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PLASMA ARC WELDING PROCESS DEVELOPMENT PROGRAM
(Volumes I, II, and III)

W. D. Gaw
and
G. L. Starr

Aerojet-General Corporation

Technical Report AFML-TR-68-379, Vol I
April 1969

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Air Force Materials Laboratory
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PLASMA ARC WELDING PROCESS DEVELOPMENT PROGRAM

W. D. Gaw
and
G. L. Starr

FOREWORD

This Final Technical Report covers all work performed under Contract AF33(615)-5353 from July 1966 to March 1969. The manuscript was released by the authors in March 1969 for publication.

This contract with Aerojet-General Corporation, Fullerton, California was initiated under Manufacturing Methods Project 9-800, Plasma Arc Welding Development. The work was administered under the technical direction of Mr. Frederick R. Miller, Fabrication Branch (MATF), Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

Mr. B. L. Baird was Program Manager for Aerojet-General Corporation and Mr. W. D. Gaw was the Project Engineer, assisted by Mr. G. L. Starr.

This project has been accomplished as a part of the Air Force Manufacturing Methods Program, the primary objective of which is to develop, on a timely basis, manufacturing processes, techniques and equipment for use in economical production of USAF materials and components.

Your comments are solicited on the potential utilization of the information contained herein as applied to your present and/or future production programs. Suggestions concerning additional manufacturing methods development required on this or other subjects will be appreciated.

This technical report has been reviewed and is approved.

J. R. Marsh

JACK R. MARSH, Chief
Fabrication Branch
Manufacturing Technology Division

All equipment items compared in this report or on this contract are commerical hardware that were not necessarily developed or manufactured to meet Government specifications, to withstand the tests to which they were subjected, or to operate as they were applied during this study, Any failure, either objective relative or implied, to meet the objectives of this study is no reflection on any of the equipment items discussed herein or on any manufacturer.

ABSTRACT

The objective of work reported in this volume was to evaluate the Linde PT-8 and Thermal Dynamics U-5T plasma arc welding torches for fabricating rocket motor cases and weight-critical unfired pressure vessels. Welding studies were accomplished utilizing 0.25-in.-thick 6Al-4V titanium and Inconel 718, and 0.063-in.-thick Rene 41.

The PT-8 and U-5T torches were found to require different pilot arc circuits and orifice gas flow ranges. To achieve contract objectives it was necessary to install pilot arc cutout circuitry and a multifunction plasma gas control to provide satisfactory controls and range for both torches.

Single pass flat position square butt welds were made in 0.25-in.-thick 6Al-4V titanium with both torches at welding speeds of 6, 12, and 18 ipm. No single-pass welds were completely free of top bead underfill; a second (or cover) pass was needed to eliminate this. Circumferential keyhole welding procedures were developed at 12 ipm weld speed with the PT-8 torch for both flat and horizontal position square butt welds. Orifice gas downslope rate appeared to exert greatest influence on quality in the keyhole withdrawal area. The U-5T torch exhibited inconsistancy in penetrating force of the plasma arc and was not used extensively for circumferential weld procedure development. Combined mismatch and gaps up to 0.080 and 0.070-in., respectively, were keyhole welded in the flat position without melting holes in the weld. Plasma arc welds were essentially free of porosity within the range of weld joint cleanliness levels evaluated.

Transweld tensile and precrack Charpy properties of plasma arc welds in titanium were satisfactory for the most critical applications. Weld metal oxygen content of plasma arc welds was 25% to 40% less than in parent metal. Miscrostructures were normal in all respects for fusion welds. Hardness in weld fusion and heat-affected zones ranged between R_c 31 and 37 in all welds, after stress-relieving at about 1000°F for 4 hr. Low-cycle fatigue life of these welds may be less than 10% of parent metal at equivalent stress levels.

Keyhole welds in Inconel 718 were produced at 6-ipm weld speed and exhibited transweld strength of 99% of parent metal. A simulated circumferential weld exhibited root bead cracks at the keyhole withdrawal point.

Applications of these plasma torches for sheet metal welding may have limited value because requirements for torch orifice-end access prevent narrow chill bar spacing, which causes excessive weld distortion.

The standard shield gas area coverage of both torches was unsatisfactory for materials covered in this volume. A trailing shield provided suitable shielding and was easily adaptable to both torches. When assembled with care, both torches were free of water leakage, and factory-recommended procedures yielded apparently satisfactory electrode setback and centering adjustments.

The plasma arc welding process produced welds exceptionally free of defects. Weld physical properties were at least equivalent with those reported for GTAW, GMAW, and electron beam processes in 0.25-in.-thick 6Al-4V titanium and Inconel 718. Overall plasma arc weld time is less than one third that required by GTAW or GMAW for equivalent applications on these materials. Plasma arc and electron beam overall weld times were nominally identical, but the quality and properties of plasma arc welds were superior in 0.25-in.-thick 6Al-4V titanium.

Although plasma arc welding requires more equipment components than GTAW or GMAW, it is little more difficult to train operators for this process than for other automatic welding processes.

Conventional GTAW weld tooling can be employed for plasma arc welding if relief is provided on the root bead side to dissipate the plasma flame that protrudes through the keyhole.

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PREFACE

During the last 20 years the gas-tungsten arc welding process (GTAW) has achieved a widely respected position in the aerospace industry because it can consistently produce high-quality fusion welds in a wide variety of materials, and because the equipment used is well understood. Although the GTAW process affords comparatively low welding speeds, it is used almost exclusively for welding rocket motor cases and most weight-critical unfired pressure vessels. As vessel size and wall thickness increase, the GTAW process becomes more time consuming and expensive. Therefore, more economical processes for producing premium quality welds are constantly being sought. Although the gas-metal arc and submerged arc welding processes (GMAW and SAW) offer much greater welding speed potential than the GTAW process, evaluation of these processes on certain high-strength steels has disclosed that weld quality and properties are frequently inferior. The plasma arc and portable chamber electron beam welding processes exhibit somewhat the same potential for reducing overall welding time, but plasma arc weld quality does not depend on the integrity of a partial vacuum and plasma accessory equipment is generally less cumbersome. For this and other reasons, welding applications of the plasma arc have received increasing attention during the last 5 years.

The plasma arc welding process evolved during the development of the high-energy transferred-arc plasma torch for metal cutting operations when it was observed that insufficient plasma stream energy sometimes yielded a weld rather than a cut. It was found that the principal differences between cutting and welding plasma arcs were the magnitudes of the interrelated plasma stream energy factors: mass flow rate of plasma (orifice) gas and arc power density. The plasma arc employed for plate thickness welding requires the plasma (orifice) gas flow to be accurately controlled; flow rates for welding are generally less than 10% of those used for plasma cutting. Arc power density can be adjusted over the entire range between the cutting plasma arc and the unconstricted gas-tungsten arc to obtain virtually any desired welding arc characteristic.

In suitable material thicknesses, certain combinations of plasma gas flow, arc current, and weld travel speed will produce a relatively small weld puddle with a hole penetrating completely through the weld plate at the leading edge of the weld puddle (called the keyhole), an unusual and exclusive characteristic of plasma arc among the gas-shielded welding processes. In a stable keyhole mode weld, molten metal is displaced to the top bead surface by the plasma stream (in penetrating the plate) to form the characteristic keyhole. As the plasma arc torch is mechanically moved along the weld joint, metal melted by the arc is forced to flow around the plasma stream along the molten side surfaces of the keyhole to the rear where the weld puddle forms and solidifies. Thus, the keyhole mechanism forms a relatively narrow and very deep "melt-thru" fusion weld of unusually high quality.

Section I

INTRODUCTION

Plasma arc torches designed specifically for welding have been marketed by two firms for about 5 years: Linde Division of Union Carbide Corporation produces the PT-8 torch, and Thermal Dynamics Corporation produces the U-5T torch. These torches reflect several iteratively developed configuration and design features that vary according to the manufacturer's objectives, and a plasma gas control console is made for each torch to provide for their individual service and process requirements. (These plasma arc welding torches and the process in general are discussed in References 1 through 9.) Previous work in evaluating these torches for practical applications has been largely qualitative; relatively little numerical data concerning the plate thickness welding characteristics of the process and equipment has been developed in the following categories:

a. Repeatability characteristics of available equipment for producing premium quality keyhole mode butt welds in high-strength steel, titanium, and nickel base alloys in the flat and horizontal weld positions.

b. Procedural methods and repeatability for making keyhole mode circumferential welds in the above materials in thicknesses up to 0.62 in., and in particular, the consistency of weld quality in the weld zone where overlap of the keyhole initiation point and keyhole withdrawal occurs.

c. Correlation between plasma arc welding variables and weld properties in certain alloys that may exhibit sensitivity between mechanical properties and weld energy input.

d. Comparisons of the different plasma arc welding torches available for production applications.

The objective of this contract was to contribute data describing the capabilities of the plasma arc welding process for making circumferential welds in rocket motor cases and other weight-critical pressure vessels, and to quantitatively compare the process with other more widely applied welding processes now used for welding high-strength alloys. The materials used for welding the studies for Categories a, b, and c were an 18% Ni maraging steel of 200-ksi minimum yield stress (in thicknesses of 0.25 and 0.62 in.), 180-ksi minimum yield stress 9Ni-4Co-.25C steel (in thicknesses of 0.25 and 0.62 in.), solution treated and aged 6Al-4V titanium alloy (0.25 in. thick) and, to a lesser extent, Inconel Alloy 718 (0.25 in. thick) and Rene' 41 (0.063 in. thick). Category d was evaluated by applying the results of investigations of Categories a, b, and c to produce girth welds in six 24-in.-diameter spherical pressure vessels. Three of these spheres were 0.25-in.-thick 6Al-4V titanium alloy, and three were 0.50-in.-thick 18% Ni 200 grade steel. The welded vessels were inspected using normal nondestructive techniques, heat treated, then hydrostatically tested to failure. Hydrostatic pressure and related strain gage data were recorded for all tests, and acoustical wave emission measurements corresponding to incremental flaw growth were attempted for two burst tests.

This volume extensively discusses methods and results relative to pressure vessel fabrication and burst testing, and Section III includes an updated discussion of the comparable features of the Linde PT-8 and Thermal Dynamics U-5T plasma arc welding torches. It is probably the most relevant discussion of torch performance in this report because it includes the results of some very recent work with the U-5T that is meaningful in terms of performance advertised for this torch.

SECTION II

TECHNICAL DISCUSSION

2.1 GENERAL

The work accomplished during evaluation of the PT-8 and U-5T plasma arc welding torches for welding titanium and nickel alloys is described in this section. The major objective was to determine the capabilities of these torches for producing butt welds of very high quality. The scope of this work comprised extensive evaluation of specific plasma arc welding conditions and equipment requirements, nondestructive testing of welds, and metallurgical evaluation of weld cross sections; further testing of welds in certain materials was accomplished to determine characteristic tensile properties, precrack Charpy impact properties, and low cycle fatigue properties. Weld conditions data were obtained for several different materials during this time. (See Appendix I.)

Two kinds of weldment configuration are important in this work. The simplest configuration is the straight seam butt weld, where the weld can be initiated and terminated on disposable runoff tabs; this eliminates the arc start and stop areas from the weldment proper. The more critical circumferential type of joint (girth weld) must include the weld arc start and stop areas within the weld deposit, and somewhat different procedures are usually required to obtain satisfactory weld quality in these areas. Plasma arc welding has been represented as a significant advance in fusion welding process technology for both of these weldment configurations, particularly for material thicknesses of 0.090 in. and heavier. The work reported emphasized developing welding conditions for making butt welds in a simulated circumferential weldment configuration, because it was necessary to determine the practicability of girth welding spherical pressure vessels. Where applicable, potential for making simulated circumferential welds in the horizontal welding position was evaluated.

2.2 EQUIPMENT DESCRIPTION

2.2.1 Plasma Arc Welding Torches

The plasma arc welding torches utilized for all welding on this program are shown in Figures 1, 2, and 3; Figure 1 provides a useful size comparison. The PT-3 torch was used only very briefly at the start of this program, before the PT-8 became available.

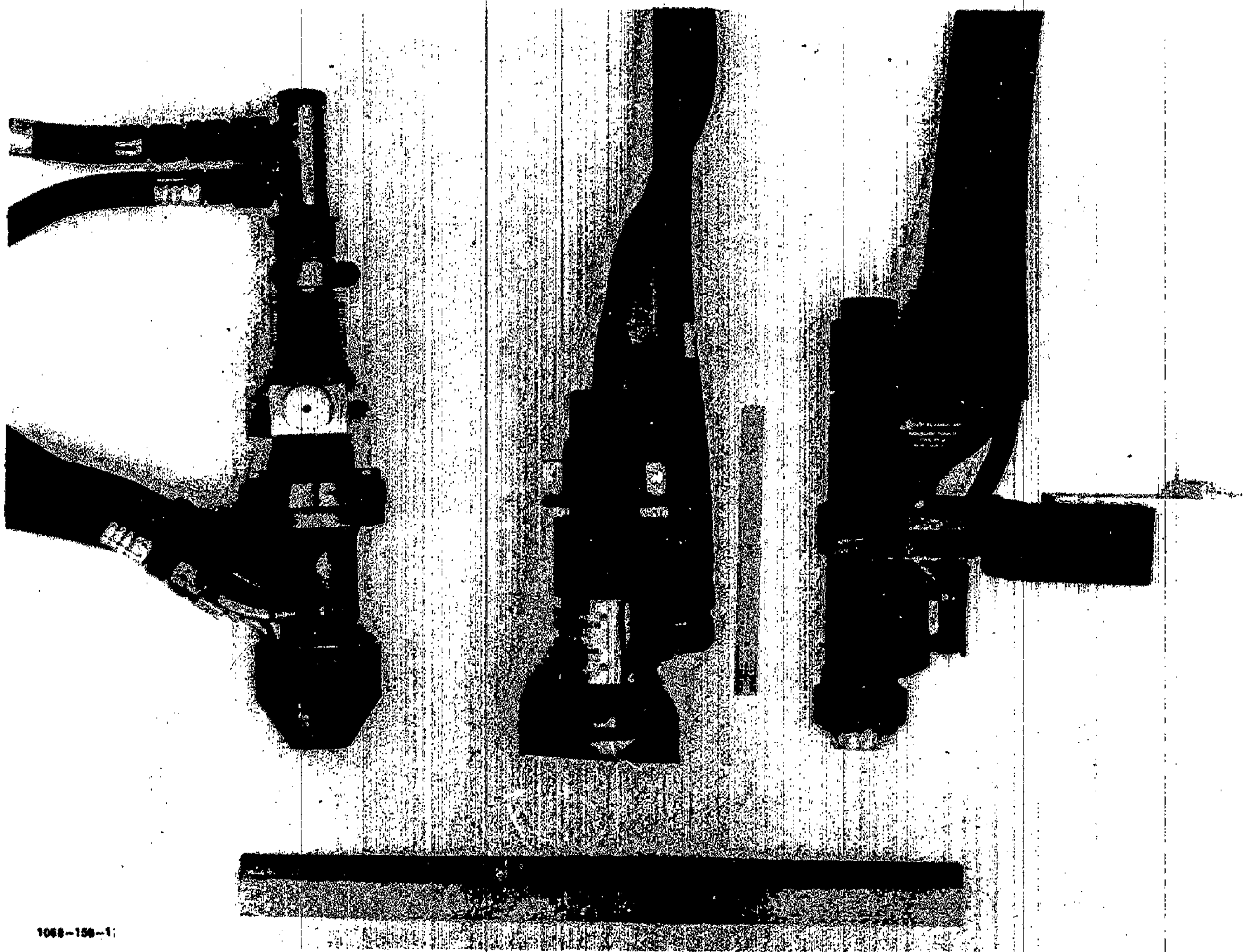
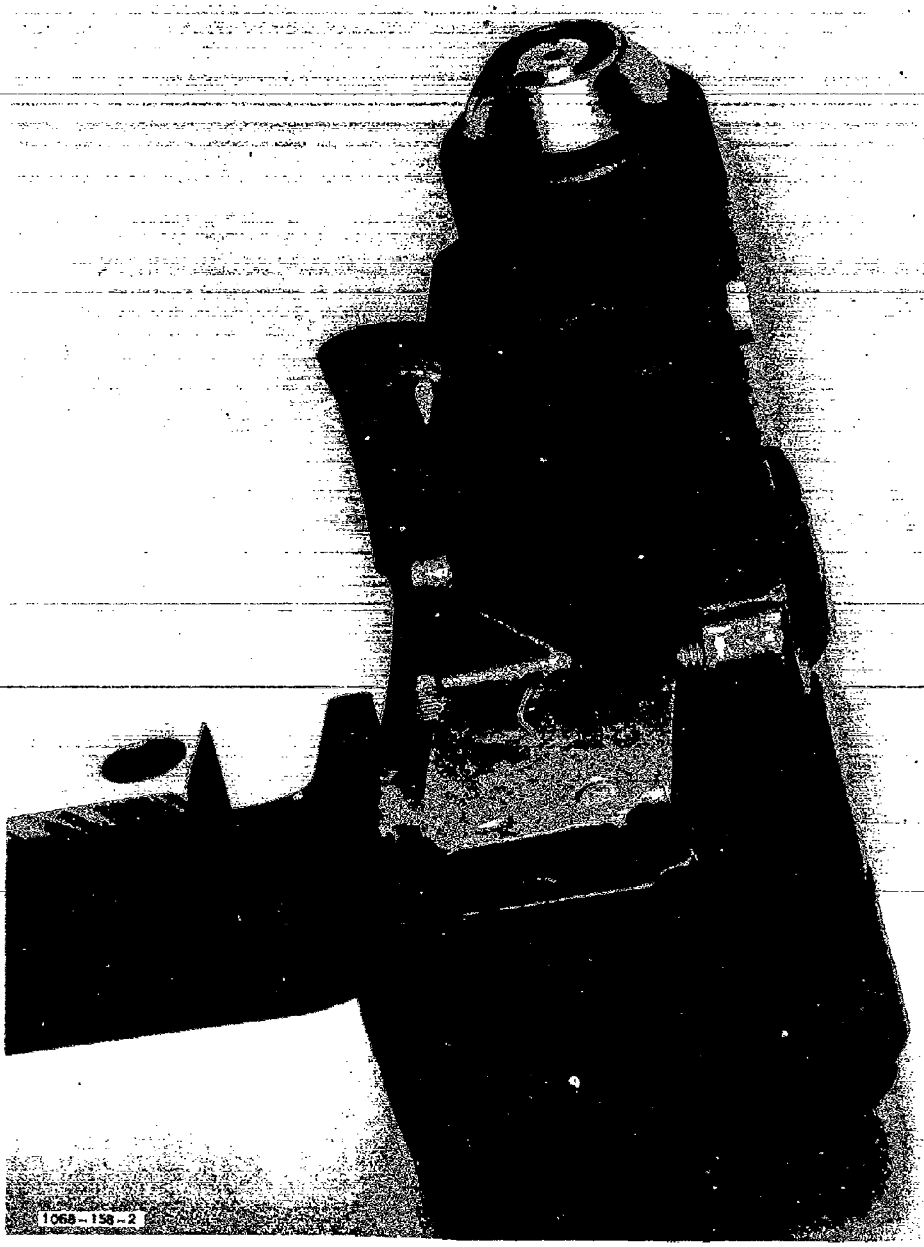


Figure 1. Commercially Marketed Plasma Arc Welding Torches.



A.

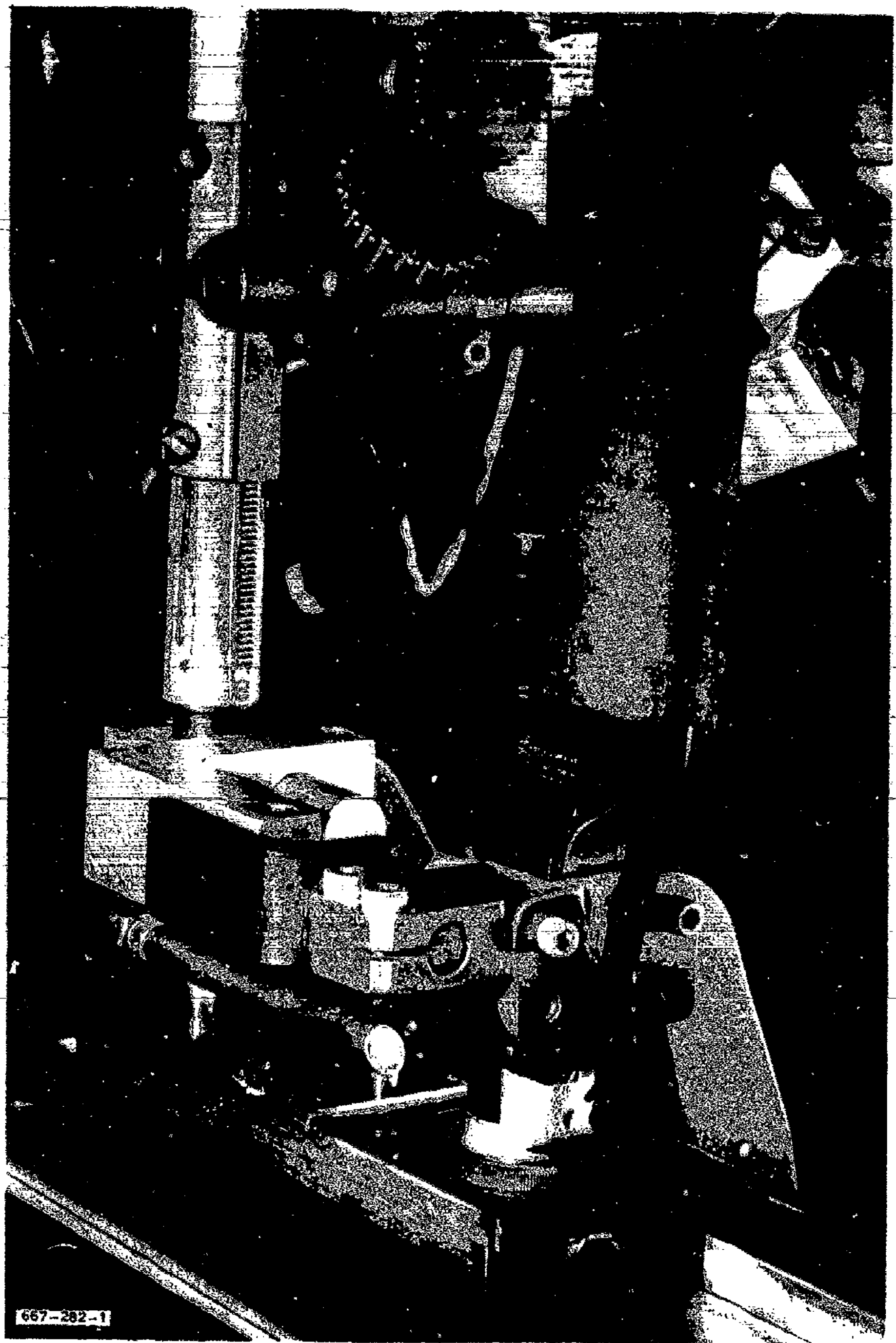


Figure 2. Linde PT-8 Plasma Arc Welding Torch.

B.

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A.

Figure 3. General Features of U-5T Torch.

B.

At the start of the program, one of the authors visited the welding laboratory facilities of both Linde and Thermal Dynamics for briefings on the latest setup and application procedures recommended for the PT-8 and U-5T torches. Two days were spent with each firm; both contributed information and engineering data on torch design, operating principles, and process applications. Linde personnel supplied useful data on welding conditions for several materials and thicknesses.

The PT-8 and U-5T torches, as they appear in Figures 2 and 3, represent the August 1967 state of the art (of the United States) in transferred-arc plasma welding torches made for plate thickness welding. The electrical circuit difference between a transferred and a nontransferred arc torch is illustrated in Figure 4. The nontransferred arc generally delivers larger quantities of heat to the orifice (which is really the anode) than a transferred arc and it has not been developed practically to yield a plasma configuration satisfactory for keyhole mode welding in plate thickness material.

The PT-8 and U-5T plasma torch designs utilize tungsten bodies for the negative electrode element (cathode), and water-cooled copper bodies for the orifice element that forms the plasma stream. Both torches utilize the inner orifice wall as a high-voltage/high-frequency current conductor during the arc starting interval. The plasma arc is started as a low-current discharge between the electrode and the orifice wall, which then changes to the transferred-arc mode as the ionized gas created by the pilot arc is swept (by the orifice gas flow) into the normally nonconductive space between the electrode and work piece. One difference between the two torches is the magnitude of the low-current (pilot arc) discharge used to initiate the plasma arc. The PT-8 pilot arc operates at less than 5 amp; the U-5T operates at about 20 amp. Due to the inherent potential for arc power losses, the U-5T employs a switching setup to deenergize the pilot arc circuit and thereby electrically neutralize the orifice after the plasma arc is established. Although normal operation of the PT-8 does not require that the orifice be electrically neutral, it was simpler for this program to connect the pilot arc circuit as shown in Figure 5. An industrial induction-motor starter relay is employed to open the pilot arc circuit at a preset time after plasma arc ignition. With this arrangement, the time interval of pilot arc circuit continuity for starting the plasma arc from either torch can be optimized. A simple knife switch is employed to connect the plasma arc starting high-frequency generator circuit with the orifice of the torch being used for welding.

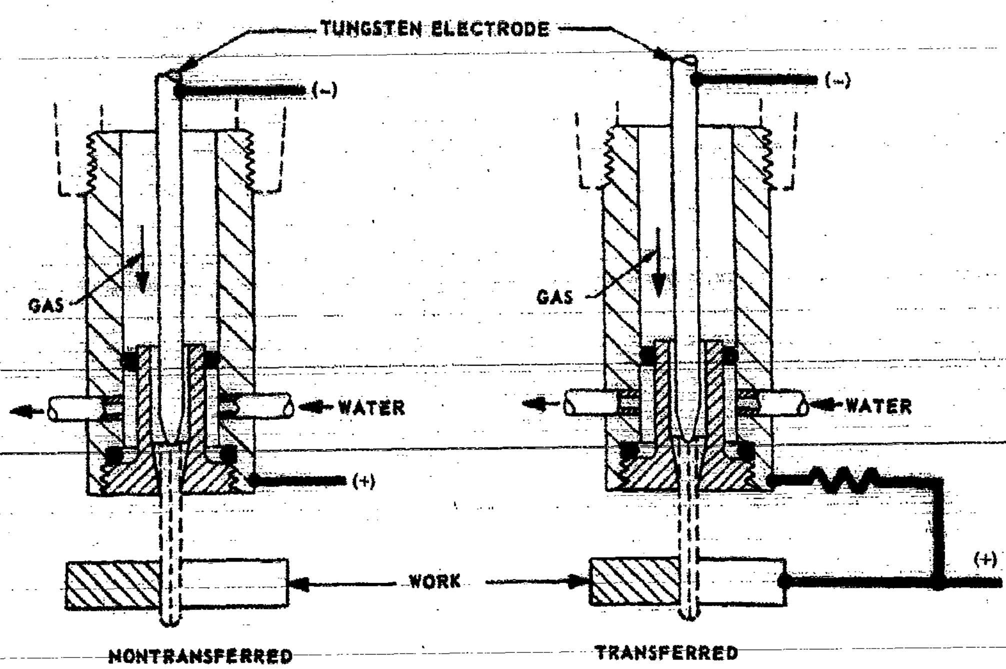


Figure 4. Electrical Connection Differences for Nontransferred and Transferred Arc Torches.

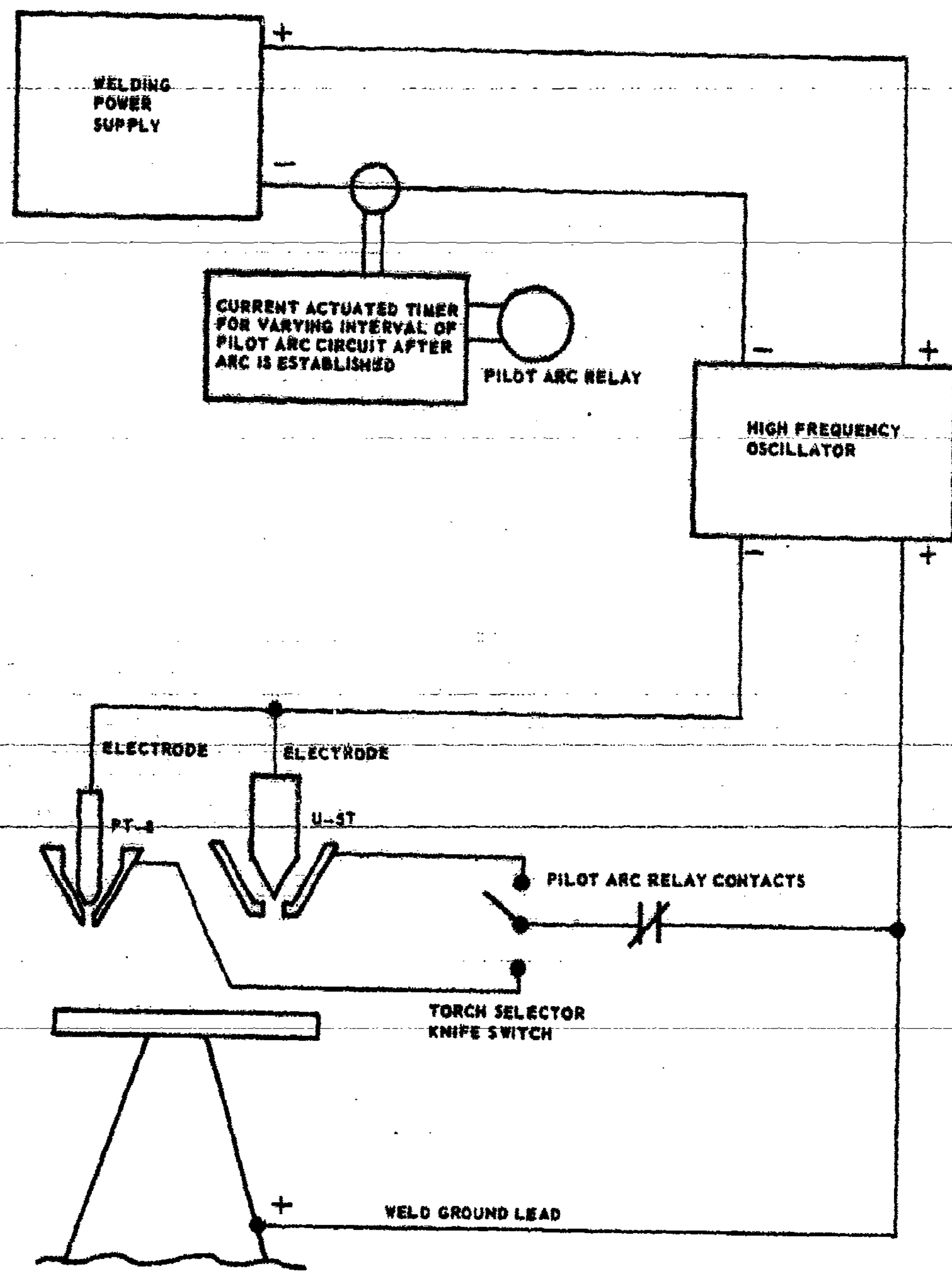


Figure 5. Pilot Arc Circuit Continuity Control Schematic.

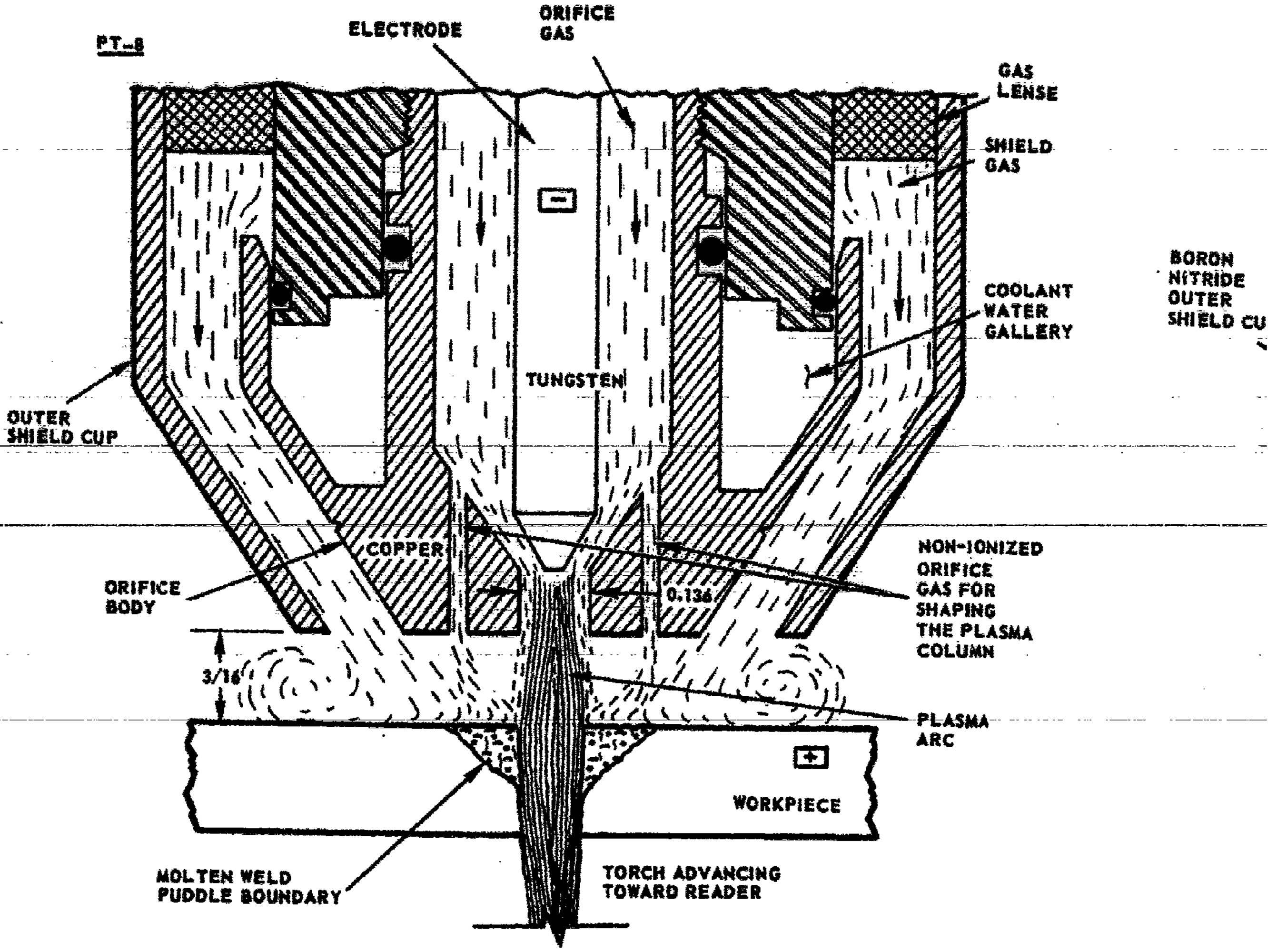
Alignment of the electrode within the plasma-forming orifice is important for consistent plasma arc starting and for symmetry of the velocity profile across the plasma arc. Proper alignment consists of two steps: (1) setting the electrode the correct distance inside the orifice (electrode setback), and (2) centering of the electrode within the orifice.

The PT-8 and U-5T utilize somewhat different component forms to develop and shape the plasma arc. One result of this is a difference in the recommended ranges of plasma (orifice) gas flow. Figure 6 illustrates the significant configuration differences, and the idealized inert gas flow patterns characteristic of each. The minimum and maximum factory-recommended orifice gas flow levels are shown in Table I for each torch, along with other procedural data.

Table I. Orifice Gas Flow Levels.

	CFH	Material	Weld Current (amp)	Weld Speed (ipm)
PT-8 (Linde Process Manual)				
Minimum flow	7.5	70/30 brass 0.080 in. thick	140	21
Maximum flow	27	Titanium, 1.00 in. thick (0.44 Root Land, 60° included angle.	250	5.2
U-5T (Thermal Dynamics U-5T Torch Manual)				
Minimum flow	2	304 stainless steel, 0.125 in. thick	150	15
Maximum flow	4	304 stainless steel, 0.375 in. thick	350	9

No attempt was made to verify these conditions because they did not directly apply for the materials and thicknesses specified in this program.


PT-8
ELECTRODE
ORIFICE
GAS
GAS
LENSE
SHIELD
GAS
BORON
NITRIDE
OUTER
SHIELD CU
COOLANT
WATER
GALLERY
TUNGSTEN
OUTER
SHIELD CUP
COPPER
ORIFICE
BODY
0.136
NON-IONIZED
ORIFICE
GAS FOR
SHAPING
THE PLASMA
COLUMN
3/16
PLASMA
ARC
WORKPIECE
MOLTEN WELD
PUDDLE BOUNDARY
TORCH ADVANCING
TOWARD READER

A.

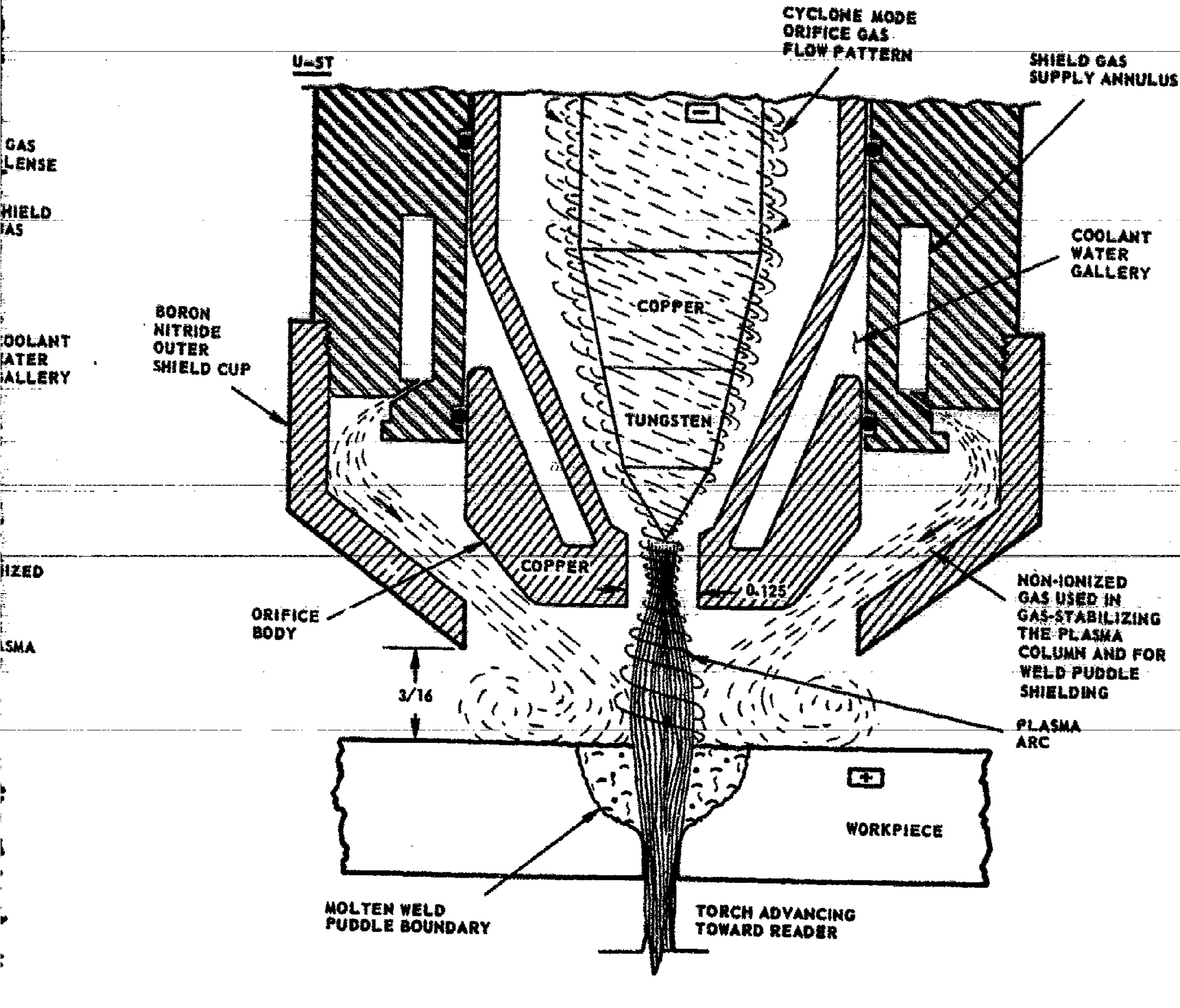


Figure 6. PT-8 and U-5T Torches; Idealized Plasma and Shield Gas Flow Patterns.

B.

2.2.2 Plasma Gas Control System

Early in the program it became apparent that a plasma gas control system capable of producing satisfactory welds with either torch was an urgent necessity, but program funding did not provide for its procurement. Although a built-in plasma gas control was included in the program control power supply used for this work (Linde Missile Maker, SN 17), the system was severely limited in gas mixing capability, and accurate flow control of orifice gas at the very low rates recommended by the manufacturer for the U-5T was not possible. In addition, existing copper tube joints could not be sealed to completely eliminate gas leakage; plasma gas contamination with air, apparently by a boundary layer reverse flow mechanism (Reference 10), was found to be present. Four attempts were made to temporarily modify this built-in system, but none of the modifications performed satisfactorily.

A completely new plasma gas control system was designed and fabricated with components common to the old system. The manufacturer's torch operating parameters and service requirements were used to establish weld sequence timing provisions and inert gas flow range limits. This system was laid up on a large plywood board, as shown in Figure 7. The plumbing and electrical schematics of the gas flow control functions are included as Appendixes II and III.

The system was electrically integrated with the programming module of the weld power supply. The important operating characteristics of this plasma gas system are described below.

2.2.2.1 Gas Flow Functions

A major objective of using this system was to obtain a range of gas flow metering that included the extreme limits of flow recommended for either torch. Accuracy was also important; to ensure that gas flow rates were accurate, the flowmeters to be employed for plasma (orifice) gas metering were subjected to flow calibration by a certified engineering laboratory. Certification sheets were obtained with flow curves for each flowmeter, included as Appendix IV, which indicate that the absolute accuracy of the calibrated flowmeters at any point on the flow curve was within 0.02% of the total flow range. The flow settings data reported in this program are conservatively estimated as being accurate to ± 0.5% of full flow range.

The flowmeters were mounted at eye level in the aluminum frame (shown in Figure 8) mounted on the board (Figure 7). The eye level position was selected to minimize errors in float setting due to parallax. To set flow

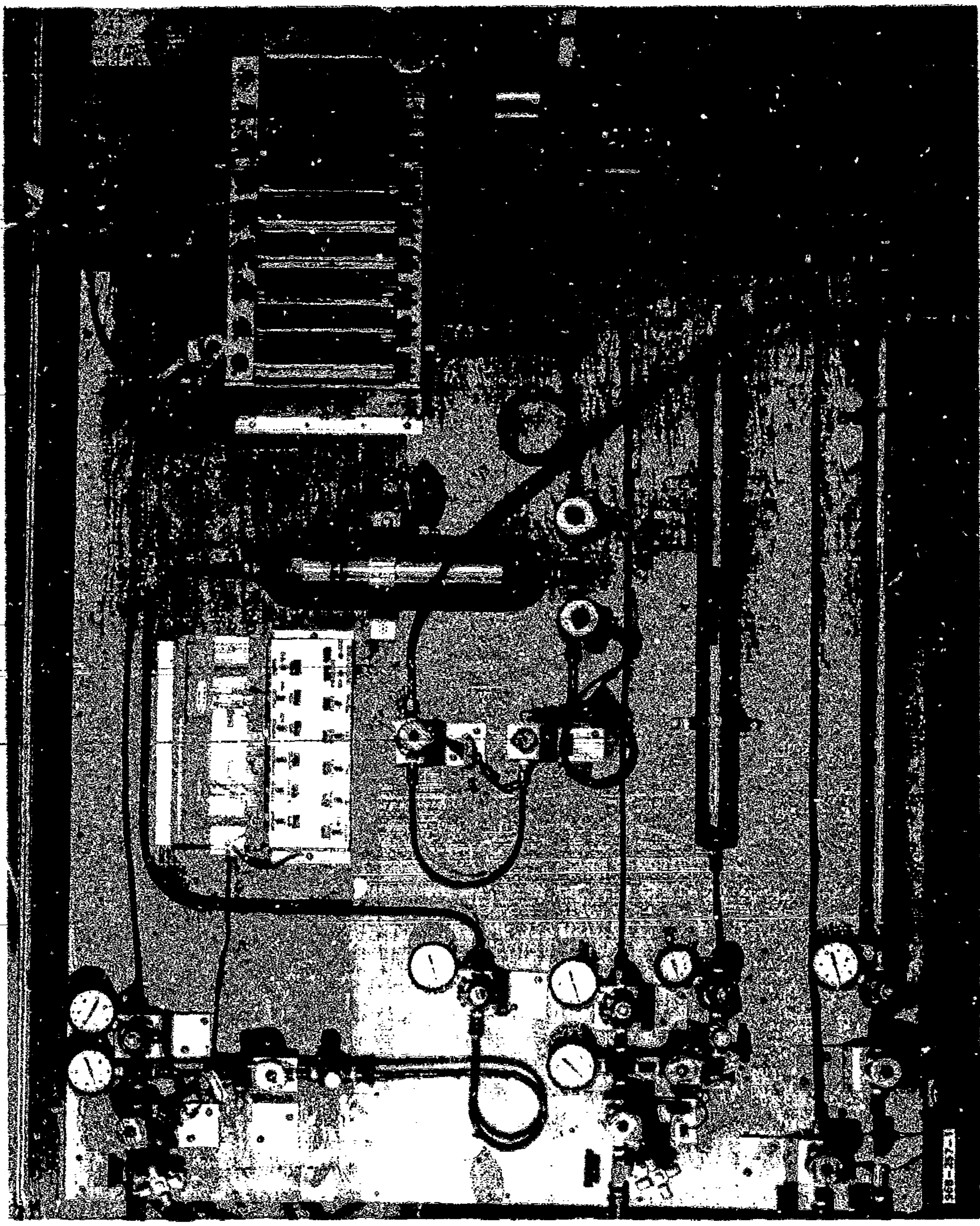


Figure 7. Component Setup on Multifunction Plasma Gas Control Panel.

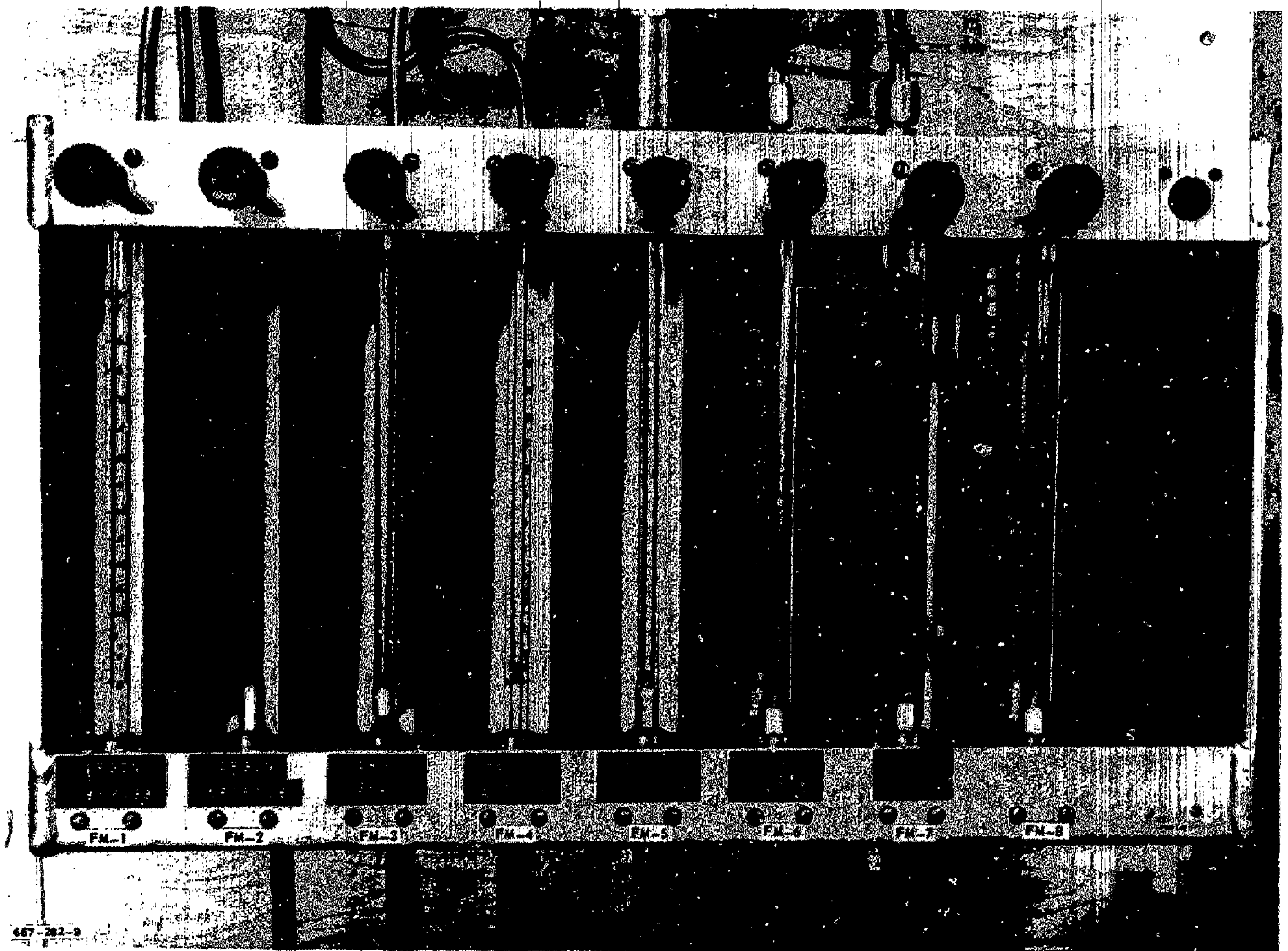


Figure 8. High Accuracy Inert Gas Flowmeters on Plasma Gas Control Panel.

rate, the top of the spherical float was aligned with the desired graduation on the tube. The gas flow ranges obtainable with this arrangement were as follows:

Argon orifice gas

Bypass gas flow -- 0.46 to 7.39 cfh (FM-1).

Keyhole gas flow -- 0.46 to 45.32 cfh (FM-1, -2, and -3).

Argon shield gas flow -- 0 to 160 cfh (FM-6).

Helium orifice gas

Bypass gas flow -- 0.28 to 4.90 cfh (FM-4).

Keyhole gas flow -- 0.28 to 22.96 cfh (FM-4 and -5).

Helium shield gas flow -- 0 to 230 cfh (FM-7).

Hydrogen orifice gas

Bypass gas flow -- 0.16 to 2.71 cfh (FM-4).

Keyhole gas flow -- 0.16 to 17.13 cfh (FM-4 and -5).

Micrometer thimble needle valves were used to allow stepless adjustment of orifice gas upslope and downslope intervals. These units provided the following ranges of interval control, within the indicated repeatability tolerance:

a. Upslope of orifice gas from bypass to keyhole flow level, 2.0 to 97.0 sec; repeatability accurate to ± 0.5 sec (by stopwatch).

b. Downslope of orifice gas from keyhole to bypass flow level, 5.0 to 150 sec; repeatability accurate to ± 0.5 sec (by stopwatch).

Figure 9 illustrates a characteristic gas flow downslope curve for this system. The linearity in gas flow decay with time is retained over a wide range of downslope intervals.

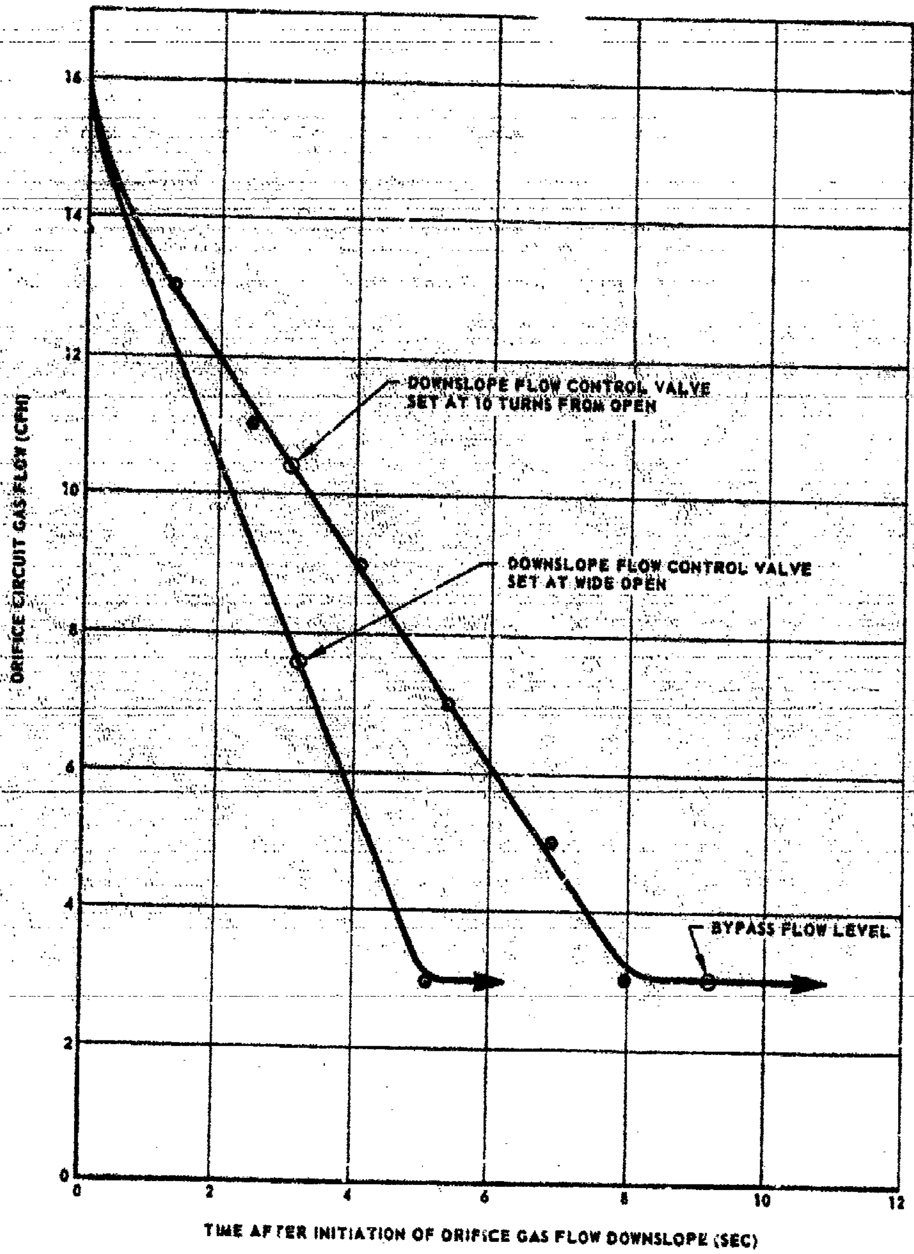


Figure 9. Characteristic Orifice Gas Flow Downslope Curve, New Plasma Gas System.

2.2.2.2 Orifice Gas Flow Slope Timing

The start of orifice gas upslope could be delayed by a timer for periods up to 30 sec after the arc had been started. The downslope of orifice gas started immediately when the automated weld stop cycle was initiated; the downslope of weld current, travel speed, and wire feed speed could be delayed by timers for periods up to 30 sec after the automated weld stop cycle had been initiated. These functions sloped together because their generators were connected to the same rate control. Wire feed and weld travel could be stopped automatically by timers before the arc was extinguished to allow gradual reduction of puddle size by current downslope to control weld crater cracking(for simulated circumferential welds). These functions were repeatable within $\pm$ 0.5 sec.

2.2.2.3 Gas Mixing Functions

Gas mixing could be accomplished by making appropriate changes in the solenoid sequence switches; these switches (14) are mounted on a panel in the upper left center of the board of Figure 7. Gas flow control was arranged so that the orifice and shield gas circuits were purged at abnormally high flow rates with pure argon prior to arc ignition, and the arc was always started in pure argon gas; mixing could be delayed by a timer for intervals of up to 30 sec after the arc was started. Mixing gradually proceeded to desired proportions according to a slope-up rate preset by needle valves in both orifice and shield gas circuits; it was found to be helpful to slope up helium or hydrogen gas in both the orifice and shield gas circuits, because sudden mixing (by a solenoid valve) was accompanied by a gas flow surge which sometimes extinguished the plasma arc. Using this system, either hydrogen or helium could be mixed with argon. The gas mixture proportions obtainable depended to some extent on the total orifice gas flow desired; however, it was possible to obtain accurate mixtures of up to 90% helium -- 10% argon at total orifice gas flow rates as low as 4.6 cfh. In using mixtures of hydrogen with argon, the 1% to 11% hydrogen range for orifice gas composition had been suggested for nickel base alloys (Reference 6); with this system, hydrogen could be mixed with argon at a minimum hydrogen content of 4%, at a total orifice gas flow rate as low as 0.48 cfh.

2.2.3 Weld Program Control Power Supply

The welding power supply employed for this program is illustrated in Figure 10 (Linde Missile Maker, SN17). It is basically a constant-current power source and is capable of producing a maximum current of 275 amp

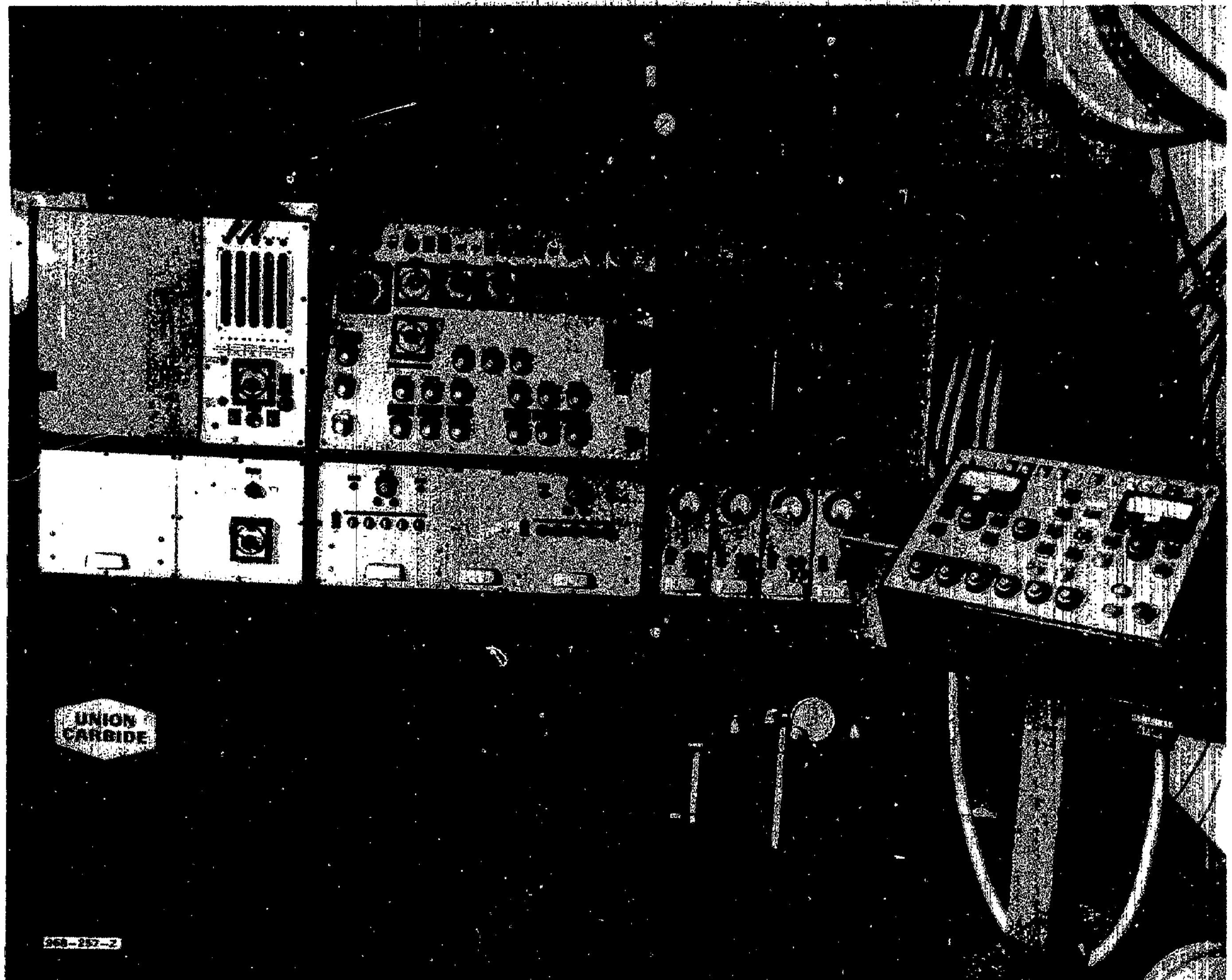


Figure 10. Front Panel and Pendant Control Panel, Linde Missile Maker No. 17.

at about 37 arc volts. Higher currents were available with lower load voltages at a maximum power output of about 10 kw. Maximum current was limited on this power supply because the power transformer was altered prior to this contract to provide better regulation at very low weld currents for GTAW welding. The maximum open circuit voltage available for arc starting was 62 vdc regardless of start current setting. Figure 11 illustrates the correlation between the weld current control potentiometer setting and output current for this machine; the data for this plot were obtained using the U-5T torch. The current control automatically maintains weld current at a preset level within $\pm$ 3 amp.

This machine is capable of automatically reproducing weld programs with satisfactory accuracy. The weld program for any welding task is necessarily divided into four basic intervals by the programming module arrangement: preflow interval, hot start interval, weld interval, and crater fill interval. The new plasma gas control system is electrically integrated with the program control module so that all essential plasma arc welding functions are coordinated and repeatable. (Appendix V illustrates the programmed sequence of events in a standard keyhole mode plasma arc weld, produced with this machine.)

2.2.4 Trailing Shield Considerations

The PT-8 and U-5T torches produced a keyhole mode weld without augmented inert gas shielding of the weld puddle area, but oxidation of the weld area was generally severe when using only the shielding gas coverage provided by the standard torch components. Early in the program, a suitable trailing shield for titanium welds was developed (Figure 12); it was dragged along the surface of the work by the torch, which contacted the shield only at points on the transparent electrical insulator. The transparent insulator was employed because it was necessary to observe the weld in progress, and because it was vital for arc starting to electrically isolate the torch from the shield. It developed that the minimum space between the torch and the shield should be 3/8 in., to prevent undesirable arcing to the shield during plasma arc starting. The Pyrex glass insulator material performed satisfactorily when handled with care. This shield purged to an inert gas purity satisfactory for keeping titanium welds bright silver, in 1 min at 200 cfh argon flow. It was satisfactory for welding 1/4-in.-thick titanium at speeds up to 14 ipm; some discoloration developed on welds in this material at a travel speed of 18 ipm. This shield was about 11-1/2 in. long.

Figures 13 and 14 illustrate unsuccessful trailing shield configurations. The Figure 13 configuration shielded effectively but the insulator fused where plasma backstreaming from the keyhole impinged; this caused early failure of the insulator. The Figure 14 configuration did not provide consistent shielding.

2.2.5 Weld Fixture Considerations

The weld fixture employed for all straight seam welds on this contract is shown in cross section in Figure 15. This fixture purged to satisfactory inert gas purity in 1 min at 100 cfh argon flow. The steel bars that formed the sides of the backup groove could be adjusted to provide different groove widths to vary tool heat absorption effects. The copper backing plate effectively prevented the floor of the groove from being eroded by the plasma flame protruding through the keyhole. Properly adjusted plasma flame impinged directly on the copper plate; however, no measurements were made to determine whether an effective parallel current path existed with this arrangement. Figures 16 and 17 illustrate this fixture setup for flat and horizontal position welds.

2.3 WELDING INVESTIGATIONS AND RESULTS

2.3.1 Titanium 6Al-4V Plate, Nominally 0.25 in. Thick

2.3.1.1 Initial Keyhole Mode Weld Procedure Development

Initial welding comprised examining welding conditions for flat position single pass keyhole mode welds with both torches, primarily to determine the compatibility problems between the new torches (PT-8 and U-5T) and the Aerojet welding equipment and tooling. It was found that 65 psi was not enough coolant inlet pressure for the U-5T torch, but a 125-psi Thermal Dynamics pump satisfactorily solved this problem. Unsatisfactory low-range orifice gas flow control indicated a need for an improved plasma gas system; however, a temporary setup incorporating a flowmeter recommended by Thermal Dynamics was used to make a number of welds. Development of an efficient trailing shield compatible with both torches was initiated. This and later work on Inconel 718 showed conclusively that, to be positively effective in excluding air from the top bead surface of the weld, the shield must enclose the torch end in the manner of the shroud-type shield illustrated in Figure 12.

