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Eldon D. Brandon

THE DOW CHEMICAL COMPANY
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PARAMETERS FOR PRESSURIZED INERT GAS METAL ARC WELDING OF ALUMINUM

Eldon D. Brandon

Abstract. This study was designed to establish the significance of various process parameters in *pressurized inert gas metal arc (*PIGMA) welding. Specifically, the effects of arc voltage, wire speed, travel speed, and chamber pressure were determined. The measured responses were arc mode and stability, weld appearance, soundness, area, width, penetration, reinforcement, and depth-to-width ratio.

Using predetermined combinations of parameters, bead-on-plate welds were made on an 8-inch diameter by 1-inch wall of a Type-1100 aluminum cylinder. The filler wire was a 0.030-inch diameter of Type-718 aluminum. The welding was performed in a pressure chamber with the cylinder in the horizontal-rolled position. After welding, the welds were X-rayed and visually and metallographically examined.

For purposes of analysis, the raw data of each response were treated using a multiple regression analysis technique. By this technique, the variability in ratings caused by each independent variable and in lower order interactions was determined. Calculated ratings were obtained for each combination of parameters. The results of the study were derived using the trends of the calculated ratings.

Findings are briefly described:

Chamber Pressure, in general when increased, acts to reduce weld appearance, weld width, and arc stability and increases the depth-to-width ratio. Increased pressure shortens the arc and changes the transfer mode to short circuiting.

Arc Voltage, when increased from 22 to 28 volts, exhibits relatively minor influence on weld soundness and appearance but did increase the weld penetration and area.

Travel Speed, when increased from 60 to 120 inches per minute, decreased weld penetration, width, and cross-sectional area.

Wire Speed was the most significant factor affecting weld appearance, soundness, reinforcement, penetration, width, area, and depth-to-width ratio. The best appearing and soundest welds occurred at lower wire-feed rates. As would be expected, the size of the weld increased with wire-feed rate.

Using criteria of acceptable appearance and soundness. the maximum depth-to-width ratio (1.2:1) was obtained at 29 volts, 800 inches per minute, 70 inches per minute travel, and 82 pounds per square inch absolute pressure.

INTRODUCTION

Pressurized Inert Gas Metal Arc or PIGMA welding is a relatively new technique being used at the Rocky Flats Plant to reduce weld-metal porosity to extremely low levels, when other techniques fail. Other desirable conditions, such as a narrower, more concentrated arc profile, have been realized.

The PIGMA process is essentially the same as gas metal arc (GMA) welding, except that the arc is enclosed within a pressure chamber. The chamber (Figure 1) can contain the torch, torch manipulator, work piece, and fixture; or can enclose only the torch, manipulator, and work piece (see Figure 2). For welding, the chamber is pressurized to some elevated pressure in the range of 20 to 100 pounds per square inch absolute (psia). The chamber may or may not be evacuated before being pressurized. Inert gas is normally used to backfill the chamber after evacuation. However compressed air may be used if an inert atmosphere is not required. After the desired pressure is reached, the welding proceeds in the normal manner, except, of course, the operation must be carried out by remote control.

The basic process and equipment have been described in more detail by R. Barker.[1]

The current program was designed to establish the significance of various process parameters in PIGMA welding.

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[1] R. Barker, "Pigma Welding—A Method for Reducing Weld Porosity." *Welding Journal,* Pages 1s to 6s. January 1965.

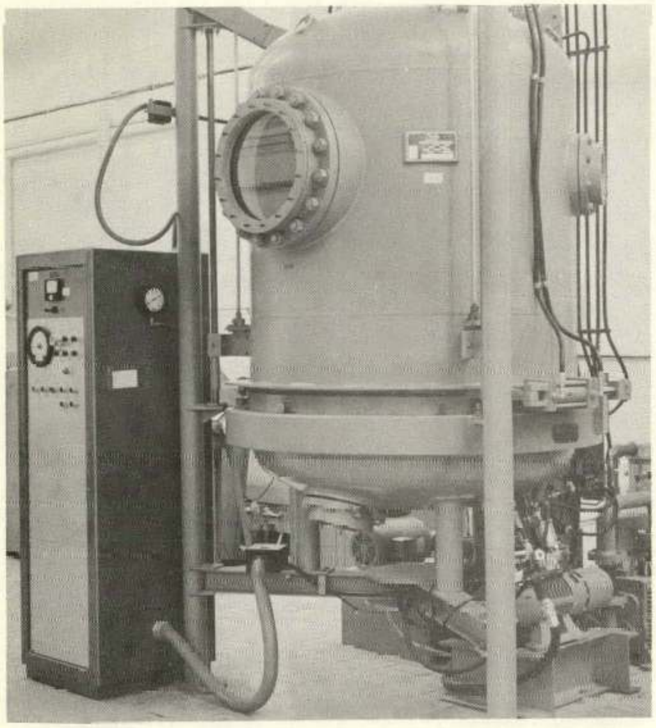

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FIGURE 1. Welding Chamber, Vertical Design.

FIGURE 2. Welding Chamber Mounted on Between-Centers Rotating Fixture.

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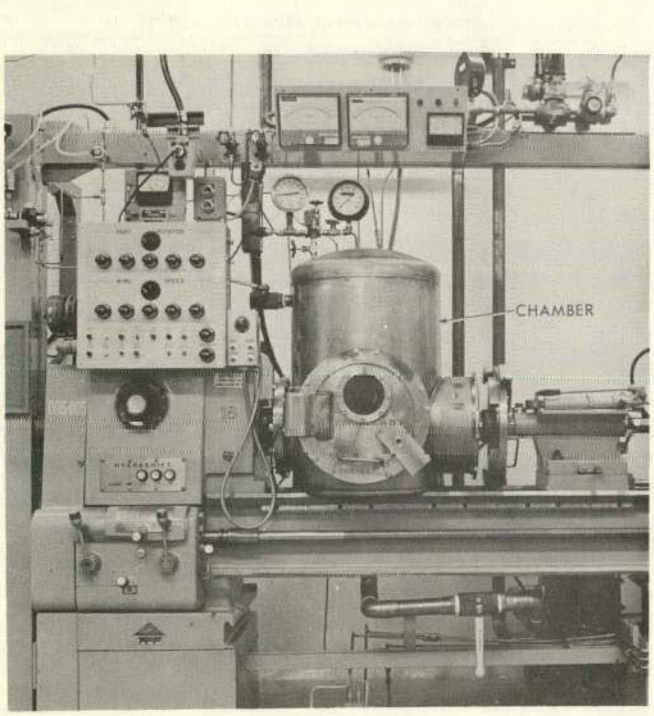

Several response variables were measured to find their relationships to the basic welding parameters. Also, a wide range of variable levels was used. Thus, a set of limits was established wherein acceptable welds could be made.

EXPERIMENTAL

Materials: The selected base metal, Type-1100 aluminum alloy, was cylindrical, 8.38 inches outside diameter by 1-inch wall by 13 inches long. Type-1100 aluminum is a 99 percent purity alloy containing small amounts of copper, silicon, and iron. The filler wire was of a 0.030-inch diameter, Type-718 aluminum alloy. Chemistry of this alloy is 12 percent silicon, balance aluminum.

Before welding, the cylinder was degreased by wiping with acetone-soaked tissues followed by a light etch by bathing in nitric acid for 25 minutes. After a cold and hot tap-water rinse, the cylinder was warmed with an oxy-acetylene torch and then stored in the evacuated welding chamber until the welding started.

No attempt was made to clean the filler wire which remained in a mill-applied sealed plastic bag until the welding started.

Equipment: A commercial 500-ampere, 440-volt, three-phase, constant-potential welding power supply was used. An inductance package had been added to the power supply with inductance set at maximum throughout the test. The welding chamber and fixture are shown in Figure 3.

The torch, torch manipulator, fixture, and sequencing controls were all of an in-house design and manufacture. Briefly, the torch wire-feeder assembly (Figure 4) was a compact unit using a 1-inch diameter smooth drive and back-up rolls and a $2^1/_{16}$-inch long copper contact tube.

The wire-drive motor utilized a clutch drive to gain faster wire starts. A 9.5-degree bend in the contact tube (arrow) was used to as an attempt to improve the consistency of *contact tube-to-wire* contact (see Figure 5).

The fixture-torch manipulator was designed to accommodate a variety of welding positions and weldment configurations. The part -drive motor was connected by a clutch to gain faster part starts.

The sequence control (Figure 6) was designed to provide completely automatic control over the welding operation. The operator locates the part in the proper position for welding, sets the controls, including the wire-feed rate, arc voltage, travel speed, weld time, and gas-flow rate, and depresses the *weld-sequence-start* button. For this experiment, the weld time was set to produce a weld approximately two inches long.

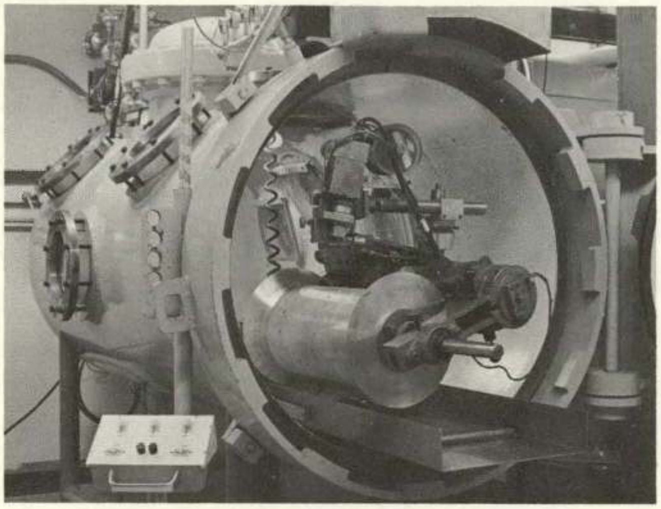

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FIGURE 3. Welding Chamber and Fixture Used for PIGMA Welding Study.

FIGURE 4. Close-up of Torch Wire-Feeder Assembly.

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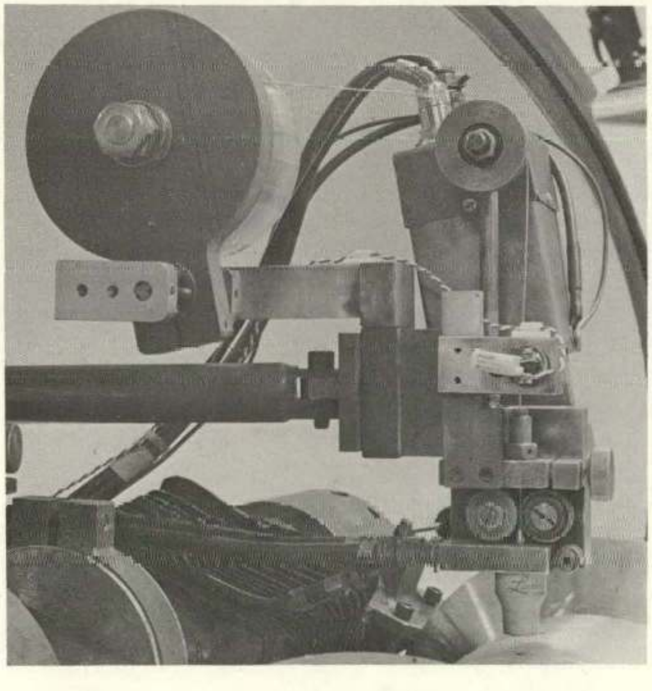

The welding procedure is summarized in Table I.

Experimental Design:

Bead-on-plate welds were made on the aluminum cylinder. The welds were made with the cylinder in the horizontal-rolled position and the torch vertical at the 12 o'clock position.

The four welding variables and levels are given in Table II.

The values in Table II were chosen since they cover the range of, what might be considered, normal welding practice. Atmospheric pressure 12 psia, was chosen as the lowest pressure.

A full factorial test plan involving the four factors at four levels would require 4^4 or 256 welds. At the cost of losing

FIGURE 5. Gas Metal Arc Torch with Gas Cup Removed to Show Angled Contact Tube.

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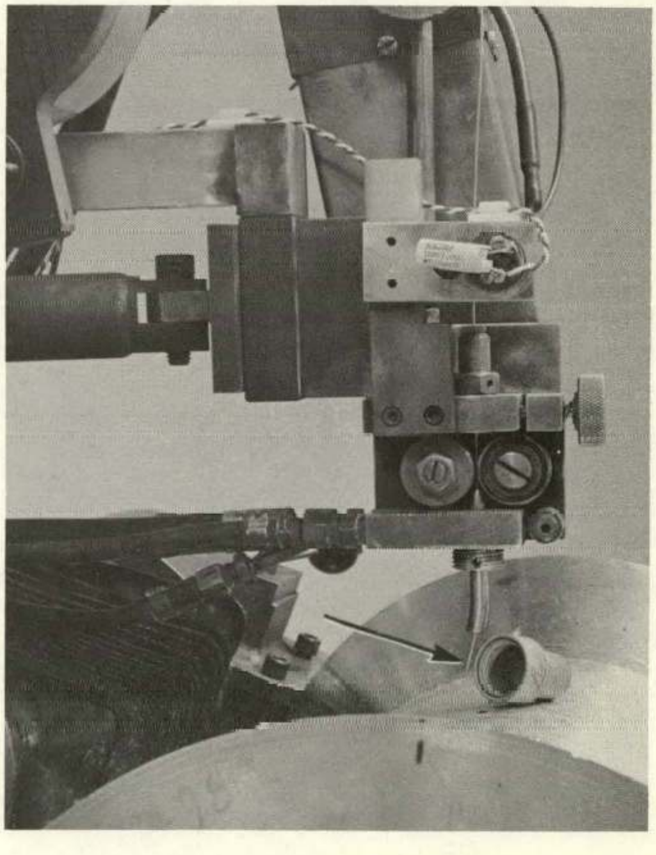

TABLE I. Summary of Pressurized Inert Gas Metal Arc Welding Procedure.

Process	– Automatic gas metal arc
Base Metal	– Type-1100 alloy aluminum cylinder 8.38-inch outside diameter by 1-inch wall by 13 inches long
Filler Metal	– Type-718 alloy aluminum, 0.030-inch diameter
Preweld Cleaning (base metal)	– Degreased with acetone Nitric acid etch Cold- and hot-water rinse Wire brushed before welding
Joint Configuration	– Bead-on-surface
Temperature Control	– Base metal at room temperature at start of each weld
Welding Position	– Cylinder horizontal-rolled Torch vertical at 12 o'clock
Polarity	– Direct current reverse polarity
Shielding Gas (torch)	– Ratio of 5:1, helium to argon (by volume) 60 cubic feet per hour (cfh) at 12 and 32 pounds per square inch absolute (psia); 120 cfh at 52 psia; 180 cfh at 72 psia
Chamber Gas	– Compressed air
Power Supply	– Vickers 500-ampere, 3-phase, resistance controlled, DC Variable Reactance Unit, Model 965, Serial 6511
Welding Fixture	– Dow-designed and built Universal orientation for between-centers or turntable operation
Welding Chamber	– Horizontal cylinder approximately 3 feet in diameter by 8 feet long Breech-lock door closure Designed for vacuum or pressure
Welding Torch	– Dow-designed and built Integral with wire-drive rolls Water-cooled Gas lens Contact tube bent 9.5 degrees into direction of travel
Welding Controls	– Dow-designed and built Programable automatic sequence
Instrumentation	– Honeywell Visicorder to record instantaneous voltage, average voltage, wire speed, welding current, and part-travel speed
Chamber Pressure	– 12, 32, 52, 72 pounds per square inch absolute (psia) (Chamber door open for 12 psia)
Arc Voltage	– 22, 24, 26, 28 volts (measured between torch and fixture)
Wire-Feed Speed	– 500, 700, 900, 1100 inches per minute (ipm) (measured by Servotek Model SS-779E1 tachometer driven directly by wire)
Part-Travel Speed	– 60, 80, 100, 120 ipm

TABLE II. Welding Variables.

