VPPA Weld Model Evaluation

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LIST OF ACRONYMS AND ABBREVIATIONS

ARI	Applied Research Incorporated
ASOC	Automatic Stand-Off Control
AVC	Automatic Voltage Control
Hz	Hertz (cycles/second)
ipm	Inches Per Minute
LVDT	Linear Variable Differential Transformer
mm	Millimeter
ms	Millisecond
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NRC	Nichols Research Corporation
Pc	Power Delivered to the Weld Crown
Pd	Power Delivered
Pg	Power Generated
Pr	Power Delivered to the Weld Root
RMS	Root Mean Square
SCFH	Standard Cubic Feet per Hour
Ta	Ambient Temperature
Tm	Melting Temperature
UAH	University of Alabama at Huntsville
UTS	Ultimate Tensile Strength
VPPA	Variable Polarity Plasma Arc
VPPAW	Variable Polarity Plasma Arc Welding
vs	Versus

SECTION 1. EXECUTIVE SUMMARY

NASA uses the Variable Polarity Plasma Arc Welding (VPPAW) process extensively for fabrication of Space Shuttle External Tanks. This welding process has been in use at NASA since the late 1970's (ref. 1), but the physics of the process have never been satisfactorily modeled and understood. In an attempt to advance the level of understanding of VPPAW, Dr. Arthur C. Nunes, Jr., (NASA) has developed a mathematical model of the process. The work described in this report evaluated and used two versions (level-0 and level-1) of Dr. Nunes' model, and a model derived by the University of Alabama at Huntsville (UAH) from Dr. Nunes' level-1 model.

Two series of VPPAW experiments were done, using over 400 different combinations of welding parameters. Observations were made of VPPAW process behavior as a function of specific welding parameter changes. Data from these weld experiments was used to evaluate and suggest improvements to Dr. Nunes' model.

Experimental data and correlations with the model were used to develop a multi-variable control algorithm for use with a future VPPAW controller. This algorithm is designed to control weld widths (both on the crown and root of the weld) based upon the weld parameters, base metal properties, and real-time observation of the crown width. The algorithm exhibited accuracy comparable to that of the weld width measurements for both aluminum and mild steel welds.

SECTION 2. INTRODUCTION

2.1 PURPOSE

Nichols Research Corporation (NRC) submits this final report as partial fulfillment of NASA contract #NAS8-38812.

The purpose of this work was:

(1) To evaluate empirically a mathematical model developed by Dr. Arthur C. Nunes, Jr., of NASA. This model predicts Variable Polarity Plasma Arc (VPPA) weld crown widths, crown heights, root widths, and root heights as functions of weld parameters and base metal properties.

(2) To develop a multi-variable control algorithm based upon the model and the experimental results.

This work relates to prior work (ref. 2) involving predictions of Ultimate Tensile Strength (UTS) of welds based on weld geometry. These two projects provide a basis for the development of an engineering work station in which desired VPPA weld UTS is input and the work station outputs weld parameters designed to achieved that desired strength.

The objectives of this project are to:

(1) Increase understanding of the VPPAW process and power supply characteristics.

(2) Verify or improve assumptions both in physics (fluid flow, heat transfer, arc physics) and material properties used in the model.

(3) Provide the theoretical foundation for an engineering work station in which desired weld geometry is input, and weld parameters are output.

(4) Enable weld 'experiments' to be simulated by computer rather than having to make the welds.

(5) Compare model outputs to experimental results and investigate causes of discrepancies to improve the model or the experimental procedures.

(6) Characterize weld geometry sensitivity to specific parameter changes, both intentional (weld schedules) and unintentional (noise/disturbances), to provide insight into how best to change parameters to modify weld geometry.

(7) Develop a prototype multi-variable control algorithm that can be used in real-time with an automated weld system. The system will maintain desired weld geometry (crown width and root width) provided it is input the following: weld crown width (from a weld contour sensor), material properties, and actual weld parameters (which may vary significantly from the input weld schedule).

(8) Publication of the model and results to disseminate the knowledge gained.

2.2 BACKGROUND

The model has three forms. Two were derived by Dr. Nunes at NASA, and the third was derived from Dr. Nunes' model by Dr. Ru Hung and his associates at the University of Alabama at Huntsville (UAH). Each form is described briefly below, and in more detail in Section 5 of this report.

The first form of the model (designated the level-0 model) is the simplest, and will be incorporated into a real-time controller. The general form is derived from a steady state solution to the linear (constant thermal properties) heat diffusion equation:

$$\text{width} = (C1 / \text{Travel Speed}) * e^{(C2 / \text{Power Delivered})}$$

where the constant terms (C1, C2) are derived from material properties.

The second form of the model (designated the level-1 model) is more mathematically intensive than the level-0 model. Specifically, the enthalpy along the plasma column is integrated for regions within the orifice, stand-off and keyhole. This provides a more detailed analysis of energy transfer and considers such factors as plasma flow rate. Width is then predicted using the level-0 equation.

The third form of the model (designated the UAH model) attempts to model the process very accurately and requires significant computation. This is a more detailed version of the level-1 model. Most of the work on this model has been conducted by UAH. Their final report (ref. 3) describes this work (through June 1992) in detail. Further improvements to the UAH model are expected.

2.3 METHODOLOGY

Two sets of weld experiments were completed. In the first set of experiments, VPPA bead-on-plate welds were made on 0.25" (6.35 mm) 2219-T87 aluminum, 0.25" (6.35 mm) A36 mild steel, and 0.25" (6.35 mm) and 0.188" (4.78 mm) 304 stainless steel. Torch stand-offs were manually set using a dial indicator attached to the torch such that the tip rode on the surface of the plate being welded. The weld head was locked, i.e., Automatic Voltage Control (AVC) disabled. Strip chart recordings were made of forward and reverse weld current, forward and reverse weld voltage, shield gas flow rate, plasma gas flow rate, and back purge pressure. Photographs were taken of oscilloscope traces of the pilot arc current and voltage during welding. Measurements from the strip charts, photographs, and the welds themselves were tabulated and used as inputs to the model. Comparisons were then made between model calculation predictions and experimental results.

There were two problems with the first set of experiments. The first problem was a lack of instrumentation for stand-off. Stand-off proved (in the first set of experiments) to be critical, with slight variations causing large differences in weld geometry. During the first set of experiments, variations in weld arc voltage of 0.5 volts occurred in supposedly identical welds. It is suspected that this was the result of stand-off variations of 0.01" (0.25 mm) (based on 2 volts/mm assumed voltage drop in the plasma column). It is believed that this was a major cause of weld repeatability problems, since the VPPA welding process is sensitive to stand-off, as discussed in Section 4.2.3. Sometimes this 0.01" (0.25 mm) stand-off variation was enough to transition a weld from welding to cutting, with higher stand-offs always causing cutting.

The second problem was malfunctions of the strip chart recorder, which occurred often and required many welds to be repeated. Manual readings of values from the strip chart were difficult, time consuming, and subject to error.

To improve stand-off measurement in the second set of experiments, NRC fabricated a linear variable differential transformer (LVDT) based stand-off sensor. This sensor attached to the torch such that a rolling metal wheel rode on the surface of the plate. This provided measurements of stand-off over the length of the weld. This worked so well that part way through the second set of experiments the weld station was modified to provide closed loop control of stand-off based on the output from this sensor, changing Automatic Voltage Control (AVC) to Automatic Stand-Off Control (ASOC). This switch from AVC to ASOC reduced the need for manual intervention during welding. The number of welds that had to be repeated due to AVC-related welding problems was greatly reduced.

To improve data acquisition during the second set of experiments, a NASA computerized data acquisition system with an NRC power isolation board and custom NRC software took data for weld arc current, weld arc voltage, pilot arc current, pilot arc voltage, shield gas flow rate, plasma gas flow rate, torch stand-off, and travel speed. The sampling rate for each channel was 2500 Hz. Shield gas flow rate, plasma gas flow rate, torch stand-off, and travel speed data was reduced to provide a sampling rate of 10 Hz. This data was stored on floppy disks. For these welds the data over the final ten seconds of stable weld times (or four to ten seconds during stable weld times for welds in which parameters varied during the weld) was averaged to provide accurate measurements of weld parameters. These measurements were then tabulated. The models were run using data from these tables, and model predictions were compared to experimental results. Results from these comparisons were used to develop and evaluate a multi-variable (simultaneously controlling forward weld current and travel speed) control algorithm based on the level-0 model.

SECTION 3. EXPERIMENTS

3.1 EQUIPMENT

All welding was done at weld station #2 (NASA/MSFC building 4711). This weld station consists of the following equipment:

Hobart/GDI VPPAW controller (NASA property #732629)

Hobart Cyber-Tig II weld power supply (NASA property #733257)

Hobart shield gas controller (NASA property #289414)

Hobart plasma arc power supply and plasma gas controller (NASA property #732630)

Hobart 300A Hot Block (NASA property #732628)

Progressive Welder & Machine Company Manipulator (NASA property #546761)

The following equipment was added to the weld station for these experiments:

Shield Gas Flowmeter: Brooks mass flowmeter, serial #89044C033649/1

Plasma Gas Flowmeter: Brooks mass flowmeter, serial #840644048

Back Purge Pressure Sensor: Sensotec, serial #292008

Gould 2400S 4-channel strip chart recorder (NASA property #731531)

Tektronix 7623A oscilloscope (NASA property #545470)

PC-based (386 WIN, serial #AT09031207) 8-channel data acquisition system using a Metrobyte-16 data acquisition board, NRC custom written software, and an NRC power isolation board (a similar board was made and delivered to NASA under this contract).

An LVDT-based NRC custom made stand-off sensor, with the LVDT output amplified to 5-30 volts to drive a Cyclomatic AVC unit.

3.2 WELD MATRICES

Tables 1 and 2 list the weld matrices used for both the first and second sets of experiments, respectively.

Table 1. Weld Matrix For First Set Of Experiments

Base Material	Thickness (inches/mm)	Weld Set	Weld ID	Torch Stand-Off (mm)	Welding Current (amps)	Shield Gas Flowrate (scfh)	Plasma Gas Flowrate (scfh)	Travel Speed (ipm)	Weld Position
Aluminum	0.25/6.35	F	F201001	1	130	100	6	8	Vertical Up
			F201002	2	130	100	6	8	Vertical Up
			F201004	4	130	100	6	8	Vertical Up
			F201006	6	130	100	6	8	Vertical Up
			F201008	8	130	100	6	8	Vertical Up
Aluminum	0.25/6.35	G	G211042A	2	130	40	6	8	Vertical Up
			G201062A	2	130	60	6	8	Vertical Up
			G201062B	2	130	100	6	8	Vertical Up
			G202064A	4	130	60	6	8	Vertical Up
			G202064B	4	130	100	6	8	Vertical Up
			G203068A	8	130	60	6	8	Vertical Up
			G203068B	8	130	100	6	8	Vertical Up
			G204122A	2	130	120	6	8	Vertical Up
			G204122B	2	130	140	6	8	Vertical Up
			G205124A	4	130	120	6	8	Vertical Up
			G205124B	4	130	140	6	8	Vertical Up
			G206128A	8	130	120	6	8	Vertical Up
			G206128B	8	130	140	6	8	Vertical Up
			G208182A	2	130	180	6	8	Vertical Up
			G208182B	2	130	200	6	8	Vertical Up
			G209184A	4	130	180	6	8	Vertical Up
			G209184B	4	130	200	6	8	Vertical Up
			G210188A	8	130	180	6	8	Vertical Up
			G210188B	8	130	200	6	8	Vertical Up
Aluminum	0.25/6.35	H	H201022A	2	130	100	2	8	Vertical Up
			H201022B	2	130	100	4	8	Vertical Up
			H202024A	4	130	100	2	8	Vertical Up
			H202024B	4	130	100	4	8	Vertical Up
			H203028A	8	130	100	2	8	Vertical Up
			H203028B	8	130	100	4	8	Vertical Up
			H204082A	2	130	100	8	8	Vertical Up
			H204082B	2	130	100	10	8	Vertical Up
			H205084A	4	130	100	8	8	Vertical Up
			H205084B	4	130	100	10	8	Vertical Up
			H206088A	8	130	100	8	8	Vertical Up
			H206088B	8	130	100	10	8	Vertical Up
Aluminum	0.25/6.35	I	I202092A	2	110	100	6	8	Vertical Up
			I202092B	2	90	100	6	8	Vertical Up
			I203094A	4	90	100	6	8	Vertical Up
			I203094B	4	110	100	6	8	Vertical Up
			I208098A	8	90	100	6	8	Vertical Up
			I208098B	8	110	100	6	8	Vertical Up
			I205152A	2	150	100	6	8	Vertical Up
			I205152B	2	180	100	6	8	Vertical Up
			I206154A	4	150	100	6	8	Vertical Up
			I206154B	4	180	100	6	8	Vertical Up
			I207158A	8	150	100	6	8	Vertical Up
			I207158B	8	180	100	6	8	Vertical Up

Table 1. Weld Matrix For First Set Of Experiments (Continued)

Base Material	Thickness (inches/mm)	Weld Set	Weld ID	Torch Stand-Off (mm)	Welding Current (amps)	Shield Gas Flowrate (scfh)	Plasma Gas Flowrate (scfh)	Travel Speed (ipm)	Weld Position
Aluminum	0.25/6.35	J	J201052A	2	130	100	6	5	Vertical Up
			J201052B	2	130	100	6	10	Vertical Up
			J202054A	4	130	100	6	5	Vertical Up
			J202054B	4	130	100	6	10	Vertical Up
			J203058A	8	130	100	6	5	Vertical Up
			J203058B	8	130	100	6	10	Vertical Up
			J207132A	2	130	100	6	13	Vertical Up
			J207132B	2	130	100	6	16	Vertical Up
			J205134A	4	130	100	6	13	Vertical Up
			J205134B	4	130	100	6	16	Vertical Up
			J206138A	8	130	100	6	13	Vertical Up
			J206138B	8	130	100	6	16	Vertical Up
Aluminum	0.25/6.35	K	K201002A	2	130	80	6.5	12.5	Downhand
			K201002B	2	130	80	6.5	16.0	Downhand
			K202004A	4	130	80	6.5	12.5	Downhand
			K202004B	4	130	80	6.5	16.0	Downhand
			K203006A	6	130	80	6.5	12.5	Downhand
			K203006B	6	130	80	6.5	16.0	Downhand
			K204008A	8	130	80	6.5	12.5	Downhand
			K204008B	8	130	80	6.5	16.0	Downhand
			K205010A	10	130	80	6.5	12.5	Downhand
			K205010B	10	130	80	6.5	16.0	Downhand
Aluminum	0.25/6.35	Orthogonal Array	0101	2	114	140	4.50	6.0	Vertical Up
			0102	2	127	140	5.75	7.3	Vertical Up
			0103	2	140	140	7.00	8.6	Vertical Up
			0104	4	114	140	4.50	7.3	Vertical Up
			0105	4	127	140	5.75	8.6	Vertical Up
			0106	4	140	140	7.00	6.0	Vertical Up
			0107-2	6	114	140	5.75	6.0	Vertical Up
			0108	6	127	140	7.00	7.3	Vertical Up
			0109	6	140	140	4.50	8.6	Vertical Up
			0110-2	2	114	200	7.00	8.6	Vertical Up
			0111-2	2	127	200	4.50	6.0	Vertical Up
			0112	2	140	200	5.75	7.3	Vertical Up
			0113-2	4	114	200	5.75	8.6	Vertical Up
			0114-2	4	127	200	7.00	6.0	Vertical Up
			0115	4	140	200	4.50	7.3	Vertical Up
			0116	6	114	200	7.00	7.3	Vertical Up
			0117-3	6	127	200	4.50	8.6	Vertical Up
			0118	6	140	200	5.75	6.0	Vertical Up
			0119-A	4	140	140	4.50	7.3	Vertical Up
			0123	6	140	140	7.00	6.0	Vertical Up
			0126	2	114	200	4.50	8.6	Vertical Up
Mild Steel	0.25/6.35	F	F203044A	4	155	50	4	3.7	Vertical Up
			F203044B	2	155	50	4	3.7	Vertical Up
			F204066A	6	155	50	4	3.7	Vertical Up
			F204066B	8	155	50	4	3.7	Vertical Up
			F204066C	10	155	50	4	3.7	Vertical Up

Table 1. Weld Matrix For First Set Of Experiments (Continued)

Base Material	Thickness (inches/mm)	Weld Set	Weld ID	Torch Stand-Off (mm)	Welding Current (amps)	Shield Gas Flowrate (scfh)	Plasma Gas Flowrate (scfh)	Travel Speed (ipm)	Weld Position
Mild Steel	0.25/6.35	G	G201502A	2	155	50	4	3.7	Vertical Up
			G201502B	2	155	40	4	3.7	Vertical Up
			G201502C	2	155	20	4	3.7	Vertical Up
			G202602A	2	155	60	4	3.7	Vertical Up
			G202602B	2	155	80	4	3.7	Vertical Up
			G202602C	2	155	100	4	3.7	Vertical Up
			G203504A	4	155	50	4	3.7	Vertical Up
			G203504B	4	155	40	4	3.7	Vertical Up
			G203504C	4	155	20	4	3.7	Vertical Up
			G204604A	4	155	60	4	3.7	Vertical Up
			G204604B	4	155	80	4	3.7	Vertical Up
			G204604C	4	155	100	4	3.7	Vertical Up
			G205508A	8	155	50	4	3.7	Vertical Up
			G205508B	8	155	40	4	3.7	Vertical Up
			G205508C	8	155	20	4	3.7	Vertical Up
			G206608A	8	155	60	4	3.7	Vertical Up
			G206608B	8	155	80	4	3.7	Vertical Up
			G206608C	8	155	100	4	3.7	Vertical Up
Mild Steel	0.25/6.35	H	H204022B	2	155	50	8	3.7	Vertical Up
			H204022C	2	155	50	10	3.7	Vertical Up
			H205024A	4	155	50	2	3.7	Vertical Up
			H205024B	4	155	50	8	3.7	Vertical Up
			H205024C	4	155	50	10	3.7	Vertical Up
			H206028A	8	155	50	2	3.7	Vertical Up
			H206028B	8	155	50	8	3.7	Vertical Up
			H206028C	8	155	50	10	3.7	Vertical Up
Mild Steel	0.25/6.35	I	I201134A	4	135	50	4	3.7	Vertical Up
			I201134B	4	110	50	4	3.7	Vertical Up
			I202132A	2	135	50	4	3.7	Vertical Up
			I202132B	2	110	50	4	3.7	Vertical Up
			I203138A	8	135	50	4	3.7	Vertical Up
			I203138B	8	110	50	4	3.7	Vertical Up
			I204174A	4	175	50	4	3.7	Vertical Up
			I204174B	4	200	50	4	3.7	Vertical Up
			I204172A	2	175	50	4	3.7	Vertical Up
			I204172B	2	200	50	4	3.7	Vertical Up
			I204178A	8	175	50	4	3.7	Vertical Up
			I204178B	8	200	50	4	3.7	Vertical Up
Mild Steel	0.25/6.35	J	J201034A	4	155	50	4	3	Vertical Up
			J201034B	4	155	50	4	2	Vertical Up
			J202032A	2	155	50	4	3	Vertical Up
			J202032B	2	155	50	4	2	Vertical Up
			J203038A	8	155	50	4	3	Vertical Up
			J203038B	8	155	50	4	2	Vertical Up
			J204064A	4	155	50	4	6	Vertical Up
			J204064B	4	155	50	4	8	Vertical Up
			J205062A	2	155	50	4	6	Vertical Up
			J205062B	2	155	50	4	8	Vertical Up
			J206068A	8	155	50	4	6	Vertical Up
			J206068B	8	155	50	4	8	Vertical Up

Table 1. Weld Matrix For First Set Of Experiments (Concluded)

Base Material	Thickness (inches/mm)	Weld Set	Weld ID	Torch Stand-Off (mm)	Welding Current (amps)	Shield Gas Flowrate (scfh)	Plasma Gas Flowrate (scfh)	Travel Speed (ipm)	Weld Position
Mild Steel	0.25/6.35	K	K203022A	2	155	50	4	3.7	Downhand
			K203022B	4	155	50	4	3.7	Downhand
			K204066A	6	155	50	4	3.7	Downhand
			K204066B	8	155	50	4	3.7	Downhand
Stainless Steel	0.25/6.35	F	F201044A	2	135	50	5.8	3.7	Vertical Up
			F201044B	4	135	50	5.8	3.7	Vertical Up
			F203066A	6	135	50	5.8	3.7	Vertical Up
			F203066B	8	135	50	5.8	3.7	Vertical Up
Stainless Steel	0.25/6.35	H	H201044A	4	135	50	4	3.7	Vertical Up
			H201044B	4	135	50	8	3.7	Vertical Up
			H201044C	4	135	50	10	3.7	Vertical Up
			H202046A	6	135	50	4	3.7	Vertical Up
			H202046B	6	135	50	8	3.7	Vertical Up
			H202046C	6	135	50	10	3.7	Vertical Up
Stainless Steel	0.25/6.35	I	I201114A	4	110	50	5.8	3.7	Vertical Up
			I201114B	4	150	50	5.8	3.7	Vertical Up
			I201114C	4	180	50	5.8	3.7	Vertical Up
			I202114A	6	110	50	5.8	3.7	Vertical Up
			I202114B	2	150	50	5.8	3.7	Vertical Up
			I202114C	2	180	50	5.8	3.7	Vertical Up
Stainless Steel	0.25/6.35	J	J201024A	4	135	50	5.8	2	Vertical Up
			J201024B	4	135	50	5.8	6	Vertical Up
			J201024C	4	135	50	5.8	8	Vertical Up
			J202026A	6	135	50	5.8	2	Vertical Up
			J202026B	6	135	50	5.8	6	Vertical Up
			J202026C	6	135	50	5.8	8	Vertical Up
Stainless Steel	0.25/6.35	K	K203022A	2	135	50	5.8	3.7	Downhand
			K203022B	4	135	50	5.8	3.7	Downhand
			K202066A	6	135	50	5.8	3.7	Downhand
			K202066B	8	135	50	5.8	3.7	Downhand
Stainless Steel	0.188/4.76	F	F201044A	4	135	50	4	6.1	Vertical Up
			F201044B	2	135	50	4	6.1	Vertical Up
			F202066A	6	135	50	4	6.1	Vertical Up
			F202066B	8	135	50	4	6.1	Vertical Up
Stainless Steel	0.188/4.76	H	H201044A	4	135	50	4	6.1	Vertical Up
			H201044B	4	135	50	8	6.1	Vertical Up
			H201044C	4	135	50	10	6.1	Vertical Up
Stainless Steel	0.188/4.76	I	I201114A	4	110	50	4	6.1	Vertical Up
			I201114B	4	150	50	4	6.1	Vertical Up
			I201114C	4	180	50	4	6.1	Vertical Up
Stainless Steel	0.188/4.76	J	J201064A	4	135	50	4	6	Vertical Up
			J201064B	4	135	50	4	8	Vertical Up
			J201064C	4	135	50	4	2	Vertical Up

Table 2. Weld Matrix For Second Set Of Experiments

Base Material	Thickness (inches/mm)	Weld Set	Weld ID	Stand-Off (mm)	Welding Current (amps)	Shield Gas Flowrate (scfh)	Plasma Gas Flowrate (scfh)	Travel Speed (ipm)	Weld Position	Misc.
Aluminum	0.25/6.35	1	1C	4	165	75	4	11	Vertical Up	In Bag
			1D	4	165	75	4	11	Vertical Up	In Atmosphere
Aluminum	0.25/6.35	2	2A	4	130	80	5.0	10.0	Vertical Up	
			2B	4	130	80	5.0	9.0	Vertical Up	
			2C	4	130	80	5.0	11.0	Vertical Up	
			2D	4	130	80	5.0	12.0	Vertical Up	
			2E	4	130	80	5.0	12.0	Vertical Up	
			2F	4	130	80	5.0	10.0	Vertical Up	
			2G	4	130	80	5.0	9.0	Vertical Up	
			2H	4	130	80	5.0	11.0	Vertical Up	
			2I	4	130	80	5.0	11.0	Vertical Up	
			2J	4	130	80	5.0	10.0	Vertical Up	
			2K	4	130	80	5.0	12.0	Vertical Up	
			2L	4	130	80	5.0	9.0	Vertical Up	
Aluminum	0.50/12.7	2	2M	4	260	80	7.5	8.0	Vertical Up	
			2N	4	260	80	7.5	6.5	Vertical Up	
			2O	4	260	80	7.5	9.5	Vertical Up	
			2P	4	260	80	7.5	11.0	Vertical Up	
			2Q	4	260	80	7.5	11.0	Vertical Up	
			2R	4	260	80	7.5	8.0	Vertical Up	
			2S	4	260	80	7.5	6.5	Vertical Up	
			2T	4	260	80	7.5	9.5	Vertical Up	
			2U	4	260	80	7.5	9.5	Vertical Up	
			2V	4	260	80	7.5	8.0	Vertical Up	
			2W	4	260	80	7.5	11.0	Vertical Up	
			2X	4	260	80	7.5	6.5	Vertical Up	
Aluminum	0.50/12.7	3	3A	4	260	80	7.5	8	Vertical Up	
			3B	4	260	80	6	8	Vertical Up	
			3C	4	260	80	9	8	Vertical Up	
			3D	4	260	80	4.5	8	Vertical Up	
			3E	4	260	80	4.5	8	Vertical Up	
			3F	4	260	80	7.5	8	Vertical Up	
			3G	4	260	80	6	8	Vertical Up	
			3H	4	260	80	9	8	Vertical Up	
			3I	4	260	80	9	8	Vertical Up	
			3J	4	260	80	7.5	8	Vertical Up	
			3K	4	260	80	4.5	8	Vertical Up	
			3L	4	260	80	6	8	Vertical Up	
Aluminum	0.25/6.35	3	3M	4	130	80	5	10	Vertical Up	
			3N	4	130	80	4	10	Vertical Up	
			3O	4	130	80	6	10	Vertical Up	
			3P	4	130	80	3	10	Vertical Up	
			3Q	4	130	80	3	10	Vertical Up	
			3R	4	130	80	5	10	Vertical Up	
			3S	4	130	80	4	10	Vertical Up	
			3T	4	130	80	6	10	Vertical Up	
			3U	4	130	80	6	10	Vertical Up	
			3V	4	130	80	5	10	Vertical Up	
			3W	4	130	80	3	10	Vertical Up	
			3X	4	130	80	4	10	Vertical Up	

Table 2. Weld Matrix For Second Set Of Experiments (Continued)

Base Material	Thickness (inches/mm)	Weld Set	Weld ID	Stand-Off (mm)	Welding Current (amps)	Shield Gas Flowrate (scfh)	Plasma Gas Flowrate (scfh)	Travel Speed (ipm)	Weld Position	Misc.
Aluminum	0.25/6.35	4	4A	4	130	80	5	10	Vertical Up	Wire Feed 40 ipm
			4B	4	130	80	5	10	Vertical Up	Wire Feed 20 ipm
			4C	4	130	80	5	10	Vertical Up	Wire Feed 60 ipm
Aluminum	0.25/6.35	5	5A	4	130	80	5	10	Vertical Up	Electrode and
			5B	4	130	80	5	10	Vertical Up	Orifice
			5C	4	130	80	5	10	Vertical Up	Parameters
			5D	4	130	80	5	10	Vertical Up	Varied for
			5E	4	130	80	5	10	Vertical Up	These Welds.
			5F	4	130	80	5	10	Vertical Up	See Experiment
			5G	4	130	80	5	10	Vertical Up	#4 Data Table
			5H	4	130	80	5	10	Vertical Up	For Specifics
Aluminum	0.25/6.35	6	6A	4	130	80	5	10	Vertical Up	
			6B	4	130	80	5	10	Vertical Up	
			6C	4	130	80	5	10	Vertical Up	
			6D	4	115	80	5	10	Vertical Up	
			6E	4	115	80	5	10	Vertical Up	
			6F	4	115	80	5	10	Vertical Up	
			6G	4	145	80	5	10	Vertical Up	
			6H	4	145	80	5	10	Vertical Up	
			6I	4	145	80	5	10	Vertical Up	
Aluminum	0.25/6.35	7	7A	4	120/140/160	80	5.00	9.5	Vertical Up	Waveform: 19-4
			7B	4	120/140/160	80	5.00	9.5	Vertical Up	Waveform: 16-8
			7C	4	120/140/160	80	5.00	9.5	Vertical Up	Waveform: 12-12
			7D	4	120/140/160	80	5.00	9.5	Vertical Up	Waveform: 8-16
			7E	4	120/140/160	80	5.00	30.0	Vertical Up	Waveform: 19-4
			7F	4	120/140/160	80	5.00	30.0	Vertical Up	Waveform: 16-8
			7G	4	120/140/160	80	5.00	30.0	Vertical Up	Waveform: 12-12
			7H	4	120/140/160	80	5.00	30.0	Vertical Up	Waveform: 8-16
Mild Steel	0.25/6.35	7	7I	4	120/140/160	80	5.00	5.0	Vertical Up	Waveform: 19-4
			7J	4	120/140/160	80	5.00	5.0	Vertical Up	Waveform: 16-8
			7K	4	120/140/160	80	5.00	5.0	Vertical Up	Waveform: 12-12
			7L	4	120/140/160	80	5.00	5.0	Vertical Up	Waveform: 8-16
			7M	4	120/140/160	80	5.00	15.0	Vertical Up	Waveform: 19-4
			7N	4	120/140/160	80	5.00	15.0	Vertical Up	Waveform: 16-8
			7O	4	120/140/160	80	5.00	15.0	Vertical Up	Waveform: 12-12
			7P	4	120/140/160	80	5.00	15.0	Vertical Up	Waveform: 8-16
Aluminum	0.25/6.35	8	8A	4.0	120	80	2	9	Vertical Up	Wire Feed 30 ipm
			8B	4.0	120	50	2	9	Vertical Up	Wire Feed 30 ipm
			8C	4.0	120	110	2	9	Vertical Up	Wire Feed 30 ipm
			8D	4.0	120	80	2	9	Vertical Up	Wire Feed 20 ipm
			8E	4.0	120	80	2	9	Vertical Up	Wire Feed 40 ipm
			8F	4.0	90	80	2	9	Vertical Up	Wire Feed 30 ipm
			8G	4.0	140	80	2	9	Vertical Up	Wire Feed 30 ipm
Mild Steel	0.25/6.35	8	8H	4.5	125	50	2	5	Vertical Up	Wire Feed 10 ipm
			8I	4.5	125	35	2	5	Vertical Up	Wire Feed 10 ipm
			8J	4.5	125	65	2	5	Vertical Up	Wire Feed 10 ipm
			8K	4.5	125	50	2	5	Vertical Up	Wire Feed 7.5 ipm
			8L	4.5	125	50	2	5	Vertical Up	Wire Feed 12 ipm
			8M	4.5	110	50	2	5	Vertical Up	Wire Feed 10 ipm
			8N	4.5	140	50	2	5	Vertical Up	Wire Feed 10 ipm

Table 2. Weld Matrix For Second Set Of Experiments (Continued)

Base Material	Thickness (inches/mm)	Weld Set	Weld ID	Stand-Off (mm)	Welding Current (amps)	Shield Gas Flowrate (scfh)	Plasma Gas Flowrate (scfh)	Travel Speed (ipm)	Weld Position	Misc.
Aluminum	0.25/6.35	9	9A	4.0	130.0	80	5	10.0	Vertical Up	No Filler Wire
			9B	4.0	115.0	80	5	10.5	Vertical Up	No Filler Wire
			9C	4.0	120.0	80	2	9.0	Vertical Up	Wire Feed 30 ipm
			9D	4.0	105.0	80	2	9.5	Vertical Up	Wire Feed 30 ipm
			9E	4.0	145.0	80	5	9.5	Vertical Up	No Filler Wire
			9F	4.0	130.0	80	5	10.0	Vertical Up	No Filler Wire
			9G	4.0	135.0	80	2	8.5	Vertical Up	Wire Feed 30 ipm
			9H	4.0	120.0	80	2	9.0	Vertical Up	Wire Feed 30 ipm
			9I	4.0	145.0	80	5	9.5	Vertical Up	No Filler Wire
			9J	4.0	115.0	80	5	10.5	Vertical Up	No Filler Wire
			9K	4.0	135.0	80	2	8.5	Vertical Up	Wire Feed 30 ipm
			9L	4.0	105.0	80	2	9.5	Vertical Up	Wire Feed 30 ipm
			9M	4.0	115.0	80	5	10.5	Vertical Up	No Filler Wire
			9N	4.0	130.0	80	5	10.0	Vertical Up	No Filler Wire
			9O	4.0	105.0	80	2	9.5	Vertical Up	Wire Feed 30 ipm
			9P	4.0	120.0	80	2	9.0	Vertical Up	Wire Feed 30 ipm
			9Q	4.0	130.0	80	5	10.0	Vertical Up	No Filler Wire
			9R	4.0	145.0	80	5	9.5	Vertical Up	No Filler Wire
			9S	4.0	120.0	80	2	9.0	Vertical Up	Wire Feed 30 ipm
			9T	4.0	135.0	80	2	8.5	Vertical Up	Wire Feed 30 ipm
			9U	4.0	115.0	80	5	10.5	Vertical Up	No Filler Wire
			9V	4.0	145.0	80	5	9.5	Vertical Up	No Filler Wire
			9W	4.0	105.0	80	2	9.5	Vertical Up	Wire Feed 30 ipm
			9X	4.0	135.0	80	2	8.5	Vertical Up	Wire Feed 30 ipm
Mild Steel	0.25/6.35	9	9AA	4.5	150.0	50	4	4.0	Vertical Up	No Filler Wire
			9AB	4.5	142.5	50	4	4.2	Vertical Up	No Filler Wire
			9AC	4.5	125.0	50	2	5.0	Vertical Up	Wire Feed 10 ipm
			9AD	4.5	118.5	50	2	5.3	Vertical Up	Wire Feed 10 ipm
			9AE	4.5	158.0	50	4	3.7	Vertical Up	No Filler Wire
			9AF	4.5	150.0	50	4	4.0	Vertical Up	No Filler Wire
			9AG	4.5	132.0	50	2	4.7	Vertical Up	Wire Feed 10 ipm
			9AH	4.5	125.0	50	2	5.0	Vertical Up	Wire Feed 10 ipm
			9AI	4.5	158.0	50	4	3.7	Vertical Up	No Filler Wire
			9AJ	4.5	142.0	50	4	4.2	Vertical Up	No Filler Wire
			9AK	4.5	135.0	50	2	4.7	Vertical Up	Wire Feed 10 ipm
			9AL	4.5	118.0	50	2	5.3	Vertical Up	Wire Feed 10 ipm
			9AM	4.5	142.0	50	4	4.2	Vertical Up	No Filler Wire
			9AN	4.5	150.0	50	4	4.0	Vertical Up	No Filler Wire
			9AO	4.5	118.0	50	2	5.3	Vertical Up	Wire Feed 10 ipm
			9AP	4.5	125.0	50	2	5.0	Vertical Up	Wire Feed 10 ipm
			9AQ	4.5	150.0	50	4	4.0	Vertical Up	No Filler Wire
			9AR	4.5	158.0	50	4	3.7	Vertical Up	No Filler Wire
			9AS	4.5	125.0	50	2	5.0	Vertical Up	Wire Feed 10 ipm
			9AT	4.5	135.0	50	2	4.7	Vertical Up	Wire Feed 10 ipm
			9AU	4.5	142.0	50	4	4.2	Vertical Up	No Filler Wire
			9AV	4.5	158.0	50	4	3.7	Vertical Up	No Filler Wire
			9AW	4.5	118.0	50	2	5.3	Vertical Up	Wire Feed 10 ipm
			9AX	4.5	135.0	50	2	4.7	Vertical Up	Wire Feed 10 ipm

Table 2. Weld Matrix For Second Set Of Experiments (Concluded)

Base Material	Thickness (inches/mm)	Weld Set	Weld ID	Stand-Off (mm)	Welding Current (amps)	Shield Gas Flowrate (scfh)	Plasma Gas Flowrate (scfh)	Travel Speed (ipm)	Weld Position	Misc.
Aluminum	0.25/6.35	10	10A	6	120/140/160	80	5	9.5	Vertical Up	Waveform: 19-4
			10B	6	120/140/160	80	5	9.5	Vertical Up	Waveform: 16-8
			10C	6	120/140/160	80	5	9.5	Vertical Up	Waveform: 12-12
			10D	6	120/140/160	80	5	9.5	Vertical Up	Waveform: 8-16
			10E	6	120/140/160	80	5	30.0	Vertical Up	Waveform: 19-4
			10F	6	120/140/160	80	5	30.0	Vertical Up	Waveform: 16-8
			10G	6	120/140/160	80	5	30.0	Vertical Up	Waveform: 12-12
			10H	6	120/140/160	80	5	30.0	Vertical Up	Waveform: 8-16
			10I	6	120/140/160	80	5	30.0	Vertical Up	Waveform: 19-4
			10J	4	120/140/160	80	5	9.5	Vertical Up	Waveform: 12-12. No Add. Rev. Current
			10K	4	120/140/160	80	5	9.5	Vertical Up	Waveform: 8-16. No Add. Rev. Current
			10L	4	120/140/160	80	5	30.0	Vertical Up	Waveform: 12-12. No Add. Rev. Current
			10M	4	120/140/160	80	5	30.0	Vertical Up	Waveform: 8-16. No Add. Rev. Current

3.3 MEASUREMENTS

3.3.1 DEFINITIONS

The weld measurements made were crown width, crown height, root width, and root height (Figure 1). For some welds keyhole leading edge angles were also measured (Figure 2). Note that the height measurements are for future reference only - they were not used in the analysis or algorithm development. Bead appearances were noted according to the code shown in Figure 3.

Appendices A through N list all the data for all the experiments. Note that all weld arc and pilot arc current and voltage values are positive. This is explained as follows, with reference to Figure 4. During straight polarity, positive weld arc current (electron flow) is from point A to C, with A being at a higher voltage than C. Pilot arc current is from A to B, with A being at a higher voltage than B. During reverse polarity the weld arc current is from C to A, with C being at a higher voltage than A. The pilot arc current is not variable polarity, so it must now flow through the welding arc power supply, through the workpiece, and from C to B. The voltage measured for the pilot arc is still between A and B, with B being at the higher voltage. The effect is that during the reverse polarity portion of the cycle the pilot arc current polarity does not change but the pilot arc voltage polarity does (according to measurements made at the pilot arc power supply). In essence, the pilot arc location changes from between A and B during straight polarity to between C and B during reverse polarity. Additionally, the welding arc power supply regulates the current, so during the reverse polarity cycle it restricts passage of the pilot arc current. This shows up in the data tables as lower pilot arc currents during reverse polarity.

