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UNIQUE VARIABLE POLARITY PLASMA ARC WELDING FOR SPACE SHUTTLE

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Materials and Processes Laboratory
Science and Engineering Directorate

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16. ABSTRACT

Since the introduction of the Plasma Arc Torch by Linde in 1955 and subsequent to the work at Boeing in the 1960's, significant improvements crucial to success have been made in the Variable Polarity Plasma Arc (VPPA) Process at the Marshall Space Flight Center. This report gives several very important advantages to this process, and it discusses the genesis of PA welding, genesis of VPPA welding, theory of VPPA welding, special equipment requirements, weld property development, results with other aluminum alloys, and the eventual successful VPPA transition to production operations.

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ABSTRACT

Since the introduction of the Plasma Arc Torch by Linde in 1955 and subsequent to the work at Boeing in the 1960's, significant improvements have been made in the Variable Polarity Plasma Arc (VPPA) process. Currently the process has several very important advantages:

1. The collimated plasma jet renders stray air currents and external magnetic field influences far less disruptive in the welding process.

2. Cathodic cleaning allows welding of most aluminum alloys without special scraping or cleaning.

3. The alternating square wave nature of the weld current produces Lorentz forces in the weld puddle and a swirling action which helps remove contaminants.

4. The "keyhole" mode of melting facilitates removal of potential contaminants, and guarantees there can be no incomplete penetration welds.

5. Weldment distortion is minimized.

6. Weld repairs due to porosity are virtually eliminated.

7. Radiographic inspection can be eliminated in many cases.

Improvements necessary to reach the current level of reliability involved computer control, weld torch redesign, modified Automatic Voltage Control (AVC), gas purification, enhanced critical diagnostics, and electromagnetic interference reduction.

A-basis allowable tensile properties development has shown that in the 2219 alloy the properties are typically better than the Gas Tungsten Arc (GTA) counterparts, and standard deviations are smaller for VPPA. No reduction in weldment fracture toughness or fatigue life has resulted.

Studies of other aluminum alloys indicate that the beneficial VPPA advantages generally accrue to these alloys as well. The only exception noted so far had to do with an apparent lack of cleanliness appearance of the as-welded 5000 series alloys, although tensile properties were not degraded.

The transition to production operations at the Michoud (New Orleans) Space Shuttle External Tank Assembly Plant has been smooth to date, with seven of 16 fixtures converted to VPPA from GTA welding. Two of three basic categories of weld torch-to-workpiece geometry have been evaluated to date.

The VPPA process has proven to be the single most significant improvement in space vehicle aluminum welding in 28 years at the Marshall Space Flight Center. Over 190,000 inches of 2219 aluminum alloy weld have been made in thicknesses up to 1 inch without a single internal defect occurring.

PROLOGUE

The special Variable Polarity Plasma Arc (VPPA) Welding Process initiated at the George C. Marshall Space Flight Center, and subsequently jointly developed with the Martin Marietta Corporation in the government facility at the Michoud (New Orleans) Facility has revolutionized the welding of the 2219 aluminum alloy from which the large Space Shuttle External Tank (ET) is manufactured. The Space Shuttle ET is the largest known "drop tank," carrying 140,000 gallons of lox and 380,000 gallons of hydrogen, with the dimensions 28.6 feet in diameter and 154 feet in length. Some appreciation for the magnitude of the welding problem and the general size of the huge tank can be seen in Picture 1. From the initiation of ET production, the conventional gas tungsten arc (GTA) welding system operating in the direct current electrode negative (CDEN) mode has been used. The initial selection of the GTA system for Shuttle ET welding was predicated largely on the level of success attained in the fabrication of the large Saturn lunar rocket first stage, the S-IC. In fabricating the S-IC stage, weld porosity and inclusions were ever-present problems throughout the entire program, and the decision to use 100% radiographic inspection was made at the outset. Weld porosity and inclusions were systematically ground out and weld repaired. The so-called "water clear" welds were a firm requirement. At the conclusion of the Saturn V program, metallurgical investigations already underway at the Marshall Space Flight Center showed conclusively that porosity reduced the weld strength in direct proportion to the reduction in cross-sectional area of the weld, so the concerns were well-founded.

Genesis of Plasma Arc (PA) Welding

In 1955 Linde Air Products introduced a PA torch for metal cutting applications, and by 1965 Linde had developed an automatic PA welding facility for the Westinghouse Electric Corporation to fabricate 120 in. diameter, 3/8 in. thick D6AC steel rocket motor cases for the Titan III-C booster assembly.[1,2] The PA welding process was reported to have halved the welding time required. Then in 1965 Thermal Dynamics Corporation reported the use of D.C. reversed polarity (workpiece negative) PA to join 1/4 in. thick aluminum plate.[3]

Genesis of Variable Polarity Plasma Arc (VPPA) Welding

At the end of the decade of the 60's, Van Cleave at the Boeing Company began his efforts to combine the PA process with a variable polarity feature wherein the electrode polarity was periodically reversed. Alternating electrode potential for aluminum welding had been investigated as early as 1947.[4] Difficulties with welding power supplies in this application were evident early-on and when VPPA welding was used in the U.S. Army Roland Missile Production Program, development problems such as arc pressure pulsations were noted.[5] As a result of Van Cleave's promising work at Boeing, a VPPA research and development project was initiated in 1978 at the George C. Marshall Space Flight Center, intended to determine the potential for replacing the GTA welding system used in the fabrication of the Space Shuttle ET. Only after certain mandatory improvements were made to the original equipment and process, has the VPPA finally exceeded the fondest expectations. So far, over 190,000 inches of VPPA weld have been made, in 2219 alloy thickness up to 1 inch without a single internal defect resulting. To our knowledge, such performance is without precedent in 2219 aluminum alloy welding, and the conversion to VPPA from the GTA process is progressing rapidly in the Space Shuttle ET production facility.

Theory of VPPA Welding

The uniqueness of the VPPA process can best be appreciated by understanding the basic elements embodied in the process. In the welding arc, the significant charge carriers are electrons and positive ions. Electrons constitute the preponderance of the charge carriers. Because of the mass factor of 1800, the positive ions are accelerated more slowly than electrons in the plasma, and they are attracted to the negative element — either welding electrode or workpiece, depending on the polarity arrangement selected. The polarity selected will determine which element receives the preponderance of the energy — workpiece or electrode. The element of positive potential receiving the electron impact will be heated considerably more than will the negative element. Consequently when maximum energy is to be delivered to the workpiece, then direct current electrode negative (DCEN) polarity is selected. Simultaneously, positive ions bombard the negative element, the welding electrode. When element polarity is reversed to direct current electrode negative (DCEP), the workpiece, now negative, then receives a positive ion bombardment which performs an excellent cathodic cleaning function. At this negative element, or cathode, hydrocarbons are dissociated and the tenacious aluminum oxides are removed as metal oxide molecules, and absorbed gases are expelled as well. These benefits all contribute to vastly improved weld puddle flow and solidification quality. But continuous reverse polarity operation is not feasible because in this mode most of the arc heat is actually delivered to the positive polarity welding electrode, which makes for inefficient energy transfer to the workpiece and has the propensity to rapidly deteriorate the welding electrode.