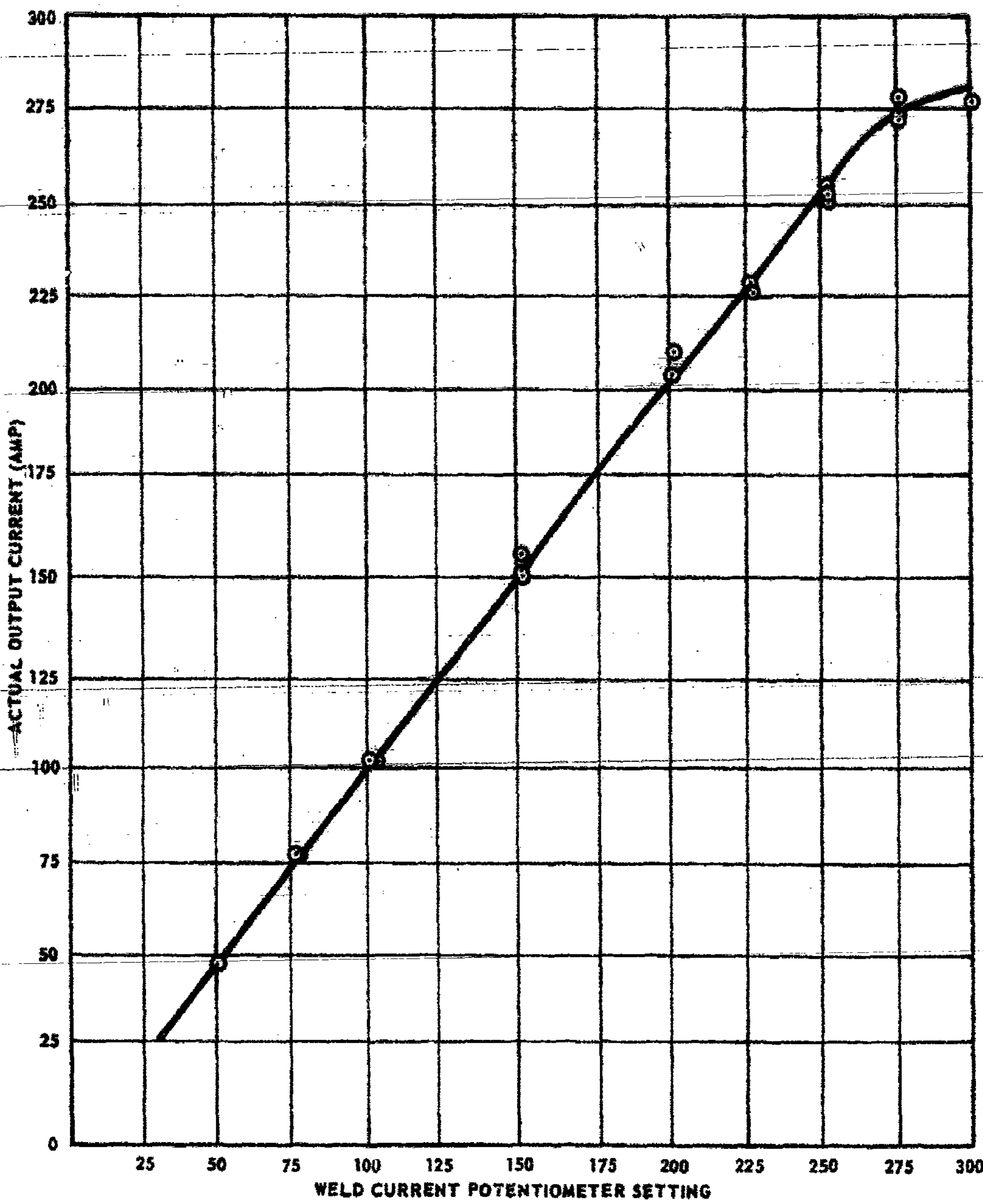
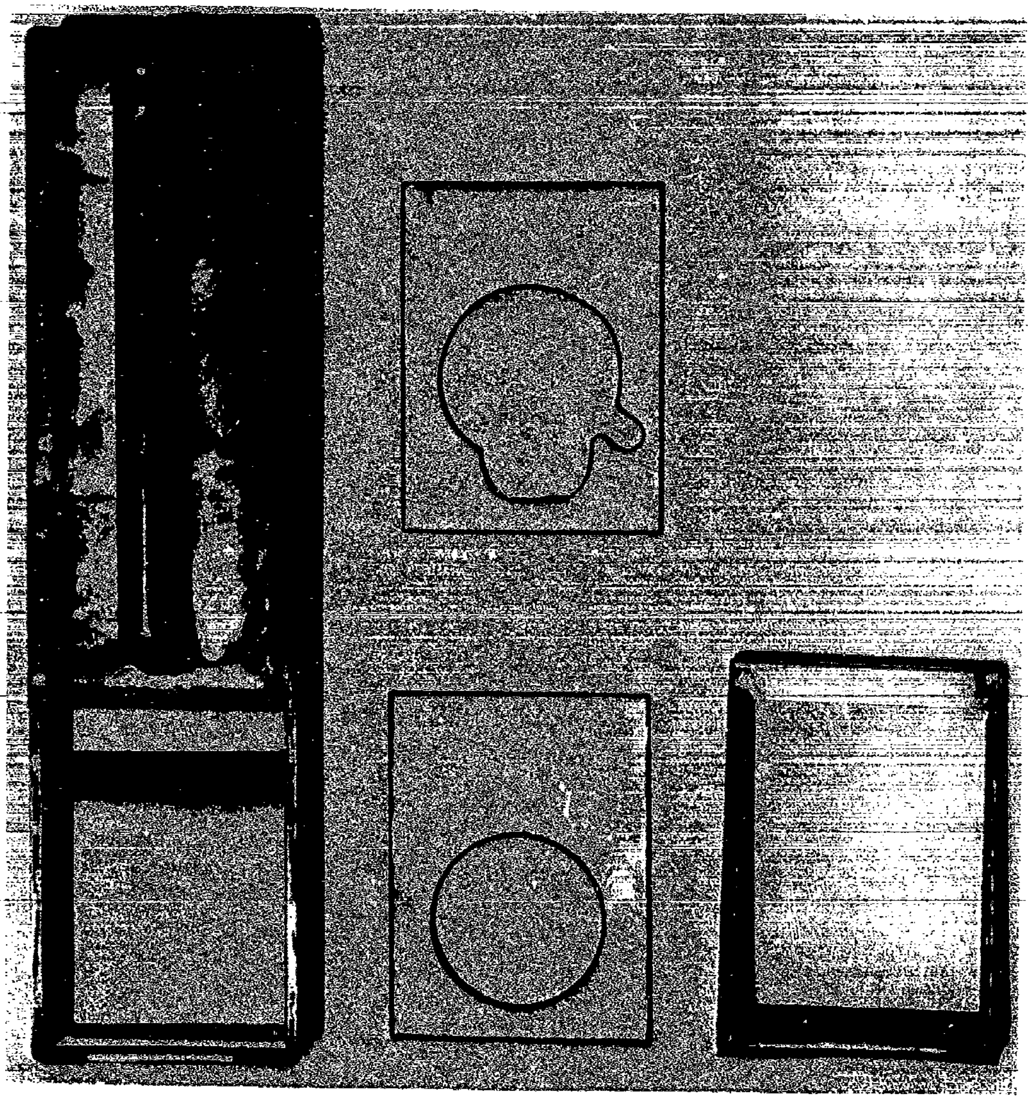


Figure 11. Output Current Range and Regulation, Linde Missile Maker No. 17.



0.55X

TOP VIEW

A.

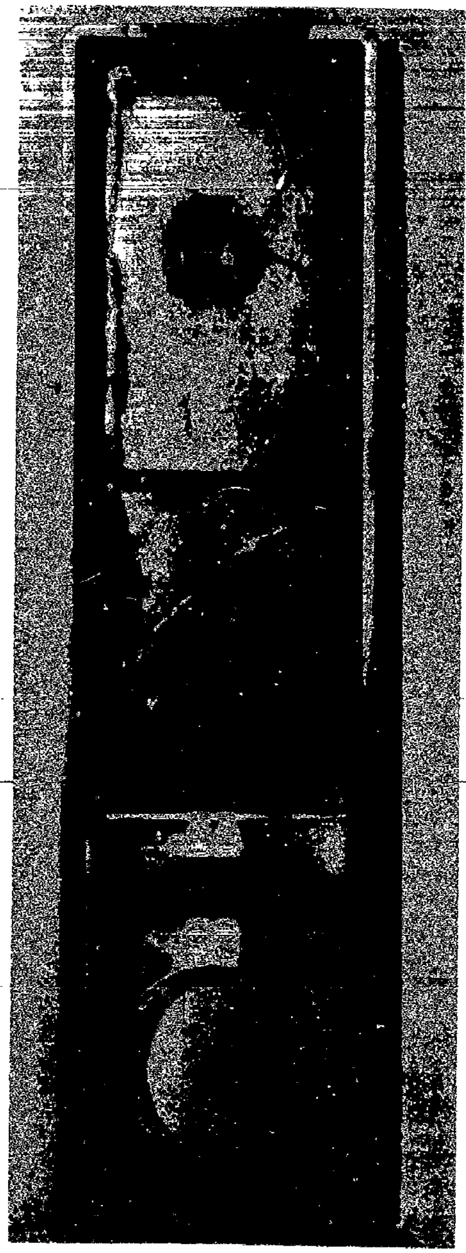
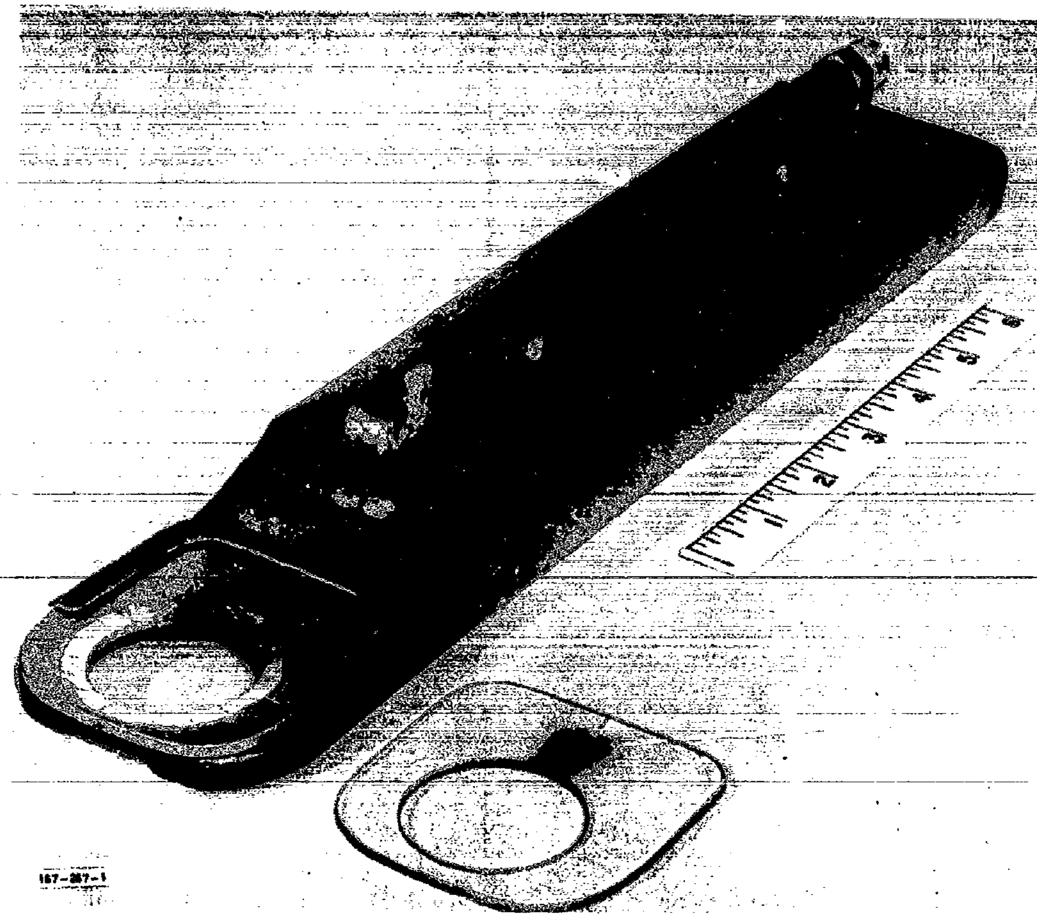


Figure 12. Shroud-Type Trailing Shield Configuration of Proven Performance, Showing Pyrex Glass Torch-To-Shield Insulator.

B.



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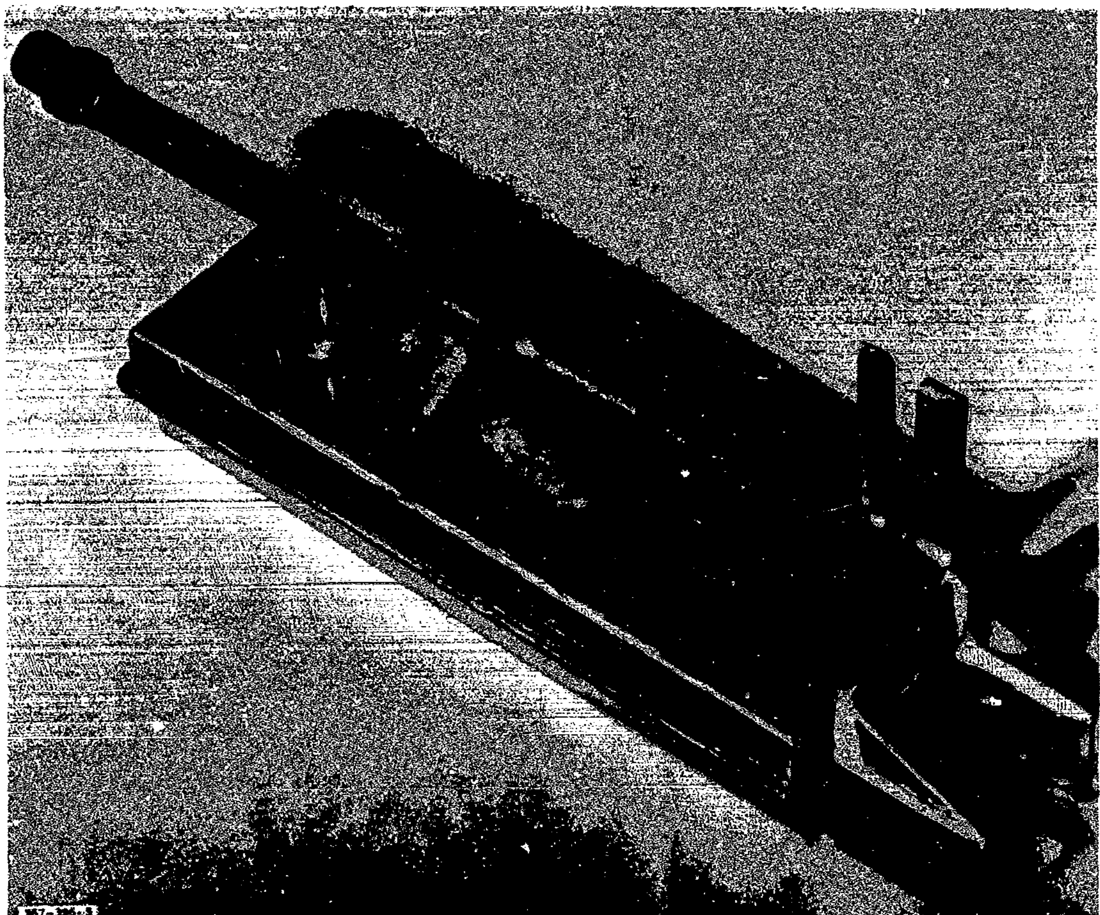
TOP VIEW

167-276-1

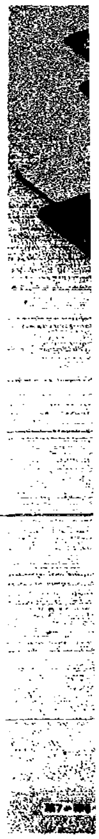
A.

BOTTOM VIEW

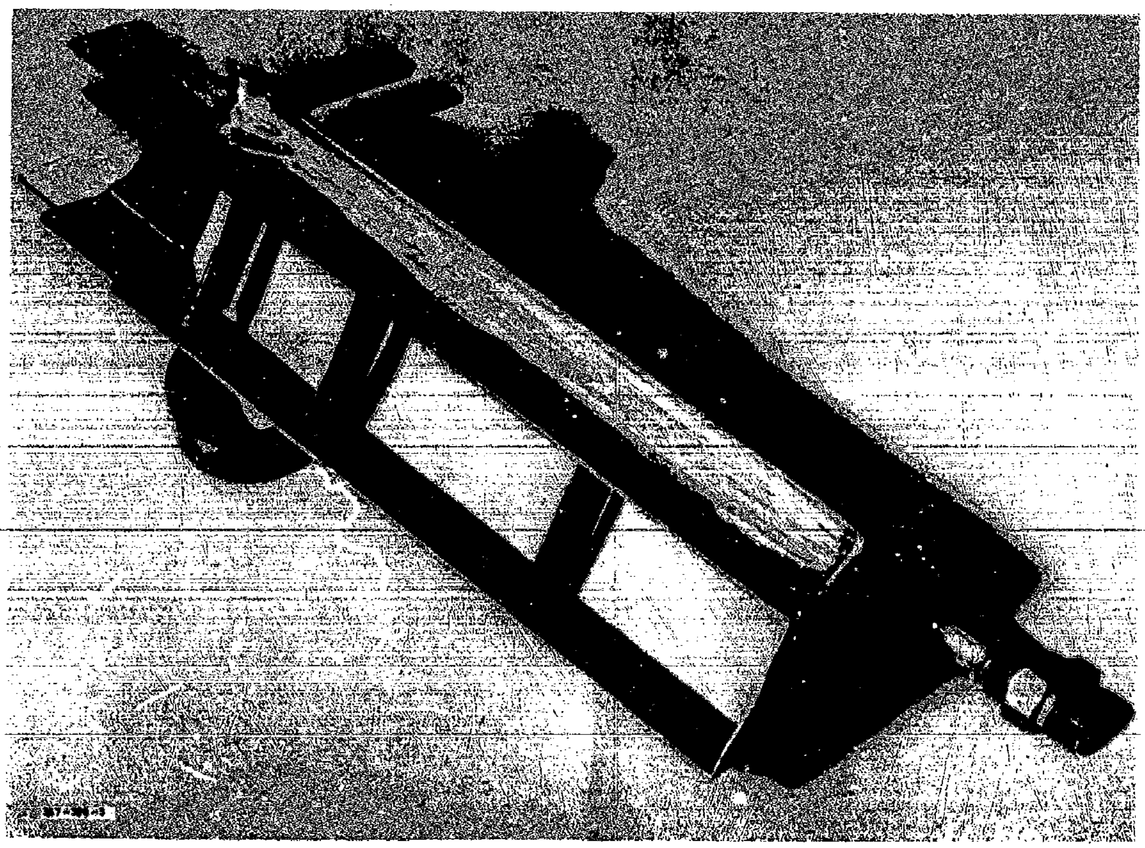
Figure 13. Unsatisfactory Trailing Shield Configuration.



TOP VIEW



A1



BOTTOM VIEW

Figure 14. Unsatisfactory Trailing Shield Configuration.

B. 29, 30

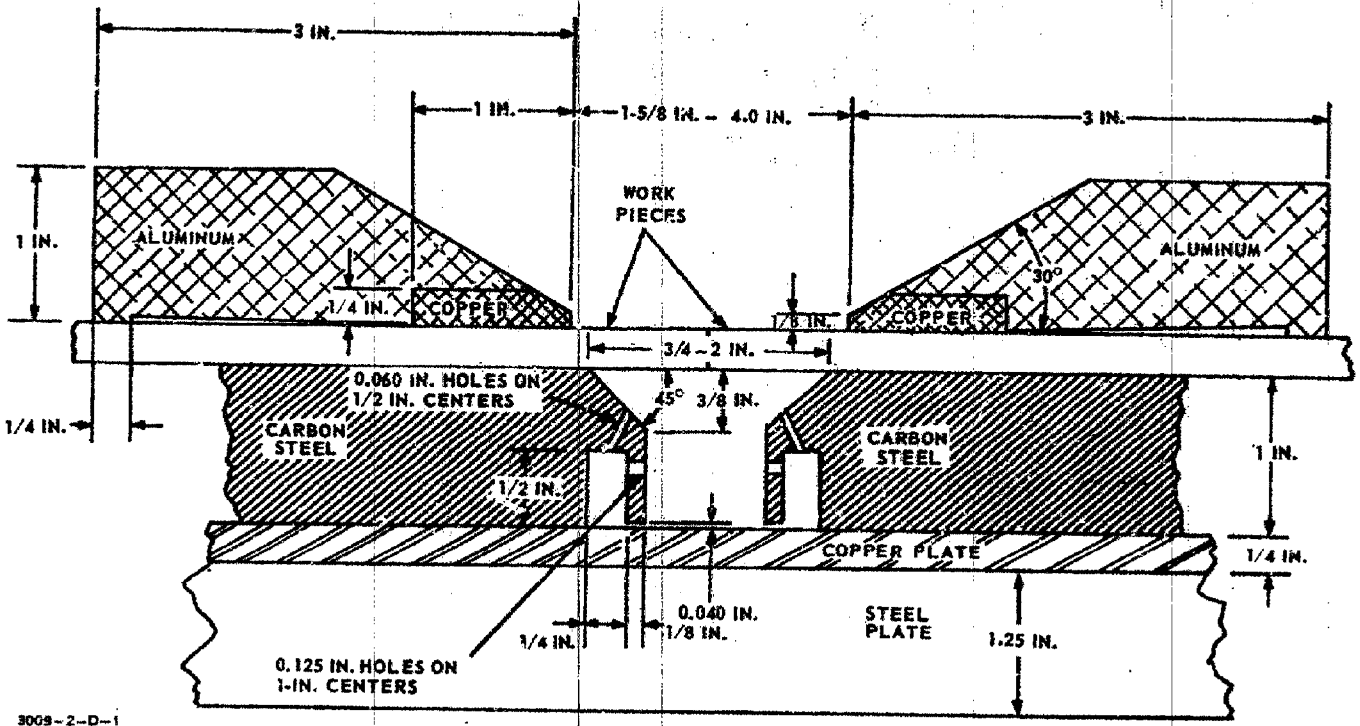


Figure 15. Section View Showing Weld Fixture Configuration and Materials of Construction.

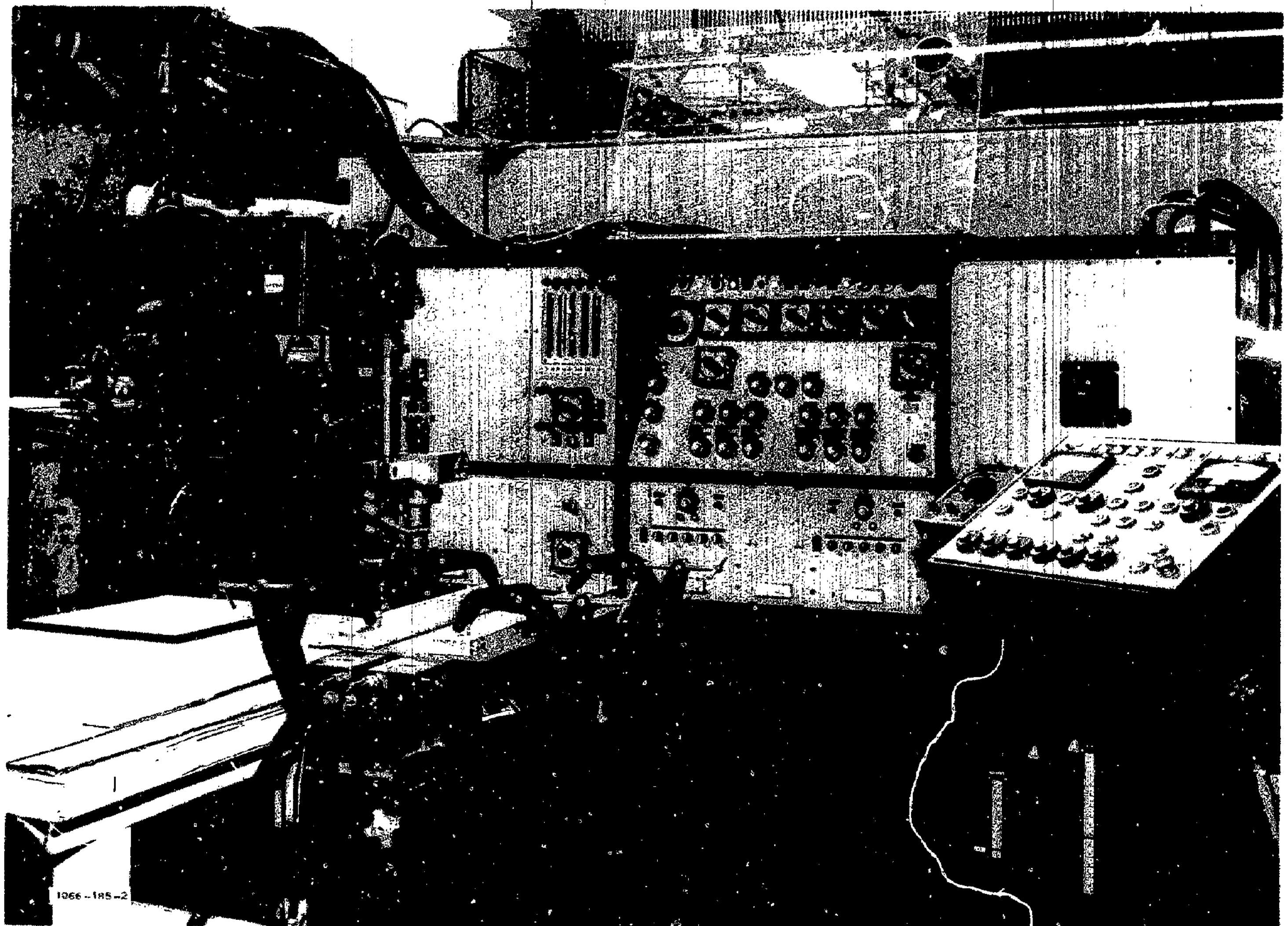


Figure 16. Tool Setup for Flat Position Welding.

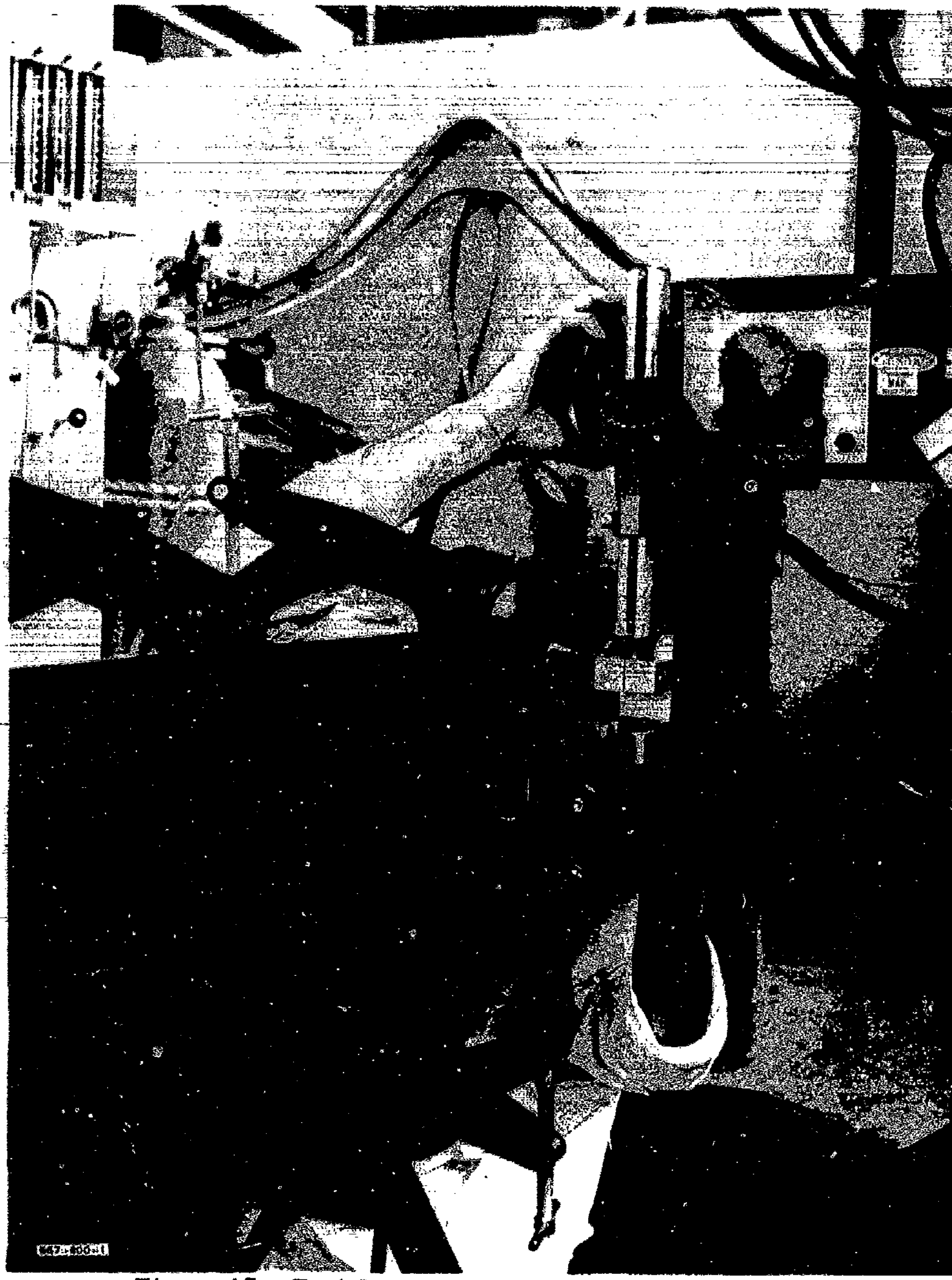


Figure 17. Tool Setup for Horizontal Position Welding.

After solutions for torch compatibility and shielding problems had been initiated, emphasis was placed on evaluating welding procedures for single pass keyhole mode welds without the addition of cold filler wire, utilizing the existing equipment. Comparable weld conditions for the two torches were not found in the manufacturer's literature. Therefore, limited exploratory welding was performed to determine starting point conditions. Weld travel speed was maintained at 6 ipm initially and orifice (plasma) gas flow and arc current were adjusted as necessary to establish reasonably stable keyhole welding conditions. Welding was performed on titanium plate cleaned in 3% HF/40% HNO_3 solution, then wiped with alcohol just before welding; welds were keyholed into plate without a machined butt joint. The more important results of this first work are illustrated in Figures 18 through 22.

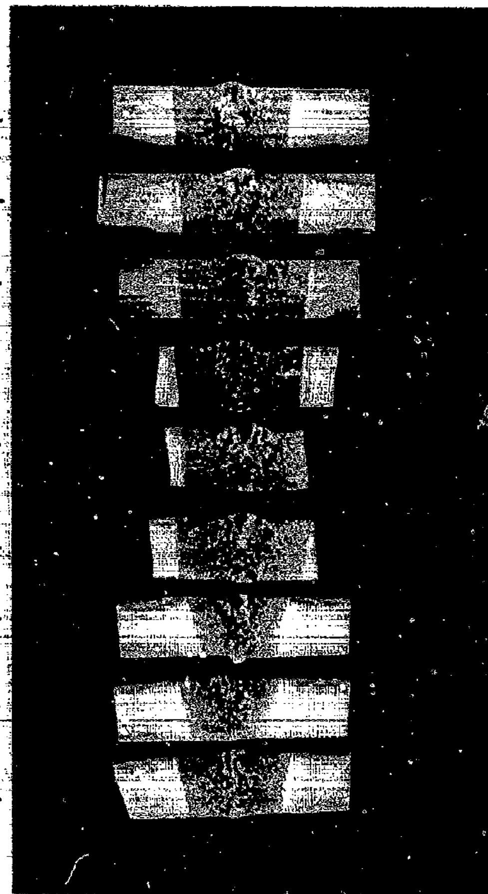
The effects of variations in torch-to-work distance (standoff) using both torches at a common travel speed of 6 ipm are shown in Figure 18. Standoff variations in the range from 1/8 to 1/4 in. did not seriously alter the quality or configuration of weld top or root bead surfaces, although no single pass keyhole mode welds were made in 0.25-in.-thick plate that were completely free of top bead underfill. The principal effect of standoff increases (in this range) was to diminish the keyholing force of the plasma arc. Heat-affected zone width was reduced as standoff was reduced from 1/4 to 1/8 in., without significant change in fusion zone size.

Pure argon is compared with a helium-argon mixture as the orifice gas in Figure 19. Use of helium-argon mixtures for orifice gas produced a more diffuse, less penetrating plasma arc and somewhat wider fusion and heat-affected zones than pure argon at 6 ipm travel speed.

Effects of limited variations in travel speed are shown in Figure 20. Increases in travel speed required corresponding arc current increases, resulting in reduced fusion and heat-affected zone widths.

In efforts to develop an effective trailing shield, some 0.125-in.-thick material was welded to minimize the consumption of more expensive 0.25-in.-thick plate. The welds illustrated in Figure 21 were produced using the PT-8 torch; this illustrates that severity of top bead underfill moderately increases with material thickness in keyhole mode welds.

The production of satisfactory keyhole mode welds in square butt joints requires that the keyhole be centered in the butt joint to melt both plate edges, with some tolerance for error in tracking alignment of the keyhole



3009-2-E-1

Figure 18. Effects of Torch Standoff Distance on Plasma Arc Welds in 0.260-in.-Thick Mill-Annealed Titanium 6Al-4V Plate, Single Pass Flat Position Welds, No Filler Wire Addition, as Welded.

PT-8 TORCH

3009-2-Q-1

Figure 19. Single Pass Flat Position Plasma Arc Welds in 0.250-in.-Thick Mill-Annealed Titanium 6Al-4V Plate, No Filler Wire Added, as-Welded, Showing Effects of 2 Different Orifice Gases on Weld Fusion Zones and Heat-Affected Zones.

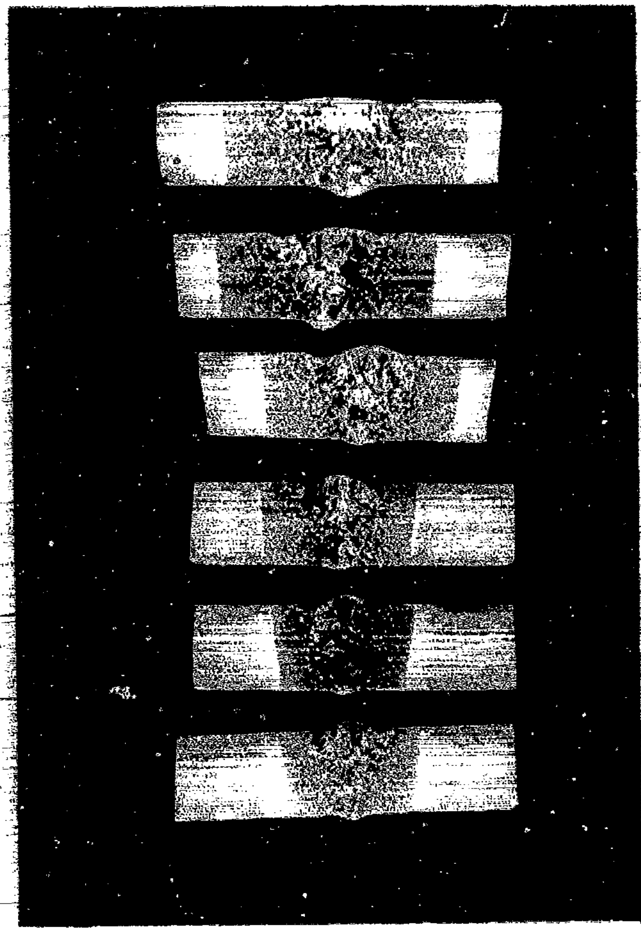
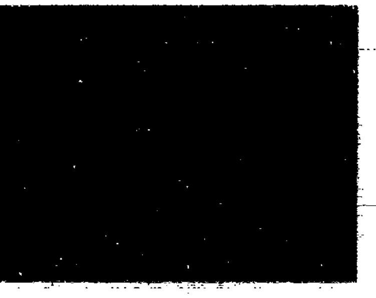


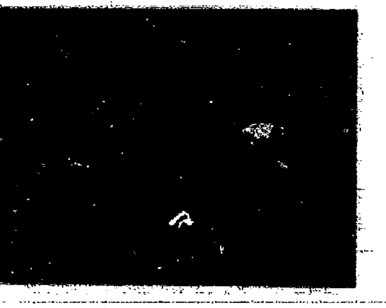
Figure 20. Effects of Weld Travel Speed on Plasma Arc Welds in 0.250-in.-Thick Mill-Annealed Titanium 6Al-4V Plate, Single Pass Flat Position Welds, No Filler Wire Addition, as-Welded.

3009-2-0-1

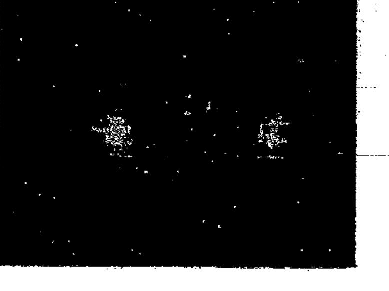
0.125 IN. THICK
6AL–4V TITANIUM,
SQUARE BUTT JOINT,
SINGLE PASS WELD



0.187 IN. THICK
6AL–4V TITANIUM,
SQUARE BUTT JOINT,
SINGLE PASS WELD
(SIMULATED
MINUTEMAN
MOTOR CASE
WELD)



0.250 IN. THICK
6AL–4V TITANIUM,
SQUARE BUTT JOINT,
SINGLE PASS WELD



1568–191–11

Figure 21. Flat Position Keyhole Mode Plasma Arc Welds in Various Thicknesses of 6Al-4V Titanium, illustrating Weld Root Bead and Crown Configuration.

U-5T TORCH

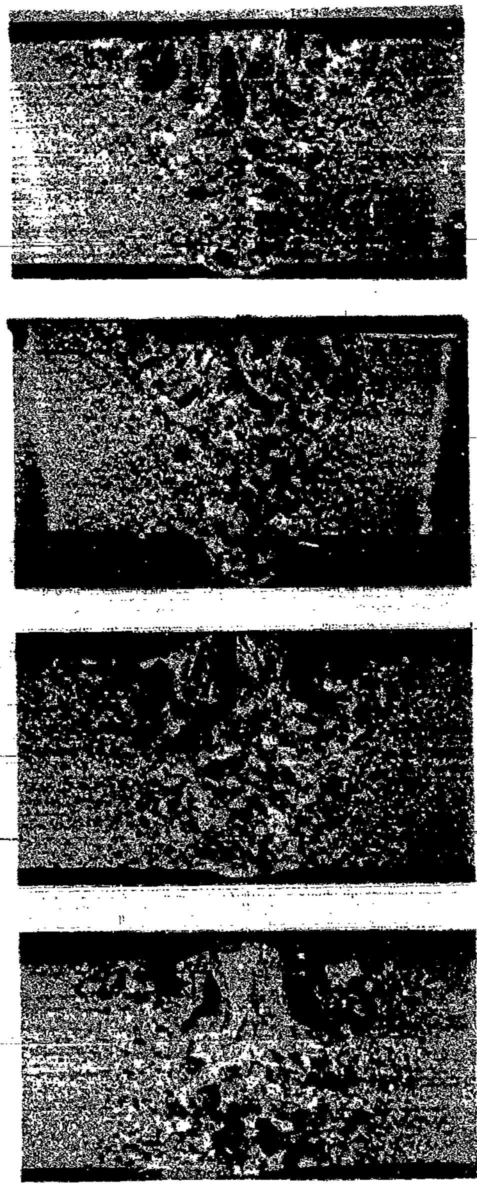
T2A1-1, 1/16 IN. ORIFICE

T2A1-2, 3/32 IN. ORIFICE

T1A1-13, 1/8 IN ORIFICE

PT-8 TORCH

T2A1-3, 136-M ORIFICE



8X HNO$_3$/HF ETCH

3009-2-AM Figure 22. Single Pass Flat Position Plasma Arc Welds in 0.250-in.-Thick Mill-Annealed Titanium 6Al-4V Plate Made with Different Torch Orifices, No Filler Wire Added, as-Welded.

on the joint line. The PT-8, using the 136-M orifice insert, produced a weld with a minimum fusion zone (root bead) width of about 1/8 in. in this material, which was satisfactory if the joint tracking alignment of the torch was maintained. Although narrower weld fusion and heat-affected zones were obtained using the U-5T with 1/16- and 3/32-in. orifice tips, the minimum fusion zone width yielded by these orifices was also narrower; this reduced the tracking alignment tolerance. Figure 22 illustrates welds made at 6 ipm for comparing minimum fusion zone (root bead) widths. The U-5T torch could produce a root bead over 0.10-in. wide when the 1/8-in. orifice tip was used, but the resulting weld top bead and heat-affected zones were slightly wider than comparable areas in welds made with the PT-8 at the same weld speed.

The keyhole initiation, overlap, and withdrawal areas were initially considered as separate elements of the weld. Efforts were concentrated on evaluating various methods for starting the keyhole to determine where emphasis should later be placed. A critical review of keyhole initiation techniques for circumferential plasma arc welds was not found. Therefore, to clarify an area of uncertainty, first efforts were concentrated on simultaneously starting the arc and the keyhole from a dead stop. It was not possible to produce a keyhole from a standing start without exceeding the 20% maximum weld width variation specified in Appendix VI. It was also demonstrated that, for overlap welds, the keyhole can exhibit inconsistency in penetrating the thickened weld path area that frequently results from weld metal displacement at the point to keyhole initiation. Use of a drilled hole to start the keyhole did not effectively reduce weld start width or weld metal buildup (see Figures 23, 24, and 25). Therefore, work on the standing start keyhole initiation technique was stopped, and traveling keyhole initiation procedures were evaluated for ability to be welded over by a keyhole pass without causing quality problems. A satisfactory procedure was developed and most starts obtained from this procedure were sound. However, occasionally plasma gas entrapment caused internal voids of various lengths. It was found that these voids could be welded over with a keyhole and consistently eliminated. Therefore, the occurrence of voids in the weld start area was not considered to be a serious problem.

2.3.1.2 Development of Procedures for Circumferential Welds

The methods used to evaluate keyhole mode welding conditions for circumferential butt joints in 6Al-4V titanium were oriented toward development of quality-optimized welding procedures. Therefore, it was necessary to first define the process variables that might significantly affect the

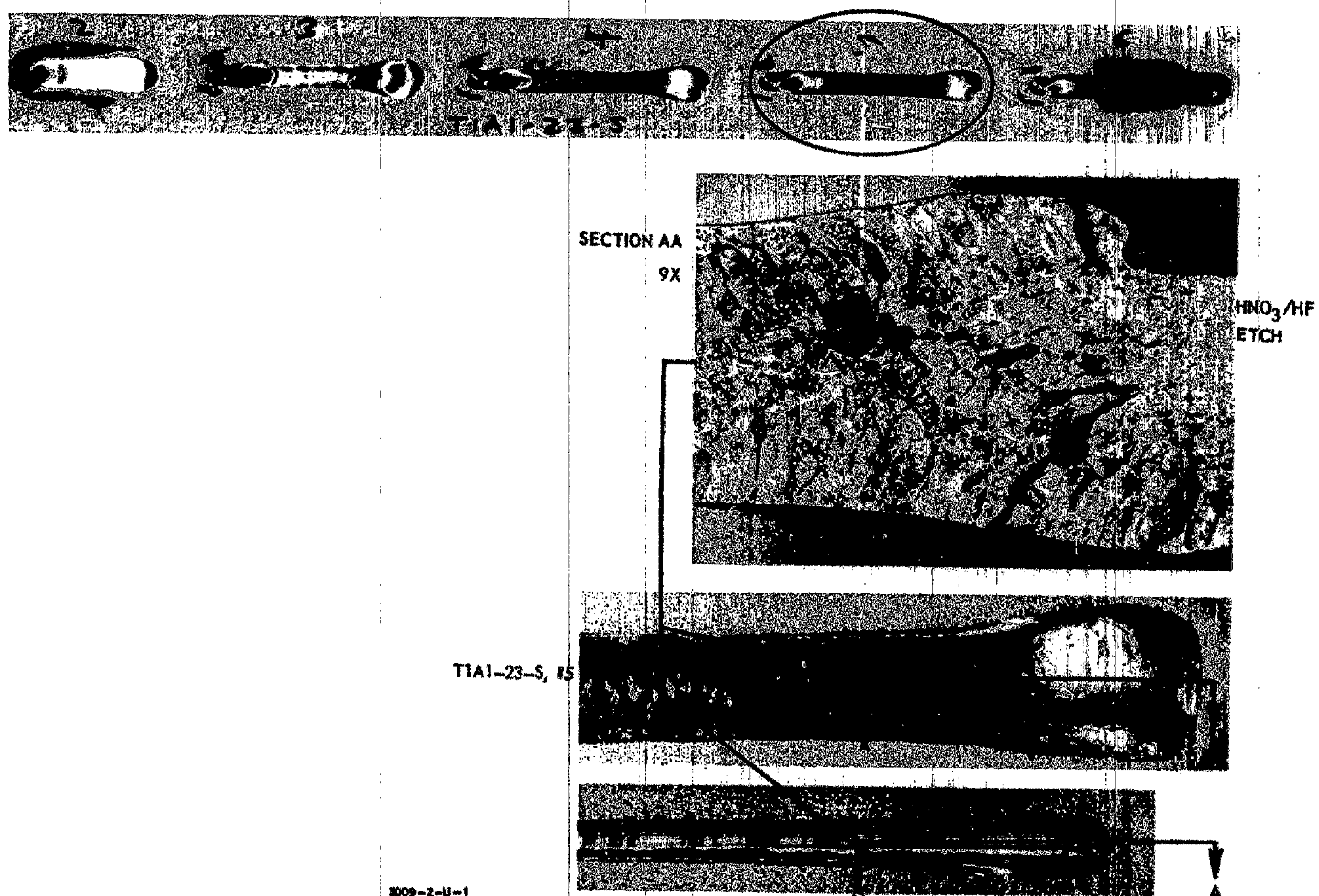


Figure 23. Plasma Arc Weld Start Procedure Evaluation Sample, 0.250-in.-Thick Mill-Annealed Titanium 6Al-4V Plate, 0.156-in.-Diameter Start Hole, PT-8 Torch, Argon Orifice Gas, 136-M Orifice.

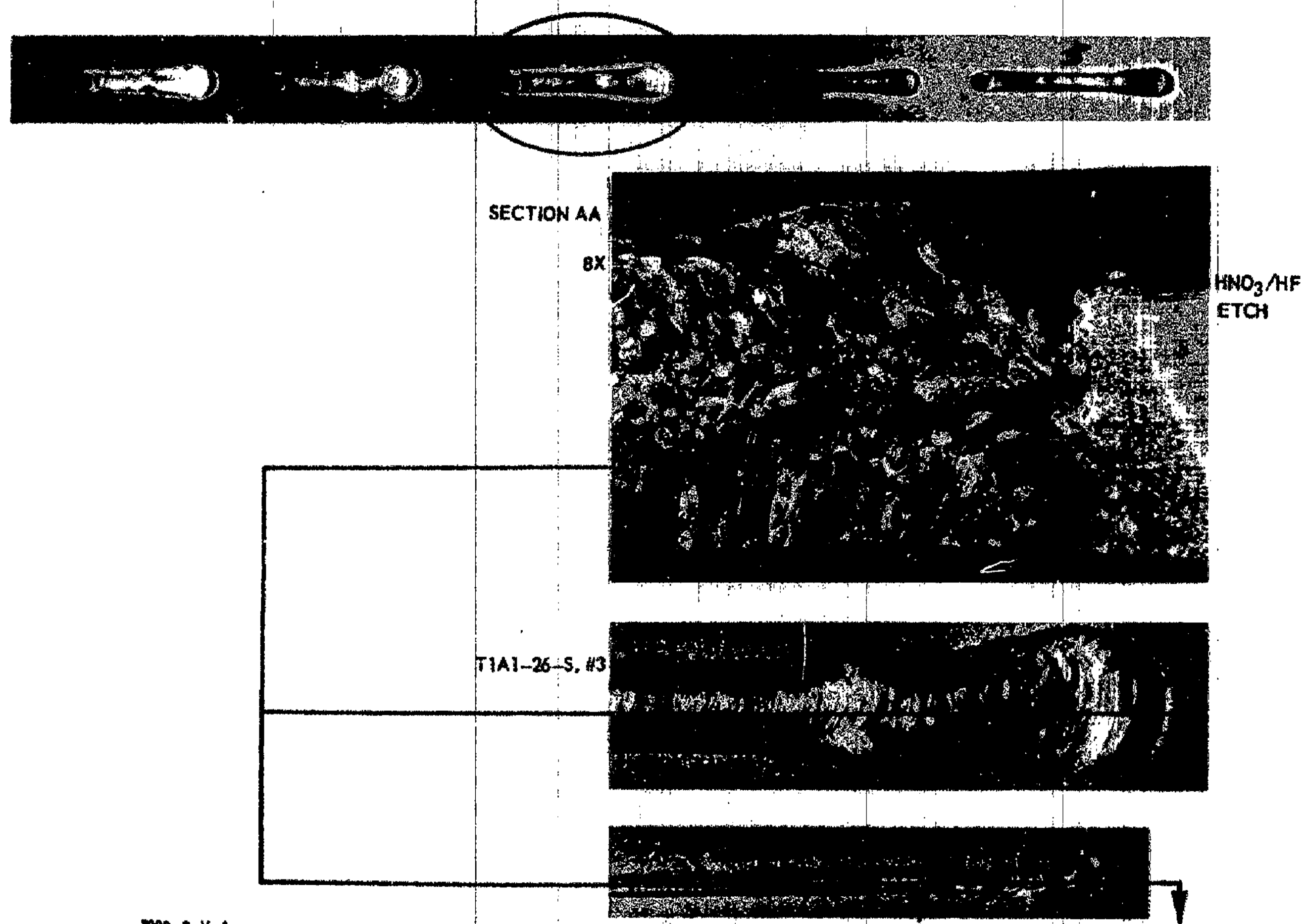


Figure 24. Plasma Arc Weld Start Procedure Evaluation Sample, 0.250-in.-Thick Mill-Annealed Titanium 6Al-4V Plate, 0.156-in.-Diameter Start Hole, U-5T Torch, Argon Gas, 1/16-in. Orifice.

3009-2-Y-1

Figure 25. Longitudinal Cross Sections of Plasma Arc Weld Start Areas Illustrating the Types of Defects That Can Occur in Keyhole Initiation Areas When a Standing Start Technique is Employed. (Single Pass Flat Position Weld in 0.250-in.-Thick Mill-Annealed Titanium 6Al-4V Plate, No Filler Wire Added, as-Welded.)

quality of this kind of weld. Initial work suggested that the following variables could affect quality in both the steady-state weld and keyhole withdrawal areas:

Torch configuration

PT-8	Orifice diameter Single or multiport orifice Electrode setback Electrode point configuration
U-5T	Orifice diameter Electrode setback Electrode size

Torch standoff distance

Weld current

Weld travel speed

Orifice gas

Orifice gas flow

Shield gas

Shield gas flow

Material thickness (and liquid phase characteristics)

Orifice gas flow downslope rate

Weld current downslope rate

Minimum weld current level (during downslope)

Weld travel speed downslope rate

Time phasing of current and travel downslope relative to orifice gas flow downslope

Weld tooling configuration

A review of potentially suitable statistical methods for evaluating the relative influences of this array of variables on weld quality suggested the use of a factorial experiment design. However, it was found that a full factorial experiment for evaluating the main effects and interactions of the listed variables would require more than 16,000 tests. The same kind of experimental design for 7 variables required 128 treatment combinations at 10 replications each, for a total of 1,280 tests. Because of uncertainty as to the limits to be applied on the evaluation range for each variable, statisticians could not guarantee that such a 7-variable experimental design would provide sufficient data to define a keyhole overlap and tail-off procedure capable of producing acceptable weld quality in these areas consistently. Statistical experimental designs of this nature were not originally a part of this work; practical limits existed on the relative amount of weld testing that could be devoted to this work, and these kinds of statistical experimental designs were therefore not employed in optimizing keyhole overlap and tail-off procedures.

At this point it was clearly necessary to substantially reduce the number of variables to be studied in developing keyhole overlap and tail-off procedures. Each torch was restricted for further work to a single combination of electrode, orifice, and electrode setback. Standoff distance and weld tooling configuration were fixed. Limited weld testing was then undertaken to define a range of steady-state welding speeds with reasonable potential for producing satisfactory quality in keyhole overlap and keyhole withdrawal areas. Flat position square butt welds were produced in 0.26-in.-thick mill annealed 6Al-4V titanium plate; arc current, orifice gas flow, and shield gas flow were adjusted to produce a strong, stable keyhole at weld speeds of 6, 12, and 18 ipm. In these tests, the criterion for a strong keyhole was that the residual plasma flame protruding through the keyhole impinge on the copper floor plate of the fixture (1 in. away) without loss in flame diameter. This work and all subsequent welding on this contract was accomplished using the multifunction gas control illustrated in Figure 7 and the trailing shield shown in Figure 12.

Welds made at 6, 12, and 18 ipm under stable keyhole conditions were free of defects except that all specimens exhibited degrees of top bead underfill at both fusion zone edges. It is probable that welding speeds above 18 ipm are practical for this material and thicknesses on straight seam joints, but at 18 ipm, 290 amp were necessary to achieve a stable keyhole using the PT-8 torch. This is above the 250-amp limit suggested for this torch and orifice in Reference 6, although no orifice damage was detected after the relatively short weld specimens (24 in.) used in this test series were completed.

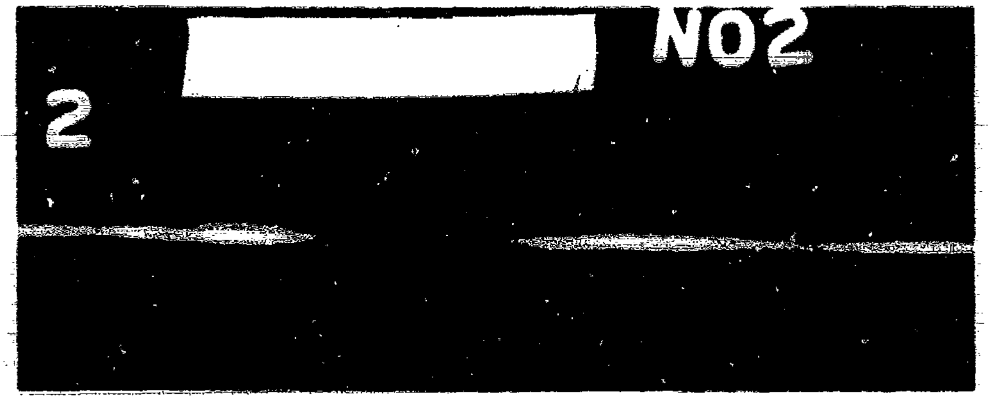
After satisfactory steady-state keyhole conditions were established with each torch at the three weld speeds, overlap and keyhole withdrawal procedures were evaluated. A simulated circumferential weld joint configuration was used; this comprised a square butt joint 24 in. long in which the first keyhole weld was initiated in the center of the joint (using a programmed start cycle) and carried to the end of the plate where it was terminated with a rapid slope-down cycle. A second keyhole weld was then started at the opposite end of the plate using a short keyhole start cycle, carried toward the start of the first weld and over it, then sloped down, using a controlled keyhole withdrawal program to simulate the keyhole closeout in a circumferential weld joint.

It was found that it was possible to weld over keyhole initiation areas without loss of the keyhole at all three welding speeds. The root bead (or melt-thru) protruded from the plate surface more in the overlap area than in steady weld areas because even the running keyhole initiation procedure leaves a thickened area where the keyhole first appears. Root bead protrusion effects were greater in welds made with the U-5T torch.

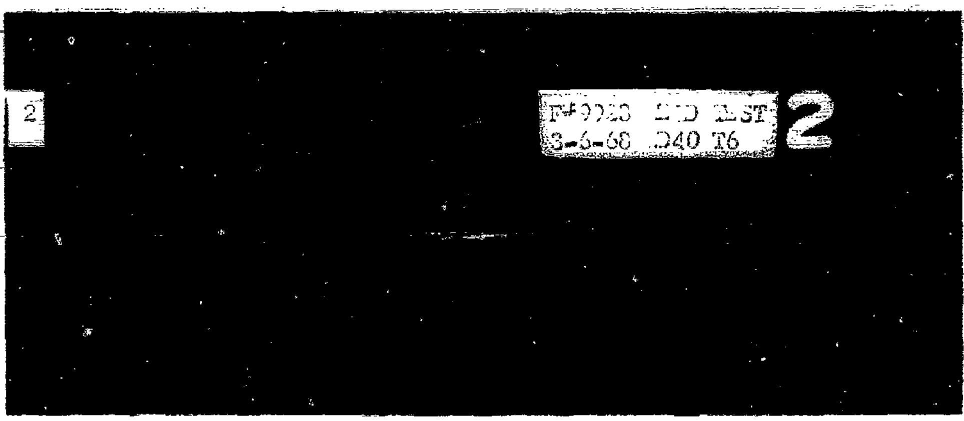
The consistent production of a defect-free keyhole withdrawal area was the major problem encountered in developing circumferential welding procedures for 6Al-4V titanium. Two weld quality features were important in this problem: (1) there was always an area of combined underfill and localized concavity on the top bead surface where the keyhole ceased to penetrate the plate (keyhole withdrawal); and (2) plasma gas entrapment in the form of closed, irregularly shaped subsurface voids was found at points along the weld from 3/8 to 1-1/2 in. after keyhole withdrawal occurred. Typical X-rays of void-free and void-containing keyhole withdrawal zones are shown in Figure 26. Although limited welding was accomplished at 18 ipm, the severity of the top bead concavity and underfill at the keyhole withdrawal point was such that satisfactory coverage of this area with a second weld was judged to be impractical using a constant filler wire feed rate. Therefore, work on 18 ipm keyhole withdrawal procedures was discontinued and effort was concentrated on 12-ipm procedures because both 6- and 12-ipm conditions yielded top bead contours that could be satisfactorily removed with a second or cosmetic weld pass.

At the point in this program when the weld variables influencing keyhole withdrawal quality were being studied, the U-5T torch began to exhibit inconsistent arc force. This effect essentially invalidated previous weld procedure development work. While Thermal Dynamics personnel were evaluating this problem, weld testing was accomplished only with the PT-8 torch.

VOID IN KEYHOLE WITHDRAWAL AREA, SINGLE PASS WELD



VOID FREE KEYHOLE WITHDRAWAL AREA, SINGLE PASS WELD



X-RAY CLEAR KEYHOLE WITHDRAWAL AREA AFTER WIRE COVER WELD

Figure 26. X-rays of Keyhole Withdrawal Areas in 0.250-in.-Thick 6Al-4V Titanium Plate.

Additional procedure development welding indicated the weld variables that have greatest influence on the quality of the keyhole withdrawal zone are

a. Orifice gas flow downslope rate.

b. Time phasing of weld current downslope following initiation of orifice gas flow downslope.

c. Material thickness.

d. Welding position.

Unfortunately, their effect on flat position overlap weld quality was only generally established during this program. The most significant data are presented in Table II; void occurrence in the keyhole withdrawal zone is shown relative to material thickness and orifice gas flow downslope interval. The apparent influence of gas downslope interval on void occurrence in the 0.248- to 0.252-in. thickness range suggests this is the variable of greatest significance. In 19 tests, 19 void-free keyhole withdrawal areas were obtained in this thickness at the 7.7-sec gas downslope interval. Simple statistical treatment of the data on flat position welds at this downslope interval yields the following success and confidence estimates of weld quality potential, based on a sample population of 15:

Satisfactory Overlaps to be Expected in 10 Attempts (%)	Lower Confidence Level (%)
95	50
92	70
90	80
85	90
82	95

The other three variables exhibit uncertain significance. It can be inferred that the greatest potential for producing a void-free overlap exists when orifice gas flow downslope is completed before current downslope is started, but there were enough successes (14) when that was not the case to decrease confidence in any trend; the contradictory successes all occurred at gas downslope intervals in excess of 7.7 sec. Material thickness effects were not thoroughly evaluated, but increases in parent metal thickness cause proportionate increases in the volume of molten metal carried in the weld puddle behind the keyhole; it is this molten metal that must solidify progressively without voids during keyhole withdrawal to yield an acceptable weld.

Table II. Effects of Orifice Gas Downslope Interval or Void Occurrence in Keyhole Withdrawal Area, 0.25-in.-Thick Titanium, Both Torches.

Parent Metal Thickness (in.)	Orifice Gas Downslope Interval Variation Results																	
	14 Seconds		12.4 Seconds		11 Seconds		10 Seconds		8 Seconds		7.7 Seconds		7 Seconds		6.4 Seconds		5 Seconds	
	No Voids	Voids	No Voids	Voids	No Voids	Voids	No Voids	Voids	No Voids	Voids	No Voids	Voids	No Voids	Voids	No Voids	Voids	No Voids	Voids
0.235 to 0.241	3[a]	2	2	0	3[b]	0	-	-	1[a]	1[a]	-	-	-	-	-	-	-	-
0.248 to 0.252	-	-	-	-	-	-	5	1	1[c]	0	19[d]	0	2	0	2	1	-	-
0.258 to 0.262	1	2	3	9	-	-	6	0	-	-	3[e]	2	-	-	-	-	-	-
0.273 to 0.277	-	-	-	-	-	-	1	5[a]	-	-	1[a]	0	-	-	-	-	1	0

a. One U-5T weld
b. All U-5T welds
c. Horizontal position weld
d. Four horizontal position welds
e. Two horizontal position welds
\- No test data
0 Welds in which current downslope was started before orifice gas downslope was complete.

Parent Metal Thickness (in.)	Torch	Weld Position	Overlap Areas X-Rayed	Overlap Areas Without Voids	
				No.	(%)
0.235 to 0.241	PT-8	Flat	6	4	67
	U-5T	Flat	6	5	83
0.248 to 0.252	PT-8	Flat	26	20	77
	PT-8	Horizontal	5	5	100
0.258 to 0.262	PT-8	Flat	15	11	73
	PT-8	Horizontal	2	2	100
0.273 to 0.277	PT-8	Flat	6	2	33
	U-5T	Flat	2	1	50

As a variable, material thickness exhibited the expected effect in that more voids were found in thicker material. The significant liquid phase properties of titanium, and particularly the influence of chemical composition on viscosity and surface tension, were not found in the technical literature. Therefore, potentially signficant molten metal surface tension and viscosity variations associated with chemical composition differences could not be evaluated. The influences of material variables did not appear to be predominant at the 0.248- to 0.252-in. thickness level, where a large part of the Table II welding data were obtained. Additionally, no voids were found in the keyhole withdrawal area of any of the horizontal position welds; more data would be needed to establish the statistical importance of the position variable because the sample population was only four tests.

Figure 27 illustrates a successful combination of welding conditions and timing for keyhole mode circumferential welds, using the PT-8 torch. Figure 28 shows the conditions required to make a circumferential keyhole mode weld both before and after the problem of reduced keyholing force occurred with the U-5T.

Melt-in mode welds can be made with either plasma torch by minimizing the penetrating force of the plasma arc and by spreading the weld puddle; this was accomplished by reducing total orifice gas flow and using large percentages of helium in the orifice gas. It was found that melt-in mode welds could be produced with either torch using similar conditions, except for total orifice gas flow. Steady-state keyhole mode welds in 0.25-in.-thick titanium were satisfactorily covered using a melt-in fusion cover pass, without filler wire addition to eliminate top bead underfill. Because keyhole withdrawal produces a characteristically concave top bead area, some filler wire addition during the cosmetic cover pass is necessary to fill this area. Figure 27 illustrates satisfactory melt-in mode cover weld conditions for the PT-8 (or U-5T) torch on this material. Arc initiation and tail-off procedures for melt-in mode plasma arc welds are relatively noncritical.

Figure 29 illustrates top and root bead surfaces in the overlap area of a weld that was used for initial physical properties evaluation; some root bead heaviness in the overlap area is apparent. Figure 30 illustrates cross sections from two areas of each of the first physical properties evaluation welds produced with PT-8 and U-5T torches. These photographs illustrate weld surface and cross section quality to be expected using these torches with this material.

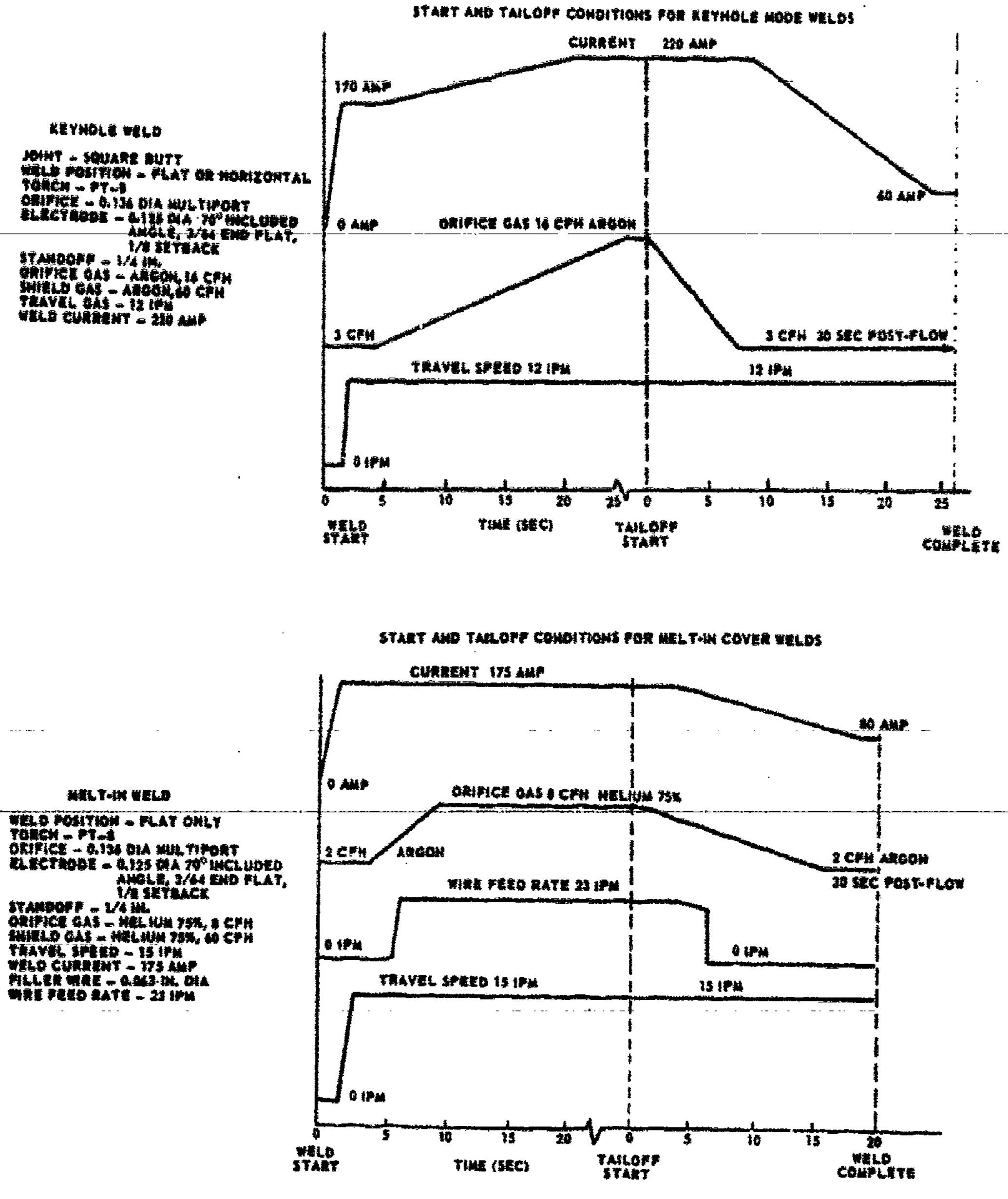


Figure 27. Welding Conditions and Timing for Continuous Circumferential Plasma Arc Welds in 0.25-in.-Thick 6Al-4V Titanium, U-5T Torch.