3.3.2 TECHNIQUES

The original plan was to use a NASA owned ARI weld bead profile sensor for all weld geometry measurement, but initial trials revealed repeatability and accuracy problems with that sensor on the weld geometries obtained during this project. Therefore, all weld measurements were made by hand using dial calipers (for weld widths) and a dial indicator (for weld heights). Keyhole leading edge angles (only done for the second set of experiments) were measured from molds of the keyholes (Figure 5) using an optical comparator. Weld parameter values were read from strip charts and oscilloscope trace photographs for the first set of experiments and from the data acquisition system values for the second set of experiments.

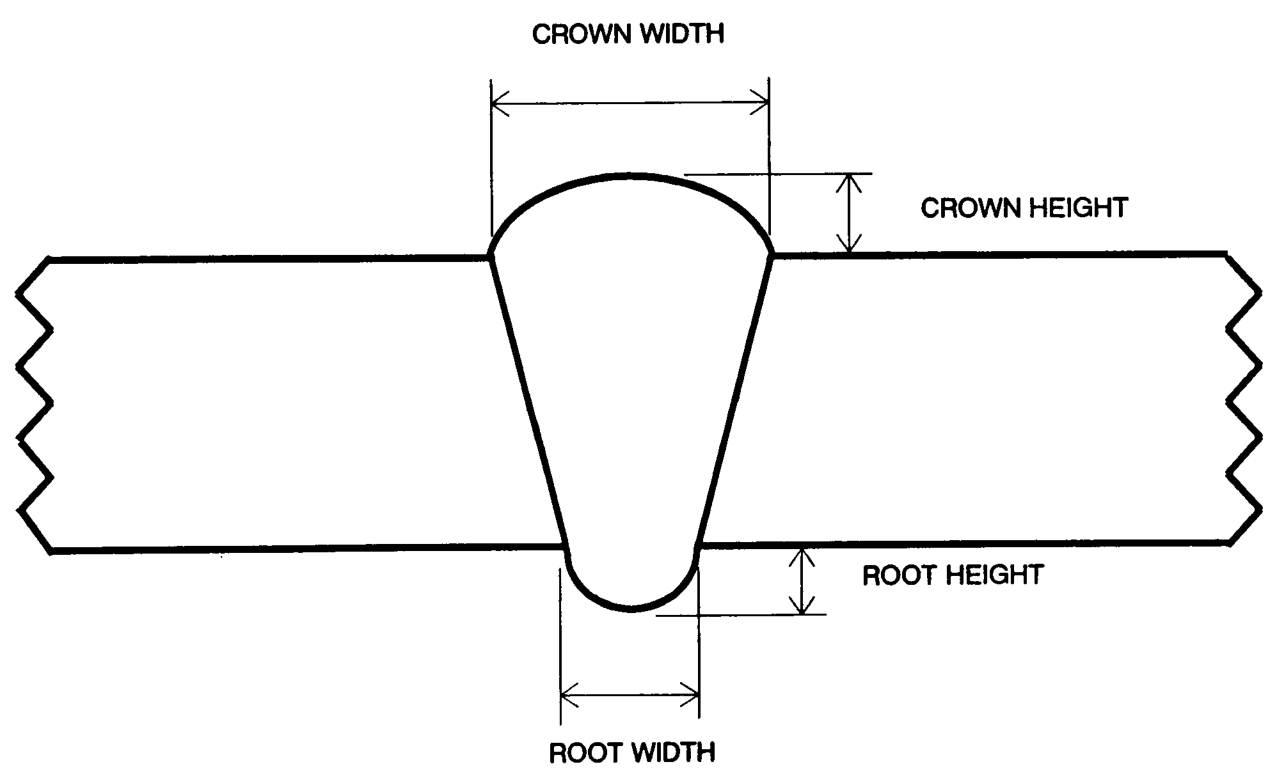


Figure 1. Weld Width and Height Definition

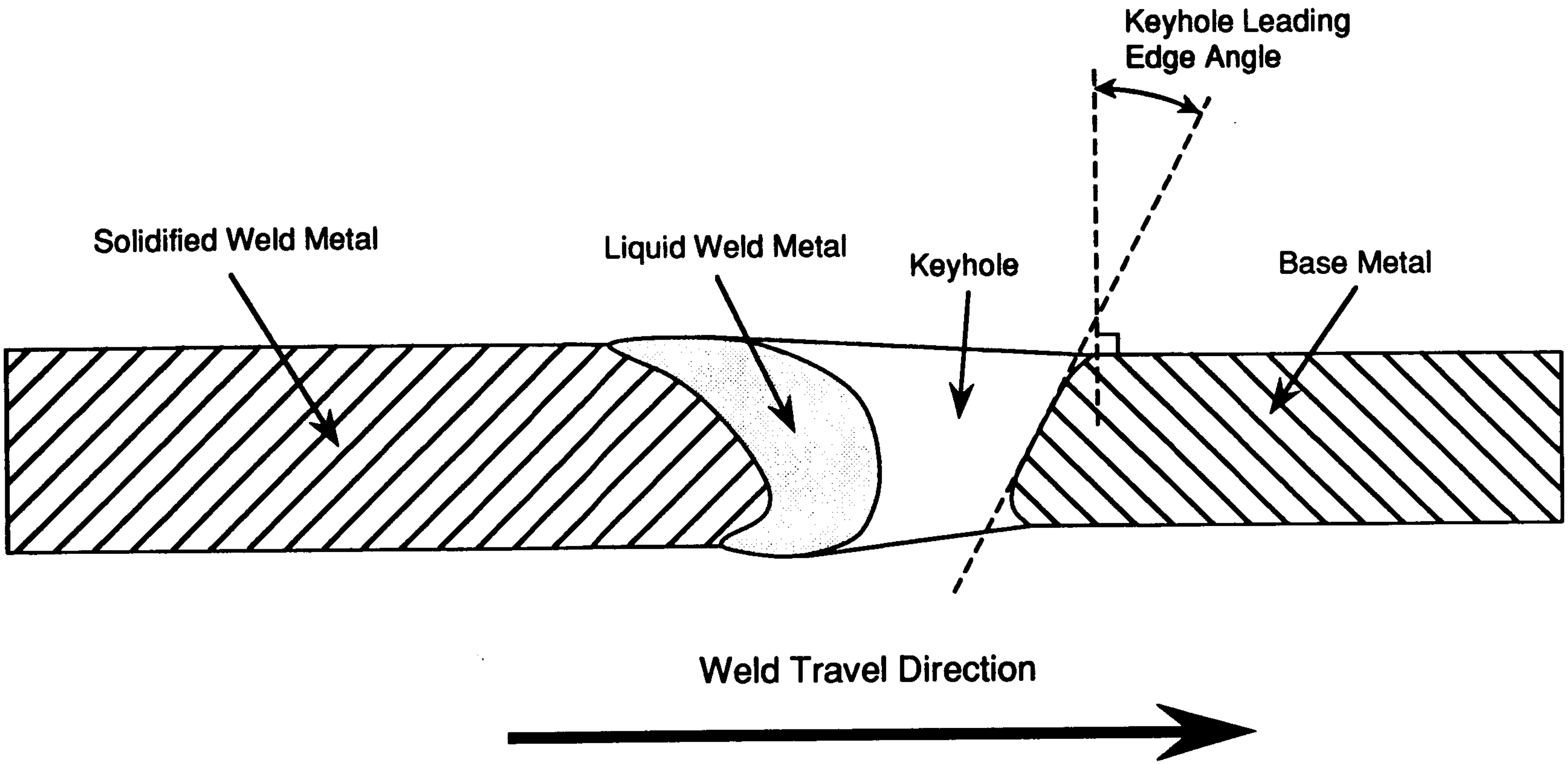
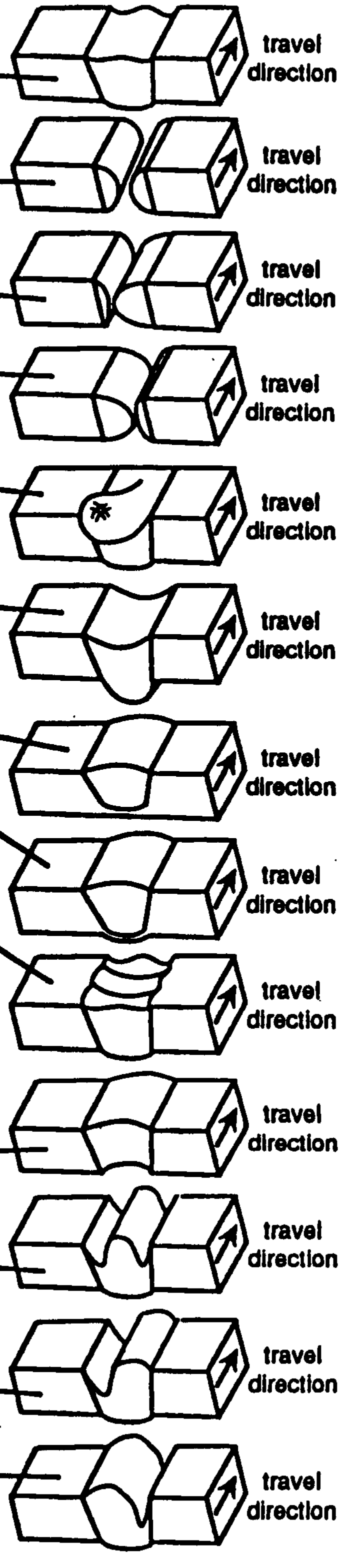


Figure 2. Keyhole Leading Edge Angle Definition

VPPAW MODELING BEAD APPEARANCE CODES

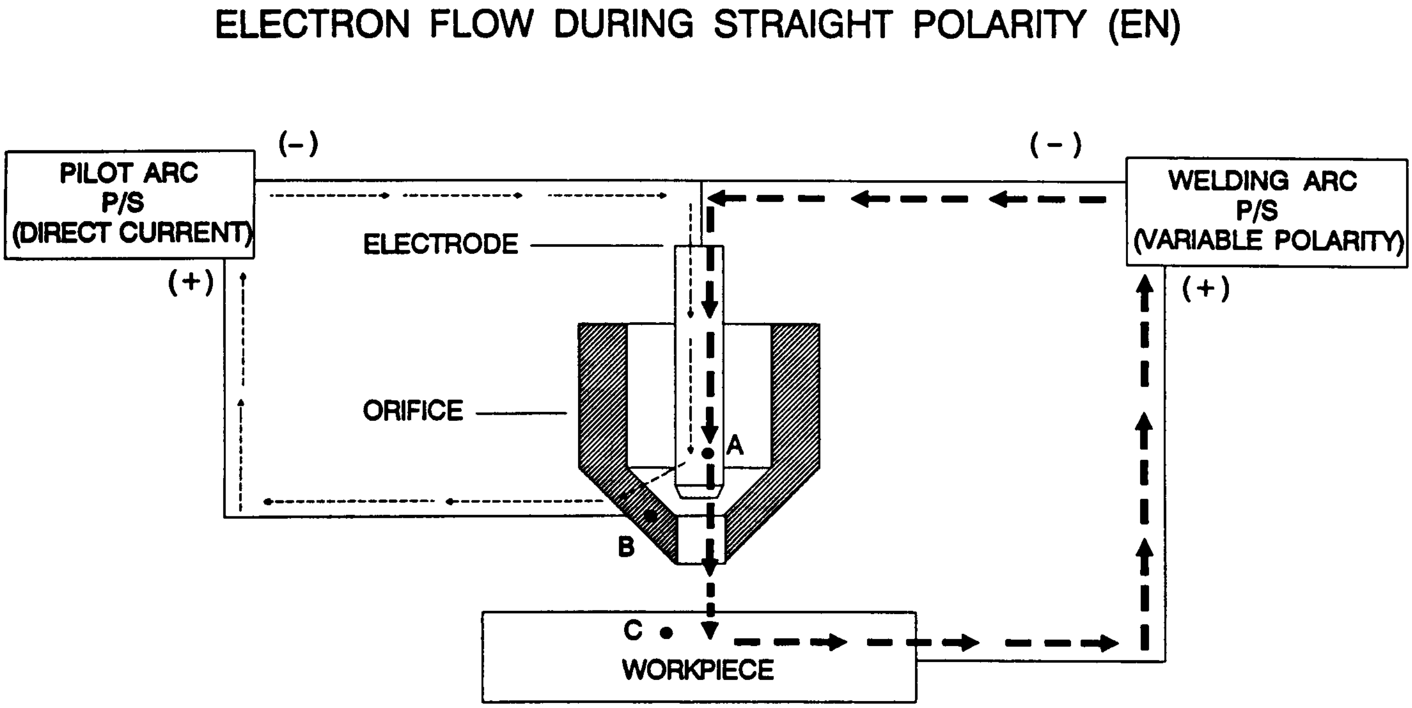
CODE	MEANING
N	Normal Weld (Little or No Undercut)
C	Cutting
LC	Cutting On Left Edge Of Bead
RC	Cutting On Right Edge Of Bead
D	Drooping (Weld Metal Hanging In Blobs)
ED	Excessive Drop-through
PP	Partial Penetration Weld
PT	Pushed Through, But Root Surface Not Fully Melted
R	Ripples (Larger Than Normal) On Crown And Root
RR	Ripples (Larger Than Normal) On Root
S	Shiny Bead Surface
SB	Suckback (Root Weld Surface Below Flush)
U	Undercut (Symmetrical, On Both Edges Of Weld)
LU	Undercut On The Left Edge Of Weld
RU	Undercut On The Right Edge Of Weld
X	Prefix Meaning 'Extreme' (Ex: XU means Extreme Undercut)

APPEARANCE



Notes:
- All Welds Are Full Penetration Unless Denoted 'PP' or 'PT'
- 'U' Used in Conjunction With 'RU' or 'LU' Indicates Undercut is on Both Edges, but Deeper on the Referenced Edge

Figure 3. Weld Bead Appearance Codes



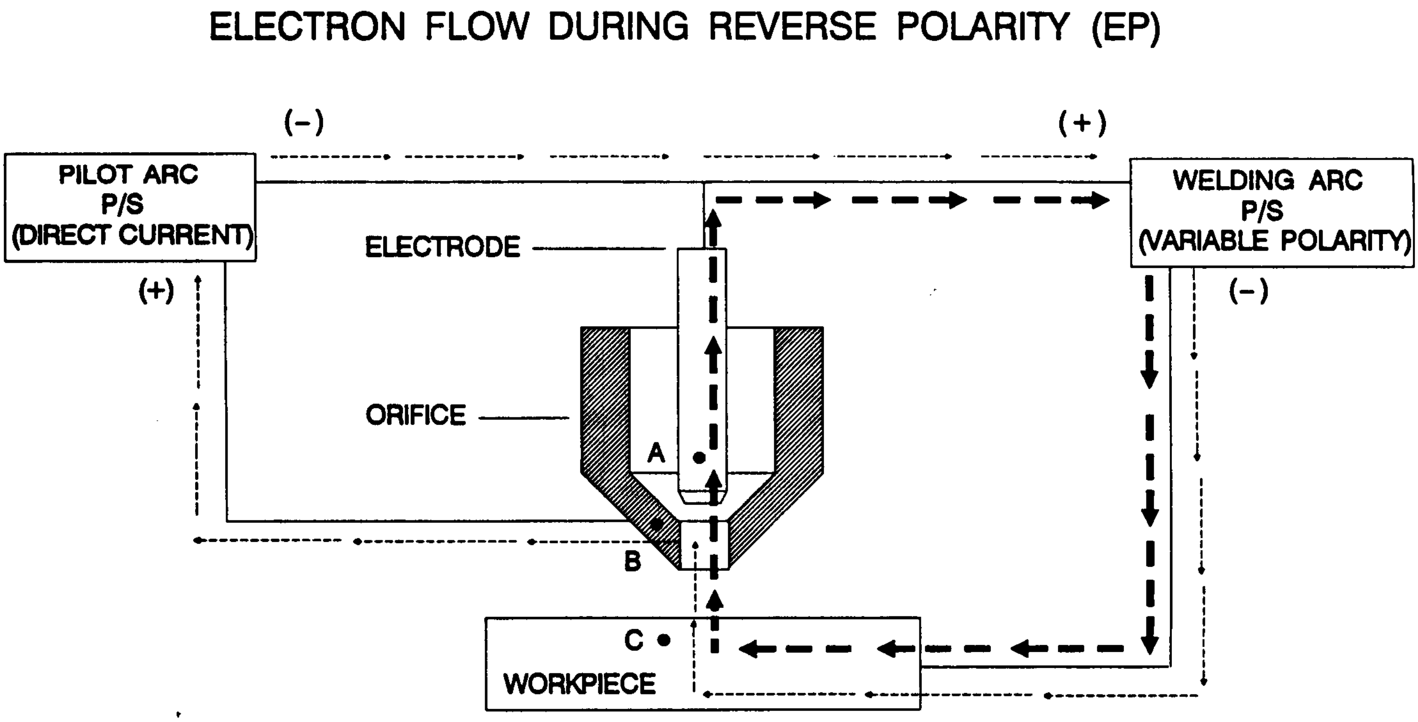
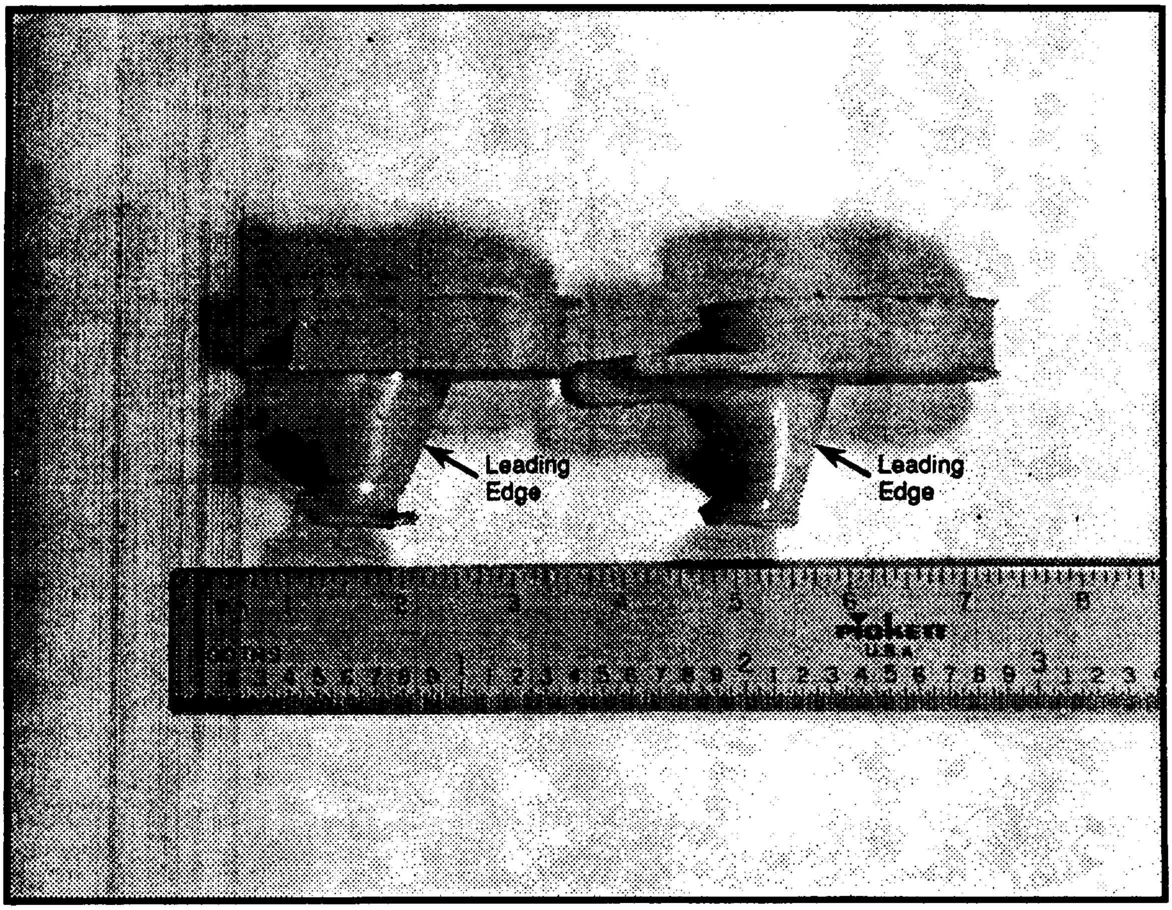


Figure 4. Electron Flow Paths During Straight and Reverse Portions of Variable Polarity Cycle

SILICONE MOLDS OF KEY HOLES



Silicone molds of VPPAW keyholes used to measure leading edge angles.

The two examples shown here are (from left to right): Weld 3D (leading edge angle = 23°)
Weld 3G (leading edge angle = 16°)

Figure 5. Silicone Molds Of Keyholes

SECTION 4. RESULTS

4.1 DATA

Appendices A through D contain data tables for all the welds done in the first set of experiments. Appendices E through N contain data tables for all the welds done in the second set of experiments. All this data has been supplied to NASA for support of any evolutionary modifications of the model and to UAH for use in their evaluation of the UAH model (ref. 3). NRC used this data to develop the control algorithm described in Section 5.

4.2 DATA ANALYSIS

The UAH final report (ref. 3) presents quantitative comparisons between experimental results and the UAH model predictions, so they are not repeated here. The following paragraphs present several key observations and qualitative analyses of specific sub-sets of data.

4.2.1 CROWN WIDTH

Crown width is of particular interest because it is readily observable during the welding process, and therefore will be a real-time input to the controller during welding.

Sections 4.2.1.1 through 4.2.1.5 present crown width observations based on graphs of predicted versus observed behavior for aluminum welds presented in the UAH final report (ref. 3).

4.2.1.1 Shield Gas Flow Rate Effects

The UAH model predictions showed essentially no effect of shield gas flow rate on crown width. This correlated very well with test results for welds made at 2 and 4 mm stand-offs. Most welds cut at 8 mm stand-off, resulting in wider crown widths for lower shield gas flow rates and poor correlation with UAH model predictions.

4.2.1.2 Stand-Off Effects

The UAH model predicted crown width increases for larger stand-offs. This was observed in test results, but crown widths tended to be increasingly larger than predicted as stand-off increased. Cutting usually occurred at stand-offs of 8 mm or more.

4.2.1.3 Weld Current Effects

The UAH model predicted crown width increases with higher weld currents. This trend was observed in test results, however crown widths did not increase as much as the UAH model calculations predicted.

4.2.1.4 Plasma Gas Flow Rate Effects

The UAH model predicted very little effect of plasma gas flow rate on crown width. This correlated moderately well with test results for welds made at 2 and 4 mm stand-offs. Most welds cut at 8 mm stand-off, resulting in wider crown widths for lower plasma gas flow rates and poor correlation with UAH model predictions.

4.2.1.5 Travel Speed Effects

The UAH model predicted crown width decreases with higher travel speeds. This trend was observed in test results, however crown widths did not decrease as much as the UAH model calculations predicted.

4.2.2 ROOT WIDTH

Root width became a feature of particular interest because it was generally more sensitive than crown width to parameter changes. This can be observed in Figure 6, which shows the results of an orthogonal array set of aluminum VPPA welds. While these welds represent a narrow range of the total parameter variations used, the trends are representative of those for the overall data set.

Sections 4.2.2.1 through 4.2.2.5 present root width observations based on graphs of predicted versus observed behavior for aluminum welds presented in the UAH final report (ref. 3).

4.2.2.1 Shield Gas Flow Rate Effects

The UAH model predicted essentially no effect of shield gas flow rate on root widths. This correlated very well with test results for welds made at 2 and 4 mm stand-offs. Most welds cut at 8 mm stand-off, resulting in wider root widths for lower shield gas flow rates and poor correlation with UAH model predictions.

4.2.2.2 Stand-Off Effects

The UAH model predicted slight root width increases for larger stand-offs. Test results also showed root width increases for larger stand-offs, however the root widths tended to be increasingly larger than predicted as stand-off increased. Cutting usually occurred at stand-offs of 8 mm or more.

4.2.2.3 Weld Current Effects

The UAH model predicted root width increases with higher weld currents. This correlated very well with test results for welds made at 2 and 4 mm stand-offs. Most welds cut at 8 mm stand-off, resulting in wider root widths than the UAH model calculations predicted.

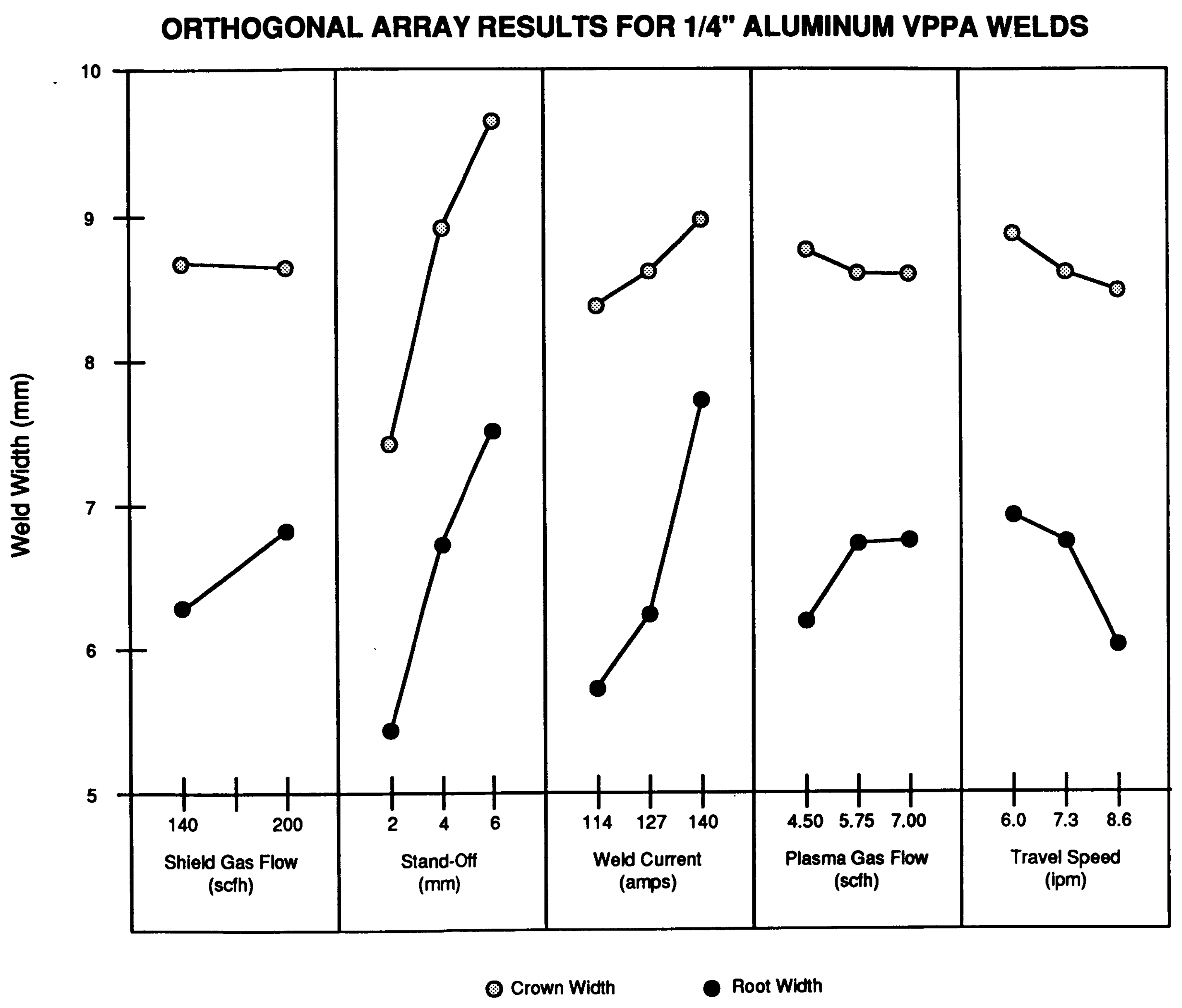


Figure 6. Orthogonal Array Results For 1/4" Aluminum Aluminum

4.2.2.4 Plasma Gas Flow Rate Effects

The UAH model predicted very little effect of plasma gas flow rate on root width. This correlated moderately well with test results for welds made at 2 and 4 mm stand-offs, which showed slight increases in root width with increasing plasma gas flow rates. Most welds cut at 8 mm stand-off, resulting in wider root widths for lower plasma gas flow rates and poor correlation with UAH model predictions.

4.2.2.5 Travel Speed Effects

The UAH model predicted root width decreases with higher travel speeds. This trend was observed in test results, however root widths did not decrease as much as the UAH model calculations predicted.

4.2.3 CROWN AND ROOT WIDTH INTERACTIONS

Figure 6 shows that weld current and torch stand-off caused the largest changes in both crown and root weld widths. This high sensitivity to these parameters was the primary driver for measuring and controlling stand-off, and improving data acquisition for the second set of experiments.

Another important observation from Figure 6 is the way individual parameters change crown and root widths. For example, as weld current increases, both crown and root width increase by approximately the same amount, whereas increases in travel speed cause root widths to decrease more than crown widths. This is important for controller development because it enables the system to independently control crown and root width by varying multiple weld parameters.

Forward weld current and travel speed were chosen as primary control variables for the prototype multi-variable weld controller. These were chosen for the following reasons:

(1) Relative independence from other parameters
(2) Ease of monitoring accurately
(3) Ease of varying rapidly
(4) They provide a good combination of effects on crown and root widths to enable a multi-variable controller to independently control those widths.

4.2.4 CUTTING

The onset of cutting was found to have a strong correlation to root width. Transitioning from not cutting to cutting occurred at root widths of about 9.5 mm for 1/4" (6.35 mm) aluminum (Figure 7) and 7 mm for 1/4" (6.35 mm) mild steel (Figure 8). The transition to cutting was less distinct for the stainless steel welds. It occurred at root widths of 7 to 8 mm for 1/4" (6.35 mm) stainless steel (Figure 9), and seemed more a function of crown width (cutting at crown widths above 8 mm) than root

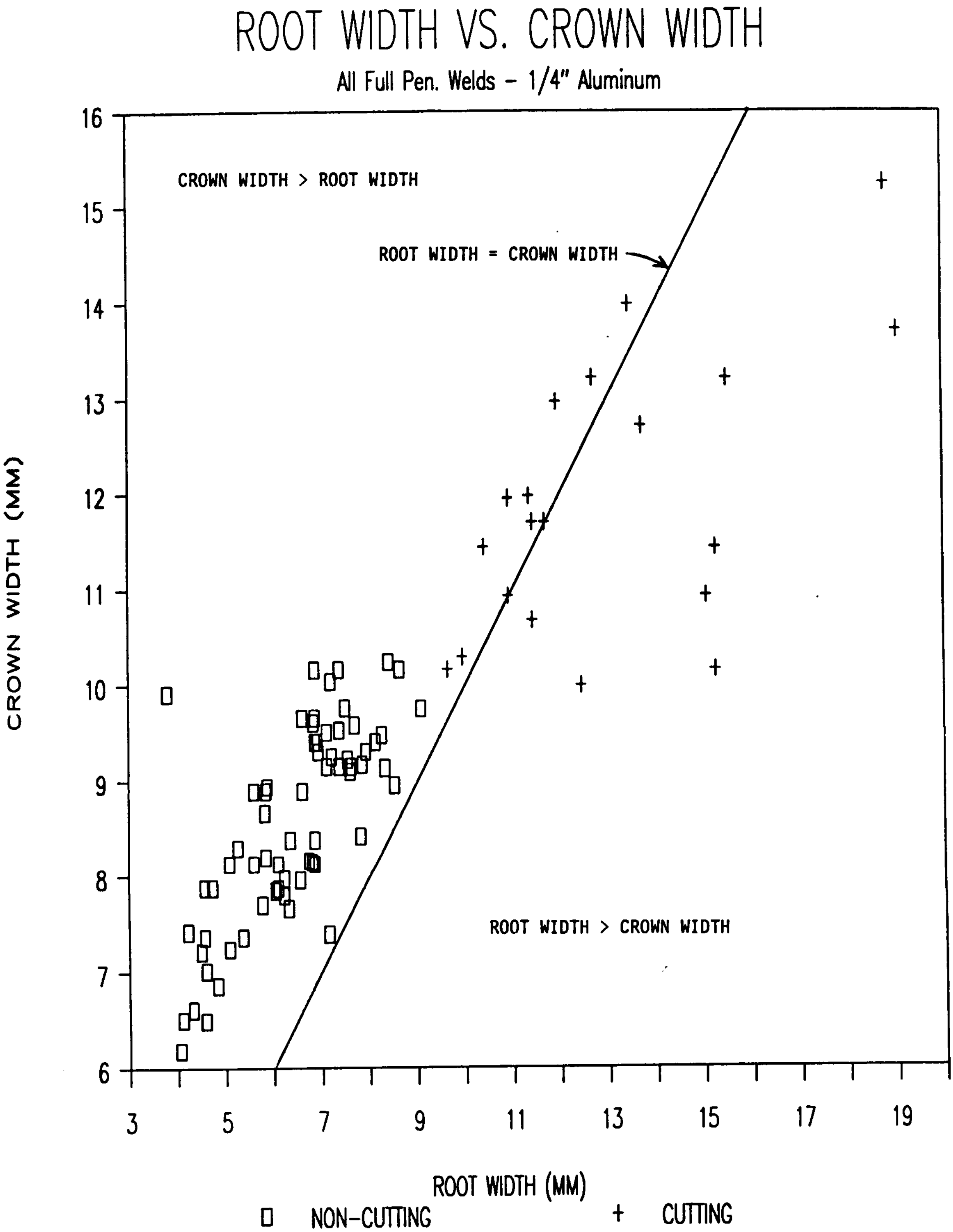


Figure 7. Root Width vs Crown Width, 1/4" Aluminum

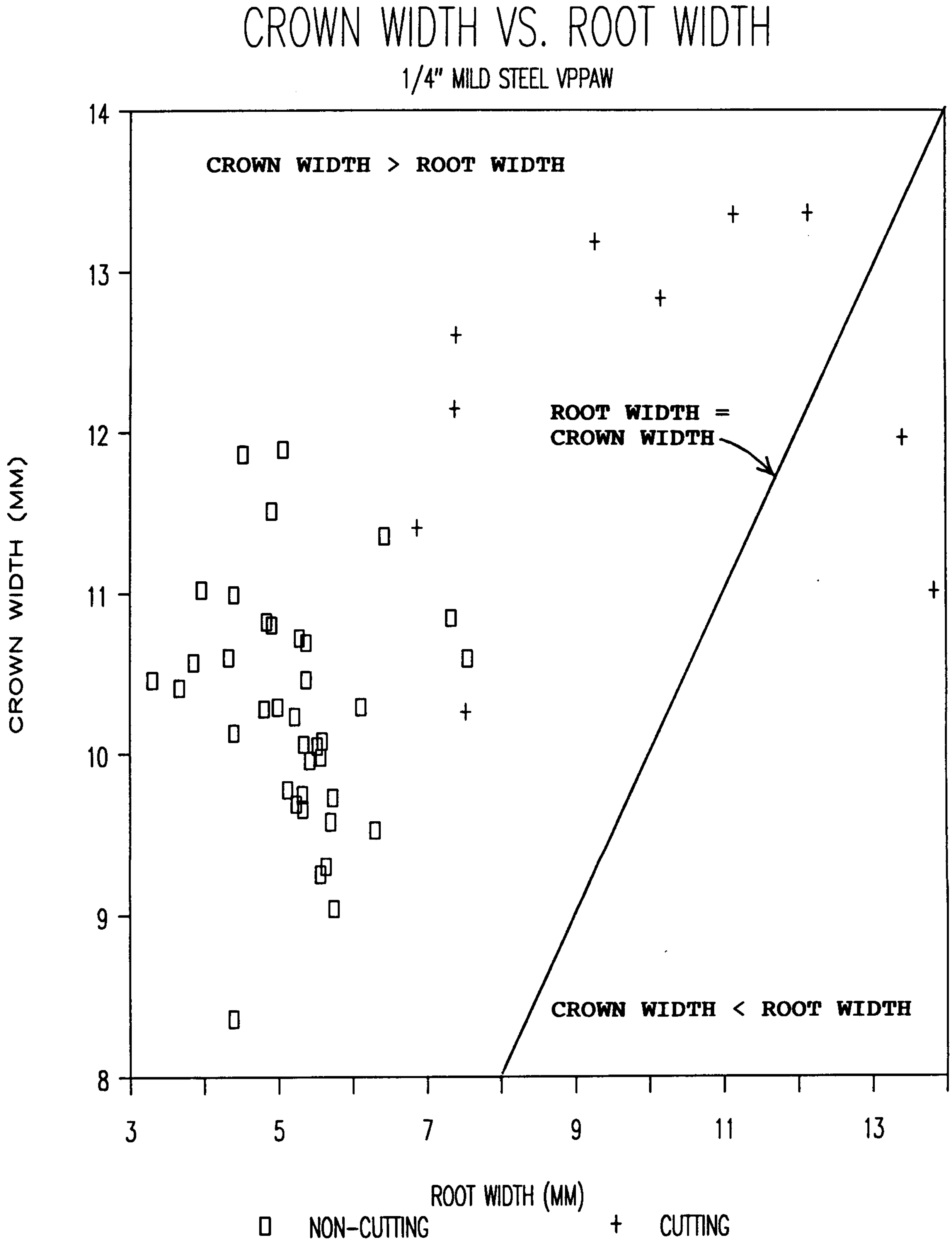


Figure 8. Root Width vs Crown Width, 1/4" Mild Steel

width for 3/16" (4.76 mm) stainless steel (Figure 10). Figures 7 through 10 also show that all non-cutting welds had crown widths larger than their root widths.

Dr. Nunes has hypothesized that the onset of cutting may be caused by increasing amounts of atmospheric contamination entering the weld as the weld pool enlarges beyond the area protected by the shield gas flow. This hypothesis is based upon prior work (ref. 4) modeling the effect of oxygen contamination upon undercutting. That work showed large increases in undercutting occurring as weld puddle widths increased beyond the width of the shield gas cover. This shield gas cover (focused by the shield gas cup) is about 10 mm wide. This implies that weld widths of more than 10 mm would be prone to excessive undercutting and cutting. With relatively low thermal conductivity materials, weld widths may be under 10 mm while the weld pool length exceeds 10 mm, thereby extending beyond the shield gas cover. This would explain the observed transition to cutting at smaller weld widths for the steels than aluminum. However, the fact that root widths seems to be more significant than crown widths for the transition to cutting is not in clear agreement with the above hypothesis.

