	0.659	43.4	39.5	1.72	1.37	2.98		
	EBW (HAZ)	CEHF-3	15.4	0.607	58.9	53.6	3.17	1.22	3.33	150.5	137.0
		CEHF-4	12.9	0.506	47.1	42.9	2.03	1.45	2.75		
	LBW	CLFF-1	14.5	0.569	54.6	49.7	2.73	1.15	2.77	144.2	131.2
		CLFF-2	15.7	0.617	54.4	49.5	2.71	1.12	2.87		
	LBW (HAZ)	CLHF-1	14.5	0.569	62.9	57.2	3.61	1.30	3.59	139.0	126.5
		CLHF-2	16.7	0.657	53.7	48.9	2.64	1.37	3.68		

⁽¹⁾⁽²⁾ These parameters are included for informational purposes only, as per ASTM E399-74 with P_{max}/P_Q greater than 1.10, K_Q bears no relation whatsoever to K_{IC} .

⁽³⁾ Specimen Strength Ratio — total stress ($M/I + P/A$)/yield strength.

⁽⁴⁾ K_{IC} obtained using J-Integral method per Begley, J. A. and J. D. Landes, "The J-Integral As a Fracture Criterion," ASTM STP 514, 1972, and Bucci, R. J., P. C. Paris, et. al, "J-Integral Estimation Procedures," ASTM 514, 1972.

In accordance with ASTM E399-74, specimen size requirements must be met to assure linear elastic behavior. Thickness must be ample such that the crack tip plastic zone is constrained by sufficient elastically loaded material to assure failure without significant plastic deformation. Testing of the subject materials, in the 1W configuration, indicated considerably insufficient thickness to obtain plane-strain conditions. Therefore, the J-Integral approach⁽¹⁾⁽²⁾ was used in an attempt to obtain K_{IC} values. This approach to fracture behavior yields linear elastic fracture toughness values from thinner plastically loaded specimens.

The J-Integral analysis of the A106B parent material indicated a $K_{IC}(J)$ fracture toughness value of 195.1 MPa√m (177.5 ksi√in.). For the AISI 304L parent material no $K_{IC}(J)$ value could be obtained, as such large amounts of plastic deformation occurred that only a reduction in specimen thickness resulted. No crack growth whatsoever occurred as anticipated for the small specimens of AISI 304L material. It was hoped that "embrittlement" due to the welding processes

would result in typical fracture toughness specimen behavior; however, this did not happen. The fracture appearance of the AISI 304L and A106B specimens illustrates the fracture behavior differences between materials. Typical parent material specimens are presented in Figure 46. Viewing the actual load/displacement curves obtained for the AISI 304L (Figure 47) and A106B (Figure 48) parent materials also illustrates the fracture behavior differences between the two materials.

For the A106B parent and welded materials, the K_{IC} (J) fracture toughness values obtained in this program are listed in Table XIII. The limited test data indicate K_{IC} (J) values lowest for the LBW material with considerably higher values for the conventional weld processes. In view of this observation, further study should be considered to establish statistically sound information as to the fracture toughness of the LBW material as compared to the conventionally welded material.

Details of the J-Integral approach used, and its limitation, are presented in Section VI.D.

C. TEST PROCEDURE

Fracture toughness tests were conducted using the procedures of ASTM E399-74, "Plane Strain Fracture Toughness of Metallic Materials," where applicable, with the 1W, 12.7 mm (0.5 in.) thick, compact tensile specimens described in Section III.D and detailed in Figure 28.

Specimens were axially tension-tension fatigue precracked at 24°C (75°F) using a dual-headed fatigue machine (Figure 49) operating at a frequency of 30 Hz (1800 cpm), under controlled fatigue stress intensity, K_r , as required to comply with the ASTM specification. Fracture toughness tests were conducted on the test machines used for the tensile tests. The test equipment and related instrumentation readout equipment are described and illustrated in Section IV, Paragraph C.

Load-displacement curves were plotted by an X-Y recorder from the outputs of a load transducer and a load-line displacement extensometer system (Figure 50). This extensometer system was utilized in lieu of the standard crack opening displacement (COD) clip gage, placed across the notch opening of the specimen, to facilitate and simplify J-Integral calculations. A typical load-displacement curve generated during an actual fracture toughness test is presented in Figure 51.