Factor	Level (volts)	Factor	Level (inches per minute)
Voltage	22	Travel Speed	60
	24		80
	26		100
	28		120
	(inches per minute)		(pounds per square inch absolute)
Wire Speed	500	Chamber Pressure	12
	700		32
	900		52
	1100		72

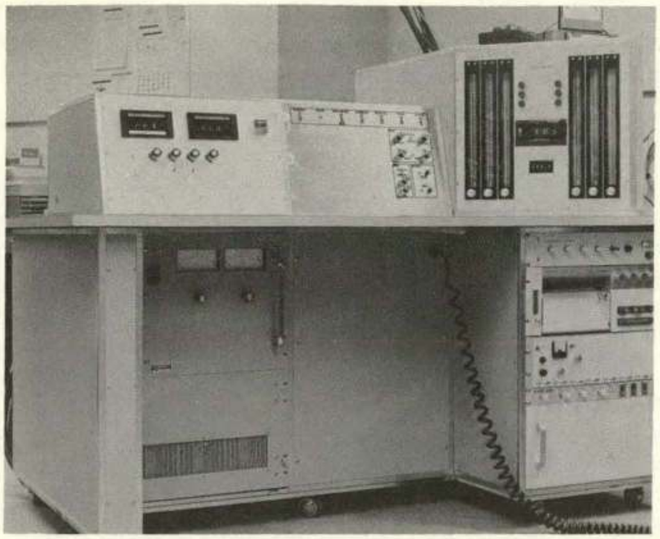

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FIGURE 6. Welding Control Console.

information on several higher order interactions, a ¼-fractional factorial design requiring only 64 welds was used. In addition, 8 duplicate welds were made in order to completely measure the variability. The order of making the welds was completely randomized to minimize the effects of uncontrolled and unknown variables such as contact tube changes, etc. The test plan is shown in Figure 7. The numbers inside of the parallelograms of the figure refer to the order in which the welds were made.

After welding, the welds were visually examined, X-rayed, sectioned, and metallographically examined. The measured responses were as follows: (1) general appearance, (2) radiographic soundness, (3) arc stability, (4) arc mode, (5) cross-sectional area of the weld, (6) weld-bead reinforcement, (7) weld penetration, (8) weld width, and (9) depth-to-width ratio. Evaluation of the first four responses was necessarily subjective.

In rating *general appearance,* each weld was assigned a rating of *1* to *5* with the best welds assigned a *5* and the poorest were assigned a *1*. Both types of welds, (a) and (b) are shown in Figure 8.

Radiographic soundness was similarly evaluated and each weld was rated with a *1, 3,* or *5.* A *5* represented a completely sound weld, and a rating of *1,* a weld containing large voids. Visual appearance was disregarded in rating the soundness. Erratic, but sound welds were assigned a *5* rating.

Arc stability was determined and rated *1, 3,* or *5* according to oscillographic recordings of arc voltage and current. Stable arc action was assigned a *5,* and unstable and erratic arcs a *1.*

Arc mode (spray, transition, or short circuiting) was also determined from the oscillographic recording. Spray-arc conditions were assigned a *5;* short-circuiting conditions, a *1;* and intermediate conditions, a *3.*

Weld area, reinforcement, penetration, and *width* were measured from a photomacrograph of a cross section of each weld as shown in Figure 9.

The aluminum cylinder in Figure 10 shows the welds which were made. The 72 welds were subsequently visually examined, X-rayed, and then cut out and metallographically examined. The nine responses were then measured on each of the 72 welds. These measurements (or raw data) are tabulated in Appendix A, Page 25.

ANALYSIS OF RESULTS

For purposes of analysis, the raw data, or ratings, of each response were treated using a multiple regression analysis technique. By this technique, the influence on rating caused by each independent variable and lower order interactions could be determined. The calculated ratings were determined by applying an equation of the form:

$$R = C_0 + C_1 \cdot V + C_2 \cdot T + C_3 \cdot W + C_4 \cdot P + C_5 \cdot V \cdot T + C_6 \cdot V \cdot W + C_7 \cdot V \cdot P + C_8 \cdot T \cdot W + C_9 \cdot T \cdot P$$

$$+ C_{10} \cdot W \cdot P + C_{11} \cdot V^2 + C_{12} \cdot T^2 + C_{13} \cdot W^2 + C_{14} \cdot P^2$$

Where, R = calculated rating

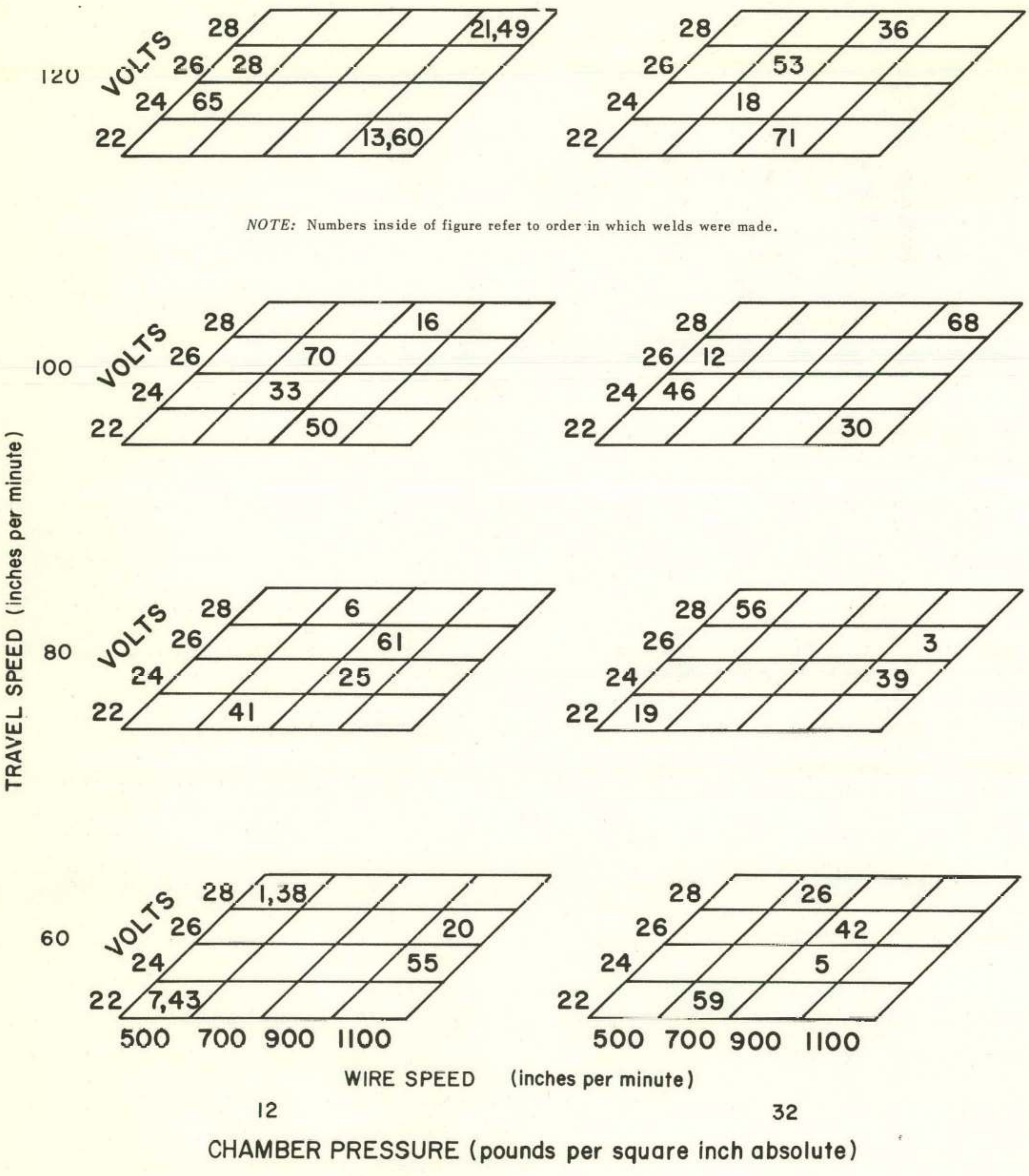
C_x = constants determined by regression analysis (C_0, C_1, C_2)

V = normalized voltage

T = normalized travel speed

W = normalized wire speed

P = normalized chamber pressure



NOTE: Numbers inside of figure refer to order in which welds were made.

FIGURE 7. Test Plan for Welding Parameters Study.

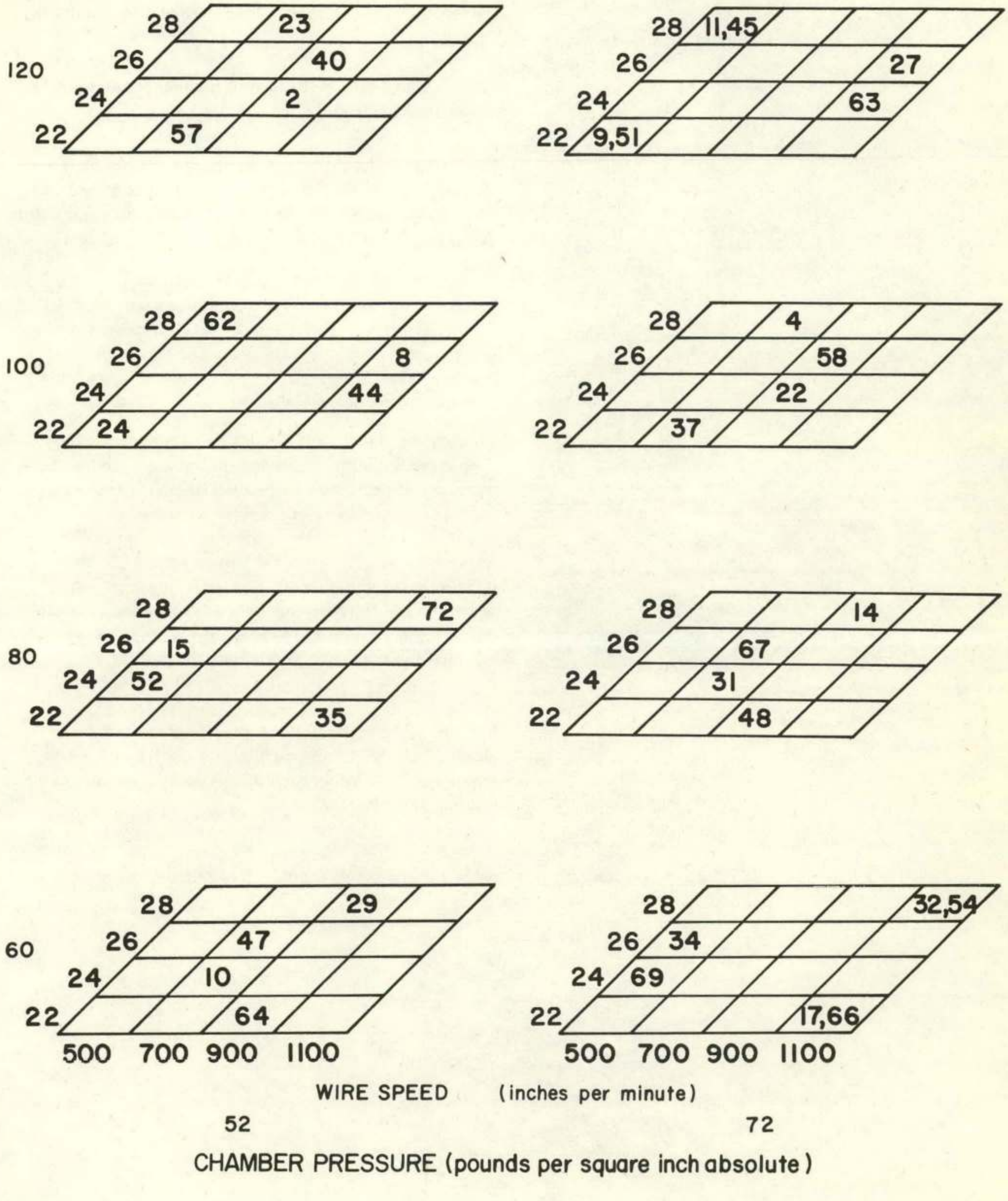

120
28
23
26
40
24
2
22
57
28
11,45
26
27
24
63
22
9,51
100
28
62
26
8
24
44
22
24
28
4
26
58
24
22
22
37
80
28
72
26
15
24
52
22
35
28
14
26
67
24
31
22
48
60
28
29
26
47
24
10
22
64
28
32,54
26
34
24
69
22
17,66
500 700 900 1100
500 700 900 1100
WIRE SPEED (inches per minute)
52
72
CHAMBER PRESSURE (pounds per square inch absolute)

FIGURE 7. →

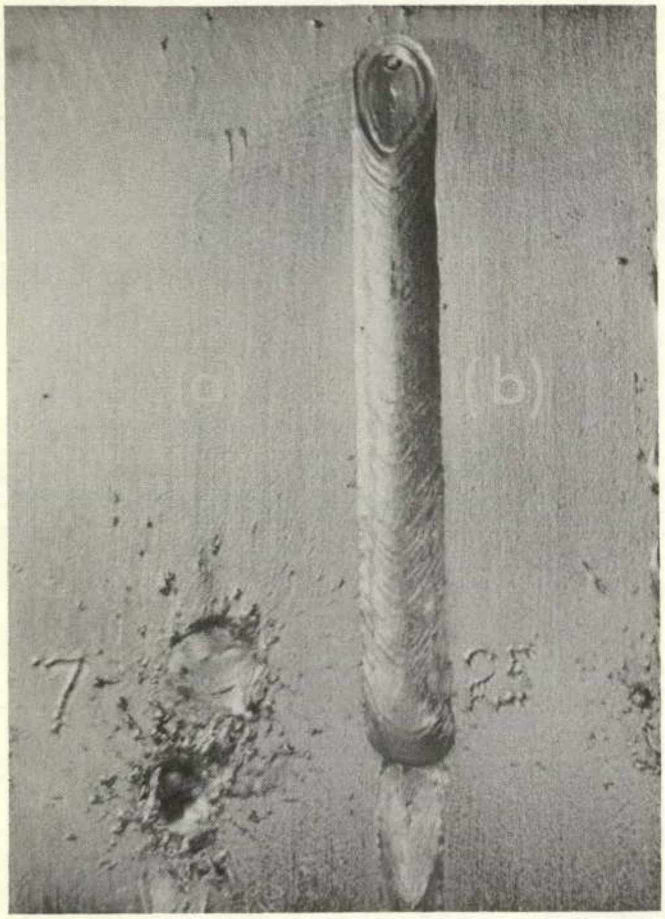


FIGURE 8. Example of Poor Weld (a) Rated 1 and Good Weld (b) Rated 5.