A similar hypothesis was proposed to explain excessive undercutting when the arc skews. Experiment #1 of the second set of experiments showed that excessive undercutting occurred on the opposite edge than that suggested by the hypothesis, and that identical undercutting occurred when the entire weld operation was carried out in an inert environment which precluded any atmospheric contamination. As a result Dr. Nunes proposed a hypothesis in which arc skewing causes uneven temperature distribution on the pool surface, which creates asymmetrical surface tension driven flows resulting in the excessive undercut. This hypothesis agrees qualitatively with experiment #1 results, but should be regarded as conjecture pending further evaluation.

4.2.5 KEYHOLE GEOMETRY

UAH noted in their analysis of data from the first set of weld experiments that the worst correlation between their model predictions and experimental results occurred for those experiments in which travel speed varied. With increases in travel speed, crown widths were not decreasing as much as expected and root widths were decreasing more than expected. This indicated possible variations in the through-thickness heat distribution into the workpiece. It was hypothesized that variations in travel speed caused changes in the keyhole leading edge angle, which affected the through-thickness heat transfer distribution from the plasma column into the workpiece. Plasma gas flow rate was also expected to affect the keyhole leading edge angle. Therefore the second set of weld experiments had weld experiments (#2 and #3) to determine the effects of travel speed and plasma gas flow rate, respectively, on the keyhole leading edge angle. The results (Figures 11 and 12) show that

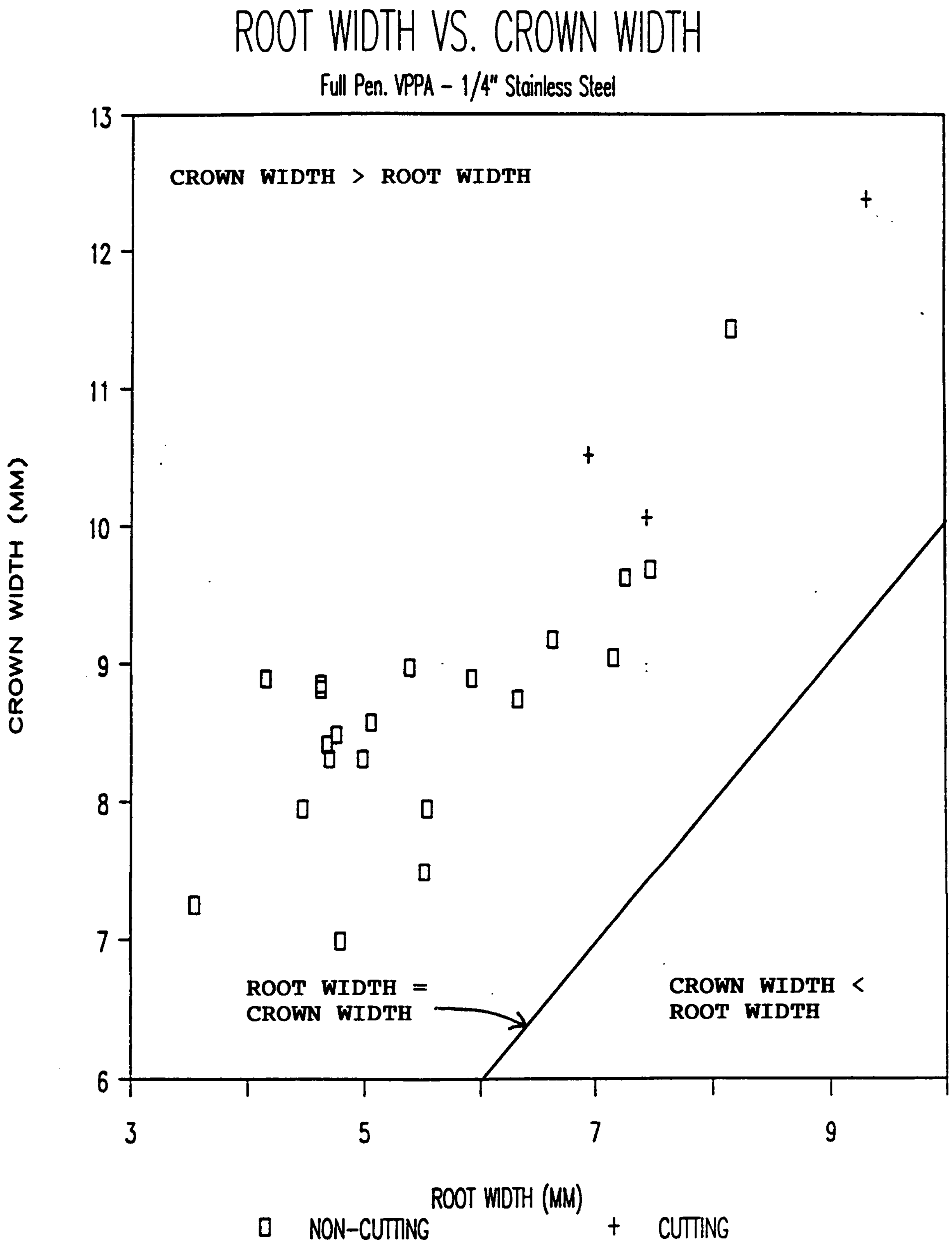


Figure 9. Root Width vs Crown Width, 1/4" Stainless Steel

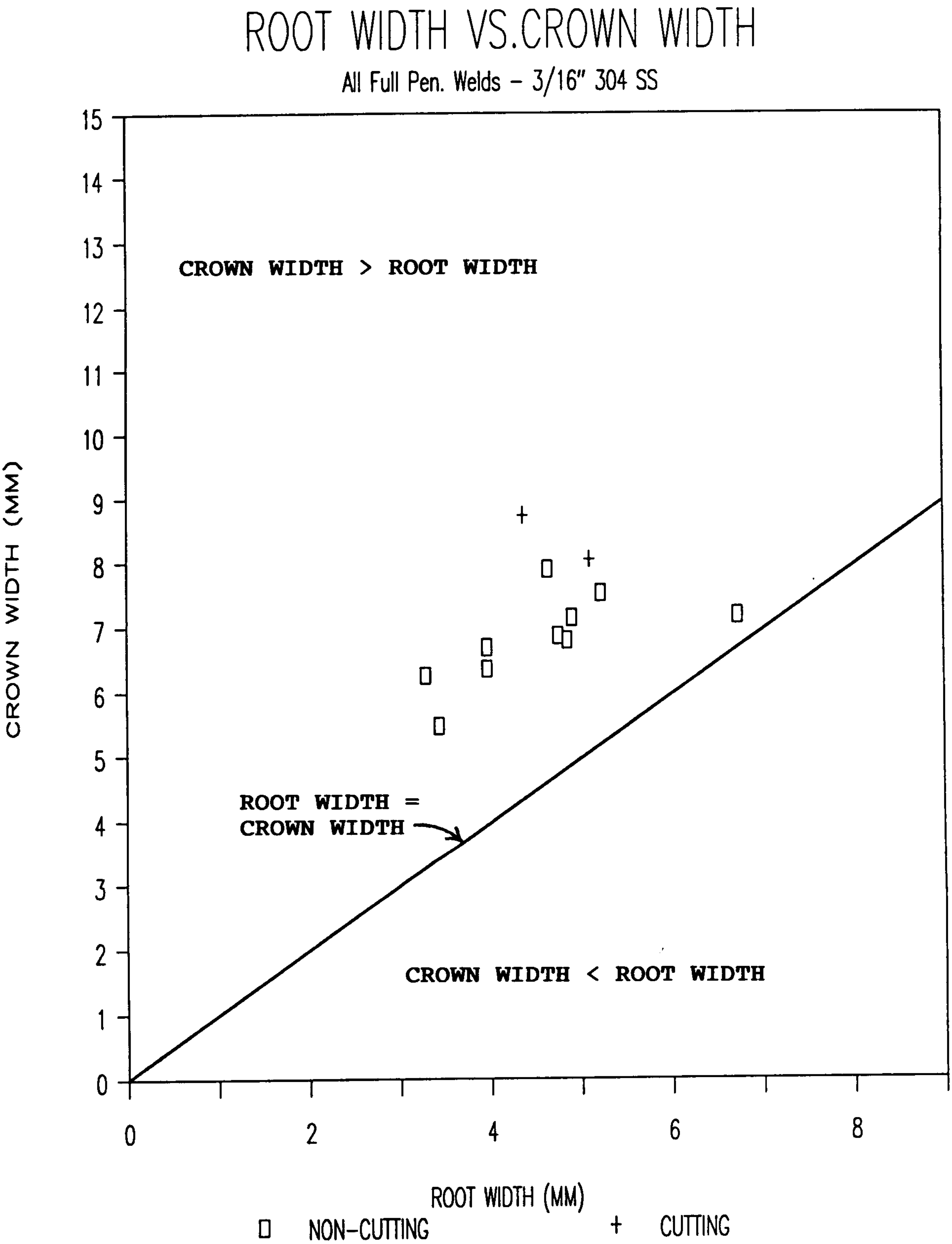


Figure 10. Root Width vs Crown Width, 3/16" Stainless Steel

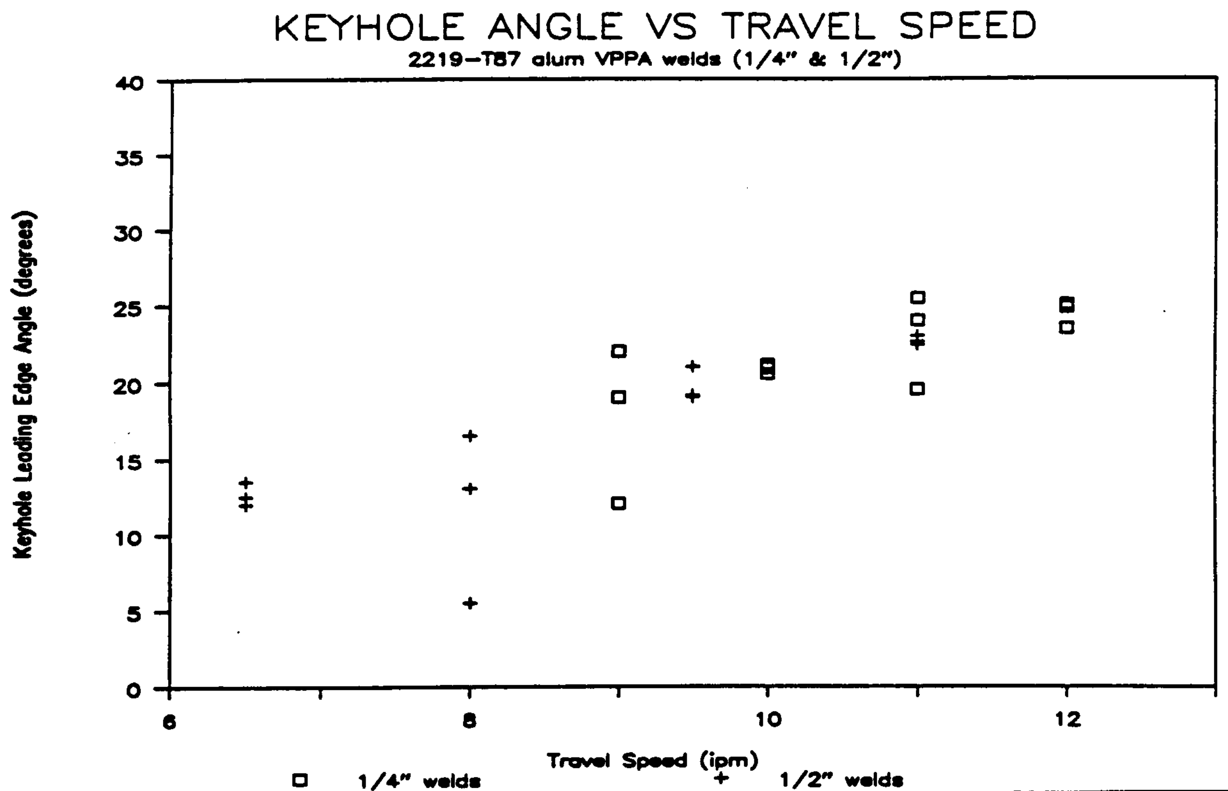
both travel speed and plasma gas flow rates did alter the keyhole leading edge angle. Dr. Nunes proposed a theory for this, based on an existing model of electron beam weld cavities (ref. 5), where the leading edge angle adjusts to absorb sufficient power to maintain forward motion of the keyhole at the given travel speed. The plasma gas effect is tentatively interpreted as a result of boundary layer thickening within the keyhole at lower plasma gas flow rates. Preliminary computations of leading edge angles made by UAH (ref. 1) using this theory show good agreement with test results.

4.2.6 REPEATABILITY

For the second set of experiments, torch stand-off was instrumented and an improved data acquisition system was implemented. The primary remaining known sources of error were weld repeatability variations and errors from manual weld geometry measurements. To determine the noise levels associated with these, a set of welds (experiment #9) was made specifically to quantify these errors. This quantification of known error in the data was used during control algorithm evaluation to define acceptable accuracy. For experiment #9, sets of welds with identical parameters were made on different days, during different times of the day, and in different sequences on the plate. Figure 13 graphically shows the results obtained. Several of these welds were measured repeatedly at marked locations to quantify how much variation occurred from manual measurements. Figure 14 shows the results. These two figures show that much of the weld repeatability variation is due to measurement variations. Standard deviation values for these errors were calculated and used during the evaluation of the control algorithm. Table 3 lists these values.

Table 3. Standard Deviations of weld and measurement repeatability tests. All values are in mm.

	Weld Repeatability		Measurement Repeatability	
	Aluminum	Mild Steel	Aluminum	Mild Steel
Crowns	0.21	0.33	0.13	0.26
Roots	0.21	0.31	0.21	0.12
Overall	0.21	0.32	0.18	0.20



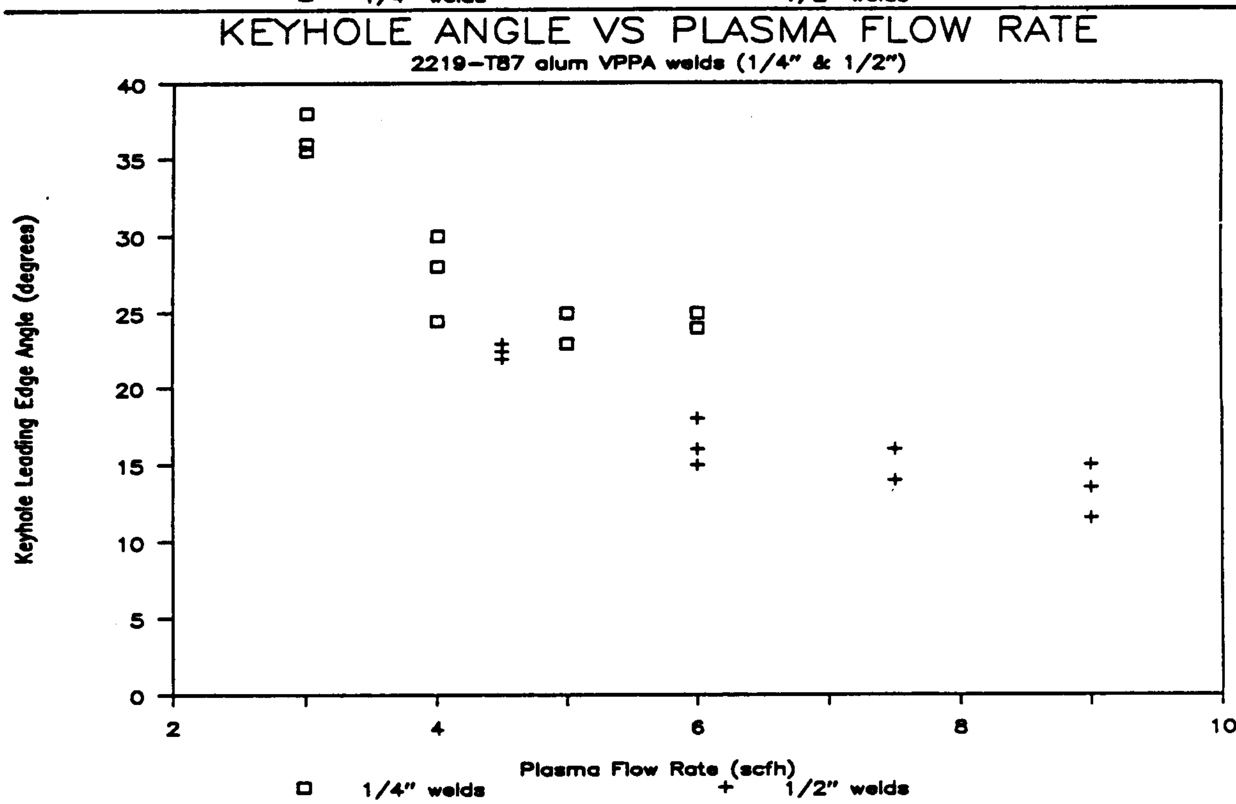
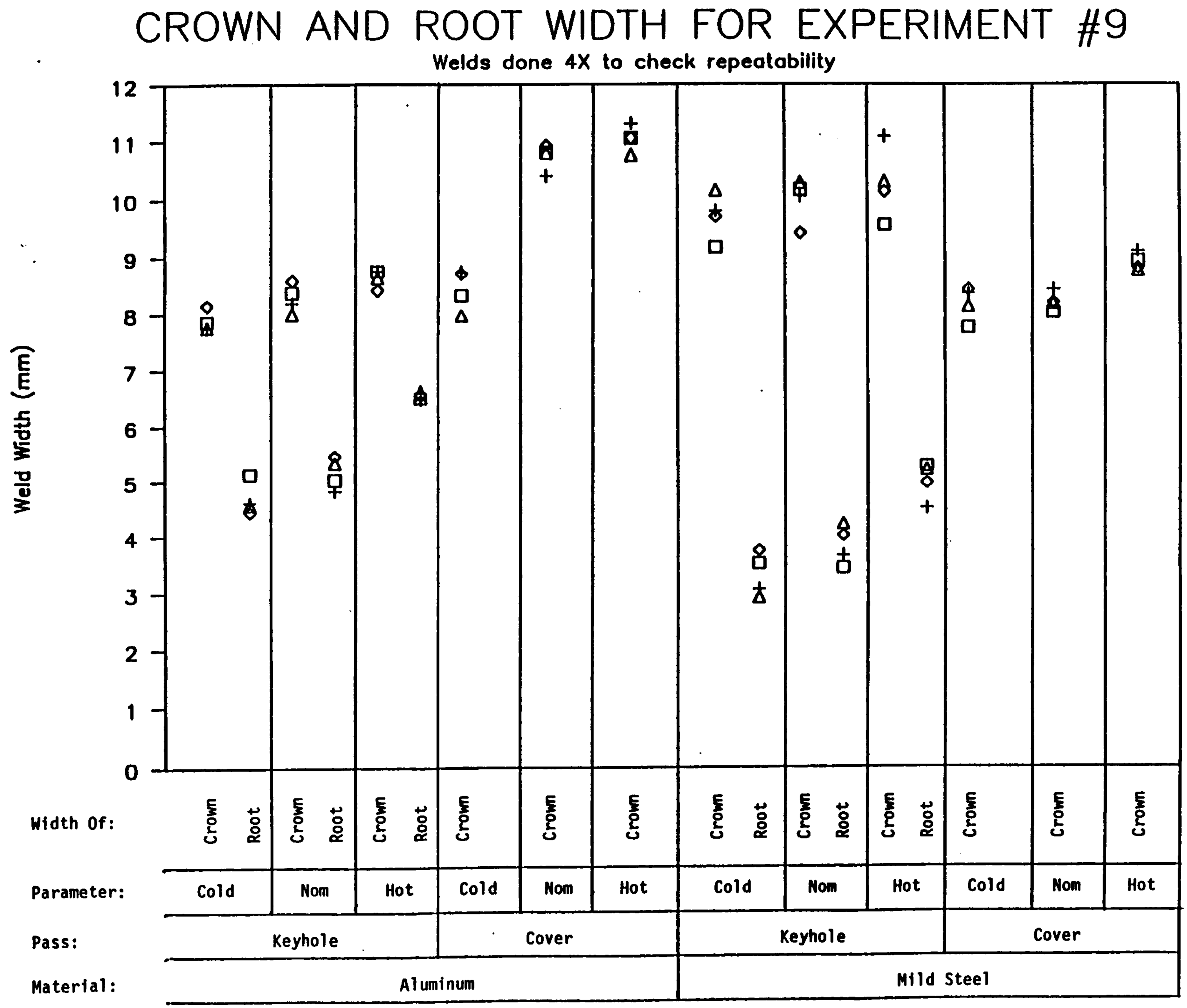


Figure 11 (top). Keyhole Angle vs Travel Speed

Figure 12 (bottom). Keyhole Angle vs Plasma Flow Rate

Figure 13. Weld Repeatability Results



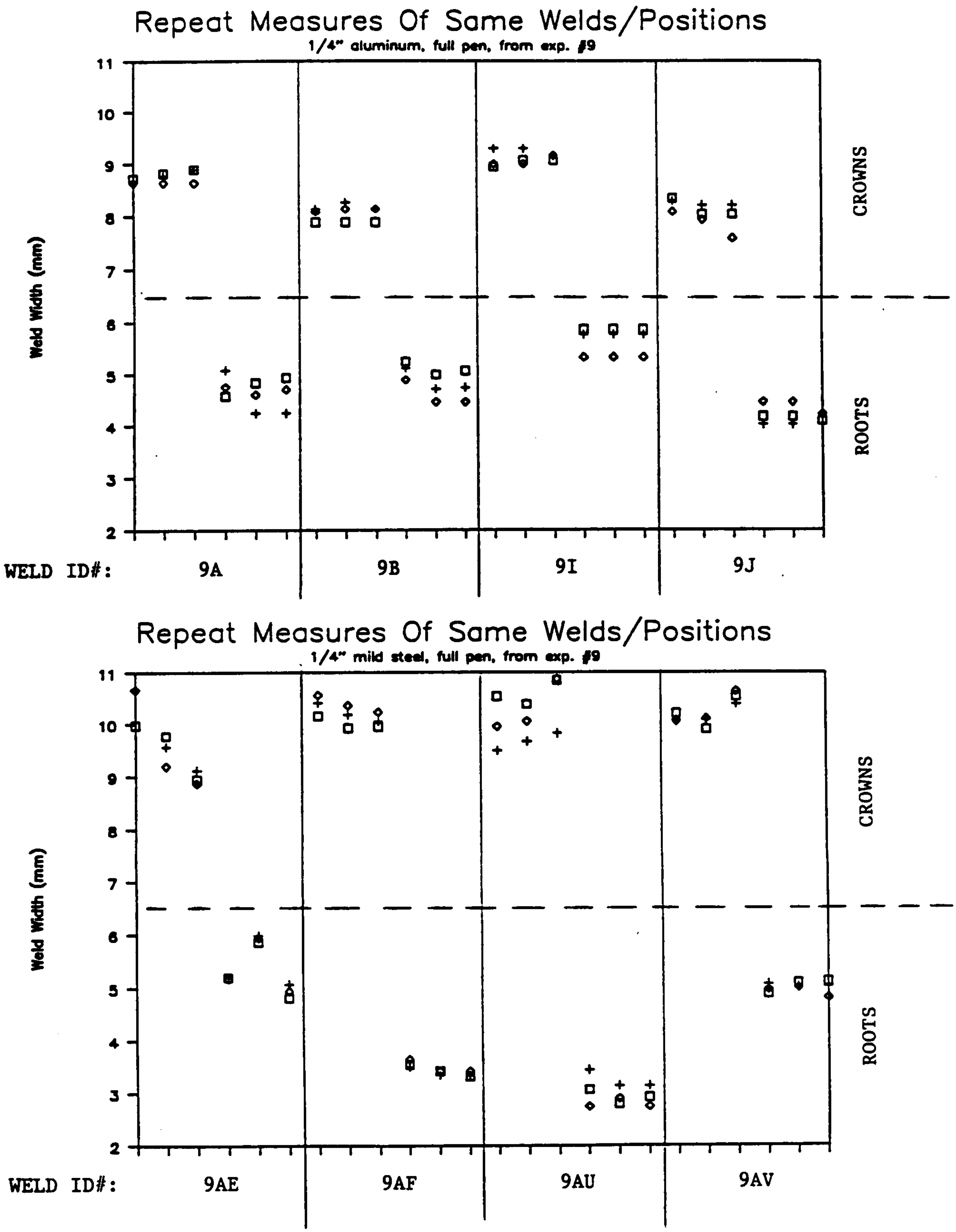


Figure 14. Measurement Repeatability Results

4.2.7 STRAIGHT TO REVERSE POLARITY TIME RATIO

Two weld experiments (#7 and #10) were done to repeat and expand upon prior experimental work (unpublished) done by Dr. Nunes and J. Gregory at NASA/MSFC in 1989. That work was to determine the effect of varying the variable polarity timing on measured weld arc voltages. Figure 15 shows the result of that work. Figures 16 through 19 shows the results from experiments 7 and 10. The trends are the same but the values vary from the 1989 results. The voltage variations noted are believed to be caused by changes in emissivity as surface films aiding emission are reduced on the cathode. A quantitative theory has not yet been developed. However, analysis of these results are underway and will be reported separately when completed. The results of this analysis may enable waveform variations to be a controllable for future controllers. These results may also provide insight into the physics of the VPPAW process.

The results of these experiments were not used for the current controller development effort, because the waveform (19ms/4ms) is not a control variable.

4.2.8 WELDING POWER SUPPLY PERFORMANCE

The welding power supply is suspected of causing some of the lack of repeatability since variations in power (forward current multiplied by forward voltage) over the course of a weld with constant parameters have been observed. Figure 20 shows several examples. Dr. Nunes speculates that these power fluctuations (about 5%) may be caused by minor cathodic surface structure changes affecting emissivity, and that these power fluctuations may be responsible for the occasional lower than normal UTS values reported for VPPAW tensile specimens when adjacent specimens from the same plate have normal UTS.

Sensitivity studies from the first set of weld experiments showed large discrepancies between commanded parameters and measured (read) values, particularly for weld current (when welding all materials) and shield gas flow rates (when welding mild steel with Argon shield gas). Figures 21 through 23 show the results of these sensitivity studies.

A quirk of the power supply, noted during analysis of the experiments 7 and 10 data, is that the error between the commanded weld current and the measured weld current increases as the variable polarity waveform timing deviates farther from the standard 19ms/4ms (Figure 24). Additionally, the dials for setting the waveform timing were not accurate. To get accurate timing an oscilloscope had to be used.

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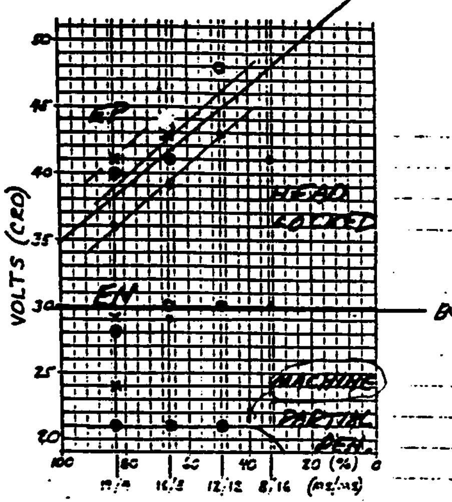
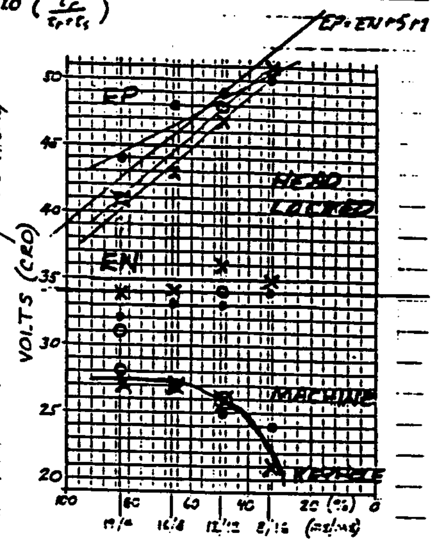


DCEN : DCEP RATIOS
- • AL-9 120 A 23^v
- o AL-10 140 A 23^v
- x AL-11 160 A 23^v

Cathode Ray Oscilloscope



DCEN : DCEP RATIOS
- • AL-7 120 A 27^v
- c AL-6 140 A 27^v
- x AL-8 160 A 27^v

Ref: Gregory, J.T. : Weld Strength Variability and Weld Modelling, 1988 Senior Research Associate, National Research Council

Note: Above runs on 1/4-inch 2219-T87 Aluminum

$$\mathcal{E}_r \cong \mathcal{E}_s + 5 + 20\left(\frac{t_r}{t_r+t_s}\right)$$

FOR 2219-T87 ALUMINUM
BOTH COVER & KEYHOLE PASS

WHERE $\mathcal{E}_r$ = VOLTAGE IN REVERSE POLARI

$\mathcal{E}_s$ " " STRAIGHT "

t_r = REVERSE CYCLE TIME

t_s = STRAIGHT CYCLE TIME

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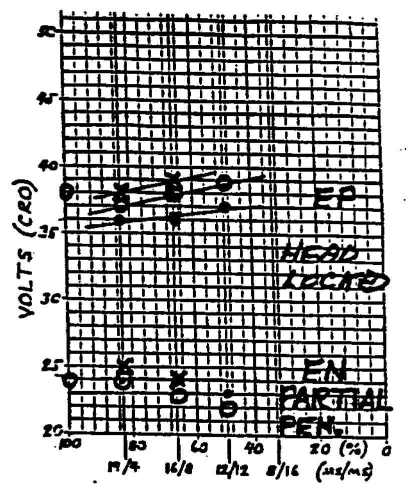


DCEN : DCEP RATIOS
- • MS-14 120 A
- o MS-15 140 A
- x MS-16 160 A

} 23^V

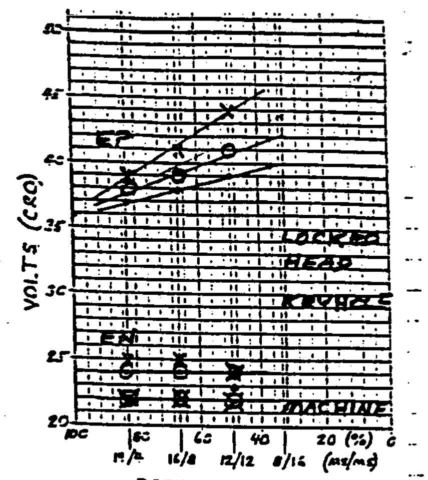
$$\mathcal{E}_s = 24 - 2\left(\frac{t_r}{t_r+t_s}\right)$$

$$\mathcal{E}_r = 30 + 5\left(\frac{t_r}{t_r+t_s}\right)$$

$$\mathcal{E}_r = \mathcal{E}_s + 12 + 7\left(\frac{t_r}{t_r+t_s}\right)$$

COVER PASS

MILD STEEL



DCEN : DCEP RATIOS
- • MS-11 120 A
- o MS-12 140 A
- x MS-13 160 A

23^V?

$$\mathcal{E}_s = 24$$

$$\mathcal{E}_r = 35.5 + 12\left(\frac{t_r}{t_r+t_s}\right)$$

$$\mathcal{E}_r = \mathcal{E}_s + 11.5 + 12\left(\frac{t_r}{t_r+t_s}\right)$$

KEYHOLE PASS

MILD STEEL

To Page No.

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		Recorded by ACN	2 Oct 89

4-15

Figure 15. Measured Voltages vs % Electrode Negative (1989 Results)

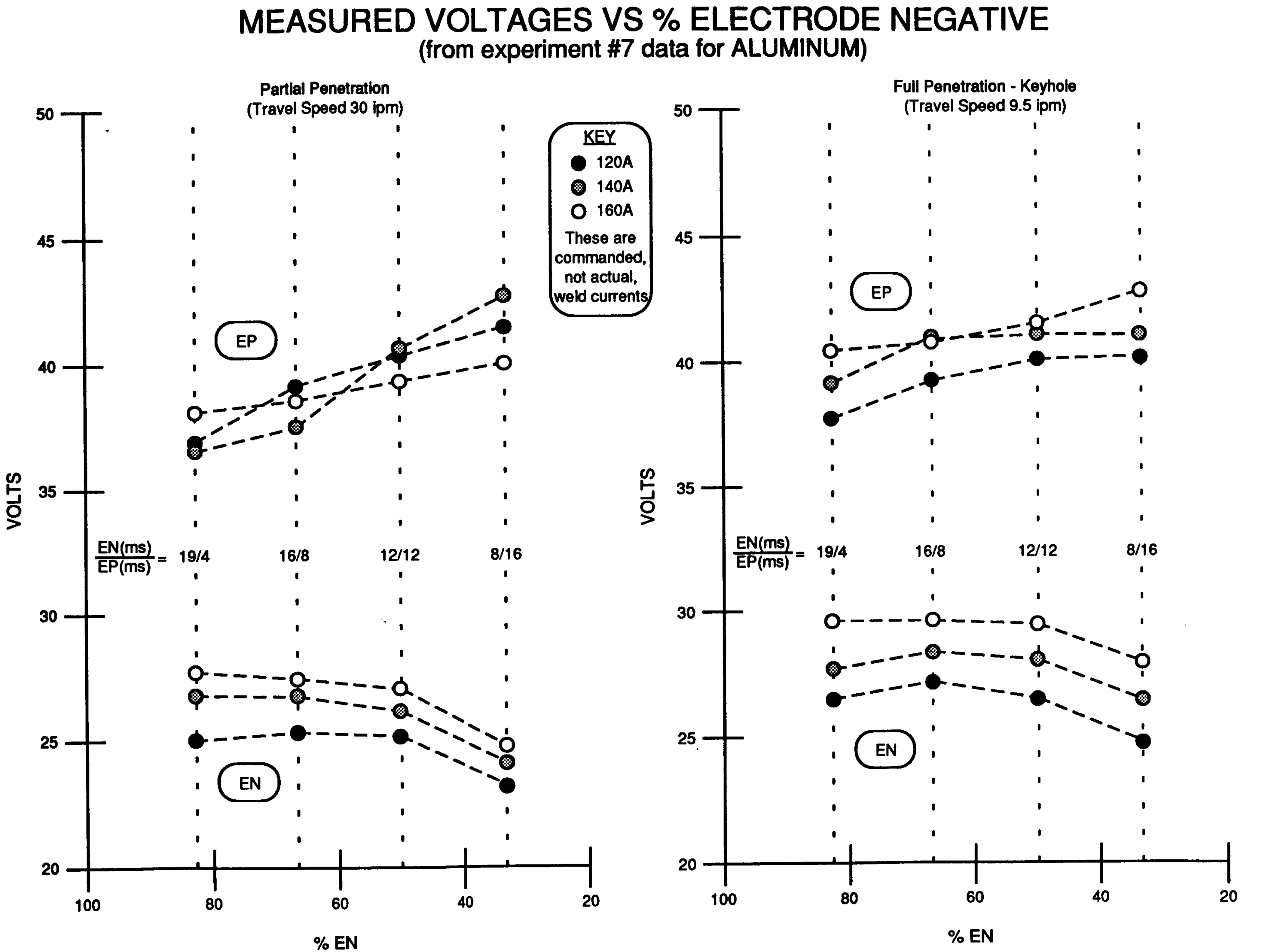


Figure 16. Measured Voltages vs % Electrode Negative (From Exp. #7 Data For Aluminum)

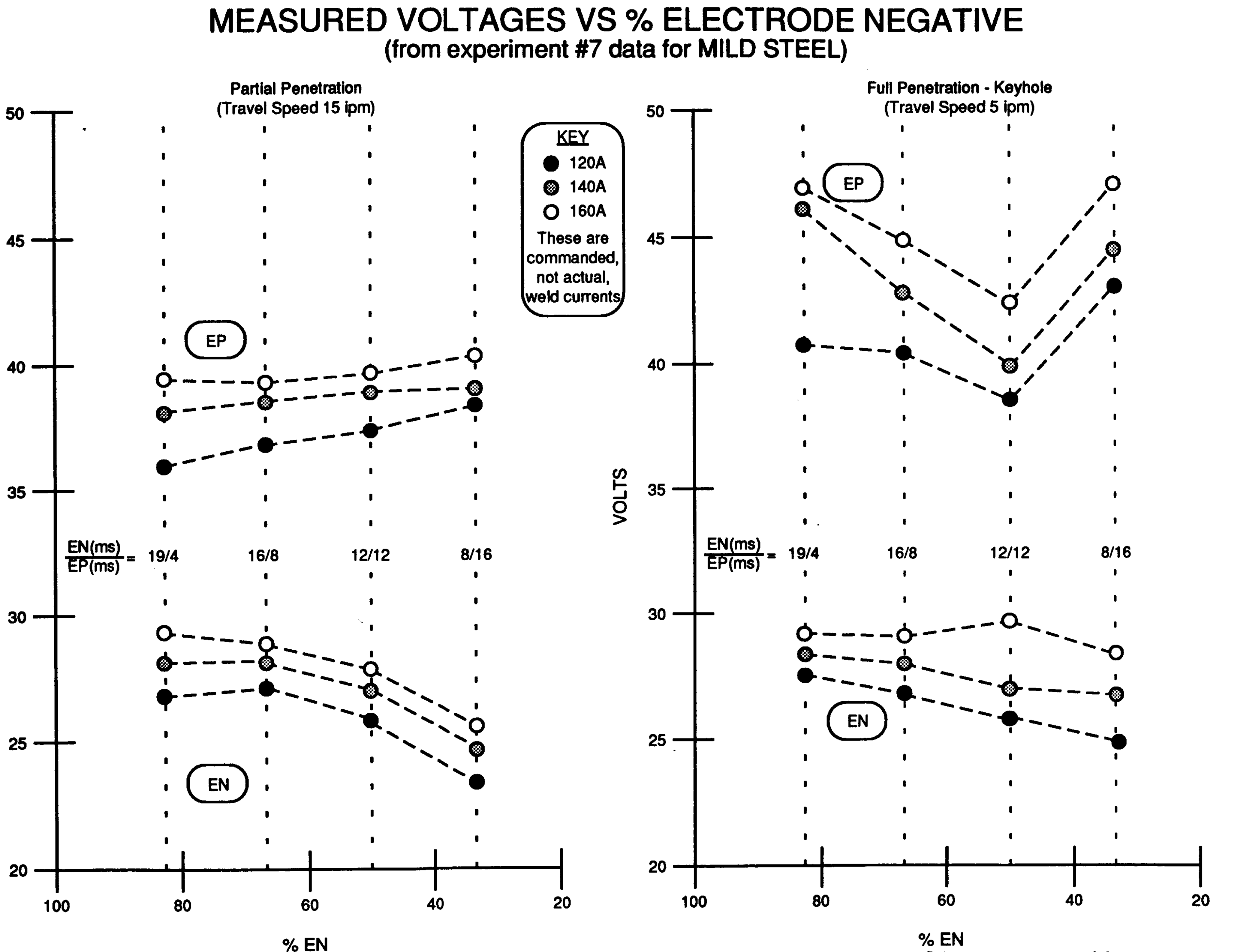


Figure 17. Measured Voltages vs % Electrode Negative (From Exp. #7 Data For Mild Steel)