Fracture toughness values (K_Q) for the compact tensile specimen were calculated from the load (P_Q), corresponding to a 2% crack extension, established by a 5% deviation from the linear portion of the recorded load-displacement curve (Figure 51), the specimen thickness (B), width (W), and the crack length (a) after fracture by the equation:

$$K_Q = (P_Q/BW^{3/2})[29.6(a/W)^{1/2} - 185.5(a/W)^{3/2} + 655.7(a/W)^{5/2} - 1017.0(a/W)^{7/2} + 638.9(a/W)^{9/2}].$$

K_Q was deemed a valid K_{IC} if both the specimen thickness (B) and the crack length (a) exceed $2.5 (K_{IC}/\sigma_{YS})^2$, where σ_{YS} is the 0.2% offset yield strength of the material for the temperature and loading rate of the test, and/or P_{max}/P_Q does not exceed 1.10, where P_{max} is the maximum load the specimen was able to sustain. As discussed in Paragraph B of this section, valid K_Q parameters per ASTM E399 could not be met. Therefore, an alternate method of this procedure was used. It covers the determination of the specimen strength ratio, R_{SC} , a function of the total stress (M_c/I and P/A stresses) at the crack tip; resulting from the maximum load the specimen can sustain, and the yield strength of the material. R_{SC} for these materials in the configuration tested was calculated from the equation:

$$R_{SC} = 2P_{max} (2W+a)/B(W-a)^2 \sigma_{YS}.$$

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FAL 47423

Mag: 3X

FD 144696

Figure 16. Fracture Appearance of Typical AISI 304L (Left) and A106B (Right) Parent Material Fracture Toughness Specimens

FD 144697

Figure 47. Actual Fracture Toughness Load/Displacement Curves Generated for AISI 304L Parent Material Tests, Spec S/N SPMF-1 and 2

Figure 48. Actual Fracture Toughness Load/Displacement Curves Generated for A106B Parent Material Tests, Spec S/N SPMF-1 and 2

FD 84316

Figure 49. P&WA Designed Dual Head Fatigue Machine

**A. Overall Showing Load-Train,
Extensometer Rods and Tubes,
and Displacement Transducers**

**B. Closeup Showing Attachment
to Specimen and Adaptors**

FD 144699

Figure 50. Fracture Toughness Load-Line Deflection Extensometer

FD 84318

Figure 51. Typical Load-Displacement Curve

The J-Integral analysis, used to obtain K_{Ic} values for the A106B material, was performed in accordance with References 1 and 2 and is detailed below.

Several compact tension specimens (for this program two specimens were used) are precracked to various crack lengths (a_i) and tested per ASTM E399, where applicable. Load/displacement curves are obtained for each specimen tested (Figure 52). For given values of displacement ($\Delta\delta$) the area under each load displacement curve is interpreted as the "pseudo-potential energy" (U) at that displacement. Energy levels are normalized per unit thickness (U/B) and plotted vs a_i for given constant $\Delta\delta$ (Figure 53). The negative slopes of the U/B vs a_i curves (J) are calculated for given constant $\Delta\delta$.

From the J vs $\Delta\delta$ relationship, the critical displacement ($\Delta\delta_{cr}$) is used to determine a critical J (J_{Ic}). For this program $\Delta\delta_{cr}$ was determined as that point on each of the load/displacement curves where maximum load began to drop off. The average value of critical displacement ($\Delta\delta_{cr}$) is used to determine J_{Ic} (Figure 54).

The J_{Ic} value is converted to K_{Ic} using the relationship,

$$K_{Ic}^2 = \frac{E}{1 - \mu^2} \times J_{Ic},$$

where E is Young's Modulus and μ is Poisson's ratio. The symbol K_{Ic} (J) distinguishes values obtained using the J-Integral technique and the above equation from K_{Ic} data determined per ASTM E399.

¹ Begley, J. A. and J. D. Landes, "The J-Integral As A Fracture Criterion," ASTM STP 514, 1972.

² Bucci, R. J., and P. C. Parris, et al., "J-Integral Estimation Procedures," ASTM STP 514, 1972.

FD 139282

Figure 52. Load-Displacement Records at Various Initial Crack Lengths

FD 144700

Figure 53. Energy Per Unit Thickness vs Crack Length

FD 139860

Figure 54. J Integral vs Displacement

D. DISCUSSION

In calculation K_{IC} (J) values in this program for the A106B parent and welded materials, only two specimens were tested per configuration. Using this approach, only linear energy vs initial crack length curves could be established, resulting in a single J vs displacement curve. This single curve indicates that J is only dependent on displacement and not initial crack length. Additional testing to include the instantaneous measurement of crack length or the evaluation of several specimens of varying initial crack lengths per material configuration, would establish the dependence of crack length on J and possibly result in different K_{IC} (J) values than reported.