The normalized values of the four independent variables and the values of the constants, C_x, are listed in Appendix B, Page 29.

The calculated ratings for each of the nine responses are given in Appendix C, Page 31.

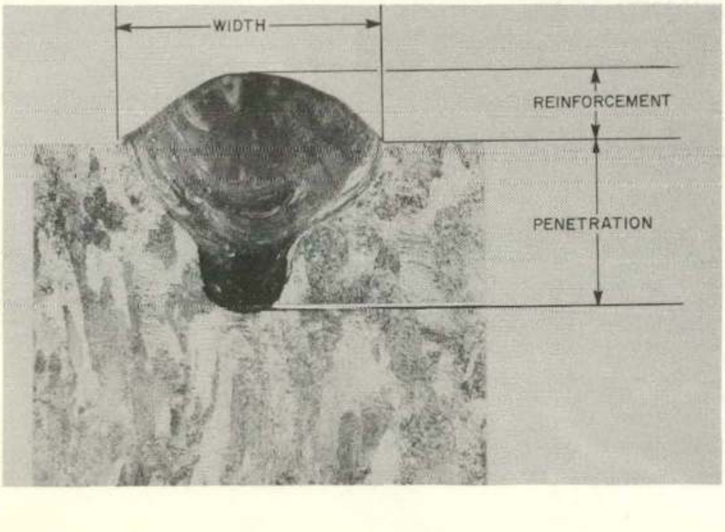
In addition to the calculated ratings, the significant factors affecting each of the nine responses were determined using the Student-*t*-Test. The results of this analysis readily show the effects of each factor by itself, as well as the significant interactions.

Table III tabulates the welding parameters which significantly affect each of the responses. Of importance here is the magnitude of the *t*-statistic. The greater the absolute value of the *t*-statistic, the more influential that factor is in affecting the response.

A negative *t*-statistic for the single factors indicates an inverse relationship. As the welding parameter is increased, the response decreases. A product of two factors indicates an interrelationship. For example, when one of the factors is low, an increase in the other may increase the response. However, when the first factor is high, an increase in the second may decrease the response. A squared single factor simply indicates a nonlinear, second-degree curve relationship between the welding parameter and the response. In this case, the positive or negative sign indicates the direction of curvature.

Because of the amount of information that can be gleaned from this study, each response will be discussed separately followed by brief details on optimization of welding parameters.

FIGURE 9. A Cross Section of the Weld Showing Measured Responses.



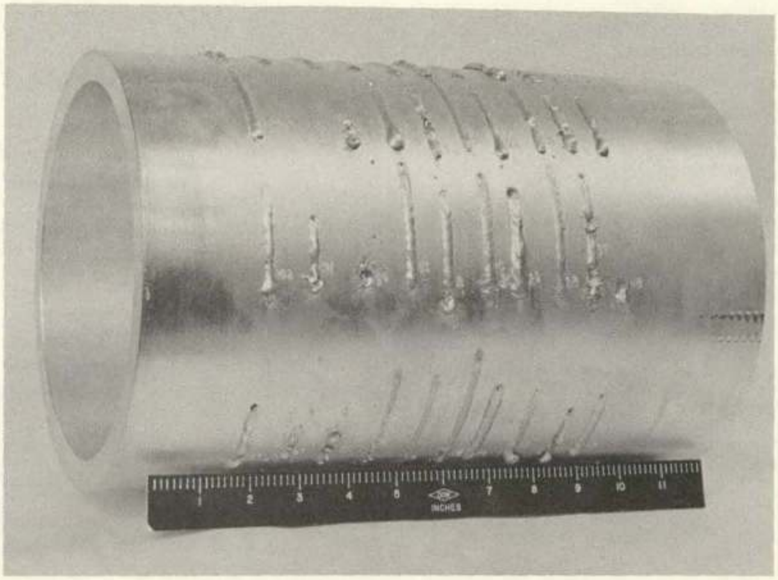


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FIGURE 10. Aluminum Cylinder with Welds.

TABLE III. Significant Factors Contributing to Responses.

Student *t*-test analysis:

	Factor	*t-Statistic
General Appearance	wire speed	−8.450
	chamber pressure	−3.001
	voltage x pressure	2.911
	$(\text{wire speed})^2$	−2.710
	travel x pressure	2.169
Weld Soundness	wire speed	−9.122
	$(\text{wire speed})^2$	−3.837
** Arc Mode	voltage	9.858
	pressure	−4.955
	wire speed	4.854
	travel speed	3.234
	$(\text{wire speed})^2$	2.366
Arc Stability	wire speed	−4.637
	voltage	2.855
	pressure	−2.784
	voltage x pressure	2.499
Weld Area	wire speed	9.017
	travel speed	−4.441
	voltage	3.972
	voltage x pressure	2.866
	voltage x wire	2.565
	wire x pressure	−2.201
	pressure	2.041
	$(\text{voltage})^2$	−2.012
Weld Width	wire x pressure	−3.685
	pressure	−2.997
	wire speed	−2.898
	travel speed	−2.709
	voltage	2.169
	$(\text{voltage})^2$	−2.126
Weld Reinforcement	wire speed	13.123
	travel speed	−4.626
	$(\text{wire speed})^2$	3.276
	voltage x wire	2.305
	voltage x pressure	2.224
Weld Penetration	wire speed	16.145
	pressure	5.516
	voltage	3.053
	travel speed	−2.998
	voltage x pressure	2.823
	travel x wire	−2.209
Depth to Width Ratio	wire speed	12.553
	pressure	6.450
	wire x pressure	4.189
	$(\text{wire speed})^2$	2.125
	voltage x travel	−2.028
	voltage x pressure	2.025

---

* The 0.05 level of significance – 2.000.

** Spray mode indicated by high positive *t*-statistic.

General Appearance:

From Table III, wire speed appears as the most significant parameter affecting weld appearance. Increased wire speed, within the limits of this study, is detrimental. Chamber pressure is also inversely related to weld appearance. Arc voltage and travel speed also affect the weld appearance.

Figure 11 displays graphically the calculated results. Each of the small squares is a plot of appearance rating as a function of arc voltage and wire-feed at a particular combination of chamber pressure and travel speed. Each contour line represents a particular appearance-rating value. In other words, a weld made with any combination of voltage and wire speed along any of the contour lines would be rated similarly.

Plots wherein the contour lines are relatively vertical (a) indicate that, at that combination of pressure and travel speed, arc voltage is insignificant in affecting the response (in this case, *general appearance*). Similarly, when the contour lines are relatively horizontal (b), wire speed is insignificant.

However, vertical contour lines do indicate that wire speed is significant. And, of course, horizontal lines indicate the significance of voltage.

Welds rated better than *4* would normally be acceptable. Welds rated less than *2* would rarely be acceptable. To emphasize these two areas, the plots are shown as dot patterns (4 or above) and as cross-hatch patterns (2 or less).

Going across the chart from left to right corresponds to an increase in travel speed from 60 to 80 to 100 to 120 inches per minute (ipm). Thus, in any horizontal row, any change in appearance of the plots is a result of the increased travel speed only.

Going up the chart corresponds to an increase in chamber pressure from 12 to 32 to 52 to 72 psia. The voltage and wire-speed scales remain the same. Thus, any change in appearance of the plots in any vertical column is a result of the increased pressure only.

Looking across the bottom row from left to right, the dot-pattern area, representing acceptable welds, changes only slightly. Hence, at atmospheric pressure, weld appearance is relatively insensitive to travel speed. In the bottom-left plot, arc voltage is insignificant. In the bottom-right plot, increased arc voltage is detrimental. In each of the bottom plots, wire speed is a significant variable.

Now, looking across the top row from left to right, the dot-pattern area increases. Therefore, at 72 psia, increased travel speed is desirable. In each of these plots, low wire speed and high voltage are preferred.

Looking at the chart as a whole, in only two plots does the *5* rating line appear. These are both at 72 psia. Hence, if optimum appearance is desired the combination of 72 psia chamber pressure, 120-ipm travel speed, 28 volts, and 500-ipm wire speed would be used.

Weld Soundness:

Referring to the X-ray results, Table III shows the significant parameters affecting weld soundness. Only wire-feed speed is significant. Again, the negative sign for the *t*-statistic indicates that wire speed and weld soundness are inversely related.

The contour rating chart of Figure 12 reflects the relative insignificance of chamber pressure, travel speed, and arc voltage. Wire speed is significant, as indicated by the close vertical contours. In each of the sixteen plots, high wire speed is detrimental. Assuming the wire speed is appropriate, sound welds can be made at all levels of chamber pressure and travel speed. However porous welds (the only radiographically detectable defects found in this study) can also be made at each combination of pressure and travel speed by the use of high wire speed.

Arc Mode:

Table III shows that each of the four main effects are independently significant in affecting arc mode.

In this case, the higher the *t*-statistic, the greater the tendency for the arc to operate in the spray mode.

As would be expected, increased arc voltage produces a spray arc. Increased pressure produces a short-circuiting arc. Increased wire speed and travel speed produce a spray arc.

Figure 13 shows this same information graphically. The cross-hatch area represents the short circuiting mode, and the dot-pattern area represents the spray mode. The area between the two shadings represents the transition zone.

Arc Stability:

Table III shows that wire speed is the most significant parameter and is inversely related to arc stability. Increased arc voltage promotes arc stability, while increased pressure is detrimental. Examination of the contour rating chart of Figure 14 shows

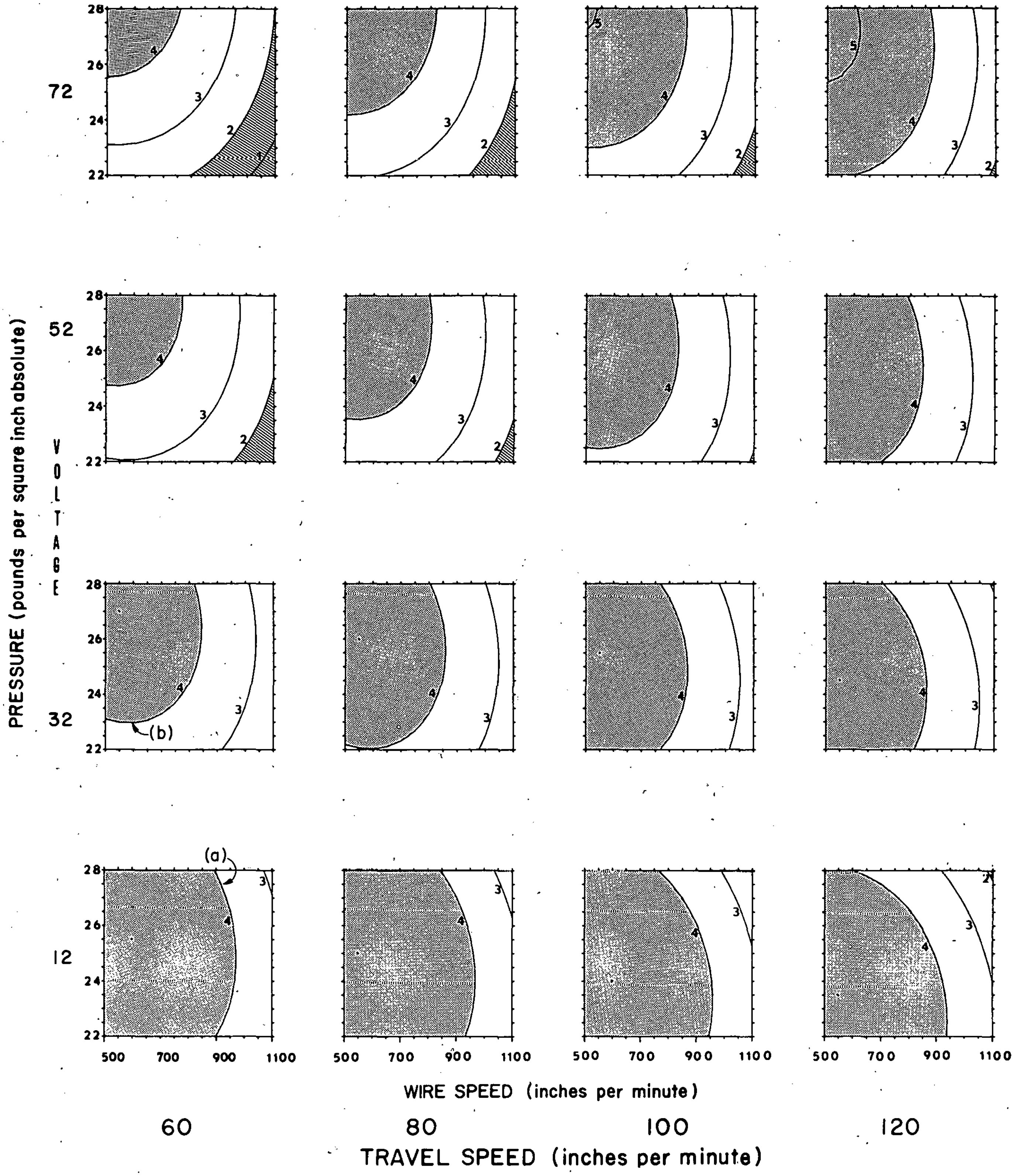


FIGURE 11. General Appearance, Contour Chart.