It has been found that the advantages of reverse polarity can be attained, and still accompanied by efficient heat transfer to the workpiece, by alternately reversing the polarity. Experience has shown that there is an optimum weighting of the time when the electrode is positive versus the time the electrode is negative. The cycle time optimized and currently in use can be readily determined from the illustration in Figure 1. The cycle is time-weighted about 19 milliseconds with the welding electrode at the negative polarity (DCEN), and 4 milliseconds with the electrode at positive polarity (DCEP). The alternating frequency is therefore about 43.5 hertz. Extensive process sensitivity analyses involving the variation of both the alternating frequency and the reverse polarity cycle time have shown conclusively that for the material and ranges of thicknesses involved in this discussion, the noted frequency and reverse polarity proportions have been optimized.

In addition to the controlled manipulation of weld current pulse width and polarity, the Argon gas flowing through the central plasma orifice is a crucial element in the VPPA system. The Argon gas velocity is quite high. So high in fact that the arc operates in the so-called "keyhole" mode; i.e., the plasma punches completely through the workpiece. This hole melted in the workpiece opens up ahead of the plasma jet in the direction of travel, and the pure molten puddle material is washed back downstream, and solidifies behind the plasma jet. Because of this "blow-thru" mode of welding, the ever-present worry of a long incompletely penetrated weld bead which passes x-ray inspection (due to the weld nugget shrinkage stress closing the crack) is no longer a concern. Acoustic levels are higher than those normally associated with the GTA process, however, running on the order of about 85 decibels and generally requiring appropriate hearing protection. This keyhole mode of operation is quite beneficial in preventing entrapment of gases in the weld bead by aiding and abetting the egress of outgas products from the backside of the workpiece. Also, gas purity is mandatory in this process. It was found necessary to flow the orifice gas through a filter containing a titanium gettering system to avoid delivery of moisture containing gas to the welding torch. Moisture in the weld gas causes disruption of the weld bead formation resulting in a roughened contour.

A schematic illustration of the VPPA welding system as compared with the conventional GTA welding system is seen in Figure 2. Although somewhat enhanced for effect, note that the VPPA arc is more collimated and that the resultant weld nugget aspect ratio is more favorable for the VPPA. This attribute provides welds with less workpiece distortion than for comparable GTA welded parts.

Advantages of the VPPA Process

Because of the unique combination of the plasma arc principle coupled with optimized alternating cathodic cleaning pulsations, the VPPA provides several advantages within a single process. The salient features are as follows:

1. The high velocity collimated Argon plasma jet generally dominates stray air currents, thereby minimizing arc-wander. Air currents impinging on the arc are frequently a problem with the conventional GTA process.

2. The solenoidal plasma pinch effect in the collimated "stiffened" Argon jet also contributes to domination over disturbing external magnetic fields — The VPPA is calculated to be only one-sixteenth as sensitive to external magnetic field disturbance as is the conventional GTA process, hence it suffers less arc wander caused by magnetic deflection.

3. The alternating DCEP causes workpiece cathodic cleaning by positive Argon ion bombardment. Hydrocarbons on the workpiece are decomposed by ion bombardment. Aluminum oxides are removed as metal oxide molecules, and absorbed gas layers are expelled as well. Generally, no special scraping or cleaning is needed for aluminum alloy welding.

4. The rapidly reversing welding current gives rise to an alternating Lorentz force in the weld puddle, producing a swirling action which further aids in the expulsion of both gaseous and solid contaminants.

5. The Argon orifice gas is converted to a constricted high velocity plasma stream which physically punches deep into the molten metal, moving the metal aside and penetrating completely through the material being welded. As noted previously, because of its appearance, it is called the "keyhole" effect. This keyhole allows ample opportunity for entrapped gases to egress the workpiece at the backside, thereby avoiding the usual weld porosity so common to GTA aluminum welding. Any lack of penetration is immediately obvious, and a weld bead made, is a-priori proof of full penetration. In essence, a weld that looks good, is always a good weld internally.

6. The plasma arc collimating effect also produces improved weld bead geometry, resulting in an improved weld bead aspect ratio, which helps to reduce weldment distortion.

The above noted advantages have all been demonstrated in an extensive development program. The combined VPPA weldments at MSFC at the MMC Michoud plant now total about 190,000 inches of 2219 alloy weld in thicknesses from 1/8 inch to 1.0 inch. Not a single rejectable internal weld defect has been reported so far. There has not, to our knowledge, been anything remotely approaching this kind of flawless performance in the welding of this alloy in the past.

Special Equipment Requirements for VPPA Welding

But in order to make the VPPA process usable for welding the large Space Shuttle External Tank, certain developments and refinements proved mandatory. These special improvements were:

1. Computer Control
2. Welding Torch Re-design
3. Modified Arc Voltage Control
4. Gas Purification
5. Enhanced Diagnostics and Control
6. Electromagnetic Interference Reduction.

It was found early in 1978 that to render the VPPA process practical for ET production use, computer control similar to that already employed in the GTA process would be required. Because the wall thickness of the ET pressure vessel varies (e.g., the liquid oxygen tank nose section varies in thickness at the weld joints from 0.140 to 0.367 in. and the liquid hydrogen tank varies in thickness from 0.140 to 1.00 in.) tapered longitudinal and circumferential welds are frequently encountered. A computer to control welding parameters is required, because tapered welds require too high a level of skill and attention to be practical as manual welds in a production environment. By 1980, computer control was accomplished. The computer sets weld parameters in accordance with set point inputs by the welding engineer, and it can vary the parameters to produce tapered welds. A recent modification of the system, closing the control loop on the weld parameters, permits the system to continuously force measured parameters to coincide with desired set points. This has decreased the sensitivity of the system to variations in calibration.(6) The entire VPPA system, including the manipulator and weld wire feed, as well as the torch control and power supply, is now computer controlled, and digital displays are used throughout the system. Experience to date with this system has been good. The system has functioned according to design and has been convenient to use. There is virtually no limit to the size of the weld program library which can be recorded. Figure 3 shows a block diagram of the entire computerized VPPA welding system.

Problems with the existing VPPA weld torch were evident early-on. Coolant leaks into the gas passages were systemic. Electrode alignment problems were severe, and "double-arcing" frequently occurred, wherein the arc proceeded from electrode to nozzle and thence to the workpiece. Orifice geometry was extremely difficult to control, so performance characteristics were highly variable. All these difficulties prompted a torch redesign effort which has been very successful. Torch problems have subsequently paled into insignificance.

Although arc voltage control (AVC) is not a new welding concept, implementing the idea took on new significance with the VPPA process. The interference caused by the reverse polarity portion of the current cycle caused considerable difficulty in maintaining constant arc voltage. A suitable electrical filter system was eventually added and the problem was eliminated.

Welding gas purity problems also plagued the early VPPA efforts at MSFC. Gas purity is essential in achieving quality welds in any shielded arc process. Although the best solution to a contaminated gas supply usually is to change out the supply, there is a definite advantage to being able to accommodate transient periods of minor gas contamination. This strategem will frequently allow the successful completion of very long weld seams of the type common to the 28.5 ft. diameter Space Shuttle ET. Water vapor contamination, in particular, causes excess hydrogen in the weld. At a level of about 0.1 cm^3 of hydrogen per 100 grams of metal, serious porosity can result in a GTA weld bead. It has been shown (3) that the critical concentration of water vapor in the Argon plasma gas can be estimated by the relationship:

$$C_{crit} \quad \frac{5AV}{\dot{Q}}$$

where: C_{crit} is the water contamination level, A is the aluminum weld cross sectional area, V is weld speed and $\dot{Q}$ is the Argon weld gas flow rate. And for helium shield gas the relationship is as follows:

$$C_{crit} \quad \frac{50\ AV}{\dot{Q}}$$

The solution to the transient gas contamination roughened weld bead problem finally proved to be the installation of titanium gettering furnace/filters between the Argon and helium gas supplies, and the VPPA welding torch. The furnace/filters pass the gases over titanium at 800°C thereby effectively gettering the impurities.