APPENDIX A

POROSITY CHARTS

UA-65 Acceptance Standards for Radiographically Determined Porosity In Welds

(a) These standards are applicable to ferritic, austenitic, and nonferrous materials.

(b) The total area of porosity as determined from the radiographic film shall not exceed $0.060T$ square inches in any six inch length of weld, where T is the thickness of the weld. If the weld is less than six inches long, the total area of porosity will be reduced in proportion.

(1) The maximum pore dimension shall be 20 per cent of T , or $\frac{1}{8}$ in., whichever is smaller except that an isolated pore separated from an adjacent pore by one inch or more may be 30 per cent of T , or $\frac{1}{4}$ in., whichever is less.

(2) Dark images of a generally circular or oval shape shall be interpreted as porosity for the purposes of this standard.

(c) The porosity charts in this Appendix illustrate various types of assorted and uniform, randomly dispersed porosity indications. These charts for each thickness represent the maximum acceptable porosity. The charts represent full scale six inch radiographs, and shall not be enlarged or reduced. The porosity distributions shown are not necessarily the patterns that may appear on the radiograph, but are typical of the

number and size of indications permitted. When porosity indications differ significantly from the porosity charts, the actual numbers and sizes of the pores may be measured and the total area of porosity calculated.

(d) In any one inch length of weld or $2T$, whichever is smaller, porosity may be clustered to a concentration four times that permitted by $0.060T$. Such clustered porosity shall be included in the porosity in any six inch length of weld which includes the cluster.

(e) Aligned porosity shall be acceptable providing the summation of the diameters of the pores is no more than T in a length $12T$, or 6 inches, whichever is less, providing each pore is separated by a distance at least six times the diameter of the largest adjacent pore. Aligned porosity indications shall be counted in the total area of permissible indications in any six inch length of weld.

(f) Permissible porosity indications for weld thicknesses intermediate to those illustrated may be evaluated either by comparison with the next thinner material or by calculation as shown in Table UA-65.

Permissible porosity for greater thicknesses shall not exceed $0.060T$ square inches in any 6-inch length of weld.

TABLE UA-65
MAXIMUM PERMISSIBLE POROSITY INDICATIONS IN
RADIOGRAPHS PER 6 IN. LENGTH OF WELD

Weld Thickness (Inches)	Total Area of Permitted Porosity (Square Inches)	LARGE Pore Size (In.)			MEDIUM Pore Size (In.)			FINE Pore Size (In.)		
		Approx. Fraction	Decimal Value (1)	No.	Approx. Fraction	Decimal Value (1)	No.	Approx. Fraction	Decimal Value (1)	No.
$\frac{1}{8}$	.0075							$\frac{1}{64}$	.014	49
$\frac{1}{4}$	.015				$\frac{3}{128}$	.023	31	$\frac{1}{64}$	.0188	100
$\frac{1}{2}$	.030	$\frac{3}{32}$	.10	4	$\frac{1}{32}$	.031	40	$\frac{3}{128}$	.0195	101
$\frac{3}{4}$	.045	$\frac{1}{8}$	.125	4	$\frac{1}{32}$	.034	50	$\frac{3}{128}$	.024	99
1	.060	$\frac{1}{8}$	.125	5	$\frac{1}{32}$	.039	50	$\frac{1}{32}$	.0275	101
$1\frac{1}{4}$	.090	$\frac{1}{8}$	.125	7	$\frac{3}{64}$	.048	50	$\frac{1}{32}$	.034	99
2	.120	$\frac{1}{8}$	.125	10	$\frac{1}{32}$	.055	51	$\frac{3}{128}$	.039	100
$2\frac{1}{2}$	.150	$\frac{1}{8}$	.125	12	$\frac{1}{16}$	.061	51	$\frac{1}{64}$	.044	99
3	.180	$\frac{1}{8}$	.125	15	$\frac{1}{16}$	.068	50	$\frac{1}{64}$	.048	99
$3\frac{1}{2}$	.210	$\frac{1}{8}$	.125	17	$\frac{3}{64}$	.073	50	$\frac{1}{32}$	.052	99
4	.240	$\frac{1}{8}$	.125	20	$\frac{3}{64}$	.078	50	$\frac{1}{32}$	.055	101

(1) These values used for calculating total area of permissible porosity given in second column.

TYPICAL NUMBER AND SIZE PERMITTED
 IN ANY SIX INCH LENGTH OF WELD
 ONE HALF INCH WELD THICKNESS
 TOTAL PORE AREA PERMITTED IS .030 SQ. IN.