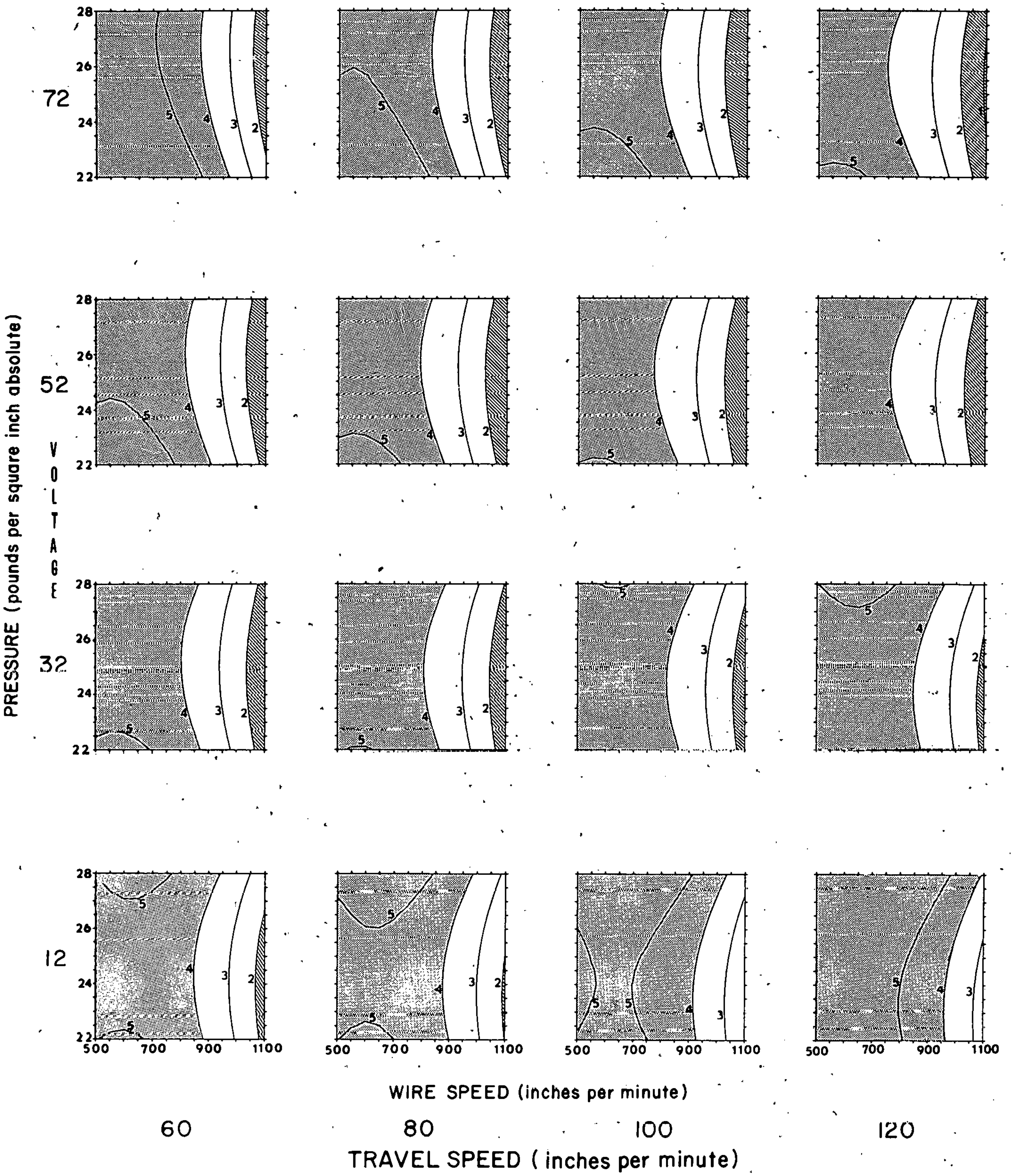


FIGURE 12. Weld Soundness, Contour Chart.

a graphical interpretation of the voltage times pressure interaction.

The dot-pattern areas in the figure are used to indicate the regions of most stable arc operation.

At low pressures, particularly atmospheric, arc stability is relatively insensitive to voltage. However, at high pressures, increased arc voltage acts to increase the stability of the arc. This illustrates the requirement of increasing the arc voltage when increased ambient pressure is used.

Again, within the limits of this study, low wire-feed speeds give the most stable arc conditions.

Weld Area:

The mathematical analysis of data in Table III shows that the weld cross-sectional area is increased by increasing the wire speed, arc voltage, and chamber pressure. Travel speed is inversely related to weld area. Wire speed is the most significant parameter.

These same results are shown graphically in Figure 15. The numbers associated with the contour represent *square inches* of area.

The largest area (0.40 square inches) occurred at 60 ipm travel speed, 1100 ipm wire speed, and 28 volts. At this combination, chamber pressure was relatively insignificant. However, according to Figures 11 and 12, welds made at this combination were unsatisfactory from the standpoints of appearance and soundness.

The smallest welds (0.10 square inches) generally resulted from the use of 22 volts, and 500 ipm wire. In this case, travel speed and chamber pressure were relatively insignificant. This general combination produced sound, good appearing welds.

Weld Width:

According to the data in Table III, each of the main effects is independently significant in affecting weld width. Only voltage is apparently directly related. However, the voltage squared term indicates that the relationship is not linear.

Figure 16 is a graphical presentation of weld width as a function of the weld parameters.

The meaning of the interaction term between wire speed and chamber pressure is shown. The maximum weld width occurs at the *x* points as noted. At low chamber pressures, the maximum occurs near the high end of the wire-speed scale. However, at high pressure, the maximum width occurs at low wire speeds. The widest welds were somewhat greater than a ¼ inch, actually 0.27 inches. The narrowest welds were somewhat less than 0.10 inches, but occurred in an area of poor appearance and soundness.

Weld Reinforcement:

From Table III, wire-feed speed is the most significant factor affecting weld reinforcement. Travel speed is inversely related, and, to a lesser degree, voltage and pressure are significant in interactions.

The contour rating chart for weld reinforcement is shown in Figure 17. The greatest reinforcement was 0.12 inches and occurred at 28 volts, 1100 ipm wire speed, 60 ipm travel speed, and 72 psia pressure. The least reinforcement was 0.01 inches and occurred at 28 volts, 500 ipm wire speed, 120 ipm travel speed, and at atmospheric pressure.

Generally, welds with high reinforcement also exhibited poor appearance and soundness. Wire speed was the most significant factor related to each of these three responses. High wire speed gave high reinforcement and also contributed to poor appearance and soundness. By contrast, welds exhibiting low reinforcement were also sound and visually acceptable.

Weld Penetration:

From Table III, weld penetration is most affected by wire speed, and, to a lesser extent, by the other three main effects. Except for travel speed, all are directly related to the response.

Figure 18 verifies that wire speed is a significant parameter. In each of the 16 plots, the penetration is at least doubled in going from 500 to 1100 ipm wire speed.

The greatest penetration was 0.28 inches and occurred at 60 ipm travel speed, 72 psia pressure, 28 volts, and 1100 ipm wire speed. However, this is also an unsatisfactory combination to produce sound, visually acceptable welds.

From Figure 18, the least penetration is predicted to occur at 120 ipm travel speed, 12 psia pressure, 28 volts, and 500 ipm wire speed. The calculated penetration at this point is 0.03 inches.

Weld Depth-to-Width Ratio:

Table III shows that increased wire speed and chamber pressure increase the *weld depth-to-width* ratio. Arc voltage and travel speed are also significant, but to a lesser degree. Figure 19 illustrates the trends. The most obvious trend is that increased wire speed increases the *depth-to-width* ratio. Also, increased chamber pressure exerts the same effect, particularly at high travel speed.

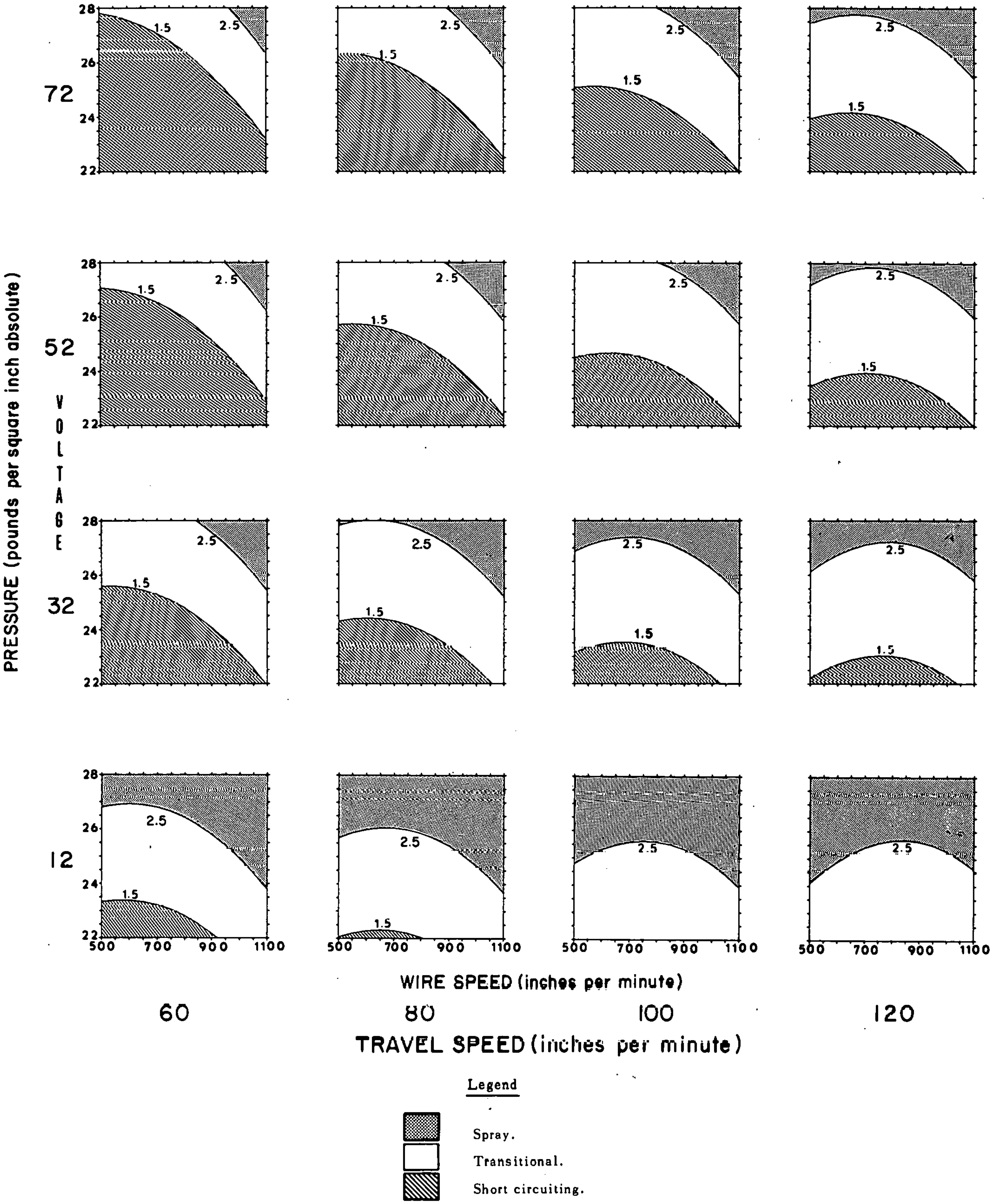


FIGURE 13. Arc Mode, Contour Chart.

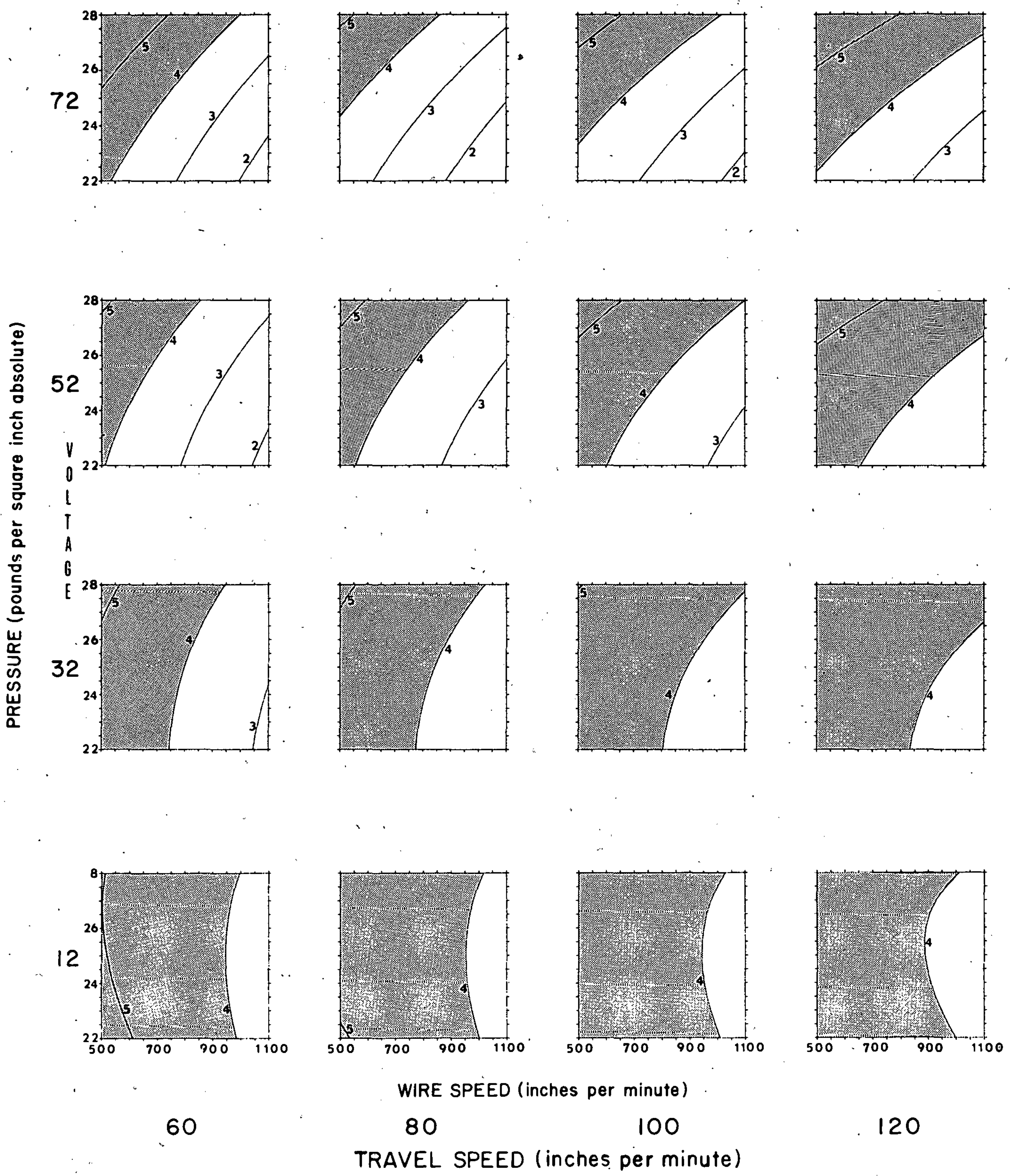


FIGURE 14. Arc Stability, Contour Chart.