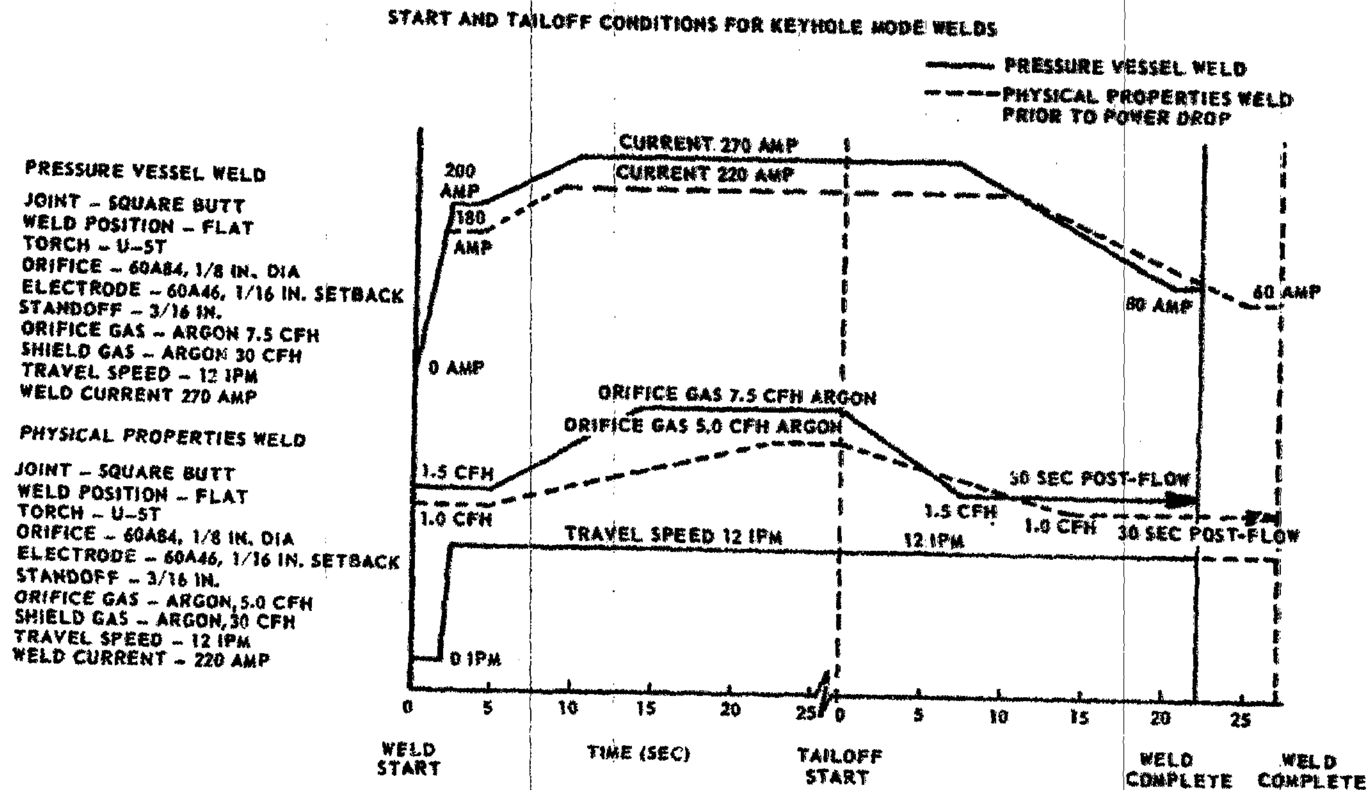
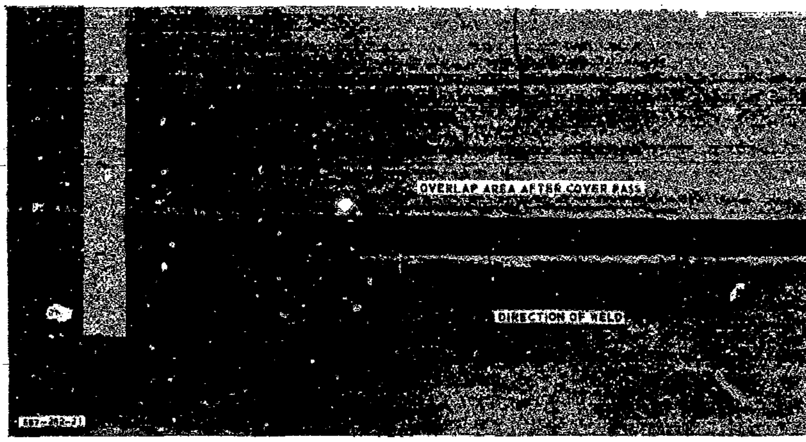
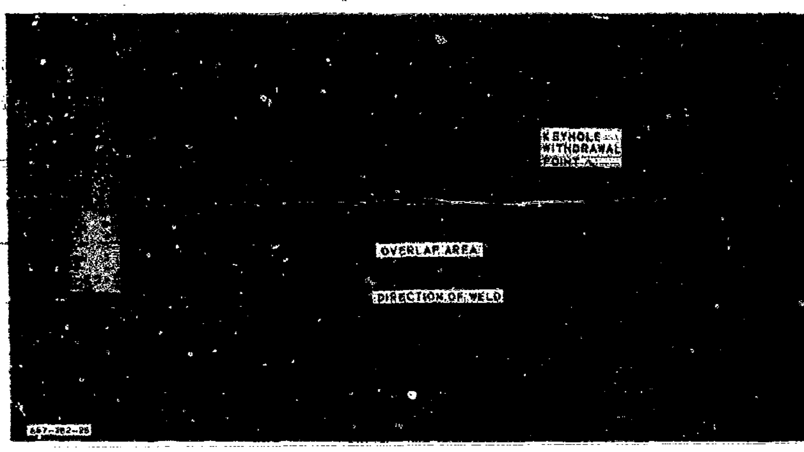


Figure 28. Welding Conditions and Timing for Keyhole Mode Welds in 0.25-in.-Thick 6A1-4V Titanium, U-5T Torch.



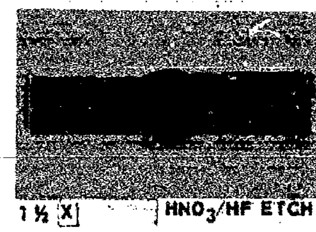
TOP BEAD SURFACE OF WELD NO. T2A2-2



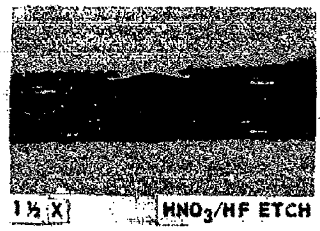
ROOT BEAD SURFACE OF WELD NO. T2A2-2

Figure 29. Flat Position Square Butt Weld in 6Al-4V Titanium Plate, 0.235-in. Thick, 2 Passes Illustrating Typical Weld Surface Quality in Area of Satisfactory Overlap.

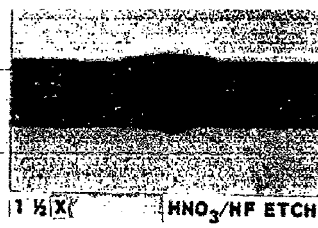
PT-8 TORCH, 1 KEYHOLE WELD,
12 IPM WELD SPEED, WELD T2A2-1



U-5T TORCH, 1 KEYHOLE WELD,
12 IPM WELD SPEED, WELD T2A2-14



PT-8 TORCH, 1 KEYHOLE WELD
PLUS 1 COVER WELD, 12 IPM
WELD SPEED, WELD T2A2-2



U-5T TORCH, 1 KEYHOLE WELD PLUS
1 COVER WELD, 12 IPM WELD SPEED,
WELD T2A2-14

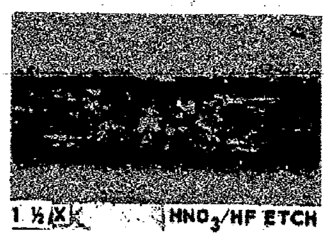


Figure 30. Flat Position Keyhole Mode Square Butt Welds in 0.24-in.-Thick 6Al-4V Titanium, Both Torches.

2.3.1.3 Process Tolerance for Fitup and Cleanliness Variations

Work was done to establish quantitative data on the process tolerance for weld joint fitup and cleanliness variations. These variables were examined individually within fairly large limits.

Butt weld joint fitup variations normally take two forms, excluding local thickness differences. These are: (1) butting edge mismatch in the plane of the plate, and (2) deviations from continuous butt edge contact (gaps). These factors were studied individually and in combination. The specimen employed for gap evaluation is shown in Figure 31. Figure 32 illustrates the specimen setup employed for evaluating the effects of combined gap and mismatch. The effects of fitup variables were evaluated on flat position square butt welds without keyhole overlap or withdrawal areas. All welds were made with the PT-8. The criteria for evaluating the effects of these variables on weld quality were by visually determined weld surface qualities and X-ray soundness. Root bead concavity was evaluated in this study as a condition different from underfill.

Figure 33 illustrates the effect of various gap widths on weld cross section features. The keyhole was continuously maintained at gaps up to 0.070 in. (the greatest tested) without causing a hole in the weld. Some root bead concavity at fusion zone edges was resolvable at local gap areas over 0.020 in. wide, both visually and by X-ray; however, based on these data, it appears that gaps near 0.030 in. wide could exist in a pressure vessel butt weldment intended for flat position welding without seriously degrading weld quality or properties, if keyhole mode plasma arc welding were to be employed. At this gap setting, root bead concavity is less than 0.004 in. With the electron beam welding process, continuous weld in the presence of gaps above 0.010 in. would be difficult to produce. Reference 11 describes some results of fatigue tests on welds in other materials to evaluate effects of root bead concavity.

Figure 34 illustrates the effect of various levels of mismatch on weld cross section features. As before, the keyhole was maintained at all points along the weld joint without causing holes in the weld. Mismatch conditions up to 0.080-in. offset (32% mismatch) did not cause undercutting on the root bead side of the weld. The plasma flame protruding through the keyhole was progressively deflected toward the higher side of the joint as mismatch was increased. Any of the top bead conditions illustrated in Figure 34 could be satisfactorily covered with a cosmetic weld pass employing filler wire addition; therefore, constraints on allowable mismatch for keyhole mode plasma arc welds would most likely be defined by transweld load path discontinuity allowables and ability to achieve a satisfactory keyhole withdrawal zone.

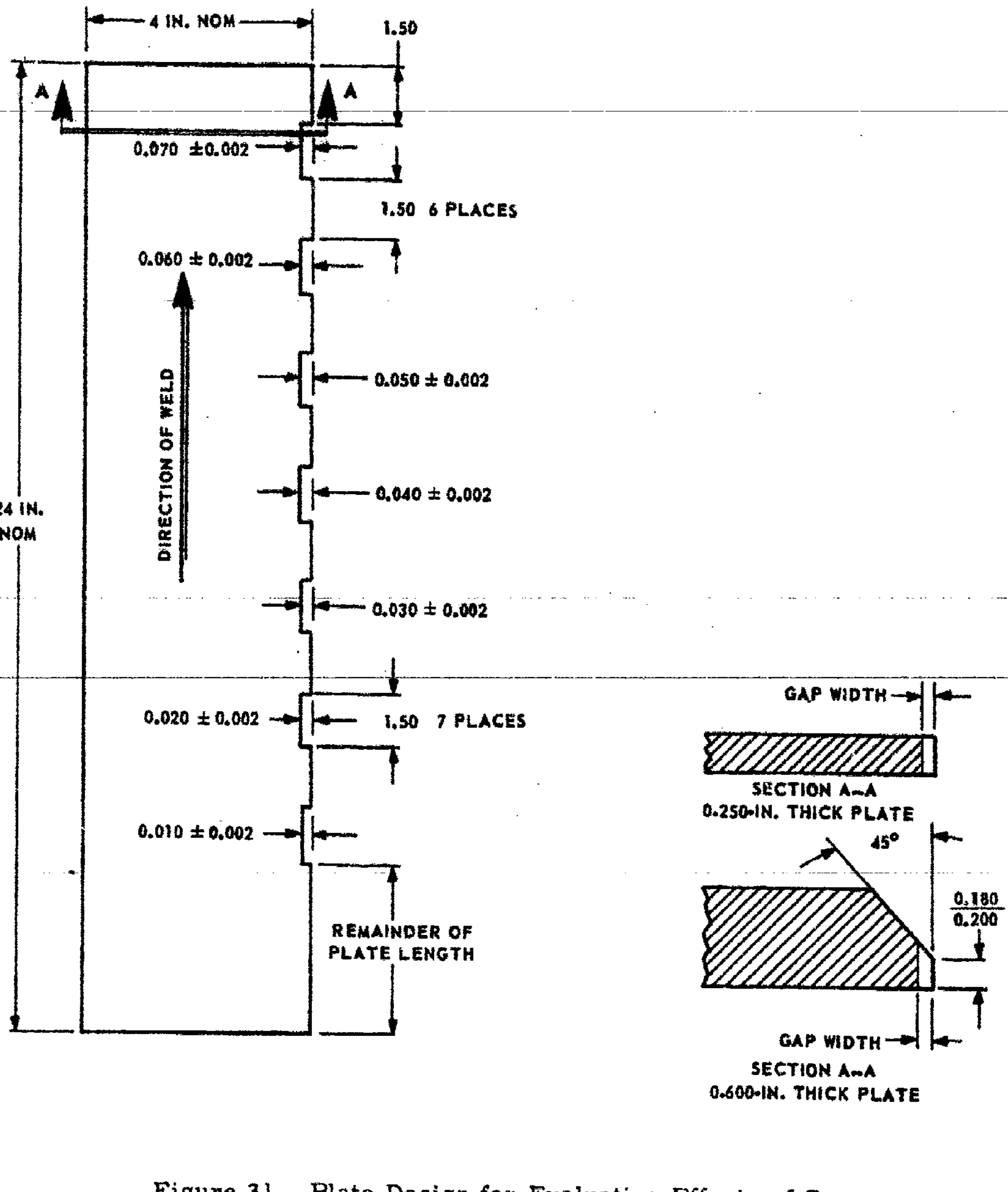


Figure 31. Plate Design for Evaluating Effects of Gap.

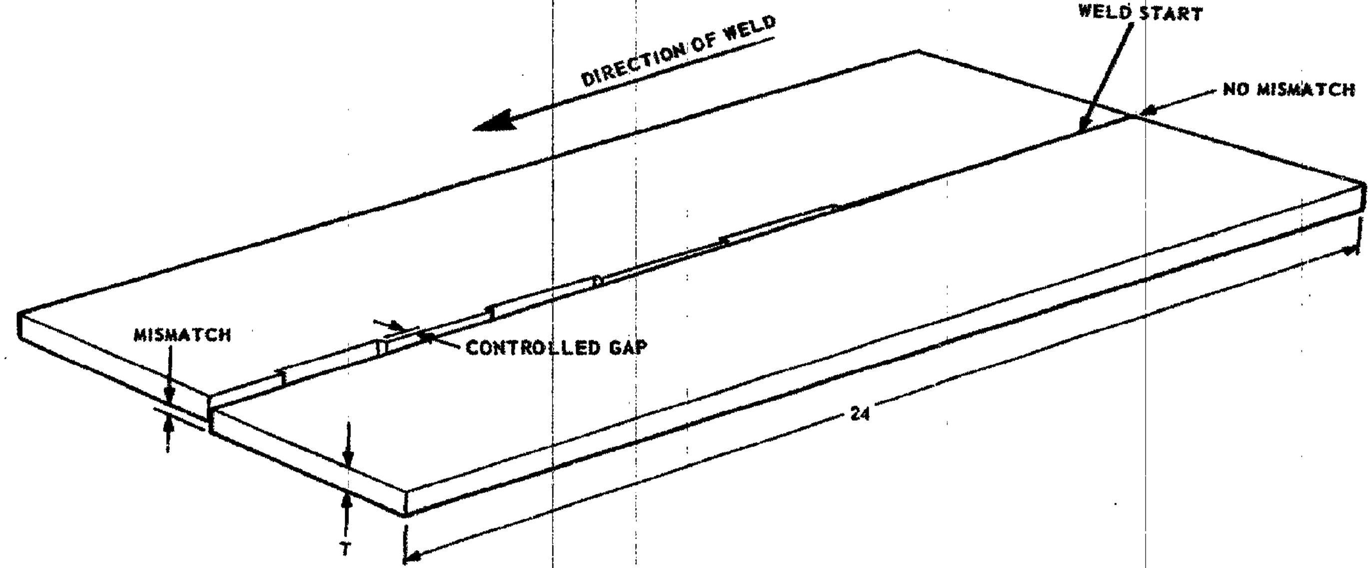


Figure 32. Typical Weld Plate Setup for Evaluation of Weld Joint Fitup Effects.

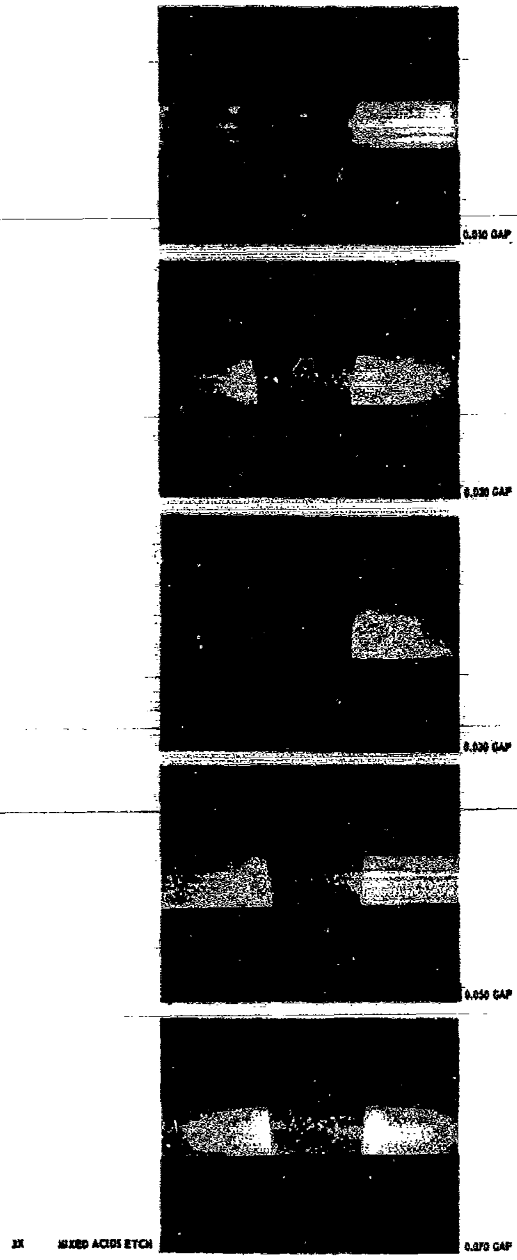


Figure 33. Effects of Gap on Single Pass Flat Position Keyhole Mode Plasma Arc Welds, Square Butt Weld Joints in 0.250-in.-Thick 6Al-4V Titanium Plate.

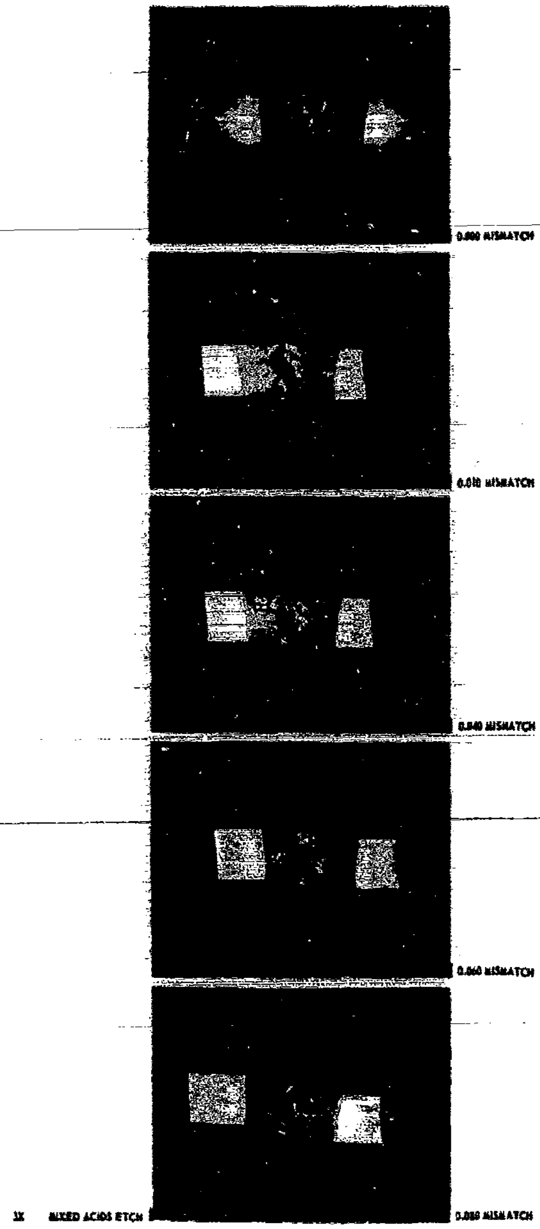


Figure 34. Effects of Mismatch on Single Pass Flat Position Keyhole Mode Plasma Arc Welds, Square Butt Weld Joints in 0.250-in.-Thick 6Al-4V Titanium Plate.

Figure 35 illustrates the effects of various combinations of gaps and mismatch on weld cross section features. As before, the keyhole was maintained at all points along the weld joint without causing holes in the weld. It would appear that constraints on mismatch would also apply for combined conditions, although at combinations of gap and mismatch over 0.030 and 0.040 in., respectively, the root bead surface exhibits larger discontinuities.

The effects of preweld cleaning on the quality of square butt plasma arc welds in 0.25-in.-thick 6Al-4V titanium were evaluated using three levels of cleanliness; data on the effects of cleanliness were obtained over the duration of the program. The standard cleaning procedures were :

a. As-received plate (pickled at mill), milled square butt edge; deburr the sharp edges, and store up to 6 months for later use. Wipe butt edges with clean rag saturated with MEK or methyl alcohol; assemble, purge, GTAW tack weld, then keyhole weld.

b. As-received plate (pickled at mill), milled square butt edge; deburr the sharp edges, etch in 3% HF/40% HNO_3 solution, dry and wrap in kraft paper, and store up to 3 months for later use. Wipe butt edges with clean rag saturated with MEK or methyl alcohol; assemble, purge GTAW tack weld, then keyhole weld.

c. As-received plate, (pickled at mill) milled square butt edge; deburr the sharp edges, etch in 3% HF/40% HNO_3 solution, dry and immediately prepare for welding. Wipe butt edges with clean rag saturated with MEK or methyl alcohol; assemble, purge, GTAW tack weld, then keyhole weld.

During this program, 120 ft of the 390 ft of keyhole mode butt welding in this material was inspected by flurorescent penetrant and X-ray methods. This comprised 51 two-ft-long plate weldments and three pressure vessels with 6 ft of weld each. No surface defects were found, except that single pass welds exhibited top bead underfill at the fusion zone edges; two pass welds were completely free of surface defects. Porosity was found in four plate weldments; in three of these, the defect was in the form of an individual pore less than 0.030 in. in diameter. In the fourth case, the defect was light nonlinear porosity about 0.020 in. in diameter in a 1-in.-long section of the weld. None of the porosity was rejectable by the X-ray acceptance criteria (Appendix VII). These data were obtained from welds in

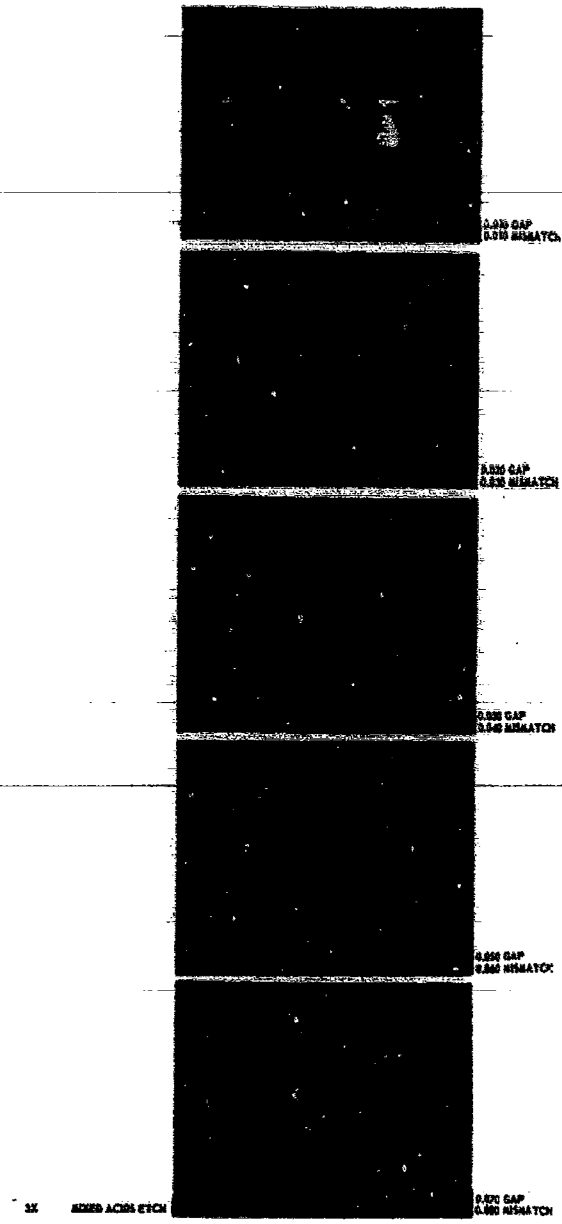


Figure 35. Effects of Combined Gap and Mismatch on Single Pass Flat Position Keyhole Mode Plasma Arc Welds, Square Butt Weld Joints in 0.250-in.-Thick 6Al-4V Titanium Plate.

three heats of material. There was no correlation between cleaning procedure, heat of material, and occurrence of porosity. Only one flat position weld exhibited porosity, but three horizontal position welds exhibited porosity. These data strongly substantiate previous claims of very high weld quality potential inherent with the plasma arc welding process. (These data may be more impressive to those readers familiar with the problem of producing titanium weldments that must comply with restrictive porosity acceptance criteria.) The fact that 25% of the welds X-rayed were made with plates that were simply washed with solvent after edge machining seems very significant. The puddle agitation and surface sweeping action of keyhole mode welding appears to substantially suppress the confirmed tendency of titanium weld metal to form porosity, at least for surface cleanliness and interstitial levels within the ranges examined.

2.3.1.4 Evaluation of Horizontal Position Welding

Limited welding was performed to determine the capabilities of the plasma arc welding process for producing high-quality butt welds in 0.250-in.-thick 6Al-4V titanium plate in the horizontal welding position. The equipment setup in Figure 17, including the PT-8 torch, was used for all horizontal position welding of flat plate.

Because reasonable success was achieved at 12 ipm on flat position welds, this speed was also used for all horizontal position welds. It was found that keyhole mode welding conditions developed for flat position welds could also be utilized for horizontal position welds, with the PT-8 torch. Figure 36 shows the torch side surface of a horizontal position weld in an area free of keyhole initiations or overlaps.

There were no voids found in the keyhole withdrawal area in any of the seven horizontal position welds that were X-rayed (Table II). The concave area that occurred on the torch side of flat position welds at the keyhole withdrawal point was not as deep in horizontal position welds. It appears that the welding conditions and time phasing of Figure 28 are reasonably satisfactory for keyhole overlap and withdrawal operations in horizontal position welds.

Because the torch-side surface concavity of horizontal position welds was shallower in the overlap area than in flat position welds, it was decided to examine conditions for cover welds without employing filler wire addition. This was satisfactorily accomplished using the conditions and procedures shown in Figure 37.

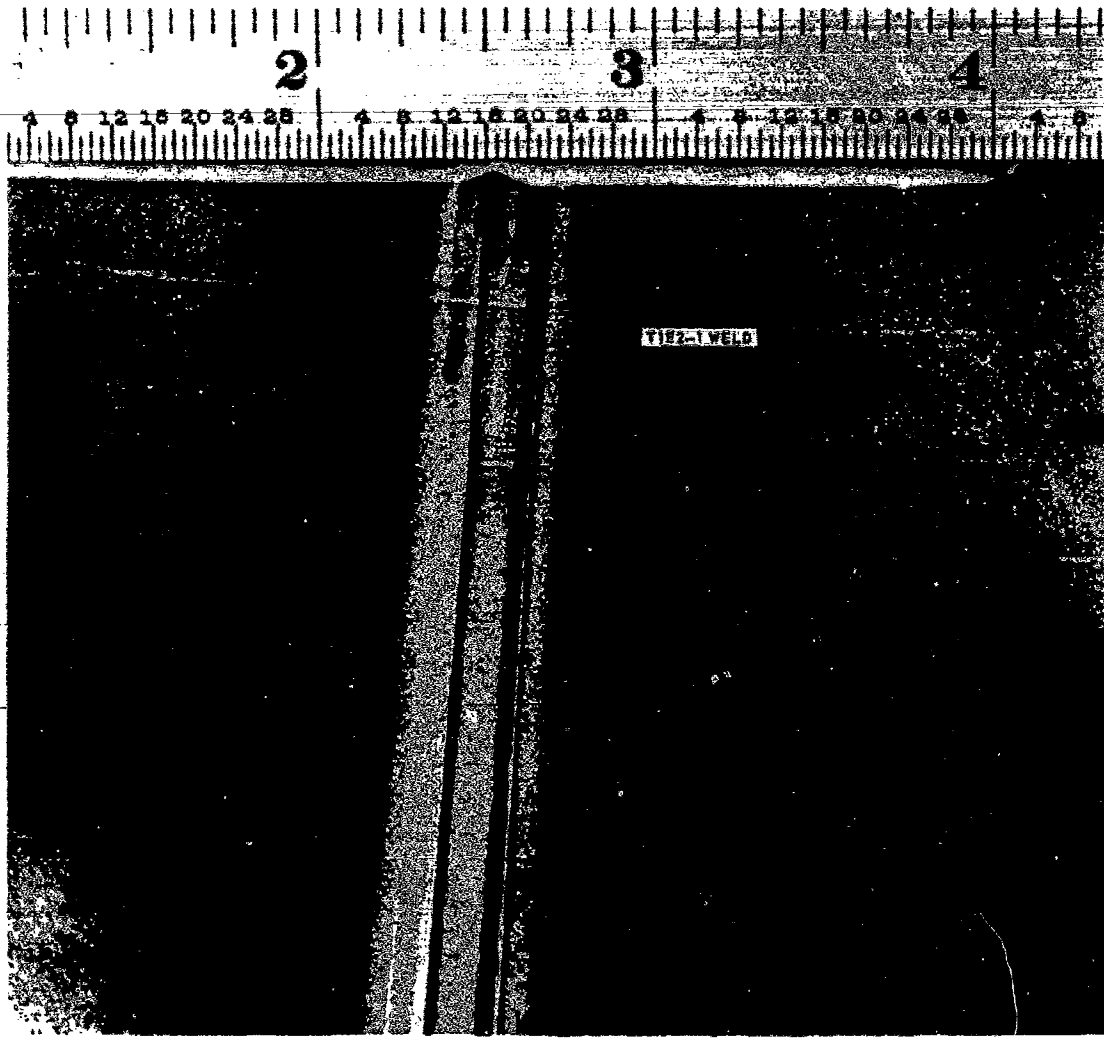
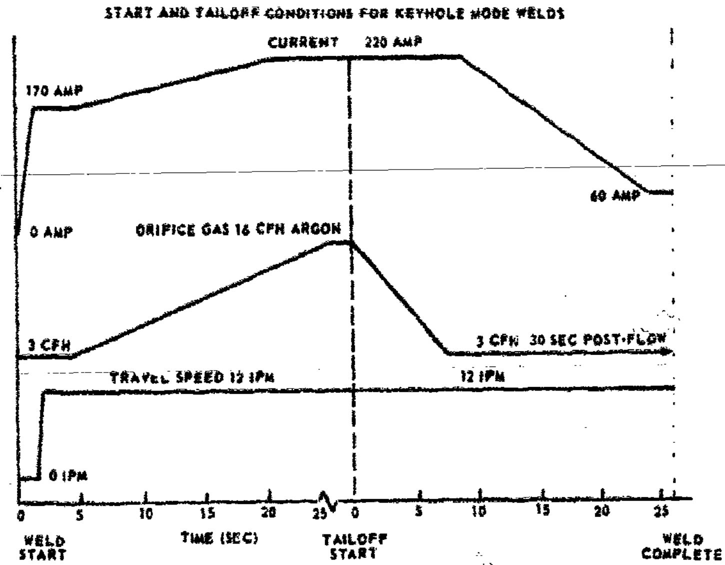
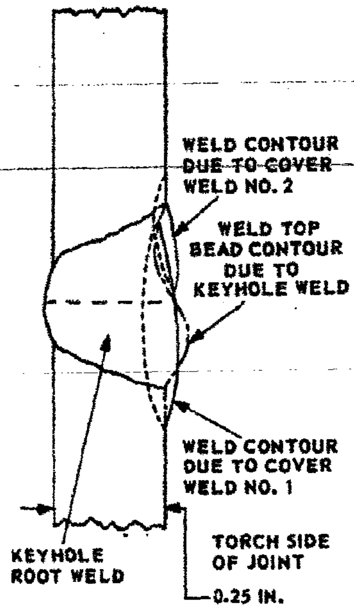


Figure 36. Top Bead Surface of Single Pass Horizontal Position Square Butt Weld in 0.25-in.-Thick 6Al-4V Titanium Plate.

KEYHOLE WELD

JOINT – SQUARE BUTT
WELD POSITION – FLAT OR HORIZONTAL
TORCH – PT-8
ORIFICE – 0.136 DIA MULTIPORT
ELECTRODE – 0.125 DIA 70° INCLUDED ANGLE, 3/64 END FLAT, 1/8 SETBACK
STANDOFF – 1/4 IN.
ORIFICE GAS – ARGON, 16 CFH
SHIELD GAS – ARGON, 60 CFH
TRAVEL GAS – 12 IPM
WELD CURRENT – 220 AMP





MELT-IN MODE COVER WELDS

	1ST COVER PASS	2ND COVER PASS
ORIFICE GAS	HE 75, 8 CFH	HE 75, 8 CFH
SHIELD GAS	HE 75, 60 CFH	HE 75, 60 CFH
TRAILING SHIELD GAS	ARGON, 100 CFH	ARGON, 100 CFH
BACKING GAS	ARGON, 20 CFH	ARGON, 20 CFH
WELD CURRENT	175 AMP	90 AMP
TRAVEL SPEED	12 IPM	12 IPM
TORCH STANDOFF	1/4 IN.	1/4 IN.
FILLER WIRE	NONE	NONE
ARC VOLTAGE	26.5 V	25.0 V
HEAT INPUT	23.2 KJOULE/IN.	11.2 KJOULE/IN.

TOTAL HEAT INPUT (ALL PASSES) = 65.8 KJOULE/IN.

Figure 37. Weld Conditions and Timing for Horizontal Position Welds in Titanium.

2.3.1.5 Weld Properties Evaluations

Welds for mechanical properties evaluations were produced in 6Al-4V titanium plate that was solution-treated at a temperature just below the beta-transus for 1 hr and quenched in water, then aged at about 1000°F for 4 hr (Condition STA). Transweld tensile properties and precrack Charpy impact (PCI) energy absorption characteristics were measured to evaluate the effects of certain procedural variations. Welding conditions were then finalized and more transweld tensile testing and PCI testing was done together with some low-cycle fatigue testing. Chemical composition data and results obtained from tensile and PCI testing of welds in this material are reported in Table III. Specific welding conditions employed for physical test weldments are recorded in Appendix VIII. Figures 38, 39, 40, 41, 42, and 43 illustrate macro- and microstructural characteristics and hardness data for certain welds. Figure 44 illustrates the results of limited low-cycle fatigue testing.

The tensile testing of all welds was accomplished using transweld test specimens machined to the configuration shown in Figure 45. All-weld-metal and longitudinal weld tensile properties were not determined. Tensile specimens were machined, stress-relieved at the indicated temperature and time, and tested at room temperature. Tensile tests were conducted at strain rates between 0.003 and 0.007 in./in./min to 0.2% offset yield stress; strain rate was then increased to cause failure in approximately one additional minute. Weld reinforcement was left as-welded on all tensile test specimens to determine the uniaxial properties of these welds in the configuration that is exposed to service loads, and to indicate whether increased weld land thickness would be required for the titanium pressure vessels, which were to be fabricated later in the program. Because of the way the weld test plates were cut at the mill, the transweld tensile load direction was necessarily transverse to the final rolling direction of the parent metal in all cases.

The welding conditions for 6Al-4V titanium were first optimized to meet quality requirements for circumferential welds. The tensile data reported in Table III represent properties of a relatively fixed set of welding conditions; most evaluations were made using the welding conditions presented in Figures 27 or 37. Tensile test results for certain PT-8 welds are summarized in Table IV.

A literature search failed to reveal published tensile data for fusion butt welds in 6Al-4V titanium higher than that in Table IV; however, no welds were produced that exhibited 100% of the parent metal tensile strength. Flat position welds made with a two-pass procedure incorporating filler wire addition on the cover pass were about 3 ksi higher in tensile strength than single-pass welds, regardless of filler wire composition. The absence of filler wire composition effects is attributed to very little filler wire being added, thus weld metal dilution is negligible. However, weld T2A2-8 exhibited very low tensile properties (Table III). This was attributed to the higher heat input (36 kjoules/in. versus about 20 kjoules/in.) employed for the cover pass. Commercially pure wire was used for this weld, and this may also have contributed to reduced properties; more weld metal dilution was caused by the higher cover pass heat input. Increasing cover weld speed (thereby reducing the value of the heat input) from 6 to 12 ipm significantly improved and stabilized transweld tensile properties, whether or not filler wire was added; further speed increases to 15 ipm for the cover weld did not significantly alter these properties.

The transweld properties of one horizontal position weld were essentially identical with those of two-pass flat position welds.

Further review of Table III tensile data clearly indicates there is no significant difference between the tensile properties of the steady-state weld and the keyhole overlap and withdrawal areas. To evaluate a potential repair procedure, a second keyhole weld was made in a welded joint that had an overlap void (10-sec orifice gas downslope interval), and a satisfactory overlap was made using the 7.7-sec downslope; the tensile strength in the overlap area (essentially three passes) was slightly higher than in the two pass keyhole area. This suggests that the keyhole overlap and withdrawal procedure illustrated in Figure 27 produces welds essentially equivalent in tensile strength at all points on the weld, either in the initial welds or for the case where a keyhole repair weld may be desirable. At least three keyhole welds could be made in a square butt weld joint without degrading tensile properties. It is apparent that total heat input is not a very significant quantity for comparing weld procedures and tensile properties in this material; total heat input as high as 87 kjoules/in. had no apparent effect. Heat input up to 30 kjoules/in. in a keyhole weld apparently had no degrading effect on weld tensile properties. The influence of interpass temperature higher than 100°F on tensile properties was not evaluated.

Table III. Summary of 6Al-4V Titanium Par
Properties.

Weld Procedures and Properties

Weld Procedures										Mechanical Properties at Room Temperature							
				Heat Input (kjoule/in.)						Uniaxial Tensile Data[c]					Precrack Charpy Energy Absorption (in.-lb/in.²)		
Weld No. and Position	Plate Thickness (in.)	Joint Design	Total No. of Passes	On Root Pass	On 1st Filler Pass	Total All Passes	Filler Wire Heat No.	Backup Groove Width (in.)	Postweld Heat Treat	0.2% Offset YS[d] (ksi)	Percent of PM[e] YS	UTS[f] (ksi)	Percent of PM UTS	Elongation in 1 in. (%)	Notch Location	Average 3 Tests	Spread
T2A2-1, Flat	0.235 (Lot B)	Sq Butt	1	24.4	-	24.4	NA	3/4	a	147.2	98	157.8	95	10.0	Weld G	914	842/1026
T2A2-2, Flat	0.241 (Lot A)		2	24.4	16.2	40.6				145.8	95	157.9	94	11.0	-	-	-
T2A2-2, Flat	0.241 (Lot A)		2	24.4	18.7	43.1				146.3	96	161.1	96	10.3	Weld ℄	988	830/1156
T2A2-2, Flat	0.241 (Lot A)		2	24.4 24.4	18.7	67.5	NA			145.9	96	158.3	94	8.5	-	-	-
T2A2-8, Flat	0.244 (Lot A)		2	23.0	36.0	59.0	301525 (CP)			112.0	73	125.9	75	9.3	-	-	-
T2A2-14, Flat	0.235 (Lot B)		1	26.2	-	26.2	NA			119.4	79	129.0	78	12.3	-	-	-
T2A2-14, Flat	0.235 (Lot B)		2	26.2	21.6	47.8	NA	3/4	a	142.0	94	152.8	92	8.5	-	-	-
T2A2-30, Flat	0.250 (G-4956)		2	30.2	19.1	49.3	301525 (CP)	1-3/4	b	145.8	85	160.9	89	7.0	Weld ℄ HAZ	1072 1026	1013/1115 869/1183
T2A2-30, Flat			2 plus overlap area	30.2 30.2	19.1	79.5	301525 (CP)			146.1	85	160.6	89	8.0	-	-	-
T2A2-31, Flat			2	29.9	19.2	49.1	3204-D1 (6Al-4V)			144.8	84	161.3	89	6.0	Weld ℄	1069	1026/1098
T2A2-32, Flat			2	29.9	18.3	48.2	3204-D1 (6Al-4V)			147.5	86	161.9	90	7.6	Weld ℄ HAZ	1064 859	930/1221 821/916
T2A2-33, Flat			2 keyhole welds only	29.0 29.0	-	58.0	NA			143.6	84	156.9	87	6.0	Weld ℄	1082	981/1150
T2A2-33, Flat			2 keyhole welds plus overlap	29.0 29.0 29.0	-	87.0				143.7	84	157.7	87	6.3	-	-	-
T2A2-34, Flat			1	28.6	-	28.6				144.6	84	156.4	86	5.7	Weld ℄ HAZ	1059 879	894/1146 841/950
T2A2-34, Flat			1 keyhole weld plus 1 overlap	28.6 28.6	-	57.2				143.4	84	158.0	87	7.3	-	-	-
T2E2-3, Horizontal			1 keyhole weld plus 2 melt-in	29.7	19.0 10.3	59.0		1-3/4		148.5	87	161.6	89	9.3	Weld ℄ HAZ	905 1041	833/959 871/1181
EB weld, Flat	0.250 (G-4956)	Sq Butt	1	-	-	-	NA	NA	b	148.7	87	158.1	87	4.1	Weld ℄	565	557/572

a. 1000°F for 4 hr in air, then air-cooled.
b. 1025°F for 4 hr in air, then air-cooled.
c. All tensile data obtained from specimens with weld reinforcement left as-welded, per Figure 45.
d. Yield stress
e. Parent metal
f. Ultimate tensile strength

A.

ry of 6Al-4V Titanium Parent Metal and Weld
Properties.

ies at Room Temperature

Elongation in 1 in. (%)	Precrack Charpy Energy Absorption (in.-lb/in.²)		
	Notch Location	Average 3 Tests	Spread
10.0	Weld ℄	914	842/1026
11.0	-	-	-
10.3	Weld ℄	988	830/1156
8.5	-	-	-
9.3	-	-	-
12.3	-	-	-
8.5	-	-	-
7.0	Weld ℄ HAZ	1072 1026	1013/1115 869/1183
8.0	-	-	-
6.0	Weld ℄	1069	1026/1098
7.6	Weld ℄ HAZ	1064 859	930/1221 821/916
6.0	Weld ℄	1082	981/1150
6.3	-	-	-
5.7	Weld ℄ HAZ	1059 879	894/1146 841/950
7.3	-	-	-
9.3	Weld ℄ HAZ	905 1041	833/959 871/1181
4.1	Weld ℄	565	557/572

Parent Metal and Filler Wire Chemistry

Material	Heat No.	Composition (% by Wt or ppm by Wt)							Data Source
		Al (%)	V (%)	Fe (%)	C (%)	O_2 (ppm)	N_2 (ppm)	H_2 (%)	
0.235-in.-thick plate	293281, Lot B	6.5	4.3	0.10	0.02	1390	120	58/84	Vendor
0.241-in.-thick plate	293281, Lot A	6.5	4.3	0.10	0.02	1160	120	55/88	Vendor
0.258-in.-thick plate	G-4956	6.0	4.1	0.10	0.025	2000	100	90	Vendor
0.258-in.-thick plate	G-4956	-	-	-	-	2000	100	26	Aerojet
0.275-in. thick plate	302257	6.3	4.5	0.08	0.03	1330	110	65	Vendor
0.063-in.-dia wire	3204-D1 (6-4)	6.08	4.18	0.10	0.010	800	70	8	Vendor
0.063-in.-dia wire	3204-D1 (6-4)	6.41	4.25	-	-	800	80	19	Aerojet
0.063-in.-dia wire	301525 (CP)	0.27	<0.05	-	-	1400	60	60	Aerojet

Parent Metal Mechanical Properties - Room Temperature, Aerojet Data

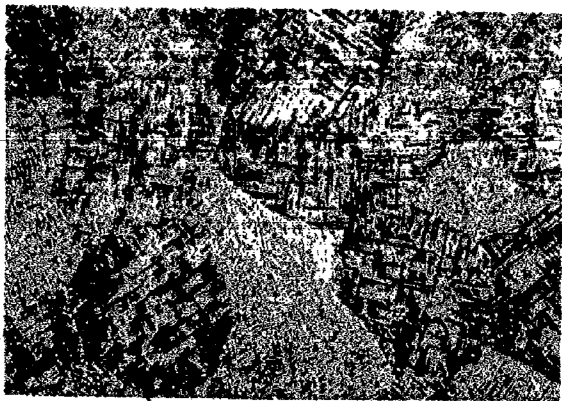
Heat No. and Lot	Direction of Rolling vs Direction of Test	Heat Treat Condition	0.2% Offset YS[e] (ksi)	UTS[f] (ksi)	Elongation in 1 in. (%)	Precrack Charpy Data (in.-lb/in.²)	
						Average 3 Tests	Spread
293281, Lot A	Parallel	As received	142.5	160.8	10.0	-	-
	Parallel	a	147.4	164.3	11.3	879	804/925
	Transverse	As received	152.9	169.9	8.0	-	-
	Transverse	a	152.2	168.4	11.3	574	554/595
293281, Lot B	Parallel	As received	139.7	161.0	11.3	-	-
	Parallel	a	144.2	159.6	12.7	1201	1136/1235
	Transverse	As received	146.8	163.4	10.0	-	-
	Transverse	a	150.1	165.2	12.0	823	805/847
G-4956	Parallel	As received	154.1	169.5	10.7	582	563/606
	Parallel	b	154.2	167.8	12.3	566	544/605
	Transverse	As received	169.7	181.7	14.6	622	571/671
	Transverse	b	171.6	180.9	12.0	601	583/630

Weld Metal Gas Analyses by Aerojet

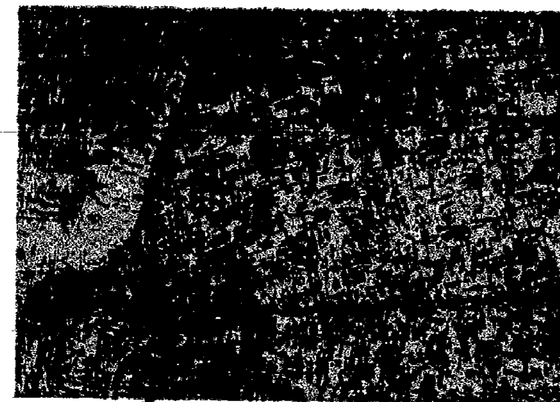
Weld No.	Composition (ppm by Wt)		
	O_2	N_2	H_2
T2A2-30	1200	80	90
T2A2-31	1500	90	33
T2A2-32	1300	80	37
T2A2-33	1500	100	40
T2E2-3	1400	80	65

B.

NOT REPRODUCIBLE



100X HF/HNO_3 ETCH



100X HF/HNO_3 ETCH

1/16

1/16

R_c HARDNESS BY KNOI
CONVERSION, 500 GM L

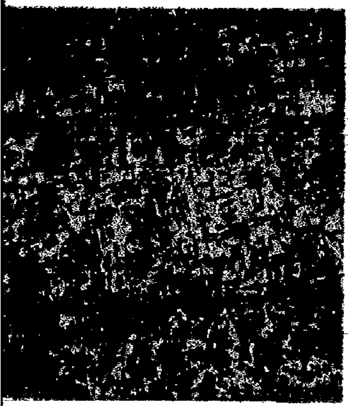
3X HF/HNO ETCH

0.150

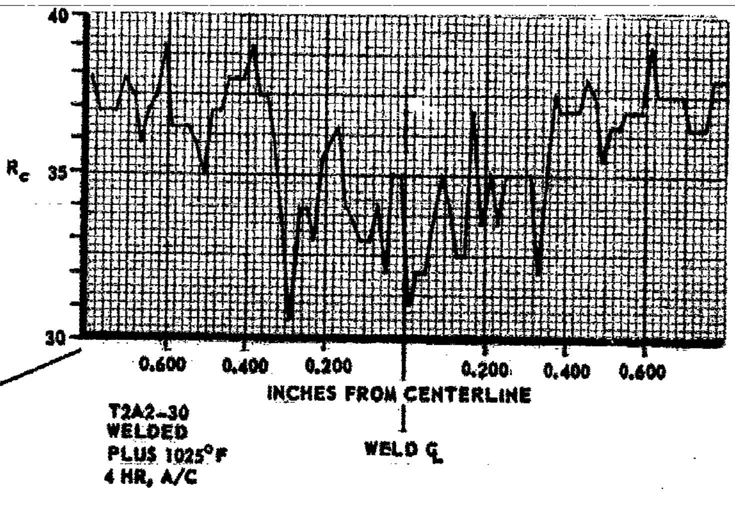
WELD ℄
NOTCH LOCATION

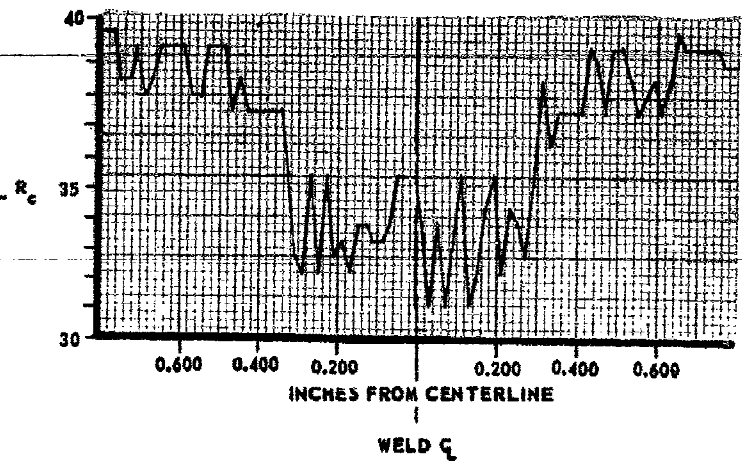
WELD HAZ
NOTCH LOCATION

A.



HF/HNO$_3$ ETCH

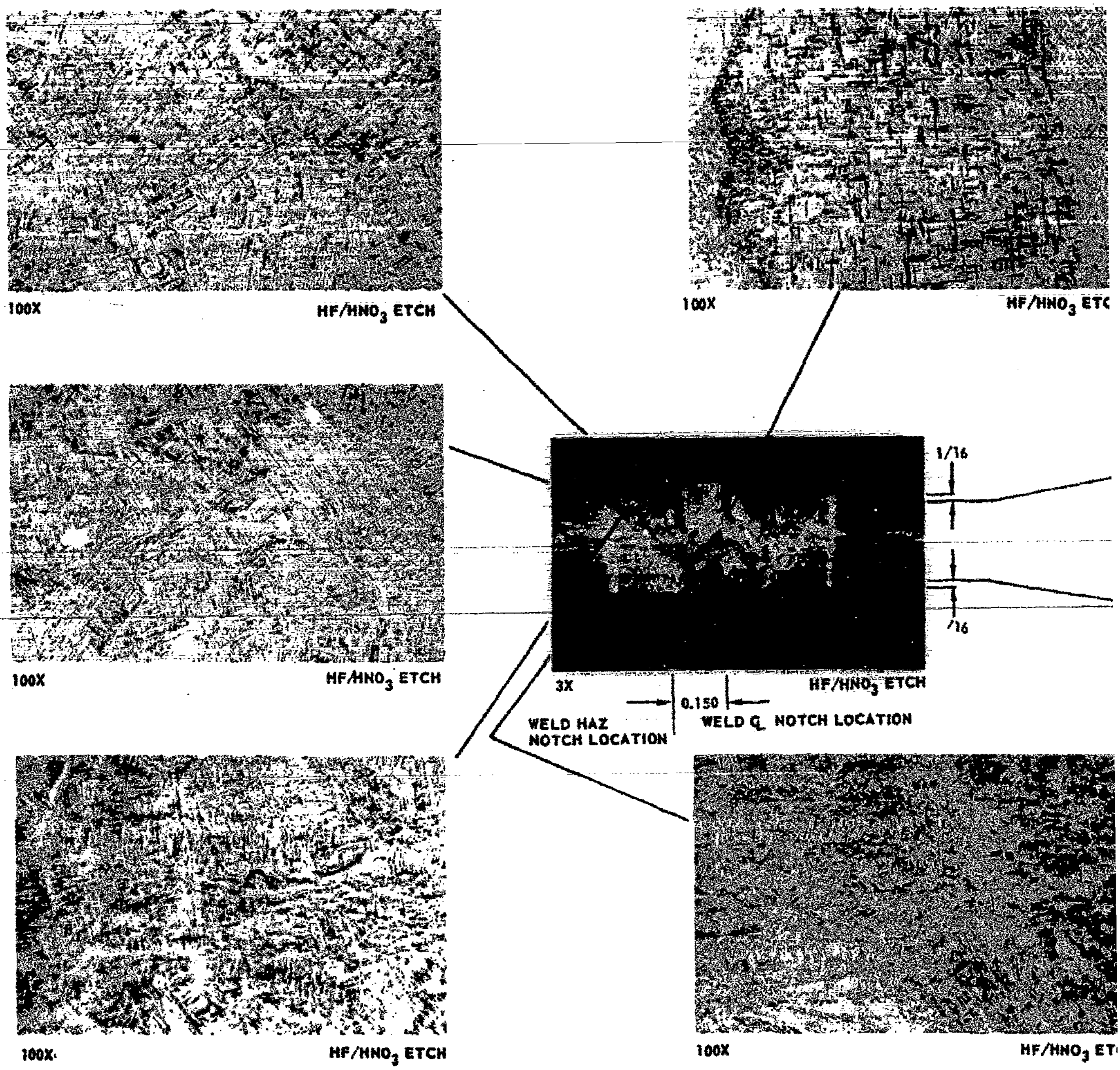




R_c HARDNESS BY KNOOP CONVERSION, 500 GM LOAD

B.

Figure 38. Flat Position Two Pass Square Butt Weld in 0.250-in.-Thick 6Al-4V Titanium Plate (Cond STA), Commercially Pure Titanium Filler Wire HT 301525 Added on Second Pass.


100X
HF/HNO3 ETCH
100X
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HF/HNO3 ETCH
1/16
/16
3X
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WELD HAZ
NOTCH LOCATION
WELD ℄ NOTCH LOCATION
100X
HF/HNO3 ETCH
100X
HF/HNO3 ET

A.

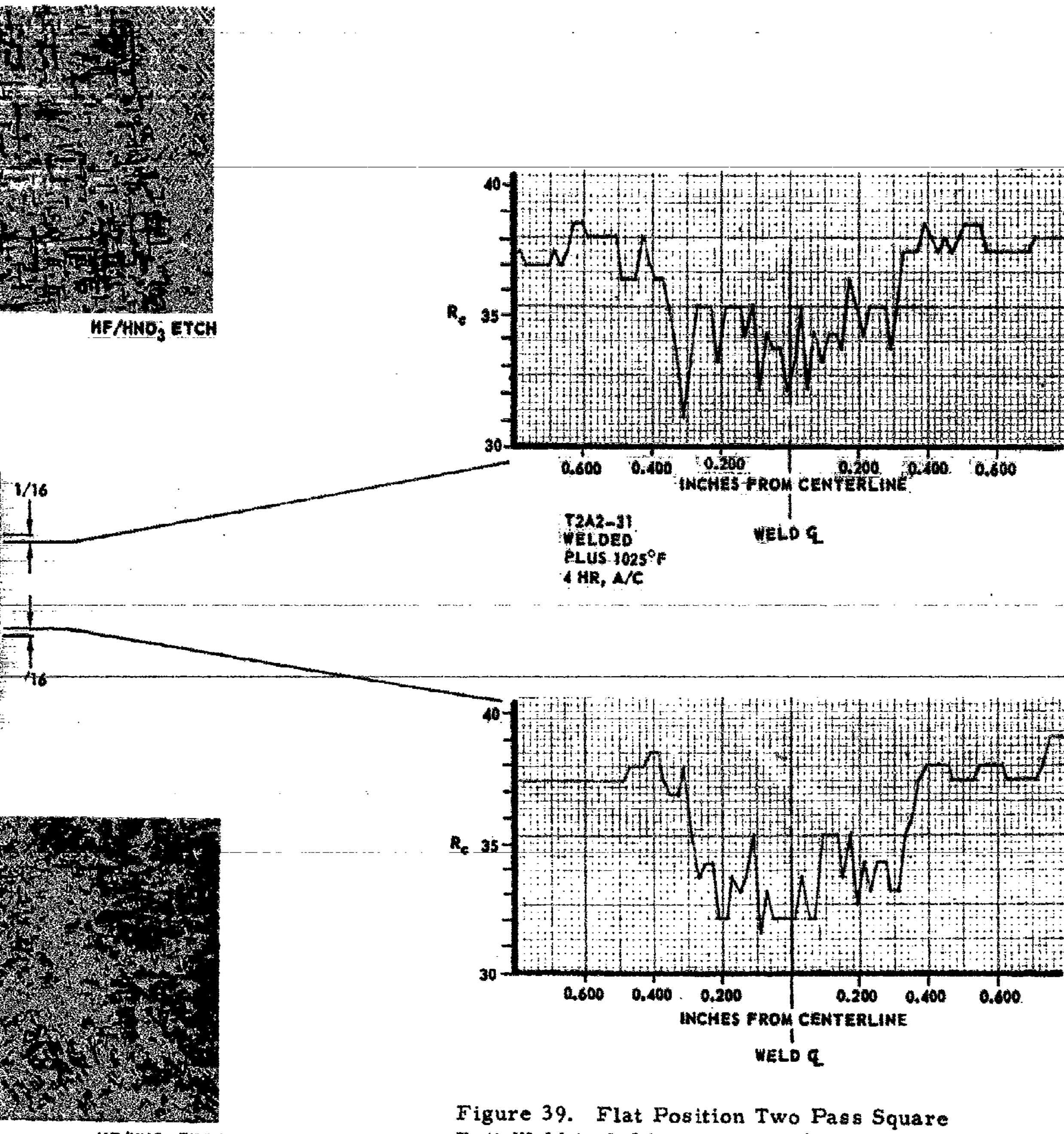
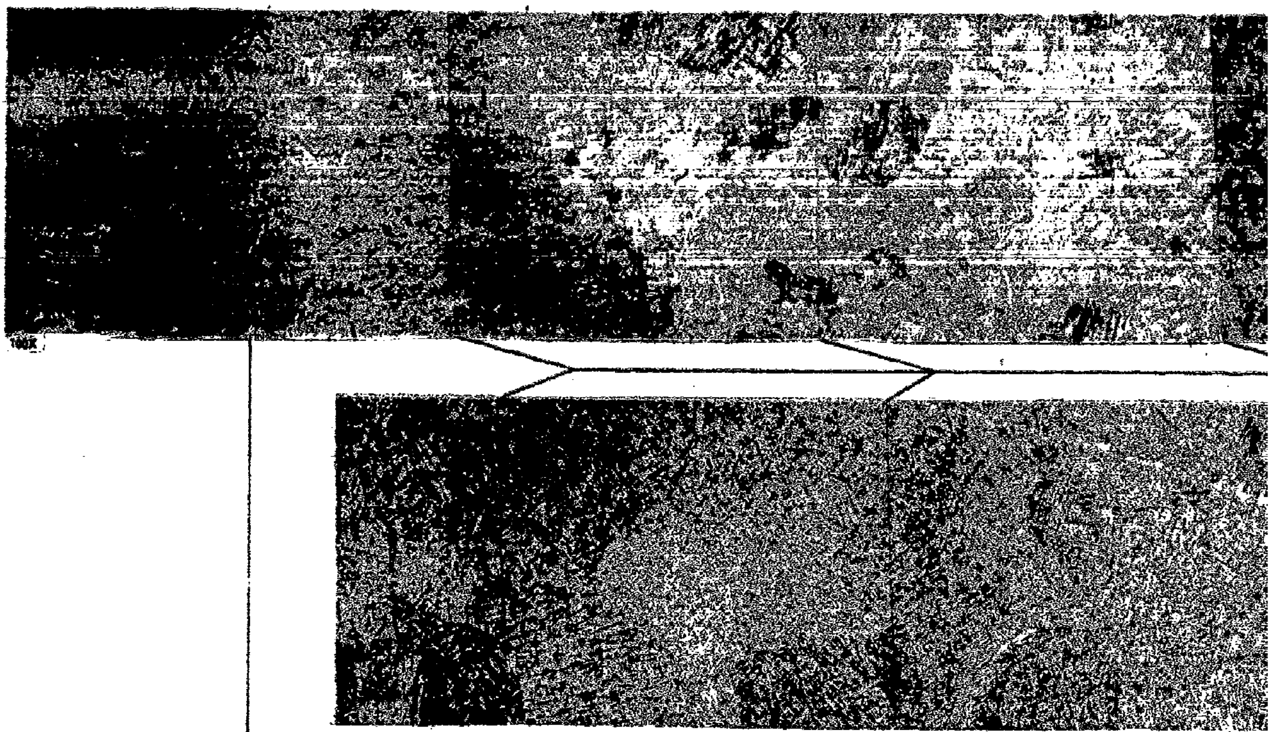


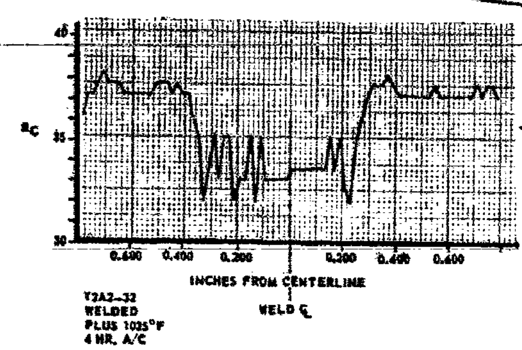
Figure 39. Flat Position Two Pass Square Butt Weld in 0.250-in.-Thick 6Al-4V Titanium Plate (Cond STA), Filler Wire HT 3204-DI (6Al-4V Ti, ELI Grade) Added on Second Pass at 12-ipm Weld Speed.

B.

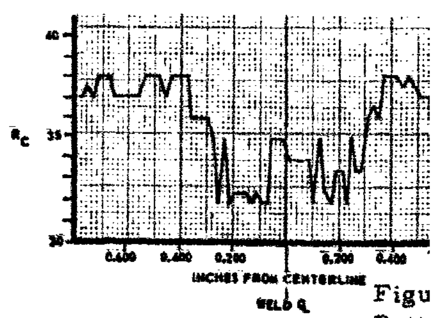
NOT REPRODUCIBLE

NO





MICROSTRUCTURE



Figu
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Pass

A.

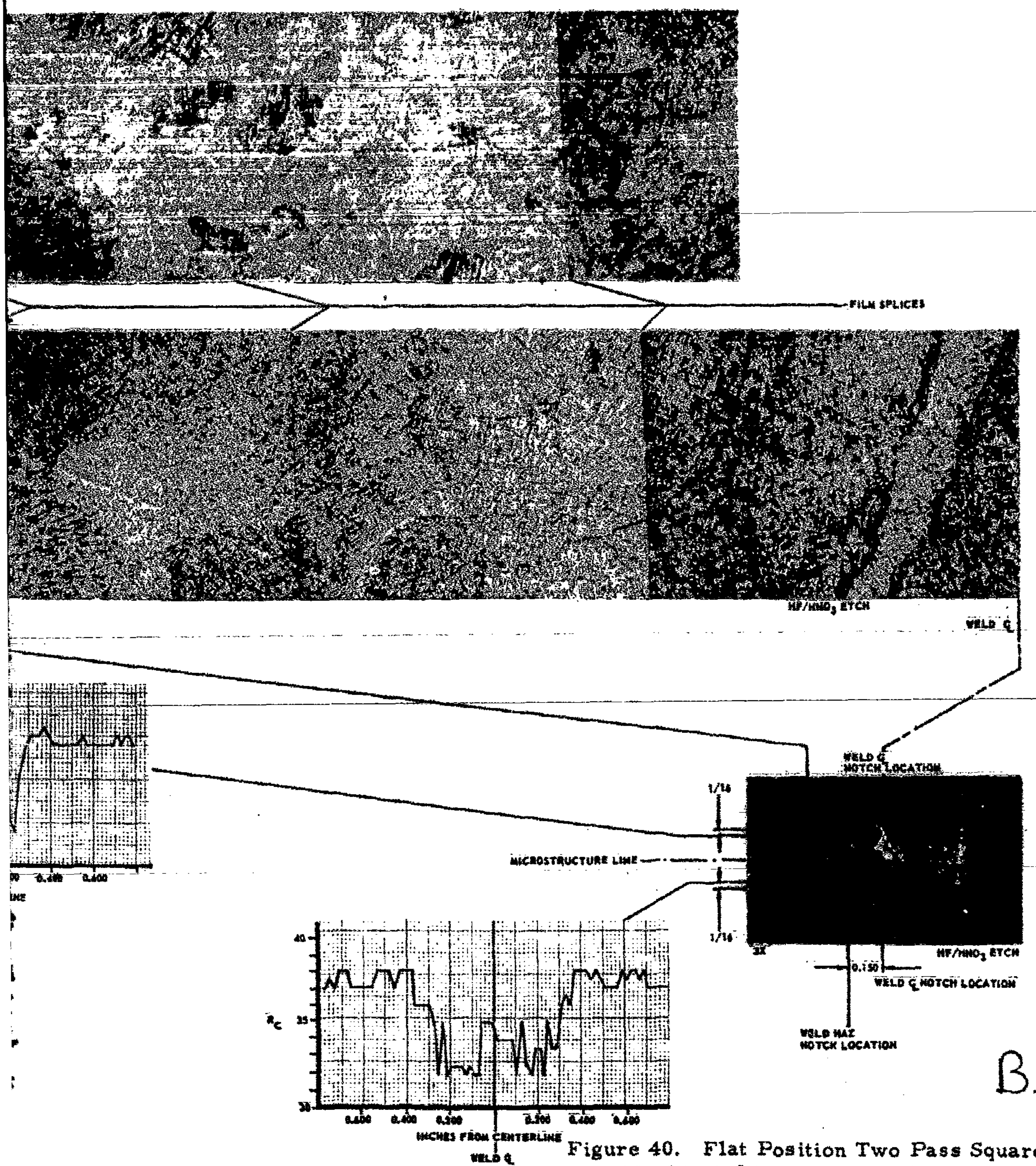
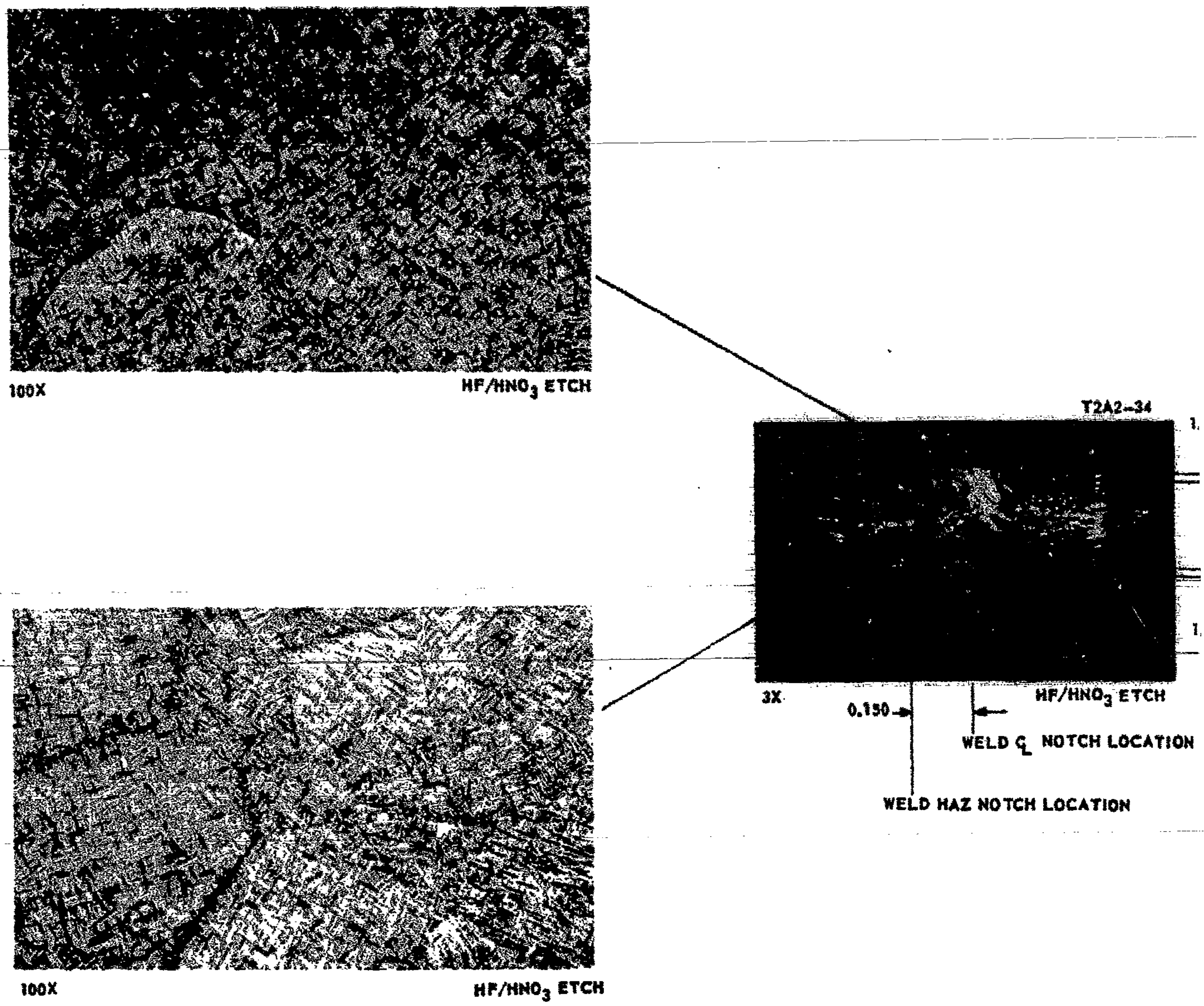


Figure 40. Flat Position Two Pass Square Butt Weld in 0.250-in.-Thick 6Al-4V Titanium Plate (Cond STA) Filler Wire HT 3204-D1 (6Al-4V Ti, ELI Grade) Added on Second Pass at 15-ipm Weld Speed.