The obvious deficiencies in VPPA weld variable diagnostics in the mid-70's constituted the single largest impediment to quality welding with the VPPA. Weld bead reliability and repeatability were only marginal at best. Plasma arc current and voltage and pilot current and voltage were analog measurements. These were converted to digital measurements. The travel speed measurement and control was converted to solid state motor control using the microprocessor. The plasma arc gas and the shield gas were converted from simple needle valve setting controls to precise measuring and control systems. These changes all proved to be mandatory to the attainment of an acceptable level of quality and reliability.

The final area of difficulty in the successful development of a continuous duty, reliable VPPA welding system had to do with electromagnetic interference (EMI). The magnitude, frequency, and wave shape of the alternating current wave virtually assured electromagnetic induction of appreciable consequence. The current pulse wave front and decay closely resemble a square wave configuration, and the resultant rate of change of magnetic flux is disconcertingly effective in generating EMI in any electrically conducting material in proximity. Electrical noise was initially evident in the intercom system and in the computer video monitor, counting errors showed up in the weld length encoder, and documenting video equipment was not usable in the area due to EMI. EMI was either eliminated or reduced to tolerable levels by separating power and signal leads, using twisted pairs in the power cables, providing noise by-pass capacitors in the encoder, and physically increasing the distance between power and control cabinets. These are all relatively straight forward solutions, but they are frequently overlooked.

Weld Property Development

Whereas the statistical pedigree of aerospace design properties in the past had usually been of the "B" basis allowables type, the decision to shift the entire ET production facility to the VPPA welding mode was predicated primarily on being able to attain weld properties meeting the specifications at an "A" basis allowables assurance level. The allowable design values thus developed, guarantee that the critical weld properties will attain at least the "A" basis allowable value 99% of the time, at a 95% confidence level. Figure 4 illustrates how the ultimate strength of 3/8 inch thick 2219-T87 weldments varies according to the welding process used. Note also that the VPPA gives somewhat improved properties with slightly smaller standard deviations. The difference in standard deviation between as-welded versus shaved has to do with notch effects in the as-welded specimens. The difference in strength between as-welded and shaved welds is largely due to weld bead cross-sectional area differences.

Figure 5 captioned "VPPA welded 2219-T87 baseline tensile strength" shows how VPPA welded ultimate tensile strength of 2219-T87 alloy varies with material thickness, test temperature and number of weld passes. It is probable that the sharp increase in strength precisely at the change to 2-pass welding is related to total heat input effects on the weldment.

In discussing the beneficial effects of VPPA on weldment distortion, it is useful to describe the semantics used to categorize weldment distortion. Figure 6 shows the two common types of deficiencies incurred in GTA welding. Mismatch is generally a manifestation of improper fitup, while peaking is less a result of fitup per se, than it is of weld geometry, heat input to the weld, and the material thickness involved. Both types of deficiency were investigated in considerable detail with the VPPA welding process. Figure 7 shows how mismatch and peaking affect the strength of a VPPA welded 3/8 in. thick tensile specimen of 2219-T87 alloy. In general, this process has been shown to produce significantly less distortion than the alternative GTA welding process currently in use.

Table I shows a comparison of 2219-T87 VPPA weld allowables compared with current GTA requirements, for a range of material thicknesses from 1/8 to 1.0 in.

Although it is not a primary design material property, fracture toughness is used to provide a rational basis for establishing weld inspection requirements, and also to make the important safety-related assessments regarding leak-before-burst behavior on the ET. Figure 8 shows typical VPPA fracture toughness data plotted with comparable GTA data, with the inspection requirement shown for reference. It is seen that, despite the increased energy input inherent in the VPPA process, the fracture mechanics-related performance has not been compromised.

Results With Other Aluminum Alloys

Results with 2219-T87 alloy have been excellent, and a very large body of statistical data has been developed. The alloys 6061-T6, 5456-H32 and 2014-T3 have also been welded using the VPPA process. These results are also quite encouraging. Table II shows some recent work done on these three common aerospace alloys, and while these data are quite encouraging, with no internal defects evident, they by no means constitute the kind of cardinal "A" basis allowable data developed for the 2219 alloy. Interestingly, the 5000 series alloy, the 5456, had a rather dirty appearance as-welded.

VPPA Transition to Production Operations

In July/August 1982 the VPPA system was demonstrated on the 5015 vertical barrel assembly welding fixture at the Michoud Assembly Plant in which panels comprising a 15 ft. long barrel section of the External Tank were joined. The basic weld thickness is 0.320 in. with tapers to 0.0650 in. Two and three passes were used to join tapered seams.

All the weld strengths developed on the 5015 fixture were comparable to those of corresponding GTA welds made on the same fixture.

During this period, the welding engineers and welders from the Michoud Assembly Facility were trained in the theory and use of VPPA welding equipment in the welding research laboratory at the Marshall Space Flight Center. The main emphasis in the training program which covered theory, equipment, and program (A-allowables), was "hands-on" operation of the equipment. Welder trainees were asked to diagnose deliberately set equipment maladjustments and to restore correct operation. Length of training varied from one to four weeks, depending on the release time permitted by the trainees' work schedules. Additional problem solving time for welding engineers was, and is, arranged when necessary in the context of general operations. Picture 2 shows the full-scale horizontal weld fixture used at the George C. Marshall Space Flight Center to develop the necessary VPPA improvements, and to do much of the training noted above.

The transition to production effort is now in the pathfinder phase of development. "Pathfinders" are subassemblies produced on a production fixture to demonstrate the acceptability of a major tool, hardware or process change. Pathfinders normally become flight articles if, after inspection and associated witness panel testing, it can be demonstrated that all engineering requirements for the article have been met. In the External Tank VPPA weld demonstration project, the major welding tools have been divided into three categories based on the attitude of the welding torch, and the relative motion between the torch and part. A VPPA-welding demonstration pathfinder will be cycled through one tool in each category with the results accepted as applicable to all other tools in the same group. The categories consist of:

I. A fixed part with horizontal torch attitude and vertical torch movement.

II. A fixed part with torch moving from horizontal position to vertical (down hand) position.

III. A part rotating about its horizontal axis with a fixed horizontal torch.

There is a total of sixteen weld fixtures to be converted to VPPA at the Michoud Assembly Plant. Four fixtures in category I have already been converted and three fixtures in category II have been converted. Because of the excellent record to date with regard to internal defects, it is highly probable that 100% radiographic inspection will no longer be required to assure the quality of the External Tanks.

SUMMARY

Since the introduction of the Plasma Arc Torch by Linde in 1955 and subsequent to the work at Boeing in the 1960's, significant improvements have been made in the Variable Polarity Plasma Arc (VPPA) process. Currently the process has several very important advantages:

1. The collimated plasma jet renders stray air currents and external magnetic field influences far less disruptive in the welding process.

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The author wishes to acknowledge the following contributions to this paper, and in the development of the variable polarity plasma arc process: The Martin Marietta Corporation, Michoud Plant, The Hobart Co., Inc., and of course the salient leadership and direction of all participating MSFC personnel, but particularly the Metals Processes Branch of the Process Engineering Division.