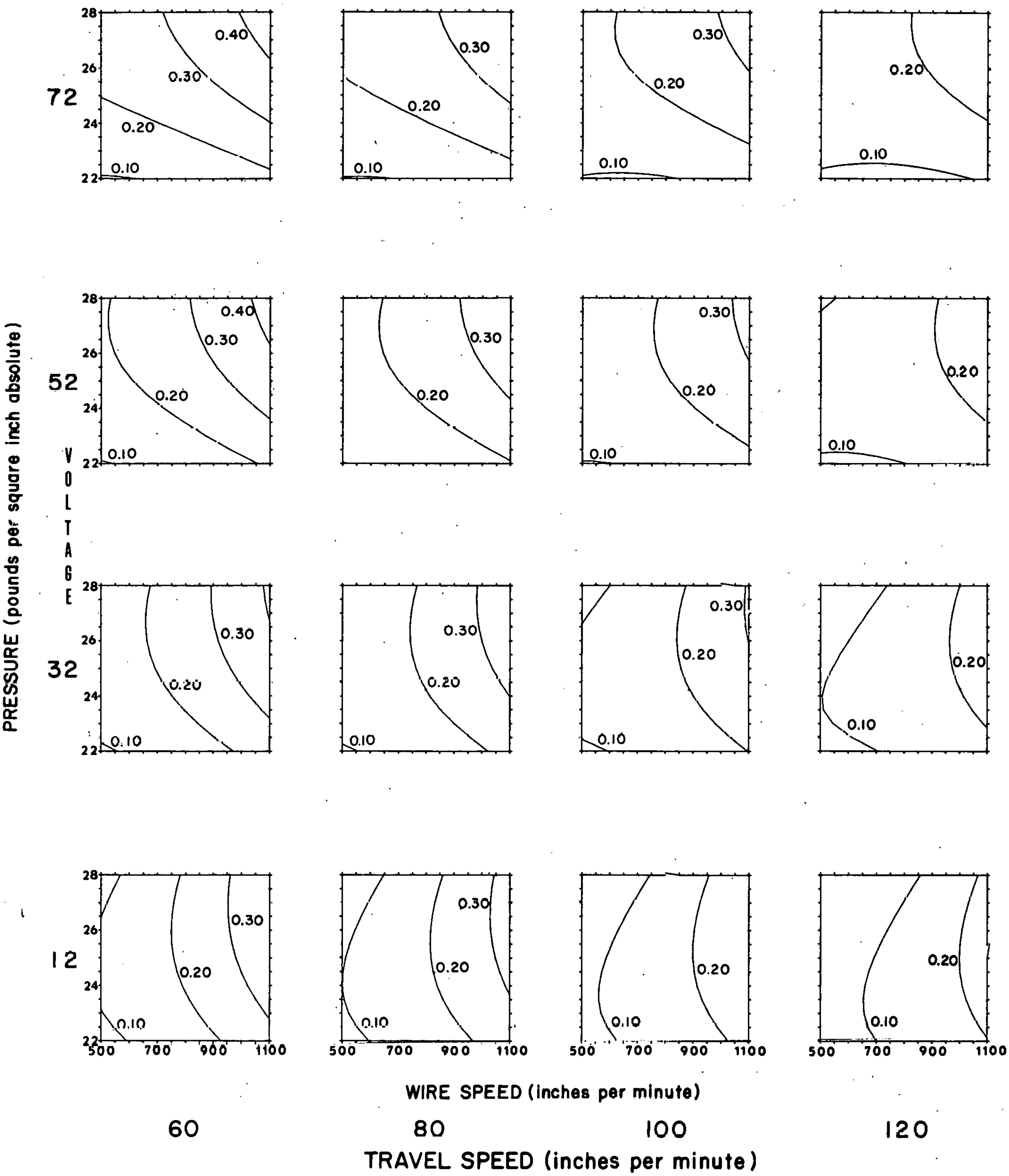
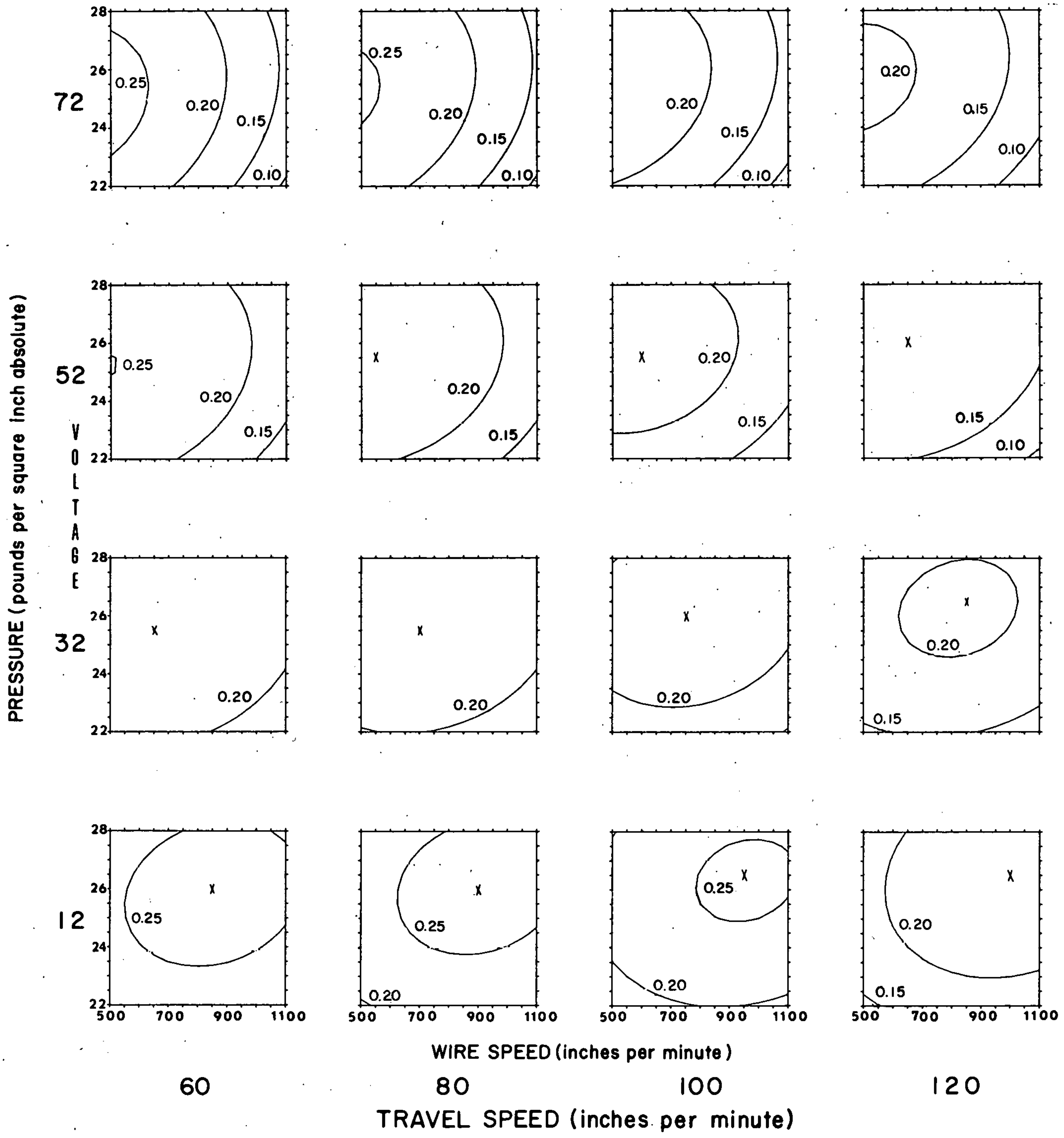


FIGURE 15. Weld Area, Contour Chart.



Legend

X = Maximum width.

FIGURE 16. Weld Width, Contour Chart.

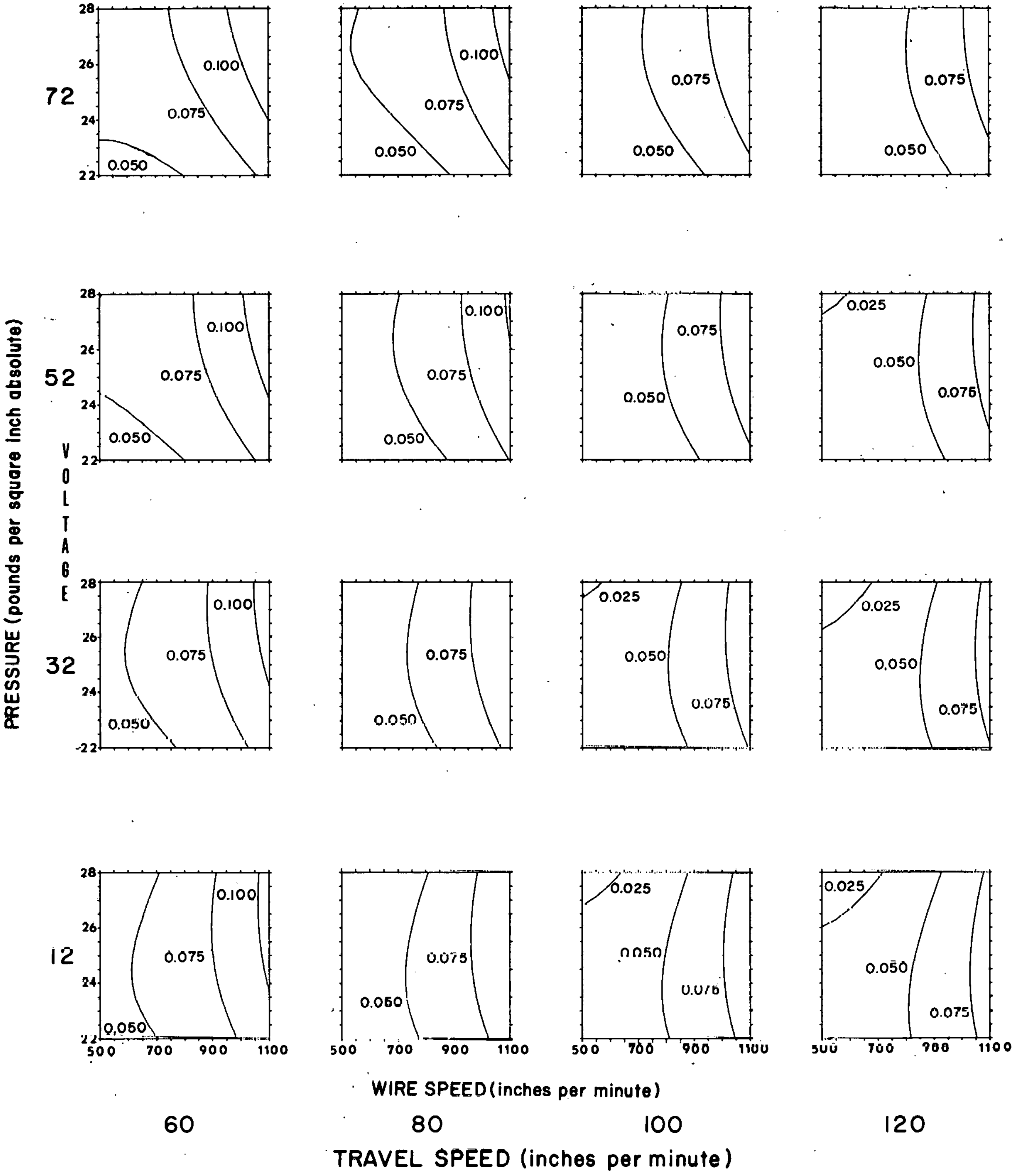


FIGURE 17. Weld Reinforcement, Contour Chart.

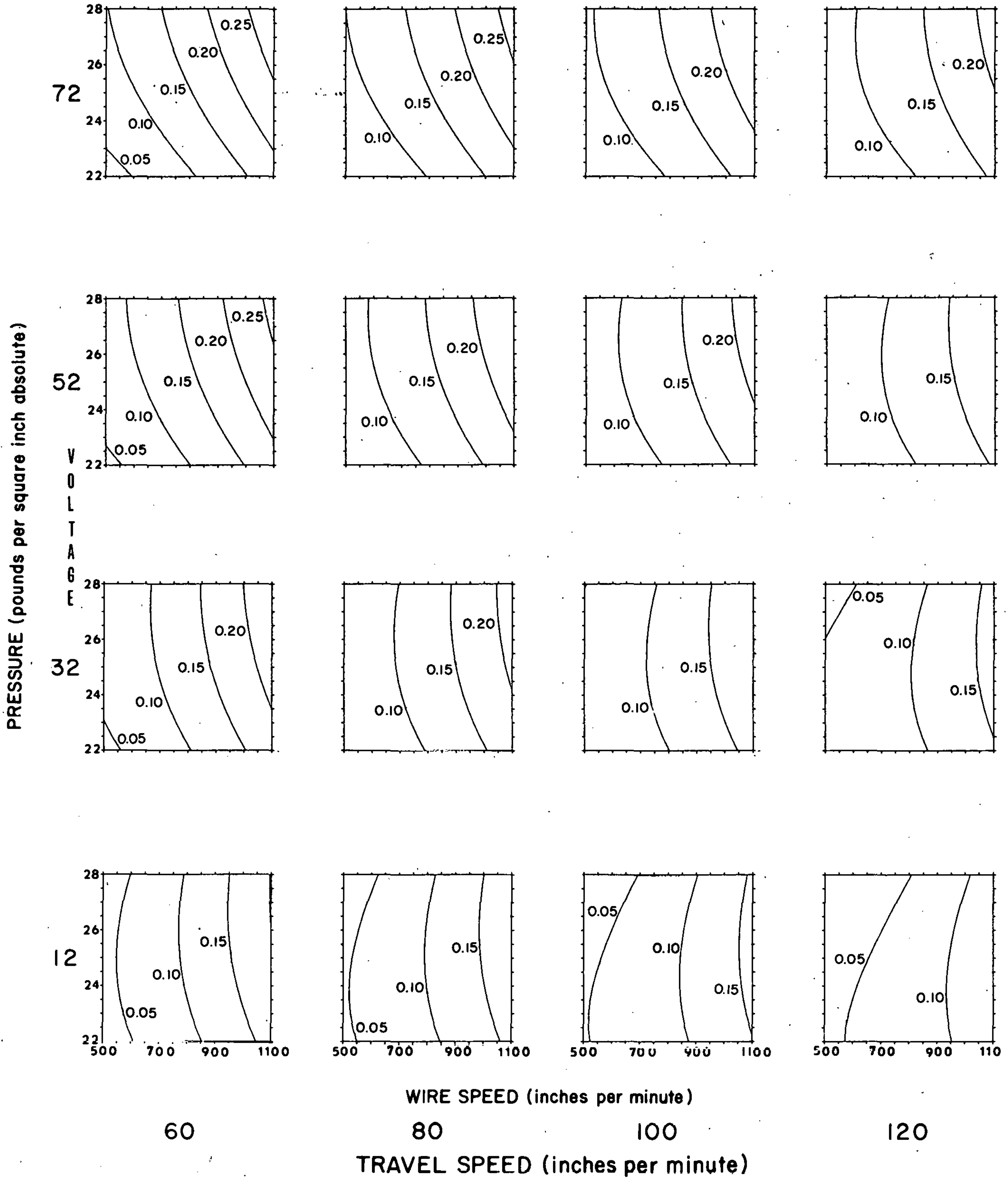


FIGURE 18. Weld Penetration, Contour Chart.