MEASURED VOLTAGES VS % ELECTRODE NEGATIVE

(from experiment #10 data for ALUMINUM
welded at 6 mm stand-off (instead of the usual 4 mm))

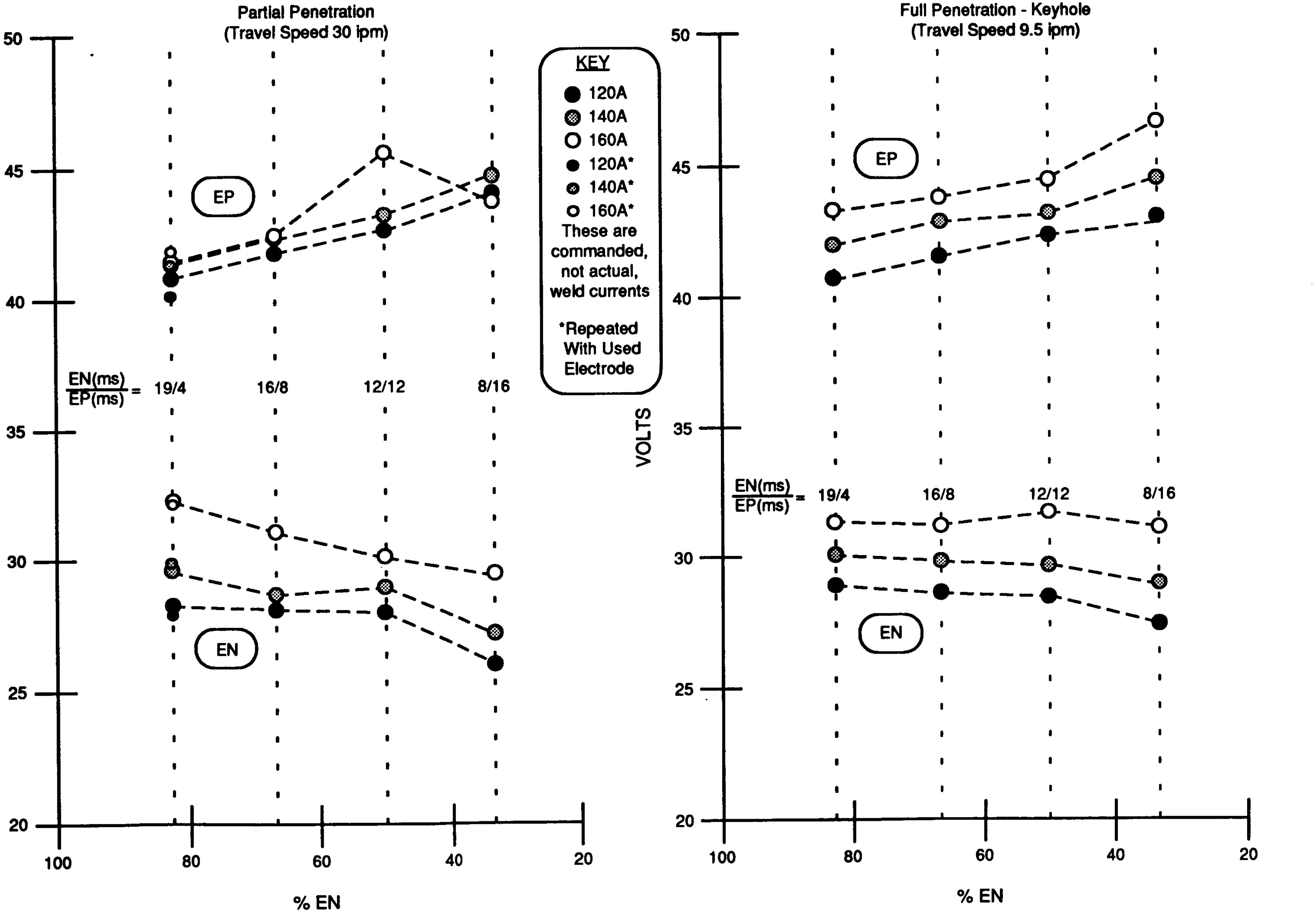


Figure 18. Measured Voltages vs % Electrode Negative (From Exp. #10 Data, Aluminum, 6 mm Stand-Off)

MEASURED VOLTAGES VS % ELECTRODE NEGATIVE
(from experiment #10 data for ALUMINUM
welded at 4 mm stand-off without additional reverse current)

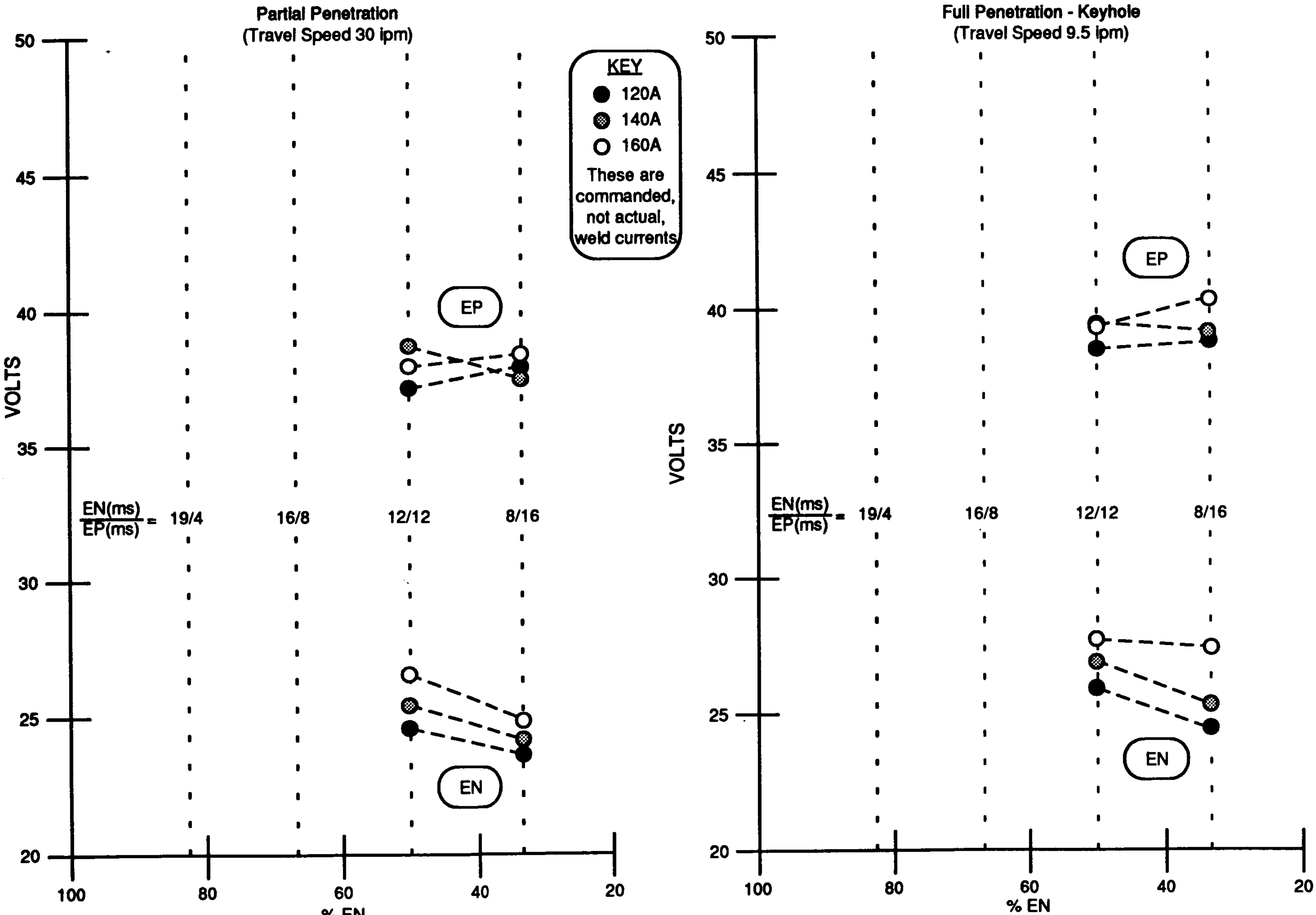
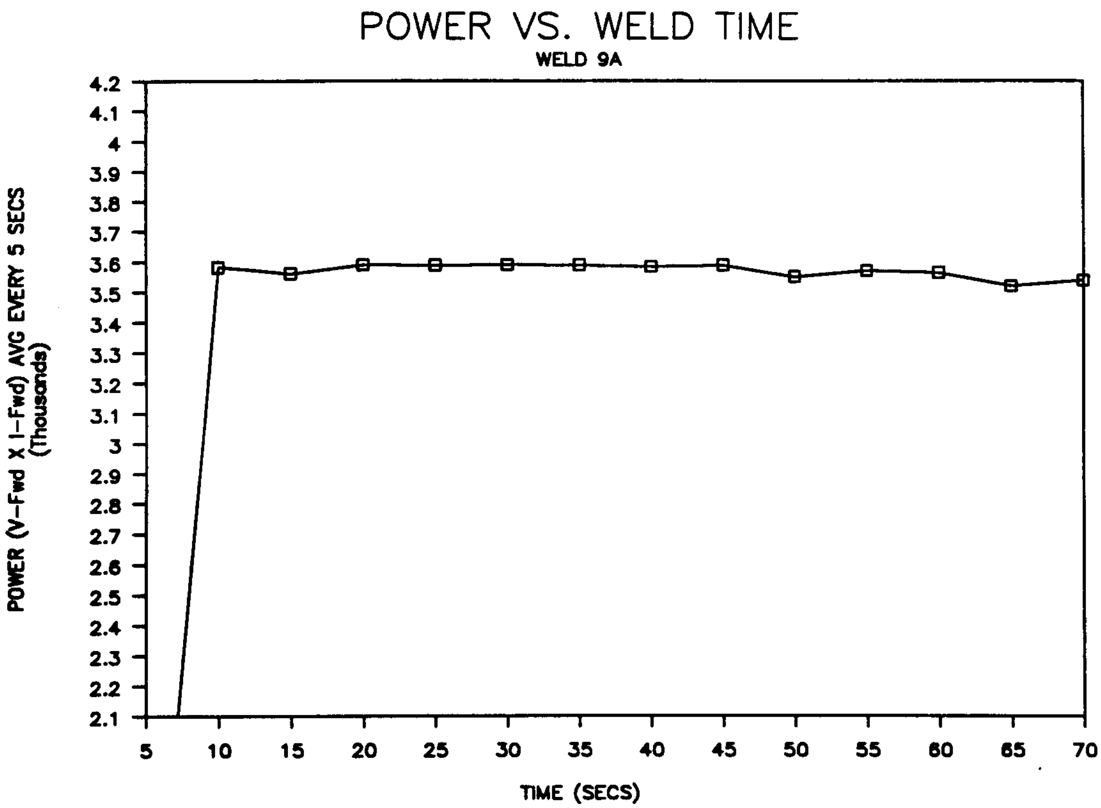


Figure 19. Measured Voltages vs % Electrode Neagative (From Exp. #10 Data, Aluminum, No Additional Reverse Current)



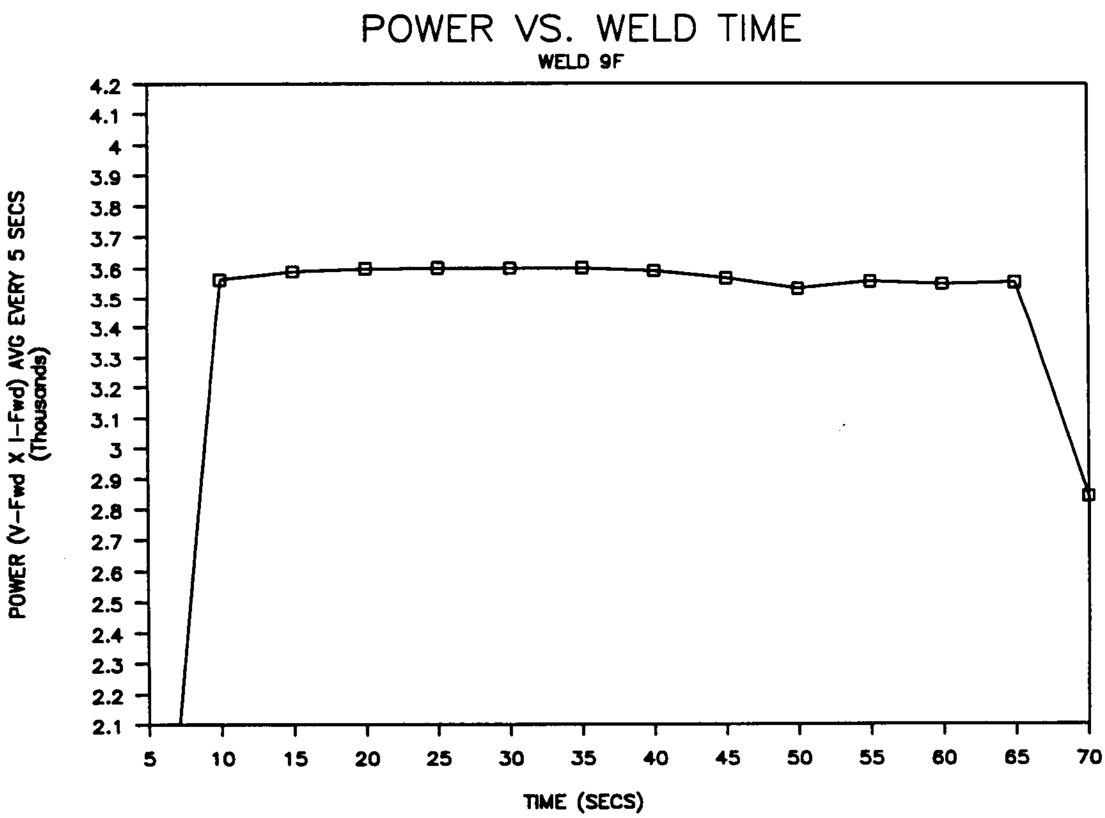


Figure 20. Examples of Power Fluctuations During Constant Parameter Welds

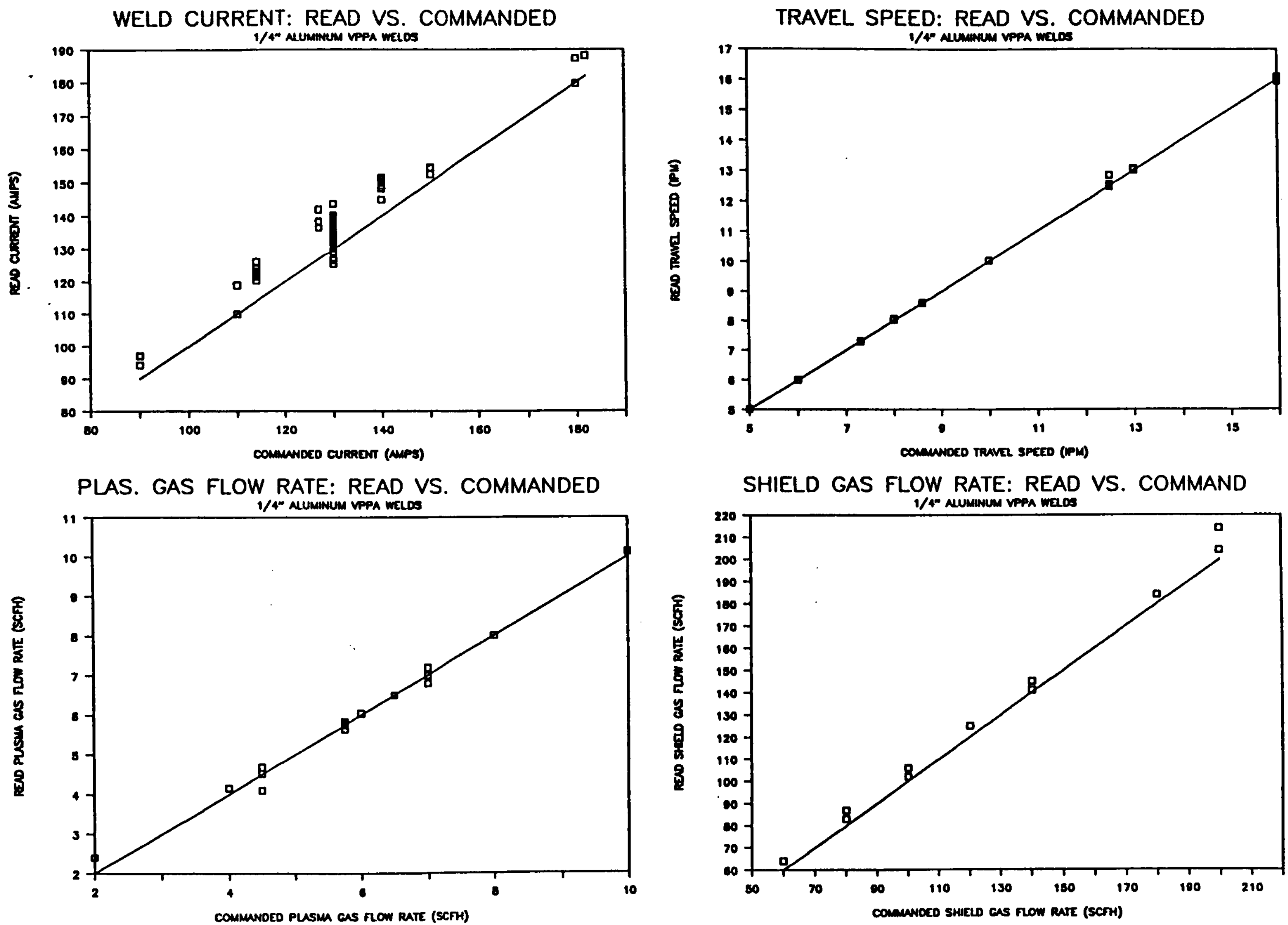


Figure 21. Parameter Sensitivity Study, 1/4" Aluminum VPPA Welds

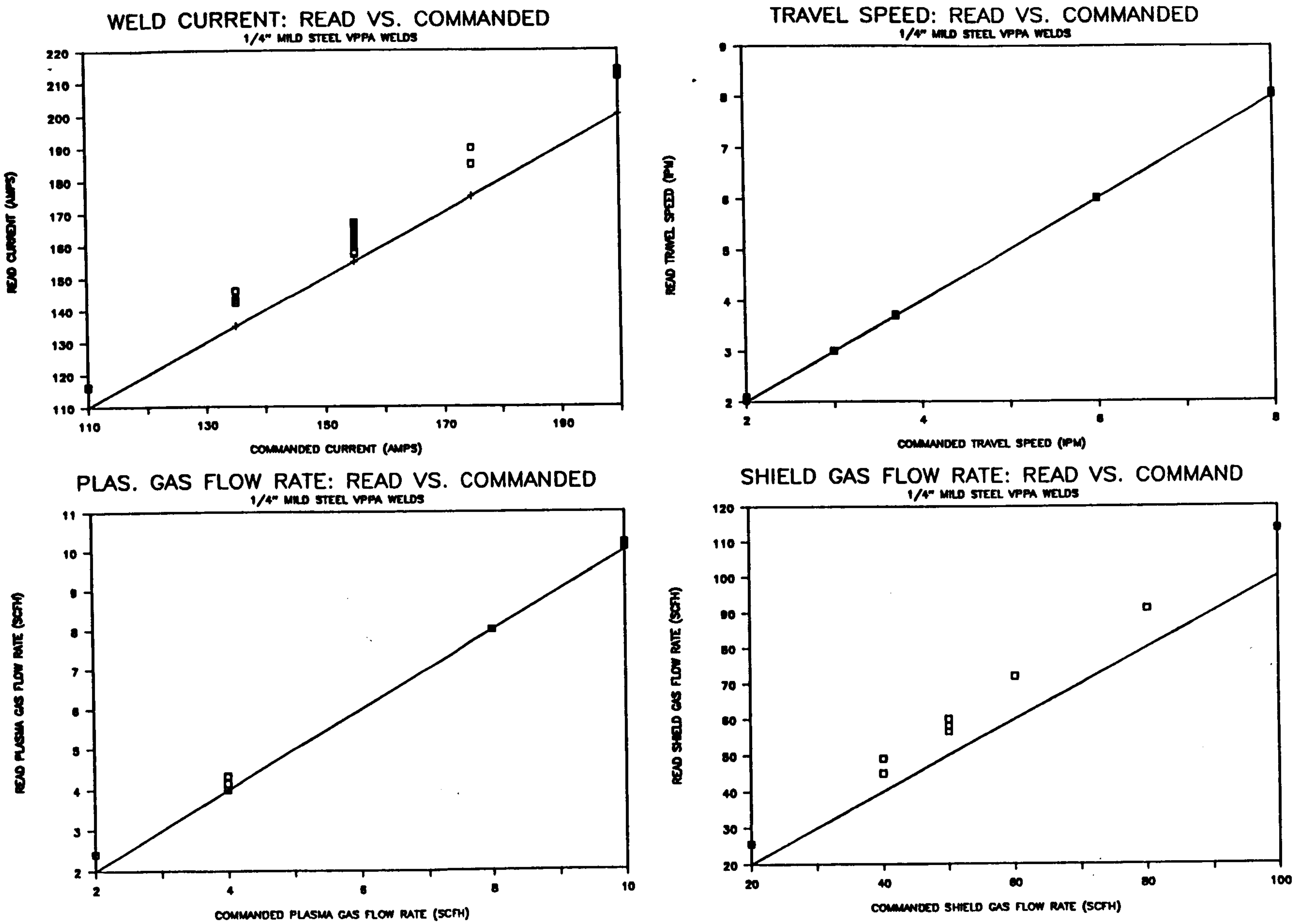
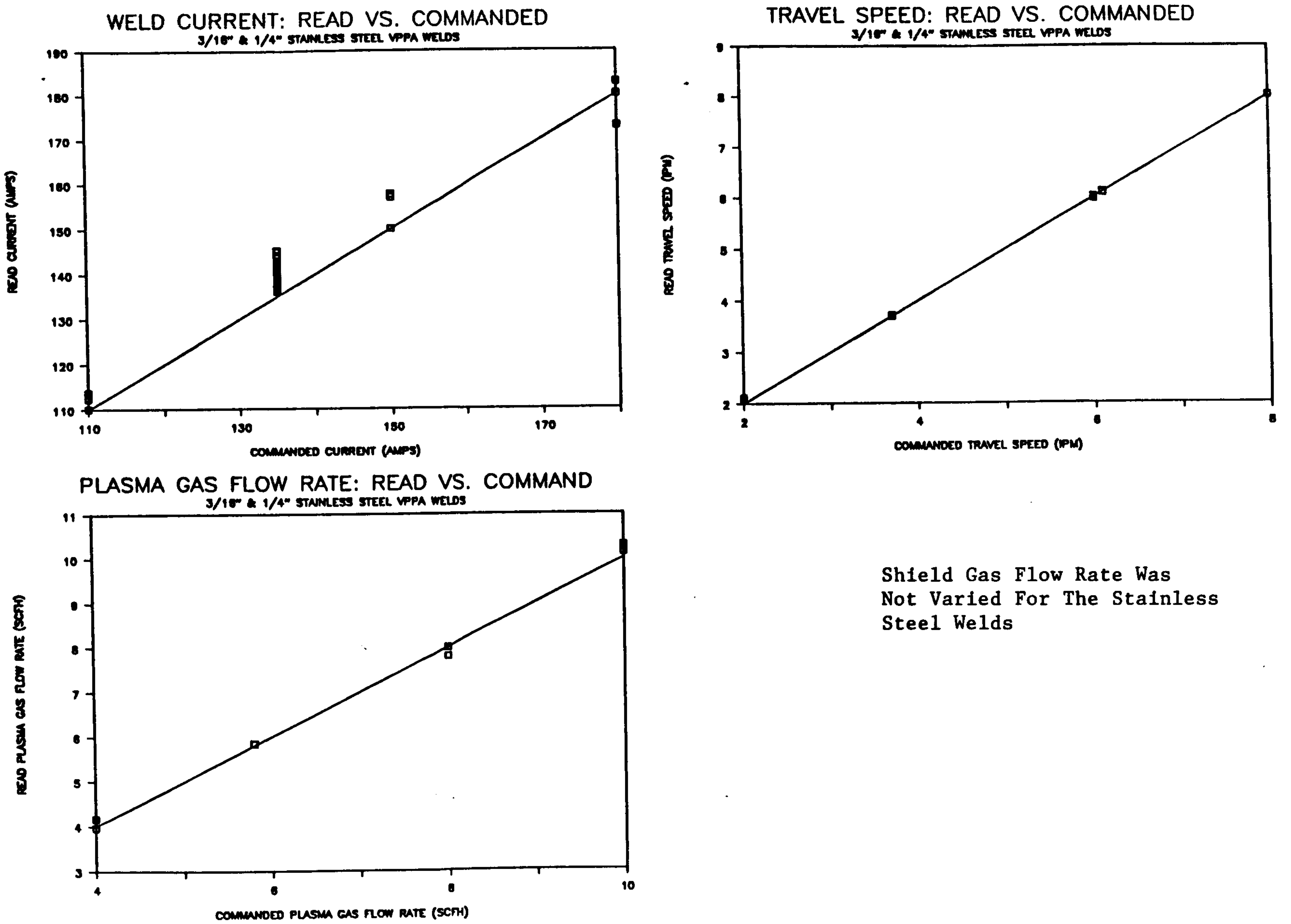


Figure 22. Parameter Sensitivity Study, 1/4" Mild Steel VPPA Welds



Shield Gas Flow Rate Was
Not Varied For The Stainless
Steel Welds

Figure 23. Parameter Sensitivity Study, 3/16" & 1/4" Stainless Steel VPPA Welds

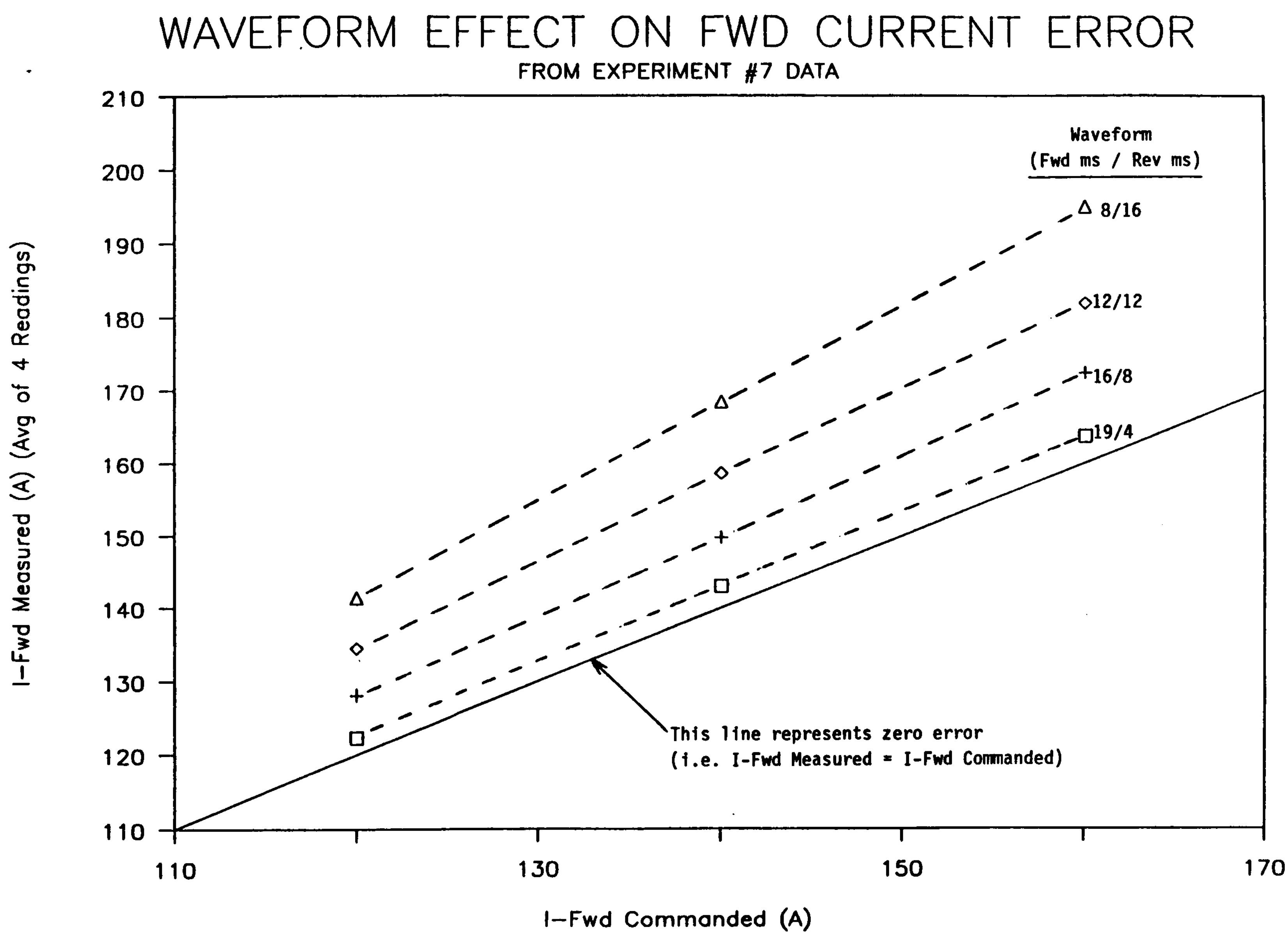


Figure 24. Waveform Effect On Forward Current Error

SECTION 5. CONTROLLER

The control system will have two major components: an observer and a controller. The observer will use measurements of crown width, power generated, travel speed, shield gas flow rate and plasma gas flow rate to determine the state of the system (power efficiency). For this contract, observations were taken manually and no information about sensor or process transient behavior was obtained, i.e. steady state was assumed.

Dr. Nunes has proposed that thermal transients cause emissivity transients, and thus voltage transients, at the electrode. Dynamic effects have been modeled for other welding processes (ref. 6 and 7). To complete the VPPAW control analysis, dynamic responses of all system components must be determined. Additional experiments and analysis will be required to deal with transient behavior.

The controller is based on an inversion of a system model, i.e., given the desired crown and root widths, compute the control variables (travel speed and weld current). Four models were considered: an empirically derived model, the NASA level-0 and level-1 models, and UAH models. The empirical model was based on the first set of experiments and was not continued due to the success of the level-0 implementation, described below. Other research has been done on applying empirical VPPAW models (ref. 8).

5.1 VPPA MODELS

The level-0, level-1 and UAH models predict weld crown and root widths and heights given the weld conditions. These conditions are specified as:

- Material Properties, e.g. conductivity, density, thickness and ambient temperature.
- Control Parameters, e.g. current, travel speed, standoff, wirefeed and gas flow rates.
- Weld Station Description, e.g. orifice and electrode dimensions.
- Thermodynamic Properties, e.g. gas entropies, radiation and convection coefficients.
- Electrical Parameters, e.g. work functions, column and cathode/anode drops.

The models require the following three calculations: power generated, power delivered to the workpiece, and distribution of heat within the workpiece. Power generated (pg) is computed from measured currents and measured or predicted voltages, and is weighted by the appropriate times, i.e.:

$$pg = \frac{\text{(forward power)(19ms) + (reverse power)(4ms)}}{\text{(23ms)}}$$

where 19ms and 4ms are nominal forward and reverse times.

The models differ in the complexity of the energy delivery calculation. The level-0 model assumes that energy efficiency is known (efficiency is defined as power delivered divided by power generated). The level-1 model uses measured currents, predicts voltages, and integrates the enthalpy within the orifice, along the standoff gap, and within the workpiece. The UAH model performs the most detailed calculation and is described in detail in their final report (ref. 3).

All the models use solutions to the linear (constant thermal properties) heat diffusion equation to predict crown and root widths. Analytical solutions exist for such configurations as point and line sources. The level-0 model assumes that the distribution of energy is known. Both the level-1 and UAH models divide the workpiece into segments and compute the heat transferred into each segment. The UAH calculation is more complete, assuming an effective source location and allowing conduction between segments.

The models were used to predict the results of both sets of experiments. Comparison with measured results allowed the models to be improved. Due to problems experienced with the first set of experiments (described in Section 2.3), results in this section refer only to panels from the second set of experiments.

5.2 CONTROLLER STUDIES

The greatest uncertainty in the models is assumed to be energy delivery, i.e. efficiency. The losses associated with radiation, convection and conduction in such an intense process are difficult to predict. Fortunately, measured crown width provides a good indication of the energy transferred to the workpiece.

The second significant uncertainty is related to the distribution of energy absorbed by the workpiece. The shape of the keyhole, convection, pressure, magnetic and gravitational forces control the circulation of molten material in the weld pool. Of particular interest is the relative size of the crown and root widths. A parameter was defined for each model to represent through-thickness power delivered distribution. Values for this parameter were then determined from experiment results as a function of weld conditions.

5.2.1 UAH IMPLEMENTATION

The initial approach was to use the most accurate model to develop a non-real-time control logic and then abstract a real-time implementation. To control efficiency within the UAH model, an 'effective' power (or travel speed) was used that could be adjusted to allow the model to predict the observed crown width.

Distribution was adjusted using the UAH parameter HH, defined to be the position of a 'pseudo' heat source within the workpiece. This parameter was determined from four selected experiment #9 panels as a linear function of current, as follows:

$$HH = (1.0169 + -0.0025 * \text{current}) * \text{width}$$

To evaluate the model, 19 panels were studied with the following procedure:

- The parameter HH was calculated from the measured forward current.
- The 'effective' current was adjusted until the model predicted the measured crown width.
- The predicted root width was compared to the measured root width.

The resulting RMS root prediction error was 0.45 mm (comparable results can be obtained by adjusting travel speed or standoff). This compares favorably with the 0.21 mm repeatability and measurement errors referenced in Section 4.2.6, and continued analysis would reduce this error. The UAH model established the feasibility of a control model but was not continued for the following reasons:

- Computation requirements
- Sensitivity to the source location (HH) parameter
- Unreliable convergence for low (<~120A) currents.

5.2.2 LEVEL-1 IMPLEMENTATION

The level-1 model predicts forward and reverse voltages from work functions and assumed voltage drops. As the voltage prediction error was correlated with error in predicted weld pool volume, a step was added to the analysis procedure that adjusted plasma conductance (column drop) to allow the model to predict measured voltage. As with the UAH model, energy delivery uncertainty was expressed as a current (or speed) multiplier, i.e.:

$$(\text{model input current}) = (\text{ratio}) * (\text{actual current})$$

with the ratio being adjusted to allow the model to predict the measured crown width.

Power distribution was introduced into the level-1 model by introducing a parameter (alpha) that systematically adjusted the plasma enthalpy gradient within the workpiece, i.e.:

integrated gradient = f(alpha,depth) * calculated gradient

f(alpha,depth) = 1.0 + 2.0 * alpha * (0.5 - depth)

where a depth of zero corresponds to the crown and one to the root. Results obtained from root width predictions were comparable to the UAH results.

5.2.3 LEVEL-0 IMPLEMENTATION

The level-0 model is simply:

$$\text{crown width} = C1 * e^{(-C2\ /\ Pc)}$$
$$\text{root width} = C1 * e^{(-C2\ /\ Pr)}$$

where C1 = 4.491567 * (diffusivity / travel speed)
C2 = 2 * pi * conductivity * (width/2) * (Tm - Ta)
Pc (power delivered to the weld crown)
= efficiency * (power generated) * (1.0 + alpha)/2
Pr (power delivered to the weld root)
= efficiency * (power generated) * (1.0 - alpha)/2
Tm = melting temperature
Ta = ambient temperature

Using crown width to determine weld state (efficiency), and weld parameters to predict distribution, this model will satisfactorily predict root widths. The remainder of this section will describe the supporting analysis.

5.3 MODEL ANALYSIS

5.3.1 ALUMINUM

Data from forty-one autogenous full penetration welds was chosen from tests that used 1/4" 2219-T87 aluminum with near nominal values for standoff (4 mm), plasma flow rate (5 scfh argon), shield flow rate (60 scfh helium) and forward/reverse times (19ms/4ms). Forward currents varied from 120A to 160A, and travel speeds varied from 8.7 ipm to 11.7 ipm.

The optimum constant value for alpha was 0.0935 and the RMS root prediction error was 0.56 mm.

As a preliminary technique for improving the model, a correlation study was made of root prediction error against several parameters. Defining two 41 element vectors (one for each panel condition) X and Y,

$$\text{correlation} = \frac{(X - mx) \cdot (Y - my)}{lx * ly}, \text{ where}$$

. = dot product
mx,my = mean value of the components
lx,ly = vector length, e.g. sqrt((X - mx).(X - mx))

The results were:

forward measured voltage	-0.7666
reverse measured voltage	-0.3475
forward predicted voltage	-0.0239
reverse predicted voltage	-0.0235
forward voltage error	-0.7010
reverse voltage error	-0.3564
forward measured current	-0.7803
reverse measured current	-0.7120
reverse current error	0.0119
measured power	-0.8010
delivered power	0.0250
velocity	0.2765
standoff	0.0100
efficiency	0.8122
plasma	-0.0254
shield	-0.0317

The strongest correlations were with power generated terms. The method selected for introducing a correction was to include a linear correction to the distribution parameter for power generated (pg). Solving

$$\text{alpha} = 0.27 - 0.00004522 * pg$$

reduced the RMS root prediction error to 0.35 mm.

5.3.2 MILD STEEL

Twelve autogenous full penetration welds were chosen from tests that used 1/4" A36 mild steel with near nominal values for standoff (4.5 mm), plasma flow rate (4 scfh argon), shield flow rate (40 scfh argon) and forward/reverse times (19ms/4ms). Forward currents varied from 140A to 160A, and travel speeds varied from 4.0 ipm to 4.5 ipm. Optimum constant distribution was 0.59 yielding an RMS root error of 1.25 mm. The resulting correlation analysis demonstrated a stronger correlation with power delivered than power generated, as shown by the following:

forward measured voltage	-0.6743
reverse measured voltage	-0.3582
forward predicted voltage	-0.2911
reverse predicted voltage	-0.2906
forward voltage error	-0.6247
reverse voltage error	-0.3362
forward measured current	-0.7019
reverse measured current	-0.6985
reverse current error	0.5231
measured power	-0.7668
delivered power	0.9389
velocity	0.7139
standoff	-0.3173
efficiency	0.9691
plasma	0.0739
shield	-0.0757

5.3.3 ALUMINUM AND MILD STEEL

To produce a common model for both aluminum and mild steel, the distribution parameter was redefined in terms of both power generated and power delivered (pd), i.e.:

$$\text{alpha} = 0.677 - 0.0001554 * pg + 0.0002167 * pd$$

producing an RMS root error of 0.28 mm.