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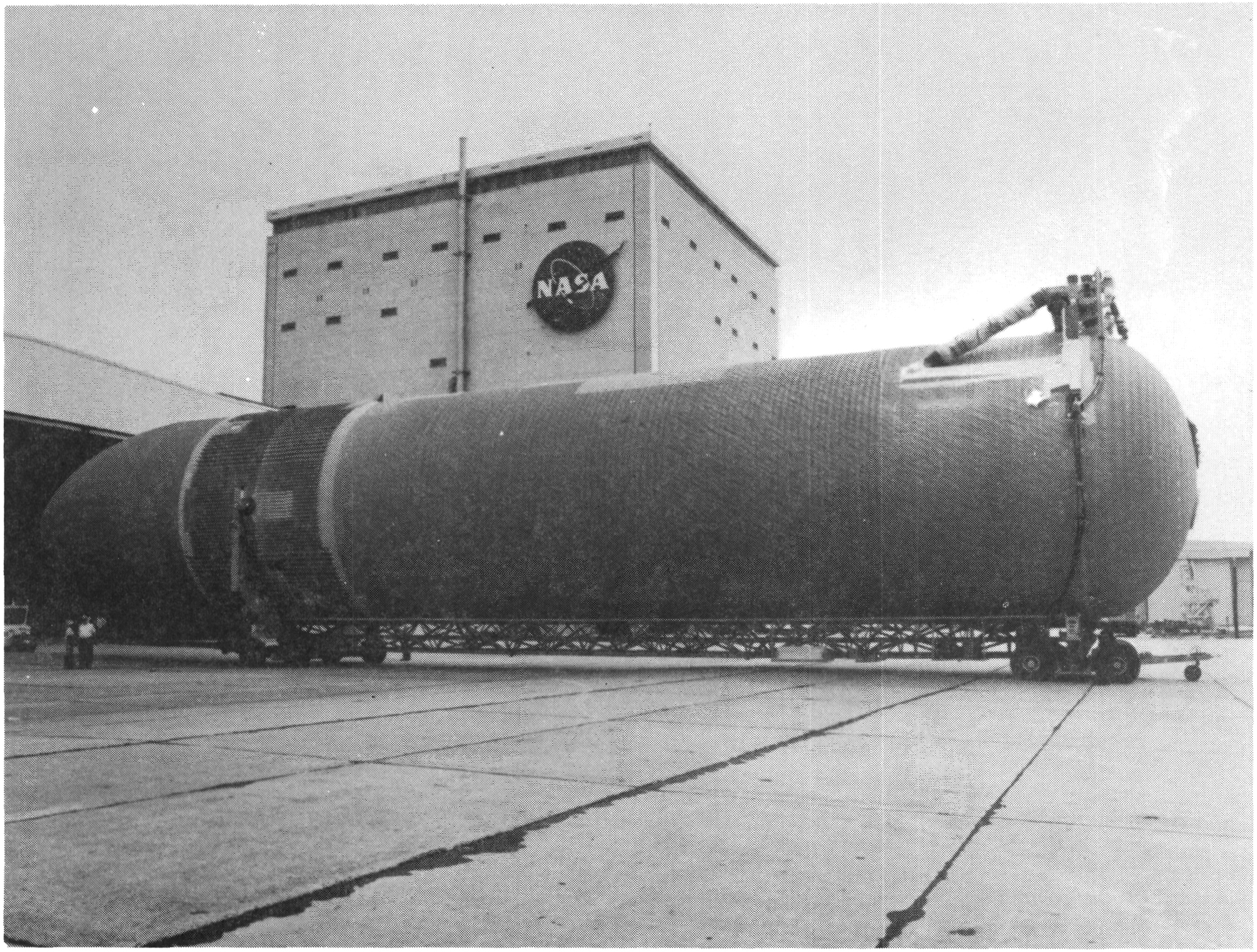
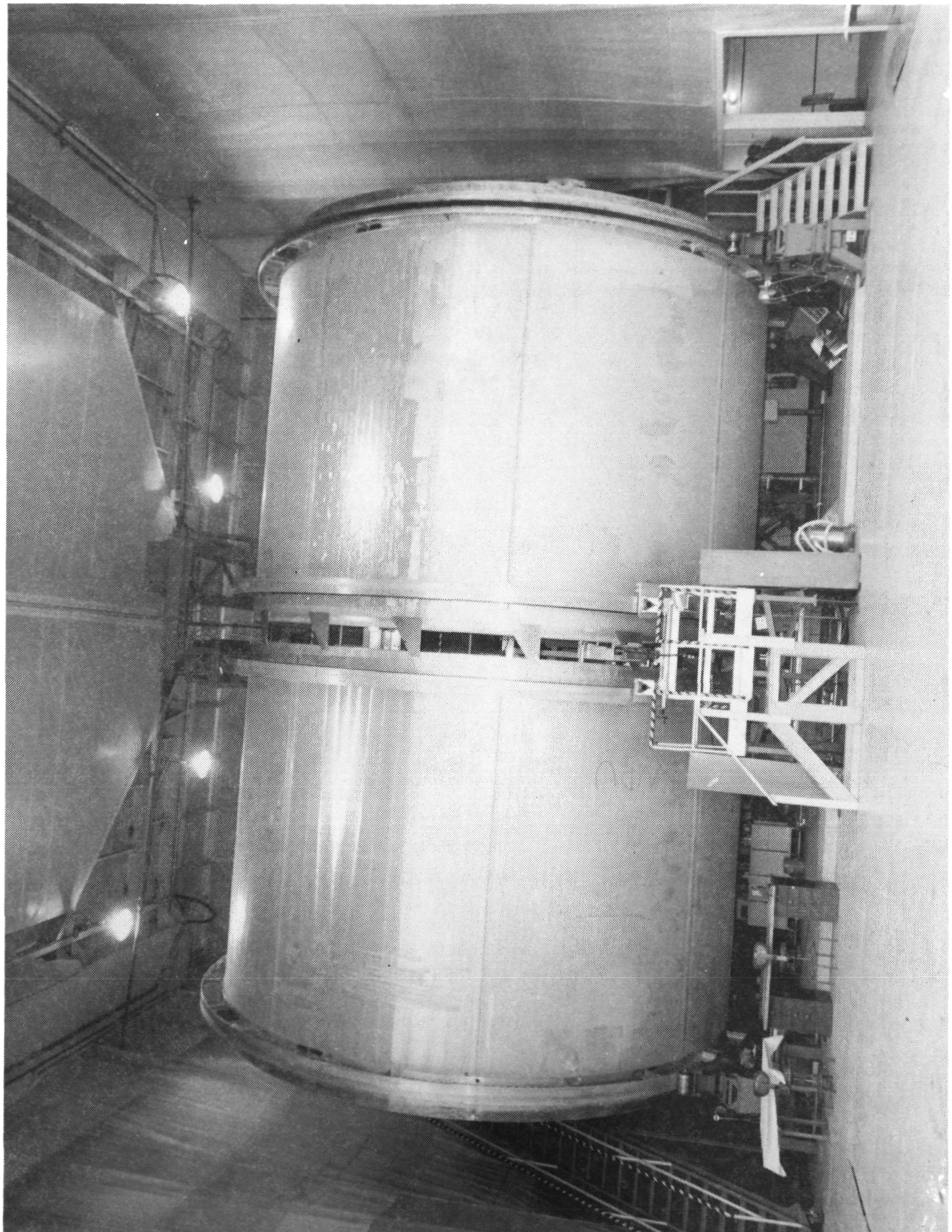


Picture 1. Space Shuttle External Tank.