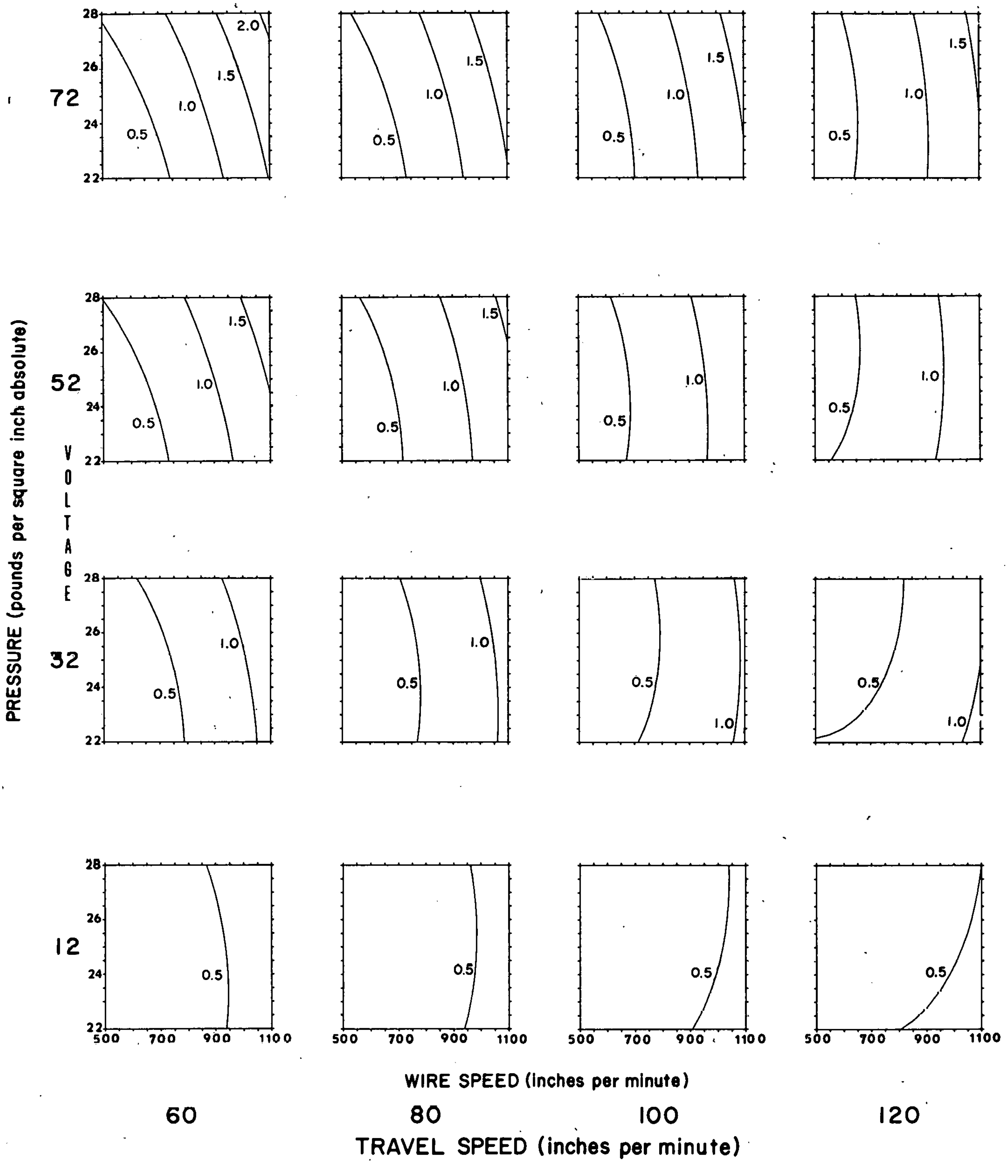


FIGURE 19. Weld Depth-To-Width Ratio, Contour Chart.

The maximum *depth-to-width* ratio (2.1:1) occurred at 60 ipm travel speed, 72 psia pressure, 1100 ipm wire speed, and 28 volts. At this point, the depth (penetration) was 0.28 inches and the width was 0.13 inches. However, the weld was unsatisfactory because of poor soundness and appearance.

Optimization:

Finally, comes the question: What combination of parameters gives the best overall weld?

The question can be answered mathematically, by using the equation for the calculated ratings, as noted on Page 5, and in Appendix B, Page 29. First, however, several restrictions or criteria must be established.

Appearance and soundness must be acceptable. Minimum responses of *4* can be established for these responses.

Weld reinforcement should be minimized. This, however, can be neglected since combinations of welding parameters which resulted in good appearance, also gave low reinforcement. Good arc stability is also desired, but is synonymous with good appearance and can be neglected. For many applications, deep penetration, or more specifically, a high depth-to-width ratio is desired so that this response would be maximized. Finally, the welding parameters are restricted to practical values.

Based on these criteria, a computerized optimization program was run with the results summarized in Table IV. The first optimization gave the welding parameters which would result in a depth-to-width ratio of 1.2:1. This

TABLE IV. Results of Optimization of Parameters.

Criteria:

Appearance Rating >4
Soundness Rating >4
Depth-to-Width maximize

	Restrictions	Results of Optimization	
Run No. 1			
1. Voltage	21 to 29	29	Appearance = 4
Wire Speed (inches per minute)	400 to 1200	800	Soundness = 4
Travel Speed (inches per minute)	50 to 130	70	Depth-to-Width = 1.2:1
Chamber Pressure (pounds per square inch absolute)	2 to 82	82	
Run No. 2			
2. Voltage	21 to 32	32	Appearance = 4
Wire Speed (inches per minute)	400 to 1300	600	Soundness = 6
Travel Speed (inches per minute)	50 to 130	60	Depth-to-Width = 1.96:1
Chamber Pressure (pounds per square inch absolute)	12 to 92	92	
Run No. 3			
3. Voltage	21 to 29	21.7	Appearance = 4.
Wire Speed (inches per minute)	400 to 1200	933	Soundness = 4.4
Travel Speed (inches per minute)	50 to 130	123	Depth-to-Width = 0.65:1
Chamber Pressure (pounds per square inch absolute)	12	12	

occurred at 29 volts and 82 psia chamber pressure which were the maximums allowed for those parameters.

A second run was made with those limits raised to 32 volts and 92 psia. The depth-to-width ratio was then predicted to be 1.9:1.

A third run was made with the pressure limited to one atmosphere. In this case, the depth-to-width ratio was cut to 0.65.

DISCUSSION

It is important to realize that, although many data have been collected from the study, the results are applicable to only limited conditions. The investigation covered only one combination of aluminum alloys. No joint or weld groove was involved. The welding was all downhand. Power-supply characteristics were not varied.

An area of particular concern which would supplement the study involves arc shielding.[2] At elevated ambient pressures, different arc-shielding techniques may be required. Also, the use of an inert gas rather than normal air to backfill the welding chamber may be beneficial.

This study program was begun with an underlying thought of proving the merits of welding under pressure to eliminate porosity in aluminum welds. The results in Table III and in Figure 12 show there is no significant correlation between ambient pressure and weld soundness.

Added pressure is, however, beneficial for improving the depth-to-width ratio in welds while maintaining satisfactory weld appearance and soundness. Table IV shows that depth-to-width ratio of 1.2:1 was realized, while at atmospheric pressure the depth-to-width ratio was 0.65:1. Especially for metals that are sensitive to heat input, welding under pressure may be advantageous.

Since welds exhibiting good appearance were also internally sound, assurance may be given that arc stability is associated with good appearance and soundness. Arc mode was not directly related to appearance, soundness, or stability.

Weld metal porosity was the only type of metallographically or radiographically discovered defect. The porosity ranged from small (0.010-inch diameter) pores to larger, irregular voids. The latter effects were apparently caused by erratic solidification which, in turn, was caused by turbulent arc and puddle action.

Of interest was the definite correlation between even the small porosity and welding parameters. Wire speed was the only parameter significantly affecting weld soundness. Low wire speeds gave completely sound welds. High wire speeds gave large voids. The small pores occurred between these two extremes. Hypothetically perhaps even the small porosity is caused by arc turbulence.

The accuracy of the results reported depends largely on the correlation between the experimental results and the mathematical model derived from those results. The standard error of the calculated ratings gives an indication of how well the observed values and the calculated values agree. Approximately 67 percent of the observed ratings or measurements will fall within plus or minus one standard error of the calculated ratings. Approximately 95 percent will be within plus or minus two standard errors. (This assumes a normal distribution for the observed ratings.)

Table V lists the standard errors of the calculated ratings. The standard errors for weld soundness and arc stability appear to be somewhat out of line. Calculated ratings of these responses should not be interpreted to be exact. However the main objective is not to determine exact values, but to reveal trends. The indicated trends are not invalidated by inexact predicted ratings or measurements.

CONCLUSIONS

The following conclusions should be considered applicable only to the particular conditions specified in the report. The restrictions include material, welding position, arc atmosphere, and range of welding parameters.

TABLE V. Standard Errors of Calculated Ratings and Measurements.

Response	Ratings or Measurements	*Standard Error
General Appearance	1, 2, 3, 4, 5	0.753
Weld Soundness	1, 3, 5	1.05
Arc Mode	1, 3, 5	0.432
Arc Stability	1, 3, 5	0.978
Weld Area	0.04 to 0.48	0.055
Weld Width	0.110 to 0.338	0.042
Weld Reinforcement	0.025 to 0.138	0.012
Weld Penetration	0.025 to 0.300	0.025
Depth-to-Width Ratio	0.14 to 2.73	0.230

* Errors are in the same units as the ratings.

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[2] Eldon D. Brandon and W. L. Bush. "Gas Coverage for PIGMA Welding." RFP-1550. (Publication in process.)

TABLE VI. Summary of Conclusions.

	Affects — in Direction of Arrow								
Increase in:	Weld Appearance	Weld Soundness	Arc Stability	*Arc Mode	Penetration	Width	Reinforcement	Area	Depth to Width
Wire Speed (ws)	↓	↓	↓	↑	↑	↓	↑	↑	↑
Voltage (v)	f(p)	—	↑	↑	↑	↑	f(ws)	↑	f(p,ts)
Travel Speed (ts)	f(p)	—	f(v)	↑	↓	↓	↓	↓	f(v)
Pressure (p)	↓	—	↓	↓	↑	↓	f(v)	↑	↑

*↓ = Tends toward short circuiting.
↑ = Increase in value of response.
↓ = Decrease in value of response.
— = No effect on response.
f(p) = Direction of change is function of pressure, etc.

1. The conclusions may be summarized as shown in Table VI. The summary shows the reaction of each of the nine responses as each main factor is increased. The responses move in the direction indicated by the arrows.

2. Wire-feed speed is the single most important factor in gas metal arc (GMA) and pressurized inert gas metal arc (PIGMA) welding. Increased wire speed acts to decrease weld appearance, weld soundness, arc stability, and weld deposit width; and will increase weld penetration, the depth-to-width ratio, reinforcement, and area; and will cause the arc to operate in the spray mode.

3. Arc voltage was the most important factor in influencing the arc mode of metal transfer. As would be expected, increased arc voltage caused the arc to operate in the spray mode. Increased arc voltage also acted to increase arc stability, weld penetration, width, and cross-sectional area.

4. Increased welding travel speed served to decrease weld penetration, width, reinforcement, and area. Spray transfer was encouraged by faster travel speed.

5. Increased chamber pressure resulted in a decrease in weld appearance, arc stability, and weld width, and an increase in depth-to-width ratio, and overall weld area.

6. Using good weld appearance and soundness as criteria, a maximum weld depth-to-width would result at 29 volts, 800 ipm wire speed, 70 ipm travel speed, and 92 psia chamber pressure.

7. High wire speeds (above 1000 ipm) should be avoided because of poor weld appearance and soundness above this level.

8. Weld appearance and soundness generally occur together. A deterioration in one is usually accompanied by a deterioration in the other.

Appendix A. Raw Data from Pressurized Gas Metal Arc Study

Appendix B. Method for Determining Calculated Ratings

Appendix C. Calculated Ratings for Each of Nine Responses

APPENDIX A. Raw Data from Pressurized Inert Gas Metal Arc Study.

Weld No.	General Appearance Rating	X-ray Rating	Arc Stability	Arc Mode	Weld Width (inches)	Weld Reinforcement (inches)	Weld Penetration (inches)	Weld Area (inches^2)	Depth-to-Width Ratio (x:1) (x values)
1	5	5	5	SC	0.205	0.031	0.035	0.07	0.17
2	3	5	3	Tr	0.181	0.050	0.138	0.16	0.76
3	2	1	3	Sp	0.188	0.104	0.219	0.38	1.16
4	5	5	5	Tr	0.200	0.040	0.103	0.15	0.52
5	5	5	5	SC	0.251	0.074	0.113	0.24	0.45
6	5	5	5	Sp	0.194	0.044	0.043	0.09	0.22
7	4	5	5	SC	0.213	0.038	0.038	0.08	0.18
8	2	1	3	Sp	0.144	0.080	0.208	0.28	1.44
9	5	5	5	SC	0.153	0.028	0.051	0.06	0.33
10	4	5	5	SC	0.213	0.043	0.085	0.14	0.40
11	5	5	5	Tr	0.194	0.030	0.068	0.10	0.35
12	5	5	5	Sp	0.206	0.026	0.059	0.08	0.29
13	2	1	3	Tr	0.173	0.098	0.138	0.22	0.80
14	4	5	3	Sp	0.188	0.074	0.211	0.31	1.12
15	5	5	5	SC	0.216	0.030	0.063	0.10	0.29
16	2	5	3	Sp	0.281	0.054	0.135	0.19	0.48
17	1	–	1	–		← No Weld →			
18	5	5	5	SC	0.200	0.034	0.070	0.10	0.35
19	4	5	5	SC	0.185	0.035	0.038	0.07	0.21
20	3	3	3	Sp	0.273	0.106	0.203	0.35	0.74
21	3	5	5	Sp	0.225	0.073	0.059	0.17	0.26

(continued) →

Legend

General Appearance Ratings	X-ray Ratings	Stability	Mode
1. No weld	1. Large voids	1. Extremely erratic	SC – Short Circuiting
2. Extremely erratic			
3. Rough	3. Some porosity	3. Unstable	Tr – Transition
4. Some roughness			
5. Good	5. Sound	5. Stable	Sp – Spray

Weld No.	General Appearance Rating	X-ray Rating	Arc Stability	Arc Mode	Weld Width (inches)	Weld Reinforcement (inches)	Weld Penetration (inches)	Weld Area (inches^2)	Depth-to-Width Ratio (x:1) (x values)
22	4	5	5	SC	0.175	0.053	0.130	0.17	0.74
23	5	5	5	Sp	0.193	0.036	0.090	0.14	0.47
24	5	5	5	SC	0.173	0.028	0.040	0.07	0.23
25	5	3	5	Tr	0.260	0.051	0.103	0.19	0.23
26	5	5	5	Tr	0.285	0.044	0.103	0.22	0.40
27	2	1	3	Tr	0.131	0.100	0.200	0.26	1.53
28	4	5	5	Sp	0.181	0.026	0.025	0.04	0.14
29	2	1	3	Tr	0.213	0.105	0.203	0.36	0.95
30	3	1	3	Tr	0.144	0.088	0.169	0.22	1.17
31	2	5	1	–	0.256	0.063	0.178	0.26	0.70
32	2	3	3	Sp	0.110	0.138	0.300	0.48	2.73
33	5	3	3	Tr	0.210	0.043	0.069	0.12	0.33
34	4	5	5	SC	0.352	0.075	0.120	0.35	0.34
35	2	1	3	SC	0.138	0.055	0.188	0.19	1.36
36	4	5	5	Sp	0.200	0.051	0.131	0.17	0.66
37	5	5	3	SC	0.325	0.070	0.178	0.39	0.55
38	5	5	5	Sp	0.225	0.038	0.031	0.08	0.14
39	3	1	3	Tr	0.180	0.093	0.200	0.29	1.11
40	2	1	3	Sp	0.150	0.050	0.183	0.22	1.22
41	5	5	5	SC	0.213	0.046	0.063	0.12	0.30
42	3	3	3	Tr	0.488	0.156	0.275	0.93	0.56
43	5	5	5	SC	0.214	0.051	0.061	0.11	0.29
44	2	1	3	Tr	0.113	0.110	0.173	0.22	1.53
45	4	3	5	Sp	0.175	0.025	0.086	0.12	0.49
46	4	5	5	SC	0.338	0.063	0.103	0.27	0.30
47	5	5	5	SC	0.275	0.050	0.106	0.21	0.39
48	1	–	1	–		← No Weld →			
49	2	3	5	Sp	0.275	0.090	0.138	0.25	0.50
50	4	5	5	Tr	0.178	0.056	0.098	0.14	0.55
51	4	5	5	SC	0.150	0.031	0.056	0.07	0.37
52	4	5	5	SC	0.200	0.038	0.068	0.11	0.34
53	5	5	5	Tr	0.196	0.038	0.093	0.13	0.47
54	2	1	3	Sp	0.181	0.118	0.269	0.44	1.49
55	3	1	3	Sp	0.250	0.105	0.216	0.38	0.86