NOT REPRODUCIBLE



A.

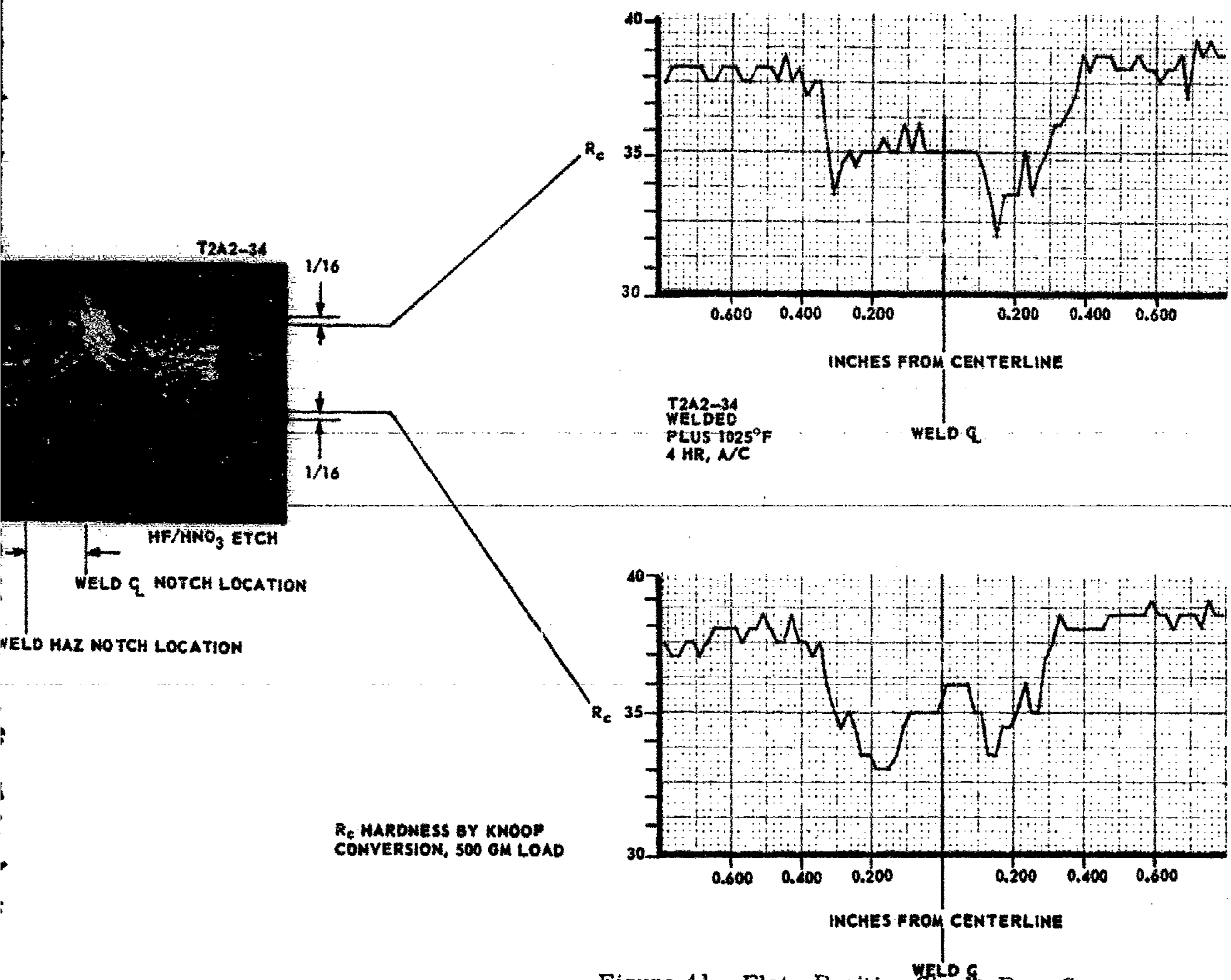
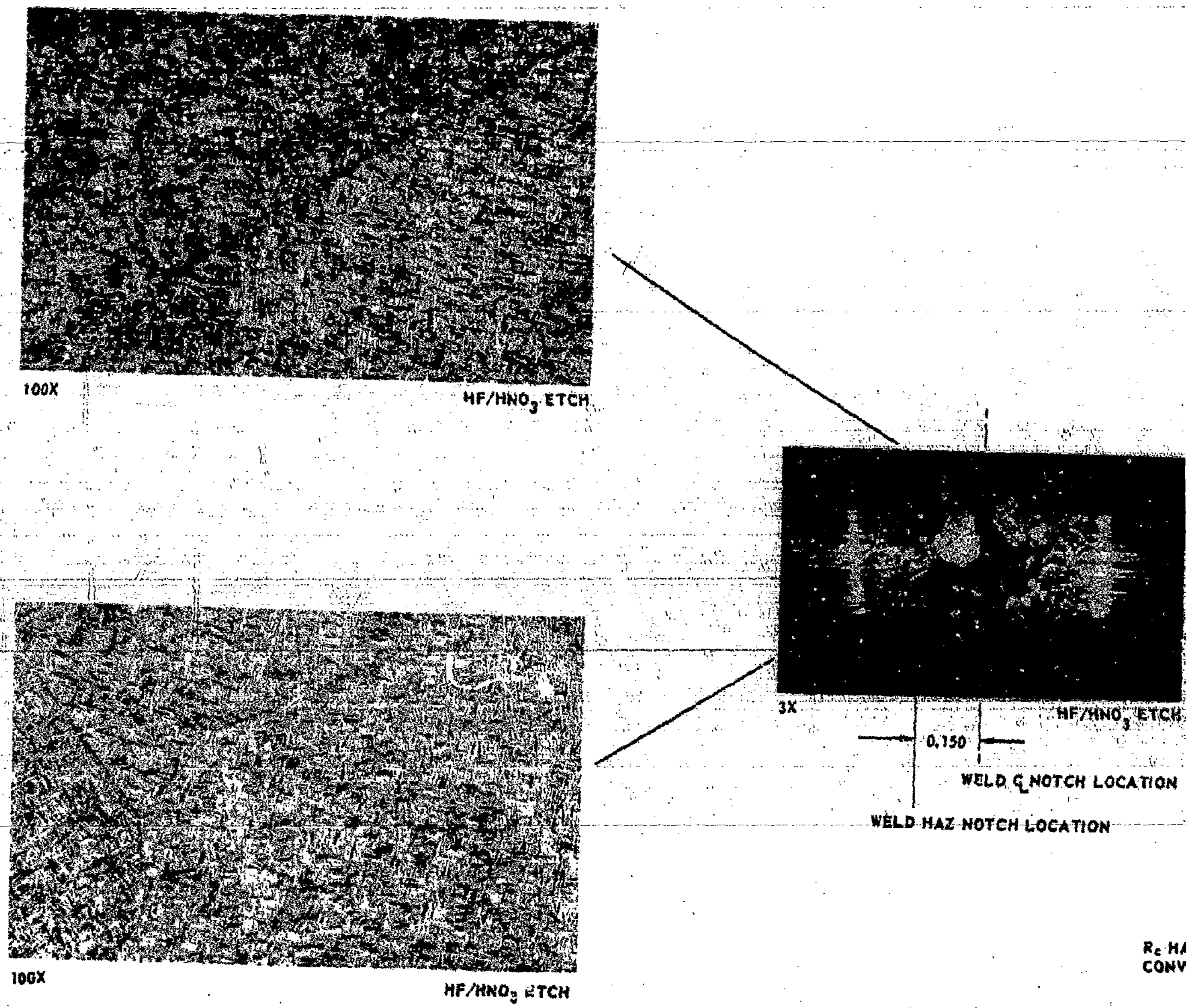


Figure 41. Flat Position Single Pass Square Butt Weld in 0.250-in.-Thick 6Al-4V Titanium Plate (Cond STA).

B.

NOT REPRODUCIBLE



R_c HA
CONV

A.

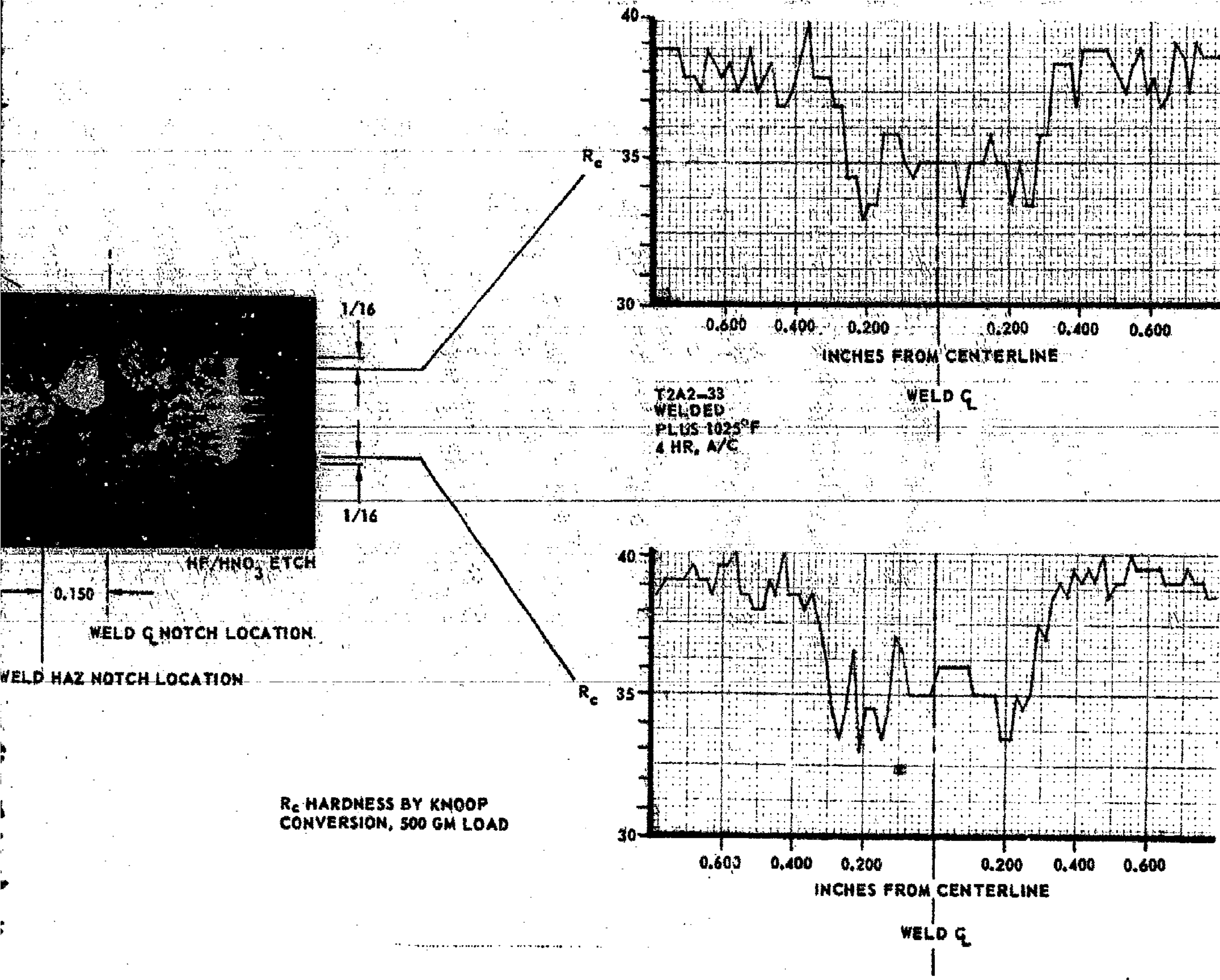
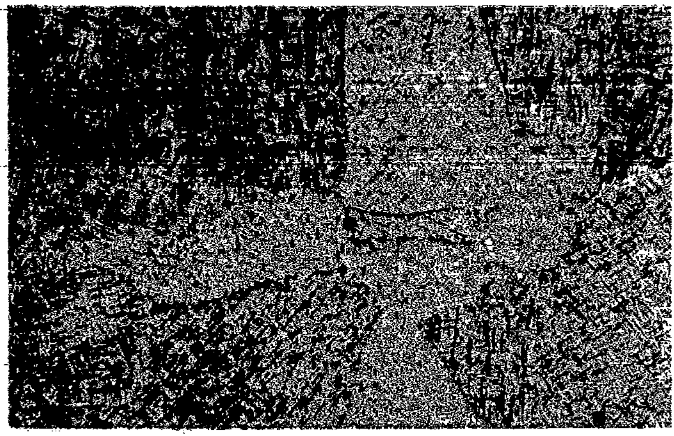


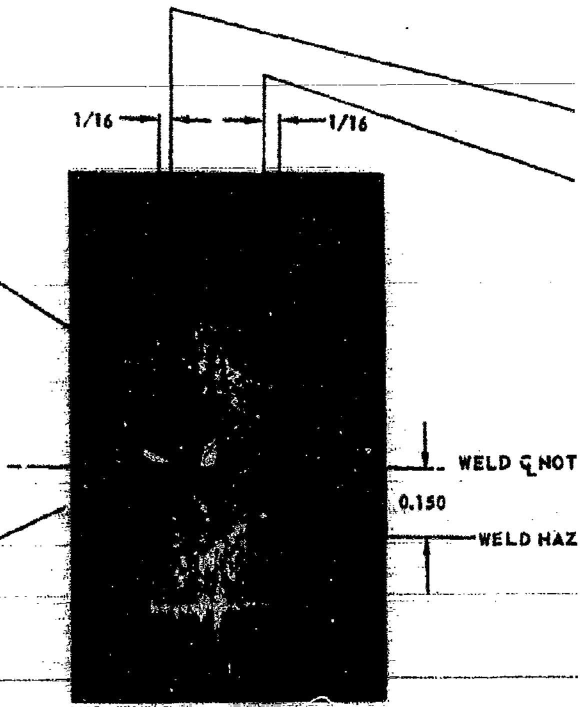
Figure 42. Area Where Three Keyhole Passes Were Made in Flat Position Square Butt Weld in 0.250-in.-Thick 6Al-4V Titanium Plate (Cond STA).

B.

NOT REPRODUCIBLE

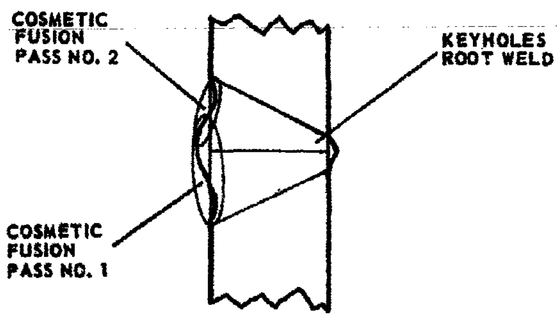


100X HF/HNO_3 ETCH



3X HF/HNO_3 ETCH

100X HF/HNO_3 ETCH



WELDING SEQUENCE – NOTE THAT NO FILLER WIRE IS USED

A.

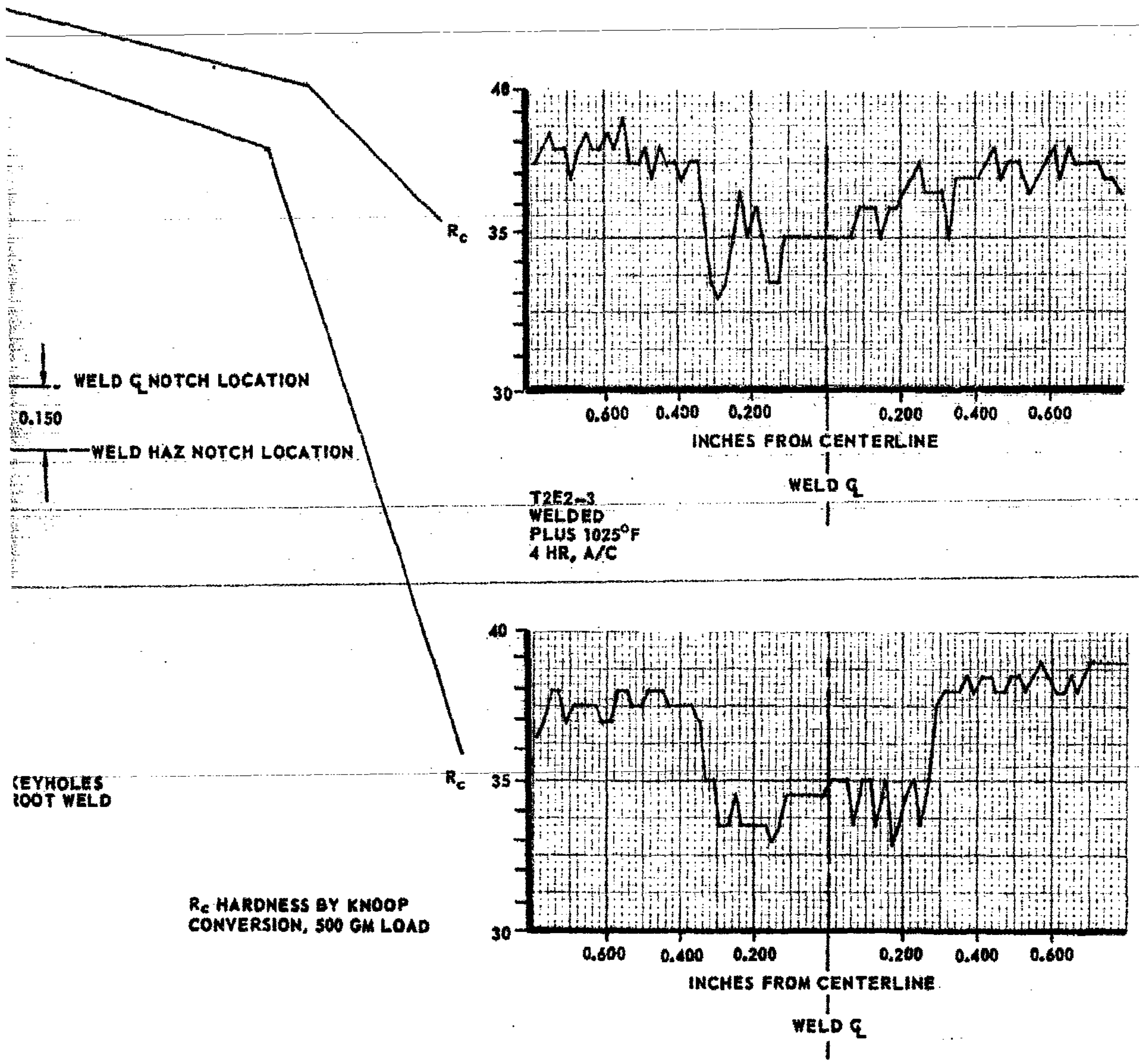


Figure 43. Horizontal Position Square Butt Weld, 0.250-in.-Thick 6Al-4V Titanium Plate (Condition STA).

B.

Table IV. Tensile Test Results.

Weld Description	Transweld Tensile Properties at Room Temperature	
	Ultimate Tensile Strength (ksi)	Elongation (in 1 in.) (%)
Flat Position welds		
Single pass keyhole mode weld	156.4	5.7
Overlap area (above weld)	158.0	7.3
Two keyhole mode welds	156.9	6.0
Overlap area (above weld)	157.7	6.3
Single pass keyhole mode weld covered with one pass, using commercially pure titanium wire	160.9	8.0
Overlap area (above weld)	160.6	8.0
Single pass keyhole mode weld covered with one pass, using 6Al-4V alloy wire at 12 ipm	161.3	6.0
Single pass keyhole mode weld covered with one pass, using 6Al-4V alloy wire at 15 ipm	161.9	7.6
Horizontal position weld		
Single pass keyhole mode weld covered in two passes, without using any filler wire addition	161.6	9.3

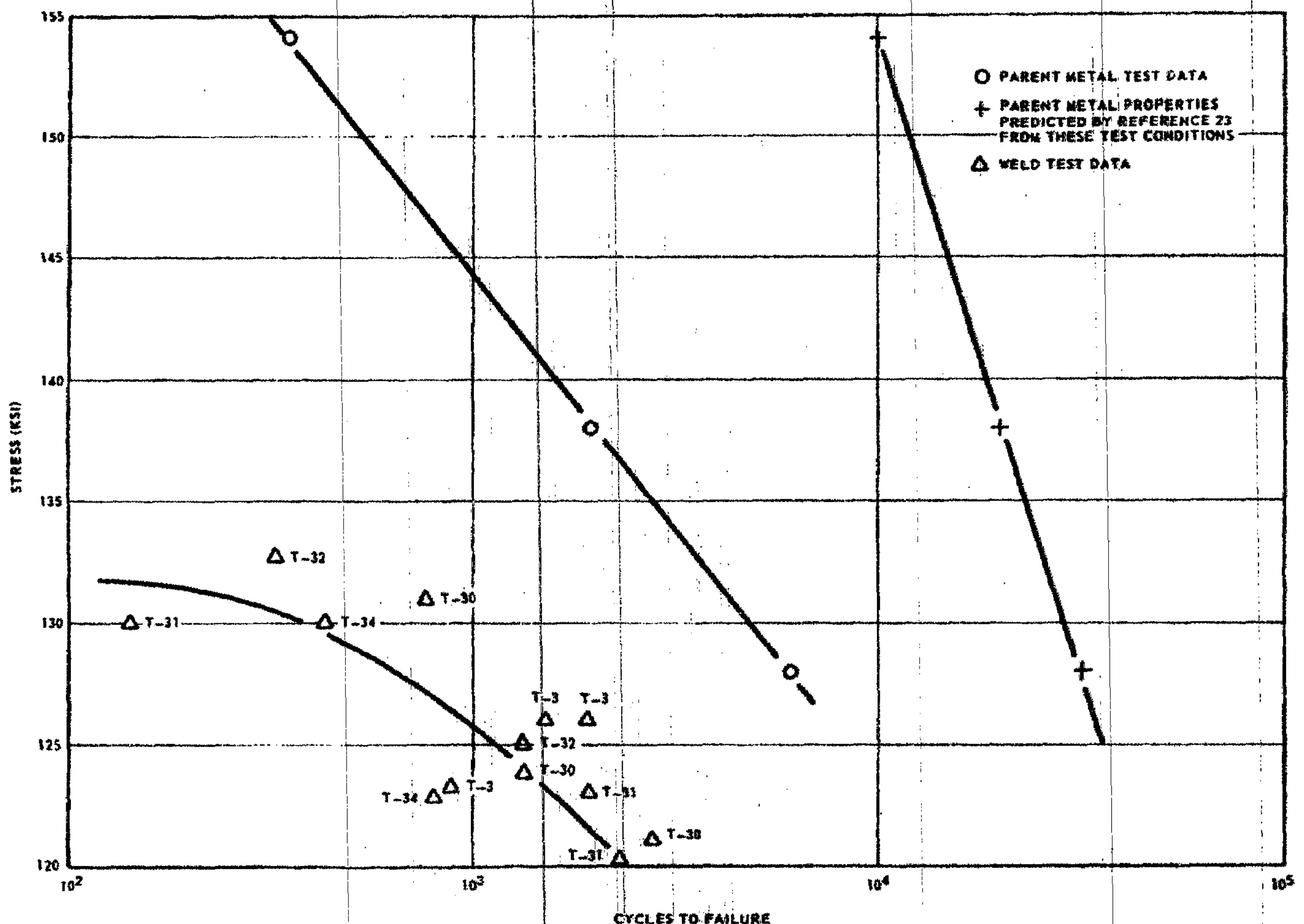


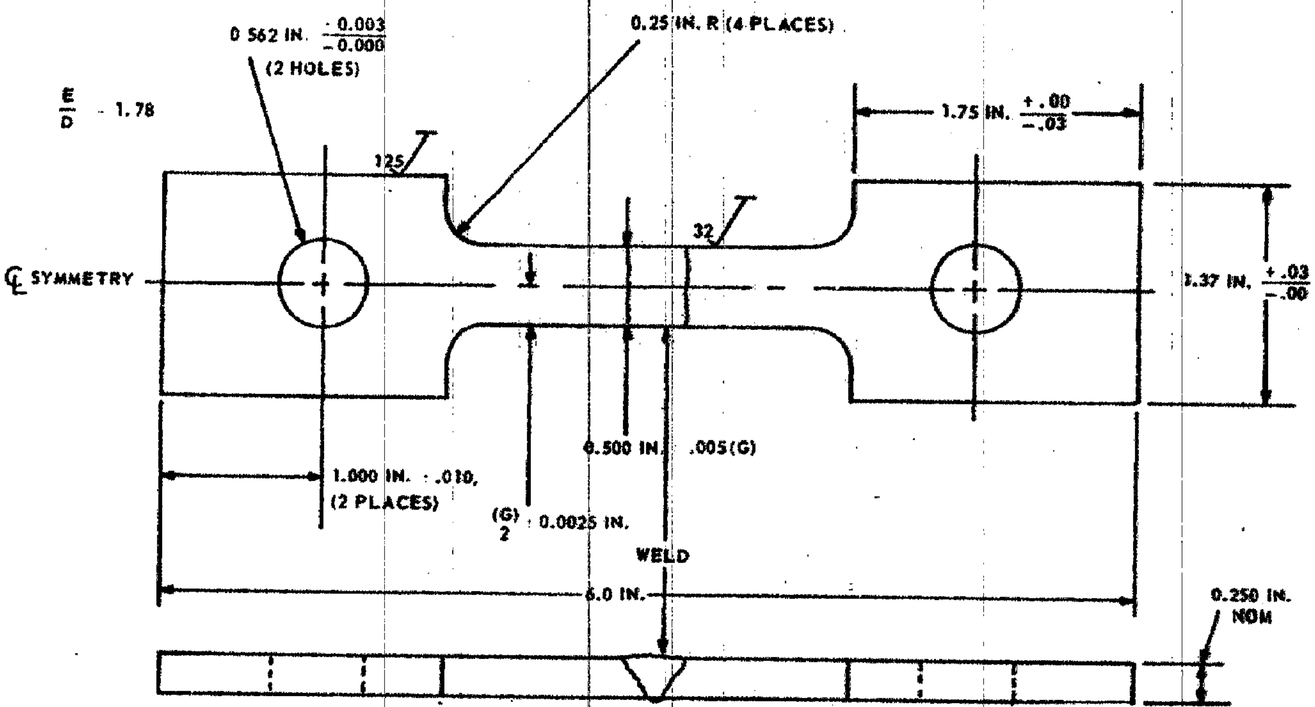
Figure 44. Low Cycle Fatigue Life Data on Parent Metal and Plasma Arc Welds in 0.250-in.-Thick 6Al-4V Plate.

The consistency in the transweld tensile properties of welds made with the conditions of Figure 27 (PT-8 torch) is remarkable. The information obtained for the single U-5T weld (T2A2-14) does not constitute enough work for extensive comment; this weld did exhibit lower strength than PT-8 welds. The transweld tensile strength of two pass PT-8 welds was between 157 and 162 ksi, for welds made in two heats of material using different backing bar spacing; this tends to substantiate consistency observations.

Tensile testing of specimens machined to the Figure 45 configuration produced fractures that characteristically followed a plane diagonal to the weld surface about 1/16 in. away from the fusion zone boundary (see Figure 46). This suggests a plane of low ductility exists that is closely related to the weld fusion zone boundary. Hardness surveys of this area (Figures 38 through 43) show that there is a definite zone of reduced hardness extending about 3/16 in. beyond the fusion zone boundary in all cases.

Precrack Charpy impact test specimens were taken from weld centerline locations in nine different welds (Table III); the properties of the heat-affected zone were evaluated using specimens taken from four welds. Two parent metal heats were evaluated. The PCI blanks were cut from weld locations shown in Figure 47. The orientation of the notch at the weld centerline and heat-affected zone positions with respect to the weld are also shown in Figure 47. PCI specimen dimensions and fatigue precrack tolerances are shown in Figure 48. The notch for all heat-affected zone evaluations was placed 0.150 in. away from the weld centerline (see Figures 38 through 43). This location placed the heat-affected zone notch in a position intersecting the characteristic fracture path observed in transweld tensile tests. The PCI specimens were stress-relieved along with weld tensile specimens, ground to size and notched, then fatigue precracked on a Man-Labs fatigue loading machine (Figure 49). Impact testing was conducted with a Man-Labs Impact Testing Machine, Model CIM-24 (Figure 49), capable of delivering a maximum force of 24 ft-lb. This machine was calibrated to record fracture absorption energy within a tolerance of less than $\pm$ 0.10 ft-lb. Parent metal, weld, and heat affected zone energy absorption levels were converted to inch-pounds per square inch of fracture surface, using standard practices, and are reported in Table III. Selected fracture surfaces are shown in Figure 50.

The transverse parent metal PCI properties measured for both heats tested are reasonable values for normal interstitial level 6Al-4V titanium in the



NOTES:

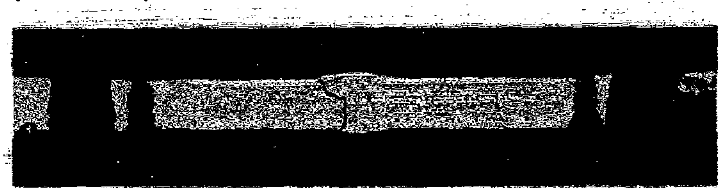
1. ENDS OF REDUCED SECTION SHALL NOT BE NARROWER THAN CENTER; REDUCED SECTION MAY TAPER TO GREATER WIDTH AT ENDS, FROM CENTER, WITHIN INDICATED TOLERANCES.
2. LOAD TABS TO BE SYMMETRICAL ABOUT CENTERLINE OF PIN HOLES.
3. LEAVE WELD REINFORCEMENTS AS-WELDED.

3009-2-J-1

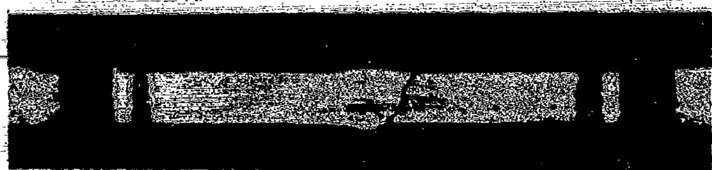
Figure 45. Tensile Specimen Design; 1/4-in. Plate Materials.

T2A2-30 TYPICAL TENSILE FAILURE
(2 PASS WELD)

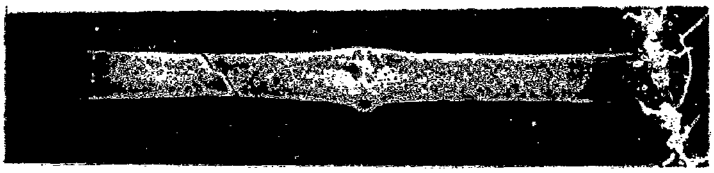
T2A2-34 TYPICAL TENSILE FAILURE
(1 PASS WELD)



T2A2-30 TYPICAL FATIGUE FAILURE
(2 PASS WELD)
(CP WIRE COVER PASS)

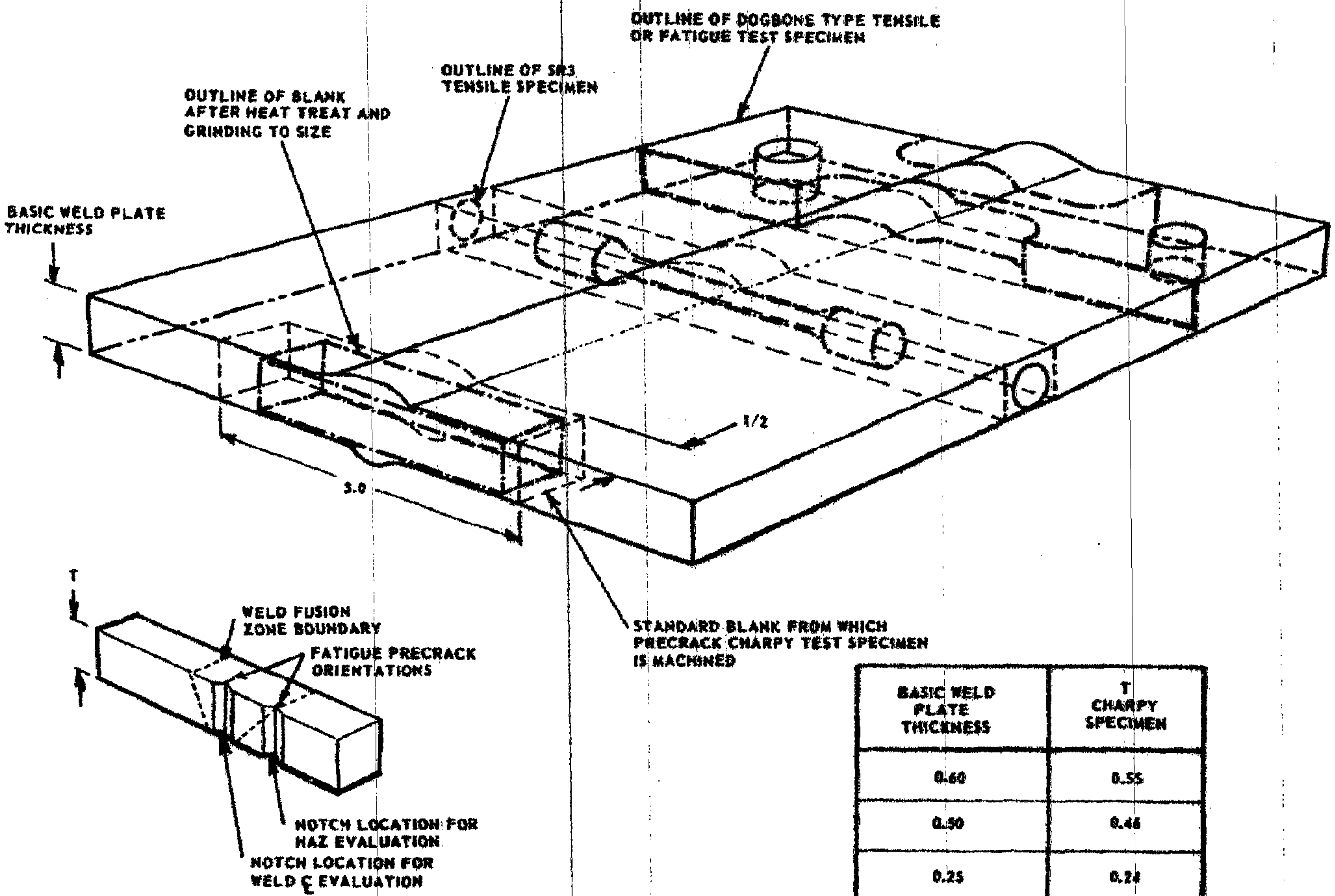


T2A2-32 TYPICAL FATIGUE FAILURE
(2 PASS WELD)
(6Al-4V Ti
WIRE COVER PASS)



K1A2-10 TYPICAL TENSILE FAILURE

Figure 46. Characteristic Weld Fracture Paths in Titanium and Inconel 718, 0.25-in. Thick.



BASIC WELD PLATE THICKNESS	T CHARPY SPECIMEN
0.60	0.55
0.50	0.46
0.25	0.24

Figure 47. Location and Orientation of Transweld Fatigue and Precrack Charpy Test Specimens.

2.3.2 Inconel 718, Nominally 0.25 in. Thick

2.3.2.1 Keyhole Mode Weld Procedure Development

The welding performed on Inconel 718 was intended to develop data similar to that reported for 0.25-in.-thick 6Al-4V titanium. Welds were initially keyholed in plate without a machined joint, using the PT-8 torch, to select plasma arc conditions for welding at 6 ipm; the U-5T was not used for the first welds in this material because Thermal Dynamics personnel were evaluating different electrode configurations. Difficulties were encountered in obtaining adequate weld top bead shielding, primarily because the first 20% of this welding was accomplished without the trailing shield in Figure 12. Air contamination of the weld top bead surface in Inconel 718 had much greater influence on molten weld metal flow characteristics than in titanium. Preweld cleaning of all plate surfaces, with silicon carbide abrasive discs appeared to provide optimum cleanliness for welding.

Flat position keyhole mode welds were readily produced; cross sections from the first weld attempted are shown in Figure 54. The weld fusion zone configuration is very similar to that of single-pass keyhole welds in titanium. The root bead melt-thru is somewhat heavier than in titanium, but top bead surfaces are almost free of underfill. Welds were made to investigate the effects of small variations in weld conditions on fusion zone geometry, and Figure 55 illustrates three important effects. Weld heat input and arc energy-density varied considerably with standoff variations when small amounts of hydrogen were present, even when hydrogen was used only in the shield gas stream. Satisfactory keyhole mode welds were obtained using pure argon orifice gas, and little additional work was done with hydrogen mixtures, mostly because of effects in exaggerating heat input during small standoff variations. Variation in fusion zone geometry was caused by unsatisfactory top bead gas shielding, and is illustrated by sections from Weld K1A2-1 in Figure 55. This weld is made with the trailing shield illustrated in Figure 14. The relative heaviness of root bead melt-thru caused by the PT-8 torch outer shield configuration is illustrated in sections taken from Welds K1A2-5 and K1A2-8. Keyhole weld root bead smoothness and uniformity were directly related to the stability of the keyholing process. An unstable keyhole could be identified by observing the weld puddle top surface behind the keyhole; fluttering in the molten puddle surface was one kind of instability and, for the welds made in 0.25-in.-thick Inconel 718, this was always associated with root bead roughness and nonuniformity. Weld heat input and orifice gas flow settings governed keyhole stability to a large extent, but in this material the configuration of the torch outer shield also affected keyhole stability and could contribute to measurable variation in root bead smoothness. This shield

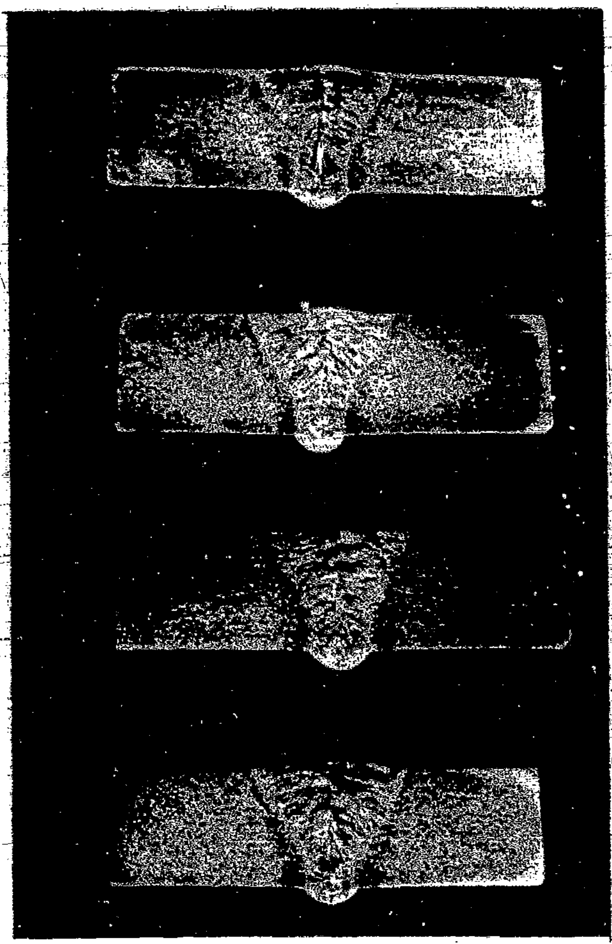


Figure 54. Single Pass Flat Position Plasma Arc Welds in 3009-2-AB 0.250-in.-Thick Inconel Alloy 718, No Filler Wire Added; as-Welded.

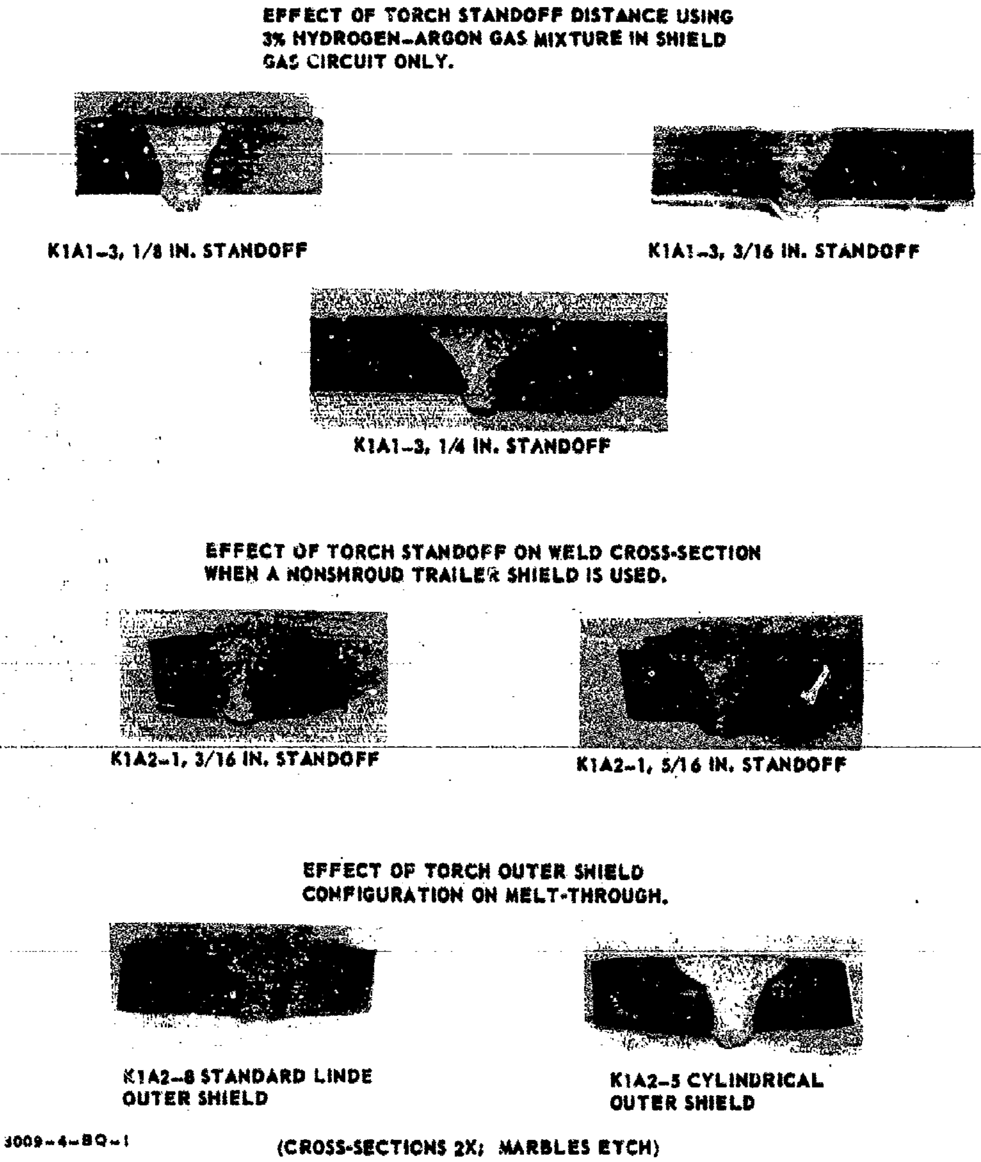


Figure 55. Flat Position Butt Weld Cross Sections from 0.25-in.-Thick Inconel 718 Plate; PT-8 Torch, As-Welded.

configuration influenced the stability of the keyhole (when using the PT-8) torch by interferring with the plasma flame component that normally is deflected back over the weld puddle away from the direction of travel. Two outer shield designs were examined; these were the standard Linde vented nozzle and a nonvented cylindrical wide coverage nozzle. The cylindrical nozzle interfered with plasma flame backflow, creating enough keyhole disturbance to cause a rough and heavy root bead (Figure 56-left side). The standard vented shield, with the vent facing away from the direction of weld travel, produced the smoother root bead (Figure 56-right side). However, if the vent was aligned in a position other than away from travel, the vented shield also caused moderate keyhold instability and root bead roughness.

2.3.2.2 Evaluation of Conditions for Making Circumferential Welds

Conditions for starting and tailing off keyhole mode welds in square butt joints were determined using the PT-8 torch without filler metal addition. Cross sections from Weld K1A2-10 (Figure 57) show that both one- and two-pass areas have satisfactory weld surface configurations; Figure 58 illustrates root bead smoothness. Several welds were made using K1A2-10 conditions; all were visually acceptable, except for some top bead concavity at the keyhole withdrawal point. The U-5T weld shown in Figure 57 was made before the keyhole force problem occurred; note the narrower fusion zone width, compared with the PT-8 weld. A cosmetic cover weld pass without filler wire added was able to eliminate all top bead underfill but did not completely remove tailoff concavity. Manual weld repair using filler addition was necessary. Time phasing of the significant weld variables employed for both keyhole and melt-in mode welds in this alloy is graphically illustrated in Figure 59. This procedure occasionally produced welds without any surface defects, and a very satisfactory melt-in mode cover pass could also be obtained. Argon-hydrogen mixtures were not as critical for cover weld procedures as for keyhole welds.

Visual and X-ray inspection of weld K1A2-10 revealed no defects other than the top bead concavity. Fluorescent penetration inspection (see Appendix VII for acceptance criteria) revealed a root bead defect close to the spot where the overlapping keyhole weld had ceased to penetrate the plate (Figure 58, Section AA). Figure 60 illustrates this defect. The two cracks were in the weld melt-thru and seem to be related with the keyhole withdrawal point. There is evidence that this heat of Inconel 718 is relatively dirty from the standpoint of inclusions. Further, the root bead cracks illustrated in Figure 60 both exhibit a light etching phase on the crack surfaces. The observed potential in this material for keyhole instability, illustrated previously, seems important. It was established later in this

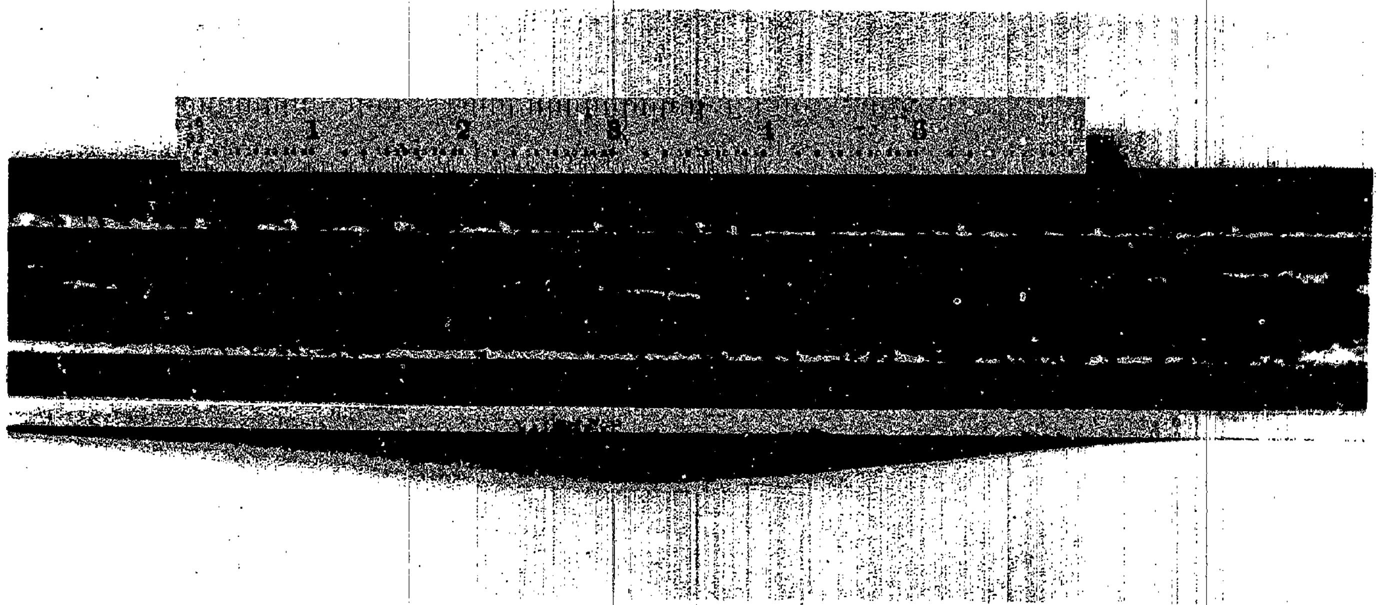
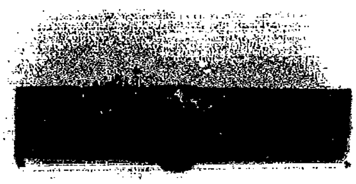


Figure 56. Weld Root Bead Surfaces, 0.25-in.-Thick Inconel Alloy 718, Illustrating Effects of Torch Outer Shield, PT-8.

(CROSS-SECTIONS 2X; MARBLES ETCH)

K1A2-2 U-5T



K1A2-10-1 PT-8

K1A2-10-2 PT-8

3009-4-BR-1

Figure 57. Flat Position Butt Weld Cross Sections From 0.25-in.-Thick Inconel 718; As-Welded (U-5T and PT-8 Torches).

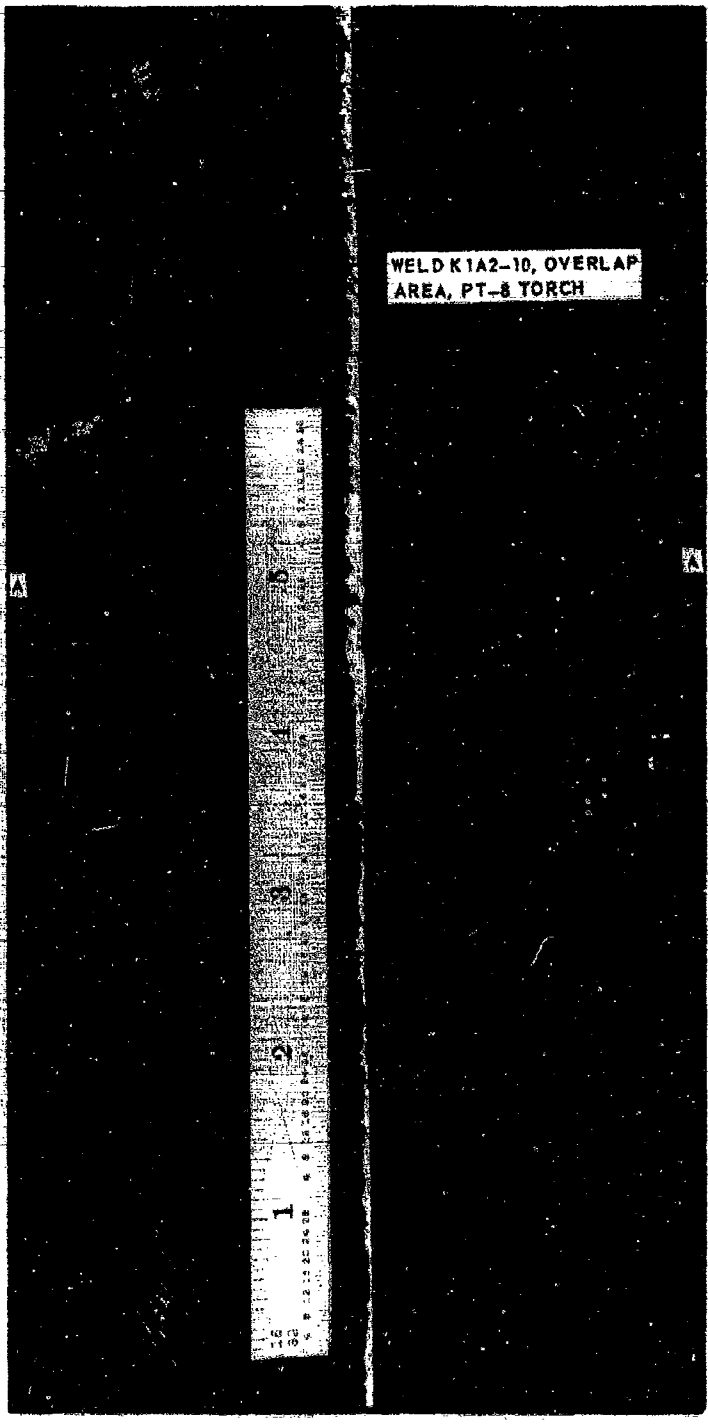


Figure 58. Root Bead Surface, Keyhole Mode Square Butt Used in 0.250-in.-Thick Inconel Alloy 718.

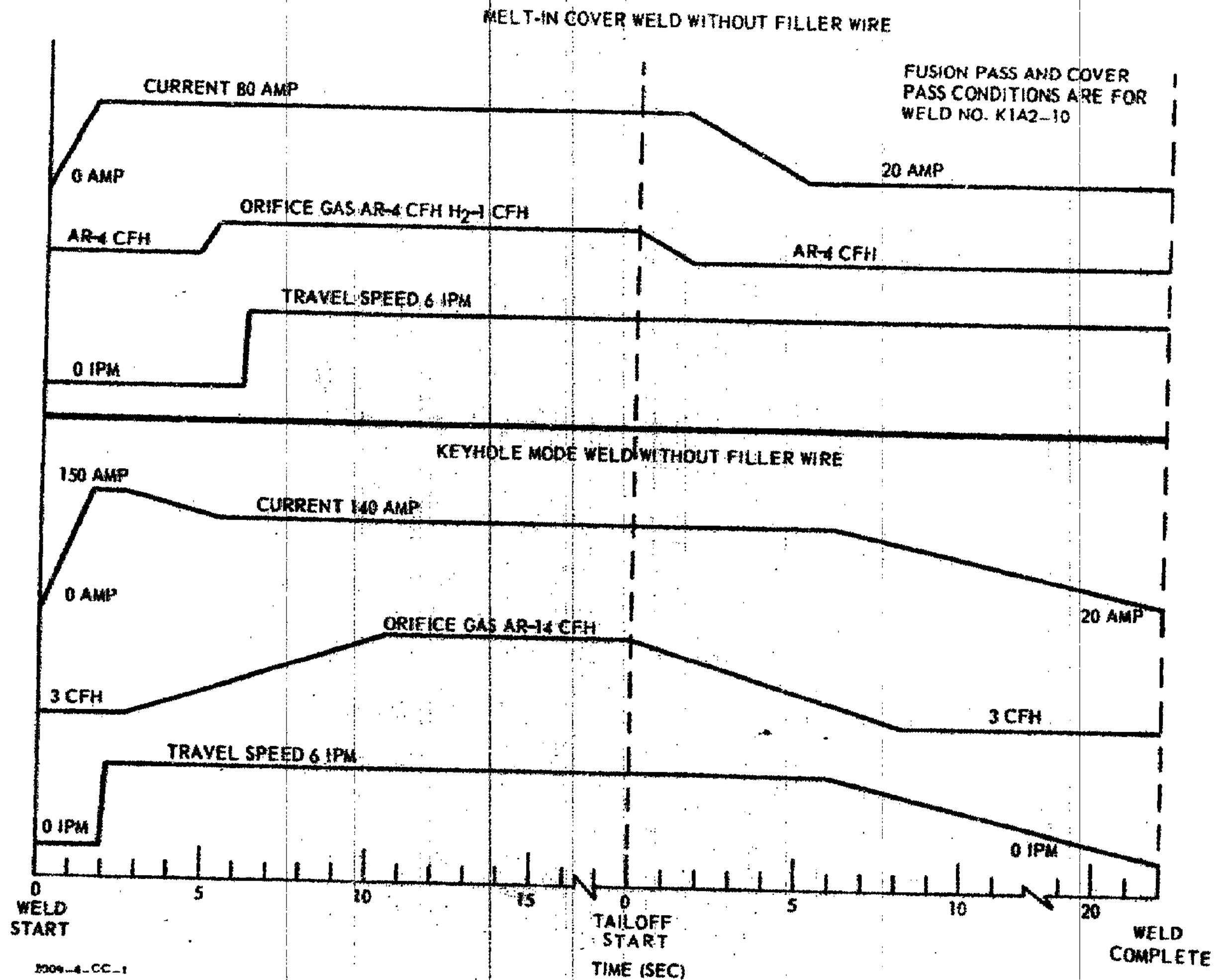


Figure 59. Start and Tailoff Conditions for Single Pass, Flat Position, Square Butt Welds, Without Filler Metal Addition, in 0.25-in.-Thick Inconel 718 Plate, PT-8 Torch.

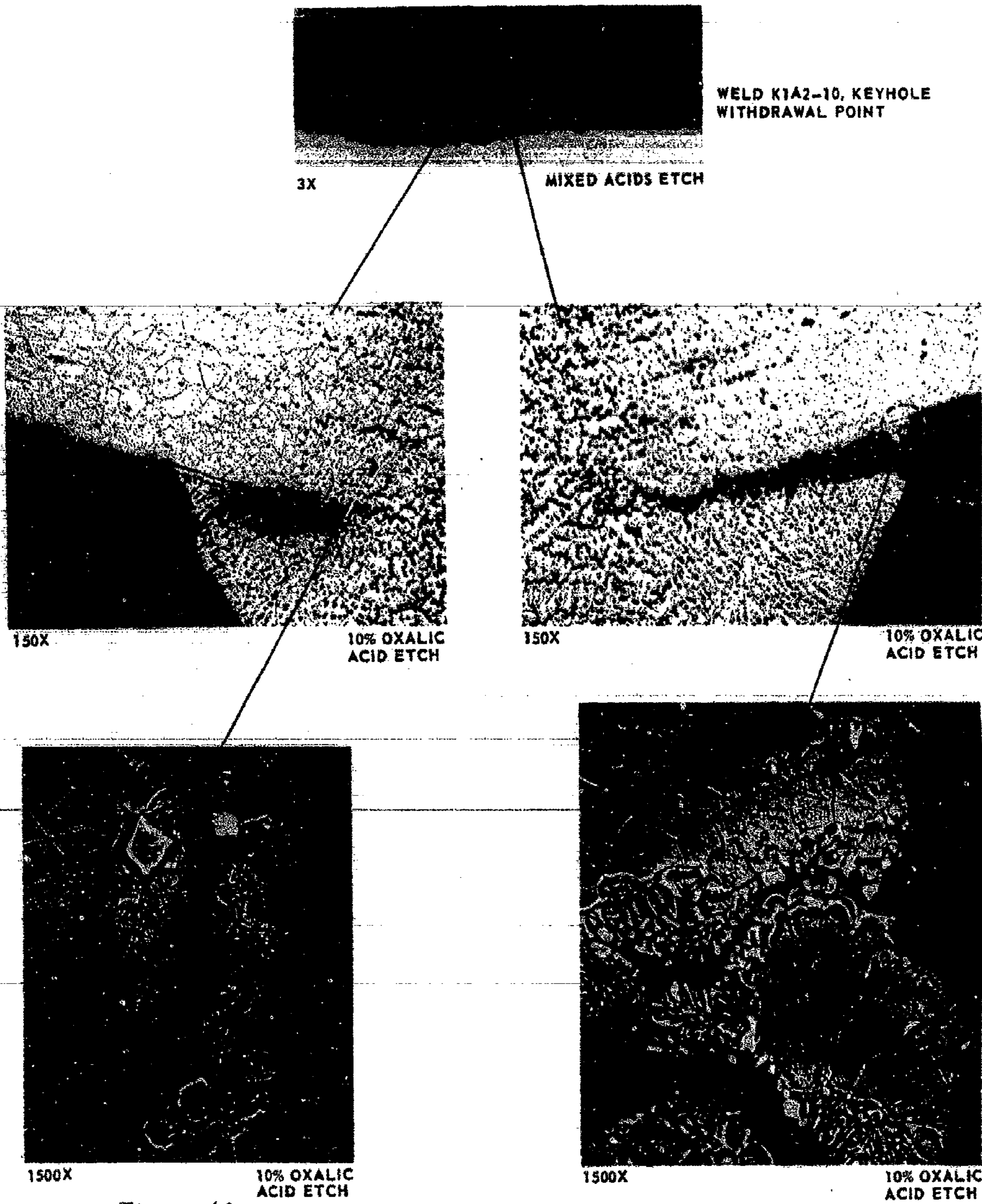


Figure 60. Cross Section (Section AA of Figure 58) of Flat Position Two Pass Square Butt Keyhole Mode Weld in 0.25-in.-Thick Inconel Alloy 718, Illustrating Overlap Problem.

program that keyhole withdrawal in any material was accompanied by a short interval of flutter and turbulence in the weld puddle. Any possible interaction between basic material properties and keyhole withdrawal dynamics relative to this cracking problem was not clear at this point.

Because certain material options existed in this program, it was necessary to decide the extent of further work required with Inconel 718. The cause of the cracking observed may or may not have been associated with some unusual procedural event. Because statistical evaluations were beyond the scope of planned work, it was reluctantly decided to restrict future work on this material to a study of weld properties, and allow the root bead overlap crack problem to remain unsolved. For this reason, no welding was performed at speeds other than 6 ipm.

2.3.2.3 Mechanical Properties Evaluation

Sections from one- and two-pass areas in Weld K1A2-10 were selected for tensile testing; tensile specimen configuration is shown in Figure 45. Weld root and top surface crowns were left intact. Table VI lists composition and tensile test data; all parent metal and weld tensile test specimens were heat-treated prior to test, as shown. Only unnotched tensile tests were made. All the weld test specimens fractured well away from the weld and heat-affected zone, exhibiting uniform elongation without significant localized area reduction at tensile fracture sites (see Figure 46). It is clear that the ductility of the two-pass weld is slightly better than that of the one-pass weld (20% versus 17% in 2 in.). Joint efficiencies, based on averages of transverse parent metal properties, were as follows:

Weld	Joint Efficiency at 0.2% Offset Yield	Joint Efficiency at Ultimate Tensile Stress
K1A2-10 one-pass weld	$\frac{153,800}{156,500} = 99\%$	$\frac{185,600}{188,800} = 98\%$
K1A2-10 two-pass weld	$\frac{156,300}{156,500} = 100\%$	$\frac{186,100}{188,800} = 99\%$

These data relate to welded Inconel 718 intended for tensile limited applications only. The 1950°F solution treatment employed has been shown to be necessary to yield consistently high ductility in welds and heavy forgings; however, this high ductility is reported to be obtained at some expense in stress rupture and notch ductility properties over the 1200° to 1350°F temperature range (Reference 17).

Table VI. Parent Metal and Weld Characteristics.

Material Heat No.	Chemical Composition (% by Weight)														
	Cr	Fe	C	Si	Cb	Ni	Mo	Cb-Ta	Mn	P	S	Al	Ti	B	Cu
218-277	18.97	Balance	0.04	0.22	0.05	52.05	3.09	5.14	0.06	0.001	0.009	0.60	0.85	0.005	0.01
AGC44093 (Reference)	17 to 21	Balance	0.08 (max)	0.45 (max)	1.0 (max)	50 to 55	2.8 to 3.3	4.75 to 5.5	0.45 (max)	0	0.015 (max)	0.10 to 0.80	0.65 to 1.40	0.006 (max)	0.30 (max)

PHYSICAL PROPERTIES DATA

Material		Description of Test and Final PM[a] Rolling Direction vs Direction of Test	Postweld or Pretest Heat-Treat Cycle	Tensile Data					
				0.2% Offset Yield Stress (ksi)	Tensile Strength (ksi)	Elongation		Failure Location	Data Source
Heat No.	Thickness (in.)					% in 1 in.	% in 2 in.		
218-277	0.25	PM	1950°F, 1 hr, 1350°F, 9 hr/ 1200°F for 20-hr total age						Aerojet
		Parallel		157.2	189.8	26.0	21.3	PM	
		Transverse		156.5	198.8	25.3	21.6	PM	
218-277	0.25	PM direction of rolling relative to direction of test not indicated.	1800°F, 1 hr, 1325°F, 8 hr/ 1150°F for 20-hr total age	158.1	195.0		19.0	PM	Vendor certification
218-277	0.25	K1A2-10, transweld test, transverse to grain direction	1950°F, 1 hr, 1350°F, 9 hr/ 1200°F for 20-hr total age						Aerojet
		One pass area[b]		153.8	185.6	23.3	17.2	PM	
		Two pass area[b]		156.3	186.1	27.4	28.5	PM	

a. Parent Metal.

b. Weld reinforcement left in as-welded condition.

2.3.3 Rene 41, Nominally 0.063 in. Thick

This material was evaluated because the feasibility of using these plasma arc torches for welding high-strength materials in sheet metal thicknesses had not been established. This thickness range is such that melt-in mode plasma arc welding techniques are suggested.

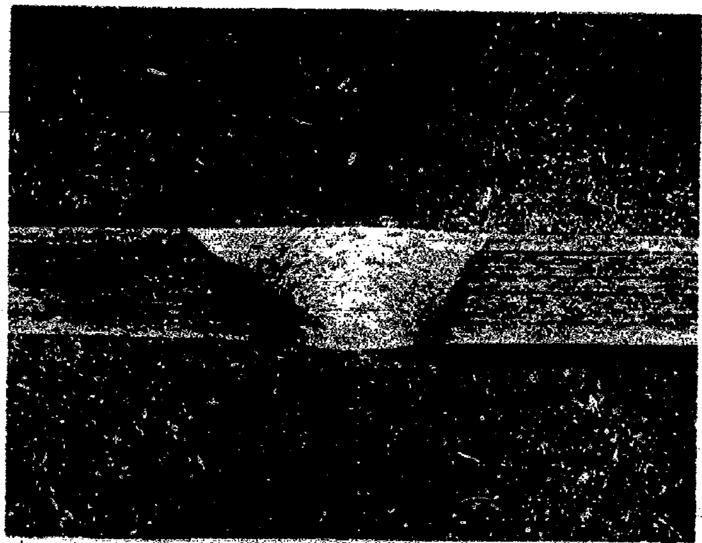
Melt-in mode welding conditions were examined by welding at 31 ipm (the maximum speed possible with the Aerojet equipment) and adjusting welding conditions to obtain reasonably satisfactory welds. The initial welds were made using He75 orifice gas with the PT-8 torch. Figure 61 illustrates the effects of current on fusion zone geometry. Weld top surface oxidation was heavier than it should be when He75 orifice gas was used. Hydrogen mixtures were then investigated; however, this was before the multifunction plasma gas control panel illustrated in Figure 7 was available, so premixed gas was used. Figure 62 illustrates the effects of torch standoff on fusion zone geometry in this material.