5.4 MODEL PERFORMANCE

5.4.1 RESIDUALS

The aluminum model was corrected to be

$$\text{alpha} = 0.158 - 0.000053601 * pg + 0.00009743 * pd$$

and the new RMS root error was 0.33 mm.

The residual root errors (predicted - measured) are:

Panel ID	Root Error	Generated Power	Efficiency	Travel Speed	Shield Flow
2A	-0.69	3894.8	0.3838	9.80	61.30
2B	0.02	3875.6	0.3748	8.90	61.00
2C	-0.25	3869.5	0.3897	10.80	61.70
2D	-0.23	3867.3	0.4020	11.70	61.70
2E	-0.06	3850.4	0.4032	11.70	61.80
2F	-0.18	3852.5	0.3877	9.80	61.50
2G	0.34	3852.8	0.3752	8.90	61.30
2H	0.04	3863.2	0.3996	10.80	60.90
2I	0.06	3834.2	0.3933	10.70	61.30
2J	0.01	3891.7	0.3754	9.80	61.20
2K	0.01	3862.5	0.4050	11.70	60.60
2L	0.42	3842.6	0.3672	8.70	61.00
3M	-0.64	3869.9	0.3783	9.70	62.20
3R	-0.09	3851.4	0.3818	9.70	61.30
3V	-0.50	3844.0	0.3689	9.70	60.80
5A	-0.31	3785.9	0.3858	9.50	62.20
5D	0.04	3803.6	0.3833	9.60	61.80
6A	-0.76	3838.5	0.3780	9.70	61.60
6B	0.55	3798.2	0.3929	10.80	61.70
6C	0.01	3817.4	0.3745	8.90	61.20
6D	0.36	3356.7	0.4475	10.90	61.20
6E	0.21	3360.4	0.4259	9.90	61.60
6F	0.09	3339.6	0.4116	9.00	61.20
6G	-0.01	4381.3	0.3334	9.00	61.40
6H	0.36	4345.1	0.3553	10.00	61.40
6I	-0.19	4342.7	0.3622	10.90	61.80
7A1	0.63	3472.3	0.4006	9.50	92.20
7A2	0.37	4191.2	0.3514	9.50	92.20
7A3	0.42	5023.4	0.3195	9.50	92.10
9A	0.36	3778.8	0.3915	9.90	61.70
9B	-0.58	3325.0	0.4337	10.40	62.20
9E	-0.16	4303.8	0.3520	9.50	65.20
9F	0.46	3784.2	0.3890	10.00	64.90
9I	-0.02	4384.9	0.3451	9.40	60.30
9J	-0.09	3365.3	0.4266	10.40	61.70
9M	0.30	3361.2	0.4365	10.40	62.20
9N	0.05	3775.9	0.3961	9.90	62.20
9Q	-0.03	3880.8	0.3751	9.90	62.10
9R	-0.27	4409.9	0.3377	9.40	62.00
9U	0.04	3425.1	0.4205	10.40	62.00
9V	-0.15	4457.0	0.3402	9.50	62.10

Results for the mild steel panels are:

Panel ID	Root Error	Generated Power	Efficiency	Travel Speed	Shield Flow
9AA	0.43	4031.1	0.6626	4.30	41.00
9AB	-0.01	3783.2	0.6032	4.50	40.30
9AE	-0.20	4465.4	0.4618	4.00	40.80
9AF	0.50	4151.9	0.6296	4.30	40.70
9AI	-0.01	4259.5	0.6585	4.00	42.00
9AJ	0.20	3823.9	0.7040	4.50	41.80
9AM	-0.44	3807.5	0.6873	4.50	36.20
9AN	0.23	4113.9	0.5452	4.30	42.70
9AQ	-0.39	4064.6	0.6795	4.30	40.90
9AR	-0.01	4349.0	0.5268	4.00	40.60
9AU	-0.10	3829.9	0.7771	4.50	40.20
9AV	-0.19	4389.7	0.5424	4.00	40.40

5.4.2 CORRELATIONS

The aluminum and steel correlations are:

	Aluminum	Steel
forward measured voltage	-0.1010	-0.1030
reverse measured voltage	-0.2886	0.1149
forward predicted voltage	0.0190	0.2584
reverse predicted voltage	0.0192	0.2593
forward voltage error	-0.1005	-0.1589
reverse voltage error	-0.3108	0.0940
forward measured current	-0.0064	-0.0001
reverse measured current	0.0376	-0.0329
reverse current error	0.1009	-0.0412
measured power	-0.0229	-0.0202
delivered power	-0.0155	0.0200
velocity	-0.0705	0.0780
standoff	-0.0506	0.1959
efficiency	0.0474	0.0031
plasma	-0.0300	-0.0638
shield	0.4024	0.5397

With both metals, shield flow rate is the most significant factor in root width prediction error. The correlations may be used to make an additive correction to the model, e.g. for aluminum:

$$\text{delta} = -0.4024 * \overset{\text{root err length}}{0.2133} * (\text{shield flow} - \overset{\text{shield mean}}{63.9463}) / \overset{\text{shield length}}{51.0835}$$

This correction reduces the RMS root error to 0.30 mm.

Similarly, the steel correction is:

$$\text{delta} = -0.5397 * \underset{\text{length}}{\overset{\text{root err}}{0.0979}} * (\text{shield flow} - \underset{\text{mean}}{\overset{\text{shield}}{40.6333}}) \;/\; \underset{\text{length}}{\overset{\text{shield}}{5.2675}}$$

and the resulting root error is 0.24 mm. It should be noted that the weld controller will assume the nominal (mean) value will be used for shield gas flow rate. Flow rate control may be required if there are significant differences between measured and commanded flow rates.

5.5 CONTROLLER DESCRIPTION

Figure 25 shows an overview describing the control logic. Figure 26 shows a flow chart for the control algorithm. This algorithm will periodically output commanded values for weld power and travel speed, and these values will be maintained by independent feedback control. For power, the measured value can be adjusted using primary current or standoff (voltage), or a combination of the two. A procedure must be selected and stability evaluated.

The principal outputs of the welding process are the measured crown width and the instantaneous values for power generated and travel speed. The control logic will compare the power generated and the measured crown width to estimate efficiency. Based on assumed efficiency, the model will be inverted to predict the power and travel speed required to maintain the specified crown and root widths. It is expected that this control system will converge to the desired crown width, and that the residual root error will be a function of the model's ability to predict distribution from the weld conditions. However, until time dynamics are studied, stability and convergence characteristics will remain unknown. In addition, use of the model presented earlier assumes that the set of experiment panels studied represent the panels to be welded by the controller.

5.5.1 OBSERVER COMPUTATIONS

The observer uses crown width to estimate power delivered (pd). As described in section 5.2.3 (note the factor 1/2 has been removed for clarity):

crown = C1 * exp(-C2 / (pd * (1 + alpha))) , where

alpha = k0 + k1 * pg + k2 * pd.

Substitution produces the quadratic

0 = A * (pd * pd) + B * pd + C, where

A = k2, B = 1 + k0 + k1 * pg and C = C2 / ln(crown / C1) .

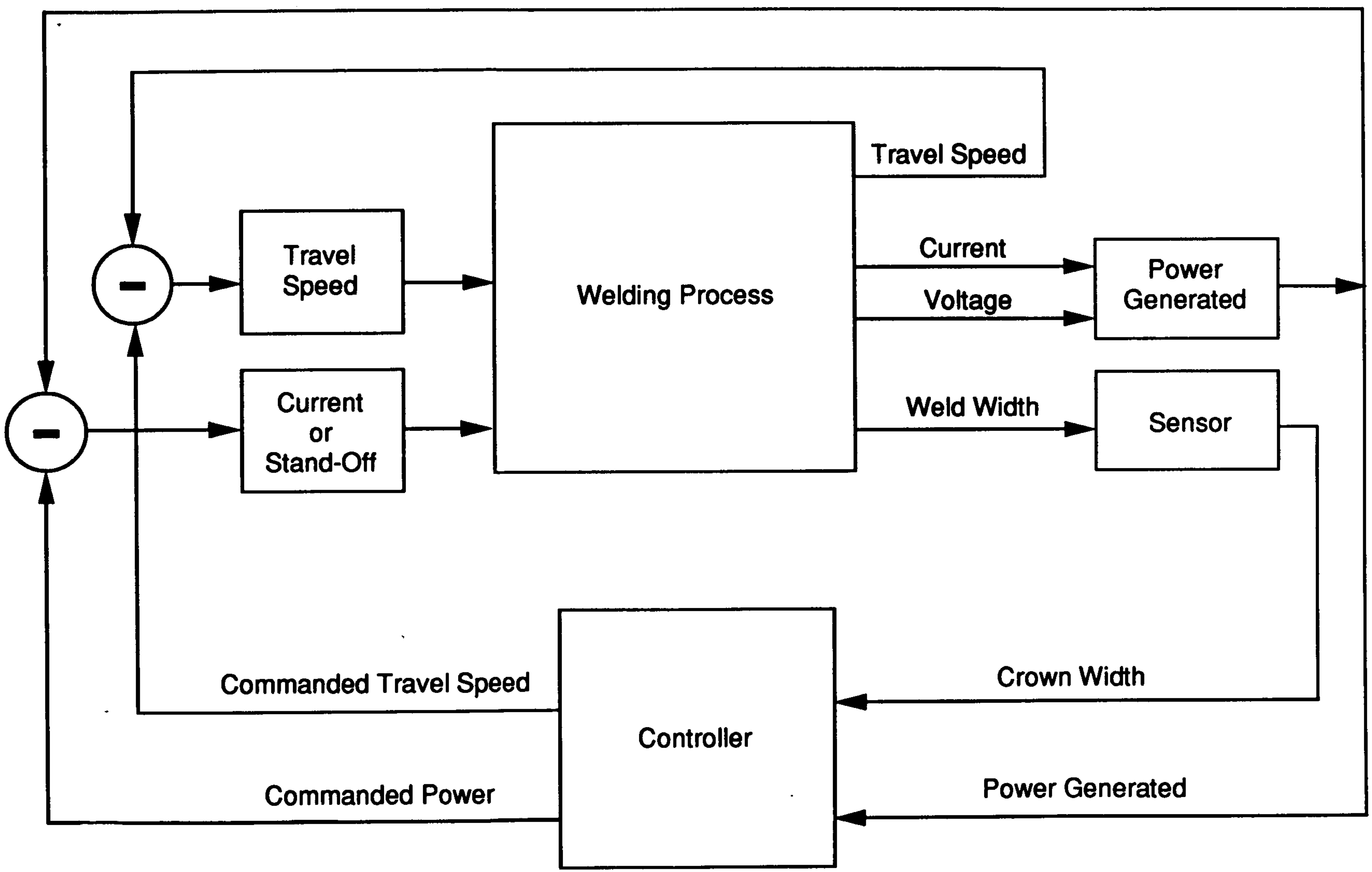


FIGURE 25. CONTROLLER OVERVIEW

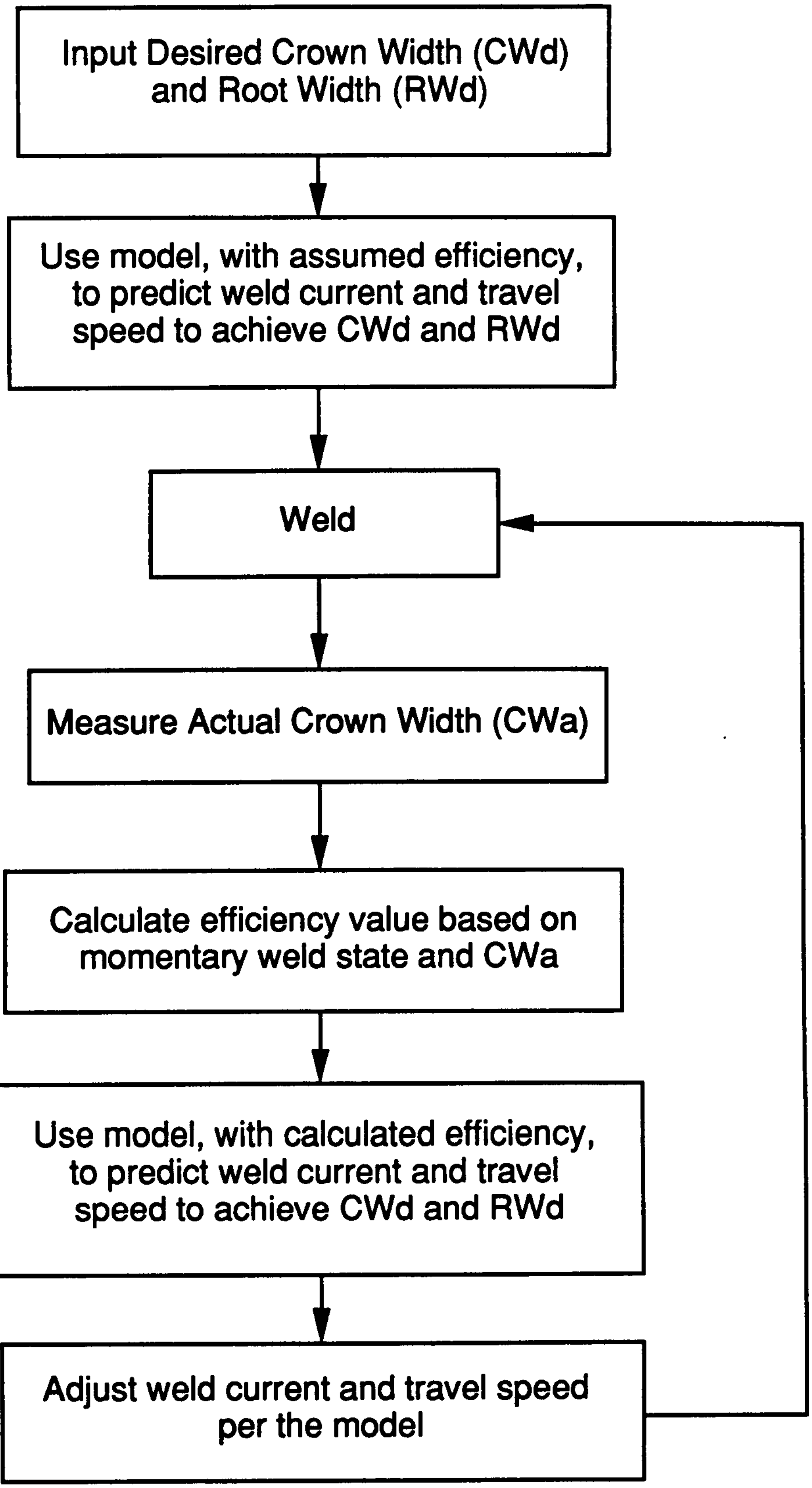


FIGURE 26. CONTROL ALGORITHM

This may be solved using

$$pd = (-B + \mathrm{sqrt}(B * B - 4 * A * C)) / (2 * A)$$

and efficiency = pd / pg.

5.5.2 CONTROLLER COMPUTATIONS

Assuming the efficiency calculated above, and using the desired crown and root widths, the required power input and travel speed are determined as described in section 5.2.3.

Using

$$crown = C1 * \exp(-C2 / (pd * (1 + alpha))) \quad (1)$$
$$root = C1 * \exp(-C2 / (pd * (1 - alpha))) \quad (2)$$

divide equation (1) by equation (2):

$$\frac{crown}{root} = \frac{\exp(-C2 / (pd * (1 + alpha)))}{\exp(-C2 / (pd * (1 - alpha)))}$$

then take the natural log of both sides of the above equation:

$$\ln(crown/root) = \frac{C2}{pd * (1 - alpha)} - \frac{C2}{pd * (1 + alpha)}$$

which reduces to:

$$0 = pd * (1 - alpha^2) * \ln(crown/root) - 2 * C2 * alpha$$

As efficiency is assumed known,

$$pd = efficiency * pg$$
$$alpha = k0 + pg * (k1 + efficiency * k2).$$

This equation is a cubic in pg which may be solved analytically or by iteration (e.g. Newton-Raphson). Having found pg, travel speed is obtained from C1 in (1) or (2), above. If efficiency is determined to be a strong function of power generated, this formulation may have to be modified.

SECTION 6. CONCLUSIONS

Based on this work, the following conclusions are made:

VPPAW weld widths are particularly sensitive to weld current and torch stand-off changes. In general, root width is more sensitive than crown width to parameter changes.

Transitioning from welding to cutting in VPPAW occurs when the weld root width exceeds a critical width, which is dependent on the weldment material/thickness combination.

Slight variations in torch stand-off are suspected of contributing to lack of weld repeatability during the first set of experiments. An NRC fabricated stand-off sensor, developed for the second set of experiments, provided real-time stand-off monitoring and closed-loop control of stand-off. This improved process repeatability.

Another suspected source of lack of weld repeatability is power supply fluctuations. Variations in power generated of about 5% were observed for VPPA welds with static parameters. This problem may vary significantly from one power supply to another. Significant errors between measured and commanded values for weld current and shield gas flow rates were also observed.

Accurate and reliable data acquisition is necessary to perform the type of analyses done for this project. Improvements made by NRC to a NASA-owned data acquisition system (writing custom software and fabricating a power isolation board) were necessary for this project to enable taking accurate data at sufficient sampling rates.

Parameter variations alter keyhole geometry. This affects through-thickness heat distribution into the workpiece, which is represented in the model by integrating heat transfer through the workpiece. Changing this heat transfer distribution from a constant to a parameter-dependent variable improves correlation between the model predictions and test results.

A multi-variable VPPAW control algorithm developed during this project will be capable of real-time control of weld crown and root widths. This algorithm is based on Dr. Nunes' level-0 model. The algorithm controls weld current and travel speed to provide independent control of crown and root widths for 1/4" (6.35 mm) aluminum and mild steel autogenous full penetration welds. By applying the algorithm to sets of welds made during this project, the algorithm accuracy was demonstrated to be comparable to the weld width measurements accuracy.

SECTION 7. RECOMMENDATIONS

Based on the results of this project, the following actions are recommended:

Implement the control algorithm developed for 1/4" aluminum and mild steel VPPA welds into an existing VPPAW controller interfaced with a sensor capable of providing real-time weld crown width measurement. Evaluate performance of this prototype controller. Do additional weld experiments on other material/thickness combinations, and use the results to evaluate and modify (as necessary) the control algorithm to deal with these material/thickness combinations.

Do additional weld experiments and analyses to determine the time dynamic behavior of the VPPAW process. Evaluate and modify (as necessary) the control algorithm to deal with transients.

Perform similar analyses to evaluate and modify (as necessary) the control algorithm for other combinations of thickness & material, for partial penetration welds (cover passes), and for welds with filler wire addition.

Improve repeatability of weld width measurements for any additional weld experiments by automating the width measurement, preferably using the same sensor that will be used in real-time at the VPPAW station.

Improve power supply instrumentation, particularly for weld current and shield gas flow.

Use data acquisition system to regularly monitor the performance of all the VPPAW power supplies at NASA/MSFC. Identify power supply problems so that they can be repaired or accounted for. This will also prevent R&D work from unknowingly being done with a malfunctioning power supply which could cause erroneous results. This could require work to have to be repeated or, worse yet, could cause incorrect conclusions to be reached and disseminated.

Instrument stand-off on the VPPA weld stations. Consider ASOC as an alternative for AVC, at least for stand-off critical R&D welds.

SECTION 8. SUMMARY

NASA uses the VPPAW process extensively for fabrication of Space Shuttle External Tanks. This welding process has been in use at NASA since the late 1970's (ref. 1) but the physics of the process have never been thoroughly understood. In an attempt to advance the level of understanding of VPPAW, Dr. Nunes (NASA) has developed a mathematical model of the process. The work described in this report evaluated and used two versions (level-0 and level-1) of Dr. Nunes' model, and a model derived by Dr. Hung and associates (at UAH) which carries Dr. Nunes' work to a higher level of detail.

Two series of VPPAW experiments were done, using over 400 different welding conditions. Observations were made regarding the behavior of the VPPAW process as a function of specific parameter changes. Process understanding was increased specifically with regards to transitioning from welding to cutting as weld root widths increased above critical widths, the relative effects of parameters on crown and root widths, and the effects of travel speed and plasma gas flow rate on keyhole geometry.

Data acquisition and process control problems were identified in the first set of weld experiments. Improvements in data acquisition and process control were implemented for the second set of experiments. Data from all weld experiments was used to evaluate and suggest improvements to Dr. Nunes' model.

Experimental data and correlations with the model were used to develop a multi-variable control algorithm for use with a future VPPAW controller. This algorithm, based on the level-0 model, was designed to control weld widths (both on the crown and root of the weld) based upon the weld parameters, base metal properties, and real-time observation of the crown width. The algorithm demonstrated accuracy comparable to the weld width measurement accuracy for both aluminum and mild steel welds.

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The authors also would like to thank Dr. Hung and his associates at UAH for their ongoing effort and cooperation in support of this project.

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APPENDIX A
Data Tables For First Set Of Experiments, 1/4" Aluminum

EXPERIMENT #F
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary Torch Standoff: 1, 2, 4, 6, 8 mm

WELD CONDITIONS:

Date of Experiment:	July 25, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No Wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.740"(69.60 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.044"(1.12 mm)
Orifice Thickness L2:	0.129"(3.28 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W279692 #097 Airco
Plasma Gas Flow Rate (scfh)	6.0
Shield Gas:	Helium
Shield Gas Bottle ID:	A01291801KF
Shield Gas Flow Rate (scfh):	100.0

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	130.0
Reverse Current (amps):	130.0
Add. Reverse Current (amps):	60.0
Forward Time (msec):	19.0
Reverse Time (msec):	4.0
Pilot Current (amps):	25.0
Travel Speed (ipm):	8.0
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS

WELD SET: F
PURPOSE: Vary Torch Standoff-1,2,4,6,8 mm
DATE OF LAST CHANGE: 01\20\92
MATERIAL: 1\4"(6.35mm) 2219-T87 Aluminum

Weld	S-O	Weld Current(A)		Weld Voltage(V)		Pilot Current(A)		Pilot Voltage(V)		SGas	PGas	Travel	Weld Width(mm)		Weld Height(mm)		Bead
ID	(mm)	Forward	Reverse	Forward	Reverse	Forward	Reverse	Forward	Reverse	(scfh)	(scfh)	(ipm)	Crown	Root	Crown	Root	Appearance
F201001	1.0	135.5	138.3	24.0	38.0	30.9	41.1	16.5	20.1	102.0	6.04	8.04	7.24	5.08	0.00	1.08	RU,R
F202002	2.0	125.5	129.4	25.6	38.5	30.9	41.1	17.5	18.1	102.0	6.04	8.04	7.85	6.05	0.24	1.24	R
F203004*	4.0	136.7	120.6	29.0	40.0	30.9	42.4	17.5	15.8	102.0	6.04	8.04	9.50	7.11	-0.08	0.99	N
F204006	6.0	131.5	127.5	29.0	40.0	30.9	41.1	17.8	17.5	102.0	6.04	8.04	10.24	8.41	0.08	0.91	N,RR
F205008	8.0	136.2	126.9	36.0	46.0	33.5	41.1	17.5	17.5	102.0	6.04	8.04	11.96	11.35	**	**	RC

* Nominal Weld Parameters and Geometry
** Measurement not available since cutting occurred

EXPERIMENT #G
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary shield gas flow rate: 60, 100, 120, 140 scfh
Vary Torch Standoff: 2, 4, 8 mm

WELD CONDITIONS:

Date of Experiment:	July 26, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	76

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.740"(69.60 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.044"(1.12 mm)
Orifice Thickness L2:	0.129"(3.28 mm)
Electrode Cooling Water Flow Rate:	2 liter\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W279692 #097 Airco
Plasma Gas Flow Rate (scfh)	6.0
Shield Gas:	Helium
Shield Gas Bottle ID:	A01291801KF
Shield Gas Flow Rate (scfh):	variable

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	3.0
Straight Current (amps):	130.0
Reverse Current (amps):	130.0
Add. Reverse Current (amps):	60.0
Forward Time (msec):	19.0
Reverse Time (msec):	4.0
Pilot Current (amps):	25.0
Travel Speed (ipm):	8.0
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS
WELD SET: G
PURPOSE: Vary Shield Gas Flow Rate-60,100,120 140,180,200 SCFH
DATE OF LAST CHANGE: 10\15\91
MATERIAL: 1\4"(6.35mm) 2219-T87 Aluminum

Weld ID	S-O (mm)	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
NOMINAL	4.0	136.7	120.6	29.0	40.0	30.9	42.4	17.5	15.8	102.0	6.04	8.04	9.50	7.11	-0.08	0.99	N
G211042A	2.0	139.0	136.6	24.0	36.0	26.9	37.1	17.8	15.8	45.0	6.04	7.99	7.70	5.77	0.19	0.54	N
G211042B	2.0	136.9	137.8	24.0	36.0	26.9	37.1	17.8	15.8	45.0	6.04	7.99	7.42	4.22	0.52	-0.07	SB
G201062A	2.0	136.8	137.5	26.0	36.0	30.9	41.1	15.9	17.8	64.0	6.04	8.02	8.38	6.86	0.13	0.99	R,LU
G201062B	2.0	140.3	127.1	27.0	38.0	30.9	41.1	15.9	17.8	102.0	6.04	8.02	8.13	6.86	-0.04	1.30	R,LU
G204122A	2.0	134.8	135.0	26.0	36.0	30.9	41.1	14.8	17.8	125.0	6.04	8.03	7.98	6.22	0.09	1.23	R
G204122B	2.0	135.1	132.8	26.0	38.0	30.9	41.1	14.8	17.8	141.0	6.04	8.03	7.80	6.22	0.09	0.96	R
G208182A	2.0	140.2	117.2	28.0	40.0	30.9	40.5	13.8	16.2	184.0	6.04	8.05	8.20	5.84	-1.22	2.47	R,RU,ED
G208182B	2.0	138.2	125.7	28.0	42.0	30.9	40.5	13.8	16.2	204.0	6.04	8.05	7.87	6.10	-1.52	2.56	R,RU,ED
G202064A	4.0	136.6	133.3	30.0	41.0	30.9	43.7	17.5	16.8	64.0	6.04	8.04	9.58	7.70	-0.17	1.02	N
G202064B	4.0	137.1	133.3	30.0	41.0	30.9	43.7	17.5	16.8	102.0	6.04	8.04	9.53	7.37	-0.06	0.86	N
G205124A	4.0	138.5	130.1	28.8	40.0	30.9	42.4	16.5	17.5	125.0	6.04	8.03	9.14	7.60	-0.16	1.01	N
G205124B	4.0	135.8	129.8	28.0	40.0	30.9	42.4	16.5	17.5	141.0	6.04	8.03	9.14	7.62	-0.12	0.98	N
G209184A	4.0	137.5	127.8	28.5	40.0	28.9	40.4	16.5	15.8	184.0	6.04	8.04	9.22	7.54	-0.14	1.08	N
G208184B	4.0	137.0	127.8	29.0	41.0	28.9	40.4	16.5	15.8	204.0	6.04	8.04	9.47	8.26	-0.19	1.29	N,RU
G203068A	8.0	134.3	138.3	37.0	46.0	30.9	41.1	13.8	18.8	64.0	6.04	8.05	15.24	18.80	*	*	C
G203068B	8.0	133.4	130.0	36.0	46.0	30.9	41.1	13.8	18.8	102.0	6.04	8.05	13.21	12.70	*	*	RC
G206128A	8.0	139.1	125.0	36.0	46.0	28.9	41.7	15.8	14.8	125.0	6.04	8.03	11.68	11.43	*	*	LC
G206128B	8.0	136.6	125.6	35.0	45.0	28.9	41.7	15.8	14.8	141.0	6.04	8.03	11.68	11.43	*	*	LC
G210188A	8.0	130.1	132.0	36.0	45.0	28.9	39.1	15.8	16.8	184.0	6.04	8.05	10.92	10.92	*	*	RC
G210188B	8.0	136.1	127.3	35.5	44.0	28.9	39.1	15.8	16.8	204.0	6.04	8.05	10.92	10.92	*	*	RC

* Measurement not applicable since cutting occurred

EXPERIMENT #H
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary plasma gas flow rate: 2, 4, 8 scfh
Vary torch standoff: 2, 4, 8 mm

WELD CONDITIONS:

Date of Experiment:	July 29, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	2219-T87 aluminum
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.740"(69.60 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.044"(1.12 mm)
Orifice Thickness L2:	0.129"(3.28 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W279692 #097 Airco
Plasma Gas Flow Rate (scfh)	variable
Shield Gas:	Helium
Shield Gas Bottle ID:	A01291801KF
Shield Gas Flow Rate (scfh):	100

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	3.0
Straight Current (amps):	130.0
Reverse Current (amps):	130.0
Add. Reverse Current (amps):	60.0
Forward Time (msec):	19.0
Reverse Time (msec):	4.0
Pilot Current (amps):	25.0
Travel Speed (ipm):	8.0
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS
WELD SET: H
PURPOSE: Vary Plasma Gas Flow rate-2,4,8,10 SCFH
DATE OF LAST CHANGE: 10\15\91
MATERIAL: 1\4"(6.35mm) 2219-T87 Aluminum

Weld ID	S-O (mm)	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
NOMINAL	4.0	136.7	120.6	29.0	40.0	30.9	42.4	17.5	15.8	102.0	6.04	8.04	9.50	7.11	-0.08	0.99	N
H201022A	2.0	139.3	136.0	23.0	33.0	30.9	39.8	14.8	15.5	102.0	2.40	8.04	8.38	*	0.20	*	PP
H201022B	2.0	136.1	135.0	25.0	35.0	30.9	39.8	14.8	15.5	102.0	4.16	8.04	7.87	4.57	0.16	0.64	N
H204082A	2.0	139.7	136.9	28.0	39.0	28.9	37.8	16.8	18.5	102.0	8.00	8.05	8.13	6.10	-0.12	0.97	R,LU
H204082B	2.0	137.4	132.0	30.5	41.0	28.9	37.8	16.8	18.5	102.0	10.12	8.05	9.14	7.11	*	2.52	R,ED,XLU
H202024A	4.0	138.9	133.1	26.0	35.0	29.9	40.1	15.5	15.5	102.0	2.40	8.04	10.16	7.37	0.25	0.63	N
H202024B	4.0	137.6	128.0	27.4	38.0	29.9	40.1	15.5	15.5	102.0	4.16	8.04	9.65	6.60	-0.14	0.97	N
H205084A	4.0	137.3	133.6	31.9	43.0	28.9	37.8	15.8	17.8	102.0	8.00	8.05	9.14	7.37	-0.08	1.03	LU
H205084B	4.0	135.7	129.0	34.8	45.0	28.9	37.8	15.8	17.8	102.0	10.12	8.05	9.40	8.13	*	2.07	XLU
H203028A	8.0	135.9	135.0	30.0	40.0	30.9	43.7	14.8	15.2	102.0	2.40	8.05	13.97	13.46	*	*	C
H203028B	8.0	136.7	132.7	33.5	44.0	30.9	43.7	14.8	15.2	102.0	4.16	8.05	12.95	11.94	*	*	RC
H206088A	8.0	138.0	125.0	40.0	49.0	28.9	41.7	17.8	17.5	102.0	8.00	8.03	11.68	11.68	*	*	C
H206088B	8.0	136.5	127.0	40.0	52.0	28.9	41.7	17.8	17.5	102.0	10.12	8.03	10.67	11.43	*	*	C

* Measurement not applicable (such as for cutting) or unavailable due to severe weld deformation (such as extreme undercut)

EXPERIMENT #1
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE:	Vary weld current: 90, 110, 150, 180 amps Vary torch standoff: 2, 4, 8 mm

WELD CONDITIONS:

Date of Experiment:	July 30, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.740"(69.60 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.044"(1.12 mm)
Orifice Thickness L2:	0.129"(3.28 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W279692 #097 Airco
Plasma Gas Flow Rate (scfh)	6.0
Shield Gas:	Helium
Shield Gas Bottle ID:	A01291512WD
Shield Gas Flow Rate (scfh):	100.0

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	130.0
Reverse Current (amps):	130.0
Add. Reverse Current (amps):	60.0
Forward Time (msec):	19.0
Reverse Time (msec):	4.0
Pilot Current (amps):	25.0
Travel Speed (ipm):	8.0
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS

WELD SET: I
PURPOSE: Vary Weld Current-80,110,150,180 AMPS
DATE OF LAST CHANGE: 10\15\91
MATERIAL: 1\4"(6.35mm) 2219-T87 Aluminum

Weld ID	S-O (mm)	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
NOMINAL	4.0	136.7	120.6	29.0	40.0	30.9	42.4	17.5	15.8	102.0	6.04	8.04	9.50	7.11	-0.08	0.99	N
1202092B	2.0	94.2	106.5	22.0	37.0	28.9	37.8	16.5	15.8	106.0	6.04	8.04	7.44		*	*	D,PP
1202092A	2.0	110.0	115.6	24.0	37.0	28.9	36.6	17.5	12.8	106.0	6.04	8.04	9.91	3.81	0.47	0.16	LU,R,SB
1205152B	2.0	152.5	146.8	27.0	39.0	28.9	36.6	16.5	19.7	106.0	6.04	8.05	8.38	6.35	-0.39	1.25	N
1205152A	2.0	179.8	171.4	28.0	41.0	28.9	36.6	16.5	19.7	106.0	6.04	8.05	10.16	15.24	*	*	C
1203094B	4.0	97.0	103.8	26.0	38.0	29.3	37.6	15.8	14.5	106.0	6.04	8.04	7.79		*	*	D,PP
1203094A	4.0	118.9	116.4	29.3	41.0	29.3	37.6	15.8	14.5	106.0	6.04	8.04	8.89	5.84	0.25	0.51	N
1206154A	4.0	154.6	154.4	30.0	43.0	28.9	39.1	16.5	16.2	106.0	6.04	8.06	10.16	8.64	-0.31	1.18	N
1206154B	4.0	187.3	168.8	31.0	43.5	28.9	39.1	16.5	16.2	106.0	6.04	8.06	11.43	15.24	*	*	C
1208098B	8.0	94.7	88.2	32.0	43.7	30.2	39.2	15.8	14.8	106.0	6.04	8.04	10.16	9.65	*	*	RC
1208098A	8.0	113.7	118.8	34.0	46.0	30.2	39.2	15.8	14.8	106.0	6.04	8.04	11.43	10.41	*	*	RC
1207158A	8.0	154.2	141.9	35.0	49.0	30.2	39.2	15.8	14.8	106.0	6.04	8.05	12.70	13.72	*	*	C
1207158B	8.0	188.1	167.5	39.0	50.0	30.2	39.2	15.8	14.8	106.0	6.04	8.05	13.72	19.05	*	*	C

* Measurement not applicable (such as for cutting) or unavailable due to severe weld deformation (such as drooping)

EXPERIMENT #J
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary torch travel speed: 5, 10, 13, 16 ipm
Vary torch standoff: 2, 4, 6, 8 mm

WELD CONDITIONS:

Date of Experiment:	July 30, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.740"(69.60 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.044"(1.12 mm)
Orifice Thickness L2:	0.129"(3.28 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W279692
Plasma Gas Flow Rate (scfh)	6.0
Shield Gas:	Helium
Shield Gas Bottle ID:	A01291512WD
Shield Gas Flow Rate (scfh):	100.0

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	130.0
Reverse Current (amps):	130.0
Add. Reverse Current (amps):	60.0
Forward Time (msec):	19.0
Reverse Time (msec):	4.0
Pilot Current (amps):	25.0
Travel Speed (ipm):	8.0
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS
WELD SET: J
PURPOSE: Vary Travel Speed-5,10,13,16 IPM
DATE OF LAST CHANGE: 10\15\91
MATERIAL: 1\4"(6.35mm) 2219-T87 Aluminum

Weld ID	S-O (mm)	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
NOMINAL	4.0	136.7	120.6	29.0	40.0	30.9	42.4	17.5	15.8	102.0	6.04	8.04	9.50	7.11	-0.08	0.99	N
J201052A	2.0	133.1	136.7	26.0	38.0	30.2	36.6	16.5	18.5	106.0	6.04	5.02	8.89	6.60	-0.47	1.27	N
J201052B	2.0	132.3	129.9	26.0	38.0	30.2	36.6	16.5	18.5	106.0	6.04	10.03	7.37	4.57	0.18	1.25	R
J207132A	2.0	143.7	141.2	26.0	38.0	26.9	37.1	15.8	16.8	106.0	6.04	13.01	6.86	4.83	-0.39	2.10	LU,R,ED
J207132B	2.0	136.2	132.3	25.5	38.0	26.9	37.1	15.8	16.8	106.0	6.04	16.02	6.60	4.32	0.28	0.64	LU
J202054A	4.0	132.7	134.3	30.0	42.0	30.2	39.1	15.8	17.2	106.0	6.04	5.02	10.16	6.86	0.35	1.15	N
J202054B	4.0	133.1	133.7	29.0	42.0	30.2	39.1	15.8	17.2	106.0	6.04	10.02	8.89	5.59	-0.03	0.85	N
J205134A	4.0	130.6	127.0	28.0	42.0	30.9	38.6	15.8	16.2	106.0	6.04	13.06	8.13	5.59	0.30	0.97	U
J205134B	4.0	131.0	132.1	28.0	42.0	30.9	38.6	15.8	16.2	106.0	6.04	16.03	8.13	5.08	0.47	0.76	U
J203058A	8.0	138.7	135.7	36.0	48.0	30.9	38.6	15.8	16.2	106.0	6.04	5.00	13.21	15.49	*	*	RC
J203058B	8.0	129.1	124.6	36.0	48.0	30.9	38.6	15.8	16.2	106.0	6.04	10.03	11.94	10.92	*	*	RC
J206138A	8.0	131.3	121.3	35.9	48.0	30.2	36.6	15.8	15.8	106.0	6.04	13.06	9.65	6.86	0.10	1.45	U
J206138B	8.0	134.2	118.1	34.0	48.0	30.2	36.6	15.8	15.8	106.0	6.04	16.05	9.40	6.86	0.29	1.57	U,LU

* Measurement not applicable since cutting occurred

EXPERIMENT #K
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary torch standoff: 2, 4, 6, 8, 10 mm in Flat (Down-hand) position

WELD CONDITIONS:

Date of Experiment:	August 1, 1991
Tool:	Station #2
Weld Orientation:	Flat (Down-hand)
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	73

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.700"(68.58 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.043"(3.63 mm)
Orifice Thickness L2:	0.129"(3.28 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W279692 #097 Airco
Plasma Gas Flow Rate (scfh)	6.5
Shield Gas:	Helium
Shield Gas Bottle ID:	A01291512WD
Shield Gas Flow Rate (scfh):	80.0

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	130.0
Reverse Current (amps):	130.0
Add. Reverse Current (amps):	60.0
Forward Time (msec):	19.0
Reverse Time (msec):	4.0
Pilot Current (amps):	25.0
Travel Speed (ipm):	12.5
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS
WELD SET: K
PURPOSE: Down Hand (Flat) Welding Vary Standoff-2,4,6,8,10 mm Change Travel Speed-12.5,16 IPM
DATE OF LAST CHANGE: 10\15\91
MATERIAL: 1\4"(6.35mm) 2219-T87 Aluminum

Weld ID	S-O (mm)	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
NOMINAL	4.0	136.7	120.6	29.0	40.0	30.9	42.4	17.5	15.8	102.0	6.04	8.04	9.50	7.11	-0.08	0.99	N
K201002A	2.0	139.2	140.0	25.0	39.0	28.9	35.6	15.8	17.5	83.0	6.50	12.84	6.18	4.06	-0.48	1.46	R,LU,RU
K201002B	2.0	131.9	137.8	25.4	38.0	28.9	35.6	15.8	17.5	83.0	6.50	16.00	6.49	4.59	0.13	0.52	N
K202004A	4.0	134.9	127.9	29.6	42.0	28.9	40.4	15.8	16.5	83.0	6.50	12.52	8.17	6.74	-0.40	1.36	U
K202004B	4.0	134.2	137.5	29.6	42.0	28.9	40.4	15.8	16.5	83.0	6.50	15.99	7.96	6.56	-0.97	2.40	U,ED
K203006A	6.0	130.2	128.1	31.0	46.0	27.7	40.4	16.5	16.8	83.0	6.50	12.54	8.95	8.52	-0.67	1.77	U,ED
K203006B	6.0	133.8	122.9	32.0	46.0	27.7	40.4	16.5	16.8	83.0	6.50	16.09	8.42	7.82	-0.72	2.10	U,ED
K204008A	8.0	131.6	128.6	34.0	48.0	27.7	39.1	16.5	14.2	87.0	6.50	12.47	9.75	9.08	-0.97	2.48	U,ED,LU
K204008B	8.0	132.3	126.2	34.0	48.0	27.7	39.1	16.5	14.2	87.0	6.50	16.04	9.13	8.32	-0.99	2.47	U,ED
K205010A	10.0	126.7	132.5	36.0	49.0	28.9	36.6	15.8	16.2	87.0	6.50	12.50	10.93	15.06	*	*	C
K205010B	10.0	134.8	125.9	36.0	49.0	28.9	36.6	15.8	16.2	87.0	6.50	15.93	9.99	12.44	*	*	C

* Measurement unavailable since cutting occurred

ORTHOGONAL ARRAY EXPERIMENT
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Perform an L18 orthogonal array with two levels of shield gas (140 and 200 scfh), three levels of torch stand-off (2, 4, 6 mm), three levels of weld current (114, 127, 140 A), three levels of plasma gas (4.50, 5.75, 7.00 scfh), and three levels of travel speed (6.0, 7.3, 8.6 ipm).