(continued) →

Weld No.	General Appearance Rating	X-ray Rating	Arc Stability	Arc Mode	Weld Width (inches)	Weld Reinforcement (inches)	Weld Penetration (inches)	Weld Area (inches^2)	Depth-to-Width Ratio (x:1) (x values)
56	4	5	5	Sp	0.218	0.039	0.063	0.12	0.29
57	4	–	3	SC	0.250	0.050	0.100	–	0.40
58	4	1	5	Sp	0.150	0.073	0.175	0.22	1.17
59	4	5	5	SC	0.225	0.063	0.074	0.16	0.33
60	4	5	5	Tr	0.165	0.065	0.134	0.18	0.81
61	4	5	5	Sp	0.250	0.060	0.096	0.21	0.38
62	4	5	5	Tr	0.223	0.031	0.075	0.13	0.34
63	3	1	3	Tr	0.115	0.063	0.169	0.17	1.47
64	1	–	1	–		←	No Weld	→	
65	5	5	3	Sp	0.150	0.025	0.028	0.05	0.19
66	1	–	1	–		←	No Weld	→	
67	5	5	5	Tr	0.213	0.048	0.113	0.18	0.53
68	2	–	3	Sp	0.188	0.085	0.234	0.38	1.24
69	3	5	1	–	0.153	0.038	0.040	0.07	0.26
70	4	5	3	Tr	0.230	0.039	0.068	0.11	0.30
71	3	3	3	SC	0.169	0.048	0.110	0.14	0.65
72	2	1	3	Sp	0.213	0.080	0.243	0.35	1.14

Legend

General Appearance Ratings	X-ray Ratings	Stability	Mode
1. No weld	1. Large voids	1. Extremely erratic	SC – Short Circuiting
2. Extremely erratic			
3. Rough	3. Some porosity	3. Unstable	Tr – Transition
4. Some roughness			
5. Good	5. Sound	5. Stable	Sp – Spray

APPENDIX B. Method for Determining Calculated Ratings

APPENDIX B. Method for Determining Calculated Ratings.

Regression Equation:

$$R = C_0 + C_1 \cdot V + C_2 \cdot T + C_3 \cdot W + C_4 \cdot P + C_5 \cdot V \cdot T + C_6 \cdot V \cdot W + C_7 \cdot V \cdot P + C_8 \cdot T \cdot W + C_9 \cdot T \cdot P + C_{10} \cdot W \cdot P + C_{11} \cdot V^2 + C_{12} \cdot T^2 + C_{13} \cdot W^2 + C_{14} \cdot P^2$$

Where:

R = Calculated rating

C_x = Constants determined by regression analysis

V = Normalized voltage

T = Normalized travel speed

W = Normalized wire speed

P = Normalized chamber pressure

Normalized Factors:

Voltage (real)	Voltage (normalized)
22	−3
24	−1
26	+1
28	+3

Travel Speed (inches per minute) (real)	(normalized)
60	−3
80	−1
100	+1
120	+3

Wire Speed (inches per minute) (real)	(normalized)
500	−3
700	−1
900	+1
1100	+3

Chamber Pressure (pounds per square inch) (real)	(normalized)
12	−3
32	−1
52	+1
72	+3

Regression Coefficients:

Constant (C_x)	Appearance	Soundness	Mode	Stability	Area	Width	Reinforcement	Penetration	Depth-to-Width Ratio
C_0	4.094797	3.936162	1.710098	4.024718	2.055116×10^{-1}	2.251624×10^{-1}	5.2752×10^{-2}	1.303954×10^{-1}	6.174263×10^{-1}
C_1	0.07436471	-0.008812263	0.2761805	0.1490405	1.392594×10^{-2}	5.783912×10^{-3}	1.245444×10^{-3}	4.885652×10^{-3}	1.572587×10^{-2}
C_2	0.05813391	-0.006539434	0.08511214	0.08015839	-1.43067×10^{-2}	-6.63738×10^{-3}	-3.296863×10^{-3}	-4.40837×10^{-3}	-1.204977×10^{-2}
C_3	-0.3475127	-0.533295	0.1177686	-0.2457259	2.755008×10^{-3}	-6.735197×10^{-3}	8.870913×10^{-3}	2.252096×10^{-2}	1.595155×10^{-1}
C_4	-0.1235383	-0.07941054	-0.1359691	-0.1476961	6.603315×10^{-3}	-7.377099×10^{-3}	7.217191×10^{-4}	8.148288×10^{-3}	8.67989×10^{-2}
C_5	-0.0288459	0.01702771	-0.009234893	-0.0007009924	-2.666105×10^{-3}	5.328272×10^{-4}	-5.161672×10^{-4}	-1.192726×10^{-3}	-1.233277×10^{-2}
C_6	-0.01652776	0.01641626	-0.004130546	0.00959779	3.519121×10^{-3}	8.565442×10^{-4}	6.998113×10^{-4}	1.132405×10^{-3}	2.968406×10^{-3}
C_7	0.04958329	0.03943149	0.009688932	0.05483652	4.316833×10^{-3}	-1.262936×10^{-4}	7.409321×10^{-4}	1.940641×10^{-3}	1.268495×10^{-2}
C_8	-0.005763758	0.0174437	-0.02673111	0.02607074	-1.85678×10^{-3}	9.653907×10^{-4}	-8.895264×10^{-5}	-1.343614×10^{-3}	-8.584457×10^{-3}
C_9	0.03725765	-0.04888311	0.01503504	0.04243553	4.006765×10^{-5}	9.748978×10^{-5}	-1.610845×10^{-4}	4.06129×10^{-4}	-1.489538×10^{-3}
C_{10}	-0.01613035	-0.03311492	0.0196352	-0.02809503	-2.919954×10^{-3}	-3.718776×10^{-3}	-2.155011×10^{-4}	3.348725×10^{-4}	2.31134×10^{-2}
C_{11}	-0.03821966	0.0467491	-0.00257017	0.01213989	-3.772067×10^{-3}	-3.031844×10^{-3}	-6.306673×10^{-4}	-1.182605×10^{-3}	5.555534×10^{-3}
C_{12}	-0.00997789	0.008872585	-0.01077995	-0.004044553	-5.093743×10^{-4}	-1.107668×10^{-3}	2.53079×10^{-4}	-8.930929×10^{-4}	4.253294×10^{-3}
C_{13}	-0.06466539	-0.1279622	0.03219859	-0.004044553	2.042008×10^{-3}	-3.071903×10^{-3}	1.373161×10^{-3}	1.354501×10^{-3}	1.550090×10^{-2}
C_{14}	0.01558969	0.04962766	0.02374534	-0.02364911	-7.699827×10^{-4}	8.390416×10^{-4}	2.612943×10^{-4}	-9.422719×10^{-4}	-1.153836×10^{-2}

APPENDIX C. Calculated Ratings for Each of Nine Responses

Legend

Chamber Pressure (pounds per square inch absolute)

Travel Speed (inches per minute)

Wire Speed (inches per minute)

Voltage (volts)

APPENDIX C. Calculated Ratings for Each of Nine Responses.

General Appearance – Calculated

Chamber Pressure		12				32				52				72			
Voltage	**Wire Speed** \ **Travel Speed**	60	80	100	120	60	80	100	120	60	80	100	120	60	80	100	120
22	500	4.4	4.6	4.7	4.7	3.6	3.9	4.2	4.4	2.9	3.4	3.8	4.1	2.4	3.0	3.6	4.0
	700	4.5	4.6	4.7	4.7	3.6	3.9	4.1	4.3	2.9	3.3	3.7	4.0	2.3	2.9	3.4	3.8
	900	4.0	4.1	4.2	4.2	3.1	3.4	3.6	3.7	2.3	2.7	3.1	3.3	1.6	2.2	2.7	3.1
	1100	3.0	3.1	3.2	3.1	2.0	2.3	2.5	2.6	1.2	1.6	1.9	2.2	0.4	1.0	1.5	1.9
24	500	4.8	4.9	4.9	4.8	4.2	4.5	4.6	4.6	3.8	4.1	4.4	4.6	3.4	3.9	4.4	4.7
	700	4.8	4.9	4.8	4.7	4.2	4.4	4.5	4.5	3.6	4.0	4.2	4.4	3.2	3.7	4.1	4.4
	900	4.3	4.3	4.3	4.1	3.6	3.7	3.8	3.8	3.0	3.3	3.5	3.7	2.5	4.6	3.3	3.6
	1100	3.2	3.2	3.2	3.0	2.5	2.6	2.7	2.7	1.8	2.1	2.3	2.4	1.2	1.7	2.1	2.3
26	500	5.0	4.9	4.8	4.6	4.6	4.7	4.7	4.6	4.3	4.5	4.7	4.8	4.1	4.5	4.9	5.1
	700	4.9	4.8	4.7	4.4	4.4	4.5	4.5	4.4	4.1	4.3	4.5	4.5	3.9	4.2	4.5	4.7
	900	4.3	4.2	4.0	3.8	3.8	3.8	3.8	3.7	3.4	3.6	3.7	3.7	3.1	3.4	3.7	3.9
	1100	3.2	3.1	2.9	2.6	2.6	2.6	2.6	2.4	2.1	2.3	2.4	2.4	1.8	2.1	2.3	2.5
28	500	4.8	4.6	4.4	4.0	4.6	4.6	4.5	4.3	4.5	4.6	4.7	4.7	4.6	4.8	5.0	5.2
	700	4.6	4.4	4.2	3.8	4.4	4.3	4.2	4.0	4.2	4.3	4.4	4.3	4.2	4.5	4.6	4.7
	900	4.0	3.8	3.5	3.1	3.6	3.6	3.4	3.2	3.4	3.5	3.5	3.5	3.4	3.6	3.7	3.8
	1100	2.8	2.6	2.2	1.8	2.4	2.3	2.1	1.9	2.1	2.2	2.2	2.1	2.0	2.2	2.3	2.4

Weld Soundness – Calculated

Chamber Pressure		12				32				52				72			
Voltage	**Wire Speed** \ **Travel Speed**	60	80	100	120	60	80	100	120	60	80	100	120	60	80	100	120
22	500	5.0	5.0	5.1	5.2	5.1	5.0	4.8	4.8	5.7	5.3	5.0	4.8	6.7	6.1	5.6	5.1
	700	4.9	5.0	5.1	5.4	5.0	4.8	4.8	4.8	5.4	5.1	4.8	4.7	6.2	5.7	5.3	4.9
	900	3.9	4.0	4.2	4.5	3.8	3.7	3.7	3.8	4.1	3.8	3.6	3.5	4.8	4.3	4.0	3.6
	1100	1.8	2.0	2.3	2.6	1.5	1.6	1.6	1.8	1.7	1.5	1.4	1.4	2.3	1.9	1.6	1.4
24	500	4.6	4.7	4.8	5.0	4.6	4.5	4.5	4.5	5.0	4.7	4.5	4.3	5.9	5.3	4.9	4.5
	700	4.6	4.8	5.0	5.3	4.5	4.5	4.5	4.6	4.8	4.5	4.4	4.3	5.5	5.0	4.7	4.3
	900	3.6	3.8	4.1	4.5	3.4	3.4	3.5	3.6	3.5	3.3	3.2	3.2	4.1	3.7	3.4	3.2
	1100	1.6	1.9	2.2	2.7	1.2	1.3	1.5	1.7	1.2	1.1	1.1	1.1	1.6	1.3	1.1	0.9
26	500	4.6	4.8	5.0	5.3	4.5	4.4	4.5	4.5	4.7	4.5	4.3	4.2	5.4	5.0	4.6	4.3
	700	4.7	4.9	5.2	5.6	4.4	4.5	4.5	4.7	4.6	4.4	4.3	4.2	5.1	4.7	4.4	4.2
	900	3.8	4.1	4.4	4.8	3.4	3.5	3.6	3.8	3.4	3.2	3.2	3.2	3.7	3.4	3.2	3.0
	1100	1.8	2.2	2.6	3.1	1.3	1.4	1.7	1.9	1.1	1.1	1.1	1.2	1.4	1.2	1.0	0.9
28	500	5.0	5.2	5.5	5.9	4.7	4.7	4.8	5.0	4.8	4.6	4.5	4.5	5.3	4.9	4.6	4.4
	700	5.2	5.5	5.8	6.2	4.7	4.8	5.0	5.2	4.7	4.6	4.6	4.6	5.1	4.8	4.5	4.4
	900	4.3	4.6	5.1	5.6	3.7	3.9	4.1	4.4	3.6	3.5	3.6	3.7	3.8	3.6	3.4	3.3
	1100	2.4	2.9	3.3	3.9	1.7	1.9	2.2	2.6	1.4	1.4	1.5	1.7	1.5	1.3	1.2	1.2

Arc Mode — Calculated

Voltage	Wire Speed \ Travel Speed \ Chamber Pressure	12				32				52				72			
		60	80	100	120	60	80	100	120	60	80	100	120	60	80	100	120
22	500	1.1	1.5	1.8	2.0	0.4	0.8	1.2	1.4	-0.2	0.3	0.7	1.1	-0.5	5.1	0.5	0.9
	700	1.1	1.4	1.6	1.7	0.5	0.8	1.1	1.2	3.9	0.4	0.7	1.0	-0.2	0.2	0.6	0.9
	900	1.4	1.6	1.7	1.7	0.9	1.1	1.2	1.3	0.5	0.8	1.0	1.1	0.3	0.7	1.0	1.1
	1100	2.0	2.1	2.0	2.0	1.5	1.6	1.7	1.6	1.2	1.4	1.5	1.5	1.1	1.3	1.5	1.6
24	500	1.7	2.0	2.3	2.5	1.0	1.4	1.7	2.0	0.5	1.0	1.3	1.6	0.2	0.7	1.2	1.5
	700	1.7	2.0	2.1	2.2	1.1	1.4	1.6	1.7	0.7	1.0	1.3	1.5	0.5	0.9	1.2	1.5
	900	2.0	2.1	2.2	2.1	1.5	1.7	1.8	1.8	1.1	1.4	1.5	1.6	1.0	1.3	1.5	1.7
	1100	2.5	2.6	2.5	2.4	2.1	2.2	2.2	2.1	1.8	1.1	2.0	2.0	1.8	2.0	2.1	2.1
26	500	2.3	2.6	2.8	3.0	1.6	2.0	2.3	2.5	1.2	1.6	2.0	2.2	0.9	1.4	1.8	2.1
	700	2.3	2.5	2.6	2.6	1.7	2.0	2.1	2.2	1.3	1.6	1.9	2.0	1.1	1.5	1.8	2.0
	900	2.5	2.6	2.7	2.6	2.1	2.2	2.3	2.3	1.8	2.0	2.1	2.1	1.6	2.0	2.1	2.2
	1100	3.1	3.1	3.0	2.8	2.7	2.7	2.7	2.5	2.4	2.5	2.6	2.5	2.4	2.6	2.7	2.6
28	500	2.8	3.1	3.3	3.4	2.2	2.5	2.8	2.9	1.8	2.2	2.5	2.7	1.6	2.0	2.4	2.7
	700	2.8	3.0	3.1	3.0	2.3	2.5	2.6	2.7	1.9	2.2	2.4	2.5	1.8	2.1	2.4	2.6
	900	3.1	3.1	3.1	3.0	2.6	2.7	2.8	2.7	2.3	2.5	2.6	2.6	2.3	2.5	2.7	2.7
	1100	3.6	3.5	3.4	3.2	3.2	3.2	3.1	3.0	3.0	3.1	3.1	3.0	3.0	3.2	3.2	3.2