Picture 2. Full scale horizontal VPPA weld fixture.

TABLE I. 2219-T87 VPPA WELD ALLOWABLES

THICKNESS	AVERAGE	A-BASIS	CURRENT GTA CERT. REQ'T.	
			AVERAGE	MINIMUM
.125	45.4	41.5	42	40
.250	40	38.5	40	38
.375	41.7	39.7	40	38
.500	40.3	38.8	40	38
.650	40.6	37.9	39	36
.800	38.9	36.8	38	35
1.00	39.1	35.4	38	35

TABLE II. OTHER ALUMINUM ALLOYS VPPA WELDED

ALLOY BASE METAL	THICKNESS INCHES	FILLER ALLOY	NO. TENSILE SPECIMENS	VPPA WELDED UTS (PSI)			MSFC-SPEC-504 MIN. AV. REQ'M (PSI)
				AV.	HIGH	LOW	
6061-T6	3/8	4043	45	29,663	29,967	29,279	27,000
5456-H32	3/8	5356	30	47,965	49,947	45,596	44,000
2014-T3	1/2	4043	45	42,365	44,756	39,289	40,500

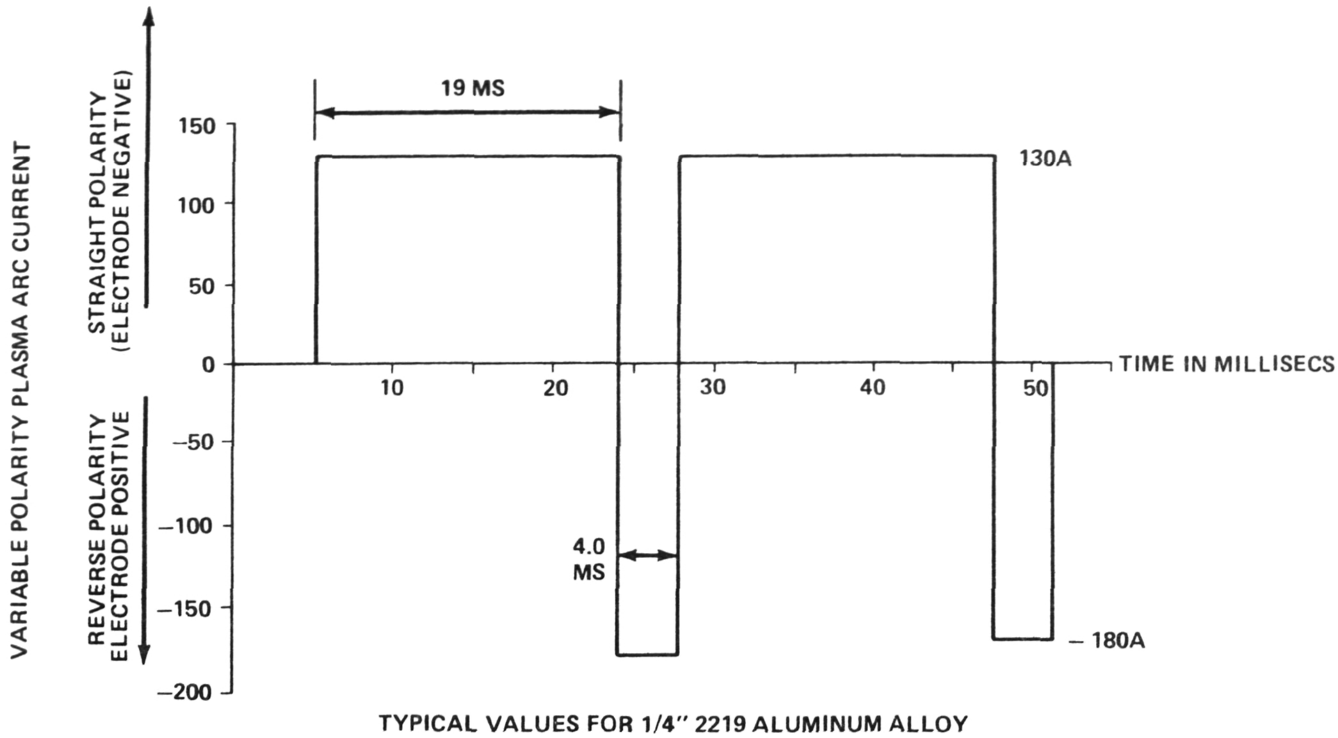


Figure 1. VPPA current, polarity and pulse width.

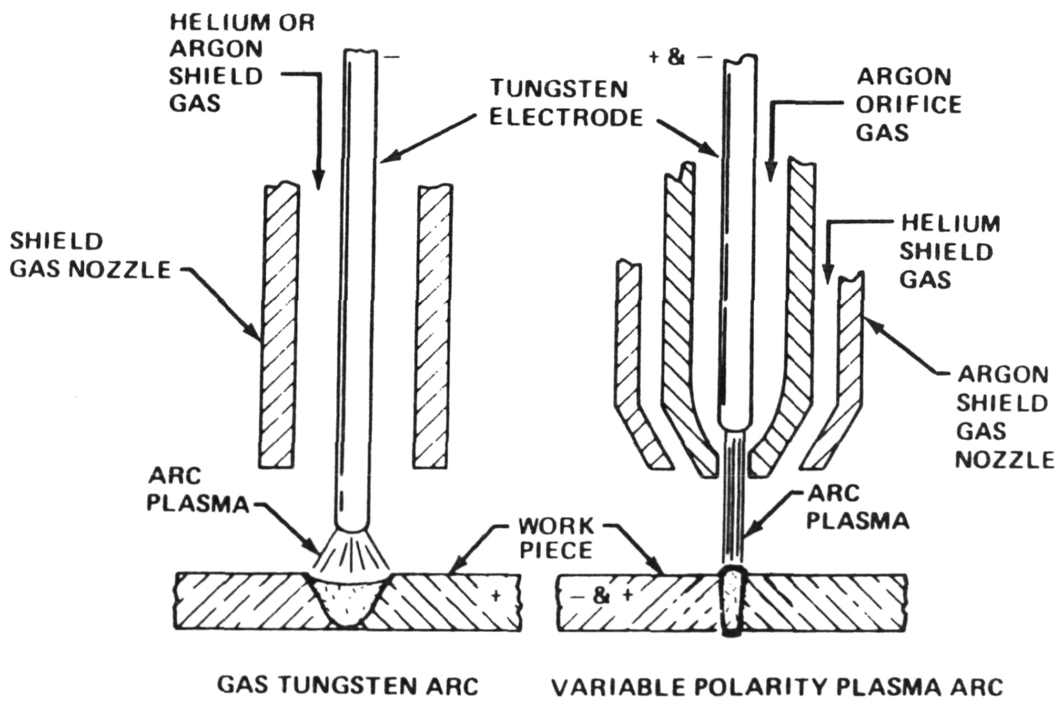


Figure 2. Comparison of GTA and VPPA welding processes.