The U-5T torch was employed for welding this material using only the 7.5% hydrogen-argon gas mixture. Figure 63 illustrates effects of standoff distance on fusion zone geometry. The conditions employed produced melt-in mode welds; however, it was possible to keyhole with the U-5T in this material. The keyhole was quite unstable and undercut was severe. The melt-in mode arc was not as unstable as the keyhole arc, but, at standoff distances greater than 0.25 in., the melt-in arc developed some directional instability.

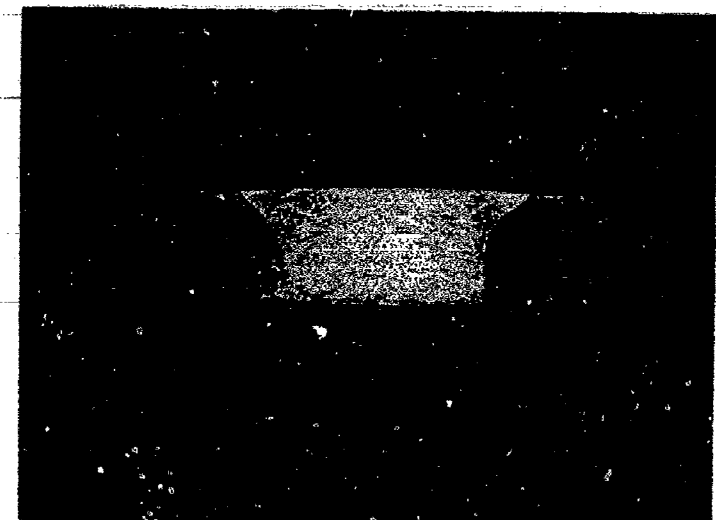
Because weld surface shielding inconsistencies created problems in this material, a trailing shield was found to be essential. The shield gas coverage provided by the standard shield components on both PT-8 and U-5T torches was inadequate to prevent weld top bead oxidation on welds in Rene 41 sheet.

Square butt welds were made with both torches. Figure 64 illustrates weld cross sections obtained. These welds (R1A2-1 and R1A2-2) were inspected carefully. The top bead surfaces of both welds appeared acceptable, as were the root beads. The cross sections examined were free of voids and fissures in fusion and heat-affected zones. Start and stop areas were not acceptable, but there is no question that acceptable quality could be obtained in these areas with slightly altered welding conditions.

X-rays of Weld R1A2-1 disclosed no internal defects, but discontinuous top bead undercut was indicated. Start and stop areas were unacceptable.



R1A1-1 105 AMP, 7/32 IN. STANDOFF, 31 IPM

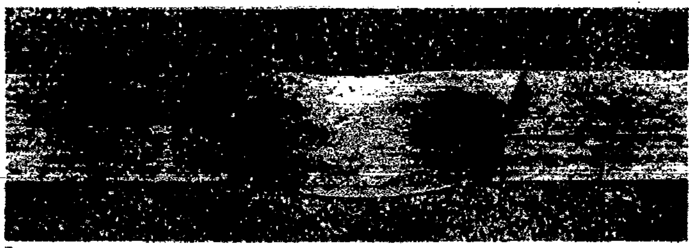


R1A1-2, 115 AMP, 7/32 IN. STANDOFF, 31 IPM

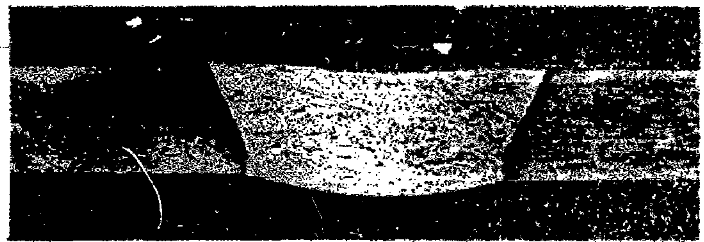
Figure 61. Cross Sections from Single Pass Flat Position Plasma Arc Weld in 0.062-in.-Thick Rene 41 Sheet, No Filler Wire Added, as-Welded (He 75 Orifice Gas).

3009-2-AF-1

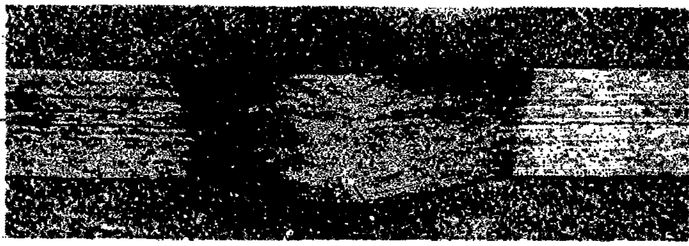
PT-8 TORCH
111-M ORIFICE
3/32 IN. DIAMETER ELECTRODE



R1A1-4-1 115 AMP, 1/8 IN. STANDOFF,
31 IPM



R1A1-4-1 115 AMP, 3/16 IN. STANDOFF,
31 IPM



R1A1-4-1 115 AMP, 1/4 IN. STANDOFF,
31 IPM

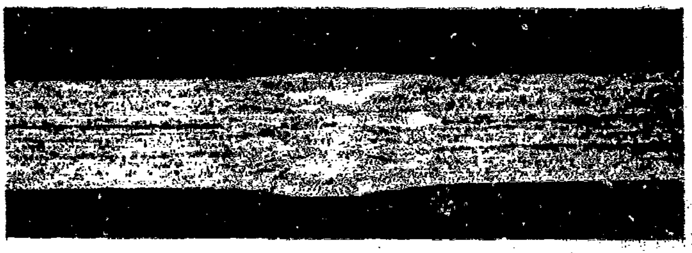
R1A1-4-1 115 AMP, 5/16 IN STANDOFF,
31 IPM

Figure 62. Effects of Torch Standoff Distance on Plasma Arc Weld in 0.062-in.-Thick Rene 41 Sheet, PT-8 Torch, Single Pass Flat Position Weld, No Filler Wire Added, as-Welded.

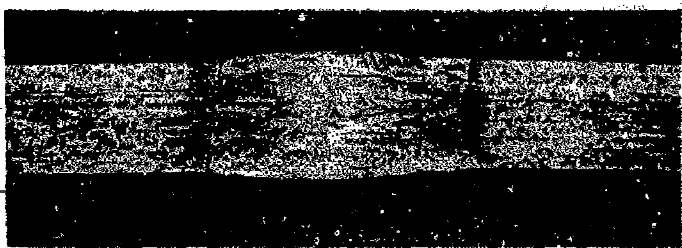
U-5T TORCH

1/16 IN. ORIFICE, 1/16 IN. DIAMETER ELECTRODE

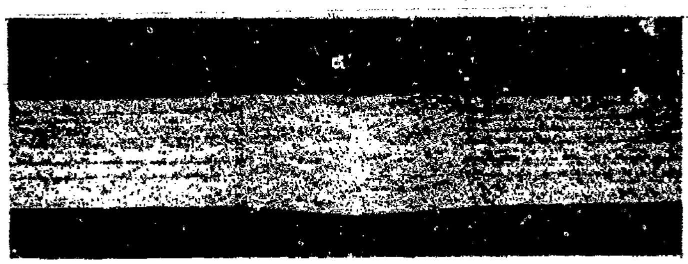
R1A1-9, 62 AMP, 3/32 IN. STANDOFF,
31 IPM



R1A1-9, 62 AMP, 3/16 IN. STANDOFF,
31 IPM



R1A1-9, 62 AMP, 1/4 IN. STANDOFF,
31 IPM



R1A1-9, 62 AMP, 5/16 IN. STANDOFF,
31 IPM

3009-2-AH-1

Figure 63. Effects of Torch Standoff Distance on Plasma Arc Weld in 0.062-in.-Thick Rene 41 Sheet, U-5T Torch, H_2 7.5 Orifice Gas, Single Pass Flat Position Weld, No Filler Wire Added, as-Welded.

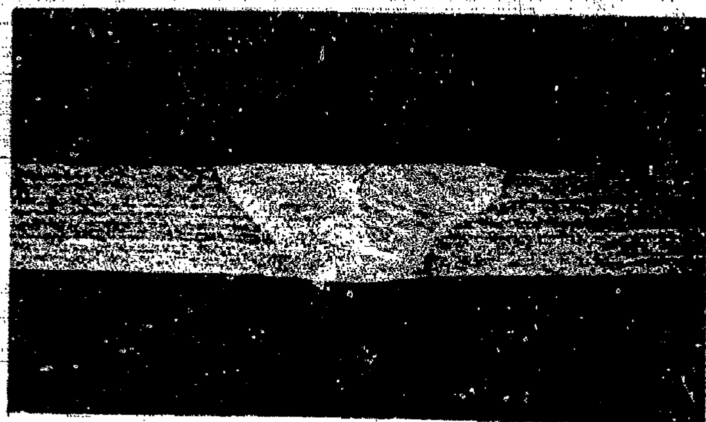
11X GLYCEREGIA ETCH

PT-8 TORCH, BUTT WELD

R1A2-1, 111-M ORIFICE, 1/16 IN. DIAMETER ELECTRODE,
115 AMP, 1/8 IN. STANDOFF, 31 IPM

11X GLYCEREGIA ETCH

U-5T TORCH, BUTT WELD



R1A2-2, 1/16 IN. ORIFICE, 1/16 IN. DIAMETER ELECTRODE,
62 AMP, 1/8 IN. STANDOFF, 31 IPM

3009-2-AE-1

Figure 64. Cross Sections from Single Pass Flat Position Plasma Arc Butt Welds in 0.062-in.-Thick Rene 41, No Filler Wire Added, as-Welded.

X-rays of Weld R1A2-2 disclosed five pores at the fusion line, two of which were unacceptable. The start and stop areas were also unacceptable. Porosity was randomly oriented as scattered pores on both edges of the fusion zone, and did not fall in a zone of weld produced at one particular standoff distance.

Figure 65 shows butt welds in 24 in.-long sheets. In these welds, it is significant that the curvature in the sheets is caused by longitudinal weld shrinkage. Although the backing bars could be moved very close together, the weld joint area could not be forced down onto the backup bars by the holddown bars (Figure 15) because of the need to space the holddown bars wide enough (about 1.25 in.) apart to provide access to the joint for the plasma torch. The net effect was that there was no rapid heat removal from the weld area, and about the same amount of longitudinal camber developed in weldments made with both torches (when weldments were removed from the welding fixture).

The need for torch access to the weld area restricted the use of chill tooling, which could greatly reduce the observed camber effects. For this application, these plasma torches seem excessively bulky in the orifice end, and may not be suitable for welding where chill bar spacing should be held to less than 1.0 in.

Mechanical property testing of welds in 0.063-in.-Rene 41 was not accomplished. Table VII illustrates composition of the Rene 41 utilized for these weld tests.

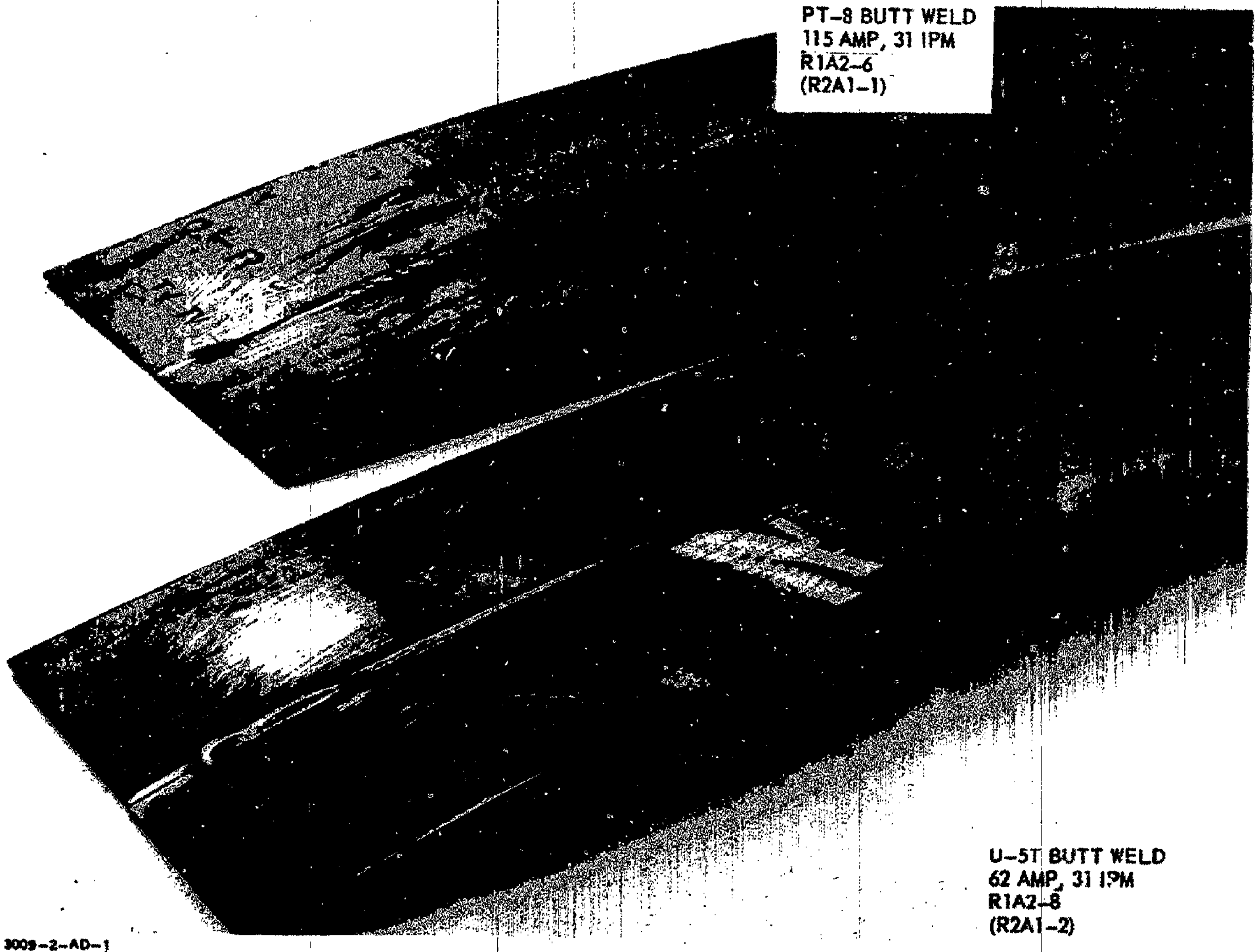


Figure 65. Single Pass Flat Position Plasma Arc Square Butt Welds in 0.062-in.-Thick Rene 41, Illustrating Typical Longitudinal Camber-Type Weld Distortion, No Filler Wire Added, as-Welded.

Table VII. Chemical Composition (% by Weight) of 0.062-in.-Thick Rene 41 Sheet.

Chemical	Percent: Heat No. TV 361	Percent: Heat No. TV 363
C	0.09	0.07
S	0.005	0.005
Cr	19.03	18.93
Ni	Bal	Bal
Mo	9.70	9.85
Co	11.04	11.08
Ti	3.13	3.21
Cb	0.0038	0.004
Mn	0.03	0.04
Si	0.05	0.08
Al	1.50	1.55
Fe	0.30	0.30

SECTION III

PROCESS PERFORMANCE EVALUATION

3.1 COMPARISONS OF PLASMA ARC, GTAW, AND GMAW PROCESSES

Several factors can be evaluated to compare plasma arc welding with other gas-shielded arc welding processes. Material thicknesses, joint designs, arc time, consumables utilized, weld quality levels and properties, and weldment and tooling configurations (straight seam or circumferential) are significant; consideration of these factors can yield a satisfactorily comprehensive process comparison. It is possible to overcompare if all time and material factors of importance are considered in detail and specific organizational cost factors are assigned. Cost elements of such comparisons are not universally applicable; therefore, detailed costing was not done in this work. The comparisons made herein relate specifically to the application of these welding processes for fabricating rocket motor cases and weight-critical unfired pressure vessels. Areas of comparison are limited to weld shop time, quantities of consumables utilized, and other factors that can influence welding process and equipment selection for hardware fabrication.

3.1.1 Comparisons of Welding Conditions

Weld shop time requirements and consumables used are compared for producing complete welds in comparable thicknesses of materials. Table VIII lists certain welding conditions found in the literature for similar thicknesses of 6Al-4V titanium. Unfortunately, the weldment configurations employed were not discussed in most of the literature; only those procedures for which weld configuration is known are compared. Reference 5 discusses the application of plasma arc welding for girth welds in a simulated Minuteman motor case; this is repeated in Table IX, as Case I, using a slightly different data arrangement.

In Case I, the principal time factors were setup time and arc time. Plasma arc welding was shown to be capable of reducing the overall weld shop time by a factor of 3, which is a substantial savings in labor hours for any shop. The wire utilized for the GTAW weld was neither a cost nor a quality factor in the plasma process and represents an additional savings factor. Gas consumption with the plasma weld procedure was less than half that required with the GTAW weld procedure, mostly because of reduced arc time. Overall unit arc times per foot of weld were 2.4 min/ft for plasma and 9.2 min/ft for GTAW.

In Case II, the weldment was a spherical vessel with only a 1.0-in.-diameter hole in the end boss areas, which precluded the use of internal tooling and necessitated a total purge. The principal cost considerations were arc time and weld wire savings; setup time was virtually the same for all three processes compared. The consumption of wire with the plasma weld procedure was less than 15% of that required with the GTAW weld procedure. Overall time in the weld shop was 1.6 times longer with GTAW than with plasma; electron beam welding required essentially the same amount of weld shop time as plasma. The gas consumption with the plasma procedure was less than half that required with the GTAW procedures. Overall unit arc times per foot of weld were 2 min/ft for plasma and 12 min/ft for GTAW.

Other data on welding conditions for titanium are shown in Table VIII. Considerable information has been published on GMAW welding of titanium plate 1.0 in. thick and heavier. In the thickness range of 0.125 to 0.75 in., GMAW welding conditions seem to imply a single-pass straight seam weld configuration. This is not directly comparable with the work done on this program and is not used for comparison purposes. It would appear that the GMAW process would be at a quality disadvantage for welding titanium because of wire surface quality inconsistency, potential contact tube seizure, and, in the case of circumferential weld joints, problems in the weld overlap and tailoff area. Electron beam welding is clearly a desirable process for welding titanium because the vacuum welding environment precludes contamination of weld metal with air. Electron beam welding can yield excellent quality titanium welds but the tendency for top bead undercut and root bead splatter to occur at the high welding speeds, as illustrated in Figures 66 and 67, suggests that it may not be especially advantageous for closed vessel butt welding. A properly setup plasma arc weld does not cause this kind of splatter.

Table X illustrates conditions for welding Inconel 718 with plasma arc, GTAW and GMAW processes. Because of the root bead cracking encountered in developing circumferential welding procedures for plasma arc welding this material there is no extensive comparison included here. It was relatively simple to plasma weld Inconel 718 in a straight seam weldment configuration (without an overlap), but it is certain that faster speeds could have been obtained using argon-hydrogen gas mixtures.

Table VIII. Welding Conditions for 100% Penetration Butt Welds in Titaniu Alloy Plate (Process Comparison Data).

Welding Process	Alloy and Thickness	Weld Joint Configuration	Joint Design		Tooling Configuration[a]	Welding Conditions												
			Root Land	Groove Angle (deg)		Weld Speed (ipm)	Weld Current		Voltage		Torch Gas Type	Torch Gas Flow (cfh)			Wire Diameter (in.)	Wire Feed (ipm)	Number of Passes	D So
							amp	ma	v	kv		Plasma Orifice	Shield	Other				
Plasma Arc	6Al-4V 0.175	Girth, Square Butt	0.187	0	B	13 8	175 150	-	26	-	Ar	--	60	Trailer 200	NA	--	2	Aerojet
	6Al-4V 0.250	Girth, Square Butt	0.250	0	B	12 15	220 170	- -	29 30	- -	Ar He 75	16 8	60 80	Trailer 200	-- 0.062	23 on cover	2	Aerojet
	6Al-4V 0.500	Straight Seam Square Butt	0.500	0	B	10.5	270	-	36	-	He 50	27	60	-	--	--	2	Linde E
	6Al-4V 0.600	Straight Seam	0.375	30	B	7.5	250	-	39	-	He 50	30	60	-	--	--	2	Referen
	6Al-4V 1.000	Straight Seam	0.437	60	B	5.2	250	-	-	-	Ar	27	150 He	-	--	--	5	Referen
GTAW-AU	6Al-4V 0.187	Girth, Single V	0.040	90	A	6	125 (av)	-	9.5 (av)	-	Ar	-	25 (av)	Trailer	0.062	14.5 (av 4 passes)	5	Aerojet-
	6Al-4V 0.285	Girth, Single U, Root	0.050	90	B	6	80	-	7.5	-	Ar	-	40	Trailer	--	--	1	Aerojet-
	6Al-4V 0.285	Girth, Single U, Cover Passes	0.050	90	B	6	155	-	8.3	-	Ar	-	40 (He 50)	Trailer	0.062	23	5	Aerojet-
	6Al-4V 0.400	Girth, Single U	0.045	20	B	6	75	-	8.0	-	Ar	-	40	Trailer	--	--	1	Aerojet-
	6Al-4V 0.400	Girth, Single U, Cover Passes	0.045	20	B	6	165	-	9.0	-	Ar	-	40	Trailer	0.062	23	5	Aerojet-
GMAW-AU	0.125					15/25	$\frac{250}{260}$	-	20	-	He 23	-	65	-	0.062	$\frac{200}{225}$	1	Referenc
	0.250					15/25	$\frac{300}{320}$	-	30	-	He 23	-	65	-	0.062	$\frac{300}{320}$	1	Referenc
	0.500					15/30	$\frac{340}{360}$	-	40	-	He 23	-	65	-	0.062	$\frac{375}{400}$	1	Referenc
	1.0					20	$\frac{320}{330}$	-	37	-	Ar	-	70	-	0.062	380	-	Referenc
Electron Beam	6Al-4V 0.191	Square Butt	0.191	0	B	98	-	170	-	28.2	-	-	-	-	--	-	1	Reference
	6Al-4V 0.2	Square Butt	0.2	0	B	18	-	8	-	125	-	-	-	-	--	--	1	Reference
	6Al-4V 0.250	Square Butt	0.250	0	B	50	-	35	-	115	-	-	-	-	--	--	1	Aerojet-G
	CP Titanium 0.250	Square Butt	0.250	0	B	25	-	10	-	138	-	-	-	-	--	--	1	Reference
	CP Titanium 0.340	Square Butt	0.340	0	B	60	-	15	-	150	-	-	-	-	--	--	1	Reference
	6Al-4V 1.0	Square Butt	1.0	0	B	15	-	300	-	23	-	-	-	-	--		1	Reference

a. Tooling Configurations:

A Hard backing bars and crown side chill rings.
B No chill tooling used.

A.

...ons for 100% Penetration Butt Welds in Titanium
...e (Process Comparison Data).

Welding Conditions										Other Information
Voltage		Torch Gas Type	Torch Gas Flow (cfh)			Wire Diameter (in.)	Wire Feed (ipm)	Number of Passes	Data Source	
v	kv		Plasma Orifice	Shield	Other					
5	-	Ar	--	60	Trailer 200	NA	--	2	Aerojet-General	
9 0	- -	Ar He 75	16 8	60 80	Trailer 200	-- 0.062	23 on cover	3	Aerojet-General	
6	-	He 50	27	60	-	--	--	2	Linde Data	
9	-	He 50	30	60	-	--	--	2	Reference 5	
	-	Ar	27	150 He	-	--	--	5	Reference 5	
5 v)	-	Ar	-	25 (av)	Trailer	0.062	14.6 (av 4 passes)	5	Aerojet-General	Minuteman motor case weld procedure.
5	-	Ar	-	40	Trailer	--	--	1	Aerojet-General	Delta helium sphere weld procedure.
3	-	Ar	-	40 (He 50)	Trailer	0.062	23	5	Aerojet-General	Delta helium sphere weld procedure.
0	-	Ar	-	40	Trailer	--	--	1	Aerojet-General	Aerobee vessel weld procedure.
0	-	Ar	-	40	Trailer	0.062	23	5	Aerojet-General	Aerobee vessel weld procedure.
	-	He 23	-	65	-	0.062	$\frac{200}{225}$	1	Reference 18	
	-	He 23	-	65	-	0.062	$\frac{300}{320}$	1	Reference 18	
	-	He 23	-	65	-	0.062	$\frac{375}{400}$	1	Reference 18	
	-	Ar	-	70	-	0.062	380	-	Reference 18	
	28.2	-	-	-	-	--	-	1	Reference 18	
	125	-	-	-	-	--	--	1	Reference 18	
	115	-	-	-	-	--	--	1	Aerojet-General	
	138	-	-	-	-	--	--	1	Reference 18	
	150	-	-	-	-	--	--	1	Reference 18	
	23	-	-	-	-	--		1	Reference 19	

B.

Table IX. Arc Time and Consumables Utilization Comparisons, 6Al-4V Titanium.

Weld Process	Total Setup and Takedown Time, Including Cleaning and Purge (hr)	Total Arc Time (min)	Total Wire Used (lb)	Total Welding Gas Used (cfh)	Other Time Factors
Case I: 0.175-in.-thick 6Al-4V titanium cylinder, 52 in. diameter					
GTAW	5.5	126	0.738	390	2 hr (Root bead routing)
Plasma arc	2.5	33	None	182	None
Case II: 0.25-in.-thick 6Al-4V titanium, spherical pressure vessel girth weld, 24 in. diameter					
GTAW	1.5	74 (6 passes)	0.7	258	None
Plasma arc	1.5	13 (2 passes)	0.1	130	None
Electron beam	1.5	6 (2 passes)	None	None	6 min (vacuum pumping)

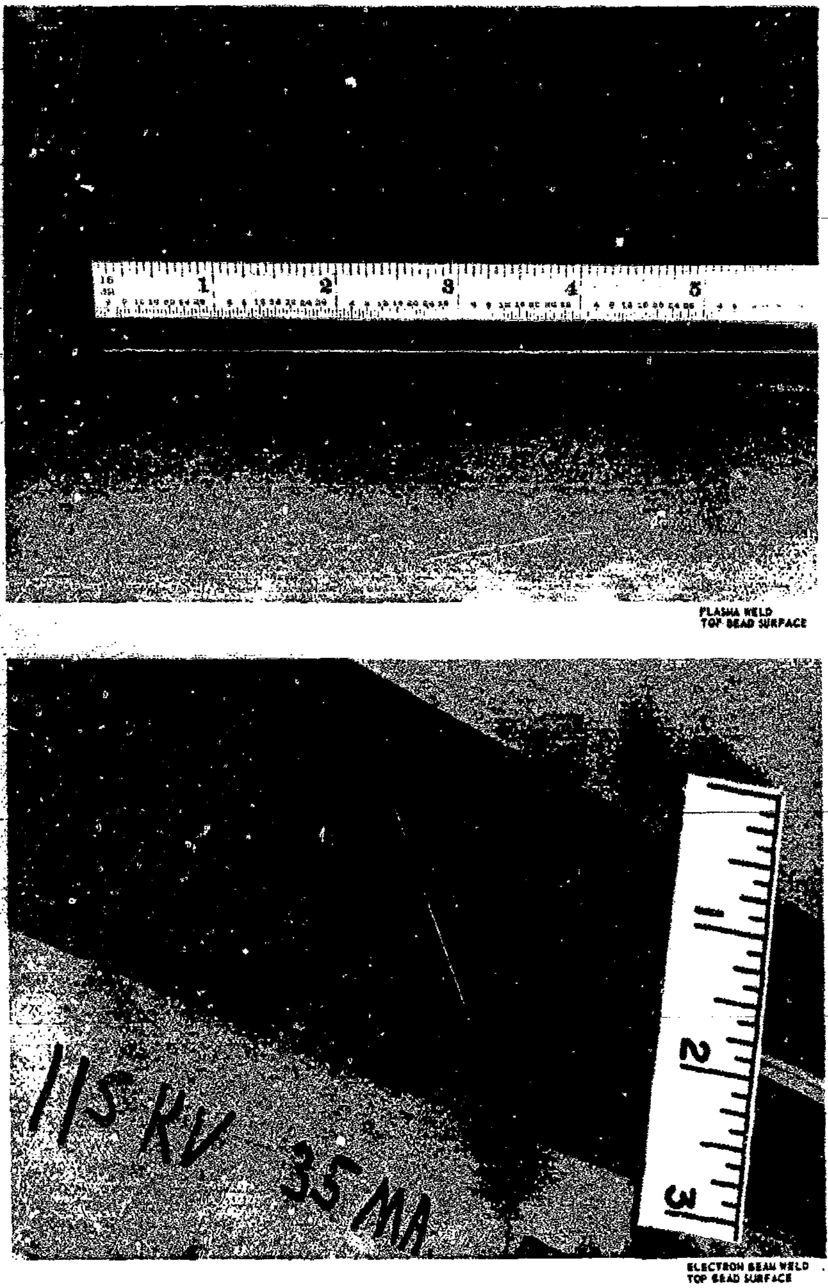
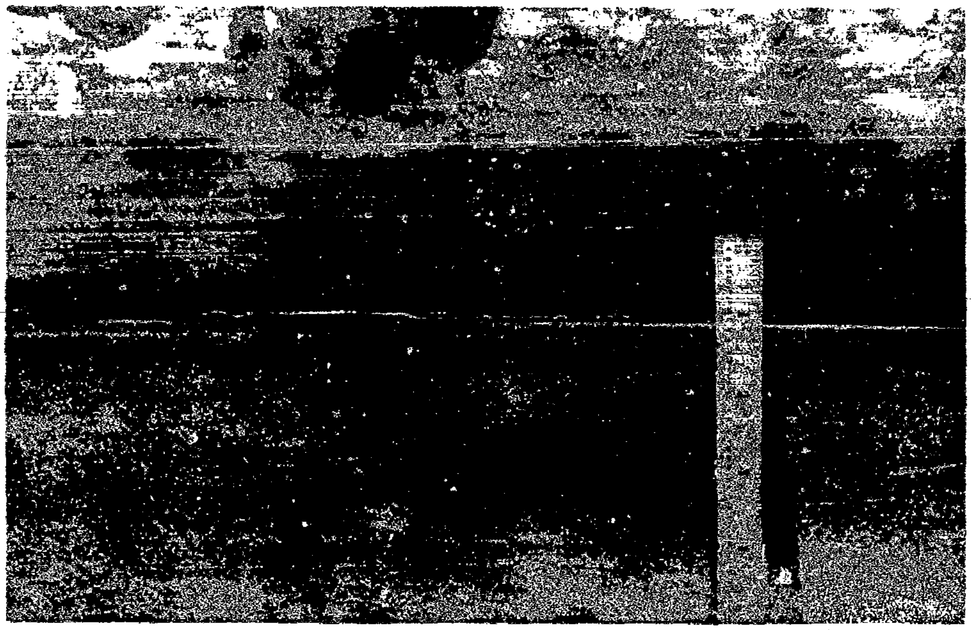
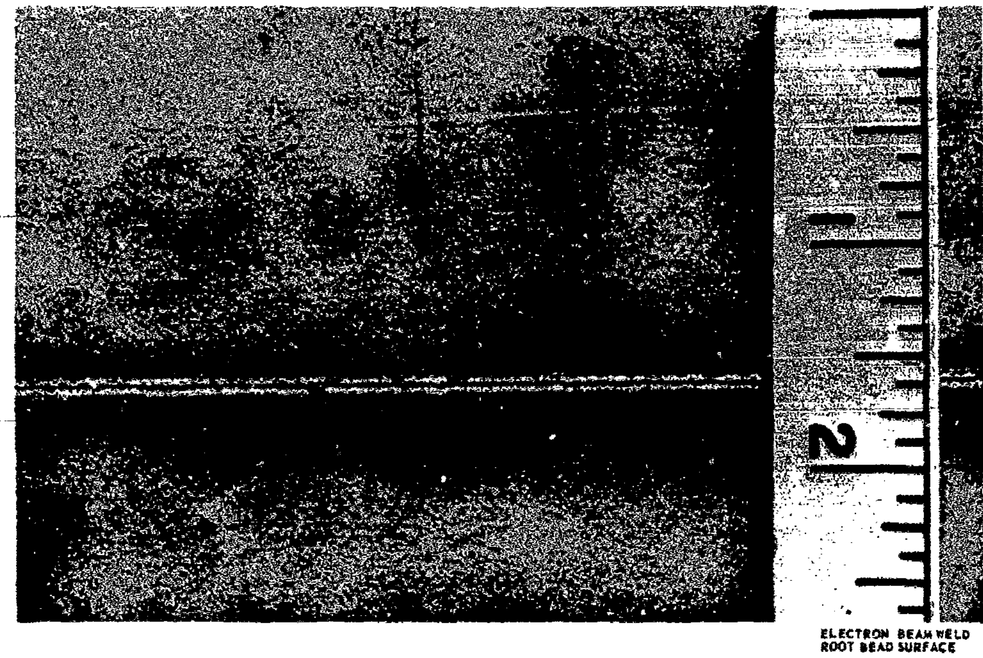


Figure 66. Top Bead Surfaces Typical of Two Flat Position Square Butt Welds in 0.25-in.-Thick 6Al-4V Titanium Plate.



PLASMA WELD
ROOT BEAD SURFACE



ELECTRON BEAM WELD
ROOT BEAD SURFACE

Figure 67. Root Bead Surfaces Typical of Two Flat Position Square Butt Welds in 0.25-in.-Thick 6Al-4V Titanium Plate.

3.1.2 Weld Properties Comparison

3.1.2.1 Mechanical Properties of Butt Welds in 0.25-in.-Thick 6Al-4V Titanium

Table XI lists certain mechanical properties of butt welds in this material. The transweld tensile properties of plasma arc welds in this material were rather high. This may be partially attributable to the tensile specimen configuration (Figure 45). The spread in ultimate tensile strength for plasma arc welds was 157 to 162 ksi. This may be a normal range for tensile properties in these heats of material. The data could also represent the upper bound of a scatter band for weld properties in quenched and aged 6Al-4V titanium. It was not possible to determine which category these tensile data represent because of the limited testing performed. However, nowhere in the literature were higher weld tensile properties reported, nor were transweld tensile properties equivalent to 100% of parent metal strength reported. Apparently, in this thickness range, plasma arc welds were at least as strong as welds made with any other process, and possibly somewhat stronger. Ductility was adequate but not consistently high. The electron beam weld in 0.250-in.-thick material exhibited surprisingly low ductility; possibly the 50-ipm weld speed employed was a contributing factor. The tensile fracture faces of these welds exhibited evidence of intergranular failure, possibly associated with nonequillibrium composition caused by the rather high solidification rate. Either commercially pure or 6Al-4V titanium weld wire could be used for the cover weld to wash out undercut in keyhole mode welds in this material, with no observable reduction in transweld tensile strength. The precrack Charpy data bear little relation to tensile ductility or strength. The fracture faces of precrack Charpy specimens from plasma arc welds were very fine grained (Figure 50), but the electron beam weld fractures were quite rough, again suggesting that failure was at least partly intergranular in nature.

Based on the results obtained on this program, plasma arc welding is capable of producing butt welds at very high levels of quality and strength in solution-treated and aged 6Al-4V titanium. Precrack Charpy test data indicate excellent weld toughness; no fracture toughness testing was performed to develop valid plane strain fracture toughness data for these welds.

3.1.2.2 Mechanical Properties of Butt Welds in 0.25-in.-Thick Inconel 718

Table XII lists tensile properties of butt welds in Inconel 718. Welds made in this program were at least as high in tensile properties as GTAW or GMAW welds. Properties of two welds listed in Table XII (GTAW-ACB and

Table X. Welding Conditions for 100% Penetration Butt We
Plate (Process Comparison Da

Welding Process	Alloy and Thickness	Weld Joint Configuration	Joint Design Root Land	Joint Design Groove Angle (deg)	Tooling Configuration[a]	Weld Speed (ipm)	Weld Current (amp)	Voltage	Torch Gas
Plasma Arc	Alloy 718 0.146	Square Butt, Straight Seam	0.146	0	-	30	-	-	-
	Alloy 718 0.250	Square Butt, Girth	0.250	0	B	6	140	-	Ar
	Alloy 600 0.260	Square Butt, Straight Seam	0.260	0	-	17	210	31	$95Ar/5H_2$
GTAW-AU	Alloy 718 0.625	Single U, Insert, Girth	0.100	20	A	6 (root)	185	11.0	He 75
	Alloy 718 0.625	Single U, Filler Passes, Girth	0.100	20	A	10	280	10.7	Ar
	Alloy 718 0.312	Single V, Girth	0.060	75	-	12	145	11.0	Ar
GMAU-	Alloy 718 0.312	Single V, Girth	0.060	75	-	22/28	100	24	He (50 cfh) M-1 (8 cfh)
	Alloy 718 0.250	Single U, Girth	0.030	30	-	28	120	25	He (50 cfh) M-1 (8 cfh)

a. Tooling Configurations

A. Hard backing bars and crown side drill rings.
B. Backing bars only.

A.

or 100% Penetration Butt Welds in Nickel Base Alloy
ate (Process Comparison Data).

Weld urrent (amp)	Voltage	Torch Gas	Welding Conditions: Torch Gas Flow (cfh)			Wire Diameter (in.)	Wire Feed (ipm)	Number of Passes	Data Source
			Plasma Orifice	Shield	Other				
-	-	-	-	-	-	-	-	1	Reference 5
140	-	Ar	14	60	Trailer 200	-	-	2	Aerojet-General
210	31	$95Ar/5H_2$	12.5	45	-	-	-	1	Reference 6
185	11.0	He 75	-	85	-	-	-	11	Reference 20
280	10.7	Ar	-	40	-	0.063 Alloy 718	50	11	Reference 20
145	11.0	Ar	-	24	-	0.035 Alloy 718	-	12	Reference 21
100	24	He (50 cfh) M-1 (8 cfh)	-	58	-	0.035 Alloy 718	222	6 - on GTAW Root Weld	Reference 21
120	25	He (50 cfh) M-1 (8 cfh)	-	58	-	0.035 Alloy 718	240	5 - on GTAW Root Weld	Reference 21

B.

Table XI. Mechanical Properties of 100% Penetration Butt Welds in Tita
(Process Comparison Data).

Welding Process	Alloy Plate Thickness Wire Composition	Process Cycle[a]	Weld Speed (ipm)	Number of Passes	Tensile Properties: Test Bar Orientation	0.2% YS[d] (ksi)	UTS[e] (ksi)	Elongation in 1/2, 1, or 2 in. (%)	Data Source
Plasma Arc	6Al-4V 0.175	BCWC	13 8	2	Transweld[b]	137.1	151.6	5.5 (2 in.)	Aerojet-Gen Reference 2
	6Al-4V 0.175	BCWC	13 8	2	Transweld[c]	140.0	153.4	6.0 (2 in.)	Aerojet-Gen Reference 2
	6Al-4V 0.241	BCWC	12 12	2	Transweld[b]	146.3	161.1	10.3 (1 in.)	Aerojet-Gen
	6Al-4V 0.250	BCWC	12 15	2	Transweld[b]	147.5	161.9	7.6 (1 in.)	Aerojet-Gen
	6Al-4V 0.250	BCWC	12 15	2	Transweld[c]	139.5	159.4	14.2 (1/2 in.)	Aerojet-Gen
GMAW-AU	6Al-4V, 6-4 Wire, no thickness listed	--	--	--	Transweld	138.0	152.0	---	Reference 18
	6Al-4V CP Wire, no thickness listed	--	--	--	Transweld	126.0	134.0	---	Reference 18
	6Al-4V, 1.0 in. thick 6-4 Wire	AW	23	15	Transweld	133.9	146.7	5.5 (2 in.)	Reference 22
Electron Beam	6Al-4V 0.250	BCWC	--	--	Transweld[b]	148.7	158.1	4.1 (1 in.)	Aerojet-Gene
	6Al-4V 1.0	BCWC	--	--	Transweld	147.7	158.9	10.0 (1 in.)	Reference 19
	6Al-4V 1.0	BCWC	--	--	Transweld	146.5	157.6	5.0 (1 in.)	Reference 19

a. Process cycle data: A - 2 Hr @ 1350°F, air cool, B - 1 Hr @ 1750°F, Water Quench, C - 4 Hr, @ 1000°F, Air Cool, W
b. Tensile tested with weld reinforcement left as-welded.
c. Smooth bar tensile test.
d. Yield stress
e. Ultimate tensile strength

A.

rties of 100% Penetration Butt Welds in Titanium Alloy Plate
Process Comparison Data).

	Tensile Properties					
n	0.2% YS[d] (ksi)	UTS[e] (ksi)	Elongation in 1/2, 1, or 2 in. (%)	Data Source	Other Information	Precrack Charpy Impact Properties (in.-lb/in.^{2})
[b]	137.1	151.6	5.5 (2 in.)	Aerojet-General Reference 23		
[c]	140.0	153.4	6.0 (2 in.)	Aerojet-General Reference 23		
[b]	146.3	161.1	10.3 (1 in.)	Aerojet-General	Data reported in this volume	988 (weld ℄)
[b]	147.5	161.9	7.6 (1 in.)	Aerojet-General	Data reported in this volume	1064 (weld ℄)
[c]	139.5	159.4	14.2 (1/2 in.)	Aerojet-General	Average properties of 3 welds in spherical pressure vessels obtained using a subsize tensile specimen. See Volume III, Table .	565 (weld ℄)
	138.0	152.0	---	Reference 18		
	126.0	134.0	---	Reference 18		
	133.9	146.7	5.5 (2 in.)	Reference 22		
	148.7	158.1	4.1 (1 in.)	Aerojet-General	Data reported in this volume	
	147.7	158.9	10.0 (1 in.)	Reference 19		
	146.5	157.6	5.0 (1 in.)	Reference 19		

'50°F, Water Quench, C - 4 Hr. @ 1000°F, Air Cool, W - Weld.

B.

Table XII. Mechanical Properties of 100% Penetration Butt Welds in Ni
Plate (Process Comparison Data).

Welding Process	Alloy and Plate Thickness	Process Cycle	Weld Speed (ipm)	Number of Passes	Tensile Properties at Room			
					Test Bar Orientation	0.2% Y S[d] (ksi)	UTS[e] (ksi)	El in 1
Plasma Arc	Alloy 718, 0.250	ACAB	6	1	Transweld[b]	153.8	185.6	23.
	Alloy 718, 0.250	ACAB	6	2	Transweld[b]	156.3	186.1	27.
GTAW-AU	Alloy 718, 0.62	DCDE	6	11	Transweld[c]	152.6	184.8	6.0 (
	Alloy 718, 0.62	ACAB	6	11	Transweld[c]	157.1	184.6	18.
	Alloy 718, 0.250	ACB	12	12	Transweld[c]	139.9	170.0	7.0
	Alloy 718, 0.250	ACAB	12	12	Transweld[c]	147.7	185.4	20.
GMAW-AU	Alloy 718, 0.250	ACB	28	5	Transweld[c]	138.1	171.9	7.2
	Alloy 718,	ACAB	28	5	Transweld[c]	150.3	184.8	15.

a. Process cycle data: A - 1950°F for 1 hr, rapid air cool; B - 1400°F for 10 hr, furnace cool to 1200°F and aging cycle of 20 hr; C - weld, D - 1800°F for 1 hr, rapid air cool; E - same as B except aging temperatu

b. Tensile tested with weld reinforcement left as-welded.

c. Smooth bar tensile test.

d. Yield stress.

e. Ultimate tensile strength.

A.

of 100% Penetration Butt Welds in Nickel Base Alloy
ocess Comparison Data).

	Tensile Properties at Room Temperature				
Test Bar Orientation	0.2% Y S[d] (ksi)	UTS[e] (ksi)	Elongation in 1/2 or 1 in. (%)	Tensile Data Source	Other Information
Transweld[b]	153.8	185.6	23.3 (1 in.)	Aerojet-General	
Transweld[b]	156.3	186.1	27.4 (1 in.)	Aerojet-General	
answeld[c]	152.6	184.8	6.0 to 16.0, (1 in.)	Reference 20	Notch tensile ratio of weld metal 1.246
Transweld[c]	157.1	184.6	18.0 to 21.0 (1 in.)	Reference 20	Notch tensile ratio weld metal 1.286
Transweld[c]	139.9	170.0	7.0 (1/2 in.)	Reference 21	
Transweld[c]	147.7	185.4	20.0 (1/2 in.)	Reference 21	
Transweld[c]	138.1	171.9	7.2 (1/2 in.)	Reference 21	
Transweld[c]	150.3	184.8	15.8 (1/2 in.)	Reference 21	

00°F for 10 hr, furnace cool to 1200°F and hold for total
ol; E - same as B except aging temperatures were 1325°F and 1150°F.

B.

GMAW-ACB) were included to illustrate the effects of aging directly after welding rather than going through a solution anneal and age cycle. The tensile properties were down (particularly yield strength and ductility). These values could be increased substantially by employing a 1950°F solution anneal after welding, then aging, which is one processing cycle employed for welds in this material that are intended for tensile limited applications.

Extensive unpublished data (References 17 and 20) have shown that aging Inconel 718 directly after welding without a solution anneal yields weld zone ductility very close to the 5% level recommended by one source as a lower bound to define the transition between ductile and brittle material behavior (Reference 24). Other unpublished GTAW weld data (Reference 20) describe notch tensile testing at room temperature with a weld metal notch acuity factor (K_t) of 6.3. The notch tensile ratio was well above unity for both conditions tested, suggesting that Alloy 718 welds are exceedingly resistant to crack propagation, even when crack-like defects exist in complex stress fields.

3.1.3 Application of Plasma Arc Welding in Production Operations

3.1.3.1 Weld Quality

Probably the major welding problem facing titanium fabricators relates to keeping rejectable weld defects within reasonable limits. The quality record built up during the plasma arc welding in this program demonstrates tremendous potential for producing consistently high quality butt welds, particularly in titanium and titanium alloys.

The action of the keyhole mode plasma arc on molten titanium weld metal seems to eliminate porosity, which can be a major quality problem in GTAW welds. In addition, much less filler wire is required in plasma arc welds, at least in the 0.25-in. thickness range, so that quality problems and costs associated with obtaining satisfactory quality titanium weld wire are minimized. Because keyhole mode plasma arc welds are made in square butt weld joints for circumferential welds in material up to 0.25-in. thick, the need for more than two passes in a weld depends only on weld position (flat position -- two passes, horizontal position -- three passes). There are very tangible benefits. Arc time is reduced to a minimum because of the inherently high welding speeds available. This in itself tends to reduce possibilities for air contamination of welds, because the total time the weld metal is in the absorptive temperature range for interstitial contaminants is minimized for all parts of the weld.

Relatively thick root welds are possible using the keyhole mode plasma arc. A type of root bead flaw found in single- and multipass GTAW welds (Appendix IX) has been described as a grain boundary separation in weld metal. It appears that GTAW welds are susceptible to this kind of defect because of the normally thin cross section in root welds necessitated by limited penetrating capability of the process. The defects are not resolvable by X-ray inspection techniques; it is necessary to resort to the use of a high-sensitivity liquid penetrant to find them, apparently because the width of surface opening of these defects is quite small (see Figure IX-2 of Appendix IX). This kind of defect is probably present in a great deal of 6Al-4V material in other existing titanium tankage where the root side of the weld is not accessible for visual and penetrant inspection. This kind of defect has not been found in the root bead fusion zone of plasma arc welds.

Weld shrinkage and distortion is reduced using the plasma arc process. Transverse shrinkage in butt welds in 0.25-in.-thick 6Al-4V titanium averages 0.045 in., with 0.030 in. occurring during the keyhole root weld and the remaining 0.015 in. resulting from the cover pass.

The possibility of getting tungsten inclusions into the weld is virtually absent. The torch is always at least 1/8-in. above the weld and the tungsten electrode is recessed into the orifice (see Figure 6); the only way for a tungsten inclusion to occur in a plasma weld is for an electrode to fragment. Although the significance of tungsten inclusions as a defect in titanium welds is questionable, the expedient of completely eliminating this kind of inclusion represents a way of improving the state of welding engineer's coexistance with many existing weld specifications.

The weld melt-thru and root bead fusion zone width are very uniform in plasma arc welds.

Although the allowable weld joint mismatch and gap in aerospace hardware are generally governed more by load path discontinuity limits than by other considerations, relatively poor fitup is of little concern when using plasma arc welding, as illustrated in Figures 33, 34, and 35.

3.1.3.2 Equipment and Personnel

The Aerojet-owned welding equipment employed for plasma arc torch operation was standard industrial welding machinery except for the program control power supply (Figure 10) and the plasma gas control system (Figure 7). Weld travel speed was provided by a standard Linde shunt-wound DC motor run from a standard Linde electronic governor. Wire feed was also provided by standard Linde equipment.

The program control power supply used for this program was an electrical machine capable of maintaining weld current at a predetermined level within close limits(± 3 amp) during variations in load voltage. This is accomplished by a servo-operated current control system built into the welding transformer; many welding machines do not include this feature. It has been suggested that common drooping characteristic welding machines (for example, the Vickers 3 phase input DC series) may be suitable for plasma arc welding; this was not confirmed for circumferential welding applications during this program. The basic equipment requirements for a given plasma arc welding setup should probably be determined by the specific application.

a. Straight Seam Welds

Weld Power Supply. Maximum 100% duty cycle current should be determined by maximum thickness and material to be welded; at least 300 amp should be available at 40 v on a 100% duty cycle basis. Conventional drooping characteristic machines may be suitable, but output should approximate a constant-current characteristic in the welding voltage range unless torch-to-work distance variations are held to less than ± 1/16 in. by fixturing.

Plasma Gas Control. The simplest gas control systems made by Linde and Thermal Dynamics should be satisfactory. Gas mixing could be a problem. However, mixed gases within a wide range of compositions can be easily obtained.

Weld Speed Control. Should be capable of maintaining weld speed within ± 0.5 ipm of a preset speed level.

b. Circumferential Welds

Weld Power Supply. Maximum 100% duty cycle current should be determined by maximum thickness and material to be welded; at least 300 amp should be available at 40 v on a 100% duty cycle basis. Conventional drooping characteristic machines may be suitable, but output should approximate a constant-current characteristic in the weld load voltage range unless torch-to-work distance variations are held to less than ± 1/16 in. by fixturing. Power supply must have the current upslope and downslope feature with slope interval controls accurate to within ± 1 sec; the need for true linearity of current slope rate was not determined, although the Aerojet equipment provides linear current slope. Current, weld travel, and wire-feed-speed slope in unison on the Aerojet equipment because the slope functions are governed by slope generator potentiometers ganged on a common shaft driven by one variable-speed motor. It was found in welding 1/4 and 5/8-in.-thick 18 Ni steel and 9 Ni steel that satisfactory keyhole withdrawal could be obtained only by sloping down weld travel independently of weld current, which would require some special sequencing circuitry in practically any plasma welding setup.

Plasma Gas Control. Must provide for orifice gas upslope and downslope with duration repeatability within $\pm$ 0.5 sec. The control must be interlocked with the weld power supply. Weld cycle sequencing controls are generally simple to arrange.

Weld Speed Control. Should be capable of maintaining weld speed within $\pm$ 0.5 ipm of a preset speed level. The previous discussion relating to weld travel downslope capability may be an important consideration for some materials.

Aerojet staffed the welding tasks on this contract with an experienced welding engineer and a conscientious technician who had never seen a weld before; the technician required about a month to familiarize himself with gas-shielded fusion welding in general and plasma arc equipment and techniques. Although plasma arc welding equipment and techniques are somewhat more complicated than GTAW or GMAW, the complexity was not a major problem in operator training. Plasma arc seems to be somewhat simpler to learn than electron beam equipment and techniques. It is felt that a production plasma arc welding operator should have some automatic GTAW or GMAW welding experience because the power sources and equipment are similar, and some experience with arcs and weld metal flow is important. It seems reasonable to expect that a qualified and interested man could learn specific production equipment and procedures in less than a week.

3.1.3.3 Fixturing and Torch Access Considerations

Keyhole mode plasma welding arcs require clearance for the plasma flame that streams through the keyhole. Figure 15 illustrates one workable plasma flame clearance groove. Weld procedures for circumferential welds were developed using this fixture. The use of exact procedures developed on this fixture produced a hotter puddle and keyhole than expected on the pressure vessel weldments (Volume III); it is suspected that the plasma flame impinging on the copper floor plate of this fixture may be providing a parallel weld current path that could be reducing the effective melting current level. For straight seam welds in a production shop, a fixture of this type milled from solid carbon steel would seem to be adequate; however, direct application of keyhole weld procedures developed on a tool such as this for untooled product weldments should be approached with caution. Figures 16, 17, 68, and 69 show tool configurations successfully used for plasma arc welding.

The size of the plasma torch orifice end is a definite consideration in designing weld tooling. The minimum spacing for holddown bars would most likely be limited by the width of the trailing shield. Welding applications of the PT-8 and U-5T torches on sheet metal joints that are normally tooled for maximum chill in the weld area were not extremely successful because torch orifice end size limited minimum chill bar spacing.

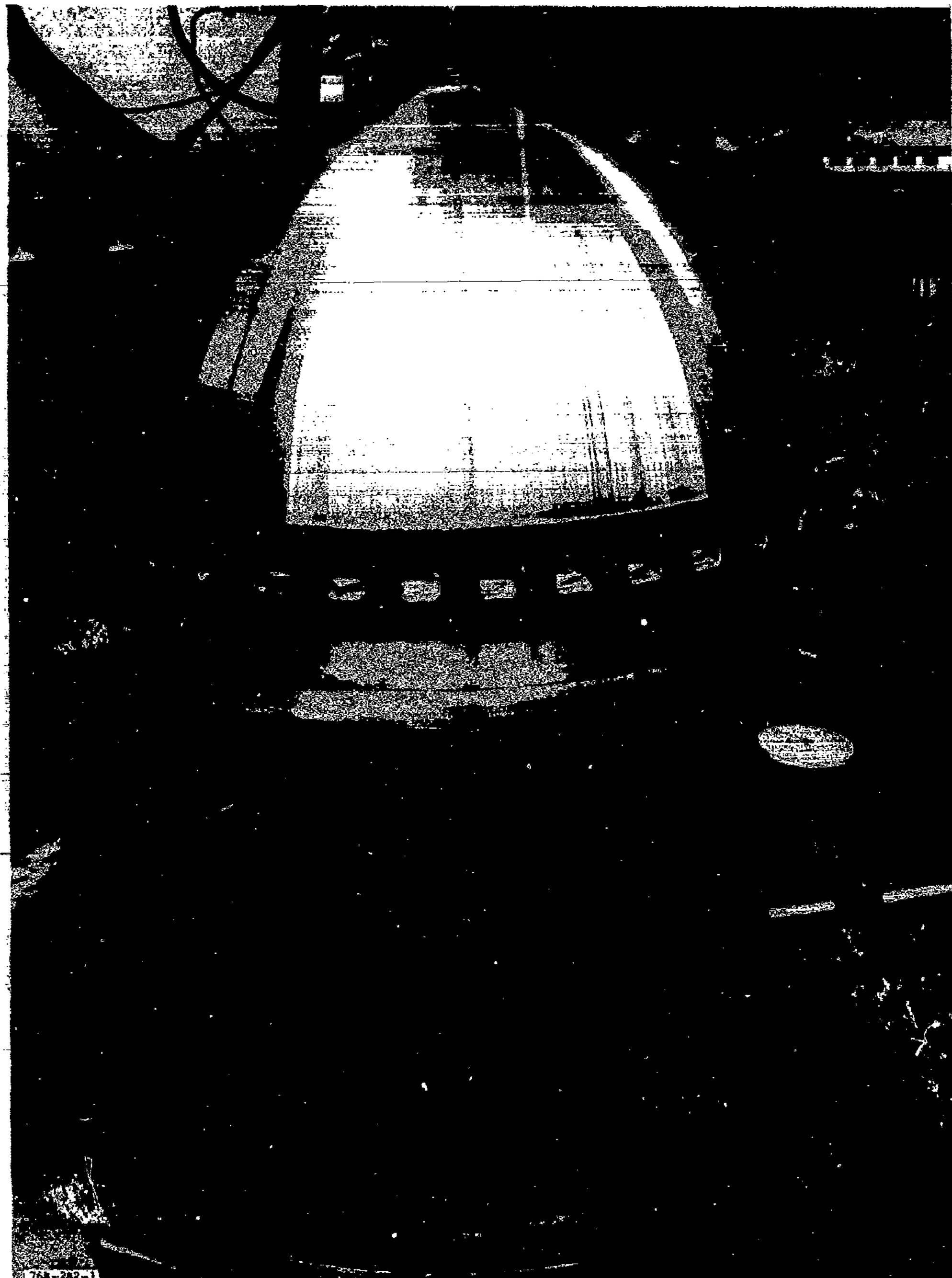


Figure 68. Weldment Assembly and Tack Weld Tooling Employed to Fabricate Spherical Pressure Vessels.

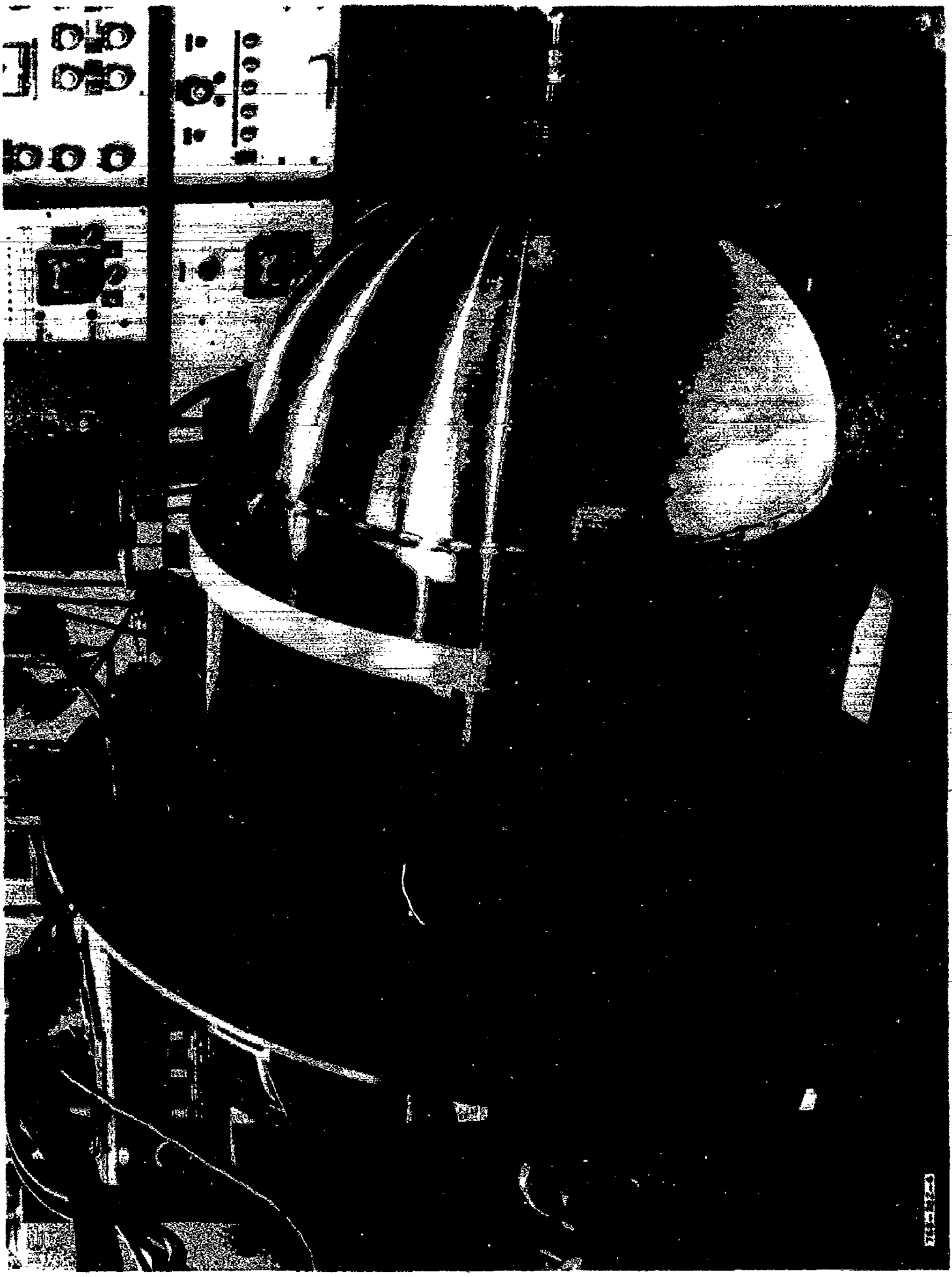


Figure 69. Weldment Rotating Tooling Setup Employed For Plasma Arc Welding Spherical Pressure Vessels.

SECTION IV

SUMMARY AND CONCLUSIONS

Keyhole mode welding conditions were developed using square butt joints for flat position single pass welds in 0.250-in. thick 6Al-4V titanium plate. Welds were made at speeds of 6, 12, and 18 ipm; slight top bead underfill was present in welds made at all speeds. A cover (cosmetic) weld pass was required to eliminate this condition; small amounts of filler wire addition during the cover pass produced a satisfactory weld top surface. Horizontal position welds in this material were satisfactorily cover-welded using a two pass procedure, without filler wire addition.

Circumferential weld procedures were developed for square butt joints in 6Al-4V titanium in the 0.250-in. thickness range at 12-ipm weld speed. It was found that internal, irregularity shaped voids, caused by plasma gas entrapment could occur from 3/8 to 1-1/2 in. past the keyhold withdrawal point; these voids were the major quality problem encountered during development of circumferential weld procedures for this material. Welding conditions and timing were determined that yielded 15 sound overlaps in 15 flat position tests, and 4 sound overlaps in 4 horizontal position tests using the PT-8 torch. Another way of stating the flat position data is to estimate success potential; for instance, the 15 out of 15 data block justifies a prediction that 9 out of every 10 welds made with this procedure will be sound, with an 80% confidence level. The success potential data reflect the uncertainty associated with making statistical estimates from a relatively small sample population.

The quality of keyhole mode plasma arc welds in titanium was exceptionally high. The incidence of weld porosity was negligible; in 102 ft of weld metal X-rayed, only 4 cases of porosity were found, all within acceptable size limits. Of the 4 cases, 3 were individual pores less than 0.030 in. in diameter; 3 cases were in horizontal position welds (which comprised less that 15% of the total weld footage inspected by X-ray). No cracks, tungsten inclusions, nonmetallic inclusions, or other internal weld defects were found in these welds. Root bead grain boundary fissures were not found in plasma arc welds, but have been noted in GTAW welds.

Repair of gas entrapment voids in 0.25-in.-thick titanium was accomplished by simply rewelding, using the keyhole mode circumferential weld procedure. The tensile and PCI properties of welds repaired in this way were not measurably effected. Voids in the keyhole initiation zone can also occur by entrapment of plasma gas, but are not serious quality problems because they can be eliminated easily during the keyhole overlap weld.

Mismatch, gaps, and combinations up to 0.080-in. mismatch and 0.070-in. gap were keyhole welded using circumferential welding conditions without melting holes in the weld joint. Mismatch alone up to 0.080 in. was keyhole welded in the flat position without root bead concavity. Gaps alone up to about 0.030 in. were welded without significant root bead concavity.

Tensile properties of plasma arc welds in solution-treated and aged 6Al-4V titanium plate exhibited ultimate tensile strengths ranging from 157 to 162 ksi at elongations greater than 6.5% in 1 in. The tensile testing accomplished on this material produced no weld strength data equal to 100% of parent metal strength.

Precrack Charpy impact values were significantly higher in titanium weld metal and heat-affected zones than in the parent metal, for all plasma arc welds tested. The plasma weld PCI data were also quite high compared with other heats of 6Al-4V titanium parent metal heat-treated to the same strength level. Specimens from several of the plasma arc welds evaluated by tensile and PCI testing were submitted for interstitial gas analyses; these analyses all suggest that the keyhole mode plasma arc actually extracts oxygen from the weld metal. The weld fusion zone in these weldments exhibited oxygen contents from 25% to 40% less than the parent metal; oxygen content of parent metal was measured at 2000 ppm by two laboratories. The precrack Charpy values for weld areas and parent metal are in good agreement with gas analyses; published data also suggest notch toughness is inversely proportional to interstitial content in titanium and its alloys.

Transweld fatigue properties of plasma arc welds in 0.25-in.-thick 6Al-4V titanium were evaluated using a uniaxial specimen (with weld reinforcement left as welded), and tension-tension loading cycles. The fatigue failures in weld specimens all began at the weld reinforcement on either the root bead or the top bead surfaces, suggesting the discontinuity effect of weld reinforcement is a significant stress concentration factor. Fatigue life was evaluated at levels of 83%, 85%, and 90% of uniaxial yield stress (0.2% offset). The data indicate that fatigue life of plasma arc welds determined as described above may be less than 10% of the parent metal life at similar stress levels.

Circumferential welding procedures were investigated for welding 0.25-in.-thick Inconel 718 square butt joints in the flat position. A simulated circumferential weld was satisfactory by X-ray inspection, but exhibited cracks in the weld melt-thru at the keyhole withdrawal point after penetrant inspection; the cause of this cracking was not determined. Welds in this material without keyhole overlap areas were normally defect free; some single pass welds were virtually free of top bead undercut. The one weld tested exhibited 98% to 100% of parent metal tensile properties after suitable heat treatment.

The PT-8 and U5T torches were used to weld square butt joints in 0.063-in.-thick Rene 41, using a melt-in mode arc. The results were not very successful because, to provide access for the plasma arc torch, the hold-down bars had to be spaced wider than desired; the result was ineffective weld-zone chill. The distortion encountered was thought to be excessive.

The PT-8 torch was employed for about 80% of the welding reported in this volume. It was found to be a rugged and flexible torch with apparently satisfactory weld schedule repeatability characteristics, particularly for circumferential welds. In straight seam keyhole mode welds in 0.25-in.-thick titanium, the nominally optimum weld schedule can vary over relatively wide limits, i.e., ± 10 amp (220 amp), ± 1/2 ipm weld speed (12 ipm), ± 1/2 cfh orifice gas flow (16 cfh), and ± 1/16-in. torch standoff (1/4 in.). The U-5T torch was used for about 20% of the welding reported in this volume. Inconsistency in the keyholing force of its arc developed literally overnight about a quarter of the way through this work. The cause(s) of this behavior were not satisfactorily explained by either Thermal Dynamics or Aerojet; therefore, only limited additional work was done with this torch. It was not possible to compare the U-5T in equivalent terms with the PT-8; therefore, comparative discussion and conclusions are not presented. Based on results of welding investigations reported in this volume, the PT-8 torch seems to be a more consistent plasma arc welding torch.

The weld top surface coverage provided by standard gas shields on both torches was unsatisfactory for the materials on which weld results are reported in this volume. Both torches were readily adapted to a trailing shield, which provided suitable weld top surface coverage.