WELD CONDITIONS:

Date of Experiment:	September 4, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.576"(65.43 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047"(1.19mm)
Orifice Thickness L2:	0.126"(3.20 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	H35687
Plasma Gas Flow Rate (scfh)	varied
Shield Gas:	Helium
Shield Gas Bottle ID:	A062230JLI2
Shield Gas Flow Rate (scfh):	varied

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	130.0
Reverse Current (amps):	130.0
Add. Reverse Current (amps):	60.0
Forward Time (msec):	19.0
Reverse Time (msec):	4.0
Pilot Current (amps):	25.0
Travel Speed (ipm):	8.0
Wire Feed Rate (ipm)	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS
WELD SET: Orthogonal Array
PURPOSE: Examine The Effects of Variation of Parameters on Weld Geometry
DATE OF LAST CHANGE: 01\20\92
MATERIAL: 1\4"(6.35mm) 2219-T87 Aluminum

Weld ID	S-O (mm)	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
MAIN ARRAY:																	
0101	2.0	121.6	131.0	24.0	36.0	28.9	37.8	15.8	18.8	145.0	4.52	6.00	7.21	4.50	0.10	0.79	R,LU
0102	2.0	136.5	135.0	26.0	37.0	28.9	37.8	14.8	18.2	145.0	5.64	7.30	7.37	5.36	-0.49	1.53	R
0103	2.0	148.4	140.0	29.0	41.0	28.9	37.8	15.8	19.8	145.0	6.80	8.61	7.67	6.32	-0.87	2.31	ED
0104	4.0	120.4	130.0	26.0	37.0	28.9	36.6	14.8	15.2	145.0	4.52	7.29	8.94	5.87	-0.06	0.82	N
0105	4.0	*127.0	**	26.0	38.0	28.2	37.1	14.8	18.2	145.0	5.64	8.60	8.66	5.82	-0.08	0.91	N,LU
0106	4.0	*140.0	**	24.0	36.0	27.7	37.8	15.8	19.2	145.0	6.80	6.00	9.17	7.85	-0.47	1.28	N
0107-2	6.0	123.1	120.0	29.0	40.0	27.7	37.8	15.8	16.2	145.0	5.84	5.99	9.60	6.83	-0.11	1.03	N
0108	6.0	142.0	126.0	29.0	40.0	27.7	39.1	16.5	16.2	145.0	7.20	7.31	9.40	6.91	-0.19	1.30	RU
0109	6.0	151.5	150.0	29.0	38.0	27.7	37.8	15.8	18.2	145.0	4.10	8.59	10.03	7.19	-0.14	1.27	N,RU
0110-2	2.0	126.2	130.0	23.0	34.0	27.7	36.6	15.8	15.8	214.0	7.00	8.60	7.01	4.60	-0.38	1.97	XU,ED
0111-2	2.0	138.2	134.0	24.0	36.0	28.9	36.6	14.8	14.8	214.0	4.52	5.99	7.87	4.72	-0.04	0.92	R
0112	2.0	149.2	145.0	28.0	41.0	28.3	38.5	15.5	17.8	214.0	5.74	7.29	7.39	7.16	-1.40	2.71	ED
0113-2	4.0	122.9	127.5	26.0	38.0	28.9	37.8	15.8	14.1	214.0	5.80	8.60	8.31	5.26	0.22	0.60	N,RU
0114-2	4.0	138.5	130.0	28.0	40.0	28.9	37.8	14.8	17.1	214.0	7.00	6.00	9.09	7.59	-0.47	1.45	LU
0115	4.0	145.0	141.0	27.4	38.0	27.7	36.6	15.5	17.5	214.0	4.68	7.30	9.30	7.92	-0.61	1.52	N
0116	6.0	122.8	128.5	30.0	40.0	27.7	35.9	14.2	16.2	214.0	7.00	7.32	9.25	7.21	-0.14	1.68	RU
0117-3	6.0	*127.0	**	26.0	36.0	27.7	36.6	15.8	12.2	214.0	4.68	8.60	9.30	6.93	-0.14	1.03	N
0118	6.0	150.9	141.0	30.0	40.0	30.2	37.8	15.8	15.5	214.0	5.64	6.00	10.29	9.96	-0.75	1.77	ED,SB,LU,LC
CONFIRMATION TESTS:																	
0119-A	4.0	148.2	147.5	28.0	37.0	27.7	36.6	14.8	16.6	145.0	4.52	7.31	9.75	7.49	-0.37	1.30	N
0123	6.0	150.2	143.5	28.0	40.0	27.7	37.8	16.8	18.5	145.0	7.00	6.00	8.15	6.81	-0.76	1.85	ED
0126	2.0	124.0	122.5	23.0	36.0	28.9	37.8	14.2	16.2	214.0	4.52	8.61	6.50	4.11	0.23	1.46	R,RU,SB

* Bad Strip Chart Recording-Forward Current From Computer Printout
** Reverse Current Not Available (not on computer printout)

APPENDIX B

Data Tables For First Set Of Experiments, 1/4" Mild Steel

EXPERIMENT #F
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary torch standoff: 2, 4, 6, 8, 10 mm

WELD CONDITIONS:

Date of Experiment:	August 23, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	Mild Steel
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.480"(62.99 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047"(1.19 mm)
Orifice Thickness L2:	0.125"(3.18 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W300287
Plasma Gas Flow Rate (scfh)	4.16
Shield Gas:	Argon
Shield Gas Bottle ID:	84260K
Shield Gas Flow Rate (scfh):	56.5
Back Purge Gas:	Helium
Gas Bottle ID:	A01291553WD
Flowrate (scfh):	70
Pressure (psia):	<15
Trailer Shield Gas:	Argon
Gas Bottle ID:	W82638
Flowrate (scfh):	60

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	145
Reverse Current (amps):	145
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4
Pilot Current (amps):	~24
Travel Speed (ipm):	2.8
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS
WELD SET: F
PURPOSE: Vary Torch Standoff-2,4,6,8,10 mm
DATE OF LAST CHANGE: 10\23\91
MATERIAL: 1\4"(6.35mm) A36 Mild Steel

Weld ID	S-O (mm)	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
F203044B	2.0	157.5	151.5	25.0	34.0	29.7	39.2	14.8	22.1	56.5	4.16	3.70	9.04	5.74	-0.54	2.30	ED,RR
F203044A*	4.0	158.0	156.1	25.0	34.0	29.7	39.2	14.8	22.1	56.5	4.16	3.70	9.75	5.31	0.41	-0.48	N
F204066A	6.0	160.8	157.1	25.0	35.0	28.9	36.6	14.8	21.2	60.0~	4.00~	3.70	10.28	4.80	1.30	0.22	U,SB
F204066B	8.0	160.6	159.7	26.0	36.0	28.9	36.6	14.8	21.2	60.0~	4.00~	3.70	10.72	5.27	2.64	-0.10	U,SB
F204066C	10.0	160.2	163.3	27.0	38.0	28.9	36.6	14.8	21.2	60.0~	4.00~	3.70	11.86	4.52	2.33	-0.13	XU,SB

* Nominal Weld Parameters and Geometry
~ Measurements Taken From Computer Print-out Since Strip Chart Recording Was Bad

EXPERIMENT #G
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary shield gas flow rate: 20, 40, 50, 60, 80, 100 scfh

WELD CONDITIONS:

Date of Experiment:	August 23, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	Mild Steel
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.650"(67.31 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.174"(4.42 mm)
Orifice Thickness L2:	0.129"(3.28 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W300287
Plasma Gas Flow Rate (scfh)	4.16
Shield Gas:	Argon
Shield Gas Bottle ID:	A8986
Shield Gas Flow Rate (scfh):	variable
Back Purge Gas:	Helium
Gas Bottle ID:	A01291552WD; A01291555WD
Flowrate (scfh):	70
Pressure (psia):	<15
Trailer Shield Gas:	Argon
Gas Bottle ID:	AA16730
Flowrate (scfh):	60

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	155
Reverse Current (amps):	155
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4
Pilot Current (amps):	~24
Travel Speed (ipm):	3.7
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS
WELD SET: G
PURPOSE: Vary Shield Gas Flow Rate-20,40,50,60,80,100 SCFH
DATE OF LAST CHANGE: 11\01\91
MATERIAL: 1\4"(6.35mm) A36 Mild Steel

Weld	S-O	Weld Current(A)		Weld Voltage(V)		Pilot Current(A)		Pilot Voltage(V)		SGas	PGas	Travel	Weld Width(mm)		Weld Height(mm)		Bead
ID	(mm)	Forward	Reverse	Forward	Reverse	Forward	Reverse	Forward	Reverse	(scfh)	(scfh)	(ipm)	Crown	Root	Crown	Root	Appearance
NOMINAL	4.0	158.0	156.1	25.0	34.0	29.7	39.2	14.8	22.1	56.5	4.16	3.70	9.75	5.31	0.41	-0.48	N
G201502C	2.0	163.9	160.0	25.0	34.0	28.4	38.6	15.2	23.2	25.5	4.16	3.71	9.98	5.56	0.01	1.52	N,RR
G201502B	2.0	165.3	157.5	25.0	34.0	28.4	38.6	15.2	23.2	49.0	4.16	3.71	9.78	5.11	0.02	1.44	N,RR
G201502A	2.0	167.1	155.0	25.0	34.0	28.4	38.6	15.2	23.2	58.0	4.16	3.71	10.05	5.51	0.07	1.37	N,RR
G202602A	2.0	162.8	160.4	25.0	34.0	28.4	38.6	15.2	23.2	72.0	4.32	3.71	9.25	5.56	-0.33	2.29	ED,RR
G202602B	2.0	163.5	159.3	25.6	34.0	28.4	38.6	15.2	23.2	91.0	4.32	3.71	9.66	5.32	-0.36	2.40	ED,RR
G202602C	2.0	163.9	160.8	26.0	34.0	28.4	38.6	15.2	23.2	113.5	4.32	3.71	9.30	5.63	-0.70	2.77	ED,RR
G203504C	4.0	164.0	160.0	26.0	34.0	30.9	41.0	15.8	23.2	25.5	4.32	3.70	9.53	6.29	0.30	1.20	N
G203504B	4.0	162.8	162.6	26.0	34.0	30.9	41.0	15.8	23.2	45.0	4.32	3.70	10.08	5.58	0.51	0.78	N
G203504A	4.0	164.5	157.6	26.0	34.0	30.9	41.0	15.8	23.2	56.5	4.32	3.70	10.46	5.36	0.84	0.80	N
G204604A	4.0	164.9	162.0	26.0	34.0	29.7	37.8	15.8	21.8	72.0	4.32	3.71	9.58	5.69	0.84	0.91	U
G204604B	4.0	161.9	155.0	26.0	34.0	29.7	37.8	15.8	21.8	91.0	4.32	3.71	9.69	5.23	0.47	1.51	RU
G204604C	4.0	160.4	160.0	26.0	34.0	29.7	37.8	15.8	21.8	113.5	4.32	3.71	9.96	5.41	0.08	2.00	RU
G205508C	8.0	166.3	165.0	28.0	36.0	*	*	*	*	25.5	4.32	3.72	10.8	4.8	1.28	0.14	SB
G205508B	8.0	163.7	161.2	28.0	36.0	*	*	*	*	49.0	4.32	3.72	10.1	4.4	1.12	0.07	SB
G205508A	8.0	164.2	157.5	28.0	36.0	*	*	*	*	58.0	4.32	3.72	10.6	4.3	1.03	0.34	U,SB
G206608A	8.0	164.6	167.0	27.0	34.0	30.9	41.0	15.8	20.8	72.0	4.16	3.71	11.0	4.4	1.75	0.18	U,SB,XRU
G206608B	8.0	163.7	167.5	27.0	34.0	30.9	41.0	15.8	20.8	91.0	4.16	3.71	10.6	3.9	1.69	0.19	U,XRU
G206608C	8.0	163.4	167.3	27.0	34.0	30.9	41.0	15.8	20.8	113.5	4.16	3.71	11.0	4.0	1.03	1.07	U,RU

*Pilot Arc Photograph Not Available For Measurement

EXPERIMENT #H
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary plasma gas flow rate: 2, 8, 10 scfh

WELD CONDITIONS:

Date of Experiment:	August 23, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	Mild Steel
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.480"- 2.625"(62.99 mm - 66.68 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047"(1.19 mm)
Orifice Thickness L2:	0.125"(3.18 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W300287
Plasma Gas Flow Rate (scfh)	variable
Shield Gas:	Argon
Shield Gas Bottle ID:	84260K
Shield Gas Flow Rate (scfh):	56.5
Back Purge Gas:	Helium
Gas Bottle ID:	A01291552WD
Flowrate (scfh):	70
Pressure (psia):	<15
Trailer Shield Gas:	Argon
Gas Bottle ID:	W82638
Flowrate (scfh):	60

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	145
Reverse Current (amps):	145
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	~24
Travel Speed (ipm):	2.8
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS

WELD SET:	H
PURPOSE:	Vary Plasma Gas-2,8,10 SCFH
DATE OF LAST CHANGE:	6\16\92
MATERIAL:	1\4"(6.35mm) A36 Mild Steel

Weld ID	S-O (mm)	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
NOMINAL	4.0	158.0	156.1	25.0	34.0	29.7	39.2	14.8	22.1	56.5	4.16	3.70	9.75	5.31	0.41	-0.48	N
H204022B	2.0	160.7	165.0	28.0	38.0	27.7	40.4	15.8	25.6	60.0	8.00	3.70	9.73	5.72	-0.67	2.91	ED
H204022C	2.0	160.6	165.0	29.0	40.0	27.7	40.4	15.8	25.6	60.0	10.20	3.70	10.06	5.33	-0.35	3.18	ED
H205024A	4.0	164.3	163.6	23.0	32.0	27.7	40.4	15.8	21.5	60.0	2.40	3.70	10.28	*	*	*	D,PP
H205024B	4.0	160.1	157.7	28.0	38.0	27.7	40.4	15.8	21.5	60.0	8.00	3.70	10.23	5.21	0.96	0.89	U,LU,SB
H205024C	4.0	160.8	160.6	29.0	39.0	27.7	40.4	15.8	21.5	60.0	10.10	3.70	10.29	4.98	1.33	1.14	U,LU,SB
H206028A	8.0	163.5	157.5	25.0	34.0	27.7	37.8	15.8	23.2	56.5	2.40	3.70	11.13	*	*	*	D,PP
H206028B	8.0	164.9	160.0	31.0	40.0	27.7	37.8	15.8	23.2	56.5	8.00	3.70	10.29	6.10	1.35	1.10	XU
H206028C	8.0	159.4	166.0	32.0	42.0	27.7	37.8	15.8	23.2	56.5	10.10	3.70	11.40	6.86	*	0.67	D,SB,C

* Measurement not applicable (such as for cutting) or unavailable due to severe weld deformation (such as drooping)

EXPERIMENT #I
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary weld current: 110, 135, 175, 200 amps

WELD CONDITIONS:

Date of Experiment:	August 23, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	Mild Steel
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.650"(67.31 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.174"(4.42 mm)
Orifice Thickness L2:	0.129"(3.28 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W300287
Plasma Gas Flow Rate (scfh)	4.0
Shield Gas:	Argon
Shield Gas Bottle ID:	A8986
Shield Gas Flow Rate (scfh):	50
Back Purge Gas:	Helium
Gas Bottle ID:	A01291555WD
Flowrate (scfh):	70
Pressure (psia):	<15
Trailer Shield Gas:	Argon
Gas Bottle ID:	AA16730
Flowrate (scfh):	60

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	155
Reverse Current (amps):	155
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4
Pilot Current (amps):	~24
Travel Speed (ipm):	3.7
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS
WELD SET: I
PURPOSE: Vary Weld Current-110,135,175,200 amps
DATE OF LAST CHANGE: 6\16\92
MATERIAL: 1\4"(6.35mm) A36 Mild Steel

Weld ID	S-O (mm)	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
NOMINAL	4.0	158.0	156.1	25.0	34.0	29.7	39.2	14.8	22.1	56.5	4.16	3.70	9.75	5.31	0.41	-0.48	N
1202132B	2.0	116.2	131.2	11.0	20.0	27.7	37.8	16.2	18.2	60.0	4.34	3.72	8.53	*	*	*	D,PP
1202132A	2.0	145.9	149.0	**	***	27.7	37.8	16.2	18.2	60.0	4.34	3.72	9.91	*	0.75	*	D,PP
1204172A	2.0	189.9	160.6	25.0	34.0	27.7	36.6	15.8	20.8	56.5	4.32	3.71	10.26	7.52	0.25	2.42	U,LU,C
1204172B	2.0	213.0	187.5	26.0	35.0	27.7	36.6	15.8	20.8	56.5	4.32	3.71	11.01	13.84	*	*	D,C
1201134B	4.0	116.2	121.0	22.0	31.0	29.7	38.6	14.8	19.2	56.5	4.32	3.71	8.89	*	1.08	*	D,PP
1201134A	4.0	143.1	148.5	24.0	32.0	29.7	38.6	14.8	19.2	56.5	4.32	3.71	10.46	3.30	1.49	-0.01	XU,SB
1204174A	4.0	184.9	163.4	26.0	35.0	27.7	39.1	15.8	19.8	60.0	4.32	3.72	10.84	7.32	0.70	1.77	XRU
1204174B	4.0	213.7	180.6	28.0	36.0	27.7	39.1	15.8	19.8	60.0	4.32	3.72	11.96	13.41	*	*	D,C
1203138B	8.0	116.0	127.7	25.0	33.0	27.7	36.6	14.8	19.6	60.0	4.32	3.70	10.06	*	*	*	D,PP
1203138A	8.0	142.2	142.0	26.0	34.0	27.7	36.6	14.8	19.6	60.0	4.32	3.70	10.41	3.66	*	*	D,SB
1204178A	8.0	184.8	161.4	28.0	38.0	27.7	36.6	15.8	21.2	56.5	4.32	3.70	12.14	7.37	*	*	D,C
1204178B	8.0	211.6	180.0	29.0	39.0	27.7	36.6	15.8	21.2	56.5	4.32	3.70	13.36	12.14	*	*	D,C

* Measurement not applicable (such as for cutting) or unavailable due to severe weld deformation (such as drooping)
** Forward Voltage Alternated Between 25 and 10 Volts
*** Reverse Voltage Alternated Between -30 and -18 Volts

EXPERIMENT #J
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary travel speed: 2, 3, 6, 8 ipm

WELD CONDITIONS:

Date of Experiment:	August 23, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	Mild Steel
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.650"(67.31 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.174"(4.42 mm)
Orifice Thickness L2:	0.129"(3.28 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W300287
Plasma Gas Flow Rate (scfh)	4.0
Shield Gas:	Argon
Shield Gas Bottle ID:	A8986
Shield Gas Flow Rate (scfh):	50
Back Purge Gas:	Helium
Gas Bottle ID:	A01291520WD
Flowrate (scfh):	70
Pressure (psia):	<15
Trailer Shield Gas:	Argon
Gas Bottle ID:	AA16730
Flowrate (scfh):	60

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	155
Reverse Current (amps):	155
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4
Pilot Current (amps):	~24
Travel Speed (ipm):	3.7
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS
WELD SET: J
PURPOSE: Vary Torch Travel Speed-2,3,6,8 ipm
DATE OF LAST CHANGE: 9\30\91
MATERIAL: 1\4"(6.35mm) A36 Mild Steel

Weld	S-O	Weld Current(A)		Weld Voltage(V)		Pilot Current(A)		Pilot Voltage(V)		SGas	PGas	Travel	Weld Width(mm)		Weld Height(mm)		Bead
ID	(mm)	Forward	Reverse	Forward	Reverse	Forward	Reverse	Forward	Reverse	(scfh)	(scfh)	(ipm)	Crown	Root	Crown	Root	Appearance
NOMINAL	4.0	158.0	156.1	25.0	34.0	29.7	39.2	14.8	22.1	56.5	4.16	3.70	9.75	5.31	0.41	-0.48	N
J202032B	2.0	162.9	155.1	26.0	36.0	27.7	36.6	14.8	22.2	56.5	4.32	2.02	12.83	10.16	0.47	1.44	LC
J202032A	2.0	163.8	154.8	26.0	34.0	27.7	36.6	14.8	22.2	56.5	4.32	3.01	10.59	7.54	0.11	1.85	N
J205062A	2.0	165.3	153.6	24.0	32.0	29.3	38.2	14.8	19.5	56.5	4.16	6.01	8.93	*	*	*	D,PP
J205062B	2.0	162.9	159.0	24.5	32.0	29.3	38.2	14.8	19.5	56.5	4.16	8.07	7.70	*	*	*	D,PP
J201034B	4.0	162.2	156.4	27.0	36.0	27.7	37.8	15.8	22.6	56.5	4.32	2.07	13.18	9.27	*	*	LC
J201034A	4.0	163.0	153.6	26.0	34.0	27.7	37.8	15.8	22.6	56.5	4.32	3.00	11.35	6.42	0.28	1.35	N
J204064A	4.0	166.5	155.0	26.0	33.0	27.7	37.8	15.8	23.2	60.0	4.32	6.01	8.36	4.39	1.93	-0.25	XU,SB
J204064B	4.0	164.9	155.6	26.0	33.0	27.7	37.8	15.8	23.2	60.0	4.32	8.02	7.57	*	*	*	D,PP
															*	*	
J203038B	8.0	163.5	150.8	29.0	38.0	27.7	37.8	15.8	23.6	56.5	4.32	2.09	13.35	11.14	*	*	ED,RC
J203038A	8.0	162.4	157.5	28.0	36.0	27.7	37.8	15.8	23.6	56.5	4.32	3.00	12.60	7.39	*	*	ED,RC
J206068A	8.0	163.2	162.3	27.0	35.0	27.7	37.8	14.8	22.8	60.0	4.16	6.00	8.94	*	*	*	D,PP
J206068B	8.0	162.0	165.0	27.0	35.0	27.7	37.8	14.8	22.8	60.0	4.16	8.03	7.70	*	*	*	D,PP

* Measurement not applicable (such as for cutting) or unavailable due to severe weld deformation (such as drooping)

EXPERIMENT #K
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary torch standoff for downhand (flat) welds: 2, 4, 6, 8 mm

WELD CONDITIONS:

Date of Experiment:	August 23, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	Mild Steel
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.830"(71.88 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047"(1.19 mm)
Orifice Thickness L2:	0.126"(3.20 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	H35687
Plasma Gas Flow Rate (scfh)	4.0
Shield Gas:	Argon
Shield Gas Bottle ID:	W25252
Shield Gas Flow Rate (scfh):	50
Back Purge Gas:	Helium
Gas Bottle ID:	A062230JL62
Flowrate (scfh):	70
Pressure (psia):	<15
Trailer Shield Gas:	Argon
Gas Bottle ID:	W188743
Flowrate (scfh):	60

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	3.0
Straight Current (amps):	145
Reverse Current (amps):	145
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4
Pilot Current (amps):	~26
Travel Speed (ipm):	2.8
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS

WELD SET:	K
PURPOSE:	Vary Torch Standoff in Down Hand Position-2,4,6,8 mm
DATE OF LAST CHANGE:	11\01\91
MATERIAL:	1\4"(6.35mm) A36 Mild Steel

Weld	S-O	Weld Current(A)		Weld Voltage(V)		Pilot Current(A)		Pilot Voltage(V)		SGas	PGas	Travel	Weld Width(mm)		Weld Height(mm)		Bead
ID	(mm)	Forward	Reverse	Forward	Reverse	Forward	Reverse	Forward	Reverse	(scfh)	(scfh)	(ipm)	Crown	Root	Crown	Root	Appearance
NOMINAL	4.0	158.0	156.1	25.0	34.0	29.7	39.2	14.8	22.1	56.5	4.16	3.70	9.75	5.31	0.41	-0.48	N
K203022A	2.0	163.6	157.5	25.2	34.0	27.7	36.6	14.8	23.2	60.0	4.16	3.70	10.69	5.36	-1.41	3.20	ED
K203022B	4.0	162.0	161.5	26.5	36.0	27.7	36.6	14.8	23.2	60.0	4.16	3.70	11.51	4.90	-1.74	3.69	ED
K204066A	6.0	162.1	155.0	27.0	34.0	27.7	39.1	14.8	23.2	56.5	4.16	3.70	10.80	4.90	-0.88	3.74	ED
K204066B	8.0	165.6	159.0	28.0	36.0	27.7	39.1	14.8	23.2	56.5	4.16	3.70	11.89	5.05	-0.93	3.84	ED

APPENDIX C

Data Tables For First Set Of Experiments, 1/4" Stainless Steel

EXPERIMENT #F
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary torch standoff: 2, 4, 6, 8 mm

WELD CONDITIONS:

Date of Experiment:	August 15, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	304 Stainless Steel
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.680"(68.07 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047"(1.19 mm)
Orifice Thickness L2:	0.125"(3.18 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W300287
Plasma Gas Flow Rate (scfh)	5.84
Shield Gas:	Argon
Shield Gas Bottle ID:	W241540
Shield Gas Flow Rate (scfh):	60
Back Purge Gas:	Helium
Gas Bottle ID:	A01291006BG
Flowrate (scfh):	100 - 105
Pressure (psia):	<15
Trailer Shield Gas:	Helium
Gas Bottle ID:	H34592
Flowrate (scfh):	125 - 150

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	135
Reverse Current (amps):	135
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4
Pilot Current (amps):	23.7
Travel Speed (ipm):	3.7
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS

WELD SET:	F
PURPOSE:	Vary Standoff-2,4,6,8 mm
DATE OF LAST CHANGE:	9\16\91
MATERIAL:	1\4"(6.35 mm) 304 Stainless Steel

Weld	S-O	Weld Current(A)		Weld Voltage(V)		Pilot Current(A)		Pilot Voltage(V)		SGas	PGas	Travel	Weld Width(mm)		Weld Height(mm)		Bead
ID	(mm)	Forward	Reverse	Forward	Reverse	Forward	Reverse	Forward	Reverse	(scfh)	(scfh)	(ipm)	Crown	Root	Crown	Root	Appearance
F201044B	2.0	144.1	138.5	25.0	36.0	28.4	37.3	14.8	20.2	60.0	5.84	3.70	8.74	6.32	-0.09	1.61	U,XR
F201044A*	4.0	142.9	138.8	25.0	36.0	28.4	37.3	14.8	20.2	60.0	5.84	3.70	8.89	5.92	0.33	1.17	N,U,R
F203066A	6.0	137.5	139.0	26.0	36.5	27.7	37.8	15.5	20.2	60.0	5.84	3.71	8.31	4.98	0.91	0.86	LU
F203066B	8.0	142.2	140.7	26.0	36.0	27.7	37.8	15.5	20.2	60.0	5.84	3.71	8.57	5.05	1.58	0.61	U,LU

* Nominal Weld Parameters and Geometry

EXPERIMENT #H
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary plasma gas flow rate: 4, 8, 10 scfh
Vary torch standoff: 4, 6 mm

WELD CONDITIONS:

Date of Experiment:	August 16, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	304 Stainless Steel
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.680"(68.07 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047"(1.19 mm)
Orifice Thickness L2:	0.125"(3.18 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W300287
Plasma Gas Flow Rate (scfh)	variable
Shield Gas:	Argon
Shield Gas Bottle ID:	84260K
Shield Gas Flow Rate (scfh):	60
Back Purge Gas:	Helium
Gas Bottle ID:	A01291006BG; A012910BML7
Flowrate (scfh):	100 - 105
Pressure (psia):	<15
Trailer Shield Gas:	Helium
Gas Bottle ID:	USN-1610325 H-74707
Flowrate (scfh):	125 - 150

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	135
Reverse Current (amps):	135
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	23.7
Travel Speed (ipm):	3.7
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS

WELD SET:	H
PURPOSE:	Vary Plasma Gas Flow Rate-4,8,10 SCFH
DATE OF LAST CHANGE:	10\21\91
MATERIAL:	1\4"(6.35 mm) 304 Stainless Steel

Weld	S-O	Weld Current(A)		Weld Voltage(V)		Pilot Current(A)		Pilot Voltage(V)		SGas	PGas	Travel	Weld Width(mm)		Weld Height(mm)		Bead
ID	(mm)	Forward	Reverse	Forward	Reverse	Forward	Reverse	Forward	Reverse	(scfh)	(scfh)	(ipm)	Crown	Root	Crown	Root	Appearance
NOMINAL	4.0	142.9	138.8	25.0	36.0	28.4	37.3	14.8	20.2	60.0	5.84	3.70	8.89	5.92	0.33	1.17	N,U,R
H201044A	4.0	140.8	138.8	24.0	37.0	28.4	38.6	15.8	20.8	60.0	4.16	3.71	8.41	4.67	1.36	0.33	U,RU
H201044B	4.0	139.1	140.6	26.5	41.0	28.4	38.6	15.8	20.8	60.0	8.00	3.71	8.48	4.75	1.32	0.57	U,RU,SB
H201044C	4.0	138.7	142.5	28.0	41.0	28.4	38.6	15.8	20.8	60.0	10.28	3.71	8.31	4.69	1.65	0.80	RU,SB
H202046A	6.0	137.1	142.7	24.5	35.0	28.4	37.3	14.2	20.8	60.0	4.16	3.71	8.89	4.15	2.48	0.11	XU,SB
H202046B	6.0	137.7	144.6	28.0	38.0	28.4	37.3	14.2	20.8	60.0	8.00	3.71	8.81	4.62	1.80	0.28	U,SB
H202046C	6.0	136.5	129.9	27.5	38.0	28.4	37.3	14.2	20.8	60.0	10.28	3.71	8.85	4.62	3.18	-0.07	U,D,SB

EXPERIMENT #I

Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary weld current: 110, 150, 180 amps
Vary torch standoff: 2, 4, 6 mm

WELD CONDITIONS:

Date of Experiment:	August 15, 1991
Tool:	Station #2
Weld Orientation:	Bead-on plate
Weld Pass:	Vertical Up
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	304 Stainless Steel
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.680"(68.07 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047"(1.19 mm)
Orifice Thickness L2:	0.125"(3.18 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W300287
Plasma Gas Flow Rate (scfh)	5.84
Shield Gas:	Argon
Shield Gas Bottle ID:	W241540
Shield Gas Flow Rate (scfh):	60
Back Purge Gas:	Helium
Gas Bottle ID:	A01291006BG
Flowrate (scfh):	100 - 105
Pressure (psia):	< 15
Trailer Shield Gas:	Helium
Gas Bottle ID:	USN-1610325 H-74707
Flowrate (scfh):	125 - 150

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	135
Reverse Current (amps):	135
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	23.7
Travel Speed (ipm):	3.7
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS

WELD SET:	I
PURPOSE:	Vary Weld Current-110,150,180 amps
DATE OF LAST CHANGE:	9\16\91
MATERIAL:	1\4"(6.35 mm) 304 Stainless Steel

Weld ID	S-O (mm)	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
NOMINAL	4.0	142.9	138.8	25.0	36.0	28.4	37.3	14.8	20.2	60.0	5.84	3.70	8.89	5.92	0.33	1.17	N,U,R
I202114B	2.0	157.7	143.3	26.5	43.0	27.7	36.6	15.8	20.8	60.0	5.84	3.70	9.04	7.16	-0.69	2.40	ED,U
I202114C	2.0	182.7	162.9	28.0	44.0	27.7	36.6	15.8	20.8	60.0	5.84	3.70	10.06	7.44	**	**	ED,U,D,LC
I201114A	4.0	*110.0	112.0	25.0	36.0	27.7	36.6	15.8	20.8	60.0	5.84	3.70	7.25	3.54	**	**	D,SB
I201114B	4.0	*150.0	115.6	24.5	36.0	27.7	36.6	15.8	20.8	60.0	5.84	3.70	9.17	6.63	-0.16	2.13	ED,LU,U
I201114C	4.0	*180.0	117.8	24.5	36.0	27.7	36.6	15.8	20.8	60.0	5.84	3.70	10.51	6.94	**	**	D,C
I202114A	6.0	113.6	121.9	26.0	34.0	27.7	36.6	15.8	20.8	60.0	5.84	3.70	7.95	4.46	**	**	D,SB

* Measurements From Computer Print-out Since Strip Chart Recording is Bad
** Measurement not applicable (such as for cutting) or unavailable due to severe weld deformation (such as drooping)

EXPERIMENT #J
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary travel speed: 2, 6, 8 ipm
Vary standoff: 4, 6 mm

WELD CONDITIONS:

Date of Experiment:	August 16, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	304 Stainless Steel
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.680"(68.07 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047"(1.19 mm)
Orifice Thickness L2:	0.125"(3.18 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W300287
Plasma Gas Flow Rate (scfh)	5.84
Shield Gas:	Argon
Shield Gas Bottle ID:	W241540
Shield Gas Flow Rate (scfh):	60
Back Purge Gas:	Helium
Gas Bottle ID:	A01291006BG
Flowrate (scfh):	100 - 105
Pressure (psia):	< 15
Trailer Shield Gas:	Helium
Gas Bottle ID:	USN-1610325 H-74707
Flowrate (scfh):	125 - 150

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	135
Reverse Current (amps):	135
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	23.7
Travel Speed (ipm):	3.7
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS
WELD SET: J
PURPOSE: Vary Travel Speed-2,6,8 inches per minute
DATE OF LAST CHANGE: 9\27\91
MATERIAL: 1\4"(6.35 mm) 304 Stainless Steel

Weld	S-O	Weld Current(A)		Weld Voltage(V)		Pilot Current(A)		Pilot Voltage(V)		SGas	PGas	Travel	Weld Width(mm)		Weld Height(mm)		Bead
ID	(mm)	Forward	Reverse	Forward	Reverse	Forward	Reverse	Forward	Reverse	(scfh)	(scfh)	(ipm)	Crown	Root	Crown	Root	Appearance
NOMINAL	4.0	142.9	138.8	25.0	36.0	28.4	37.3	14.8	20.2	60.0	5.8	3.70	8.89	5.92	0.33	1.17	N,U,R
J201024A	4.0	144.9	125.0	26.0	35.0	26.92	*	17.81	*	60.0	5.8	2.11	12.38	9.32	**	**	RC..LC
J201024B	4.0	144.9	125.0	26.0	35.0	26.92	*	17.81	*	60.0	5.8	6.00	6.99	4.79	**	**	D,SB
J201024C	4.0	145.1	125.0	26.0	35.0	26.92	*	17.81	*	60.0	5.8	8.01	6.64	**	**	**	D,PP
J202026A	6.0	139.3	136.9	26.0	36.0	27.7	37.8	15.8	19.1	60.0	5.8	2.09	11.43	8.16	-1.00	2.89	ED,U,R
J202026B	6.0	139.4	140.7	26.0	37.0	27.7	37.8	15.8	19.1	60.0	5.8	5.97	7.49	5.51	**	**	D,SB
J202026C	6.0	136.1	143.5	26.0	38.0	27.7	37.8	15.8	19.1	60.0	5.8	8.01	7.19	**	**	**	D,PP

* Pilot Arc Photograph Not Available For Measurement
** Measurement not applicable (such as for cutting) or unavailable due to severe weld deformation (such as drooping)

EXPERIMENT #K
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary torch standoff for downhand (flat) welds: 2, 4, 6, 8 mm

WELD CONDITIONS:

Date of Experiment:	August 16, 1991
Tool:	Station #2
Weld Orientation:	Downhand (flat)
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	304 Stainless Steel
Plate Thickness:	0.25"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.835"(72.01 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047"(1.19 mm)
Orifice Thickness L2:	0.126"(3.20 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	H35687
Plasma Gas Flow Rate (scfh)	5.84
Shield Gas:	Argon
Shield Gas Bottle ID:	W25252
Shield Gas Flow Rate (scfh):	50
Back Purge Gas:	Helium
Gas Bottle ID:	A062230JL62
Flowrate (scfh):	100
Pressure (psia):	<15
Trailer Shield Gas:	Helium
Gas Bottle ID:	A01291584WD
Flowrate (scfh):	125