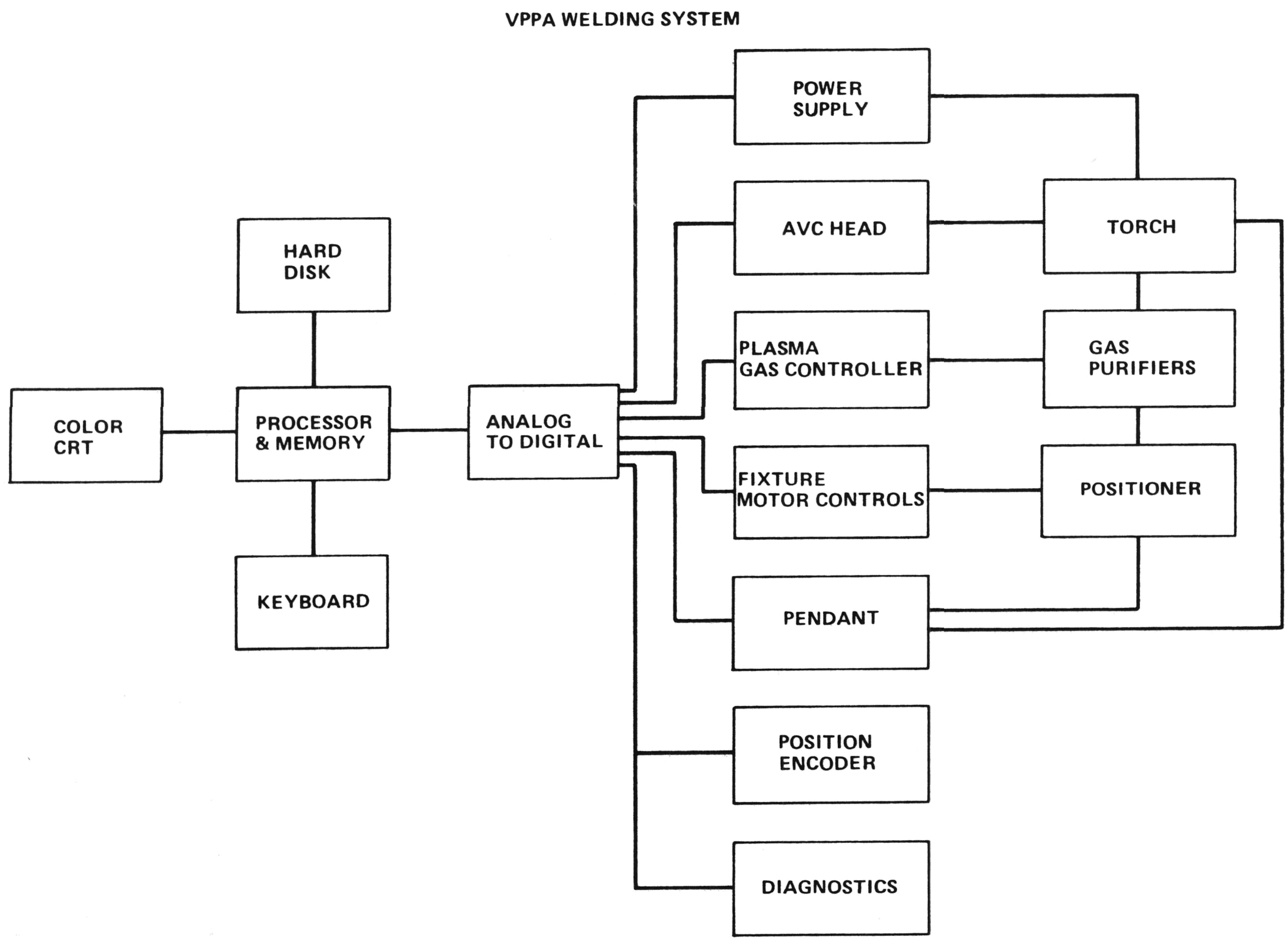


Figure 3. Variable polarity plasma arc welding controls.

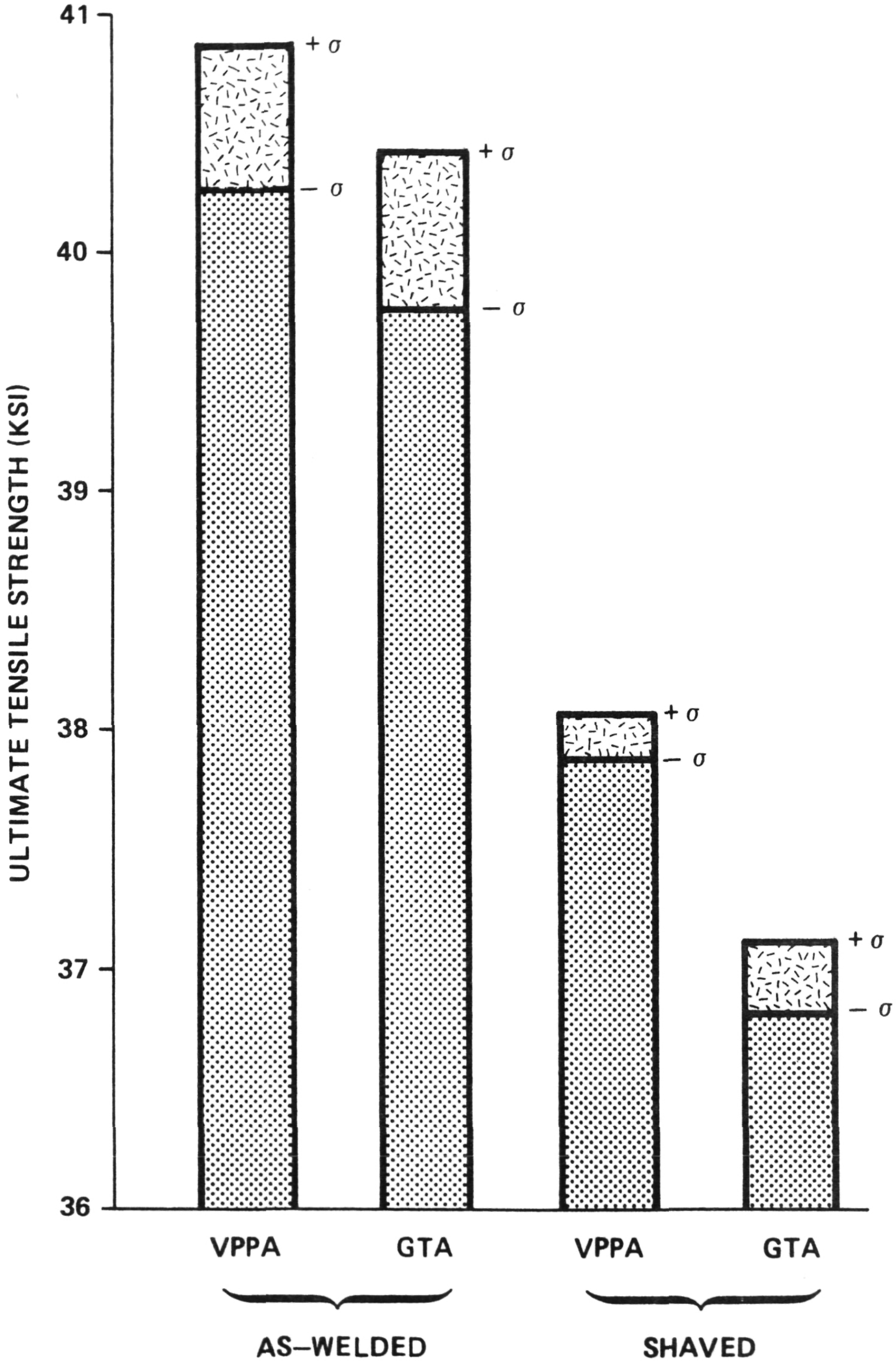


Figure 4. Ultimate tensile strengths of VPPA/GTA comparison welds (σ = standard deviation) for 3/8 in. 2219-T87 alloy.