Arc starting was found to be inconsistent with either the PT-8 or U-5T torch at standoff distances in excess of 1/8 in., particularly in horizontal position welds. This was possibly caused by the limited open circuit voltage available (62 vdc).

Some form of automatic control may be desirable for controlling torch standoff in plasma arc welding applications. The effects of torch component manufacturing tolerances, and electrode shape and setback tolerances on arc voltage in plasma torches were not evaluated during this program. These factors may seriously influence the consistency of plasma torch arc voltage; torch standoff control predicated on using fixed reference voltage settings for AVC application could be subject to similar inconsistency. Possibly a better method of automating torch standoff control would be to employ an electromechanical distance transducer to develop a proportional signal, independent of art voltage inconsistencies, for AVC system input.

Comparisons of fusion welding processes based on similar product weldment applications show that plasma arc welding offers the fabricator substantial quality and cost benefits, particularly for making butt welds in titanium and its alloys in the 0.090- to 0.50-in. thickness range. Plasma arc welds in 0.25-in.-thick titanium can be produced in one third the time required for GTAW welds. Plasma arc weld quality and properties are at least equal to, and are probably slightly higher than those of GTAW, GMAW, or electron beam welds in this material. Other fusion welding processes suitable for titanium have not exhibited the weld metal gas depletion effects that were found with the keyhole mode plasma arc. Because weld metal toughness was significantly improved without degrading tensile properties, it would appear that this effect is another of the desirable process characteristics of plasma arc welding.

Aerojet experience with specific plasma arc welding equipment and applications evaluated on this contract has been examined at length. The equipment is a little more complex than GTAW or GMAW equipment, but is judged to be less complicated than that used for electron beam welding. Welding operator requirements for plasma arc equipment and procedures are not much different than for sophisticated GTAW, GMAW, or electron beam operation. It is felt that an operator of mechanical plasma arc welding equipment should have some previous automatic welding experience using a gas shielded welding process.

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Appendix I

WELDING CONDITIONS

Table I-1. Welding Conditions Employed for Plasma

Purpose of Test	Material Description and Heat Number	Joint Configuration: V-Groove Included Angle (deg)	Joint Configuration: Root Land Thickness (in.)	Weld Identification	Torch Setup Data: Torch Type	Torch Setup Data: Orifice	Torch Setup Data: Standoff Distance (in.)	Electrode Configuration: Dia (in.)	Electrode Configuration: Included Tip Angle (deg)	Electrode Configuration: End Flat Dia (in.)	Electrode Configuration: Setback Distance (in.)	T
Weld schedule development	Mill annealed, G-2266	Weld in plate	0.26	TIA1-1-1	PT-8	136-M	3/16	1/8	-	-	1/8	A
				TIA1-1-2					-	-		
Weld schedule development				TIA1-2-1					-	-		
				TIA1-2-2					-	-		
Evaluate weld speeds				TIA1-3-1					-	-		
				TIA1-3-2			3/16		-	-		
Evaluate weld speeds				TIA1-4-1			1/8		-	-		
				TIA1-4-2					-	-		
Weld schedule development				TIA1-5-1		136-M			-	-		A
Orifice gas evaluation	Mill annealed, G-2266			TIA1-6-1		136-M			-	-		H
			0.26	TIA1-7-1		1/8			-	-		Al
Trailer shield	No heat number		0.125	TIA1-8-1		136-M	1/8	1/8	-	-	1/8	
Trailer shield	No heat number		0.125	TIA1-9-1		111-M	3/32	3/32	-	-	7/64	
Evaluate standoff	No heat number		0.126	TIA1-10-1	PT-8	111-M	3/32, 1/8, 5/32	3/32	-	-	7/64	
Weld schedule development	Mill annealed, G-2265		0.26	TIA1-11-1	U-5T	1/8	1/8	1/8	-	-	1/16	
				TIA1-11-2					-	-		
Evaluate weld speeds				TIA1-12-1					-	-		
				TIA1-12-2					-	-		
				TIA1-12-3			1/8		-	-		
Evaluate standoff				TIA1-13			1/16, 3/32,		-	-		
				TIA1-13			1/8, 3/16, 1/4		-	-		
Evaluate start conditions				TIA1-14-S-1			1/8		-	-		
				TIA1-14-S-2					-	-		
				TIA1-14-S-3					-	-		
	Mill annealed, G-2266			TIA1-14-S-4					-	-		
				TIA1-14-S-5					-	-		
				TIA1-14-S-6					-	-		
	Mill annealed, G-2190			TIA1-15-S-1					-	-		
				TIA1-15-S-2					-	-		
				TIA1-15-S-3					-	-		
				TIA1-15-S-4					-	-		
				TIA1-15-S-5					-	-		
				TIA1-15-S-6					-	-		
				TIA1-16-S-1					-	-		
				TIA1-16-S-2					-	-		
				TIA1-16-S-3					-	-		
				TIA1-16-S-4					-	-		
				TIA1-17-S-1					-	-		
				TIA1-17-S-2					-	-		
				TIA1-17-S-3					-	-		
				TIA1-17-S-4					-	-		
				TIA1-17-S-5					-	-		
				TIA1-17-S-6	U-5T	1/8			-	-	1/16	
				TIA1-18-S-1	PT-8	136-M			-	-	1/8	
				TIA1-18-S-2					-	-		
				TIA1-18-S-3					-	-		
				TIA1-19-S-1					-	-		
				TIA1-19-S-2					-	-		
Evaluate start conditions	Mill annealed, G-2190	Weld in place	0.26	TIA1-19-S-3	PT-8	136-M	1/8	1/8	-	-	1/8	Ar

A.

Conditions Employed for Plasma Arc Welding 6Al-4V Titanium.

Torch Setup Data					Welding Conditions												
	Electrode Configuration				Orifice Gas		Shield Gas						Cold Fill Wire Data			Backing Bar Groove	
Standoff Distance (in.)	Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type	Total Flow (cfh)	Type	Flow (cfh)	Backup Gas Type	Weld Current (amp)	Weld Voltage	Weld Travel Speed (ipm)	Heat No.	Dia (in.)	Feed Rate (ipm)	Width (in.)	Depth (in.)
3/16	1/8	-	-	1/8	Ar	16	Ar	40	Ar	200	-	7.0	NA	-	-	3/4	1
		-	-			16				130	-	8.0		-	-		
		-	-			16				170	-	7		-	-		
		-	-			16				130	-	7		-	-		
		-	-			18				150	-	8		-	-		
3/16		-	-			18				150	-	10		-	-		
1/8		-	-			15				135	-	7		-	-		
		-	-			15				137	-	8		-	-		
		-	-		Ar	15				120	-	7		-	-		
		-	-		He 56	16				132	-	7		-	-		
		-	-		AR	16				140	-	7		-	-		
1/8	1/8	-	-	1/8		9		40		175	-	19		-	-		
3/32	3/32	-	-	7/64				20,40,70		160	-	19		-	-		
32,1/8,5/32	3/32	-	-	7/64				40		150	-	16.1		-	-		
1/8	1/8	-	-	1/16				30		140/125	-	7		-	-		
		-	-			9				135	-	8		-	-		
		-	-			7				125	-	6		-	-		
		-	-			7				125	-	5		-	-		
1/8		-	-			7				120	-	4		-	-		
6,3/32,		-	-			8				130	-	7		-	-		
,3/16,1/4		-	-			8					-			-	-		
1/8		-	-			7					-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-			7					-			-	-		
		-	-			8					-			-	-		
		-	-			9		30			-			-	-		
		-	-					50			-			-	-		
		-	-					20			-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-							130	-			-	-		
		-	-							140	-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-			9					-			-	-		
		-	-	1/16		10		20			-			-	-		
		-	-	1/8		16		40			-			-	-		
		-	-			16					-			-	-		
		-	-			16					-			-	-		
		-	-			18					-			-	-		
		-	-			18					-			-	-		
1/8	1/8	-	-	1/8	Ar	18	Ar	40	Ar	140	-	7	NA	-	-	3/4	1

B.

Table I-1. Welding Conditions Employed for Plasma Arc Welding 6/

		Joint Configuration			Torch Setup Data							
								Electrode Configuration				Orific
Purpose of Test	Material Description and Heat Number	V-Groove Included Angle (deg)	Root Land Thickness (in.)	Weld Identification	Torch Type	Orifice	Standoff Distance (in.)	Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type
Evaluate start conditions	Mill, annealed G-2266	Weld in plate	0.26	TIA1-20-S-1	PT-8	136-M	1/8	1/8	-	-	1/8	Ar
				TIA1-20-S-2					-	-		
				TIA1-20-S-3					-	-		
				TIA1-21-S-1					-	-		
				TIA1-21-S-2					-	-		
				TIA1-21-S-3					-	-		
				TIA1-22-S-1					-	-		
				TIA1-22-S-2					-	-		
				TIA1-22-S-3					-	-		
				TIA1-22-S-4					-	-		
		Weld in plate 0.156 holes		TIA1-23-S-1					-	-		
				TIA1-23-S-2					-	-		
				TIA1-23-S-3					-	-		
				TIA1-23-S-4					-	-		
Evaluate start conditions				TIA1-23-S-5					-	-		
				TIA1-23-S-6	PT-8	136-M		1/8	-	-	1/8	
Evaluate weld conditions		Weld in plate 0.156 holes		TIA1-24-1	U-5T	1/16		1/16	-	-	3/32	
Evaluate start conditions				TIA1-25-S-1					-	-		
				TIA1-25-S-2					-	-		
				TIA1-25-S-3					-	-		
				TIA1-25-S-4					-	-		
				TIA1-25-S-5					-	-		
				TIA1-25-S-6					-	-		
				TIA1-26-S-1					-	-		
				TIA1-26-S-2					-	-		
				TIA1-26-S-3					-	-		
Evaluate start conditions				TIA1-26-S-4					-	-		
				TIA1-26-S-5					-	-		
First butt weld		Sq butt, 0.080 x 0.080 hole		TIA2-1-1					-	-		
Evaluate standoff		Sq butt, 0.080 x 0.080 hole		TIA2-2-1			1/8		-	-		
				TIA2-2-2			3/16		-	-		
Evaluate weld condition		Weld in plate 0.080 x 0.080 hole		TIA1-27-1		1/16	3/16	1/16	-	-	3/32	
Evaluate weld condition	Mill, annealed G-2266	Weld in plate no start hole		TIA1-28-1		3/32	1/8	3/32	-	-	1/16	
				TIA1-28-2					-	-		
Evaluate start condition	Mill annealed, G-2190	Weld in plate 7/64 holes		TIA1-28-S-1					-	-		
				TIA1-28-S-2					-	-		
				TIA1-28-S-3					-	-		
				TIA1-28-S-4			1/8		-	-		
				TIA1-28-S-5			3/16		-	-	1/16	
				TIA1-29-S-1					-	-	3/32	
				TIA1-29-S-2					-	-		
				TIA1-29-S-3					-	-		
				TIA1-29-S-4					-	-		
				TIA1-29-S-5					-	-		
		Weld in plate 1/8 holes		TIA1-30-1					-	-		
				TIA1-30-2					-	-		
				TIA1-30-3					-	-		
Evaluate start conditions	Mill annealed, G-2190			TIA1-30-4					-	-		
			0.26	TIA1-30-5	U-5T	3/32	3/16	3/32		-	3/32	Ar

A.

Employed for Plasma Arc Welding 6Al-4V Titanium (Continued).

Torch Setup Data					Welding Conditions												
	Electrode Configuration				Orifice Gas		Shield Gas						Cold Filler Wire Data			Backing Bar Groove	
Standoff Distance (in.)	Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type	Total Flow (cfh)	Type	Flow (cfh)	Backup Gas Type	Weld Current (amp)	Weld Voltage	Weld Travel Speed (ipm)	Heat No.	Dia (in.)	Feed Rate (ipm)	Width (in.)	Depth (in.)
1/8	1/8	-	-	1/8	Ar	18	Ar	40	Ar	140	-	7	NA	-	-	3/4	1
		-	-			18					-			-	-		
		-	-			18					-			-	-		
		-	-			16					-			-	-		
		-	-			16					-			-	-		
		-	-			16					-			-	-		
		-	-			16					-			-	-		
		-	-			16				140	-	7		-	-		
		-	-			14				148	-	6		-	-		
		-	-			14				150	-			-	-		
		-	-			16				140	-			-	-		
		-	-			16					-			-	-		
		-	-			16					-			-	-		
		-	-			16					-			-	-		
		-	-			16					-			-	-		
	1/8	-	-	1/8		16		40		140	-			-	-		
	1/16	-	-	3/32		7		30		125	-			-	-		
		-	-			2				85	-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-								-			-	-		
		-	-							85	-			-	-		
		-	-							80	-			-	-		
		-	-							80	-			-	-		
1/8		-	-							105	-			-	-		
3/16		-	-							109	-			-	-		
3/16	1/16	-	-	3/32		2				109	-			-	-		
1/8	3/32	-	-	1/16		3				115	-			-	-		
		-	-			4		30		120	-			-	-		
		-	-			2.5		20		85	-			-	-		
		-	-			6.5				85	-			-	-		
		-	-			5				95	-			-	-		
1/8		-	-			5				120	-			-	-		
3/16		-	-	1/16		5				125	-			-	-		
		-	-	3/32		5.5				125	-			-	-		
		-	-			4.5				100	-			-	-		
		-	-			4.5				120	-			-	-		
		-	-			3.9				105	-			-	-		
		-	-			3.9				110	-			-	-		
		-	-			3.9				105	-			-	-		
		-	-			3.9				110	-			-	-		
		-	-			4.4				105	-			-	-		
		-	-			4.4				105	-			-	-		
3/16	3/32		-	3/32	Ar	5	Ar	20	Ar	105	-	6	NA	-	-	3/4	1

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Table I-1. Welding Conditions Employed for Plasma Arc Weld

		Joint Configuration			Torch Setup Data							Ori
								Electrode Configuration				
Purpose of Test	Material Description and Heat Number	V-Groove Included Angle (deg)	Root Land Thickness (in.)	Weld Identification	Torch Type	Orifice	Standoff Distance (in.)	Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type
Evaluate weld condition	Mill annealed, G-2266	Weld in plate, 1/8 holes	0.26	T1A1-31-1	U-5T	3/32	3/16	3/32	-	-	3/32	Ar
				T1A1-31-2			1/4		-	-		Ar
Evaluate orifice gas and wire feed		Weld in plate, 1/8 holes		T1A1-32-1			3/16, 1/4		-	-		Ar
				T1A1-32-2	U-5T	3/32	3/16, 1/4	3/32	-	-	3/32	He 4
Evaluate weld condition		Weld in plate, 0.156 hole		T1A1-33-1	PT-8	136-M	3/16	1/8	-	-	1/8	Ar
		Sq butt		T1A1-33-2					-	-		
Evaluate start condition		Sq butt		T1A2-3-1					-	-		
		0.156 hole		T1A2-3-2					-	-		
Evaluate wire feed	Mill annealed, G-2266	Weld in plate, 0.156 hole	0.26	T1A1-34-1	PT-8	136-M		1/8	-	-	1/8	
Evaluate weld condition	No heat number	Weld in plate	0.125	T1A1-35-1	U-5T	1/16		1/16	-	-	1/16	
				T1A1-35-2			3/16		-	-		
				T1A1-35-3			1/8		-	-		
		Weld in plate		T1A1-35-4			1/4		-	-		
		Weld in sheet		T1A1-36-1		1/16	1/8	1/16	-	-	1/16	
				T1A1-37-1		3/32		3/32	-	-	3/32	
				T1A1-38-1					-	-		
				T1A1-38-2					-	-		
				T1A1-39-1			1/8		-	-		
				T1A1-39-2			3/16		-	-		
				T1A1-40-1					-	-		
				T1A1-40-2					-	-		
Evaluate weld condition	No heat number	Weld in sheet	0.125	T1A1-40-3	U-5T	3/32		3/32	-	-	3/32	
Evaluate start condition and outer shield	Mill annealed, G-2266	Sq butt	0.26	T1A2-41-S-1	PT-8	136-M		1/8	70	1/32	1/8	
				T1A2-41-S-2								
				T1A2-41-S-3								
				T1A2-41-S-4								
				T1A2-41-S-5								
Evaluate weld condition				T1A2-42-1	PT-8	136-M		1/8	70	1/32	1/8	
Evaluate start condition				T1A2-43-S-1	U-5T	3/32		3/32	-	-	3/32	
				T1A2-43-S-2					-	-		
				T1A2-44-S-1					-	-		
				T1A2-44-S-2					-	-		
				T1A2-44-S-3	U-5T	3/32		3/32	-	-	3/32	
				T1A2-44-S-4	PT-8	136-M		1/8	70	1/32	1/8	
Evaluate overlap and melt-in cover weld				T1A2-45-1								
				T1A2-45-2								Ar
				T1A2-45-3			3/16					He 50
Evaluate overlap and melt-in cover weld				T1A2-46-1			1/8					Ar
				T1A2-46-2			3/16					Ar
				T1A2-46-3			1/4					He 33
Evaluate running start condition				T1A2-47-S-1, 2, 3, 4, 5,			3/16					Ar
Evaluate weld speed	Mill annealed, G-2266			T1A2-48-S-1			1/4					Ar
				T1A2-48-S-2			1/4					Ar
		Sq butt	0.26	T1A2-48-S-3	PT-8	136-M	1/4	1/8	70	1/32	1/8	Ar

A.

mployed for Plasma Arc Welding 6Al-4V Titanium (Continued).

h Setup Data				Welding Conditions												
Electrode Configuration				Orifice Gas		Shield Gas		Backup Gas Type	Weld Current (amp)	Weld Voltage	Weld Travel Speed (ipm)	Cold Filler Wire Data			Backing Bar Groove	
Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type	Total Flow (cfh)	Type	Flow (cfh)					Heat No.	Dia (in.)	Feed Rate (ipm)	Width (in.)	Depth (in.)
3/32	-	-	3/32	Ar	4.1	Ar	20	Ar	105	-	6	NA	-	-	3/4	1
	-	-		Ar					105	-		NA	0.062	-		
	-	-		Ar					117	-		NA(CP)	0.062	14.5		
3/32	-	-	3/32	He 45	4.1		20		120	-		NA	0.062	14.5		
1/8	-	-	1/8	Ar	16		40		130	-			-	-		
	-	-							115-120	-			-	-		
	-	-							120	-			-	-		
	-	-							125	-		NA	-	-		
1/8	-	-	1/8		16		40		130	-	6	-	0.062	14.5		
1/16	-	-	1/16		4.0		20		83	-	16.1	NA	-	-		
	-	-			2.0		30		100	-			-	-		
	-	-			1.8				110	-			-	-		
	-	-			1.8				110	-			-	-		
1/16	-	-	1/16		1.7				100	-			-	-		
3/32	-	-	3/32		2.0-7.0				100	-			-	-		
	-	-			5.5				105	-			-	-		
	-	-			3.5				140	-			-	-		
	-	-			4.5				110	-			-	-		
	-	-			4.5				117	-			-	-		
	-	-			3.5				115	-	16.1		-	-		
	-	-			3.5				127	-	19.9		-	-		
3/32	-	-	3/32		3.5		30		125	-	19.9		-	-		
1/8	70	1/32	1/8		16		60		125	-	-		-	-		
									125	-	-		-	-		
									125	-	-		-	-		
									125	-	-		-	-		
									120	-	-		-	-		
1/8	70	1/32	1/8		16		60		125	-	-		-	-		
3/32	-	-	3/32		4		20		105	-	6		-	-		
	-	-			4		20		105	-			-	-		
	-	-			4		20		105	-			-	-		
	-	-			4		20		110	-			-	-		
3/32	-	-	3/32		3.6		35		110	-			-	-		
1/8	70	1/32	1/8		1.6		60		120	-			-	-		
					16		60		120	-			-	-		
				Ar	16	Ar	60		120	-			-	-		
				He 50	6	He 50	70		120	-			-	-		
				Ar	16	Ar	60		120	-			-	-		
				Ar	16	Ar	60		125	-			-	-		
				He 33	9	He 50	70		90	-			-	-		
				Ar	16	Ar	60		125	-	6		-	-		
				Ar	16	Ar	60		190	-	12		-	-		
				Ar	16	Ar	60		190	-	12		-	-		
1/8	70	1/32	1/8	Ar	16	Ar	60	Ar	190	-	12	NA	-	-	3/4	1

B.

Table I-1. Welding Conditions Employed for Plasma Arc Welding 6Al-4V

		Joint Configuration			Torch Setup Data			Electrode Configuration				Ori[fice]
Purpose of Test	Material Description and Heat Number	V-Groove Included Angle (deg)	Root Land Thickness (in.)	Weld Identification	Torch Type	Orifice	Standoff Distance (in.)	Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type
Evaluate overlap condition	Mill annealed, G-2266	Sq butt	0.26	T1A2-49-1	PT-8	136-M	1/4	1/8	70	1/32	1/8	Ar
				T1A2-49-2	PT-8	136-M	1/4	1/8	70	1/32	1/8	Ar
				T1A2-49-3	PT-8	136-M	1/4, 5/16	1/8	70	1/32	1/8	He 33
				T1A2-50-1, 2	PT-8	136-M	1/4, 5/16,	1/8	70	1/32	1/8	Ar
				T1A2-51-1	U-5T	3/32	1/4	3/32	-	-	3/32	
				T1A2-51-2					-	-		
				T1A2-51-3					-	-		
				T1A2-51-4					-	-		
Evaluate weld condition	Mill annealed, G-2190			T1A2-52-1					-	-		
				T1A2-52-1					-	-		
				T1A2-52-1	U-5T	3/32	1/4	3/32	-	-	3/32	
Evaluate start condition	Mill annealed, G-2190			T1A2-53-S-1	PT-8	136-M	3/16	1/8	60	1/32	1/8	
				T1A2-53-S-2								
				T1A2-53-S-3								
				T1A2-53-S-4								
				T1A2-53-S-5			3/16					
				T1A2-54-S-1			1/4					
				T1A2-54-S-2								
				T1A2-54-S-3								
				T1A2-54-S-4								
				T1A2-54-S-5								
				T1A2-54-S-6								
Evaluate overlap condition	Mill annealed, G-2190			T1A2-55-1								
				T1A2-55-2								
				T1A2-56-1					60			
				T1A2-56-2					70			Ar
				T1A2-56-3						1/32		He 50
				T1A2-57-1						0.045		Ar
			0.26	T1A2-57-2						0.045		
Tensile properties	Condition STA 293281		.235/.240	T2A2-1-1			1/4			0.046		
			.235/.240	T2A2-1-2			1/8					
			.237/.239	T2A2-2-1			1/8					
			.237/.239	T2A2-2-2			1/8					Ar
			.237/.239	T2A2-2-3			1/8					He 50
Horizontal position	Mill annealed, G-2190		0.26	T1E2-1-1	PT-8	136-M	1/4	1/8	70	0.046	1/8	Ar
Evaluate weld condition	Mill annealed, G-2190			T1A2-58-1	U-5T	3/32	5/8, 1/4	3/32	-	-	3/32	
				T1A2-58-2		3/32	5/8, 1/4	60A46	-	-	1/16	
				T1A2-58-3		3/32	3/16	3/32	-	-		
				T1A2-59-1		1/8	3/16	1/8	-	-		
				T1A2-59-2			3/32		-	-		
				T1A2-59-3			1/4		-	-		
				T1A2-59-4			3/32		-	-		
				T1A2-60-1		1/8	3/16	1/8	-	-		
				T1A2-61-1		3/32		3/32	-	-		
				T1A2-61-2					-	-		
				T1A2-61-3					-	-	1/16	
				T1A2-62-1					-	-	3/32	
				T1A2-62-2					-	-		
				T1A2-62-3					-	-		
				T1A2-63-1					-	-		
				T1A2-63-2			3/16		-	-		
		Sq butt	0.26	T1A2-63-3	U-5T	3/32	1/4	3/32	-	-	3/32	Ar

A.

…for Plasma Arc Welding 6Al-4V Titanium (Continued).

…rch Setup Data					Welding Conditions												
	Electrode Configuration				Orifice Gas		Shield Gas						Cold Filler Wire Data			Backing Bar Groove	
…off …nce …)	Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type	Total Flow (cfh)	Type	Flow (cfh)	Backup Gas Type	Weld Current (amp)	Weld Voltage	Weld Travel Speed (ipm)	Heat No.	Dia (in.)	Feed Rate (ipm)	Width (in.)	Depth (in.)
	1/8	70	1/32	1/8	Ar	16	Ar	60	Ar	190	-	12	NA	-	-	3/4	1
	1/8	70	1/32	1/8	Ar	16	Ar	60		195	-	-		-	-		
16	1/8	70	1/32	1/8	He 33	9	He 50	70		120-135	-	-		-	-		
6,	1/8	70	1/32	1/8	Ar	1.6	Ar	60		195	-	12		-	-		
	3/32	-	-	3/32		3.8		20		105	-	6		-	-		
		-	-			4.0				105	-	6		-	-		
		-	-							105	-	6		-	-		
		-	-							110	-	6		-	-		
		-	-							110	-	12		-	-		
		-	-							110	-	12		-	-		
	3/32	-	-	3/32		4.0		20		110	-	12		-	-		
6	1/8	60	1/32	1/8		16		60		135	-	6		-	-		
						16				140	-			-	-		
						14					-			-	-		
						16					-			-	-		
6											-			-	-		
											-			-	-		
											-			-	-		
											-			-	-		
											-			-	-		
											-			-	-		
										140	-			-	-		
										145	-			-	-		
										210	-	6		-	-		
		60						60		210	26.6	12		-	-		
		70			Ar	16	Ar	35		150	-			-	-		
			1/32		He 50	6	He 50	70		210	22.0			-	-		
			0.045		Ar	16	Ar	60		210	-			-	-		
			0.045			16				210	-			-	-		
			0.046			15				195	25.[illegible]			-	-		
						15				195	-			-	-		
						15				195	25.1			-	-		
					Ar	15	Ar	60		200	-			-	-		
					He 50	6	He 50	70		170	21.6/22.0			-	-		
	1/8	70	0.046	1/8	Ar	16	Ar	60		210	-			-	-		
4	3/32	-	-	3/32		2		10		210-260	-			-	-		
/4	60A46	-	-	1/16		3		20-15		210-246	-	12		-	-		
6	3/32	-	-					20		210-246	-	14		-	-		
6	1/8	-	-					20		240	26	12		-	-		
2		-	-					15		240	22.5			-	-		
		-	-					15		240	-			-	-		
		-	-					15		300	-			-	-		
6	1/8	-	-			3		20		300	-			-	-		
	3/32	-	-			3.5				185	-			-	-		
		-	-			3.5				220	-			-	-		
		-	-	1/16		4				225	-			-	-		
		-	-	3/32		4				200	-			-	-		
		-	-			3				200	-			-	-		
		-	-			3				210	-			-	-		
		-	-			4				160	-			-	-		
6		-	-			4				175	-			-	-		
	3/32	-	-	3/32	Ar	5	Ar	20	Ar	150	-	12	NA	-	-	3/4	1

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B.

Table I-1. Welding Conditions Employed for Plasma Arc Welding 6Al

Purpose of Test	Material Description and Heat Number	Joint Configuration: V-Groove Included Angle (deg)	Joint Configuration: Root Land Thickness (in.)	Weld Identification	Torch Setup Data: Torch Type	Orifice	Standoff Distance (in.)	Electrode Configuration: Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Orifice Type
Evaluate start condition	Mill annealed, G-2190	Sq butt	0.26	T1A2-64-S-1	U-5T	1/8	3/16	3/32	-	-	3/32	Ar
				T1A2-64-S-2					-	-		Ar
				T1A2-64-S-3					-	-		Ar
				T1A2-65-S-1					-	-		He 66
				T1A2-65-S-2					-	-		He 75
				T1A2-65-S-3	U-5T	1/8	3/16	3/32	-	-	3/32	Ar
Evaluate weld condition				T1A2-66-S-1	PT-8	136-M	1/4	1/8	60	1/32	1/8	
				T1A2-66-S-2								
				T1A2-66-S-3								
			0.26	T1A2-67-1								
			0.260	T1A2-68-1								
				T1A2-69-1					60	1/32		
Evaluate start condition	Mill annealed, G-2266			T1A2-74-S-1					70	0.040		
				T1A2-74-S-2								
				T1A2-74-S-3								
Evaluate overlap condition	Mill annealed, G-2266			T1A2-75-1								
				T1A2-75-2								Ar
				T1A2-75-3								He 50
				T1A2-76-1								Ar
				T1A2-76-2								
				T1A2-76-3						0.040		
				T1A2-77-1						0.035		
				T1A2-77-2								
				T1A2-78-1								
				T1A2-78-2								Ar
				T1A2-78-3								He 50
				T1A2-78-4								He 50
				T1A2-79-1								Ar
			0.260	T1A2-79-2	PT-8	136-M	1/4		70	0.035	1/8	
Evaluate start condition	Sta Ti 293281		0.235	T2A2-10-S-1	U-5T	1/8	3/16		-	-	1/16	
				T2A2-10-S-2					-	-		
				T2A2-10-S-3					-	-		
				T2A2-11-S-1					-	-		
				T2A2-11-S-2			3/16		-	-		
				T2A2-11-S-3			1/4		-	-		
Evaluate overlap condition				T2A2-12-S-1			3/16		-	-		
				T2A2-12-S-2					-	-		
				T2A2-12-S-3					-	-		
				T2A2-13-1					-	-		
				T2A2-13-2			3/16		-	-		Ar
				T2A2-13-3			1/4		-	-		He 75
Tensile properties				T2A2-14-1			1/4		-	-		Ar
				T2A2-14-2			1/4		-	-		Ar
		Sq butt	0.235	T2A2-14-3			1/4		-	-		He 75
Evaluate overlap and cover weld condition		Cover weld	-	T1A2-79-3			3/16, 1/4		-	-		He 75
		Cover weld	-	T1A2-79-4			1/4		-	-		He 75
Evaluate weld and overlap conditions	STA 302257	Sq butt	0.275	T2A2-15-1			1/4		-	-		Ar
		Sq butt	0.275	T2A2-15-2			1/4		-	-		Ar
		Sq butt	0.275	T2A2-15-3	U5-T	1/8	1/4	1/8	-	-	1/16	Ar

A.

...oyed for Plasma Arc Welding 6Al-4V Titanium (Continued).

...h Setup Data: Electrode Configuration Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Welding Conditions: Orifice Gas Type	Orifice Gas Total Flow (cfh)	Shield Gas Type	Shield Gas Flow (cfh)	Backup Gas Type	Weld Current (amp)	Weld Voltage	Weld Travel Speed (ipm)	Cold Filler Wire Data Heat No.	Cold Filler Wire Data Dia (in.)	Cold Filler Wire Data Feed Rate (ipm)	Backing Bar Groove Width (in.)	Backing Bar Groove Depth (in.)
3/32	-	-	3/32	Ar	4	Ar	20	Ar	175	-	12	NA	-	-	3/4	1
	-	-		Ar	5		20		210	-			-	-		
	-	-		Ar	6		30		190	-			-	-		
	-	-		He 66	6		20		210	-			-	-		
	-	-		He 75	8		20		240	-			-	-		
3/32	-	-	3/32	Ar	5		20		210	-	12		-	-		
1/8	60	1/32	1/8		16		60		325	-	18		-	-		
									310	-	18		-	-		
									280	-	18		-	-		
									290	-	18		-	-		
									210	26.5	12		-	-		
	60	1/32							290	29.2	18		-	-		
	70	0.040							210	-	12		-	-		
										-			-	-		
					16					-			-	-		
					16					-			-	-		
				Ar	16				210	-			-	-		
				He 50	6				160	-			-	-		
				Ar	16				210	-			-	-		
										-			-	-		
		0.040								-			-	-		
		0.035								-			-	-		
										-			-	-		
										-			-	-		
				Ar	16	Ar	60		210	-			-	-		
				He 50	6	He 50	70		160	-			-	-		
				He 50	6	He 50	70		160	-			-	-		
				Ar	16	Ar	60		210	-			-	-		
	70	0.035	1/8		16		60		210	-			-	-		
	-	-	1/16		5		20		175	-			-	-		
	-	-							195	-			-	-		
	-	-							200	-			-	-		
	-	-							200	-			-	-		
	-	-							200	-			-	-		
	-	-							210	-			-	-		
	-	-								-			-	-		
	-	-								-			-	-		
	-	-								-			-	-		
	-	-								-			-	-		
	-	-		Ar	5	Ar	20		210	-			-	-		
	-	-		He 75	4	He 75	60		150	-			-	-		
	-	-		Ar	5	Ar	2		207	25.0			-	-		
	-	-		Ar	5	Ar	2		207	25.0			-	-		
	-	-		He 75	4	He 75	60		160	23.2			-	-		
	-	-		He 75	4	He 75	60		160	24.5/26.5						
	-	-		He 75	4	He 75	60		160	27.8						
	-	-		Ar	5	Ar	30		225	-			-	-		
	-	-		Ar	5	Ar	30		235	-			-	-		
1/8	-	-	1/16	Ar	5	Ar	30	Ar	235	-	12	NA	-	-	3/4	1

Table I-1. Welding Conditions Employed for Plasma Arc Welding

Purpose of Test	Material Description and Heat Number	Joint Configuration: V-Groove Included Angle (deg)	Joint Configuration: Root Land Thickness (in.)	Weld Identification	Torch Setup Data: Torch Type	Orifice	Standoff Distance (in.)	Electrode Configuration: Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	O… Typ…
Evaluate weld and	STA 302257	Sq butt	0.275	T2A2-16-S-1	U-5T	1/8	3/16	1/8	-	-	1/16	Ar
overlap conditions				T2A2-16-S-2					-	-		
				T2A2-16-S-3					-	-		
				T2A2-17-1					-	-		
				T2A2-17-2					-	-		Ar
				T2A2-17-3	U-5T	1/8	3/16		-	-	1/16	He
				T2A2-18-S-1	PT-8	136-M	1/4		70	3/64	1/8	Ar
				T2A2-18-S-2								
				T2A2-18-S-3								
				T2A2-19-S-1								
				T2A2-19-S-2								
				T2A2-19-S-3								
				T2A2-20-1								
				T2A2-20-2								Ar
	STA 302257		0.275	T2A2-20-3								He 5
	STA Ti 293281		0.230	T2A2-21-S-1								Ar
				T2A2-21-S-2								Ar
				T2A2-21-S-3								Ar
				T2A2-21-S-4								He 5
				T2A2-21-S-5								He 5
				T2A2-22-S-1								Ar
				T2A2-22-S-2								Ar
				T2A2-22-S-3								Ar
	STA Ti 293281			T2A2-22-S-4								He 5
			0.230	T2A2-22-S-5								He 5
	STA Ti 302257		0.275	T2A2-23-S-1								Ar
				T2A2-23-S-2								Ar
				T2A2-23-S-3								He 5
				T2A2-24-S-1								Ar
				T2A2-24-S-2								Ar
				T2A2-24-S-3								Ar
	STA Ti 302257		0.275	T2A2-24-S-4								He 50
	STA Ti, G-4956		0.250	T2A2-25-1								Ar
				T3A2-25-2								Ar
				T2A2-25-3								Ar
				T2A2-25-4								He 50
	STA Ti, G-4956			T2A2-26								Ar
	Mill annealed, G-2266			T1A2-80-1								
				T1A2-80-2								
				T1A2-81-1								
				T1A2-81-2								
				T1A2-81-3								Ar
				T1A2-81-4								He 50
				T1A2-82-1								Ar
				T1A2-82-2								
				T1A2-82-3								
				T1A2-83-1								
				T1A2-83-2								
				T1A2-83-3								Ar
				T1A2-83-4								He 50
				T1A2-84-1								Ar
				T1A2-84-2								
			0.250	T1A2-85-1								
			0.26	T1A2-86-1								
Evaluate weld and			0.26	T1A2-86-2								
overlap conditions	Mill annealed, G-2266	Sq butt	0.26	T1A2-86-3	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar

A.

ployed for Plasma Arc Welding 6Al-4V Titanium (Continued).

Torch Setup Data					Welding Conditions												
	Electrode Configuration				Orifice Gas		Shield Gas						Cold Filler Wire Data			Backing Bar Groove	
doff ance n.)	Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type	Total Flow (cfh)	Type	Flow (cfh)	Backup Gas Type	Weld Current (amp)	Weld Voltage	Weld Travel Speed (ipm)	Heat No.	Dia (in.)	Feed Rate (ipm)	Width (in.)	Depth (in.)
/16	1/8	-	-	1/16	Ar	5	He 75	60	Ar	235	-	12	NA	-	-	3/4	1
		-	-				He 75	60		200	-			-	-		
		-	-				He 75	60		215	-			-	-		
		-	-				Ar	30		235	27.2			-	-		
		-	-		Ar	5	Ar	30		235	27.2			-	-		
/16		-	-	1/16	He 75	4	He 75	60		160	30.0			-	-		
/4		70	3/64	1/8	Ar	16	Ar			225	-			-	-		
										225	-			-	-		
										235	-			-	-		
										235	-			-	-		
										235	-			-	-		
						16				235	-			-	-		
						15				235	26.5			-	-		
					Ar	15	Ar	60		236	26.5			-	-		
					He 50	6	He 50	70		160	23.2			-	-		
					Ar	15	Ar	60		200	-			-	-		
					Ar	15	Ar	60		200	-			-	-		
					Ar	15	Ar	60		200	-			-	-		
					He 50	6	He 50	70		170	-			-	-		
					He 50	6	He 50	70		170	-			-	-		
					Ar	15	Ar	60		200	-			-	-		
					Ar	15	Ar	60		200	-			-	-		
					Ar	15	Ar	60		200	-			-	-		
					He 50	6	He 50	70		170	-			-	-		
					He 50	6	He 50	70		170	-			-	-		
					Ar	15	Ar	60		230	-			-	-		
					Ar	15	Ar	60		230	-			-	-		
					He 50	6	He 50	70		170	-			-	-		
					Ar	15	Ar	60		225	-			-	-		
					Ar	15	Ar	60		225	-			-	-		
					Ar	15	Ar	60		235	-			-	-		
					He 50	6	He 50	70		170	-			-	-	3/4	
					Ar	16	Ar	60		210	-			-	-	3-1/2	
					Ar	16	Ar	60		210	-			-	-		
					Ar	16	Ar	60		210	-			-	-		
					He 50	6	He 50	70		170	-			-	-		
					Ar	16	Ar	60		210	-			-	-	3-1/2	
										210	-			-	-	1-1/2	
										210	-			-	-		
										210	-			-	-		
										210	-			-	-		
					Ar	16	Ar	60		210	-			-	-		
					He 50	6	He 50	70		160	-			-	-		
					Ar	16	Ar	60		210	-			-	-		
										210	-		NA	-	-		
										170	-		NA(CP)	0.062	18	1-1/2	
										210	-		NA	-	-	3-1/2	
										210	-		NA	-	-		
					Ar	16	Ar	60		210	-		NA	-	-		
					He 50	6	He 50	70		160	-		NA(CP)	0.062	15	3-1/2	
					Ar	16	Ar	60		210	-		NA	-	-	1-1/2	
										210	-			-	-		
										220	-			-	-		
										220	-			-	-		
										220	-			-	-		
4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar	210	-	12	NA	-	-	1-1/2	1

Table I-1. Welding Cond. ·s Employed for Plasma Arc Welding 6Al-

Purpose of Test	Material Description and Heat Number	Joint Configuration: V-Groove Included Angle (deg)	Joint Configuration: Root Land Thickness (in.)	Weld Identification	Torch Setup Data: Torch Type	Orifice	Standoff Distance (in.)	Electrode Configuration: Dia (in.)	Electrode Configuration: Included Tip Angle (deg)	Electrode Configuration: End Flat Dia (in.)	Electrode Configuration: Setback Distance (in.)	Orifice: Type
Evaluate weld and overlap conditions	Mill annealed, G-2266	Sq butt	0.26	T1A2-86-4	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar
			0.26	T1A2-86-5								He 50
	STA Ti, G-4956		0.250	T2A2-27-1								Ar
			0.250	T2A2-27-2								Ar
			0.250	T2A2-27-3								Ar
			0.250	T2A2-27-4								He 50
Gaps	Mill annealed, G-2190		0.26	T1A2-87-1								Ar
Mismatch	Mill annealed, G-2190		0.26	T2A2-28-1								
Gaps and mismatch	Mill annealed, G-2190		0.26	T1A2-88-1								
Evaluate weld and overlap condition, horizontal position.	STA Ti, G-4956		0.250	T2E2-1-1								
				T2E2-1-2								Ar
				Cover, no wire -1								He 50
				Cover, wire -2								He 50
				T2E2-2-1								Ar
				T2E2-2-2								Ar
				T2E2-2-3								Ar
				Cover, -1								He 50
		Sq butt	0.250	Cover w/wire-2								He 50
Evaluate purge gas temperature rise in 24-in.-dia sphere	Cover weld scrap Ti ball	-	-	ϕII Test No. 1								He 50
		Keyhole	0.270	ϕII Test No.2-1								Ar
		Keyhole	0.270	Cover w/wire-2								He 50
		Keyhole	0.270	Cover w/wire-3								He 50
Evaluate overlap condition, horizontal position	Mill annealed, G-2190	Sq butt	0.26	T1E2-1-1								Ar
				T1E2-1-2								Ar
				T1E2-1-3								Ar
Cover weld procedure	Mill annealed, G-2190			T1E2-1-4								He 50
				T1E2-1-5								He 50
Evaluate overlap conditions	Mill annealed			T1A2-89-1								Ar
				T1A2-89-2								
				T1A2-89-3								
				T1A2-90-1								
				T1A2-90-2								
				T1A2-90-3								
				T1A2-91-1								
				T1A2-91-2								
			0.26	T1A2-91-3								
	STA Ti, G-4956		0.250	T2A2-28-1								
			0.250	T2A2-28-2								
			0.250	T2A2-28-3								
	Mill annealed, G-2190		0.26	T1A2-92-1								
			0.26	T1A2-92-2								
		Sq butt	0.26	T1A2-92-3								Ar
Evaluate cover weld conditions	Per weld identification	Cover weld	0.250	-1 wire on T2A2-28								He 50
		Cover weld		-2 wire on T1A2-91								He 50
		Cover weld		-3 wire on T1A2-92								He 75
		Cover weld		-1 wire on T1A2-89								He 75
		Cover weld	o.250	-2 wire on T1A2-90	PT-8	136-M	1/4	1/8	70	3/64	1/8	He 75

A

oyed for Plasma Arc Welding 6Al-4V Titanium (Continued).

orch Setup Data					Welding Conditions												
	Electrode Configuration				Orifice Gas		Shield Gas						Cold Filler Wire Data			Backing Bar Groove	
doff nce .)	Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type	Total Flow (cfh)	Type	Flow (cfh)	Backup Gas Type	Weld Current (amp)	Weld Voltage	Weld Travel Speed (ipm)	Heat No.	Dia (in.)	Feed Rate (ipm)	Width (in.)	Depth (in.)
/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar	225	-	12	NA	-	-	1-1/2	1
					He 50	6	He 50	70		150	-			-	-		
					Ar	16	Ar	60		220	-			-	-		
					Ar	16	Ar	60		220	-			-	-		
					Ar	16	Ar	60		230	-				-		
					He 50	6	He 50	70		150	-			-	-	1-1/2	
					Ar	16	Ar	60		220	-			-	-	2	
						16	Ar				-			-	-		
						16	Ar				-			-	-		
						16	Ar				-			-	-		
					Ar	16	Ar	60		220	-			-	-		
					He 50	6	He 50	70		150	-			-	-		
					He 50	6	He 50	70		130	-			-	-		
					Ar	16	Ar	60		220	-			-	-		
					Ar	16	Ar	60		220	-			-	-		
					Ar	16	Ar	60		220	-			-	-		
					He 50	6	He 50	70		150	-			-	-		
					He 50	6	He 50	70		110	-		NA	-	-		
					He 50	6	He 50	70		150	-		NA(CP)	0.062	36		
					Ar	16	Ar	60		220	-		NA	-	-		
					He 50	6	He 50	70		170	-		NA(CP)	0.062	36		
					He 50	6	He 50	70		170	-		NA	-	-		
					Ar	16	Ar	60		220	-			-	-		
					Ar	16	Ar	60		220	-			-	-		
					Ar	16	Ar	60		220	-			-	-		
					He 50	6	He 50	70		150	-			-	-		
					He 50	6	He 50	70		100	-			-	-		
					Ar	16	Ar	60		220	-			-	-		
											-			-	-		
											-			-	-		
											-			-	-		
											-			-	-		
											-			-	-		
											-			-	-		
											-			-	-		
											-			-	-		
											-			-	-		
											-			-	-		
											-			-	-		
											-			-	-		
											-			-	-		
					Ar	16	Ar	60		220	-			-	-		
					He 50	6	He 50	70		165	-	12		-	18		
					He 50	6	He 50	70		210	-	15		-	22.5		
					He 75	8	He 75	60		180	-	15		-	-		
					He 75	8	HE 75	60		190	-	15		-	22.5		
4	1/8	70	3/64	1/8	He 75	8	He 75	60	Ar	150	-	12	NA	-	18	2	1

B

Table I-1. Welding Conditions Employed for Plasma Arc Weldin

		Joint Configuration			Torch Setup Data			Electrode Configuration				Ori
Purpose of Test	Material Description and Heat Number	V-Groove Included Angle (deg)	Root Land Thickness (in.)	Weld Identification	Torch Type	Orifice	Standoff Distance (in.)	Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type
Evaluate overlap conditions	STA Ti, G-4956	Sq butt	.248/.250	T2A2-29-1	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar
			.248/.250	T2A2-29-2								Ar
Evaluate mechanical properties	STA Ti, G-4956		0.250	T2A2-30-1								Ar
				T2A2-30-2								Ar
				T2A2-30-3								He 75
				T2A2-31-1								Ar
				T2A2-31-2								Ar
				T2A2-31-3								He 75
				T2A2-32-1								Ar
				T2A2-32-2								Ar
		Sq butt		T2A2-32-3								He 75
		Repair weld in T2A2-29		T2A2-33-1								Ar
		Sq butt		T2A2-34-1								
				T2A2-34-2								
Evaluate stress relief cycles				T2A2-35-1								
Evaluate horizontal position weld	Mill annealed, G-2190			T1E2-2-1								Ar
				Cover -2								He 50
				T1E2-3-1								Ar
				T1E2-3-2								He 66
				T1E2-3-3								He 66
Evaluate mechanical properties	STA Ti, G-4956			T2E2-3-1								Ar
				T2E2-3-2								Ar
				T2E2-3-3								He 66
				T2E2-3-4								He 66
Checkout weld schedule	Mill annealed, G-2266			T1E2-4-1								Ar
				T1E2-4-2								
Evaluate Effects of Heat input on properties	STA Ti, G-4956			T2A2-36-1								
			0.250	T2A2-36-2	PT-8	136-M	1/4		70	3/64	1/8	
Evaluate weld and overlap condition	Mill annealed, G-2190		0.266	T1A2-93-1	U-5T	1/8	3/16		-	-	1/16	
				T1A2-93-2					-	-		
				T1A2-93-3					-	-		
				T1A2-94-1					-	-		
				T1A2-94-2					-	-		
				T1A2-94-3					-	-		
				T1A2-95-1					-	-		
				T1A2-95-2					-	-		
				T1A2-95-3			3/16		-	-		Ar
				Cover -4			1/4		-	-		He 75
				T1A2-96-1			3/16		-	-		Ar
				T1A2-96-2			3/16		-	-		Ar
Evaluate weld and overlap condition	Mill annealed, G-2190	Sq butt	0.266	Cover -3	U-5T	1/8	1/4	1/8	-	-	1/16	He 75

A.

Employed for Plasma Arc Welding 6Al-4V Titanium (Continued).

Torch Setup Data					Welding Conditions												
	Electrode Configuration				Orifice Gas		Shield Gas						Cold Filler Wire Data			Backing Bar Groove	
andoff stance (in.)	Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type	Total Flow (cfh)	Type	Flow (cfh)	Backup Gas Type	Weld Current (amp)	Weld Voltage	Weld Travel Speed (ipm)	Heat No.	Dia (in.)	Feed Rate (ipm)	Width (in.)	Depth (in.)
1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar	220	27.5	12	NA	-	-	2	1
					Ar	16	Ar			220	27.6		NA	-	-		
					Ar	16	Ar			220	27.5		NA	-	-		
					Ar	16	Ar			220	-		NA	-	-		
					He 75	8	He 75			150	25.5		301525	0.062	18		
					Ar	16	Ar			220	27.2		NA	-	-		
					Ar	16	Ar			220	-		NA	-	-		
					He 75	8	He 75			150	25.6		3204-01	0.062	18		
					Ar	16	Ar			220	27.2		NA	-	18		
					Ar	16	Ar			220	-		NA	-	18		
					He 75	8	He 75			175	26.2		3204-01	0.062	23		
					Ar	16	Ar			220	26.0		NA	-	-		
						16				220	27.5			-	-		
						16				220	27.0			-	-		
						16				220	-			-	-		
					Ar	16	Ar	60		220	-			-	-		
					He 50	6	He 50	70		200	-			-	-		
					Ar	16	Ar	60		220	-			-	-		
					He 66	9	He 75			150	-			-	-		
					He 66	9	He 75			90	-			-	-		
					Ar	16	Ar			220	-			-	-		
					Ar	16	Ar			220	-			-	-		
					He 66	9	He 75			150	-			-	-		
					He 66	9	He 75			90	-			-	-		
					Ar	16	Ar			220	-			-	-		
						16				220	-			-	-		
						16				220	-			-	-		
/4		70	3/64	1/8		15		60		190	-			-	-		
/16		-	-	1/16		5		30		235	-			-	-		
		-	-			6.5				240	-			-	-		
		-	-			7				260	-			-	-		
		-	-			7				260	-			-	-		
		-	-			7.5				270	-			-	-		
		-	-			7.5					-			-	-		
		-	-			8.0					-			-	-		
		-	-			8.0					-			-	-		
/16		-	-		Ar	8.5	Ar	30		270	-		NA	-	-		
/4		-	-		He 75	4	He 75	60		170	-		3204-01	0.063	23		
/16		-	-		Ar	8.0	Ar	30		270	-		NA	-	-		
/16		-	-		Ar	8.0	Ar	30		270	-		NA	-	-		
/4	1/8	-	-	1/16	He 75	4	He 75	60	Ar	170	-	12	3204-01	0.063	20	2	1

B.

Table I-2. Welding Conditions Employed for Plas
Nickel Base Alloys.

		Joint Configuration			Torch Setup Data			Electrode Configuration				Or
Purpose of Test	Material Description and Heat Number	V-Groove Included Angle (deg)	Root Land Thickness (in.)	Weld Identification	Torch Type	Orifice	Standoff Distance (in.)	Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type
Evaluate torch shield gas cups	Inconel 718	Weld in plate	0.25	K1A1-12-1	PT-8	136-M	1/4	1/8	70	1/32	1/8	Ar
		Weld in plate		K1A1-13-1								Ar
Evaluate weld condition		Sq butt		K1A2-6-1								Ar
		Cover		Cover -2								H_2 2
		Sq butt		K1A2-7-S-1								Ar
				K1A2-8-1								H_2 1
				K1A2-9A-1			1/4					Ar
				K1A2-9A-2			3/16					
				K1A2-9A-3			1/8					
				K1A2-9B-1			1/8					
				K1A2-9C-1			1/8					Ar
Evaluate tensile properties				K1A2-10A			1/4					H_2 1
				K1A2-10B								Ar
				K1A2-10C	PT-8	136-M		1/8	70	1/32	1/8	H_2 11
Evaluate welding conditions				K1A2-11-1	U-5T	3/32		3/32	-	-	3/32	Ar
				K1A2-11-2					-	-		
				K1A2-12-S-1					-	-		
				K1A2-12-S-2					-	-		
				K1A2-12-S-3					-	-		
				K1A2-13-S-1					-	-		
				K1A2-13-S-2					-	-		
				K1A2-13-S-3					-	-		
	Inconel 718		0.25	K1A2-14-S-1	U-5T	3/32	1/4		-	-	3/32	Ar
	Rene 41		0.062	R1A2-5-1S	PT-8	111-M	3/16		60	Point	1/8	H_2 3.
				R1A2-6-1					60	Point	1/8	H_2 3.
				R1A2-7-1					60	Point	1/8	H_2 10
				R1A2-8-1					60	Point	1/8	H_2 10
	Rene 41		0.062	R1A2-9-1	PT-8	111-M	3/16		60	Point	1/8	H_2 10
	Inconel 718		0.25	K1A2-15-S-1	U-5T	3/32	1/4		-	-	3/32	Ar
				K1A2-15-S-2					-	-		
				K1A2-15-S-3					-	-		
				K1A2-15-S-4					-	-		
	Inconel 718			K1A2-16-S-1			1/4		-	-		
				K1A2-16-S-2			3/16		-	-		
				K1A2-16-S-3			1/4		-	-		
			0.25	K1A2-16-S-4	U-5T	3/32	1/4		-	-	3/32	Ar
	Rene 41		0.062	R1A2-10-1	PT-8	111-M	3/16		60	Point	1/8	H_2 10
	Rene 41		0.062	R1A2-11-1		111-M	3/16		60	Point		H_2 10
	Rene 41		0.062	R1A2-12-1		111-M	3/16	3/32	60	Point		H_2 10
	Inconel 718		0.25	K1A2-17-1		136-M	1/4	1/8	70	1/32		Ar
				K1A2-17-2								Ar
				K1A2-17-3								Ar
				K1A2-17-4								Ar
				K1A2-17-5								Ar
				K1A2-17-6								H_2 20
	Inconel 718			K1A2-18-1								Ar
				K1A2-18-2								Ar
				K1A2-18-3								Ar
				K1A2-18-4								H_2 20
	Inconel 718	Sq butt		K1A2-19-1								Ar
			0.25	Cover -2	PT-8	136-M	1/4	1/8	70	1/32	1/8	H_2 20

A.

Conditions Employed for Plasma Arc Welding Nickel Base Alloys.

…ff …ce	Torch Setup Data: Electrode Configuration: Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Welding Conditions: Orifice Gas: Type	Orifice Gas: Total Flow (cfh)	Shield Gas: Type	Shield Gas: Flow (cfh)	Backup Gas Type	Weld Current (amp)	Weld Voltage	Weld Travel Speed (ipm)	Cold Filler Wire Data: Heat No.	Cold Filler Wire Data: Dia (in.)	Cold Filler Wire Data: Feed Rate (ipm)	Backing Bar Groove: Width (in.)	Backing Bar Groove: Depth (in.)
	1/8	70	1/32	1/8	Ar	12, 13, 14	Ar	60	Ar	140	-	6	NA	-	-	3/4	1
					Ar	13	Ar	60-80		140	-			-	-		
					Ar	13	Ar	60		140(160)	-			-	-		
					H_2 20	5	H_2 17			80	-			-	-		
					Ar	14	Ar			140	-			-	-		
					H_2 11	9	H_2 17			80	-			-	-		
6					Ar	14	Ar			140	23.8			-	-		
										140	22.9			-	-		
										140	21.9			-	-		
										140	-			-	-		
					Ar	14	Ar			180	-			-	-		
					H_2 11	9	H_2 11			140	-			-	-		
					Ar	14	Ar			140	-			-	-		
	1/8	70	1/32	1/8	H_2 11	9	H_2 11	60		80	-			-	-		
	3/32	-	-	3/32	Ar	3.0, 4.0, 4.8	Ar	20		105	-			-	-		
		-	-			5.0		20		105-115	-			-	-		
		-	-			5.0		20		110	-			-	-		
		-	-			5.0		20		110	-			-	-		
		-	-			5.0		30		110	-			-	-		
		-	-			5.0		30-60		115	-			-	-		
		-	-			4.0		30		115	-			-	-		
		-	-			5.0		20		115	-			-	-		
		-	-	3/32	Ar	5.0	Ar	30		115	-	6		-	-		
		60	Point	1/8	H_2 3.5	10	-	-		120	-	32		-	-		
		60	Point	1/8	H_2 3.5	10	-	-		120	-	32		-	-		
		60	Point	1/8	H_2 10	6	-	-		90	-	32		-	-		
		60	Point	1/8	H_2 10	6	-	-		90, 95	-	32		-	-		
		60	Point	1/8	H_2 10	6	-	-		90	-	32		-	-		
		-	-	3/32	Ar	4.0(3.5)	Ar	20		125	-	6		-	-		
		-	-			3.5		20		135	-			-	-		
		-	-			6.0		30		115	-			-	-		
		-	-			2.0(2.5)		30		150(200)	-			-	-		
		-	-			4.0(4.8)		20		125(135)	-			-	-		
		-	-			5.0		20		135, 125, 140	-			-	-		
		-	-			5.0		20		140	-			-	-		
		-	-	3/32	Ar	5.5, 4.5		20		135	-	6		-	-		
		60	Point	1/8	H_2 10	6		60		120	-	31		-	-		
		60	Point		H_2 10	6				110(100)	-	31		-	-		
	3/32	60	Point		H_2 10	6				100	-	31		-	-		
	1/8	70	1/32		Ar	14				140	-	6		-	-		
					Ar	14				140	-			-	-		
					Ar	15				150	-			-	-		
					Ar	14				145	-			-	-		
					Ar	14	Ar			145	-			-	-		
					H_2 20	5	H_2 17			80	-			-	-		
					Ar	14	Ar			145	-			-	-		
					Ar	14	Ar			145	-			-	-		
					Ar	14	Ar			145	-			-	-		
					H_2 20	5	H_2 17			80	-			-	-		
					Ar	14	Ar			145	-			-	-		
	1/8	70	1/32	1/8	H_2 20	5	H_2 17	60	Ar	80	-	6	NA	-	-	3/4	1

B.

Table I-2. Welding Conditions Employed for Plasm
Nickel Base Alloys (Continued).

Purpose of Test	Material Description and Heat Number	Joint Configuration: V-Groove Included Angle (deg)	Joint Configuration: Root Land Thickness (in.)	Weld Identification	Torch Setup Data: Torch Type	Torch Setup Data: Orifice	Torch Setup Data: Standoff Distance (in.)	Electrode Configuration: Dia (in.)	Electrode Configuration: Included Tip Angle (deg)	Electrode Configuration: End Flat Dia (in.)	Electrode Configuration: Setback Distance (in.)	Orific Type
Evaluate welding conditions	Rene 41	Weld in sheet	0.062	R1A1-1-0-1	PT-8	111-M	7/32	1/16	-	-	1/8	He 75
				R1A1-1-0-2				1/16	-	-		He 75
				R1A1-2-0-1				1/16	-	-		He 75
				R1A1-2-0-1				1/16	-	-		He 75
				R1A1-3-1				3/32	-	-		H_2 7.5
				R1A1-4-1					-	-		H_2 7.5
				R1A1-4-2					-	-		H_2 7.5
				R1A1-4-3					-	-		H_2 7.5
				R1A1-4-4					-	-	1/8	H_2 7.5
		Weld in sheet		R1A1-5-1			7/32	3/32	-	-	7/64	H_2 8.2
		Sq butt		R1A2-1-1	PT-8	111-M	3/32-1/8	1/16	-	-	7/64	H_2 7.5
		Weld in sheet		R1A1-7-1	U-5T	1/16	1/8	1/16	-	-	1/16	H_2 7.5
		Weld in sheet		R1A1-7-2	U-5T	1/16	1/8	1/16	-	-	1/16	H_2 7.5
	Rene 41	Sq butt	0.062	R1A2-2-1	U-5T	1/16	1/8	1/16	-	-	1/16	[illegible] 7.5
	Inconel 718	Weld in plate	0.25	K1A1-1-1	PT-8	136-M	3/16	1/8	-	-	1/8	Ar
	Rene 41	Weld in sheet	0.062	R1A1-9-1	U-5T	1/16	3/32	1/16	-	-	1/16	H_2 7.5
				R1A1-9-2			3/16		-	-		
				R1A1-9-3			1/4		-	-		
				R1A1-9-4			5/16		-	-		
				R1A1-10-1			1/8		-	-		
				R1A1-10-2			3/16		-	-		
				R1A1-10-3			1/4		-	-		
		Weld in sheet		R1A1-11-1			3/16		-	-		
				R1A1-11-2					-	-		
				R1A1-11-3					-	-		
				R1A1-11-4					-	-		
		Sq butt		R1A2-3-1					-	-		
				R1A2-3-2					-	-		
				R1A2-3-3	U-5T	1/16	3/16		-	-	1/16	
		Weld in sheet		R1A1-12-1	PT-8	111-M	1/8		-	-	1/8	
				R1A1-12-2					-	-	1/8	
				R1A1-13-1					-	-	1/8	H_2 7.5
				R1A1-13-2					-	-	3/32	H_2 9.6
				R1A1-13-3			1/8	1/16	-	-	3/32	H_2 7.5
	Rene 41	Weld in sheet	0.062	R1A1-14-1		111-M	3/16	3/32	-	-	5/32	H_2 7.5
	Inconel 718	Weld in Plate	0.25	R1A1-2-1		136-M	3/16	1/8	-	-	1/8	H_2 11.
				K1A1-3-1			1/8, 3/16, 1/4		Blunt	-		Ar
				K1A1-4-1			1/4		Blunt	-		
				K1A1-5-1			1/4		Sharp	-		
		Weld in plate		K1A1-6-1			1/4		Blunt	-		
		Sq butt		K1A2-1-1	PT-8	136-M	1/4	1/8	-	-	1/8	
		Weld in plate		K1A1-7-1	U-5T	3/32	3/16	3/32	-	-	3/32	
				K1A1-8-1			3, 4, 2, 5/16		-	-		
				K1A1-9-1			3/16, 1/4		-	-		
				K1A1-10-1			2, 3, 4, 5/16		-	-		
		Weld in plate		K1A1-11-1			5/16		-	-		
Evaluate edge properties		Sq butt		K1A2-2-1	U-5T	3/32	2, 3, 4, 5/16	3/32	-	-	3/32	
				K1A2-3A-1	PT-8	136-M	3/16	1/8	70	1/32	1/8	
				K1A2-3B-1			3/16, 1/8					Ar
				K1Aγ-3C-1			1/8					H_2 11
				K1A2-4-1			1/4					Ar
		Sq butt		K1A2-5-1			1/4					Ar
	Inconel 718	Cover	0.25	Cover -2	PT-8	136-M	1/4	1/8	70	1/32	1/8	H_2 11

A.

ing Conditions Employed for Plasma Arc Welding
Nickel Base Alloys (Continued).

Torch Setup Data					Welding Conditions												
	Electrode Configuration				Orifice Gas		Shield Gas						Cold Filler Wire Data			Backing Bar Groove	
ndoff tance (in.)	Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type	Total Flow (cfh)	Type	Flow (cfh)	Backup Gas Type	Weld Current (amp)	Weld Voltage	Weld Travel Speed (ipm)	Heat No.	Dia (in.)	Feed Rate (ipm)	Width (in.)	Depth (in.)
/32	1/16	-	-	1/8	He 75	8	Ar	40	Ar	130	-	31	NA	-	-	3/4	1
	1/16	-	-		He 75	8	Ar	40		115	-			-	-		
	1/16	-	-		He 75	8	Ar	40		115	-			-	-		
	1/16	-	-		He 75	8	Ar	40		105	-			-	-		
	3/32	-	-		H_2 7.5	6	H_2 15	25		130	-			-	-		
		-	-		H_2 7.5	6	H_2 15	25		115	-			-	-		
		-	-		H_2 7.5	6	H_2 15	25		120	-			-	-		
		-	-		H_2 7.5	6	H_2 15	25		110	-			-	-		
		-	-	1/8	H_2 7.5	6	H_2 15	25		100	-			-	-		
/32	3/32	-	-	7/64	H_2 8.2	5.5	H_2 14	25	Ar	114	-			-	-		
-1/8	1/16	-	-	7/64	H_2 7.5	5	H_2 15	25	H_2 15	115	-			-	-		
/8	1/16	-	-	1/16	H_2 7.5	2.8	H_2 15	20	Ar	100	-			-	-		
/8	1/16	-	-	1/16	H_2 7.5	2.8	H_2 15	20		77	-			-	-		
/8	1/16	-	-	1/16	H_2 7.5	2.8	H_2 15	20		62	-	31		-	-		
/16	1/8	-	-	1/8	Ar	13	Ar	40		150(140)	-	6		-	-		
/32	1/16	-	-	1/16	H_2 7.5	2.8	H_2 15	20		62	-	31		-	-		
/16		-	-			2.8	H_2 15	20		62	-	31		-	-		
/4		-	-			2.8	H_2 15	20		62	-	31		-	-		
/16		-	-			2.8	H_2 15	20		62	-	31		-	-		
/8		-	-			2.0	H_2 3	30		62(100)	-	32		-	-		
/16		-	-							62(100)	-			-	-		
/4		-	-							62(100	-			-	-		
/16		-	-							120	-			-	-		
		-	-							110	-			-	-		
		-	-							100	-			-	-		
		-	-							90	-			-	-		
		-	-							110	-			-	-		
		-	-							100	-			-	-		
/16		-	-	1/16		2.0		30	Ar	90	-			-	-		
/8		-	-	1/8		5.0		45	H_2 15	115	-			-	-		
		-	-	1/8		5.0		45	H_2 15	125	-			-	-		
		-	-	1/8	H_2 7.5	5.0		60	H_2 15	115, 125, 135	-			-	-		
		-	-	3/32	H_2 9.6	7		45	H_2 15	135	-			-	-		
/8	1/16	-	-	3/32	H_2 7.5	9	H_2 3		H_2 15	110, 120	-			-	-		
/16	3/32	-	-	5/32	H_2 7.5	10.0	H_2 15		Ar	90, 80	-	32		-	-		
/16	1/8	-	-	1/8	H_2 11.5	13.0	H_2 15			130	-	6		-	-		
16, 1/4		Blunt	-		Ar	15	H_2 3			140	-			-	-		
/4		Blunt	-			15	Ar			149	-			-	-		
/4		Sharp	-			15				140	-			-	-		
/4		Blunt	-			15				140	-			-	-		
/4	1/8	-	-	1/8		13		45		130	-			-	-		
16	3/32	-	-	3/32		7		30		120, 106, 110	-			-	-		
, 5/16		-	-			7				110	-			-	-		
, 1/4		-	-			[illegible]				110	-			-	-		
, 5/16		-	-			7	Ar			110	-			-	-		
16		-	-			7	H_2 3			110	-			-	-		
, 5/16	3/32	-	-	3/32		6.7	Ar	30		110	-			-	-		
16	1/8	70	1/32	1/8		13	Ar	50		140(150)	-			-	-		
1/8					Ar	13	Ar	80		150	-			-	-		
8					H_2 11	9	H_2 17	60		80	-			-	-		
4					Ar	13	Ar	50		140	-			-	-		
4					Ar	13	Ar	50		140	-			-	-		
4	1/8	70	1/32	1/8	H_2 11	9	H_2 17	60	Ar	80	25.7	6	NA	-	-	3/4	1

B.

Table I-3. Welding Conditions Employed for Plasma A Miscellaneous Materials.