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	2.0
Straight Current (amps):	145
Reverse Current (amps):	145
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	~24
Travel Speed (ipm):	2.8
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS
WELD SET: K
PURPOSE: Down Hand (flat) Welding Vary Torch Standoff-2,4,6,8 mm
DATE OF LAST CHANGE: 9\23\91
MATERIAL: 1\4"(6.35 mm) 304 Stainless Steel

Weld ID	S-O (mm)	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
NOMINAL	4.0	142.9	138.8	25.0	36.0	28.4	37.3	14.8	20.2	60.0	5.84	3.70	8.89	5.92	0.33	1.17	N,U,R
K203022A	2.0	140.1	134.6	25.0	40.0	27.7	39.1	15.8	23.1	60.0	5.84	3.70	8.97	5.38	-1.40	4.24	U,ED
K203022B	4.0	141.9	134.4	25.0	39.0	27.7	39.1	15.8	23.1	60.0	5.84	3.70	7.95	5.53	-1.25	4.52	ED
K202066A	6.0	142.3	140.0	26.0	37.0	27.7	37.8	14.8	25.2	56.6	5.84	3.70	9.62	7.26	-1.08	2.76	ED
K202066B	8.0	140.1	142.0	26.0	37.0	27.7	37.8	14.8	25.2	56.6	5.84	3.70	9.68	7.47	-1.03	2.75	ED

APPENDIX D

Data Tables For First Set Of Experiments, 3/16" Stainless Steel

EXPERIMENT #F
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary torch standoff: 2, 4, 6, 8 mm

WELD CONDITIONS:

Date of Experiment:	August 21, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	304 Stainless Steel
Plate Thickness:	0.188"(4.78 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.480"(62.99 mm)
Orifice Diameter:	0.093"(2.36 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047"(1.19 mm)
Orifice Thickness L2:	0.125"(3.18 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	H35687
Plasma Gas Flow Rate (scfh)	3.96
Shield Gas:	Argon
Shield Gas Bottle ID:	W25252
Shield Gas Flow Rate (scfh):	56
Back Purge Gas:	Helium
Gas Bottle ID:	A01291553WD
Flowrate (scfh):	70
Pressure (psia):	<15
Trailer Shield Gas:	Argon
Gas Bottle ID:	W82638
Flowrate (scfh):	30

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	145
Reverse Current (amps):	145
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	~24
Travel Speed (ipm):	2.8
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS
WELD SET: F
PURPOSE: Vary Standoff-2,4,6,8 mm
DATE OF LAST CHANGE: 9\26\91
MATERIAL: 3\16"(4.76 mm) 304 Stainless Steel

Weld	S-O	Weld Current(A)		Weld Voltage(V)		Pilot Current(A)		Pilot Voltage(V)		SGas	PGas	Travel	Weld Width(mm)		Weld Height(mm)		Bead
ID	(mm)	Forward	Reverse	Forward	Reverse	Forward	Reverse	Forward	Reverse	(scfh)	(scfh)	(ipm)	Crown	Root	Crown	Root	Appearance
F201044B	2.0	141.3	129.0	31.0	49.0	28.9	41.0	15.2	28.5	56.0	3.96	6.11	6.86	4.75	0.06	1.27	U,XLU,ED
F201044A*	4.0	141.5	132.6	31.0	48.0	28.9	41.0	15.2	28.5	56.0	3.96	6.11	7.52	5.22	-0.08	1.38	N,LU
F202066A	6.0	141.1	130.5	33.0	43.0	28.9	41.0	15.2	28.5	56.0	3.96	6.11	7.89	4.63	0.43	1.01	RU,D,SB
F202066B	8.0	140.9	135.2	33.0	43.0	28.9	41.0	15.2	28.5	56.0	3.96	6.11	8.04	5.10	**	**	D,C,SB

* Nominal Weld Parameters and Geometry
** Measurement not applicable (such as for cutting) or unavailable due to severe weld deformation (such as drooping)

EXPERIMENT #H
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary plasma gas flow rate: 4, 8, 10 scfh

WELD CONDITIONS:

Date of Experiment:	August 21, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	304 Stainless Steel
Plate Thickness:	0.188"(4.78 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.480"(62.99 mm)
Orifice Diameter:	0.093"(2.36 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047"(1.19 mm)
Orifice Thickness L2:	0.125"(3.18 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	H35687
Plasma Gas Flow Rate (scfh)	variable
Shield Gas:	Argon
Shield Gas Bottle ID:	W25252
Shield Gas Flow Rate (scfh):	56
Back Purge Gas:	Helium
Gas Bottle ID:	A01291553WD
Flowrate (scfh):	70
Pressure (psia):	<15
Trailer Shield Gas:	Argon
Gas Bottle ID:	W82638
Flowrate (scfh):	30

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	145
Reverse Current (amps):	145
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	~24
Travel Speed (ipm):	2.8
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS

WELD SET: H
PURPOSE: Vary Plasma Gas Flow: 4,8,10 SCFH
DATE OF LAST CHANGE: 9\26\91
MATERIAL: 3\16"(4.76 mm) 304 Stainless Steel

Weld	S-O	Weld Current(A)		Weld Voltage(V)		Pilot Current(A)		Pilot Voltage(V)		SGas	PGas	Travel	Weld Width(mm)		Weld Height(mm)		Bead
ID	(mm)	Forward	Reverse	Forward	Reverse	Forward	Reverse	Forward	Reverse	(scfh)	(scfh)	(ipm)	Crown	Root	Crown	Root	Appearance
NOMINAL	4.0	141.5	132.6	31.0	48.0	28.9	41.0	15.2	28.5	56.0	3.96	6.11	7.52	5.22	-0.08	1.38	N,LU
H201044A	4.0	140.1	133.2	32.0	50.0	28.9	35.3	16.2	15.3	60.0	4.16	6.10	6.79	4.85	-0.05	1.35	R,U,N
H201044B	4.0	139.7	132.7	32.0	50.0	28.9	35.3	16.2	15.3	60.0	7.80	6.10	6.35	3.96	1.08	0.28	R,RU,SB
H201044C	4.0	139.1	132.4	32.0	50.0	28.9	35.3	16.2	15.3	60.0	10.12	6.10	6.25	3.28	0.62	1.50	R,U,XRU,ED

EXPERIMENT #I
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary weld current: 110, 150, 180 amps

WELD CONDITIONS:

Date of Experiment:	August 21, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	304 Stainless Steel
Plate Thickness:	0.188"(4.78 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.480"(62.99 mm)
Orifice Diameter:	0.093"(2.36 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047"(1.19 mm)
Orifice Thickness L2:	0.125"(3.18 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	H35687
Plasma Gas Flow Rate (scfh)	3.96
Shield Gas:	Argon
Shield Gas Bottle ID:	W25252
Shield Gas Flow Rate (scfh):	56
Back Purge Gas:	Helium
Gas Bottle ID:	A01291553WD
Flowrate (scfh):	70
Pressure (psia):	<15
Trailer Shield Gas:	Argon
Gas Bottle ID:	W82638
Flowrate (scfh):	30

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	145
Reverse Current (amps):	145
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	~24
Travel Speed (ipm):	2.8
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS

WELD SET:	I
PURPOSE:	Vary Weld Current-110,150,180 amps
DATE OF LAST CHANGE:	9\26\91
MATERIAL:	3\16"(4.76 mm) 304 Stainless Steel

Weld	S-O	Weld Current(A)		Weld Voltage(V)		Pilot Current(A)		Pilot Voltage(V)		SGas	PGas	Travel	Weld Width(mm)		Weld Height(mm)		Bead
ID	(mm)	Forward	Reverse	Forward	Reverse	Forward	Reverse	Forward	Reverse	(scfh)	(scfh)	(ipm)	Crown	Root	Crown	Root	Appearance
NOMINAL	4.0	141.5	132.6	31.0	48.0	28.9	41.0	15.2	28.5	56.0	3.96	6.11	7.52	5.22	-0.08	1.38	N,LU
I201114A	4.0	112.4	118.9	30.0	44.0	28.9	39.1	14.8	28.5	60.0	4.16	6.09	5.47	3.43	0.56	0.84	R,U
I201114B	4.0	157.1	140.9	33.0	46.0	28.9	39.1	14.8	28.5	60.0	4.16	6.09	7.18	6.73	2.26	-1.02	XSB,R
I201114C	4.0	172.8	156.3	35.0	49.0	28.9	39.1	14.8	28.5	60.0	4.16	6.09	8.72	4.36	*	*	D,SB,C

* Measurement not applicable (such as for cutting) or unavailable due to severe weld deformation (such as drooping)

EXPERIMENT #J
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Vary travel speed: 2, 6, 8 ipm

WELD CONDITIONS:

Date of Experiment:	August 21, 1991
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Bead-on-plate
Joint Type:	N\A
Joint Gap:	N\A
Plate Material:	304 Stainless Steel
Plate Thickness:	0.188"(4.78 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.480"(62.99 mm)
Orifice Diameter:	0.093"(2.36 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047"(1.19 mm)
Orifice Thickness L2:	0.125"(3.18 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	H35687
Plasma Gas Flow Rate (scfh)	3.96
Shield Gas:	Argon
Shield Gas Bottle ID:	W25252
Shield Gas Flow Rate (scfh):	56
Back Purge Gas:	Helium
Gas Bottle ID:	A01291553WD
Flowrate (scfh):	70
Pressure (psia):	<15
Trailer Shield Gas:	Argon
Gas Bottle ID:	W82638
Flowrate (scfh):	30

CONTROL SETTINGS:

AVC (ON\OFF):	OFF
Initial Torch Standoff (mm):	4.0
Straight Current (amps):	145
Reverse Current (amps):	145
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	~24
Travel Speed (ipm):	2.8
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
1ST SET OF EXPERIMENTS

WELD SET: J
PURPOSE: Vary Torch Travel Speed-2,6,8 ipm
DATE OF LAST CHANGE: 9\27\91
MATERIAL: 3\16"(4.76 mm) 304 Stainless Steel

Weld ID	S-O (mm)	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
NOMINAL	4.0	141.5	132.6	31.0	48.0	28.9	41.0	15.2	28.5	56.0	3.96	6.11	7.52	5.22	-0.08	1.38	N,LU
J201064C	4.0	139.6	140.3	33	50.0	27.7	37.8	14.8	25.8	56.5	4.16	2.10	12.19	15.75	*	*	C
J201064A	4.0	139.3	134.0	30	44.0	27.7	37.8	14.8	25.8	56.5	4.16	6.02	7.14	4.90	0.28	1.14	N,R
J201064B	4.0	138.1	137.0	30	44.0	27.7	37.8	14.8	25.8	56.5	4.16	8.01	6.68	3.96	0.32	0.69	N,R

* Measurement not applicable since cutting occurred

APPENDIX E
Data Tables For Second Set Of Experiments, Experiment #1

EXPERIMENT #1
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Isolate the effects of sheild gas contamination (from atmosphere) on undercut by welding in a bag purged with helium.

WELD CONDITIONS:

Date of Experiment:	February 19, 1992
Tool:	Station #2
Weld Orientation:	Verical Up
Weld Pass:	Root Pass
Joint Type:	Bead-on-plate
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum
Plate Thickness:	0.250" (6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	75

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten, ground to cause arc skewing
Electrode Diameter:	0.188" (4.78 mm)
Electrode Length:	2.479" (62.97 mm)
Orifice Diameter:	0.156" (3.62 mm)
Electrode Setback (electrode to orifice distance) L1:	0.045" (1.14 mm)
Orifice Thickness L2:	0.133" (3.38 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	Y5459
Plasma Gas Flow Rate (scfh)	4.0
Shield Gas:	Helium
Shield Gas Bottle ID:	A012910BML5
Shield Gas Flow Rate (scfh):	75
Back Purge Gas:	Helium
Gas Bottle ID:	A01291850KF
Flowrate (scfh):	140
Pressure (psia):	<15
Bag Gas:	Helium
Bag Gas Bottle ID:	A01291536WD
Bag Gas Flowrate (scfh):	190

CONTROL SETTINGS:

AVC (ON\OFF):	ON
Initial Torch Standoff (mm):	Manual
Straight Current (amps):	50
Reverse Current (amps):	50
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	28
Travel Speed (ipm):	11.0
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
2ND SET OF EXPERIMENTS

EXPERIMENT #: 1

PURPOSE: Isolate effects of SGas contamination on undercut by making identical welds with a rotating skewed arc both in atmosphere and in a 'bagged' environment containing inert gas.

DATE OF LAST CHANGE: 6-30-92

MATERIAL(S): 2219-T87 Aluminum (1/4"(6.35 mm) thick)

NOTE: The data acquisition system was not available at the time of this experiment.
All data listed are parameter settings, not measured values.
Welds 1C and 1D were made within an hour of each other, to minimize time varying noise effects.
The only required result for this experiment was whether the amount of undercut varied with the different ambient atmospheres. There was no change.

Weld ID	Welding Current(A)	Welding Voltage(V)	Pilot Arc Current(A)	SGas (scfh)	PGas (scfh)	S-O (mm)	Travel (ipm)	Ambient Atmosphere	Bead Appearance
1C	165.0	21.0	30.0	75.0	4.0	~4	11.0	Helium (welded in bag)	Undercut, on alternating sides, opposite whichever side arc skewed towards.
1D	165.0	21.0	30.0	75.0	4.0	~4	11.0	Air (welded in normal atmosphere)	Same as 1C.

APPENDIX F
Data Tables For Second Set Of Experiments, Experiment #2

EXPERIMENT #2
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Determine the effect of travel speed on keyhole leading edge angle.

WELD CONDITIONS:

Date of Experiment:	February 27, 1992
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Root Pass
Joint Type:	Bead-on-plate
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum
Plate Thickness:	0.250" (6.35 mm) (2A-2L); 0.500" (12.70 mm) (2M-2X)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	79 - 82

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156" (3.96 mm)
Electrode Length:	2.925" (74.30 mm) (2A-2L); 2.905" (73.79 mm) (2M-2R); 2.866" (72.80 mm) (2S-2X)
Orifice Diameter:	0.125" (3.18 mm) (2A-2L); 0.156" (3.96 mm) (2M-2X)
Electrode Setback (electrode to orifice distance) L1:	0.045" (1.14 mm) (2A-2L, 2S-2X); 0.046" (1.17 mm) (2M-2R)
Orifice Thickness L2:	0.130" (3.30 mm) (2A-2L); 0.125" (3.18 mm) (2M-2R); 0.133" (3.38 mm) (2S-2X)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W185258 (2A-2R); W235873 (2S-2X)
Plasma Gas Flow Rate (scfh)	5 (2A-2L); 7.5 (2M-2X)
Shield Gas:	Helium
Shield Gas Bottle ID:	A01291820KF
Shield Gas Flow Rate (scfh):	80
Back Purge Gas:	None
Gas Bottle ID:	N\A
Flowrate (scfh):	N\A
Pressure (psia):	N\A

CONTROL SETTINGS:

AVC (ON\OFF):	ON
Initial Torch Standoff (mm):	Manual
Straight Current (amps):	50
Reverse Current (amps):	50
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	28.7
Travel Speed (ipm):	Varied
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
2ND SET OF EXPERIMENTS
EXPERIMENT #: 2
PURPOSE: Effect of Travel Speed on keyhole leading edge angle
DATE OF LAST CHANGE: 6-12-92
MATERIAL(S): 2219-T87 Aluminum (1/4"(6.35 mm) thick for 2A-2L; 1/2"(12.7 mm) thick for 2M-2X)

Weld	Weld Current(A)		Weld Voltage(V)		Pilot Current(A)		Pilot Voltage(V)		SGas	PGas	S-O	Travel	Weld Width(mm)		Weld Height(mm)		Leading Edge	Bead
ID	Forward	Reverse	Forward	Reverse	Forward	Reverse	Forward	Reverse	(scfh)	(scfh)	(mm)	(ipm)	Crown	Root	Crown	Root	Angle(degs)	Appearance
2A	132.0	128.5	27.5	40.1	31.2	4.8	13.3	14.5	61.3	5.1	4.3	9.8	8.57	6.35	-0.06	0.99	21.0	N
2B	131.9	128.3	27.5	39.4	31.0	5.3	13.5	14.3	61.0	5.2	4.1	8.9	8.86	5.84	-0.01	1.06	19.0	N
2C	132.4	124.5	27.5	39.8	30.9	4.2	13.5	14.0	61.7	5.2	4.0	10.8	7.95	5.46	0.21	0.81	25.5	N
2D	132.1	125.8	27.5	39.6	30.9	4.9	13.7	14.2	61.7	5.0	4.0	11.7	7.84	5.33	0.33	0.71	25.0	N
2E*	133.0	117.8	27.4	41.0	40.0	15.0	13.0	14.0	61.8	5.1	4.2	11.7	7.83	5.13	0.20	0.80	25.0	N
2F	132.0	126.2	27.4	39.4	31.0	3.8	13.5	14.1	61.5	5.1	4.1	9.8	8.59	5.79	0.12	1.06	20.5	N
2G	132.5	121.5	27.4	40.4	31.0	4.3	13.4	14.0	61.3	5.0	4.3	8.9	8.78	5.44	-0.05	1.05	17.0	N
2H	132.6	121.1	27.5	40.4	31.0	3.1	13.4	13.9	60.9	5.1	4.1	10.8	8.37	5.40	0.09	0.93	19.5	N
2I	132.7	119.4	27.4	40.0	30.9	4.2	13.6	13.9	61.3	5.1	4.2	10.7	8.05	5.17	0.27	0.73	24.0	N
2J	132.1	127.4	27.5	40.2	31.1	4.0	13.7	14.8	61.2	5.1	4.2	9.8	8.14	5.39	0.15	0.91	21.0	N
2K	132.1	125.1	27.5	39.6	31.1	3.5	13.6	14.5	60.6	5.1	4.1	11.7	7.95	5.15	0.31	0.66	23.5	N
2L	132.7	120.6	27.4	40.0	30.9	3.1	13.7	14.3	61.0	5.0	4.2	8.7	8.50	5.19	0.08	0.88	22.0	N
2M	267.6	196.4	30.0	42.7	31.2	5.0	14.3	17.3	59.9	7.7	4.4	7.9	11.46	9.27	-0.01	1.98	16.5	U
2N	266.0	203.3	29.9	42.1	31.3	7.0	14.5	18.2	61.2	7.7	4.1	6.4	11.40	10.97	-0.78	2.65	12.5	U
2O	267.5	196.8	29.9	43.2	30.8	6.0	14.8	17.1	60.0	7.7	4.4	9.2	10.57	8.08	0.62	1.40	19.0	U
2P**	290.0	220.0	30.0	43.0	40.0	15.0	14.5	17.0	80.0	7.5	4.0	11.0	10.61	7.24	1.13	1.42	22.5	U
2Q	267.3	198.5	30.0	43.1	30.7	5.6	14.8	17.0	57.6	7.4	4.6	10.6	10.26	7.72	1.32	1.39	22.5	U,LU
2R	266.5	201.5	30.0	42.1	30.8	6.9	14.9	17.2	59.6	7.7	4.3	7.9	11.73	9.18	-0.06	2.10	13.0	N
2S	267.7	192.7	30.7	45.4	30.9	6.1	15.0	16.7	61.2	7.6	3.2	6.5	9.67	11.00	***	3.35	12.0	U,ED
2T	266.3	200.7	30.0	42.7	30.7	5.1	15.2	17.3	61.7	7.6	4.6	9.3	10.52	5.54	0.48	1.62	19.0	U,LU
2U	266.3	199.2	29.9	42.9	30.6	5.6	15.2	16.8	60.8	7.6	4.3	9.4	10.30	7.67	0.52	1.71	21.0	N,LU
2V	267.5	190.8	30.0	46.0	30.4	4.9	15.5	16.0	61.3	7.6	1.9	8.0	7.73	9.14	***	***	5.5	U,ED
2W	266.2	198.4	29.9	43.6	30.7	6.0	15.5	16.9	60.9	7.6	4.4	10.8	10.30	7.54	0.78	1.79	23.0	U,D
2X	265.2	202.5	30.9	43.0	30.5	6.0	15.3	17.1	60.4	7.6	4.0	6.6	10.69	11.30	-1.65	2.86	13.5	U,ED

* Pilot arc data for this weld is from oscilloscope trace photo
** All parameter data for this weld is from strip chart, print-out, or oscilloscope trace photo
*** Measurement not applicable (such as for cutting) or unavailable due to severe weld deformation (such as drooping)

APPENDIX G

Data Tables For Second Set Of Experiments, Experiment #3

EXPERIMENT #3
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Determine the effect of plasma gas flow rate on keyhole leading edge angle

WELD CONDITIONS:

Date of Experiment:	March 2, 1992
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Root Pass
Joint Type:	Bead-on-plate
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum
Plate Thickness:	0.500" (12.70 mm) (3A-3L); 0.250" (6.35 mm) (3M-3X)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	78 - 83

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156" (3.96 mm)
Electrode Length:	2.812" (71.42 mm) (3A-3L); 2.759" (70.08 mm) (3M3X)
Orifice Diameter:	0.156" (3.96 mm) (3A-3L); 0.125" (3.18 mm) (3M-3X)
Electrode Setback (electrode to orifice distance) L1:	0.045" (1.14 mm) (3A-3L); 0.044" (1.12 mm) (3M-3X)
Orifice Thickness L2:	0.142" (3.61 mm) (3A-3L); 0.137" (3.48 mm) (3M-3X)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W235873
Plasma Gas Flow Rate (scfh)	Varied
Shield Gas:	Helium
Shield Gas Bottle ID:	A01291820KF (3A-3H); A01291558WD (3I-3X)
Shield Gas Flow Rate (scfh):	80
Back Purge Gas:	None
Gas Bottle ID:	N\A
Flowrate (scfh):	N\A
Pressure (psia):	N\A

CONTROL SETTINGS:

AVC (ON\OFF):	ON
Initial Torch Standoff (mm):	Manual
Straight Current (amps):	50
Reverse Current (amps):	50
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	28
Travel Speed (ipm):	Varied
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
2ND SET OF EXPERIMENTS
EXPERIMENT #: 3
PURPOSE: Effect of Plasma Gas flow rate on keyhole leading edge angle
DATE OF LAST CHANGE: 6-9-92
MATERIAL(S): 2219-T87 Aluminum (1/2"(12.7 mm) thick for 3A-3L; 1/4"(6.35 mm) thick for 3M-3X)

Weld ID	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	S-O (mm)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Leading Edge Angle(degs)	Bead Appearance
3A	266.8	197.8	31.8	44.3	30.8	5.0	15.3	16.5	61.5	7.6	4.6	8.0	10.77	9.60	-0.20	1.96	16.0	U,RU
3B	265.9	202.0	31.8	44.0	31.0	6.6	15.0	16.3	60.3	6.1	5.4	7.9	11.70	11.20	-0.91	3.00	18.0	U,RU
3C	265.4	198.9	31.6	43.6	30.3	4.8	15.6	17.6	60.9	9.1	2.1	7.8	8.70	9.35	*	2.69	15.0	ED,D
3D	264.8	203.1	31.7	43.7	30.5	6.6	14.5	16.2	60.5	4.6	5.6	7.9	12.45	11.43	-0.48	*	23.0	U,RC
3E	265.5	200.4	31.5	43.5	30.5	5.2	14.5	16.0	60.6	4.6	5.6	7.9	11.89	11.38	-1.07	3.67	22.5	U,RU
3F	266.4	196.0	31.6	44.8	30.4	6.1	15.1	17.2	60.5	7.6	3.1	7.9	9.76	9.91	-1.17	2.97	14.0	U,D
3G	265.1	200.7	31.4	43.7	30.6	6.0	14.7	17.1	60.5	6.1	3.9	7.9	10.78	11.43	-1.41	3.07	16.0	U,D
3H	266.2	197.5	31.7	44.0	30.2	5.1	15.4	18.2	60.8	9.2	2.2	7.9	8.62	9.47	-1.54	2.93	11.5	U,D
3I	264.9	200.7	31.6	43.4	30.3	5.9	15.3	18.2	60.9	9.2	2.0	7.9	8.92	8.53	-1.28	2.77	13.5	U
3J	265.9	198.7	31.7	44.3	30.4	6.1	15.1	17.6	60.5	7.6	3.0	7.9	10.06	10.52	-1.24	2.85	14.0	U
3K	264.3	205.1	31.3	42.4	30.7	5.9	14.5	16.8	60.5	4.6	4.8	7.9	10.84	10.80	-0.84	*	22.0	U,LU
3L	265.5	200.1	31.9	43.9	30.7	5.1	14.9	17.2	60.7	6.1	4.0	7.8	10.80	11.18	-1.45	3.43	15.0	U,RU
3M	132.7	114.5	27.8	41.3	30.1	3.9	14.6	13.2	62.2	5.0	4.2	9.7	8.28	6.10	-0.01	1.07	25.0	N
3N	131.9	123.2	27.9	41.9	30.7	3.9	13.9	13.3	61.5	4.1	5.1	9.7	8.97	6.93	0.01	1.13	28.0	N
3O	131.6	120.6	27.9	39.4	30.2	3.8	14.8	14.2	61.2	6.1	3.7	9.7	7.70	5.69	0.19	0.79	24.0	N
3P	132.4	113.1	27.9	41.7	30.7	3.6	13.1	12.2	61.5	3.1	5.9	9.7	10.22	6.81	0.13	1.13	35.5	N
3Q	131.2	123.8	27.8	41.0	30.8	4.1	13.5	12.7	60.9	3.1	5.5	9.7	9.87	7.67	0.15	1.07	36.0	U
3R	131.7	119.6	27.6	40.8	30.6	3.1	14.2	13.7	61.3	5.1	3.9	9.7	8.38	5.59	0.14	0.96	23.0	N
3S	132.7	108.0	27.9	43.1	30.6	3.8	14.1	12.0	60.6	4.1	4.7	9.7	9.02	6.60	0.00	1.06	30.0	N
3T	131.0	125.4	27.5	38.5	30.8	3.5	14.3	15.1	60.3	6.1	3.3	9.7	7.40	5.49	0.23	0.79	25.0	N
3U	131.5	122.0	27.9	39.1	30.6	3.2	14.5	14.4	60.3	6.1	3.4	9.7	7.54	5.64	0.17	0.74	25.0	N
3V	131.8	122.5	27.4	40.4	30.6	3.8	14.4	13.9	60.8	5.1	3.9	9.7	7.71	5.59	0.03	0.97	25.0	N
3W	131.9	121.3	27.7	41.2	31.0	4.1	13.3	12.9	60.7	3.1	5.5	9.7	10.72	7.37	1.14	0.90	38.0	RC
3X	132.2	118.9	27.9	42.0	30.9	3.4	14.0	12.9	60.9	4.1	4.6	9.6	9.29	5.77	-0.07	1.19	24.5	N

* Measurement not applicable (such as for cutting) or unavailable due to severe weld deformation (such as drooping)

APPENDIX H
Data Tables For Second Set Of Experiments, Experiment #4

EXPERIMENT #4
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Determine the effect of varying wire feed speed

WELD CONDITIONS:

Date of Experiment:	March 9, 1992
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Root Pass
Joint Type:	Bead-on-plate
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum
Plate Thickness:	0.250"(6.35 mm)
Wire Material:	2319 Aluminum
Wire Thickness:	0.063"(1.60 mm)
Ambient Temperature (deg F):	50 - 51

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoiriated Tungsten
Electrode Diameter:	0.156"(3.96 mm)
Electrode Length:	2.722"(69.14 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.043"(1.09 mm)
Orifice Thickness L2:	0.139"(3.53 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W235873
Plasma Gas Flow Rate (scfh)	5.0
Shield Gas:	Argon
Shield Gas Bottle ID:	A01291558WD
Shield Gas Flow Rate (scfh):	80
Back Purge Gas:	None
Gas Bottle ID:	N\A
Flowrate (scfh):	N\A
Pressure (psia):	N\A

CONTROL SETTINGS:

ASOC (ON\OFF):	ON
Initial Torch Standoff (mm):	Manual
Straight Current (amps):	50
Reverse Current (amps):	50
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	28
Travel Speed (ipm):	10
Wire Feed Rate (ipm):	Varied

VPPAW MODEL EVALUATION
2ND SET OF EXPERIMENTS
EXPERIMENT #: 4
PURPOSE: Effects of Filler Wire Speed
DATE OF LAST CHANGE: 6-9-92
MATERIAL(S): 1/4"(6.35 mm) 2219-T87 Aluminum

Weld ID	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	S-O (mm)	Travel (ipm)	Wire Feed Speed(ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Leading Edge Angle(degs)	Bead Appearance
4A	131.1	134.0	26.7	37.0	30.7	4.6	14.2	14.6	61.1	5.1	4.0	9.6	40	8.68	5.92	1.41	0.91	28.0	N
4B	132.0	132.1	27.1	38.6	30.6	4.6	14.2	14.3	60.2	5.1	4.0	9.6	20	7.45	6.44	0.73	0.97	25.0	N
4C	131.6	135.6	26.7	36.7	30.6	4.9	14.0	14.5	60.3	5.1	4.0	9.7	60	8.14	6.06	2.04	1.02	26.0	N

APPENDIX I

Data Tables For Second Set Of Experiments, Experiment #5

EXPERIMENT #5
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Determine effect of electrode and orifice variations

WELD CONDITIONS:

Date of Experiment:	March 10, 1992
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Root Pass
Joint Type:	Bead-on-plate
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum
Plate Thickness:	0.250"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	78 - 79

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	Varied as listed in table
Electrode Length:	Varied as listed in table
Orifice Diameter:	Varied as listed in table
Electrode Setback (electrode to orifice distance) L1:	Varied as listed in table
Orifice Thickness L2:	Varied as listed in table
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W235873
Plasma Gas Flow Rate (scfh)	5.0
Shield Gas:	Helium
Shield Gas Bottle ID:	A01291558WD
Shield Gas Flow Rate (scfh):	80
Back Purge Gas:	None
Gas Bottle ID:	N\A
Flowrate (scfh):	N\A
Pressure (psia):	N\A

CONTROL SETTINGS:

ASOC (ON\OFF):	ON
Initial Torch Standoff (mm):	Manual
Straight Current (amps):	50
Reverse Current (amps):	50
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	28
Travel Speed (ipm):	10
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
2ND SET OF EXPERIMENTS
EXPERIMENT #: 5
PURPOSE: Effects of Orifice and Electrode Parameters
DATE OF LAST CHANGE: 6-9-92
MATERIAL(S): 1/4"(6.35 mm) 2219-T87 Aluminum

Weld ID	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	S-O (mm)	Travel (ipm)	Electrode Parameters: Set-Back(L1) (in)	Set-Back(L1) (mm)	Diameter (in)	Diameter (mm)	Length (in)	Length (mm)	Orifice Parameters: Diameter (in)	Diameter (mm)	Thickness(L2) (in)	Thickness(L2) (mm)	Weld Measurements: Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Leading Edge Angle(degs)	Bead Appearance
5A	133.3	113.7	27.0	41.1	30.5	3.6	13.9	11.9	62.2	5.1	4.0	9.5	0.035	0.89	0.156	3.97	2.700	68.58	0.125	3.18	0.139	3.53	8.48	5.79	0.12	0.91	28.0	N
5B	132.9	123.8	21.9	35.7	30.5	3.5	13.5	9.8	62.1	5.1	4.0	9.5	0.035	0.89	0.156	3.97	2.680	68.07	0.156	3.96	0.134	3.40	9.13	5.21	0.25	0.90	36.5	U
5C	133.6	119.0	22.3	34.6	30.3	4.1	14.2	9.8	61.5	5.1	4.0	9.6	0.054	1.37	0.156	3.97	2.678	68.02	0.156	3.96	0.134	3.40	8.65	5.79	0.64	0.73	*	N,U,PT
5D	132.6	123.5	26.9	39.9	30.5	4.3	14.4	13.6	61.8	5.0	4.0	9.6	0.053	1.35	0.156	3.97	2.643	67.13	0.125	3.18	0.139	3.53	8.34	5.38	0.12	0.94	24.5	N
5E	130.9	132.2	26.2	37.7	31.1	4.8	14.2	13.6	61.7	5.0	4.0	9.6	0.036	0.91	0.188	4.76	2.807	71.30	0.125	3.18	0.139	3.53	8.21	5.03	0.10	0.82	23.0	N
5F	133.0	119.8	22.5	35.0	30.7	3.4	13.8	9.5	61.3	5.1	4.0	9.7	0.033	0.84	0.188	4.76	2.800	71.12	0.156	3.96	0.134	3.40	8.62	4.50	0.41	1.25	*	N,U,PT
5G	133.0	123.0	22.7	34.9	30.5	4.2	13.7	9.5	62.3	5.1	4.0	9.7	0.053	1.35	0.188	4.76	2.795	70.99	0.156	3.96	0.134	3.40	8.95	4.90	0.70	0.75	*	N,LU,PT
5H	133.7	113.4	27.5	40.7	30.9	3.8	13.6	13.4	62.4	5.1	4.0	9.6	0.054	1.37	0.188	4.76	2.785	70.74	0.125	3.18	0.139	3.53	8.36	5.16	0.18	0.89	27.5	RU

* These welds did not keyhole.