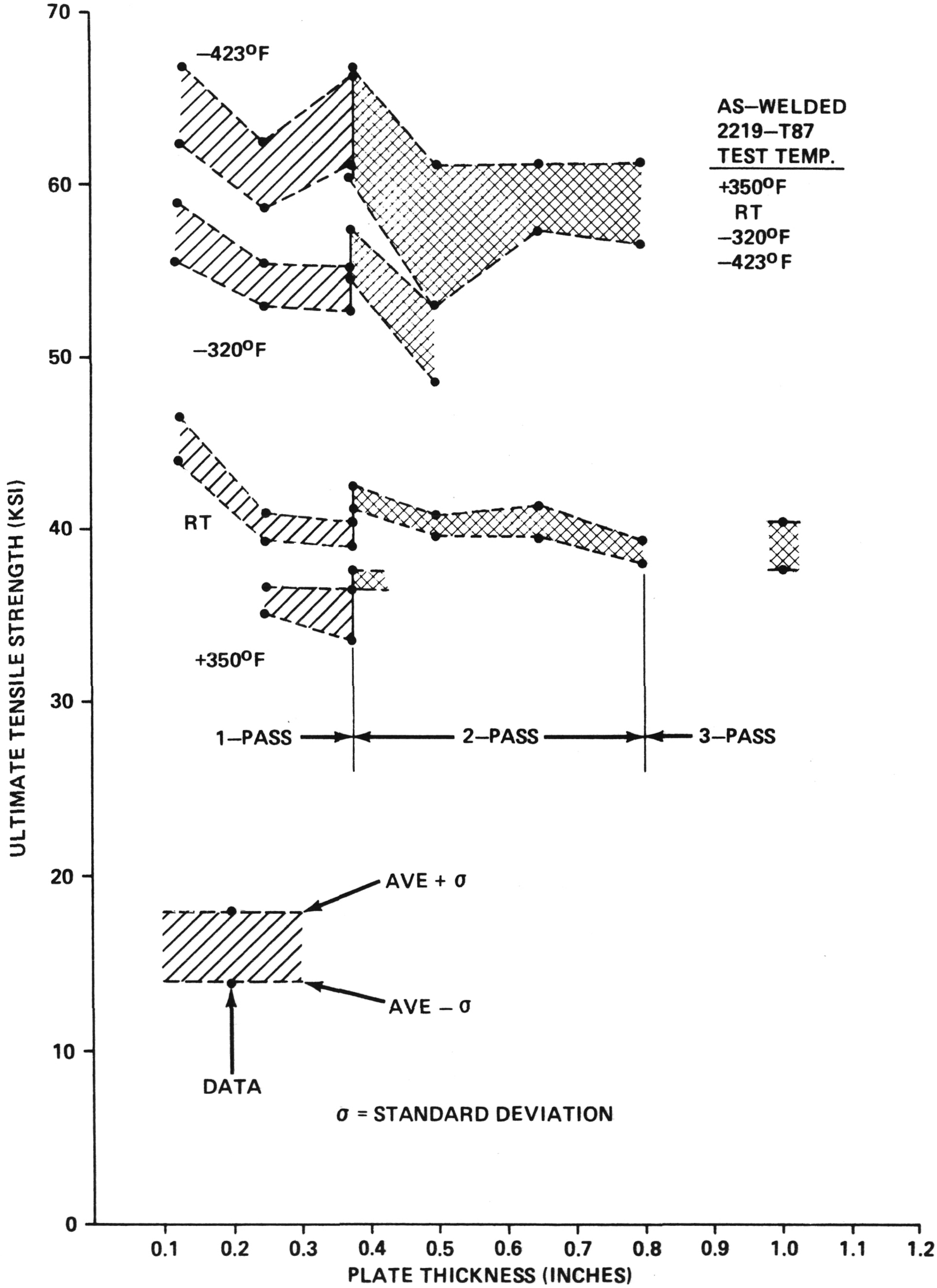


Figure 5. VPPA welded 2219–T87 baseline tensile strength.

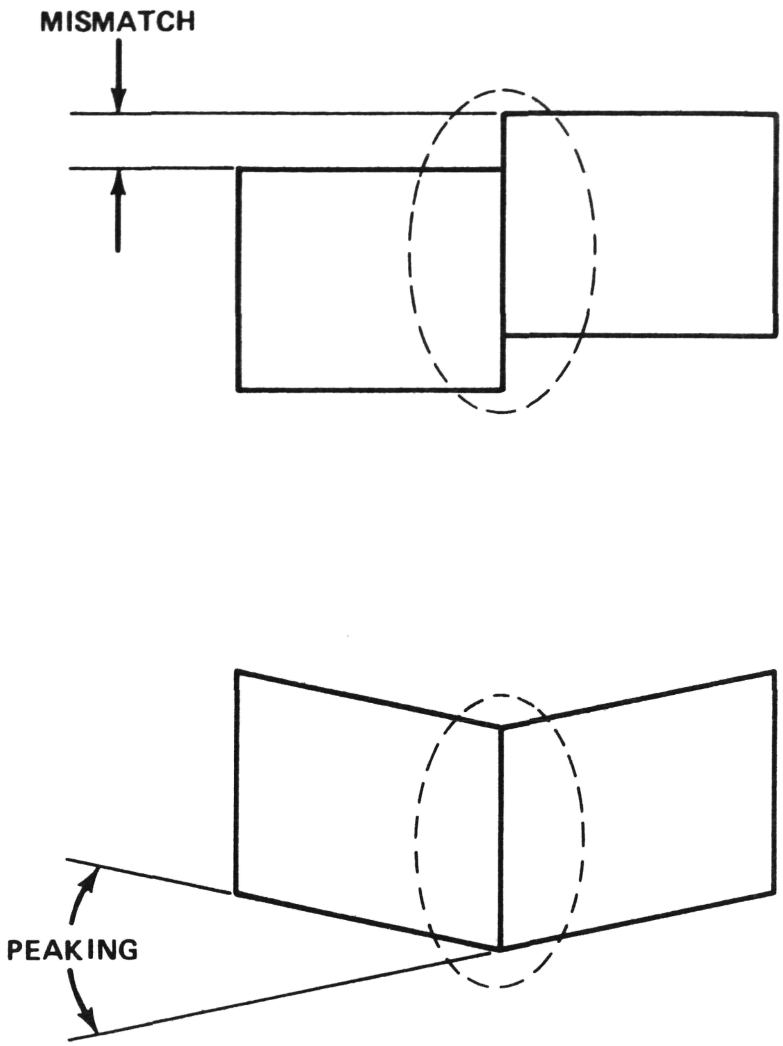


Figure 6. Weldment mismatch and peaking.