Purpose of Test	Material Description and Heat Number	Joint Configuration: V-Groove Included Angle (deg)	Joint Configuration: Root Land Thickness (in.)	Weld Identification	Torch Setup Data: Torch Type	Orifice	Standoff Distance (in.)	Electrode Configuration: Dia (in.)	Electrode Configuration: Included Tip Angle (deg)	Electrode Configuration: End Flat Dia (in.)	Electrode Configuration: Setback Distance (in.)	Orifi[c…]: Type
Setup conditions for welding 0.062 Rene 41	347 stainless steel	Weld in plate	0.062	S1A1-1	PT-8	111-M	1/8	1/16	-	-	1/8	Ar
				S1A1-2-1			7/64		-	-		Ar
				S1A1-2-2					-	-		Ar
				S1A1-3-1					-	-		He 75
				S1A1-4-1					-	-		
				S1A1-4-2					-	-		
				S1A1-5-1					-	-		
				S1A1-5-2			7/64		-	-		
				S1A1-6-1			7/32		-	-		
				S1A1-6-2			7/32		-	-		
				S1A1-7-1			1/8		-	-		
				S1A1-7-2	PT-8	111-M	1/8		-	-	1/8	He 75
				S1A1-8-1	U-5T	1/16	1/8		-	-	1/16	Ar
				S1A1-9-1	U-5T	1/16	1/16		-	-	1/16	Ar
				S1A1-10-1	U-5T	1/16	1/16	1/16	-	-	1/16	Ar
				S1A1-10-2	U-5T	1/16	1/16	1/16	-	-	1/16	Ar
	347 stainless steel	Weld in plate	0.062	S1A1-11-1	PT-8	111-M	1/8	3/32	-	-	1/8	H_2 7.5
Setup conditions for welding prototype gas turbine hardware	410 stainless steel	Sq butt	0.26	Test No. 7-1		136-M	3/16	1/8	70	1/32		Ar
			0.26	Test No. 1-2								
			0.225	Test No. 8-1								
				Test No. 8-2								
				Test No. 9-1								
				Test No. 9-2								
				Test No. 10-1								
				Test No. 10-2								
				Test No. 11-1								
				Test No. 11-2								
				Test No. 12-1								
				Test No. 12-2			3/16					
			0.225	Test No. 13-1			3/16, 1/4, 1/8					
				Rework weld		136-M	3/16		70			
			.125/.190	Test No. 14-1		111-M	3/16, 1/4, 1/8		65			
				Test No. 15-1								
			.125/.190	Test No. 16-1			3/16					
		Sq butt	.125/.190	Test No. 16-2			3/16					
		Cover	.125/.190	Test No. 16-1			5/16					
		Cover	.125/.190	Test No. 16-2			5/16					
				Test No. 16-1			3/16					
				Test No. 16-2			5/16		65	1/32		
410 Test Part No.	410 stainless steel	Sq butt	.142/.167	615537-500			3/16		60	1/64		
Setup conditions for welding prototype gas turbine hardware	Ti 5AC-2.5 SN		0.139	Ti No. 5-1			1/8					
				Ti No. 5-2			1/8					
				Ti No. 5-3			3/16					
			0.143	Ti No. 6-1			3/16					
				Ti No. 6-2			3/16					
				Ti No. 6-3			3/16					
			0.140	Ti No. 7-1			5/32					
				Ti No. 7-2								
				Ti No. 7-3								
	Ti 5 AC-2.5 SN		0.143	Ti No. 8-1								
			0.143	Ti No. 8-2								
		Sq butt	0.138	Ti No. 9-1								
			0.138	Ti No. 9-2	PT-8	111-M	5/32	1/8	60	1/64	1/8	Ar

A.

ditions Employed for Plasma Arc Welding for Certain Miscellaneous Materials.

h Setup Data				Welding Conditions												
Electrode Configuration				Orifice Gas		Shield Gas						Cold Filler Wire Data			Backing Bar Groove	
Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type	Total Flow (cfh)	Type	Flow (cfh)	Backup Gas Type	Weld Current (amp)	Weld Voltage	Weld Travel Speed (ipm)	Heat No.	Dia (in.)	Feed Rate (ipm)	Width (in.)	Depth (in.)
1/16	-	-	1/8	Ar	4	Ar	40	Ar	80	-	31	NA	-	-	3-1/4	1
	-	-		Ar	4		50		110	-			-	-		
	-	-		Ar	4		50		130	-			-	-		
	-	-		He 75	8		50		130	-			-	-		
	-	-			8		60		120	-			-	-		
	-	-			8		60		110	-			-	-		
	-	-			7		30		130	-			-	-		
	-	-			7		30		120	-			-	-		
	-	-			6		30		120	-			-	-		
	-	-			6		30		110	-			-	-		
	-	-			8		40		120	-			-	-		
	-	-	1/8	He 75	8		40		110	-			-	-		
	-	-	1/16	Ar	2		20		125	-			-	-		
	-	-	1/16	Ar	1.4		20		115(82)	-			-	-		
1/16	-	-	1/16	Ar	1.5		50		100	-			-	-		
1/16	-	-	1/16	Ar	1.5		75		105	-			-	-		
3/32	-	-	1/8	H_2 7.5	6		40		120	-	31					
1/8	70	1/32		Ar	13 (19)		60		240	-	10		-	-		
					14 (13)				250	-			-	-		
					12(13)				240	-			-	-		
					12				240	-			-	-		
									240(250)	-			-	-		
									240	-			-	-		
									240	-			-	-		
									240	-			-	-		
									240(250)	-			-	-		
					12				240	-			-	-		
					13				245	-			-	-		
					13				245	-			-	-		
1/8					13				245(255)	-			-	-		
	70				13(10)				245(220)	-	10		-	-		
1/8	65				10				225(180, 200)	-	13		-	-		
					10				225	-	13(12)		-	-		
					10				200	-	13		-	-		
					10				200	-		NA	-	-		
					5				175(190)	-		410SS	0.045	36		
					5				175	-		410 SS	0.045	40		
					10				200	-		NA	-	-		
	65	1/32			5				195	-	13	410SS	0.045	40		
	60	1/64			11				130	-	8-3/4	NA	-	-		
					9				150	-	12		-	-		
									140	-			-	-		
									150	-			-	-		
									155	-			-	-		
					9				145	-			-	-		
					8				160	-			-	-		
					10				140	-			-	-		
					11				135	-			-	-		
					11				140	-			-	-		
					11				140	-			-	-		
					11				140	-			-	-		
					11				130	-			-	-		
1/8	60	1/64	1/8	Ar	11	Ar	60	Ar	130	-	12	NA	-	-	3-1/4	1

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B.

Table I-3. Welding Conditions Employed for Plasma Arc Miscellaneous Materials (Continued)

Purpose of Test	Material Description and Heat Number	Joint Configuration: V-Groove Included Angle (deg)	Joint Configuration: Root Land Thickness (in.)	Weld Identification	Torch Setup Data: Torch Type	Torch Setup Data: Orifice	Torch Setup Data: Standoff Distance (in.)	Electrode Configuration: Dia (in.)	Electrode Configuration: Included Tip Angle (deg)	Electrode Configuration: End Flat Dia (in.)	Electrode Configuration: Setback Distance (in.)	Orifi[ce] Type
Setup conditions for welding prototype gas turbine hardware	Ti 5AC-2. 5 SN	Sq butt	0. 140	Ti No. 11-1	PT-8	111-M	5/32	1/8	60	1/64	1/8	Ar
				Ti No. 11-2								Ar
				Ti No. 11-3								Ar
				Cover 11-4								He 50
	Ti 5AL-2. 5 SN			Ti No. 12-1								Ar
				Ti No. 12-2								Ar
			0. 140	Cover 12-3								He 50
Ti Test Part No.1	410 stainless steel		. 142/. 167	618537-500								Ar
Ti Test Part No.2			. 142/. 167	618537-500			5/32		60	1/64		
			0. 130	Weld No. 16-1			3/16		65	1/32		
			0. 130	Weld No. 16-2								
			0. 140	Weld No. 17-1								
			0. 140	Weld No. 17-2								
			. 130/. 175	Weld No. 18-1								
			. 130/. 175	Weld No. 18-2								Ar
		Sq butt	. 130/. 175	Weld No. 18-3			3/16					He 50
	410 stainless steel	Cover		Weld No. 18-1			1/4		65	1/32		
Ti Test Part No.3	Ti 5AL-2. 5 SN	Sq butt	. 135/. 145	618537	PT-8	111-M	5/32	1/8	60	1/64	1/8	Ar

A.

ditions Employed for Plasma Arc Welding for Certain
scellaneous Materials (Continued).

orch Setup Data					Welding Conditions												
	Electrode Configuration				Orifice Gas		Shield Gas						Cold Filler Wire Data			Backing Bar Groove	
doff ance n.)	Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Type	Total Flow (cfh)	Type	Flow (cfh)	Backup Gas Type	Weld Current (amp)	Weld Voltage	Weld Travel Speed (ipm)	Heat No.	Dia (in.)	Feed Rate (ipm)	Width (in.)	Depth (in.)
/32	1/8	60	1/64	1/8	Ar	11	Ar	60	Ar	130	-	12	NA	-	-	3-1/4	1
					Ar	11	Ar			130	-			-	-		
					Ar	11	Ar			130	-			-	-		
					He 50	5.0	He 50			110	-			-	-		
					Ar	11	Ar			130	-			-	-		
					Ar	11	Ar			130	-			-	-		
					He 50	5	He 50			110	-	12		-	-		
					Ar	11	Ar			140(135)	-	11		-	-		
/32		60	1/64			11				130	-	11		-	-		
/16		65	1/32			10				225	-	15		-	-		
						10				235	-			-	-		
						10				225	-			-	-		
						10				225	-			-	-		
						10				225	-			-	-		
					Ar	10	Ar			225	-	18		-	-		
/16					He 50	5	He 50			110(130)	-	12		-	-		
/4		65	1/32						Ar	150(175, 180)	-			0.045	40		
/32	1/8	60	1/64	1/8	Ar	11	Ar	60	He	135		11	NA	-	-	3-1/4	1

B.

Appendix II

GAS SYSTEM PLUMBING LAYOUT

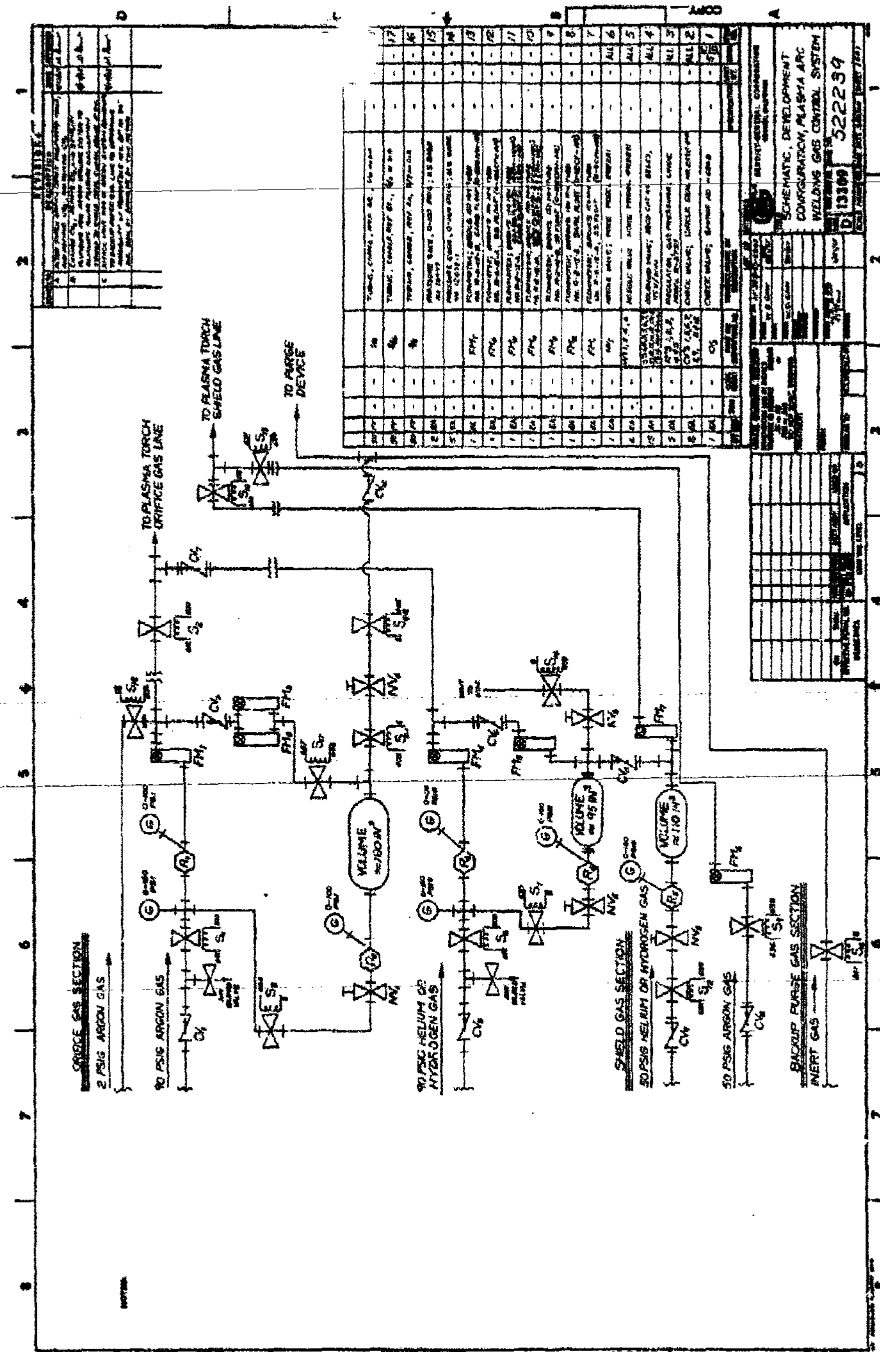


Figure II-1. Plasma Arc Welding Gas Control Plumbing.

Appendix III

GAS SYSTEM ELECTRICAL LAYOUT

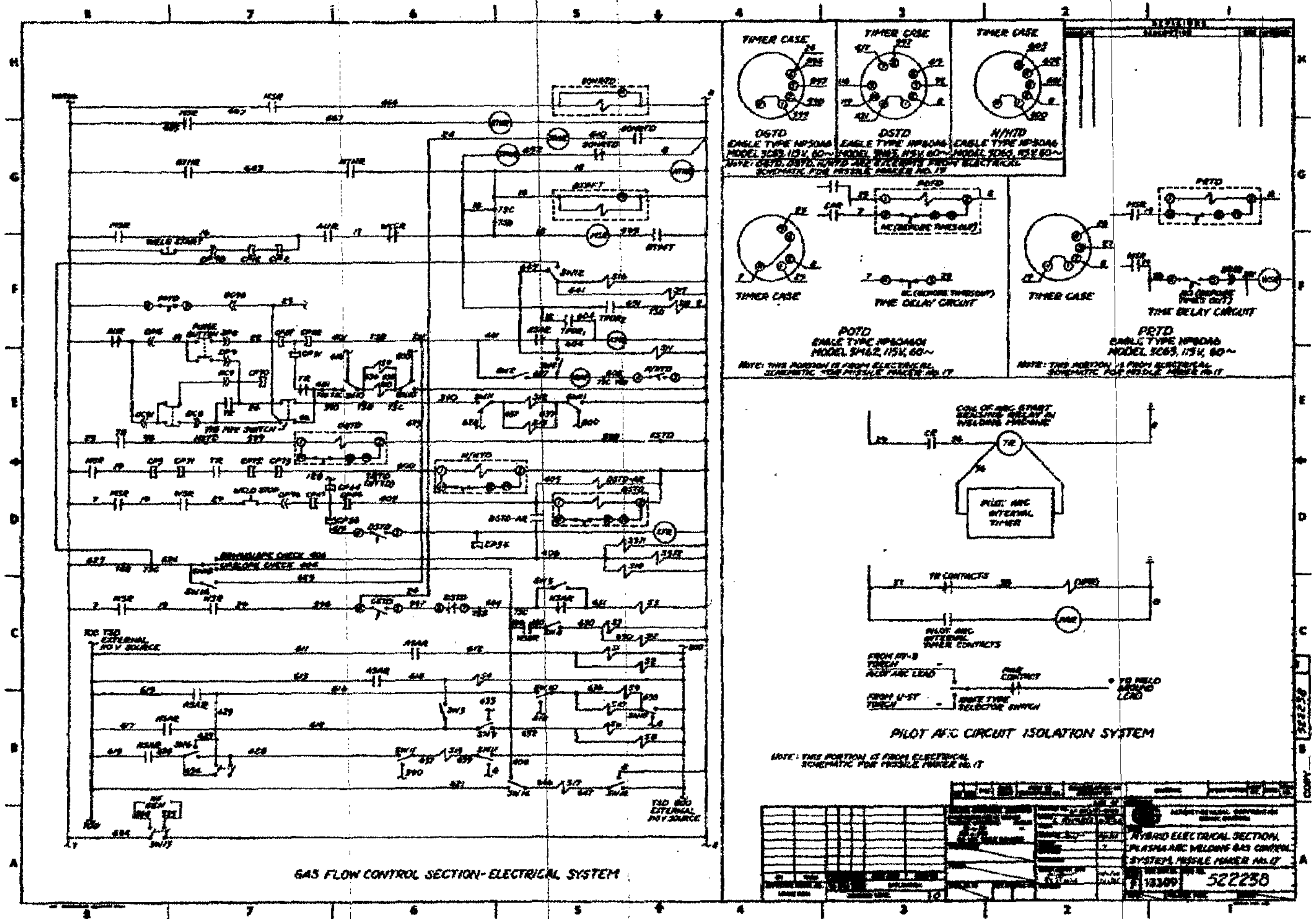


Figure III-1. Plasma Arc Welding Electrical Schematic.

Appendix IV

FLOWMETER CALIBRATION SHEETS AND FLOW CURVES

Flowmeter Certified With Homer R. Dulin Co. Equipment No. 12399 Calib. Due Aug. 67 Accuracy 0.02% FS
Certified By County of Los Angeles Sealer of Weights and Measures
Division of Metrological Services
Our Standards Are Certified By Or Are Traceable To The National Bureau of Standards and Comply With MIL-C-45662A

FLOWMETER CERTIFICATION

AEROJET GENERAL CORPORATION

F.M. SERIAL Nº Brooks 6610-60668/9
BENCH Nº Tube R-2-15-A
DEPT. Nº 1335
DIVISION Downey
DATE 5-3-67
Remarks: CM Scale calibrated in SCFH Argon @ 50 PSIG (Inlet) & 70°F.

INDICATED		ACTUAL	
CM	Remarks	SCFH	Remarks
15		7.39	Argon @ 50 PSIG & 70°F.
12		6.06	"
8		4.21	"
4		2.19	"
1		0.457	"

Req. #348319

TEST AND CERTIFICATION
BY
HOMER R. DULIN COMPANY
720 E. Anaheim St., Long Beach, Calif. 90806
NEvada 6-4056

Test by R. Dulin

FM-1, SS FLOAT

Flowmeter Certified With Homer R. Dulin Co. Equipment No. 12399 Calib. Due Aug. 67 Accuracy 0.02% FS
Certified By County of Los Angeles Sealer of Weights and Measures
Division of Metrological Services
Our Standards Are Certified By Or Are Traceable To The National Bureau of Standards and Comply With MIL-C-45662A

FLOWMETER CERTIFICATION

AEROJET GENERAL CORPORATION

F.M. SERIAL Nº Mfg. S/N Brooks [illegible]
BENCH Nº Tube R-2-15-B
DEPT. Nº 1335
DIVISION Downey
DATE 5-3-67
Remarks: S/N Ext. scale calibrated in SCFH Argon @ 50 PSIG (Inlet) & 70°F.

INDICATED		ACTUAL	
SCFH	Remarks	SCFH	Remarks
12		12.05	Argon @ 50 PSIG & 70°
10		10.14	"
7		7.43	"
4		4.76	"
1		0.67	"

Req. #348319

TEST AND CERTIFICATION
BY
HOMER R. DULIN COMPANY

Test by R. Dulin

FM-2, SAPPHIRE FLOAT

FLOWMETER CERTIFICATION

FOR:

AEROJET GENERAL CORPORATION

F.M. SERIAL Nº Brooks 6509-54916

~~BENCH Nº~~ Tube #R-2-15-B

DEPT. Nº 1355

DIVISION Downey

DATE 5-4-67

Remarks: D/R ext. scale calibrated in SCFH argon @ 50 PSIG (Inlet) & 70°F.

INDICATED		ACTUAL	
SCFH	Remarks	SCFH	Remarks
25		25.88	ARGON @ 50 PSIG & 70°F.
20		20.61	"
15		15.27	"
10		9.44	"
5		4.63	"
	Req. #348519		

TEST AND CERTIFICATION BY

HOMER R. DULIN COMPANY

Test by R. Dulin

RM-3, SS FLOAT

Flowmeter Certified With Homer R. Dulin Co. Equipment No. 12400 Calib. Due 6-67 Accuracy 0.66% FS

Certified By County of Los Angeles Sealer of Weights and Measures Division of Metrological Services

Our Standards Are Certified By Or Are Traceable To The National Bureau of Standards and Comply With MIL-C-45662A.

Flowmeter Certified With Homer R. Dulin Co. Equipment No. 12399 Calib. Due Aug., 67 Accuracy 0.02% FS
Certified By County of Los Angeles, Sealer of Weights and Measures
Division of Metrological Services
Our Standards Are Certified By Or Are Traceable To The National Bureau of Standards and Comply With MIL-C-45662A

FLOWMETER CERTIFICATION

Re:

AEROJET GENERAL CORPORATION

F.M. SERIAL Nº	Mfg. S/N Brooks 6610-60868/10
BENCH Nº	Tube R-2-15-A-Tantalum Float
DEPT. Nº	1335
DIVISION	Downey
DATE	5-2-67

Remarks: CM Scale calibrated in SCFH Helium @ 50 PSIG (Inlet) & 70°F.

INDICATED		ACTUAL	
CM	Remarks	SCFH	Remarks
15		4.90	He. @ 50 PSIG & 70°F.
12		5.16	"
8		1.60	"
4		0.85	"
1		0.28	"
	Req. #348519		

TEST AND CERTIFICATION BY HOMER R. DULIN COMPANY

Test by. R. Dulin

FM-4, 2 FLOATS

Flowmeter Certified With Homer R. Dulin Co. Equipment No. 12399 Calib. Due Aug., 67 Accuracy 0.02% FS
Certified By County of Los Angeles, Sealer of Weights and Measures
Division of Metrological Services
Our Standards Are Certified By Or Are Traceable To The National Bureau of Standards and Comply With MIL-C-45662A

FLOWMETER CERTIFICATION

Re:

AEROJET GENERAL CORPORATION

F.M. SERIAL Nº	Mfg. S/N Brooks 6610 60868/10
BENCH Nº	Tube R-2-15AA-Sapphire Float
DEPT. Nº	1335
DIVISION	Downey
DATE	5-3-67

Remarks CM scale calibrated in SCFH H_2 Gas @ 50 PSIG (Inlet) & 70°F. Calib. performed by Kinematic Simulation

INDICATED		ACTUAL	
CM	Remarks	SCFH	Remarks
15		2.71	H_2 Gas @ 50 PSIG & 70°F.
12		1.73	"
8		0.95	"
4		0.45	"
1		0.16	"
	Req. # 348519		

TEST AND CERTIFICATION BY HOMER R. DULIN COMPANY

Test by R. Dulin

FM-4, 2 FLOATS

FLOWMETER CERTIFICATION

AEROJET GENERAL CORPORATION

F.M. SERIAL Nº Mfg.S/N Brooks6610-60688/
BENCH Nº Tube R-2-15-A Carboloy Float
DEPT. Nº 1335
DIVISION Downey
DATE 5-2-67
Remarks: CM Scale calibrated in SCFH Helium @ 50 PSIG (Inlet) & 70°F.

INDICATED		ACTUAL	
CM	Remarks	SCFH	Remarks
15		18.06	He. @ 50 PSIG & 70°F.
12		14.40	"
8		9.30	"
4		3.24	"
1		0.36	"
	Req. #348319		

TEST AND CERTIFICATION BY
HOMER R. DULIN COMPANY
[illegible]

Test by R. Dulin

FM-5, 2 FLOATS

Flowmeter Certified With Homer R. Dulin Co. Equipment No. 12399 Calib. Due Aug., 67 Accuracy 0.02% FS
Certified By County of Los Angeles, Senior of Weights and Measures
Division of Metrological Services
Our Standards Are Certified By Or Are Traceable To The National Bureau
of Standards and Comply With MIL-C-45662A

FLOWMETER CERTIFICATION

AEROJET GENERAL CORPORATION

F.M. SERIAL Nº Mfg.S/N Brooks 6610 60688
BENCH Nº Tube R-2-15-A Glass Float
DEPT. Nº 1335
DIVISION Downey
DATE 5-3-67
Remarks: CM scale calibrated in SCFH H_2 Gas @ 50 PSIG (Inlet) & 70°F. Calib. performed by Kinematic Simulation

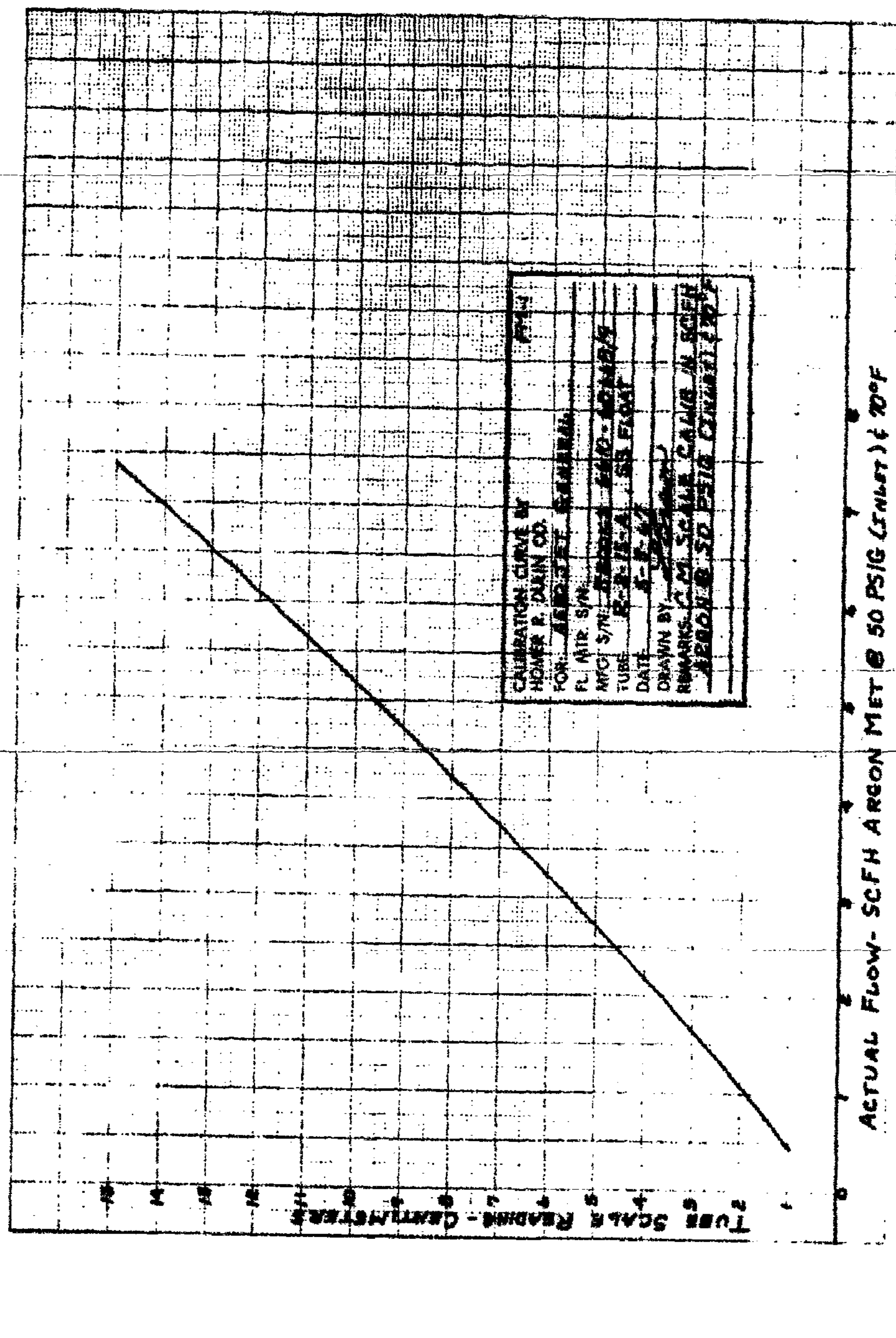
INDICATED		ACTUAL	
CM	Remarks	SCFH	Remarks
15		14.42	H_2 Gas @ 50 PSIG & 70
12		11.29	"
8		6.64	"
4		2.40	"
1		0.249	"
	Req. #348319		

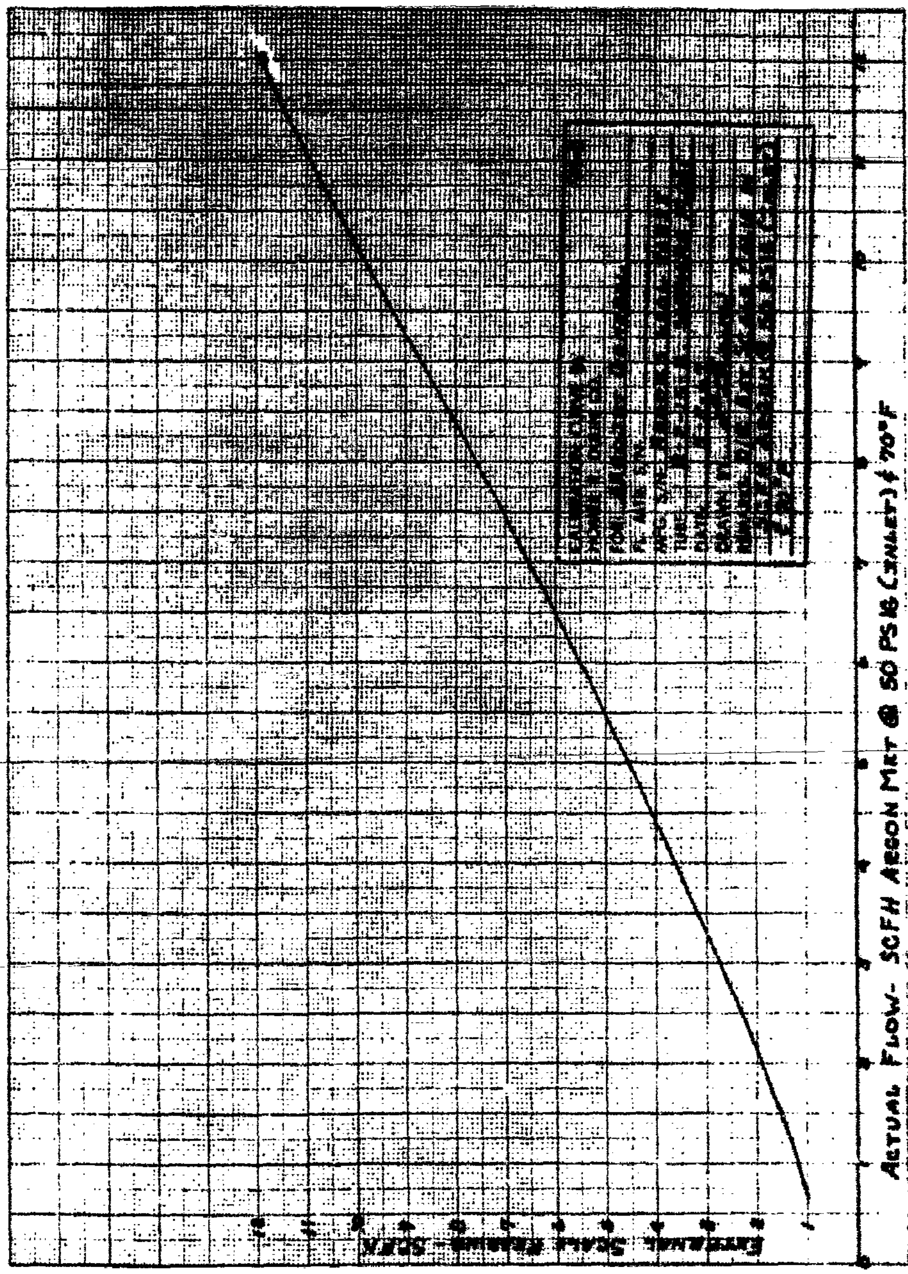
TEST AND CERTIFICATION BY
HOMER R. DULIN COMPANY
[illegible]

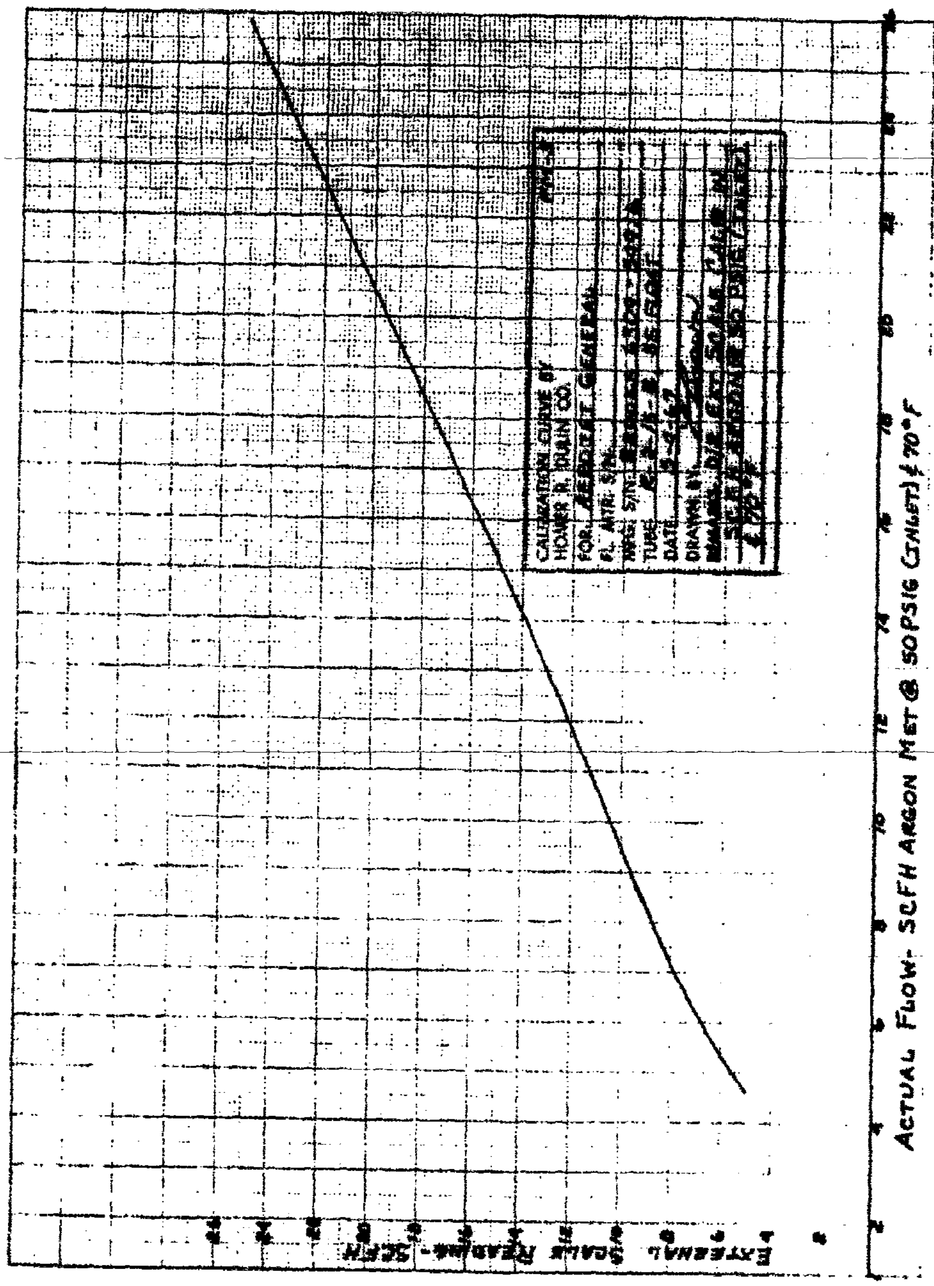
Test by R. Dulin

FM-5, 2 FLOATS

Flowmeter Certified With Homer R. Dulin Co. Equipment No. 12399 Calib. Due Aug., 67 Accuracy 0.02% FS
Certified By County of Los Angeles, Senior of Weights and Measures
Division of Metrological Services
Our Standards Are Certified By Or Are Traceable To The National Bureau
of Standards and Comply With MIL-C-45662A

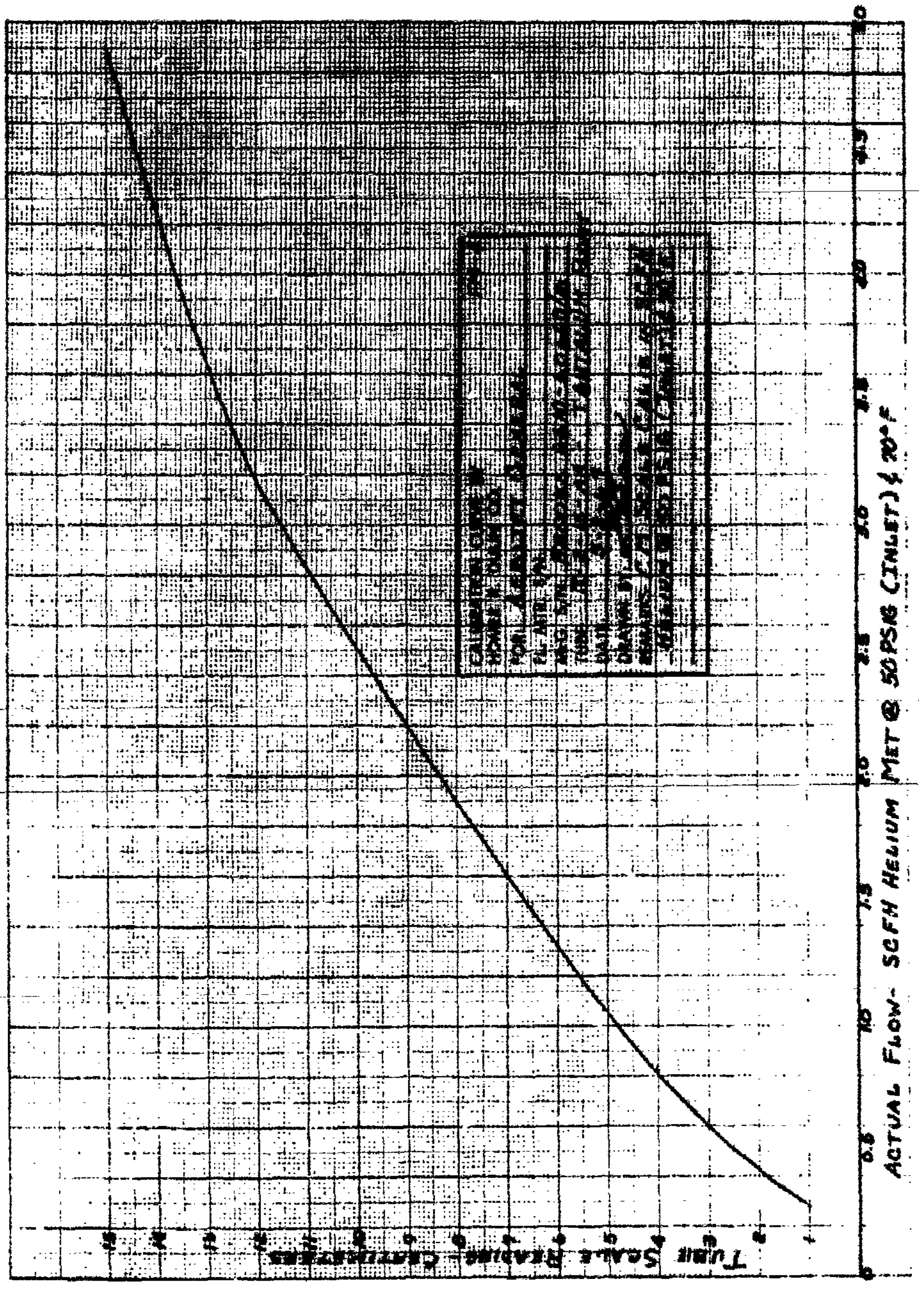

CALIBRATION CURVE BY
HOMER R. DUNN CO.
FOR: AEROJET GENERAL
FL. MTR. S/N:
MFG. S/N:
TUBE:
DATE:
DRAWN BY
REMARKS:
ACTUAL FLOW - SCFH ARGON MET @ 50 PSIG (INLET) & 70°F
TUBE SCALE READING - CENTIMETERS

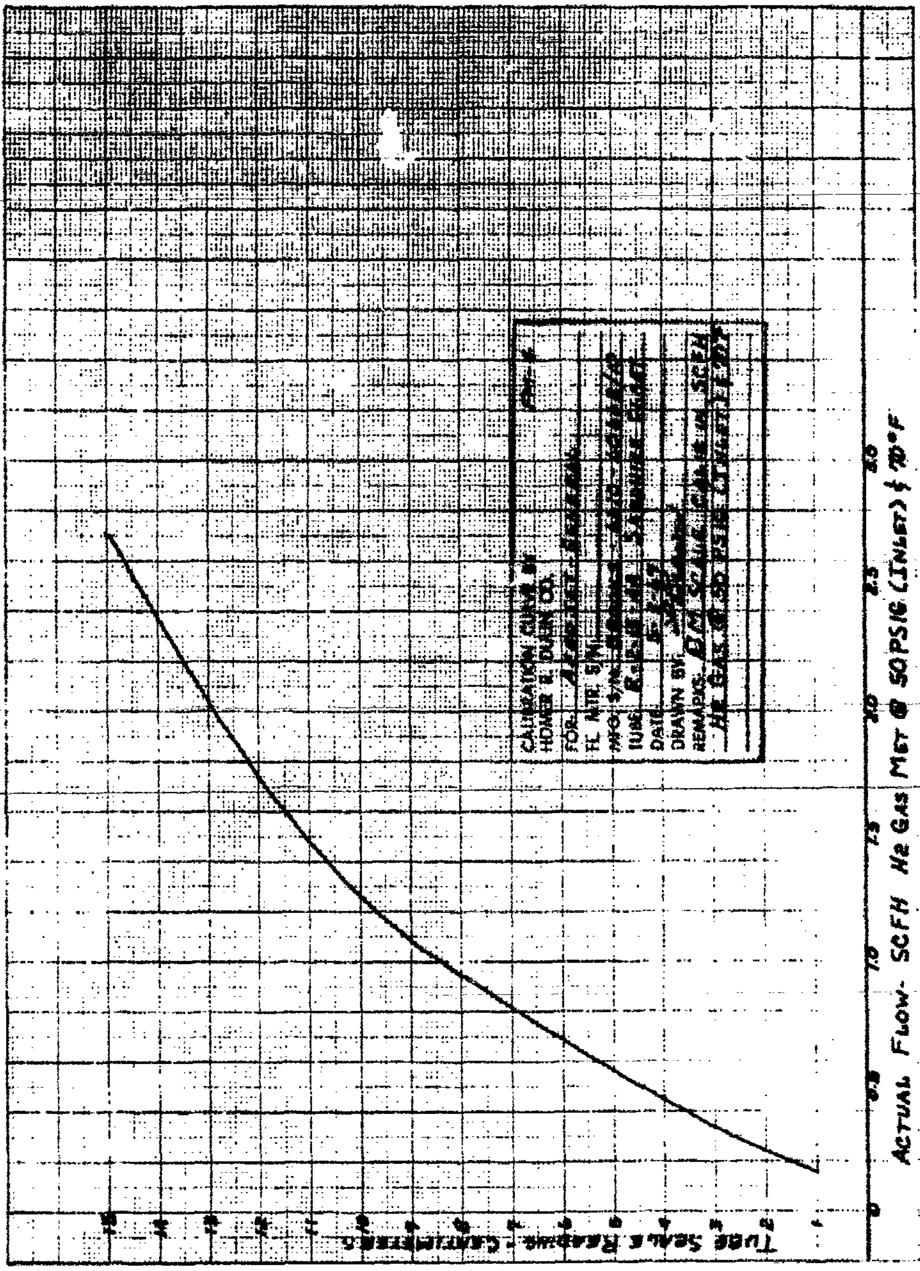

ACTUAL FLOW- SCFH ARGON MET @ 50 PSIG (INLET) & 70°F

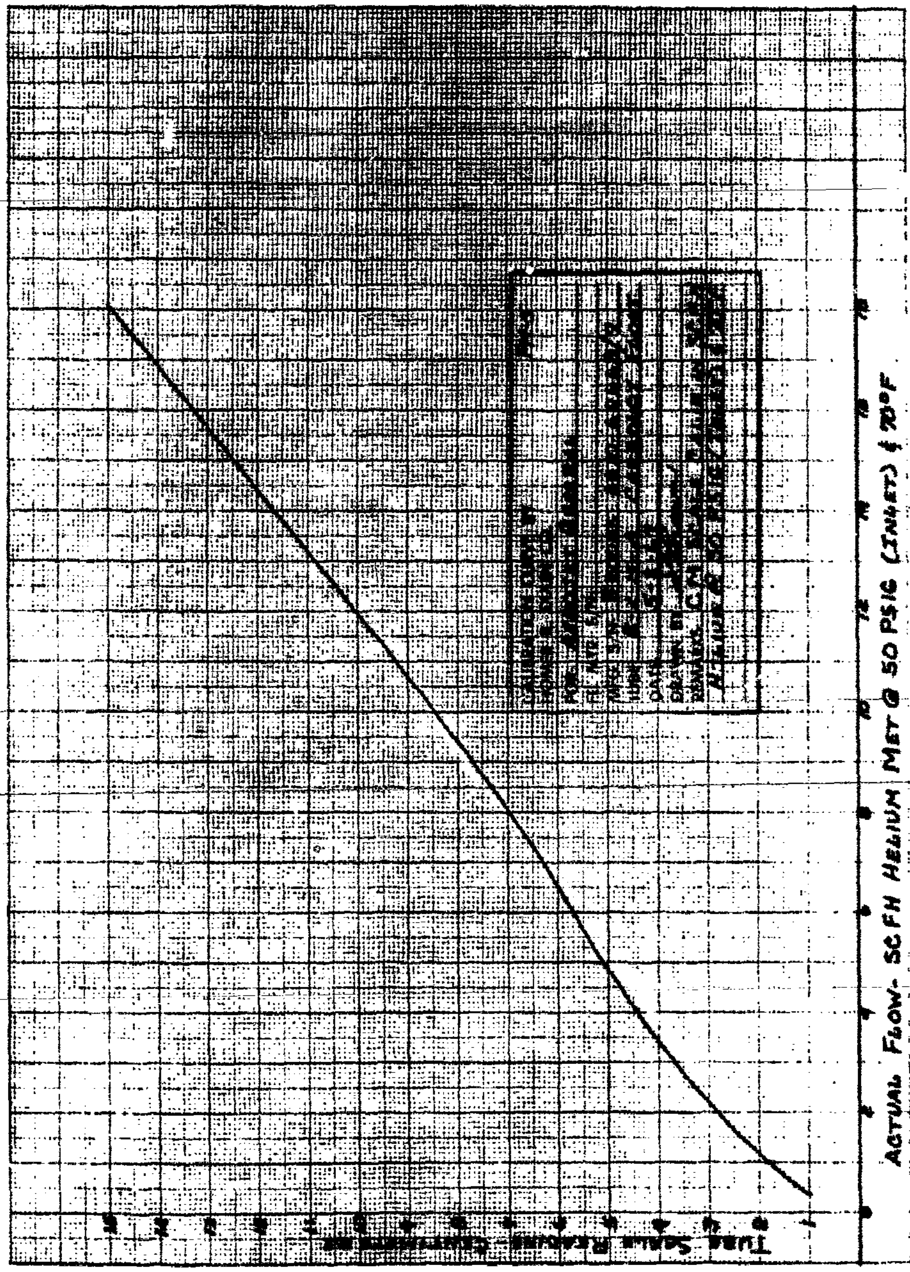

EXTERNAL SCALE READING - SCFH
ACTUAL FLOW- SCFH ARGON MET @ 50PSIG (INLET) & 70°F
CALIBRATION CURVE BY
HOMER R. DULIN CO.
FOR AEROJET GENERAL
FL. MTR. S/N
MFG. S/N
TUBE
DATE
DRAWN BY
REMARKS

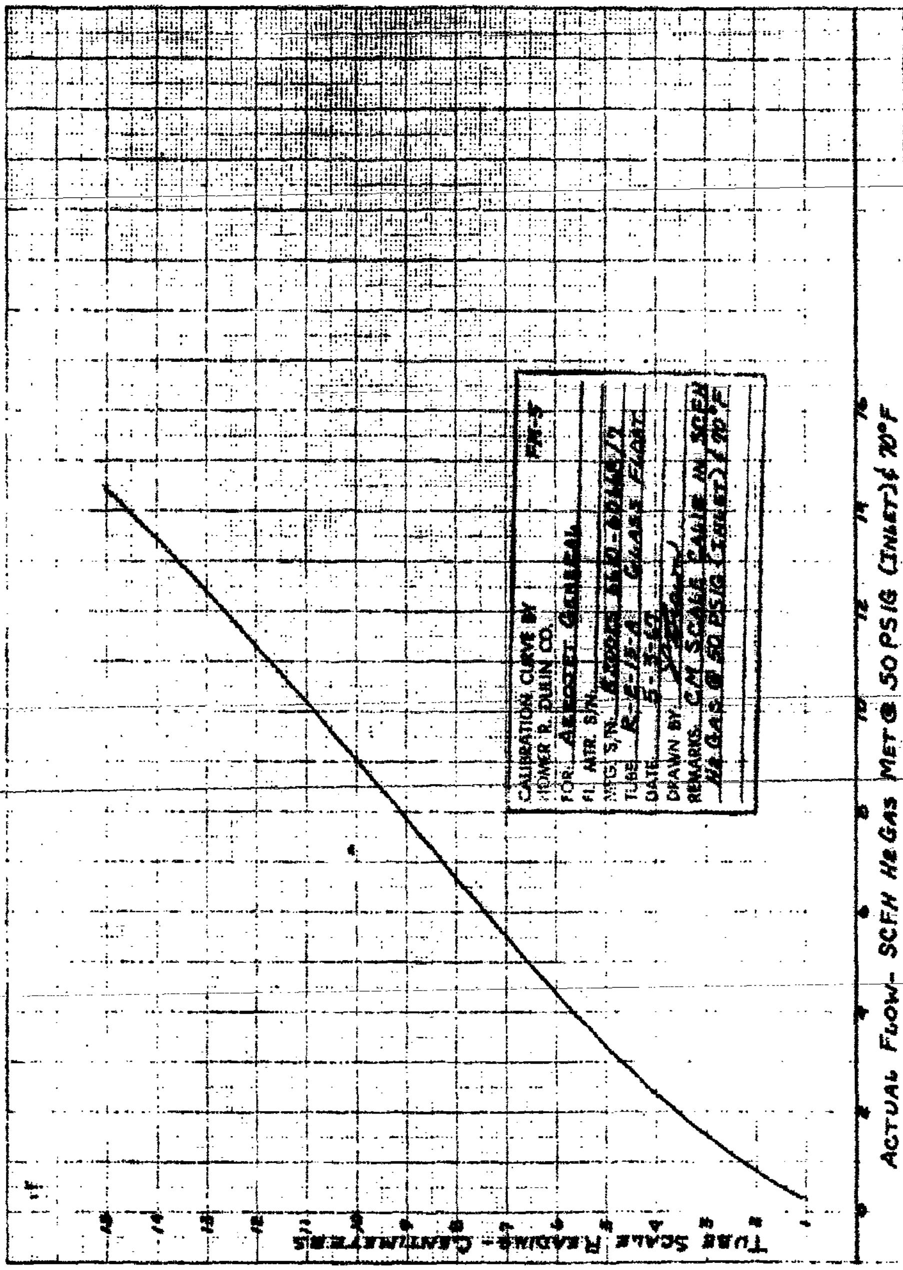
Appendix VI

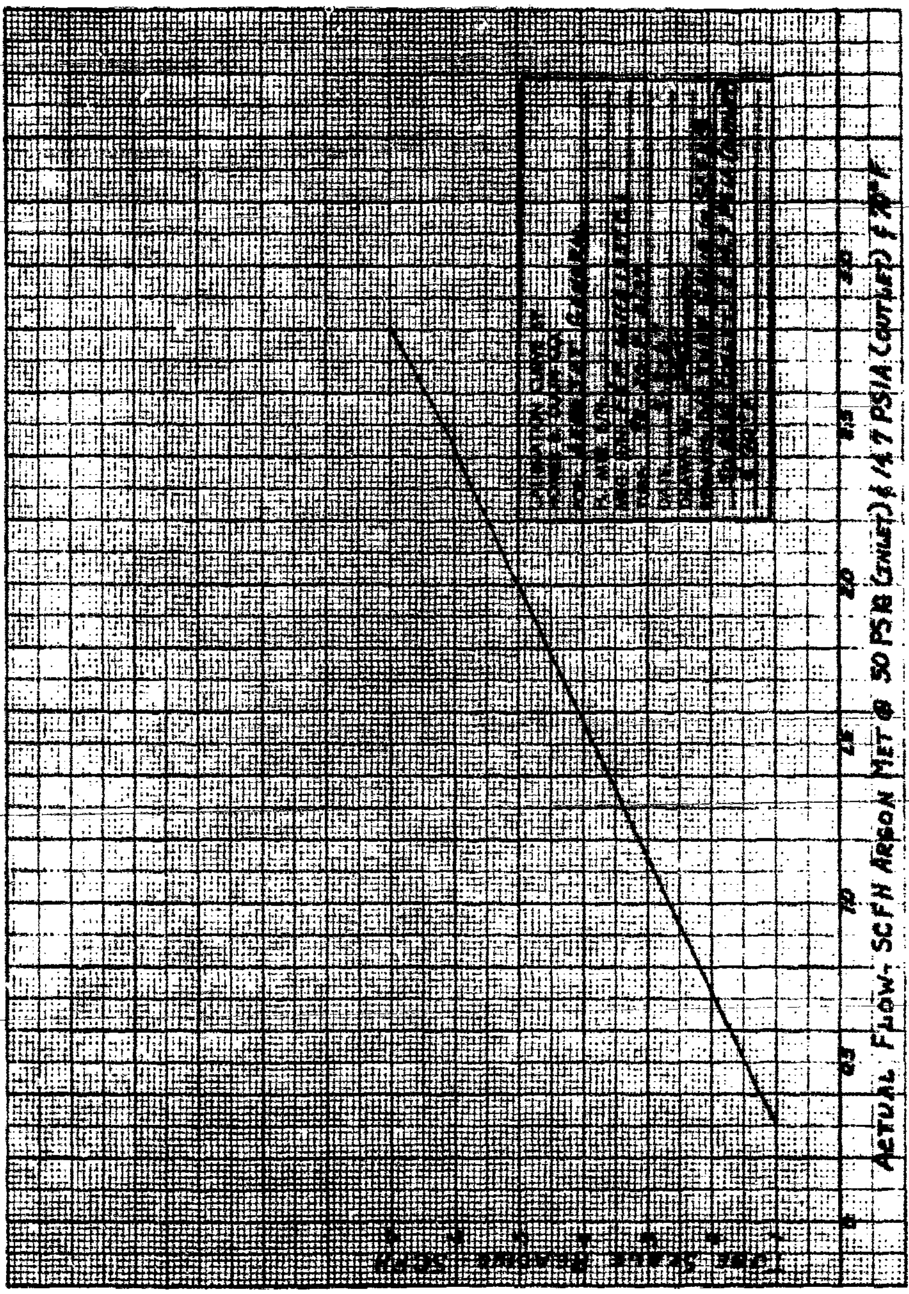
AGC-36319B COMPONENTS, MOTOR, TITANIUM, FABRICATION OF

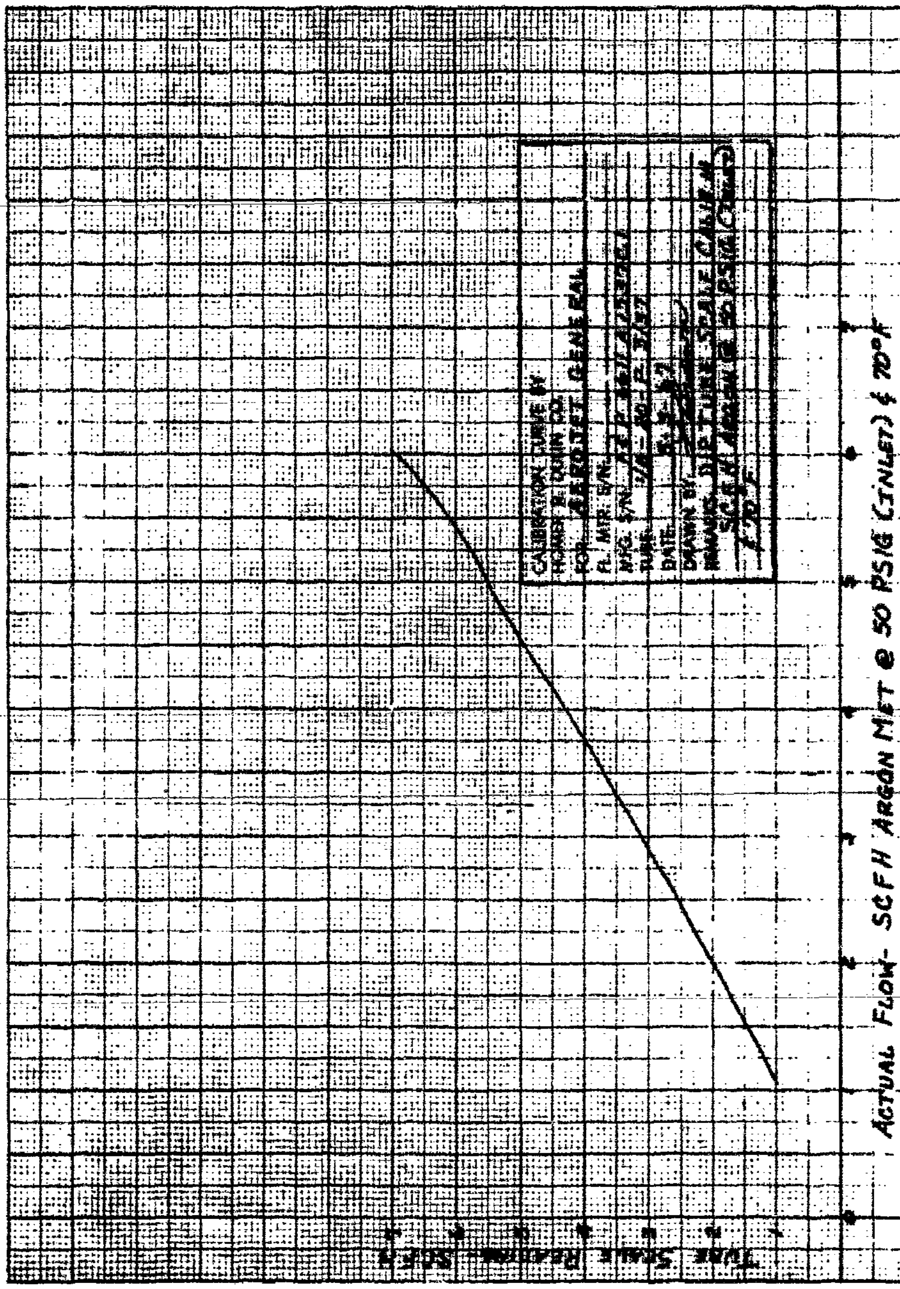

ACTUAL FLOW- SCFH HELIUM MET @ 50 PSIG (INLET) & 70°F
TUBE SCALE READING- CENTIMETERS

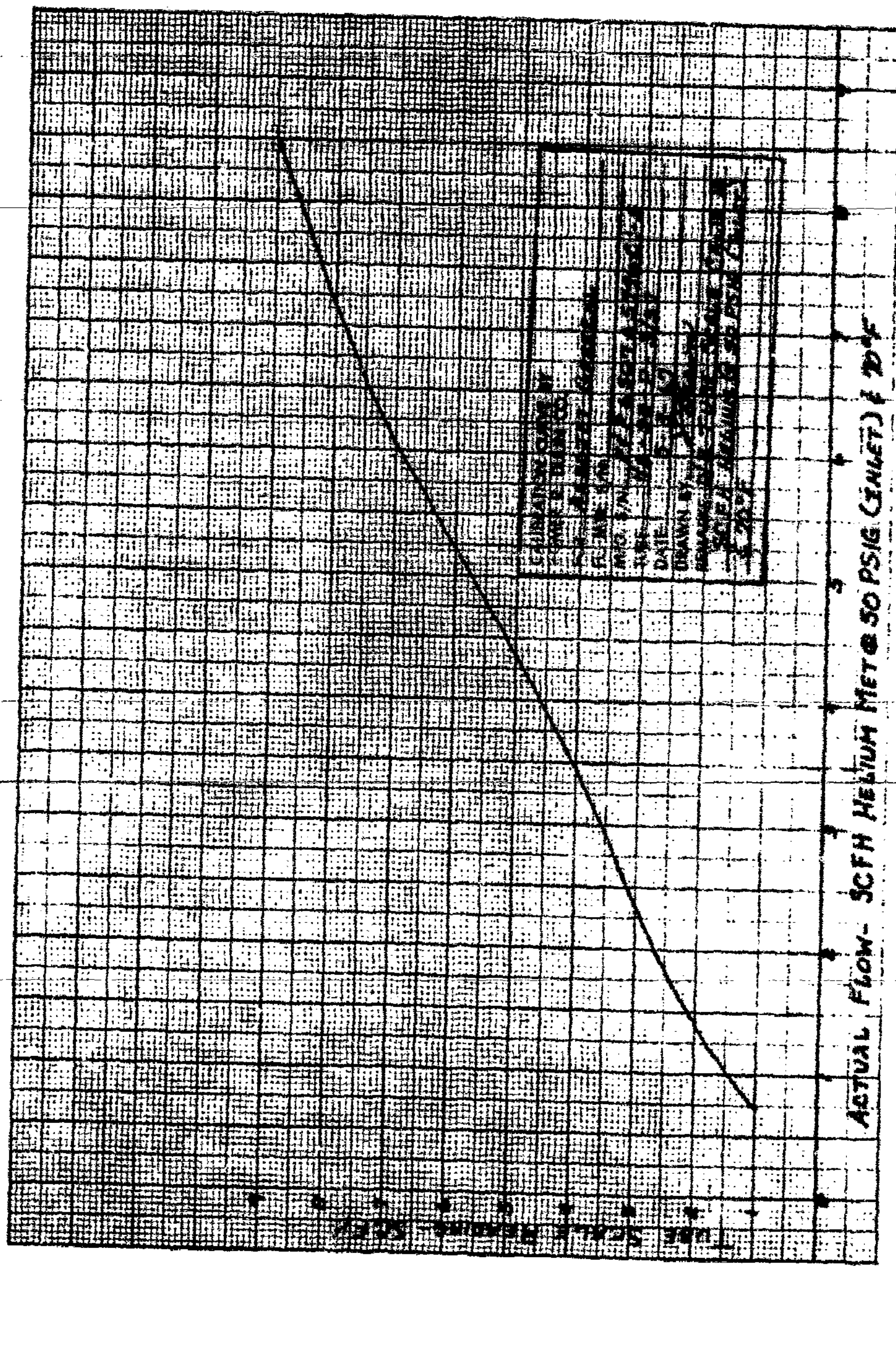

ACTUAL FLOW- SCFH H2 GAS MET @ 50PSIG (INLET) & 70°F
TUBE SCALE READING - CENTIMETERS
CALIBRATION CURVE BY
FOR
FL. MTR. S/N
MFG. S/N
TUBE
DATE
DRAWN BY
REMARKS


ACTUAL FLOW- SCFH HELIUM MET @ 50 PSIG (INLET) & 70°F
TUBE SCALE READING-CENTIMETERS


CALIBRATION CURVE BY
HOMER R. DULIN CO.
FOR: AEROJET GENERAL
FL. MTR. S/N
MFG. S/N
TUBE R-6-15-A GLASS FLOAT
DATE 5-3-60
DRAWN BY
REMARKS: CM SCALE RANGE IN SCFH He GAS @ 50 PSIG (INLET) & 70°F
FM-5
TUBE SCALE READING - CENTIMETERS
ACTUAL FLOW - SCFH He GAS MET @ 50 PSIG (INLET) & 70°F


ACTUAL FLOW - SCFH ARGON MET @ 50 PSIG (INLET) & 14.7 PSIA (OUTLET) & 70°F

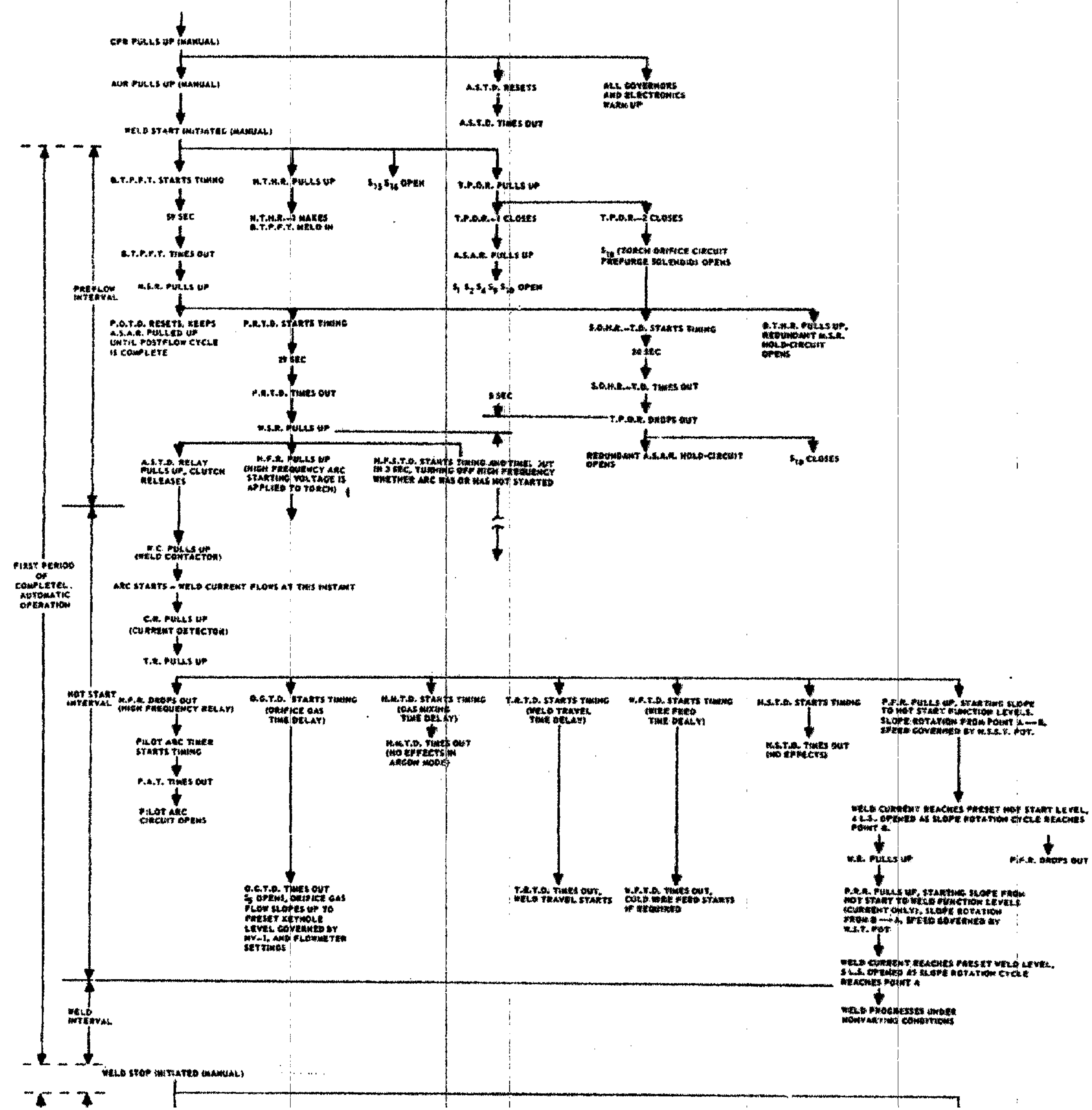

CALIBRATION CURVE BY
HOMER R. QUINN CO.
FOR AEROJET GENERAL
FL. MTR. S/N
MFG. S/N
TUBE
DATE
DRAWN BY
REMARKS
ACTUAL FLOW - SCFH ARGON MET @ 50 PSIG (INLET) & 70°F
TUBE SCALE READING - SCFH


ACTUAL FLOW- SCFH HELIUM MET @ 50 PSIG (INLET) & 70°F

Appendix V

PROGRAMMED EVENT SEQUENCE
LINDE MISSILE MAKER NO. 17

A.