APPENDIX J
Data Tables For Second Set Of Experiments, Experiment #6

EXPERIMENT #6
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Determine weld current and travel speed interactions

WELD CONDITIONS:

Date of Experiment:	March 12, 1992
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Root Pass
Joint Type:	Bead-on-plate
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum
Plate Thickness:	0.250"(6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	84 - 85

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156"(3.96mm)
Electrode Length:	2.630"(66.80 mm)
Orifice Diameter:	0.125"(3.18 mm)
Electrode Setback	
(electrode to orifice distance) L1:	0.045"(1.14 mm)
Orifice Thickness L2:	0.134"(3.40 mm)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W235873
Plasma Gas Flow Rate (scfh)	5.0
Shield Gas:	Helium
Shield Gas Bottle ID:	A01291558WD
Shield Gas Flow Rate (scfh):	80
Back Purge Gas:	None
Gas Bottle ID:	N\A
Flowrate (scfh):	N\A
Pressure (psia):	N\A

CONTROL SETTINGS:

ASOC (ON\OFF):	ON
Initial Torch Standoff (mm):	Manual
Straight Current (amps):	50
Reverse Current (amps):	50
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	28
Travel Speed (ipm):	varied
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
2ND SET OF EXPERIMENTS
EXPERIMENT #: 6
PURPOSE: Arc Current and Travel Speed Interactions
DATE OF LAST CHANGE: 6-9-92
MATERIAL(S): 1/4"(6.35 mm) 2219-T87 Aluminum

Weld ID	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	S-O (mm)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Leading Edge Angle(degs)	Bead Appearance
6A	132.3	127.3	27.1	39.6	30.4	4.3	14.1	13.6	61.6	5.1	4.0	9.7	8.14	6.10	0.08	0.97	26.0	N
6B	132.8	124.6	26.8	39.6	30.3	3.7	13.9	13.1	61.7	5.1	4.0	10.8	7.82	4.50	0.23	0.90	25.0	N
6C	133.1	121.7	27.0	40.1	30.4	3.3	13.7	13.2	61.2	5.1	4.0	8.9	8.59	5.61	-0.07	1.11	22.5	N
6D	118.5	104.1	26.8	40.5	29.9	3.4	14.2	11.2	61.2	5.1	4.0	10.9	8.19	4.39	0.49	0.72	31.0	N,RU
6E	118.1	107.2	26.8	40.0	30.2	4.0	13.9	11.7	61.6	5.1	4.0	9.9	8.10	4.52	0.27	0.69	32.0	N
6F	118.1	108.1	26.6	39.6	30.2	3.5	14.0	11.8	61.2	5.1	4.0	9.0	8.13	4.65	0.21	0.71	29.0	N
6G	147.7	135.6	28.1	40.4	30.5	4.6	13.9	14.6	61.4	5.1	4.0	9.0	8.43	6.30	-0.24	1.31	22.5	N
6H	146.3	140.6	27.9	39.8	31.1	5.4	13.8	15.1	61.4	5.1	4.0	10.0	8.64	5.92	-0.23	1.28	24.0	N
6I	147.9	131.3	27.9	40.9	30.6	3.8	14.2	14.3	61.8	5.1	4.0	10.9	8.26	6.15	-0.18	1.22	23.0	N

APPENDIX K

Data Tables For Second Set Of Experiments, Experiment #7

EXPERIMENT #7
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE:	Determine effect of changes in 19ms\4ms waveform (repeat of Joe Gregory tests)

WELD CONDITIONS:

Date of Experiment:	March 17, 1992
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Root Pass
Joint Type:	Bead-on-plate
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum (7A-7H); A36 Mild Steel (7I-7P)
Plate Thickness:	0.250" (6.35 mm)
Wire Material:	No wire
Wire Thickness:	N\A
Ambient Temperature (deg F):	77 - 82

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156" (3.96 mm)
Electrode Length:	2.607" (62.22 mm) (7A-7D); 2.546" (64.67 mm) (7E-7H) 2.468" (62.69 mm) (7I-7L); 2.502" (63.55 mm) (7M-7P)
Orifice Diameter:	0.125" (3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047" (1.19 mm)
Orifice Thickness L2:	0.134" (3.40 mm) (7A-7L); 0.132" (3.35 mm) (7M-7P)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W235873
Plasma Gas Flow Rate (scfh)	5.0
Shield Gas:	Helium (7A-7H); Argon (7I-7P)
Shield Gas Bottle ID:	A01291857KF (7A-7H); Argon Bottle ID unknown (7I-7P)
Shield Gas Flow Rate (scfh):	80
Back Purge Gas:	Helium (Used only on 7I-7L)
Gas Bottle ID:	UN1046/378983
Flowrate (scfh):	55
Pressure (psia):	< 15

CONTROL SETTINGS:

ASOC (ON\OFF):	ON
Initial Torch Standoff (mm):	Manual
Straight Current (amps):	50
Reverse Current (amps):	50
Add. Reverse Current (amps):	60
Forward Time (msec):	Varied
Reverse Time (msec):	Varied
Pilot Current (amps):	28
Travel Speed (ipm):	Varied
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
2ND SET OF EXPERIMENTS
EXPERIMENT #: 7
PURPOSE: Vary 19ms-4ms waveform (repeat of prior work by Joe Gregory)
DATE OF LAST CHANGE: 6-22-92
MATERIAL(S): 1/4"(6.35 mm) 2219-T87 Aluminum (7A-7H)
1/4"(6.35 mm) A36 Mild Steel (7I-7P)

Weld ID#	Stand-Off(mm)	Forward Time(ms)	Reverse Time(ms)	I-FWD(A) Commanded	I-FWD(A) Measured	I-REV(A) Measured	V-FWD (V)	V-REV (V)	Pilot Arc I-FWD (A)	Pilot Arc I-REV (A)	Pilot Arc V-FWD (V)	Pilot Arc V-REV (V)	Gas Flows(scfh) Shield	Gas Flows(scfh) Plasma	Measured Travel Speed(ipm)	Keyhole Weld? (Y/N)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
7A1	4	19	4	120	121.8	122.6	26.5	37.8	30.8	4.3	13.6	14.0	92.2	5.1	9.5	Y	7.92	4.16	0.34	0.75	N
7A2	4	19	4	140	141.9	138.5	27.7	39.2	30.9	5.9	13.8	15.6	92.2	5.1	9.5	Y	8.41	5.62	-0.04	1.19	N
7A3	4	19	4	160	162.2	150.1	29.6	40.5	30.9	4.9	14.0	16.7	92.1	5.1	9.5	Y	9.39	7.40	-0.09	1.68	N,RU
7B1	4	16	8	120	127.2	114.9	27.2	39.3	33.0	4.5	13.4	13.0	92.0	5.1	9.5	Y	8.28	5.74	0.23	0.98	N,RU
7B2	4	16	8	140	149.5	125.7	28.4	41.0	33.3	4.8	13.0	14.1	91.9	5.1	9.5	Y	8.75	6.86	-0.28	1.40	N
7B3	4	16	8	160	170.9	141.2	29.7	40.8	33.4	4.5	13.0	15.3	91.7	5.1	9.5	Y	9.73	9.91	*	*	RC,D
7C1	4	12	12	120	134.0	119.0	26.5	40.1	35.4	4.2	12.9	13.2	92.3	5.1	9.5	Y	8.48	5.59	-0.10	1.23	N
7C2	4	12	12	140	157.8	132.5	28.1	41.1	35.7	4.1	12.8	14.5	92.0	5.1	9.5	Y	9.58	8.47	-0.06	1.51	N,RU
7C3	4	12	12	160	179.6	148.4	29.5	41.6	36.0	6.1	12.8	15.9	92.2	5.1	9.5	Y	10.49	*	*	*	RC,D
7D1	4	8	16	120	138.4	131.3	24.8	40.2	38.1	5.3	11.7	14.2	92.5	5.1	9.4	Y	9.58	*	*	*	RC,D
7D2	4	8	16	140	163.5	147.0	26.6	41.2	38.6	5.1	11.2	15.7	92.5	5.1	9.5	Y	9.97	*	*	*	RC,D
7D3	4	8	16	160	191.0	160.2	28.0	42.9	39.0	4.4	10.4	16.5	92.4	5.1	9.5	Y	10.41	*	*	*	RC,D
7E1	4	19	4	120	122.1	123.0	25.1	36.9	30.7	4.3	13.1	12.4	92.1	5.0	29.2	N	6.65	*	0.45	*	PP,D
7E2	4	19	4	140	143.2	142.8	26.8	36.6	30.9	6.2	13.2	14.9	92.0	5.0	29.3	N	7.09	*	*	*	PP,D
7E3	4	19	4	160	163.6	152.7	27.8	38.2	30.9	5.9	13.3	15.4	92.0	5.0	29.3	N	7.65	*	*	*	PP,D
7F1	4	16	8	120	128.6	110.6	25.4	39.2	32.9	4.7	12.8	12.4	92.0	5.0	29.2	N	7.10	*	0.30	*	PP,LU
7F2	4	16	8	140	149.2	133.0	26.8	37.6	33.2	5.8	12.9	13.8	91.9	5.0	29.3	N	7.76	*	1.07	*	PP,D,LU
7F3	4	16	8	160	172.3	144.6	27.5	38.6	33.3	5.7	13.2	15.2	91.8	5.0	29.3	N	7.98	*	*	*	PP,D,U
7G1	4	12	12	120	136.2	115.1	25.2	40.4	35.1	4.2	13.1	12.9	92.1	5.1	29.2	N	7.03	*	0.46	*	PP,N
7G2	4	12	12	140	161.1	130.7	26.2	40.7	35.4	4.3	13.1	14.5	92.2	5.0	29.3	N	7.88	*	0.68	*	PP,N
7G3	4	12	12	160	183.5	149.3	27.1	39.4	35.8	4.9	12.8	15.8	92.0	5.0	29.3	N	8.33	*	*	*	PP,D,U
7H1	4	8	16	120	142.7	126.8	23.2	41.5	37.7	3.5	11.1	13.0	92.3	5.0	29.2	N	8.44	*	0.44	*	PP,U
7H2	4	8	16	140	173.0	141.2	24.1	42.8	38.2	4.2	10.8	14.4	92.0	5.0	29.3	N	9.08	*	0.94	*	PP,U
7H3	4	8	16	160	194.7	161.0	24.8	40.1	38.7	3.5	11.0	16.2	92.1	5.1	29.3	N	8.85	*	*	*	PP,D,U

Weld ID#	Stand-Off(mm)	Forward Time(ms)	Reverse Time(ms)	I-FWD(A) Commanded	I-FWD(A) Measured	I-REV(A) Measured	V-FWD (V)	V-REV (V)	-------Pilot Arc-------- I-FWD (A)	I-REV (A)	V-FWD (V)	V-REV (V)	Gas Flows(scfh) Shield	Plasma	Measured Travel Speed(ipm)	Keyhole Weld? (Y/N)	Weld Width(mm) Crown	Root	Weld Height(mm) Crown	Root	Bead Appearance
7I1	4	19	4	120	123.4	111.9	27.5	40.7	29.8	1.6	13.9	12.8	91.8	5.1	5.2	Intermit	8.37	*	*	*	U,D
7I2	4	19	4	140	143.7	125.0	28.4	46.1	30.0	2.8	14.2	14.1	91.7	5.1	5.2	Intermit	8.35	*	*	*	D
7I3	4	19	4	160	164.8	137.9	29.2	46.9	30.0	2.3	14.3	15.4	91.8	5.1	5.2	Intermit	9.40	*	*	*	D
7J1	4	16	8	120	129.6	109.2	26.8	40.4	32.1	1.8	13.5	13.6	94.4	5.1	5.2	Intermit	*	*	*	*	PP,D
7J2	4	16	8	140	151.3	122.4	28.0	42.8	32.1	1.3	13.6	14.4	91.6	5.1	5.2	Intermit	9.49	*	*	*	D
7J3	4	16	8	160	174.8	132.3	29.1	44.8	32.2	1.9	13.8	15.4	91.7	5.1	5.2	Intermit	10.49	*	*	*	D
7K1	4	12	12	120	134.9	120.4	25.8	38.5	35.4	2.4	12.3	15.8	94.2	5.1	5.2	Intermit	10.78	*	*	*	PP,D
7K2	4	12	12	140	158.1	134.0	27.0	39.9	35.3	2.2	12.0	16.4	98.3	5.1	5.2	Intermit	10.68	*	*	*	PP,D
7K3	4	12	12	160	182.4	145.4	29.7	42.3	35.6	2.2	11.6	17.0	91.6	5.0	5.2	Intermit	11.32	7.43	*	*	PP,D
7L1	4	8	16	120	144.2	126.4	24.9	43.0	38.6	3.8	10.9	16.1	91.8	5.1	5.2	Intermit	*	*	*	*	PP,D
7L2	4	8	16	140	169.8	141.0	26.7	44.5	39.3	4.1	9.9	17.7	92.0	5.1	5.2	Intermit	*	*	*	*	D
7L3	4	8	16	160	199.9	153.4	28.4	47.1	39.2	4.4	9.5	17.7	91.9	5.1	5.2	Intermit	*	*	*	*	C
7M1	4	19	4	120	121.9	120.8	26.8	35.9	31.1	3.3	13.2	13.4	91.2	5.0	14.7	N	6.32	*	*	*	PP,D
7M2	4	19	4	140	143.0	134.4	28.2	38.1	30.7	2.5	13.8	14.9	91.1	5.0	14.6	N	7.33	*	*	*	PP,D
7M3	4	19	4	160	164.1	140.7	29.3	39.4	30.0	2.4	14.2	16.2	91.0	5.0	14.7	N	7.64	*	*	*	PP,D
7N1	4	16	8	120	126.9	117.2	27.1	36.8	32.4	1.6	14.5	13.0	91.2	5.1	14.8	N	7.29	*	*	*	PP,D
7N2	4	16	8	140	149.2	130.9	28.2	38.5	32.0	1.4	14.5	14.5	91.0	5.1	14.7	N	7.76	*	*	*	PP,D
7N3	4	16	8	160	171.6	143.3	28.9	39.3	31.2	0.9	14.0	15.9	91.2	5.1	14.7	N	8.30	*	*	*	PP,D
7O1	4	12	12	120	132.9	122.2	25.8	37.3	35.6	2.4	12.0	13.3	91.4	5.0	14.9	N	8.69	*	*	*	PP,D
7O2	4	12	12	140	157.5	135.7	27.0	38.9	34.4	1.4	12.9	15.0	91.4	5.1	14.7	N	9.43	*	*	*	PP,D
7O3	4	12	12	160	182.0	149.4	27.9	39.7	34.1	0.8	12.8	16.4	91.3	5.1	14.8	N	10.31	*	*	*	PP,D
7P1	4	8	16	120	140.1	131.1	23.4	38.4	38.8	4.5	10.5	14.9	91.5	5.1	14.9	N	10.12	*	*	*	PP,D
7P2	4	8	16	140	167.5	147.8	24.7	39.1	39.6	4.3	9.6	16.9	91.5	5.1	14.8	N	10.88	*	*	*	PP,D
7P3	4	8	16	160	194.0	161.8	25.6	40.4	40.1	4.8	9.7	18.4	91.3	5.1	14.8	N	11.67	*	*	*	PP,D

* Measurement not applicable (such as for cutting) or unavailable due to severe weld deformation (such as drooping)

APPENDIX L

Data Tables For Second Set Of Experiments, Experiment #8

EXPERIMENT #8
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Determine the effects of shield gas flow, wire feed speed, and weld current on cover passes.

WELD CONDITIONS:

Date of Experiment:	March 20, 1992
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Cover Pass
Joint Type:	Bead-on-plate
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum (8A-8G); A36 Mild Steel (8H-8N)
Plate Thickness:	0.250" (6.35 mm)
Wire Material:	2319 Aluminum (8A-8G); ER-100S-1 (8H-8N)
Wire Thickness:	0.063" (1.60 mm)
Ambient Temperature (deg F):	75 - 78

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156" (3.96 mm)
Electrode Length:	2.434" (61.82 mm) (8A-8K); 2.425" (61.60 mm) (8L-8N)
Orifice Diameter:	0.125" (3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.047" (1.19 mm)
Orifice Thickness L2:	0.132" (3.35 mm) (8A-8K); 0.134" (3.40 mm) (8L-8N)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W235873
Plasma Gas Flow Rate (scfh)	2.0
Shield Gas:	Helium (8A-8G); Argon (8H-8N)
Shield Gas Bottle ID:	A01291857KF (8A-8G); Y5459 (8H-8N)
Shield Gas Flow Rate (scfh):	Varied
Back Purge Gas:	None
Gas Bottle ID:	N\A
Flowrate (scfh):	N\A
Pressure (psia):	N\A

CONTROL SETTINGS:

ASOC (ON\OFF):	ON
Initial Torch Standoff (mm):	Manual
Straight Current (amps):	50
Reverse Current (amps):	50
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	28
Travel Speed (ipm):	Varied
Wire Feed Rate (ipm):	Varied

VPPAW MODEL EVALUATION
2ND SET OF EXPERIMENTS
EXPERIMENT #: 8
PURPOSE: Effect of shield gas flow rate, wire feed speed, and weld current on cover passes.
DATE OF LAST CHANGE: 6-9-92
MATERIAL(S): 1/4"(6.35 mm) 2219-T87 Aluminum (8A-8G); 1/4"(6.35 mm) A36 Mild Steel (8H-8N)

Weld	Weld Current(A)		Weld Voltage(V)		Pilot Current(A)		Pilot Voltage(V)		SGas	PGas	S-O	Travel	Wire Feed	Weld Width(mm)		Weld Height(mm)		Bead
ID	Forward	Reverse	Forward	Reverse	Forward	Reverse	Forward	Reverse	(scfh)	(scfh)	(mm)	(ipm)	Speed(ipm)	Crown	Root	Crown	Root	Appearance
8A	122.4	127.4	22.0	32.8	31.4	4.7	12.7	12.7	60.5	2.2	4.0	9.1	30	9.86	*	1.24	*	PP,N
8B	122.2	125.8	22.4	33.0	31.5	4.6	12.4	12.5	38.6	2.2	4.0	9.1	30	9.45	*	1.30	*	PP,N
8C	122.3	128.7	22.1	32.4	31.2	4.8	13.3	12.7	83.3	2.2	4.0	9.1	30	9.40	*	1.31	*	PP,N
8D	122.3	128.1	22.4	33.3	31.1	4.5	13.3	12.7	60.9	2.2	4.0	9.1	20	9.41	*	1.08	*	PP,N
8E	122.3	127.2	22.7	33.3	31.1	5.2	13.2	12.7	61.1	2.2	4.0	9.1	40	9.58	*	1.52	*	PP,N
8F	92.8	102.5	21.4	32.2	31.3	5.7	12.1	9.6	60.9	2.2	4.0	9.1	30	5.74	*	1.70	*	PP,N
8G	142.5	139.6	24.3	35.7	30.9	5.2	13.5	13.8	61.1	2.2	4.0	9.1	30	10.03	*	1.14	0.75	PP,PT,N
8H	127.0	134.6	21.9	30.8	30.9	3.4	12.8	15.4	40.8	2.2	4.5	5.3	10	9.00	*	1.25	*	PP,N
8I	126.8	133.4	21.8	31.3	30.9	3.1	12.4	15.4	28.1	2.2	4.5	5.3	10	8.38	*	1.85	*	PP,D
8J	127.0	132.9	22.0	31.7	31.2	2.1	12.7	15.7	52.0	2.2	4.5	5.3	10	9.80	*	1.17	*	PP,D
8K	126.8	133.9	22.3	31.3	31.2	3.2	12.6	16.2	40.2	2.2	4.5	5.3	7.5	9.32	*	1.02	*	PP,D
8L	126.4	132.1	21.3	31.1	30.5	1.9	12.9	15.4	40.3	2.2	4.5	5.2	12	8.78	*	1.30	*	PP,N
8M	112.2	118.6	20.8	30.3	30.0	1.2	12.7	14.4	40.5	2.2	4.5	5.2	10	7.87	*	1.11	*	PP,N
8N	141.6	142.4	22.5	32.8	30.1	1.2	13.1	17.1	40.2	2.2	4.5	5.2	10	8.28	*	*	*	PP,D

* Measurement not applicable (such as for root since these are cover passes) or unavailable due to severe weld deformation (such as drooping)

APPENDIX M
Data Tables For Second Set Of Experiments, Experiment #9

EXPERIMENT #9
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE:	Measure weld repeatability

WELD CONDITIONS:

Date of Experiment:	March 25, 1992
Tool:	Station #2
Weld Orientation:	Vertical Up
Weld Pass:	Varied
Joint Type:	Bead-on-plate
Joint Gap:	N\A
Plate Material:	2219-T87 Aluminum (9A-9X); A36 Mild Steel (9AA-9AX)
Plate Thickness:	0.250" (6.35 mm)
Wire Material:	2319 Aluminum for aluminum cover passes; ER-100-S1 for mild steel cover passes
Wire Thickness:	0.063" (1.60 mm)
Ambient Temperature (deg F):	73 - 83

ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156" (3.96 mm)
Electrode Length:	2.549" (64.74 mm) (9A-9H); 2.543" (64.59 mm) (9I-9P); 2.530" (64.26 mm) (9Q-9X); 2.512" (63.80 mm) (9AA-9AH); 2.482" (63.04 mm) (9AI-9AP); 2.461" (62.51 mm) (9AQ-9AX)
Orifice Diameter:	0.125" (3.18 mm)
Electrode Setback (electrode to orifice distance) L1:	0.044" (1.12 mm) (9A-9H, 9M-9X, 9AA-9AH); 0.043" (1.09 mm) (9I-9L, 9AI-9AX)
Orifice Thickness L2:	0.140" (3.56 mm) (9A-9P); 0.141" (3.58 mm) (9Q-9X); 0.142" (3.61 mm) (9AA-9AX)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W235873 (9A-9X); W344124 (9AA-9AX)
Plasma Gas Flow Rate (scfh)	Varied
Shield Gas:	Helium (9A-9X); Argon (9AA-9AX)
Shield Gas Bottle ID:	A01291857KF (9A-9X); Y5459 (9AA-9AX)
Shield Gas Flow Rate (scfh):	80 (9A-9X); 50 (9AA-9AX)
Back Purge Gas:	None

CONTROL SETTINGS:

ASOC (ON\OFF):	ON
Initial Torch Standoff (mm):	Manual
Straight Current (amps):	50
Reverse Current (amps):	50
Add. Reverse Current (amps):	60
Forward Time (msec):	19
Reverse Time (msec):	4.0
Pilot Current (amps):	28
Travel Speed (ipm):	Varied
Wire Feed Rate (ipm):	30 for aluminum cover passes; 10 for mild steel

VPPAW MODEL EVALUATION
2ND SET OF EXPERIMENTS
EXPERIMENT #: 9
PURPOSE: Measure Of Weld Repeatability
The same parameters were used for each of these sets of welds. Each weld was repeated 4 times: on different days, different times of day, & different plate position.

Weld Sets:
(A,F,N,Q - Nominal Root Parameter)
(B,J,M,U - Colder Root Parameter)
(C,H,P,S - Nominal Cover Parameter)
(D,L,O,W - Colder Cover Parameter)
(E,I,R,V - Hotter Root Parameter)
(G,K,T,X - Hotter Cover Parameter)

DATE OF LAST CHANGE: 6-9-92
MATERIAL(S): 1/4"(6.35 mm) 2219-T87 Aluminum (9A-9X)
1/4"(6.35 mm) A36 Mild Steel (9AA-9AX)

Weld ID	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	S-O (mm)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Leading Edge Angle(degs)	Bead Appearance
9A	132.7	122.5	26.6	40.5	30.7	3.6	14.0	13.6	61.7	5.1	4.0	9.9	8.38	5.03	0.26	0.84	23.5	N
9B	118.0	108.9	26.3	40.2	30.5	3.9	14.1	11.8	62.2	5.1	4.0	10.4	7.87	5.13	0.35	0.73	31.0	N
9C	122.4	124.8	22.3	34.3	31.2	4.3	12.5	12.1	61.3	2.2	4.0	9.0	10.80	*	1.23	*	*	N,PP
9D	107.9	110.3	21.4	33.3	31.3	3.9	12.3	10.8	61.8	2.2	4.0	9.5	8.33	*	1.24	*	*	N,PP
9E	147.8	135.4	27.4	40.7	30.8	3.8	14.5	14.7	65.2	5.1	4.0	9.5	8.75	6.50	-0.26	1.34	20.0	N
9F	133.5	116.9	26.7	41.3	30.4	4.0	14.4	13.3	64.9	5.1	4.1	10.0	8.20	4.83	0.40	0.88	22.0	N
9G	137.1	136.8	23.8	35.1	31.2	4.5	13.1	13.3	61.9	2.2	4.1	8.6	11.05	*	1.27	*	*	N,PP
9H	122.3	124.8	22.7	34.3	31.2	4.3	12.9	12.4	62.4	2.2	4.1	9.0	10.41	*	1.26	*	*	N,PP
9I	147.7	135.5	28.0	41.1	30.4	4.5	13.9	14.7	60.3	5.1	4.1	9.4	8.75	6.48	-0.17	1.33	25.0	N
9J	118.2	107.7	26.6	41.0	30.0	4.0	14.2	11.8	61.7	5.1	4.1	10.4	7.76	4.62	0.38	0.75	31.0	N
9K	137.1	137.6	23.6	35.2	31.0	5.5	12.3	13.6	61.7	2.2	4.1	8.5	11.30	*	1.01	0.86	*	N,PP
9L	107.8	111.4	21.4	33.0	31.3	7.2	12.4	11.0	61.9	2.2	4.1	9.5	8.74	*	1.24	*	*	N,PP
9M	117.7	112.8	26.6	39.5	30.2	3.3	14.7	12.3	62.2	5.1	4.1	10.4	8.15	4.44	0.36	0.59	32.0	N
9N	133.4	116.5	26.8	40.6	30.4	4.3	13.9	12.7	62.2	5.1	4.1	9.9	8.59	5.46	0.11	1.05	20.0	N
9O	108.1	109.8	22.1	33.6	31.0	6.9	13.0	10.6	62.4	2.2	4.1	9.4	8.71	*	1.29	*	*	N,PP
9P	122.3	124.7	23.0	34.8	31.1	6.4	12.9	12.2	62.3	2.2	4.1	9.0	10.92	*	1.24	*	*	N,PP
9Q	132.4	125.5	27.5	40.0	30.7	4.9	13.7	14.6	62.1	5.1	4.1	9.9	8.00	5.33	0.12	0.89	28.5	N
9R	147.8	134.2	28.3	40.9	30.6	4.7	14.1	15.4	62.0	5.1	4.1	9.4	8.42	6.55	-0.05	1.38	21.0	N
9S	122.2	124.7	23.2	35.0	31.3	5.8	12.1	12.9	61.6	2.2	4.1	9.0	10.80	*	1.21	*	*	N,PP
9T	137.0	136.9	24.0	35.4	31.2	5.3	12.4	13.9	61.5	2.2	4.1	8.5	11.05	*	1.35	*	*	N,PP
9U	118.0	109.3	27.2	40.7	30.0	5.1	14.3	12.5	62.0	5.1	4.1	10.4	7.77	4.57	0.36	0.75	29.5	N
9V	147.4	137.0	28.6	40.9	30.4	4.6	14.1	15.3	62.1	5.1	4.1	9.5	8.64	6.63	-0.26	1.52	19.5	N
9W	107.8	110.8	22.0	33.4	31.0	5.1	12.2	11.5	61.9	2.2	4.1	9.5	7.98	*	1.37	*	*	N,PP
9X	136.8	138.9	23.6	34.4	30.9	5.8	12.8	13.7	61.8	2.2	4.1	8.5	10.76	*	1.35	*	*	N,PP

Weld ID	Weld Current(A) Forward	Weld Current(A) Reverse	Weld Voltage(V) Forward	Weld Voltage(V) Reverse	Pilot Current(A) Forward	Pilot Current(A) Reverse	Pilot Voltage(V) Forward	Pilot Voltage(V) Reverse	SGas (scfh)	PGas (scfh)	S-O (mm)	Travel (ipm)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Leading Edge Angle(degs)	Bead Appearance
9AA	153.1	144.5	24.7	36.1	29.7	0.8	13.7	18.2	41.0	4.2	4.5	4.3	10.17	3.44	1.73	0.11	21.0	N,U
9AB	145.1	142.2	24.3	35.2	30.4	0.9	13.8	17.7	40.3	4.2	4.6	4.5	9.17	3.52	2.05	-0.12	27.5	U,D
9AC	127.2	134.6	21.6	30.7	31.3	2.3	12.6	16.2	40.2	2.2	4.5	5.3	8.02	*	1.27	*	*	D,PP
9AD	121.0	129.5	21.5	30.2	31.2	2.8	12.6	15.6	41.3	2.2	4.6	5.6	7.76	*	1.19	*	*	D,PP
9AE	161.4	150.3	26.1	37.7	29.5	0.7	13.9	19.0	40.8	4.2	4.6	4.0	9.55	5.27	-0.68	1.60	18.5	U,ED,D
9AF	153.1	144.4	25.6	36.4	29.3	0.8	13.8	19.0	40.7	4.1	4.6	4.3	10.05	3.66	1.43	0.24	20.0	N,U
9AG	134.4	139.2	22.4	31.9	31.0	1.8	12.7	16.7	40.7	2.2	4.6	5.0	8.92	*	*	*	*	D,PP
9AH	127.5	134.4	21.8	31.3	30.9	2.3	12.8	16.3	40.7	2.2	4.6	5.3	8.42	*	*	*	*	D,PP
9AI	160.9	151.3	24.9	36.1	29.1	0.6	13.6	18.1	42.0	4.2	4.5	4.0	11.07	4.52	0.87	0.75	20.0	N,U
9AJ	144.6	139.8	24.4	37.4	30.5	1.5	13.4	17.5	41.8	4.2	4.5	4.5	9.80	3.06	1.88	-0.96	21.5	U,SB,D
9AK	137.4	142.1	19.4	29.6	31.1	2.5	12.5	16.4	41.3	2.2	4.5	5.0	9.09	*	1.99	*	*	D,PP
9AL	120.3	129.0	21.2	30.2	31.1	2.1	12.3	15.6	40.8	2.2	4.5	5.6	8.36	*	1.11	*	*	N,PP
9AM	143.5	141.2	25.2	33.4	29.4	0.7	12.5	15.7	36.2	4.2	4.5	4.5	9.70	3.75	*	0.30	28.0	U,D
9AN	152.4	147.6	25.5	35.2	30.0	1.2	13.3	18.9	42.7	4.2	4.5	4.3	9.41	4.01	1.5	0.26	24.5	N,U
9AO	120.7	126.7	20.8	30.6	31.1	2.5	12.2	16.1	40.4	2.2	4.5	5.6	8.43	*	1.02	*	*	N,PP
9AP	127.3	133.4	22.1	32.1	30.6	1.4	12.4	16.3	40.6	2.2	4.5	5.3	8.20	*	1.27	*	*	D,PP
9AQ	153.2	142.4	24.7	37.9	28.9	1.4	13.9	17.8	40.9	4.1	4.5	4.3	10.29	4.23	1.29	0.19	18.0	N,U
9AR	161.1	148.6	25.3	38.0	30.2	2.5	13.3	18.5	40.6	4.1	4.5	4.0	10.13	4.97	*	*	24.5	D,SB,PP
9AS	127.0	133.2	21.4	31.9	29.8	1.0	12.0	15.8	40.2	2.2	4.5	5.3	8.17	*	1.28	*	*	D,PP
9AT	136.9	141.7	22.0	31.5	30.3	2.5	12.1	16.7	40.4	2.2	4.5	5.0	8.80	*	1.45	*	*	D,PP
9AU	143.9	142.6	25.0	34.6	29.2	1.0	13.3	18.6	40.2	4.2	4.5	4.5	10.15	2.92	1.33	0.24	24.0	N,U
9AV	160.9	151.7	25.9	35.9	28.3	0.9	13.2	18.8	40.4	4.2	4.5	4.0	10.30	5.21	0.96	0.79	20.0	N,U
9AW	120.5	128.3	21.6	30.9	30.1	2.4	12.2	15.7	40.2	2.2	4.5	5.5	8.13	*	1.21	*	*	N,PP
9AX	137.0	141.6	22.5	31.8	30.0	2.0	12.4	16.9	40.1	2.2	4.5	4.9	8.76	*	1.28	*	*	D,PP

* Measurements not applicable (such as roots for cover passes) or unavailable due to severe weld deformation (such as drooping)

APPENDIX N

Data Tables For Second Set Of Experiments, Experiment #10

EXPERIMENT #10
Experimental Conditions and Control Settings

EXPERIMENT PURPOSE: Continuation of experiment 7: Determine effect of changes in 19ms\4ms waveform, first at 6mm standoff and then without additional reverse current

WELD CONDITIONS:

Date of Experiment:	
Tool:	April 13, 1992
Weld Orientation:	Station #2
Weld Pass:	Vertical Up
	Root Pass (10A-10D, 10J-10K);
Joint Type:	Cover Pass (10E-10I,10L-10M)
Joint Gap:	Bead-on-plate
Plate Material:	N\A
Plate Thickness:	2219-T87 Aluminum
Wire Material:	0.250" (6.35 mm)
Wire Thickness:	No wire
Ambient Temperature (deg F):	N\A
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ELECTRODE PROPERTIES:

Electrode Material:	2% Thoriated Tungsten
Electrode Diameter:	0.156" (3.96 mm)
Electrode Length:	2.448" (62.18 mm) before 10A;
	2.469" (62.71 mm) after 10D;
	2.370" (60.20 mm) before 10E;
	2.395" (60.83 mm) after 10I;
	2.448" (62.18 mm) (10J-10K);
	2.431" (61.75 mm) (10L-10M)
Orifice Diameter:	0.125" (3.18 mm)
Electrode Setback	
(electrode to orifice distance) L1:	0.046" (1.17 mm) (10A-10D);
	0.045" (1.14 mm) (10E-10I, 10L-10M);
	0.044" (1.12 mm) (10J-10K)
Orifice Thickness L2:	0.132" (3.35 mm) (10A-10I);
	0.134" (3.40 mm) (10J-10M)
Electrode Cooling Water Flow Rate:	2 liters\minute

GAS FLOW SETUP DATA:

Plasma Gas:	Argon
Plasma Gas Bottle ID:	W344124
Plasma Gas Flow Rate (scfh)	5.0
Shield Gas:	Helium
Shield Gas Bottle ID:	EE245
Shield Gas Flow Rate (scfh):	80
Back Purge Gas:	None

CONTROL SETTINGS:

ASOC (ON\OFF):	ON
Initial Torch Standoff (mm):	Manual
Straight Current (amps):	50
Reverse Current (amps):	50
Add. Reverse Current (amps):	60 (10A-10I); none (10J-10M)
Forward Time (msec):	Varied
Reverse Time (msec):	Varied
Pilot Current (amps):	27 - 34
Travel Speed (ipm):	varied
Wire Feed Rate (ipm):	N\A

VPPAW MODEL EVALUATION
2ND SET OF EXPERIMENTS

EXPERIMENT #: 10
PURPOSE: Vary 19ms-4ms waveform (repeat of prior work by Joe Gregory)(this is an extension of exp. #7)
DATE OF LAST CHANGE: 6-10-92
MATERIAL(S): 1/4"(6.35 mm) 2219-T87 Aluminum
COMMENTS: 10A-10H ARE REPEAT OF 7A-7H, EXCEPT STAND-OFF IS 6 MM INSTEAD OF 4 MM
10I IS A REPEAT OF 10E WITH USED/MELTED ELECTRODE INSTEAD OF FRESH ELECTRODE
10J-10M ARE REPEAT OF 7C, 7D, 7G, 7H EXCEPT ADDITIONAL REVERSE CURRENT TURNED OFF

Weld ID#	Stand-Off(mm)	Forward Time(ms)	Reverse Time(ms)	I-FWD(A) Commanded	I-FWD(A) Measured	I-REV(A) Measured	V-FWD (V)	V-REV (V)	Pilot Arc I-FWD (A)	Pilot Arc I-REV (A)	Pilot Arc V-FWD (V)	Pilot Arc V-REV (V)	Gas Flows(scfh) Shield	Gas Flows(scfh) Plasma	Measured Travel Speed(ipm)	Keyhole Weld? (Y/N)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
10A1	6	19	4	120	121.6	122.3	28.9	40.7	30.3	4.6	13.9	12.5	62.6	5.1	9.3	Y	9.38	5.87	0.18	1.14	N,U
10A2	6	19	4	140	141.8	137.4	30.1	42.0	30.4	4.9	14.0	14.2	61.5	5.1	9.3	Y	10.17	6.93	0.07	1.68	N,LU
10A3	6	19	4	160	162.8	147.6	31.4	43.3	30.3	4.7	14.4	15.2	61.0	5.1	9.3	Y	11.56	11.10	*	*	LC
10B1	6	16	8	120	127.7	111.8	28.6	41.6	32.4	3.7	13.6	11.5	62.2	5.1	9.4	Y	9.42	6.15	0.10	1.22	N
10B2	6	16	8	140	149.1	126.2	29.8	42.9	32.6	3.7	13.9	12.9	61.3	5.1	9.4	Y	10.19	6.65	0.08	1.37	N
10B3	6	16	8	160	171.2	138.8	31.2	43.8	32.8	4.4	13.7	14.1	60.8	5.1	9.4	Y	*	*	*	*	LC,D
10C1	6	12	12	120	133.7	117.6	28.4	42.3	34.9	3.8	12.9	11.5	62.9	5.1	9.3	Y	*	*	*	*	LC,D
10C2	6	12	12	140	157.2	131.8	29.7	43.2	35.2	3.7	12.8	12.9	61.5	5.1	9.4	Y	*	*	*	*	LC,D
10C3	6	12	12	160	181.1	144.9	31.7	44.5	35.5	4.7	12.8	14.1	60.9	5.1	9.4	Y	*	*	*	*	LC,D
10D1	6	8	16	120	137.4	129.7	27.4	43.1	37.5	3.4	11.0	12.8	61.9	5.1	9.4	Y	9.80	*	-0.05	*	N
10D2	6	8	16	140	163.9	144.4	29.0	44.5	38.1	5.0	10.3	14.5	61.0	5.1	9.4	Y	*	*	*	*	RC,D
10D3	6	8	16	160	190.5	158.6	31.1	46.7	38.7	4.4	9.6	16.1	60.5	5.1	9.4	Y	*	*	*	*	RC,D
10E1	6	19	4	120	121.2	116.4	28.3	40.8	30.6	4.5	12.7	12.6	64.9	5.1	29.3	N	7.13	*	0.51	*	N,LU,PP
10E2	6	19	4	140	143.2	133.2	29.6	41.4	30.7	5.6	12.8	14.4	63.6	5.0	29.3	N	7.65	*	0.64	*	N,LU,PP
10E3	6	19	4	160	162.3	153.6	32.3	41.4	30.8	4.2	13.1	16.1	62.6	5.0	29.3	N	8.90	*	*	*	U,D
10F1	6	16	8	120	126.8	112.0	28.1	41.7	32.7	3.3	12.7	11.7	62.9	5.1	29.3	N	7.80	*	0.20	*	N,PP
10F2	6	16	8	140	150.6	126.8	28.7	42.3	32.9	3.7	13.0	13.3	62.3	5.1	29.3	N	8.47	*	0.84	*	N,U,PP
10F3	6	16	8	160	170.8	143.9	31.1	42.3	33.0	4.1	13.3	15.0	61.9	5.0	29.3	N	8.64	*	*	*	U,D,PP
10G1	6	12	12	120	132.5	116.6	28.0	42.6	34.8	5.3	13.7	12.2	63.1	5.1	29.3	N	8.34	*	0.33	*	N,PP
10G2	6	12	12	140	158.4	132.3	29.0	43.2	35.2	5.2	13.4	13.8	62.6	5.1	29.3	N	8.90	*	1.11	*	U,D,PP
10G3	6	12	12	160	184.9	141.3	30.2	45.6	35.4	4.3	13.2	14.5	62.1	5.1	29.3	N	9.73	*	1.42	0.00	N,U,PP

Weld ID#	Stand-Off(mm)	Forward Time(ms)	Reverse Time(ms)	I-FWD(A) Commanded	I-FWD(A) Measured	I-REV(A) Measured	V-FWD (V)	V-REV (V)	Pilot Arc I-FWD (A)	Pilot Arc I-REV (A)	Pilot Arc V-FWD (V)	Pilot Arc V-REV (V)	Gas Flows(scfh) Shield	Gas Flows(scfh) Plasma	Measured Travel Speed(ipm)	Keyhole Weld? (Y/N)	Weld Width(mm) Crown	Weld Width(mm) Root	Weld Height(mm) Crown	Weld Height(mm) Root	Bead Appearance
10H1	6	8	16	120	139.0	127.1	26.0	44.0	37.6	3.3	11.5	13.1	63.2	5.1	29.3	N	9.03	*	0.60	*	N,U,PP
10H2	6	8	16	140	168.2	143.8	27.2	44.7	38.2	5.9	11.2	14.7	62.6	5.1	29.3	N	10.26	*	1.01	*	N,U,PP
10H3	6	8	16	160	190.2	162.1	29.5	43.8	39.2	3.5	11.4	17.9	62.1	5.1	29.3	N	9.20	*	*	*	D,PP
10I1	6	19	4	120	120.8	122.8	27.9	40.1	30.1	3.6	14.2	12.7	63.1	5.1	29.2	N	7.08	*	0.47	*	N,U,PP
10I2	6	19	4	140	142.4	137.5	29.9	41.4	30.1	4.8	14.6	14.4	62.4	5.0	29.3	N	8.03	*	0.76	*	D,PP
10I3	6	19	4	160	162.9	153.5	32.2	41.9	30.0	5.8	14.9	15.7	62.0	5.1	29.3	N	8.55	*	*	*	U,D,PP
10J1	4	12	12	120	133.2	102.7	25.8	38.4	34.2	3.8	14.0	10.5	62.5	5.1	9.4	Y	8.11	5.72	-0.07	1.25	N
10J2	4	12	12	140	157.2	117.4	26.8	39.3	34.6	3.8	13.7	12.0	61.7	5.1	9.4	Y	8.58	7.04	-0.22	2.01	N
10J3	4	12	12	160	179.7	133.3	27.7	39.2	35.1	4.8	13.2	13.5	61.3	5.1	9.4	Y	*	*	*	*	LC,D
10K1	4	8	16	120	138.1	107.2	24.3	38.7	36.7	4.0	12.7	11.2	63.7	5.2	9.4	Y	7.97	7.37	0.16	1.38	N,RU
10K2	4	8	16	140	163.8	123.3	25.3	39.1	37.2	4.9	12.2	12.9	62.3	5.2	9.4	Y	*	*	*	*	RC,D
10K3	4	8	16	160	188.3	140.0	27.3	40.3	37.7	3.9	11.9	14.3	61.6	5.2	9.4	Y	*	*	*	*	RC,D
10L1	4	12	12	120	132.7	101.4	24.5	37.0	34.3	2.8	13.5	10.6	62.2	5.1	29.4	N	6.73	*	0.19	*	PP,N
10L2	4	12	12	140	159.8	117.5	25.4	38.6	34.7	4.1	13.5	12.3	61.7	5.1	29.4	N	7.11	*	0.21	*	PP,D
10L3	4	12	12	160	180.4	134.8	26.5	37.9	35.1	5.0	13.2	13.6	61.5	5.1	29.4	N	8.16	*	*	*	PP,D,U
10M1	4	8	16	120	137.8	106.3	23.5	37.9	36.5	3.1	13.0	11.0	64.7	5.1	29.4	N	7.80	*	0.18	*	PP,N,R
10M2	4	8	16	140	163.7	124.1	24.1	37.4	37.1	4.8	12.5	12.4	63.7	5.1	29.4	N	7.70	*	0.12	*	PP,D,U
10M3	4	8	16	160	191.3	139.8	24.8	38.4	37.6	4.1	12.2	13.9	62.9	5.1	29.4	N	9.14	*	1.52	*	PP,D,U

* Measurement not applicable (such as for cutting) or unavailable due to severe weld deformation (such as drooping)

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15. Supplementary Notes

16. Abstract

A mathematical model of the VPPAW process was evaluated by comparing it to results of actual welds. Understanding of the VPPAW process was increased. Modifications were made to the model to improve correlation of model calculations to test results. A multi-variable controller algorithm was developed for simultaneously controlling weld crown and root widths.

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