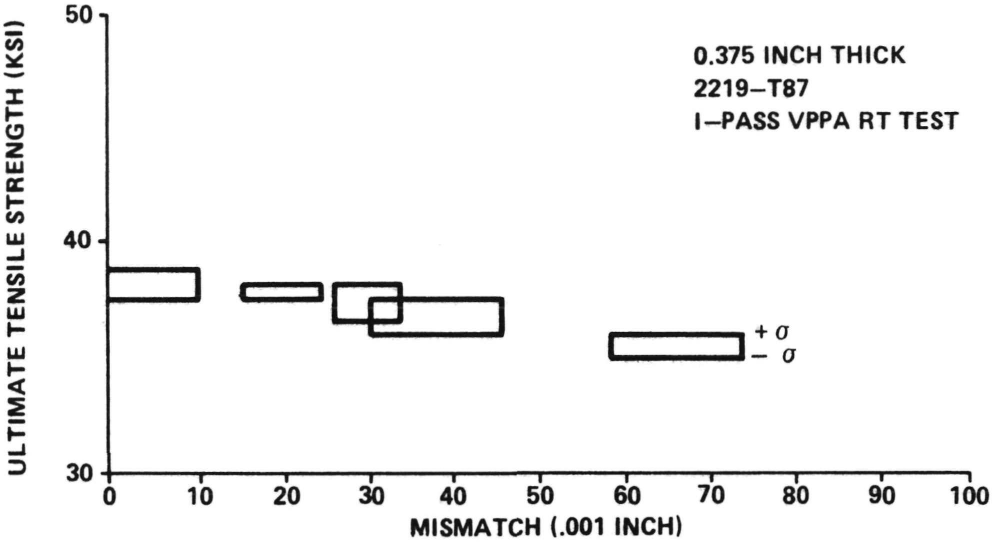


Figure 7a. Weldment mismatch influence on tensile specimen strength.

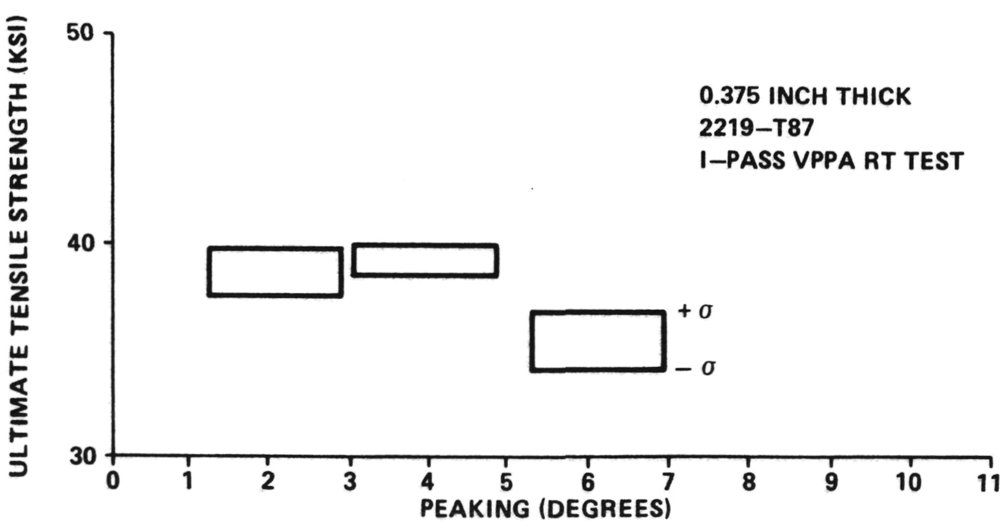


Figure 7b. Weldment peaking influence on tensile specimen strength.

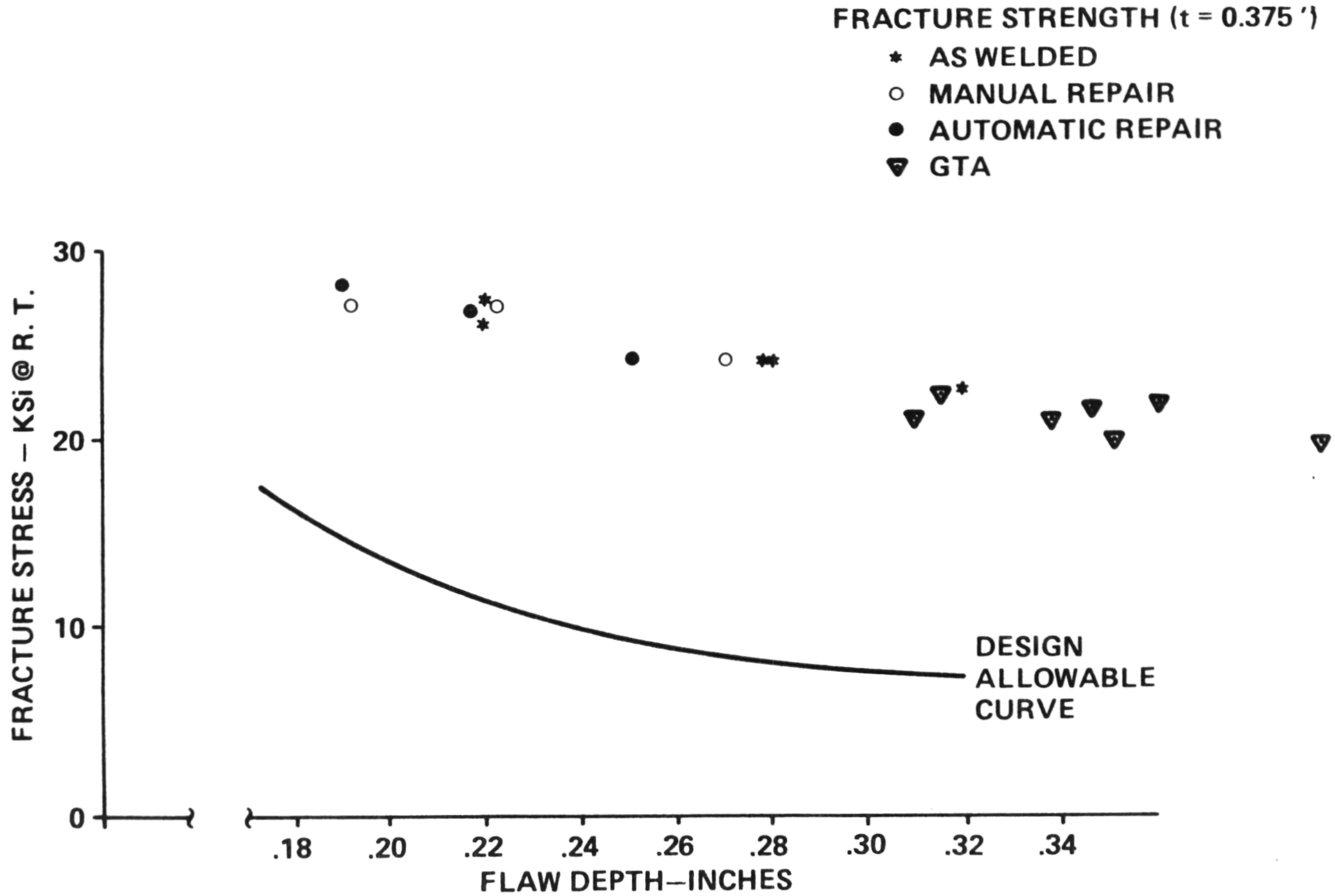


Figure 8. 2219 welds - fracture strength versus flaw depth.

APPROVAL

UNIQUE VARIABLE POLARITY PLASMA ARC WELDING FOR SPACE SHUTTLE

By R. J. Schwinghamer

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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