CPR PULLS UP (MANUAL)
AUR PULLS UP (MANUAL)
A.S.T.D. RESETS
A.S.T.D. TIMES OUT
ALL GOVERNORS AND ELECTRONICS WARM UP
WELD START INITIATED (MANUAL)
B.T.P.F.T. STARTS TIMING
59 SEC
B.T.P.F.T. TIMES OUT
N.S.R. PULLS UP
H.T.H.R. PULLS UP
H.T.H.R.—1 MAKES B.T.P.F.T. HELD IN
T.P.O.R. PULLS UP
T.P.O.R.—1 CLOSES
A.S.A.R. PULLS UP
T.P.O.R.—2 CLOSES
PREFLOW INTERVAL
P.O.T.D. RESETS, KEEPS A.S.A.R. PULLED UP UNTIL POSTFLOW CYCLE IS COMPLETE
P.R.T.D. STARTS TIMING
29 SEC
P.R.T.D. TIMES OUT
W.S.R. PULLS UP
S.O.H.R.—T.D. STARTS TIMING
30 SEC
S.O.H.R.—T.D. TIMES OUT
T.P.O.R. DROPS OUT
REDUNDANT A.S.A.R. HOLD-CIRCUIT OPENS
3 SEC
A.S.T.D. RELAY PULLS UP, CLUTCH RELEASES
H.F.R. PULLS UP (HIGH FREQUENCY ARC STARTING VOLTAGE IS APPLIED TO TORCH)
H.F.S.T.D. STARTS TIMING AND TIMES OUT IN 3 SEC, TURNING OFF HIGH FREQUENCY WHETHER ARC HAS OR HAS NOT STARTED
FIRST PERIOD OF COMPLETEL. AUTOMATIC OPERATION
W.C. PULLS UP (WELD CONTACTOR)
ARC STARTS — WELD CURRENT FLOWS AT THIS INSTANT
C.R. PULLS UP (CURRENT DETECTOR)
T.R. PULLS UP
HOT START INTERVAL
H.F.R. DROPS OUT (HIGH FREQUENCY RELAY)
PILOT ARC TIMER STARTS TIMING
P.A.T. TIMES OUT
PILOT ARC CIRCUIT OPENS
O.G.T.D. STARTS TIMING (ORIFICE GAS TIME DELAY)
O.G.T.D. TIMES OUT
H.M.T.D. STARTS TIMING (GAS MIXING TIME DELAY)
H.M.T.D. TIMES OUT (NO EFFECTS IN ARGON MODE)
T.R.T.D. STARTS TIMING (WELD TRAVEL TIME DELAY)
T.R.T.D. TIMES OUT, WELD TRAVEL STARTS
W.F.T.D. STARTS TIMING (WIRE FEED TIME DEALY)
W.F.T.D. TIMES OUT, COLD WIRE FEED STARTS IF REQUIRED
H.S.T.D. STARTS TIMING
H.S.T.D. TIMES OUT (NO EFFECTS)
WELD CURRENT REACHES PRESET HOT START LEVEL, 4 L.S. OPENED AS SLOPE ROTATION CYCLE REACHES POINT B.
W.R. PULLS UP
WELD CURRENT REACHES PRESET WELD LEVEL, 5 L.S. OPENED AS SLOPE ROTATION CYCLE REACHES POINT A
WELD INTERVAL
WELD PROGRESSES UNDER NONVARYING CONDITIONS
WELD STOP INITIATED (MANUAL)

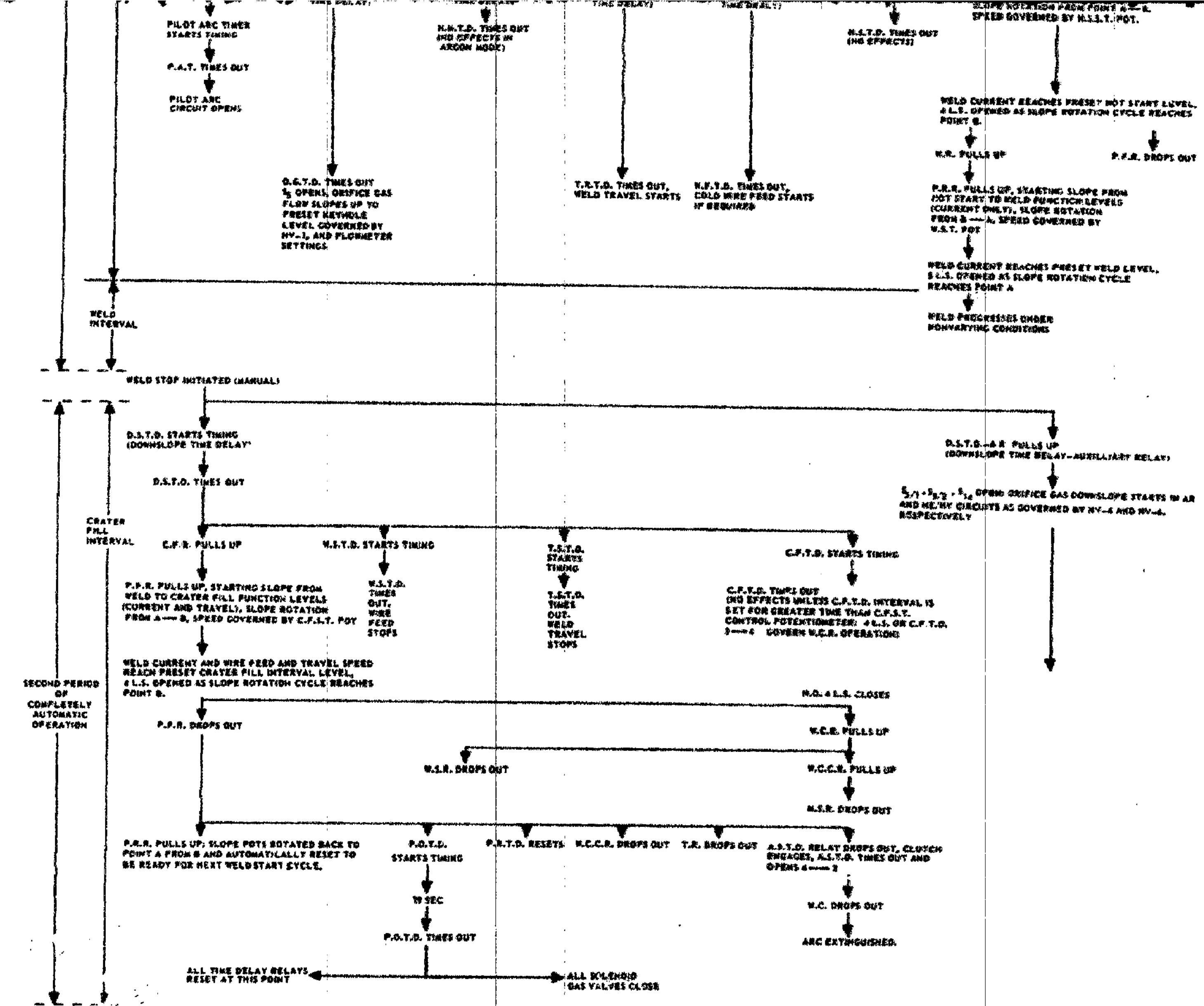


Figure V-1. Typical Plasma Arc Welding Cycle, Linde Missile Maker No. 17.

Appendix VI

AGC-36319B COMPONENTS, MOTOR, TITANIUM, FABRICATION OF

AEROJET GENERAL

AEROJET-GENERAL CORPORATION

CODE IDENT. NO. 05824

AGC-36319B
Amendment 8
19 February 1965

COMPONENTS, MOTOR, TITANIUM, FABRICATION OF

This amendment forms a part of Aerojet-General Corporation Specification AGC-36319B.

Paragraph 2.2 Add:

SPECIFICATIONS

"AGC-36459 Cleaning, Abrasive"

Paragraph 3.11.1

Delete: "...MIL-P-116, Method C-15 or C-16..."
Substitute: "...AGC-36459..."

Paragraphs 3.11.1.1 and 3.11.2 Delete.

Paragraph 3.11.3

Delete: "...MIL-P-116, using Method C-15 or C-16..."
Substitute: "...AGC-36459..."

Delete last sentence.

Authorized for Release:

J. H. Yetto, Manager
Specifications and Standards
Solid Rocket Operations
Sacramento Plant

AEROJET-GENERAL CORPORATION
CODE IDENT. NO. 05824

AGC-36319B
Amendment 7
31 December 1964

COMPONENTS, MOTOR, TITANIUM,
FABRICATION OF

This amendment forms a part of Aerojet-General Corporation Specification AGC-36319B.

Paragraph 3.8.4 Add to the end of the paragraph: "...and 3.9.2."

Add paragraph 3.9.2:

"3.9.2 Cladding of stress relieving heat-treat fixtures. - The surfaces of the stress relieving heat-treat fixtures that are in contact with the chamber shall be clad with titanium."

Authorized for Release:

for G. M. Fine
J. H. Yetto, Manager
Specifications and Standards
Solid Rocket Operations
Sacramento Plant

AEROJET-GENERAL CORPORATION
CODE IDENT. NO. 05824

AGC-36319B
~~Amendment 6~~
31 December 1964

COMPONENTS, MOTOR, TITANIUM,
FABRICATION OF

This amendment forms a part of Aerojet-General Corporation Specification AGC-36319B.

Add paragraph 3.7.10:

"3.7.10 Weld repairs. - All weld repairs shall be made under the supervision of a welding engineer."

Authorized for Release:

for J. H. Yetto, Manager
Specifications and Standards
Solid Rocket Operations
Sacramento Plant

AEROJET-GENERAL CORPORATION
CODE IDENT. NO. 05824

AGC-36319B
Amendment 5
31 December 1964

COMPONENTS, MOTOR, TITANIUM,
FABRICATION OF

This amendment forms a part of Aerojet-General Corporation Specification AGC-36319B.

Add paragraph 3.9.1:

"3.9.1 Cracks. - After chamber hydroproof, welds and the parent material, 1-1/2 in. on either side of the center of the welds, shall be radiographically inspected in accordance with 4.3.2. Internal or external cracks shall not be acceptable."

Paragraph 4.4:

Delete:	"Critical	None	None"
Substitute:	"Critical	3.9.1	4.3.2"

Authorized for Release:

for G. M. Fice
J. H. Yetto, Manager
Specifications and Standards
Solid Rocket Operations
Sacramento Plant

AEROJET-GENERAL CORPORATION
CODE IDENT. NO. 05824

AGC-36319B
Amendment 4
7 October 1963
Superseding
Amendment 3
19 February 1963

COMPONENTS, MOTOR, TITANIUM,
FABRICATION OF

This amendment forms a part of Aerojet-General Corporation Specification AGC-36319B.

Paragraph 3.5.1.1 (a) Delete and substitute:

"(a) The maximum solution heat treating temperature shall be at least 35° F below the beta transus for that particular heat of material. The part shall be held at this temperature for one to two hours."

Add paragraph 3.7.4.1:

"3.7.4.1 Weld interruption. - If welding is interrupted during a pass, the area shall be routed out prior to restarting (5.2.7)."

Paragraph 3.8.1 Add to end of sentence: "(5.2.7)"

Paragraph 3.11 Delete and substitute:

"3.11 Cleaning prior to hydrotest and prior to shipment. -

"3.11.1 Cleaning before hydrotesting. - After heat treatment, the chamber girth weld and heat affected zone shall be cleaned in accordance with Specification MIL-P-116, method C-15 or C-16, to remove all traces of oxide film and other contamination.

"3.11.1.1 Blasting material particle size. - The grit blasting material shall have a particle size of 250 to 600 mesh.

"3.11.2 Cleanliness acceptance. - The grit blasted surfaces shall be acceptable in accordance with the visual and wipe test as specified by Specification MIL-P-116.

"3.11.3 Cleaning prior to shipment. - Prior to shipment, the inner and outer chamber and closure walls, excluding mating surfaces or any surface requiring a 32 microinch finish, shall be cleaned in accordance with Specification MIL-P-116, using method C-15 or C-16, to remove all traces of oxide film and other contamination. The cleaned surfaces shall be acceptable in accordance with 3.11.2, and the material used for blasting shall be in accordance with 3.11.1.1."

Add paragraph 5.2.7:

"5.2.7 Weld repair. - At any time during the processing cycle the rewelding of a completed pass, in any area where material removal is required in order to eliminate an unacceptable weld defect, is considered a weld repair. If welding is interrupted during a pass and the area is routed out prior to restarting, this is not construed as a repair."

Authorized for Release:

J. A. Bailey
for J. H. Yetto, Manager
Specifications and Standards
Solid Rocket Plant
Sacramento

AEROJET-GENERAL CORPORATION

CODE IDENT. NO. 05824

AGC-36319B
8 October 1962
Superseding
AGC-36319A
20 June 1962

PROCESS SPECIFICATION

COMPONENTS, MOTOR, TITANIUM, FABRICATION OF

1. SCOPE

1.1 This specification covers the fabrication requirements of titanium components for solid propellant rocket motors.

2. APPLICABLE DOCUMENTS

2.1 Governmental documents. - The following documents of the issue as listed in the Department of Defense Index of Specifications and Standards in effect on the date of invitation for bids shall form a part of this specification to the extent specified herein.

SPECIFICATIONS

Military

MIL-P-116	Preservation, Method of
MIL-A-4144	Argon, Gas Welding
MIL-T-5021	Tests, Aircraft and Missile Welding Operator's Qualification
MIL-I-6866	Inspection, Penetrant Method of
MIL-H-6875	Heat Treatment of Steel (Aircraft), Process for
MIL-W-9411	Weapon Systems; Aeronautical, General Specification for

STANDARD

Federal

Fed. Test Method Std. No. 151	Metals; Test Methods

(Copies of specifications, standards, drawings, and publications required by contractors in connection with specific procurement functions should be obtained from the Superintendent of Documents, Government Printing Office, Washington 25, D. C.)

2.2 Aerojet-General Corporation documents. - The following documents of the latest issue in effect form a part of this specification to the extent specified herein.

SPECIFICATIONS

AGC-34007	Case Parts, Forged Titanium Alloy
AGC-36065	Radiographs, Weld; Inspection Requirements for
AGC-50014	Wire, Titanium, PSI Minimum

STANDARD

AS 1701	Electrode, 2% Thoriated Tungsten

3. REQUIREMENTS

3.1 Materials. - The materials used shall be titanium alloy forgings, 6Al-4V, in accordance with Specification AGC-34007.

3.2 Specimens. - All specimens shall be supplied as an integral part of the forging. The specimens representative of the final part shall remain as an integral part through the solution treating and aging operations.

3.3 Rough machining. - All parts shall be rough machined to the same thickness as those parts which were tested in accordance with the preproduction testing specified in Specification AGC-34007. Enough stock shall remain so that a minimum of 0.025 inch of material can be removed from all surfaces after heat treatment. Sufficient material shall be left as an integral part of the forging so that tensile specimens may be prepared in accordance with 4.3.1 after solution heat treat and aging.

3.4 Cleaning. - Prior to being heat treated, the part shall be cleaned in such a manner as to be acceptable in accordance with the visual test for determination of cleanliness as specified in Specification MIL-P-116. Subsequent handling shall be done while using clean gloves, clean handling devices and containers, and other means as necessary to prevent contamination of the part.

3.5 Heat treatment. - The part shall be heat treated in such a manner that after stress relieving, the part shall have the following mechanical properties:

(a)	Yield, psi, min	155,000
(b)	Ultimate strength, psi	165,000 to 180,000
(c)	Elongation, %, min	8

3.5.1 Heat treat procedure. -

3.5.1.1 Solution treatment. - The part with sufficient material for tensile specimens shall be solution heat treated as follows:

(a) The solution heat treating temperature shall be 35 to 60°F below the beta transus for that particular heat of material. The part shall be held at this temperature for 1 to 2 hours.

(b) The part shall be quenched in vigorously agitated water or a solution of three percent sodium hydroxide in water at a temperature less than 120°F. The part shall be quenched within eight seconds of removal from furnace.

3.5.1.2 Aging treatment. - The parts and sufficient material for tensile specimens shall be aged at 900 to 1150°F for a minimum of four hours.

3.5.1.3 Re-aging. - A part may be re-aged within the limits of this specification, if the part is rejected after initial heat treatment.

3.5.1.4 Temperature control. - Furnace temperature surveys, determinations of furnace temperature uniformity, and frequency of check shall be in conformance with Specification MIL-H-6875, except that test thermocouple distribution shall be one per each 35 cubic feet of furnace volume.

3.5.2 Verification of mechanical properties. - Mechanical properties of the component parts shall be verified before welding by testing (4.3.1) of three tensile specimens which have been solution treated and aged as an integral portion of the rough machined forging. The mechanical properties of all three specimens shall meet the requirements specified in 3.5. If one of the three specimens does not meet the requirements of 3.5, three more tensile tests shall be conducted. If these additional three specimens satisfy the requirements of 3.5 the component part shall be acceptable.

3.6 Machining. - Where applicable, the part shall be machined in accordance with the applicable drawing.

3.7 Welding requirements. -

3.7.1 Welding operator. - Welding shall be performed only by welding operators who are currently certified in accordance with the requirements of Specification MIL-T-5021, class A, group VI, and who have demonstrated proficiency by producing an acceptable simulated weld joint No. 7.

3.7.2 Welding procedure. - A written welding procedure shall be supplied to the procuring activity, covering technique of operations. Welding parameters shall be recorded on the Automatic Fusion Welding Schedule (see figure 1), Manual Welding Schedule, or similar form. No changes in the welding procedure shall be initiated before notification has been submitted to the procuring activity.

3.7.3 Identification. - The identification of each welder performing the welding operation shall be entered on the weld history sheets and planning paper applicable to each unit.

3.7.4 Welding process. - The welding process employed in the manufacture of this unit shall be the tungsten inert gas (TIG) method, manual or automatic.

3.7.5 Filler metal and electrodes. -

3.7.5.1 Electrodes. - Electrodes shall conform to Standard AS 1701.

3.7.5.2 Filler metal. - Filler metal shall conform to Specification AGC-50014 and shall be stored in such a manner as to prevent the accumulation of dirt, oil, or other foreign material.

3.7.6 Shielding gases. - Inert shielding gases used shall be one of the following:

(a) Argon, conforming to Specification MIL-A-4144
(b) Helium - grade A, U.S. Bureau of Mines

3.7.7 Equipment. - Welding equipment such as machines, regulators, wire feeds, and heads shall be capable of making satisfactory welds.

3.7.7.1 Crater elimination. - TIG welding equipment shall have a suitable means for crater elimination control.

3.7.8 Preparation. -

3.7.8.1 Cleaning. - Prior to welding, all parts and filler metal shall be cleaned in such a manner as to be acceptable in accordance with the visual and wipe tests for determination of cleanliness as specified in Specification MIL-P-116.

3.7.8.2 Weld alignment. - Parts to be welded shall be assembled, using necessary jigs and fixtures so that alignment and configuration of parts will conform to the engineering drawings.

3.7.8.3 Weld history. - Weld history sheets similar to figure 2 shall be maintained for each unit.

3.7.9 Weld characteristics. - Welding shall be performed to the proficiency and quality of workmanship as defined in Specification MIL-T-5021, and the following.

3.7.9.1 Internal characteristics. - When inspected in accordance with 4.3.2, the welds shall have the following internal characteristics:

3.7.9.1.1 Cracks. - Cracks shall not be acceptable.

3.7.9.1.2 Imperfect fusion. - Imperfect fusion shall not be acceptable.

3.7.9.1.3 Incomplete penetration. - Incomplete penetration shall not be acceptable in butt welds or in the roots of fillet welds.

3.7.9.1.4 Isolated porosity. - Isolated porosity shall be acceptable, except that no cavity shall be over 0.050 inch in diameter or 0.4T, whichever is smaller. There shall be no more than four cavities classified as isolated porosity in any linear inch of weld (5.2.2).

3.7.9.1.5 Linear porosity. - Linear porosity shall not be acceptable (5.2.5).

3.7.9.1.6 Scattered porosity. - Scattered porosity shall be acceptable, provided there are no more than 20 cavities per linear inch of weld (5.2.3).

3.7.9.1.7 Fine porosity. - Fine porosity shall be acceptable (5.2.6).

3.7.9.1.8 Inclusions. - Inclusions shall be acceptable if the greatest dimension of any inclusion is less than 0.20 time the adjacent parent metal thickness. There shall be no elongated inclusions with sharp tails.

3.7.9.1.9 Weld concavity. - Weld concavity shall not be acceptable if any part of a butt weld's surface is below the planes of the surfaces of the mating parts, or throat of any fillet weld is less than the drawing requirement for size.

3.7.9.2 External characteristics. - When inspected in accordance with 4.3.3 and 4.3.4, the welds shall have the following external characteristics.

3.7.9.2.1 Cracks. - Cracks shall not be acceptable. If hydrotest is applicable by drawing requirement there shall be no cracks before or after hydrotest.

3.7.9.2.2 Undercutting. - Undercut welds shall not be acceptable unless the undercut is removed in subsequent machining operations.

3.7.9.2.3 Cold laps. - There shall be no cold laps.

3.7.9.2.4 Bead width. - The bead width shall not vary more than 20 percent.

3.7.9.2.5 Weld crown removal. - When weld crown is removed, care shall be used to avoid reducing the parent metal thickness. Unless otherwise specified, the crown should not project above the adjoining parent metal by more than 1/16 inch.

3.8 Repair welding. - Except as specified in 3.8.5, repair welding before or after stress relieving shall be accomplished using procedures, materials, equipment, and the certification of welders as specified herein.

3.8.1 Number of weld repairs. - Unless otherwise specified, the total number of repairs to a particular weld defect shall not exceed three.

3.8.2 Disposition of weld repairs. - Complete records shall be maintained on repair welds as specified in 4.2.

3.8.3 Weld repair procedure. - Weld repair procedures of incomplete penetration, porosity, inclusions, and other defects shall be prepared and submitted to the procuring activity upon receipt of each contract:

3.8.4 Re-stress relieving of repaired stress relieved welds. - After repairing, the completed part shall be re-stress relieved. Re-stress relieving shall be as specified in 3.9.

3.8.5 Chamber girth welds repairs. - Repair of chamber girth welds is allowable only after specific authorization by the procuring activity. Written weld repair procedures shall be prepared by the fabricator and submitted to the procuring activity prior to the repair of welds. Complete records shall be maintained on weld repairs, as specified in 4.2.

3.9 Stress relieving. - After welding operation, the part shall be stress relieved at the lowest aging temperature for 4 $\pm$ 0.2 hours.

3.10 Verification of mechanical properties of final assembly. - Mechanical properties of the final assembly shall be verified by testing (4.3.1) of three tensile specimens which have been solution treated and aged as an integral portion of the rough machined forging, and stress relieved with the final assembly. The mechanical properties of all three specimens shall meet the requirements specified in 3.5.

3.11 Cleaning prior to hydrotesting. - After heat treatment the part shall be cleaned in accordance with Specification MIL-P-116, method C-15 to remove all traces of oxide films and other contamination. The part shall be acceptable in accordance with the visual and wipe test as specified in Specification MIL-P-116.

3.12 Final machining. - Where applicable, the part shall be machined to the final dimensions in accordance with the applicable drawing.

3.13 Final cleaning. - When all fabrication and inspections have been completed, the part shall be thoroughly cleaned by wiping with rags soaked with an approved solvent (e.g., chlorothene, trichloroethylene). The part shall be rinsed with methyl alcohol whenever any chlorinated solvents are used to clean the part. The part shall be acceptable in accordance with the visual and wipe test as specified in Specification MIL-P-116.

4. QUALITY ASSURANCE PROVISIONS

4.1 Fabricators responsibility. - The fabricator is responsible for the performance of all the processing requirements and inspection requirements as specified herein. The fabricator may utilize his own or any other inspection facilities and services acceptable to the procuring activity. Processing records and inspection records of the examination and tests shall be kept complete and available to the procuring activity.

4.1.1 Inspection. - Inspection shall be performed to assure compliance to this specification. Records of such inspection shall be maintained.

4.2 Repair records. - Records of each weld repair shall be maintained and shall be made available to the procuring activity. The records shall include the following:

(a) Inspector's name
(b) Heat treat condition of part when repaired

(c) Part number, including revision letter and serial number
(d) Area of repair
(e) Number of times repaired in given area
(f) Cause of repair
(g) Extent of repair inspection, including radiographs
(h) Results of inspection
(i) Brief description of repair technique

4.3 Test methods. - The following, or equivalent, procedures shall be used to verify that the process is in conformance with the requirements of this specification.

4.3.1 Mechanical properties. - Tensile specimens shall be prepared and tested in conformance with Standard Fed. Test Method Std. No. 151, method 211.1, type R-3.

4.3.2 Radiographic inspection. - Radiographic examination shall be conducted in accordance with Specification AGC-36065.

4.3.3 Penetrant inspection. - Penetrant inspection shall be performed in accordance with Specification MIL-I-6866.

4.3.4 Visual inspection. - Each part shall be visually inspected to determine compliance with 3.7.9.2.

4.4 Classification of characteristics. - The requirements of section 3 shall be classified as critical or major, as defined in Specification MIL-W-9411, and as shown below. Those requirements not listed shall be classified as minor, or as specified on the applicable drawing or specification.

Classification	Requirements in Section 3	Test Method
Critical	None	None
Major	3.5	4.3.1
	3.7.9.1	4.3.2
	3.7.9.2	4.3.3, 4.3.4

5. NOTES

5.1 Intended use. - This specification establishes the fabrication methods for the manufacture of a titanium rocket motor component.

5.2 Definitions. - Definition of terms related to radiographic inspection criteria shall be as follows:

5.2.1 Imperfect fusion. - Imperfect fusion is defined as a condition where the weld deposit metal fails to melt together with the base metal or previous weld deposit over the entire surfaces exposed for welding.

5.2.2 Isolated porosity. - Isolated porosity is defined as a condition existing when the image of a cavity over 0.2T in diameter is farther from another cavity over 0.2T in diameter by a distance greater than the average of the diameters of the cavities.

5.2.3 Scattered porosity. - Scattered porosity is defined as a condition existing when there are images of two or more cavities with diameter of 0.2T or less.

5.2.4 T-thickness of weld. - The T-thickness of weld is the thickness of the thinner of the two adjoining edges of material at the weld.

5.2.5 Linear porosity. - Linear porosity is defined as a condition existing when the images of three or more cavities with diameters greater than 0.12T, and an average closest approach of less than twice the average of the diameters, are located in approximately a straight line along the center line of the weld.

5.2.6 Fine porosity. - Fine porosity is defined as a condition existing when the image of a cavity is 0.010 inch or less in diameter.

Authorized for Release:

J. H. Vetto, Manager
Engineering Specifications
Solid Rocket Plant
Sacramento

Aerojet-General Corporation
AGC-36319B
Figure 1

Operation No. __________ Material ______________ Machine No. ______________

Joint Configuration: **Data**

Pass Number	1	2	3	4	5	6	7
Amperage							
* Amperage Control Setting							
Arc Voltage							
* Arc Voltage Calibrate							
Welding Speed - IPM							
* Positioner Control Setting							
Wirefeed Indicator Speed							

		Tooling and Special Instructions
Filler Material Type		
Filler Material Size		
Electrode Type		
Electrode Size		
* Torch Cup Size		
Shielding (see (A) below)		
Backup or Purge		
Trailing Cup		
Type of Current		
* Head Sensitivity		
* Head Down Speed		
* Weld Travel Delay		
* Wire Start Delay		
* Current Delay		
* Wire Stop Delay		
* Initial Heat		
* Up Slope Pre-heat Rheostat		
* Down Slope Decay Rheostat		
* Final Heat		
* Tailing Time		
* Preheat Temperature		
* Interpass Temperature		
* Post Heat Temperature		
* Wire Guide Tip Size		
Carriage Travel		
Fit Up		
Wire Brush Between Passes		
(A) Shielding - use following		
mixture helium		
argon		*For Information Only

APPROVALS

Welding Engineer ______________ Chief Welding Engineer ______________

Quality Control ______________ Government Inspector ______________

Manufacturing ______________

AUTOMATIC FUSION WELDING SCHEDULE

Figure 2

Operation No.__________ P/N__________ Machine No.________ Material__________
W. O.____________________ Unit No.__________

Joint Configuration:__________ Weld Process__________ Unit No.__________

Pass Number	1	2	3	4	5	6	7
Amperage							
Amperage Control Setting							
Arc Voltage							
Arc Voltage Calibrate							
Welding Speed - IPM							
Positioner Control Setting							
Wirefeed Indicator Speed							

Filler Material Type		Tooling and Special Instructions
Filler Material Size		1. Part welded per EWP__________
Electrode Type		
Electrode Size		
Torch Cup Size		
Shielding (see (A) below)		
Backup or Purge		
Trailing Cup		
Type of Current		
Head Sensitivity		
Head Down Speed		
Weld TravelDelay		
Wire Start Delay		
Current Delay		
Wire Stop Delay		
Initial Heat		
Up Slope Pre-heat Rheostat		
Down Slope Decay Rheostat		
Final Heat		
Tailing Time		
Preheat Temperature		
Interpass Temperature		
Post Heat Temperature		
Wire Guide Tip Size		
Carriage Travel		
Fit Up		
Wire Brush Between Passes		
(A) Shielding - use following		
mixture helium		
argon		

Welding Eng.__________ Welding Insp.__________ APPROVALS
Welding Op'r.__________

WELD HISTORY SHEET

Appendix VII

AGC-13860

RADIOGRAPHIC ACCEPTANCE LIMITS FOR FUSION WELD JOINTS

TABLE 1
RADIOGRAPHIC ACCEPTANCE LIMITS FOR FUSIONS WELD JOINTS
(Single Type Defects)

Weld Class		1	2	3	4
Weld Defects	Ref. Fig.	Allowable Acceptance Limits			
Weld cracks		U	U	U	U
Parent metal cracks		U	U	U	U
Under bead crater		U	U	U	U
Worm holes		U	U	U	U
Burn through		U	U	U	U
Incomplete penetration		U	U	U, under 1/4"T;	U, under 1/4"T;
Length	4,5			1/4"T and over, T/4 max in any 8T weld length	1/4"T and over, T/4 max in any 6T weld length
Depth	4			T/10 max.	T/10 max.
Incomplete fusion	4,5	U	U	Same as I.P.	Same as I.P.
Linear porosity*		U	U	U, under 1/4"T; 1/4"T and over	U, under 1/4"T; 1/4"T and over
Diam of cavity	6			T/5(.060"max)	T/4(.080"max)
Dist between cavities	7			6D(.090"min)	4D(.060"min)
Dist between groups	8			6T(1"min)	3T(1/2"min)
No. per inch of weld				3	5
Aligned porosity*		U			
Diam of cavity	6		T/5(.060"max)	T/5(.060"max)	T/4(.080"max)
Dist between cavities	7		8D(.125"min)	6D(.090"min)	4D(.060"min)
Dist between groups	8		6T(1"min)	6T(1"min)	3T(1/2"min)
No. per inch of weld			3	3	5
Scattered porosity*					
Spheroidal					
Diam of cavity	6	T/5(.060"max)	T/5(.060"max)	T/4(.080"max)	T/4(.080"max)
Dist between cavities	7	10D(.15min)	8D(.12"min)	6D(.090"min)	4D(.060"min)
No. per inch of weld		2	4	4	8
Elongated		U	U	U	U
Non-metallic inclusions					
Spheroidal					
Diam of inclusions	6	T/4(.080"max)	T/4(.080"max)	T/3(.100"max)	T/3(.100"max)
Dist between incl's	7	8D(.12"min)	6D(.090"min)	4D(.060"min)	3D(.060"min)
No. per inch of weld		3	5	6	10
Elongated		U	U	U	U
Metallic inclusions					
Spheroidal		Same as S.P.	Same as S.P.	Same as S.P.	Same as S.P.
Elongated		U	U	U	U
Excess penetration	10	T/4(.032"max)	T/4(.032"max)	T/4(.032"max)	T/3(.060"max)
VISUAL INSPECTION					
Excess crown	10	T/4(.032"max)	T/4(.032"max)	T/4(.032"max)	T/3(.060"max)
Undercut		U			
Depth	1		T/20	T/20	T/20
Length	2,3		5T in 50T	5T in 50T	5T in 50T
[illegible]		U	U	U	U

*Not more than three (3) consecutive inches may contain porosity. For every inch up to maximum of three (3) that contains porosity, there shall be an equal amount of sound weld on either side.

NOTE: See paragraphs 4.1, 4.2 and 3.2.1, 3.2.2 for explanations of symbols, terms, abbreviations, definitions and conditions governing single and multiple types of defects.

Refer to Figures 27 and 28 for determination of "T" used in limiting size of defects. If a weld crown or filler is subsequently machined, values of "T" used shall be adjusted in accordance with finished dimensions at the weld joint.

Appendix VIII

WELDING CONDITIONS AND WELD PROPERTIES DATA ON SQUARE BUTT WELDS IN 6A1-4V TITANIUM PLATE (SOLUTION TREATED AND AGED) NOMINALLY 0.25-IN. THICK.

Table VIII-1. Welding Conditions and Weld Properties Da
and Aged) Nomin

Heat No.	Lot	Position of Welding and/or Plate Rolling Direction	Type of Plasma Arc Weld	Root Land Thickness (in.)	Weld Identification	Torch Setup Data: Torch Type	Orifice	Standoff Distance (in.)	Electrode Configuration: Dia (in.)	Included Tip Angle (deg)	End Flat Dia (in.)	Setback Distance (in.)	Orifice Gas: Type[b]	Total[c] Flow (cfh)	Shield Gas: Type	Flow (cfh)	Bac G Ty
293281	A	Transverse	NA	0.241	PM[g] test												
	A			0.241													
	A			0.241													
293281	B			0.235													
	B			0.235													
	B	Transverse	NA	0.236	PM test												
293281	A	Flat, Transverse	Keyhole, sq butt	0.241	T2A2-1	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	15	Ar	60	Ar
	B		Keyhole, sq butt	0.235	T2A2-1	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	15	Ar	60	Ar
	A		Keyhole, sq butt	0.241	T2A2-2 root	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	15	Ar	60	Ar
	A		Melt-in	0.241	T2A2-2 150 amp cover	PT-8	136-M	1/4	1/8	70	3/64	1/8	HE 50	6	HE 50	70	Ar
	A		Keyhole, sq butt	0.241	T2A2-2 root	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	15	Ar	60	Ar
	A		Melt-in	0.241	T2A2-2 170 amp cover	PT-8	136-M	1/4	1/8	70	3/64	1/8	HE 50	6	HE 50	70	Ar
	A		Keyhole, sq butt	0.241	T2A2-2, root	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	15	Ar	60	Ar
			Keyhole, sq butt	0.241	T2A2-2, O. L.	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	15	Ar	60	Ar
			Melt-in	0.241	170 amp cover	PT-8	136-M	1/4	1/8	70	3/64	1/8	HE 50	6	HE 50	70	Ar
	A		Keyhole, sq butt	0.244	T2A2-8 root	PT-8	136-M	1/4	1/8	60	1/32	1/8	Ar	15	Ar	60	Ar
	A		Melt-in	0.244	T2A2-8 cover	PT-8	136-M	5/16	1/8	60	1/32	1/8	HE 75	10	HE 75	80	Ar
	B		Keyhole, sq butt	0.235	T2A2-14	U-5T	1/8	1/8	1/8	-	-	1/16	Ar	5	Ar	20	Ar
	B		Keyhole, sq butt	0.235	T2A2-14 root	U-5T	1/8	1/8	1/8	-	-	1/16	Ar	5	Ar	20	Ar
	B	Flat, Transverse	Melt-in	0.235	T2A2-14 cover	U-5T	1/8	1/4	1/8	-	-	1/16	HE 75	4	HE 75	60	Ar
G-4956	NA	Transverse	NA	0.251	PM test												
			NA	0.251	PM test												
			NA	0.251	PM test												
G-4956	NA		Keyhole, sq butt	0.250	T2A2-35	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
			Keyhole, sq butt	0.250	T2A2-35	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
			Keyhole, sq butt	0.250	T2A2-35	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
			Keyhole, sq butt	0.250	T2A2-35	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
			Keyhole, sq butt	0.250	T2A2-36	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	15	Ar	60	Ar
			Keyhole, sq butt	0.250	T2A2-36	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	15	Ar	60	Ar
			Keyhole, sq butt	0.250	T2A2-36	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
		Transverse	Keyhole, sq butt	0.250	T2A2-36	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
G-4956	NA	Flat, Transverse, (Phase 1C welds)	Keyhole, sq butt	0.250	T2A2-34	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
			Keyhole, sq butt	0.250	T2A2-34, overlap area	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
			Keyhole, sq butt	0.250	T2A2-33, 2 keyhole passes	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
			Keyhole, sq butt	0.250	T2A2-33, 3 keyhole passes (overlap area)	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
			Keyhole, sq butt	0.250	T2A2-30 root	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
			Melt-in	0.250	T2A2-30 cover	PT-8	136-M	1/4	1/8	70	3/64	1/8	HE 75	8	HE 75	60	Ar
			Keyhole, sq butt plus melt-in	0.250	T2A2-30	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
					root + cover	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
					in O. L. area	PT-8	136-M	1/4	1/8	70	3/64	1/8	He 75	8	He 75	60	Ar
			Keyhole, sq butt	0.250	T2A2-31 root	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
			Melt-in	0.250	T2A2-31 cover	PT-8	136-M	1/4	1/8	70	3/64	1/8	HE 75	8	HE 75	60	Ar
			Keyhole, sq butt	0.250	T2A2-32 root	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
		Flat Transverse	Melt-in	0.250	T2A2-32 cover	PT-8	136-M	1/4	1/8	70	3/64	1/8	HE 75	8	HE 75	60	Ar
		Horizontal, Transverse	Keyhole, sq butt	0.250	T2E2-3 root	PT-8	136-M	1/4	1/8	70	3/64	1/8	Ar	16	Ar	60	Ar
		Horizontal, Transverse	Melt-in	0.250	T2E2-3-1 cover	PT-8	136-M	1/4	1/8	70	3/64	1/8	HE 75	8	HE 75	60	Ar
		Horizontal, Transverse	Melt-in	0.250	T2E2-3-2 cover	PT-8	136-M	1/4	1/8	70	3/64	1/8	HE 75	8	HE 75	60	Ar
G-49561	NA	Flat-Transverse	E. B. Weld	0.250	Electron beam weld made at 115 KV, 35 MA, at 50 ipm travel speed												

NOTES:
a. Tensile properties determined with weld reinforcement left as-welded.
b. Inert gas composition abbreviations are defined as follows: AR - Argon; HE 50 - 50% Argon/50% helium; HE 75 - 25% Argon/75% helium.
c. Orifice gas flow values accurate to ±1% of full scale on flowmeters.
d. Heat input values calculated without regard for heat losses in torch orifice or radiation losses using the equation $J = \frac{E \times I \times 60}{S \times 10^3}$
e. Heat treatments shown were at indicated temperatures for 4 hr in still air, followed by still air cooling.
f. Notch located through-the-thickness of the specimen in the location indicated; notch was machined in smoothly ground rectangular cross section bar 0.24 x 0.394 x 2.10 in.
g. Parent material.
h. Fusion zone.
i. Heat affected zone.
j. Commercially pure titanium.
k. 6 Al-4V titanium, ELI grade.
l. One test only.
m. Two tests.

A.

ions and Weld Properties Data on Square Butt Welds in 6Al-4V Titanium Plate (Solution Treated and Aged) Nominally 0.25-in. Thick.

…uration …nd …ial …ia (in.)	Setback Distance (in.)	Orifice Gas Type[b]	Orifice Gas Total[c] Flow (cfh)	Shield Gas Type	Shield Gas Flow (cfh)	Backup Gas Type	Weld Current (amp)	Weld Voltage	Weld Travel Speed (ipm)	Cold Filler Wire Data Heat No.	Cold Filler Wire Data Dia (in.)	Cold Filler Wire Data Feed Rate (ipm)	Unit Weld Heat Input[d] (kjoule/in.) Each Pass	Unit Weld Heat Input[d] (kjoule/in.) Total	Backup Groove Width (in.)	Postweld Heat[e] Treatment Data (°F)	Yield Stress (ksi) Average of 3 Tests	Ultimate Tensile Stress (ksi)	% Elongation in 1 in.	Fai… Loc…
																As received	155.1	166.2	8.0	
																As received	152.9	169.9	8.0	
																1000	152.2	168.4	11.3	
																As received	151.7	163.5	10.0	
																As received	146.8	163.4	10.0	
																1000	160.1	168.3	12.8	
64	1/8	Ar	15	Ar	60	Ar	195	25.1	12.0	NA	-	-	24.4	24.4	3/4	1000	143.0[l]	154.3[l]	7.5[l]	FZ Lot
64	1/8	Ar	15	Ar	60	Ar	195	25.1	12.0	NA	-	-	24.4	24.4	3/4	1000	147.2[m]	157.8[m]	10.0[m]	FZ c Lot I
64 64	1/C 1/8	Ar HE 50	15 6	Ar HE 50	60 70	Ar Ar	195 150	25.1 21.6	12.0 12.0	NA	-	-	24.4 16.2	40.6	3/4	1000	145.8	157.9	11.0	FZ/I
64 64	1/8 1/8	Ar HE 50	15 6	Ar HE 55	60 70	Ar Ar	195 170	25.1 22.0	12.0 12.0	NA	-	-	24.4 18.7	43.1	3/4	1000	146.3	161.1	10.3	FZ/I
64 64 64	1/8 1/8 1/8	Ar Ar HE 50	15 15 6	Ar Ar HE 50	60 60 70	Ar Ar Ar	195 195 170	25.1 25.1 22.0	12.0 12.0 12.0	NA	-	-	24.4 24.4 18.7	67.5	3/4	1000	145.9	158.3	8.5	FZ/I
32 32	1/8 1/8	Ar HE 75	15 10	Ar HE 75	60 80	Ar Ar	200 160	23.0 22.5	12.0 6.0	NA 301525[j]	- 0.062	- 18.0	23.0 36.0	59.0	3/4	1000	112.0	128.9	9.3	FZ/I
	1/16	Ar	5	Ar	20	Ar	210	25.0	12.0	NA	-	-	26.2	26.2	3/4	1000	119.4	129.0	12.3	F
	1/16 1/16	Ar HE 75	5 4	Ar HE 75	20 60	Ar Ar	210 160	25.0 27.0	12.0 12.0	NA NA	- -	- -	26.2 21.6	47.8	3/4	1000	142.0	152.8	8.5	FZ/I
																As received	171.8	183.2	8.0	
																As received	169.7	181.7	14.6	
																1000	171.6	180.9	12.0	
64	1/8	Ar	16	Ar	60	Ar	220	27.2	12.0	NA	-	-	29.8	29.8		950 to 980	143.5	154.8	8.3	FZ/H
64	1/8	Ar	16	Ar	60	Ar	220	27.2	12.0	NA	-	-	29.8	29.8	1-3/4	980 to 1020	145.8	154.5	7.8	FZ/H
64	1/8	Ar	16	Ar	60	Ar	220	27.2	12.0	NA	-	-	29.8	29.8		1040 to 1060	145.2	153.7	6.8	FZ/H
64	1/8	Ar	16	Ar	60	Ar	220	27.2	12.0	NA	-	-	29.8	29.8		1080 to 1120	143.0	152.2	8.0	FZ/H
64	1/8	Ar	15	Ar	60	Ar	190	25.0	12.0	NA	-	-	23.8	23.8		925	140.0	152.9	7.6	FZ/H
64	1/8	Ar	15	Ar	60	Ar	190	25.0	12.0	NA	-	-	23.8	23.8	1-3/4	1025	145.6	154.9	7.3	FZ/H
64	1/8	Ar	16	Ar	60	Ar	220	27.2	12.0	NA	-	-	29.8	29.8		925	144.0	155.7	9.3	FZ/H
64	1/8	Ar	16	Ar	60	Ar	220	27.2	12.0	NA	-	-	29.8	29.8		1025	146.5	157.2	7.7	FZ/H
64	1/8	Ar	16	Ar	80	Ar	220	26.0	12.0	NA	-	-	28.6	28.6	1-3/4	1025	144.6	156.4	5.7	FZ/H
64	1/8	Ar	16	Ar	60	Ar	220	26.0	12.0	NA	-	-	1-28.6 2-28.6	57.2		1025	143.4	158.0	7.3	FZ/H
64	1/8	Ar	16	Ar	60	Ar	220	26.2	12.0	NA	-	-	1-29.0 2-29.0	58.0	1-3/4	1025	143.6	156.9	6.0	FZ/H
64	1/8	Ar	16	Ar	60	Ar	220	26.2	12.0	NA	-	-	1-29.0 2-29.0 3-29.0	87.0	1-3/4	1025	143.7	157.7	6.3	FZ/H
64 64	1/8 1/8	Ar HE 75	16 8	Ar HE 75	60 60	Ar Ar	220 150	27.5 25.5	12.0 12.0	NA 301525[j]	- 0.062	- 18.0	1-30.2 2-19.1	49.3	1-3/4	1025	145.8	160.9	7.0	FZ/H
64 64 64	1/8 1/8 1/8	Ar Ar He 75	16 16 8	Ar Ar He 75	60 60 60	Ar Ar Ar	220 220 150	27.5 27.5 25.5	12.0 12.0 12.0	NA NA 301525	- - 0.062	- - 18.0	1-30.2 2-30.2 3-19.1	79.5	1-3/4	1025	146.1	160.6	8.0	FZ/H
64 64	1/8 1/8	Ar HE 75	16 8	Ar HE 75	60 60	Ar Ar	220 150	27.2 25.6	12.0 12.0	NA 3204-DI[k]	- 0.062	- 18.0	1-29.9 2-19.2	49.1	1-3/4	1025	144.8	161.3	6.0	FZ/H
64 64	1/8 1/8	Ar HE 75	16 8	Ar HE 75	60 60	Ar Ar	220 175	27.2 26.2	12.0 15.0	NA 3204-DI[k]	- 0.062	- 23.0	1-29.9 2-18.3	48.2	1-3/4	1025	147.5	161.9	7.6	FZ/H
64 64 64	1/8 1/8 1/8	Ar HE 75 HE 75	16 8 8	Ar HE 75 HE 75	60 60 60	Ar Ar Ar	220 150 90	27.0 25.4 23.0	12.0 12.0 12.0	NA NA NA	- - -	- - -	1-29.7 2-19.0 3-10.3	59.0	1-3/4	1025	148.5	161.6	9.3	FZ/H
															NA	1025	148.7	158.1	4.1	FZ/H

75% helium.

t 60

0^3

ular cross section bar 0.24 x 0.394 x 2.10 in.

1 B.

utt Welds in 6Al-4V Titanium Plate (Solution Treated
Thick.

tions							Mechanical Properties[a]									
Weld Travel Speed (ipm)	Cold Filler Wire Data: Heat No.	Dia (in.)	Feed Rate (ipm)	Unit Weld Heat Input[d] (kjoule/in.): Each Pass	Total	Backup Groove Width (in.)	Postweld Heat[e] Treatment Data (°F)	Yield Stress (ksi) Average of 3 Tests	Ultimate Tensile Stress (ksi)	% Elongation in 1 in.	Failure Location	Precrack Charpy Energy Absorption[f] (in.-lb/in.[2]): Average of 3 Tests	Spread	Notch Location	Thickness (in.)	Data Source
							As received	155.1	166.2	8.0	PM					Vendor
							As received	152.9	169.9	8.0	PM				-	Aerojet
							1000	152.2	168.4	11.3	PM	574	551/595	PM	0.24	Aerojet
							As received	151.7	163.8	10.0	PM	-	-	-	-	Vendor
							As received	146.8	163.4	10.0	PM					Aerojet
							1000	150.1	165.2	12.0	PM	823	805/847	PM	0.25	Aerojet
12.0	NA	-	-	24.4	24.4	3/4	1000	143.0[l]	154.3[l]	7.5[l]	FZ[k] Lot A side	-	-	-	-	Aerojet
12.0	NA	-	-	24.4	24.4	3/4	1000	147.2[m]	157.8[m]	10.0[m]	FZ on Lot B side	914	842/1026	W℄	0.23	Aerojet
12.0 12.0	NA	-	-	24.4 16.2	40.6	3/4	1000	145.8	157.9	11.0	FZ/HAZ[i]	-	-	-	-	Aerojet
12.0 12.0	NA	-	-	24.4 18.7	43.1	3/4	1000	146.3	161.1	10.3	FZ/HAZ	988	830/1156	W℄	0.23	Aerojet
12.0 12.0 12.0	NA	-	-	24.4 24.4 18.7	67.5	3/4	1000	145.9	158.3	8.5	FZ/HAZ	-	-	-	-	Aerojet
12.0 6.0	NA 301525[j]	- 0.062	 18.0	23.0 36.0	59.0	3/4	1000	112.0	125.9	9.3	FZ/HAZ	-	-	-	-	Aerojet
12.0	NA	-	-	26.2	26.2	3/4	1000	119.4	129.0	12.3	FZ	-	-	-	-	Aerojet
12.0 12.0	NA NA	-	-	26.2 21.6	47.8	3/4	1000	142.0	152.8	8.5	FZ/HAZ	-	-	-	-	Aerojet
							As received	171.8	183.2	8.0	PM	-	-	-	-	Vendor
							As received	169.7	181.7	14.6	PM	622	571/671	PM	0.24	Aerojet
							1000	171.6	180.9	12.0	PM	601	583/630	PM	0.24	Aerojet
12.0	NA	-	-	29.8	29.8	1-3/4	950 to 980	145.5	154.8	8.3	FZ/HAZ	-	-	-	-	Aerojet
12.0	NA	-	-	29.8	29.8		980 to [illegible]	145.8	154.5	7.8	FZ/HAZ					Aerojet
12.0	NA	-	-	29.8	29.8		1040 to 1060	145.2	153.7	6.8	FZ/HAZ					Aerojet
12.0	NA	-	-	29.8	29.8		1080 to 1120	143.0	152.2	8.0	FZ/HAZ					Aerojet
12.0	NA	-	-	23.8	23.8	1-3/4	925	140.0	152.9	7.6	FZ/HAZ	-	-	-	-	Aerojet
12.0	NA	-	-	23.8	23.8		1025	145.6	154.9	7.3	FZ/HAZ					Aerojet
12.0	NA	-	-	29.8	29.8		925	144.0	155.7	9.3	FZ/HAZ					Aerojet
12.0	NA	-	-	29.8	29.8		1025	146.5	157.2	7.7	FZ/HAZ					Aerojet
12.0	NA	-	-	28.6	28.6		1025	144.6	156.4	5.7	FZ/HAZ					Aerojet
12.0	NA	-	-	1-28.6 2-28.6	57.2	1-3/4	1025	143.4	158.0	7.3	FZ/HAZ	1059 879	894/1146 841/950	W℄ HAZ	0.24 0.24	Aerojet Aerojet
12.0	NA	-	-	1-29.0 2-29.0	58.0	1-3/4	1025	143.6	156.9	6.0	FZ/HAZ	1082	981/1150	W℄	0.24	Aerojet
12.0	NA	-	-	1-29.0 2-29.0 3-29.0	87.0	1-3/4	1025	143.7	157.7	6.3	FZ/HAZ	-	-	-	-	Aerojet
12.0 12.0	NA 301525[j]	- 0.062	- 18.0	1-30.2 2-19.1	49.3	1-3/4	1025	145.8	160.9	7.0	FZ/HAZ	1072 1026	1013/1111 869/1183	W℄ HAZ	0.24 0.24	Aerojet Aerojet
12.0 12.0 12.0	NA NA 301525	- - 0.062	- - 18.0	1-30.2 2-30.2 3-19.1	79.5	1-3/4	1025	146.1	160.6	8.0	FZ/HAZ	-	-	-	-	Aerojet
12.0 12.0	NA 3204-D1[k]	- 0.062	- 18.0	1-29.9 2-19.2	49.1	1-3/4	1025	144.8	161.3	6.0	FZ/HAZ	1069	1026/1098	W℄	0.24	Aerojet
12.0 15.0	NA 3204-D1[k]	- 0.062	- 23.0	1-29.9 2-18.3	48.2	1-3/4	1025	147.5	161.9	7.6	FZ/HAZ	1064 859	930/1221 821/916	W℄ HAZ	0.24 0.24	Aerojet Aerojet
12.0 12.0 12.0	NA NA NA	- - -	- - -	1-29.7 2-19.0 3-10.3	59.0	1-3/4	1025	148.5	161.6	9.3	FZ/HAZ	905 1041	833/959 871/1181	W℄ HAZ	0.24 0.24	Aerojet Aerojet
						NA	1025	148.7	158.1	4.1	FZ/HAZ	565	557/572	W℄	0.24	Aerojet

B. C.

Appendix IX

REVEIW OF GRAIN BOUNDARY SEPARATION PROBLEM IN LM ASCENT TANK WELDS.

SPECIAL REPORT

REVIEW OF GRAIN BOUNDARY SEPARATION PROBLEM ENCOUNTERED IN LM ASCENT TANK WELDS

REPORT: 1-4081-01-5.4-005

DATE: 3 April 1968

GRUMMAN PRIME CONTRACT NAS 9-1100

APPROVED BY B. L. Baird

B. L. BAIRD, MANAGER

AEROJET-GENERAL CORPORATION

DOWNEY PLANT • 11711 WOODRUFF AVE., DOWNEY, CALIF.

CONTENTS

BRIEF DESCRIPTION OF THE NEW ALL-WELDED LM ASCENT TANK MODEL

The LM ascent tank model installed in vehicles LM-1 through LM-5 is a 49.4-in. ID titanium sphere containing two openings: a 15-in. diameter access hole at the bottom, and a 1-in. diameter helium inlet port at the top.

A titanium cover is attached to the flange surrounding the access hole, and a stainless steel helium diffuser fitting is attached to the helium inlet port. Both the titanium cover and the stainless steel fitting are fastened to the tank with bolts, and in each instance, helium leakage is restricted by a Teflon-covered stainless steel seal. The delivered weight of this tank model has averaged 73 lb.

A new all-welded tank model that will be installed in vehicles LM-6 through LM-15 is currently being developed. The bolt-on cover and diffuser fitting will be replaced by titanium closure and diffuser subassemblies welded into top and bottom openings. This modification will eliminate two helium leakage paths and reduce the tank weight by approximately 9 lb.

GRAIN BOUNDARY SEPARATIONS FOUND IN DIFFUSER-TO-TANK WELDS

An initial group of four tanks is being processed through the ten new welding operations required to fabricate the new model. The first article is merely a tool proofing unit. The second is the new qualification tank, and the third and fourth are the LM-6 fuel and oxidizer tanks.

A small crack was detected in the X-ray of the diffuser-to-tank weld (Figure 1) made on the tool proofing unit. The crack was also detected by fluorescent penetrant inspection of the root side of the weld.

A review of the data recorded when the weld was made indicated that a small water leak in the welding torch plumbing had occurred midway through the welding cycle. The cause of cracking was tentatively assigned to hydrogen contamination from the water leak.

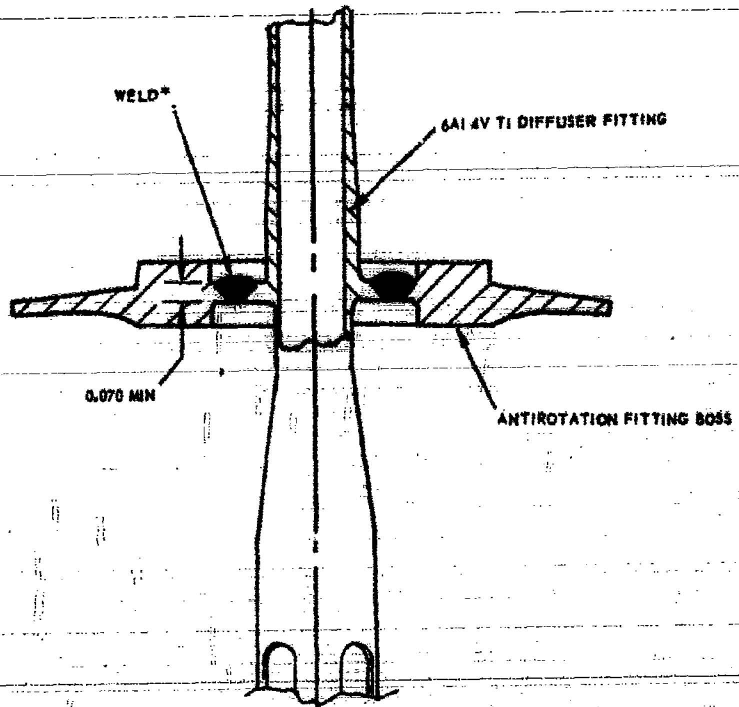


Figure X-1. Diffuser-to-Tank Weld.

Following this brief evaluation, the diffuser-to-tank weld was made in the qualification tank. No rejectable defects were found in the X-ray of this weld. However, one small crack indication was detected on the root surface by fluorescent penetrant inspection. To verify the presence of the defect, the area was washed and then reinspected by the fluorescent penetrant method. Since the second inspection indicated no defects, the conformance to specification fluorescent penetrant inspection requirements was certified by Quality Control.

Because a completely satisfactory explanation of the cause of cracking of the tool proofing tank weld had not been established, an engineering directive was issued requiring the diffuser-to-tank welds on both tool proofing and qualification units to be reinspected with a new supersensitive penetrant inspection technique. The materials required for this technique are marketed by Magnaflux Corporation under the trade name HY-REZ.

HY-REZ penetrant inspection revealed several indications on the root surfaces of both welds which appeared under microscopic examination to be small cracks located at grain boundaries. As a result, HY-REZ penetrant inspections were run on a total of seven test welds, which had previously been made in pieces approximately simulating the configuration of the diffuser-to-tank weld. Separations were found in six out of seven of these pieces (Figure 2).

In every instance the separations were located only on the root surface of the weld, near the weld centerline. Also, in every instance, the flaws followed grain boundaries.

The most common causes of 6Al-4V titanium weld cracking are

a. Interstitial contamination by nitrogen, oxygen, and hydrogen.

b. Stress corrosion cracking.

c. Residual stress cracking.

The test welds had been made in a controlled atmosphere chamber, evacuated to less than 1μ before back-filling with argon. Additionally, certification welds were made before starting and after completing the test welds to verify the purity of the chamber atmosphere. Verification was accomplished by running gas analyses on the certification welds to determine oxygen, nitrogen, and hydrogen content. Based on a review of the gas analysis data, the possibility that the cracking was caused by interstitial contamination was ruled out.

Because the welds were never subjected to the combination of corrosive environment and applied stress, stress corrosion was also eliminated as a potential cause.

A review of the joint geometry (Figure 1) focused attention on the high restraint produced in the weld by the stiffness of the surrounding antirotation fitting boss. The probable cause of cracking was therefore attributed to high residual stresses.

The following three corrective measures were investigated:

a. Changing the diffuser to commercially pure titanium to increase weld ductility.

b. Reducing the minimum thickness at the weld joint from 0.070 to 0.040 in. to decrease the weld width and, thereby, the tendency toward shrinkage.

c. Incorporating a pre- and postheat cycle into the welding schedule to permit a high postheat temperature to be maintained for a long enough time to allow the relaxing of residual stresses by yielding of the weld metal.

To evaluate corrective measures a and b, the following specimens simulating the diffuser-to-tank weld configuration were fabricated:

Type 1. Commercially pure titanium diffuser fitting, 0.070-in.-thick weld joint, 6Al-4V titanium antirotation boss.

Type 2. 6Al-4V titanium diffuser fitting, 0.040-in.-thick weld joint, 6Al-4V titanium antirotation boss.

Type 3. 6Al-4V titanium diffuser fitting, 0.070-in.-thick weld joint, 6Al-4V titanium antirotation boss.

Six each of these specimens were welded in Aerojet's controlled atmosphere chamber. Neither pre- nor postheat was used. All of the specimens were X-rayed and then HY-REZ penetrant-inspected. There were no indications of cracks in any of the three groups. The specimens were HY-REZ penetrant-inspected again 12 to 14 days after welding. There were no indications of cracks.

The configuration of the Type 3 specimens was identical to that of the initial group of seven, six of which were found to contain separations. However, the Type 3 specimens were all welded in a single chamber load, and welding parameters were closely monitored and recorded, while the initial group was welded randomly with respect to time, and the welding current was changed from specimen to specimen to develop procedure data. Additionally, the Type 3 specimens were carefully cleaned prior to welding, while those in the initial group were not.

Simultaneous with the evaluation made by welding and testing Type 1, 2, and 3 specimens, the development of two potential methods for pre- and postheating was begun. The former utilized resistance heating elements, and the latter an electric welding arc as heating sources. Neither method proved satisfactory, largely because the pre- and postheating operations are complicated by the necessity to simultaneously cool the surrounding tank membrane and the bimetal tube joint attached to the diffuser fitting.

GRAIN BOUNDARY SEPARATIONS IN CLOSURE WELDS

HY-REZ penetrant inspections were subsequently run on welds in six specimens designed to simulate the closure-to-tank weld. These welds were made with 6Al-4V titanium filler wire.

Microscopic examination showed that single indications found in three of the six welds were separations on the root side of the weld, following grain boundaries. In addition, careful examination of X-rays of one weld containing a separation demonstrated conclusively that this type of defect cannot be detected by radiographic inspection.

ACTIONS TO BE TAKEN AS A RESULT OF THE DISCOVERY OF THE GRAIN BOUNDARY SEPARATIONS

Diffuser-to-Tank Weld

a. The diffuser material will be changed to commercially pure titanium, but no pre- and postheat cycle will be incorporated into the welding schedule.

b. A HY-REZ penetrant-inspection will be made on the root side of all welds.

Closure-to-Tank Weld

a. The welding filler wire will be changed to commercially pure titanium, but no pre- and postheat cycle will be incorporated into the welding schedule.

b. At least one existing closure weld containing a separation will be pressure cycle tested to failure to obtain crack growth data.

c. Six new simulated closure-to-tank welds will be welded with commercially pure filler wire and HY-REZ penetrant-inspected. Three of these welds will be destructive-tested to failure, either by cycle or burst testing.

DISCUSSION

At the present time, although a decision has been made to proceed as described above, there is no assurance that tanks delivered to Grumman will not contain separations of the type illustrated in Figure 2. Although the diffuser-to-tank weld will be HY-REZ penetrant-inspected to assure that it is free of separations, the root side of the closure-to-tank welds is inaccessible and so cannot be inspected by this method.

To Aerojet's knowledge, there is no tank manufacturer using HY-REZ penetrant-inspection as a production inspection method. Thus, it is possible, and even probable, that this type of defect occurs in other existing titanium tankage. The high-pressure helium storage tanks used in Saturn, Apollo, and LM vehicles are thick-wall titanium tanks welded with multiple pass procedures, using 6Al-4V titanium filler wire. The root side of the girth welds in none of these tanks can be penetrant-inspected.

Aerojet believes that the use of commercially pure filler metal will reduce the tendency for separations of the type illustrated in Figure 2 to develop. Three girth seam welds (465 in. total) made with commercially pure filler material have been HY-REZ inspected, and no crack indications were found. Additionally, HY-REZ inspection revealed no separations in the six test welds simulating the welding of a commercially pure diffuser fitting to the tank.

In assessing the significance of the grain boundary separation problem discussed in this report, the following should be kept in mind: NASA's basic fracture mechanics approach, under which a limit is set on the pressure cycles permitted between proof tests, assumes that flaws considerably larger than the separations discovered in the LM tank welds are present in the structure.

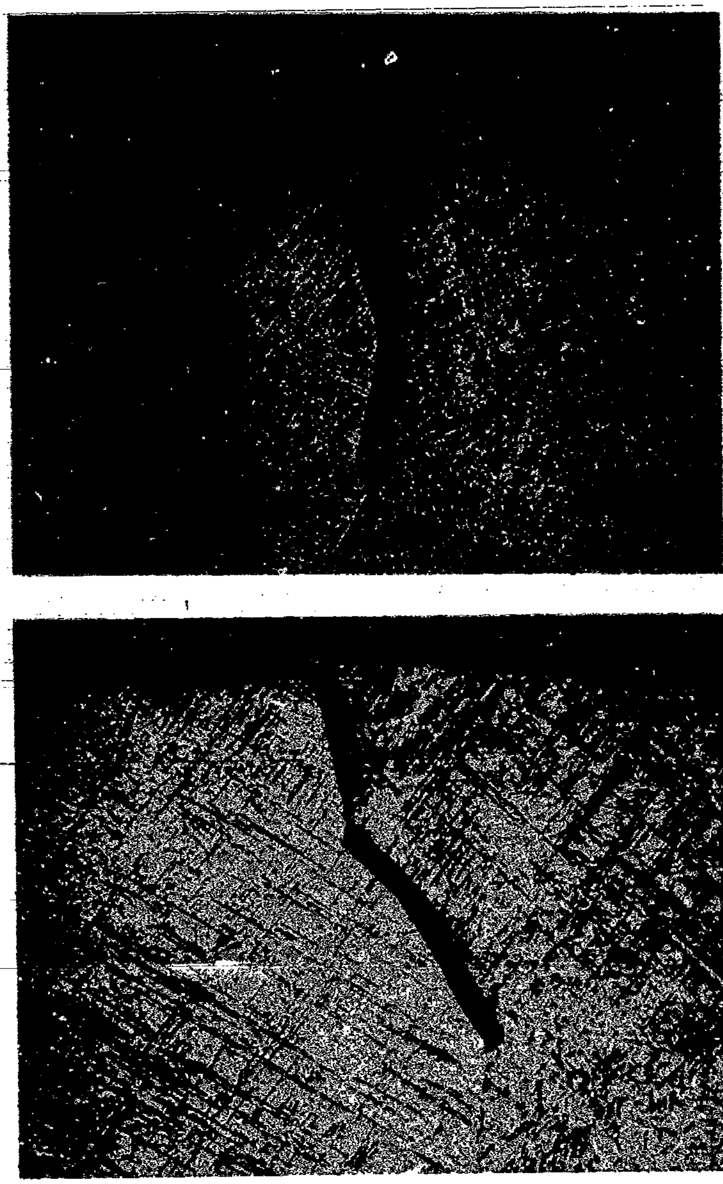


Figure IX-2. Grain Boundary Separations Found in LM Tank Welds (Magnification 250X).

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13. ABSTRACT

The objective of work reported in this volume was to evaluate the Linde PT-8 and Thermal Dynamics U-5T plasma arc welding torches for fabricating rocket motor cases and weight-critical unfired pressure vessels. Welding studies were accomplished utilizing 0.25-in.-thick 6Al-4V titanium and Inconel 718, and 0.063-in.-thick Rene 41.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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Plate thickness welding						
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