Arc Stability — Calculated

Voltage	Wire Speed \ Travel Speed \ Chamber Pressure	12				32				52				72			
		60	80	100	120	60	80	100	120	60	80	100	120	60	80	100	120
22	500	5.3	5.1	4.8	4.5	4.8	4.7	4.6	4.5	4.0	4.2	4.3	4.3	3.1	3.4	3.7	3.9
	700	4.8	4.7	4.5	4.3	4.1	4.3	4.0	4.2	3.3	3.5	3.7	3.9	2.3	2.7	3.1	3.4
	900	4.2	4.2	4.2	4.1	3.5	3.6	3.8	3.9	2.5	2.9	3.2	3.5	1.4	1.9	2.4	2.8
	1100	3.7	3.8	3.8	3.9	2.8	3.1	3.3	3.5	1.8	2.2	2.6	3.0	0.5	1.1	1.7	2.2
24	500	5.1	4.9	4.6	4.3	4.8	4.7	4.7	4.5	4.3	4.4	4.5	4.6	3.6	3.9	4.2	4.4
	700	4.6	4.5	4.4	4.2	4.3	4.3	4.0	4.3	3.6	3.8	4.0	4.2	2.8	3.2	3.6	3.9
	900	4.1	4.1	4.1	4.0	3.6	3.8	3.9	4.0	2.9	3.2	3.5	3.8	2.0	2.5	2.9	3.4
	1100	3.6	3.7	3.8	3.8	3.0	3.2	3.5	3.7	2.1	2.6	3.0	3.3	1.1	1.7	2.3	2.8
26	500	5.0	4.8	4.5	4.2	4.9	4.9	4.8	4.7	4.6	4.8	4.9	4.9	4.2	4.5	4.7	5.0
	700	4.6	4.5	4.3	4.1	4.4	4.4	4.5	4.4	4.0	4.2	4.4	4.6	3.4	3.8	4.2	4.5
	900	4.1	4.1	4.1	4.0	3.8	4.0	4.1	4.2	3.3	3.6	3.9	4.2	2.6	3.1	3.6	4.0
	1100	3.6	3.7	3.8	3.8	3.2	3.5	3.7	3.9	2.6	3.0	3.4	3.8	1.8	2.4	3.0	3.5
28	500	5.0	4.8	4.5	4.3	5.2	5.1	5.0	4.9	5.1	5.2	5.3	5.4	4.9	5.1	5.4	5.6
	700	4.6	4.5	4.4	4.2	4.7	4.7	4.7	4.7	4.5	4.7	4.9	5.1	4.1	4.5	4.9	5.2
	900	4.2	4.2	4.2	4.1	4.1	4.3	4.4	4.5	3.8	4.2	4.5	4.7	3.4	3.9	4.3	4.8
	1100	3.8	3.8	3.9	3.9	3.6	3.8	4.0	4.2	3.2	3.6	4.0	4.4	2.6	3.2	3.7	4.3

Weld Area – Calculated

	Chamber Pressure	12				32				52				72			
	Travel Speed	60	80	100	120	60	80	100	120	60	80	100	120	60	80	100	120
Voltage	Wire Speed																
22	500	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.10	0.10	0.10	0.09	0.09	0.10	0.10	0.09
	700	0.13	0.12	0.11	0.10	0.13	0.12	0.11	0.10	0.12	0.11	0.11	0.09	0.11	0.10	0.09	0.08
	900	0.19	0.18	0.16	0.14	0.18	0.17	0.15	0.13	0.16	0.15	0.13	0.11	0.13	0.12	0.11	0.09
	1100	0.27	0.25	0.23	0.20	0.24	0.22	0.20	0.17	0.21	0.19	0.17	0.14	0.18	0.16	0.13	0.11
24	500	0.11	0.10	0.09	0.07	0.14	0.13	0.12	0.10	0.16	0.15	0.14	0.12	0.17	0.17	0.15	0.14
	700	0.17	0.15	0.13	0.11	0.18	0.17	0.15	0.13	0.19	0.18	0.16	0.14	0.20	0.18	0.16	0.14
	900	0.25	0.22	0.19	0.16	0.25	0.23	0.20	0.17	0.25	0.23	0.20	0.17	0.24	0.22	0.19	0.16
	1100	0.34	0.31	0.27	0.23	0.33	0.30	0.27	0.23	0.32	0.29	0.25	0.21	0.30	0.27	0.23	0.20
26	500	0.10	0.09	0.06	0.04	0.15	0.13	0.11	0.08	0.19	0.17	0.15	0.12	0.22	0.20	0.18	0.15
	700	0.18	0.15	0.12	0.09	0.21	0.19	0.16	0.12	0.24	0.21	0.18	0.15	0.26	0.24	0.21	0.17
	900	0.27	0.24	0.20	0.16	0.29	0.26	0.22	0.18	0.31	0.27	0.24	0.20	0.32	0.28	0.25	0.21
	1100	0.38	0.34	0.29	0.24	0.39	0.35	0.30	0.25	0.39	0.35	0.31	0.26	0.39	0.35	0.30	0.25
28	500	0.07	0.04	0.01	0	0.13	0.10	0.07	0.03	0.19	0.16	0.13	0.09	0.24	0.21	0.18	0.14
	700	0.16	0.12	0.08	0.04	0.21	0.17	0.13	0.09	0.26	0.22	0.18	0.13	0.29	0.26	0.22	0.17
	900	0.26	0.22	0.17	0.12	0.30	0.26	0.21	0.16	0.34	0.29	0.24	0.19	0.36	0.32	0.27	0.22
	1100	0.39	0.33	0.29	0.22	0.41	0.36	0.31	0.25	0.43	0.38	0.33	0.28	0.45	0.40	0.34	0.28

Weld Width – Calculated

	Chamber Pressure	12				32				52				72			
	Travel Speed	60	80	100	120	60	80	100	120	60	80	100	120	60	80	100	120
Voltage	Wire Speed																
22	500	0.21	0.20	0.17	0.14	0.21	0.20	0.17	0.14	0.22	0.21	0.18	0.15	0.23	0.22	0.20	0.17
	700	0.22	0.21	0.20	0.17	0.21	0.20	0.18	0.15	0.20	0.19	0.18	0.15	0.20	0.19	0.18	0.15
	900	0.22	0.22	0.20	0.18	0.19	0.19	0.17	0.15	0.17	0.17	0.15	0.13	0.16	0.15	0.14	0.11
	1100	0.20	0.20	0.19	0.17	0.16	0.16	0.15	0.13	0.12	0.12	0.11	0.09	0.09	0.09	0.08	0.06
24	500	0.24	0.23	0.21	0.18	0.24	0.23	0.21	0.18	0.25	0.23	0.21	0.19	0.26	0.25	0.23	0.20
	700	0.26	0.25	0.23	0.21	0.24	0.24	0.22	0.19	0.23	0.23	0.21	0.19	0.23	0.23	0.21	0.19
	900	0.26	0.25	0.24	0.22	0.23	0.22	0.21	0.19	0.21	0.20	0.19	0.17	0.19	0.19	0.17	0.15
	1100	0.24	0.24	0.23	0.21	0.20	0.20	0.19	0.17	0.16	0.16	0.15	0.14	0.13	0.13	0.12	0.11
26	500	0.24	0.23	0.21	0.19	0.24	0.23	0.21	0.19	0.25	0.24	0.22	0.20	0.26	0.25	0.24	0.21
	700	0.26	0.26	0.24	0.22	0.25	0.24	0.23	0.21	0.24	0.24	0.22	0.20	0.24	0.23	0.22	0.20
	900	0.27	0.27	0.26	0.24	0.24	0.24	0.23	0.21	0.22	0.21	0.20	0.19	0.20	0.20	0.19	0.17
	1100	0.26	0.26	0.25	0.24	0.21	0.21	0.21	0.19	0.17	0.18	0.17	0.16	0.14	0.15	0.14	0.13
28	500	0.22	0.21	0.20	0.17	0.22	0.21	0.20	0.17	0.23	0.22	0.20	0.18	0.24	0.24	0.22	0.19
	700	0.25	0.24	0.23	0.21	0.23	0.23	0.22	0.19	0.22	0.22	0.21	0.19	0.22	0.22	0.21	0.19
	900	0.25	0.25	0.25	0.23	0.22	0.22	0.22	0.20	0.20	0.20	0.19	0.18	0.18	0.19	0.18	0.16
	1100	0.25	0.25	0.25	0.23	0.20	0.21	0.20	0.19	0.16	0.17	0.16	0.15	0.13	0.14	0.13	0.12

Weld Reinforcement — Calculated

	Chamber Pressure	12				32				52				72			
Voltage	Wire Speed \ Travel Speed	60	80	100	120	60	80	100	120	60	80	100	120	60	80	100	120
22	500	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.04	0.04	0.03	0.03	0.04	0.04	0.03	0.03
	700	0.05	0.05	0.04	0.04	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.05	0.04	0.03	0.03
	900	0.07	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.06	0.05	0.05	0.05	0.06	0.05	0.05	0.04
	1100	0.09	0.09	0.08	0.08	0.09	0.08	0.08	0.07	0.08	0.08	0.07	0.07	0.08	0.07	0.07	0.07
24	500	0.05	0.04	0.04	0.03	0.05	0.04	0.04	0.03	0.05	0.04	0.04	0.03	0.05	0.05	0.04	0.04
	700	0.05	0.05	0.04	0.04	0.05	0.05	0.04	0.04	0.06	0.05	0.04	0.04	0.06	0.05	0.04	0.04
	900	0.07	0.07	0.06	0.06	0.07	0.06	0.06	0.05	0.07	0.06	0.06	0.05	0.07	0.07	0.06	0.05
	1100	0.10	0.09	0.09	0.09	0.10	0.09	0.09	0.08	0.10	0.09	0.08	0.08	0.10	0.09	0.08	0.08
26	500	0.04	0.04	0.03	0.03	0.05	0.04	0.03	0.03	0.05	0.04	0.04	0.03	0.06	0.05	0.04	0.03
	700	0.05	0.05	0.04	0.03	0.06	0.05	0.04	0.04	0.06	0.05	0.04	0.04	0.07	0.06	0.05	0.04
	900	0.08	0.07	0.06	0.05	0.08	0.07	0.06	0.05	0.08	0.07	0.06	0.06	0.09	0.07	0.07	0.06
	1100	0.11	0.10	0.09	0.08	0.11	0.10	0.09	0.08	0.11	0.10	0.09	0.08	0.11	0.10	0.09	0.09
28	500	0.04	0.03	0.02	0.01	0.04	0.03	0.02	0.02	0.05	0.04	0.03	0.02	0.06	0.05	0.04	0.03
	700	0.05	0.04	0.03	0.02	0.05	0.04	0.03	0.03	0.06	0.05	0.04	0.03	0.07	0.06	0.05	0.04
	900	0.07	0.06	0.05	0.05	0.08	0.07	0.06	0.05	0.08	0.07	0.06	0.05	0.09	0.08	0.07	0.06
	1100	0.11	0.10	0.09	0.08	0.11	0.10	0.09	0.08	0.11	0.10	0.09	0.08	0.12	0.11	0.10	0.09

Weld Penetration — Calculated

	Chamber Pressure	12				32				52				72			
Voltage	Wire Speed \ Travel Speed	60	80	100	120	60	80	100	120	60	80	100	120	60	80	100	120
22	500	0.00	0.04	0.05	0.04	0.04	0.05	0.06	0.06	0.04	0.05	0.06	0.06	0.03	0.05	0.06	0.06
	700	0.07	0.07	0.07	0.06	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.08	0.07	0.08	0.09	0.08
	900	0.11	0.11	0.10	0.09	0.12	0.12	0.12	0.11	0.12	0.13	0.12	0.11	0.12	0.13	0.12	0.11
	1100	0.17	0.16	0.15	0.13	0.18	0.17	0.16	0.15	0.18	0.18	0.17	0.15	0.18	0.18	0.17	0.16
24	500	0.04	0.05	0.05	0.04	0.06	0.06	0.06	0.06	0.06	0.07	0.08	0.07	0.06	0.08	0.08	0.08
	700	0.08	0.08	0.07	0.06	0.10	0.10	0.09	0.08	0.11	0.11	0.11	0.10	0.11	0.11	0.11	0.10
	900	0.13	0.12	0.11	0.09	0.15	0.14	0.13	0.12	0.16	0.16	0.15	0.13	0.16	0.16	0.15	0.14
	1100	0.19	0.18	0.16	0.14	0.21	0.20	0.18	0.16	0.22	0.21	0.20	0.18	0.22	0.22	0.21	0.19
26	500	0.04	0.04	0.04	0.02	0.06	0.07	0.06	0.05	0.08	0.08	0.08	0.07	0.09	0.09	0.09	0.08
	700	0.08	0.08	0.07	0.05	0.11	0.10	0.10	0.08	0.12	0.12	0.12	0.10	0.13	0.13	0.13	0.12
	900	0.14	0.13	0.11	0.09	0.16	0.15	0.14	0.12	0.18	0.17	0.16	0.14	0.19	0.19	0.18	0.16
	1100	0.20	0.18	0.16	0.13	0.23	0.21	0.19	0.17	0.25	0.23	0.22	0.19	0.26	0.25	0.23	0.21
28	500	0.03	0.02	0.01	0	0.06	0.06	0.05	0.03	0.08	0.08	0.08	0.06	0.10	0.10	0.09	0.08
	700	0.08	0.07	0.05	0.03	0.11	0.10	0.09	0.07	0.13	0.13	0.12	0.10	0.15	0.15	0.14	0.12
	900	0.13	0.12	0.10	0.07	0.17	0.16	0.14	0.11	0.19	0.18	0.17	0.14	0.21	0.20	0.19	0.16
	1100	0.20	0.18	0.16	0.12	0.24	0.22	0.19	0.16	0.26	0.25	0.22	0.19	0.28	0.27	0.25	0.22

	Chamber Pressure	12				32				52				72			
Voltage	Wire Speed / Travel Speed	60	80	100	120	60	80	100	120	60	80	100	120	60	80	100	120
		Depth-to-Width Ratio															
22	500	0.14	0.22	0.33	0.47	0.20	0.27	0.37	0.51	0.17	0.23	0.33	0.46	0.04	0.10	0.19	0.32
	700	0.23	0.27	0.35	0.46	0.39	0.42	0.49	0.59	0.44	0.47	0.54	0.63	0.41	0.43	0.49	0.58
	900	0.44	0.45	0.49	0.57	0.69	0.69	0.73	0.79	0.84	0.84	0.87	0.93	0.90	0.89	0.91	0.97
	1100	0.78	0.75	0.76	0.80	1.11	1.09	1.09	1.12	1.36	1.32	1.32	1.35	1.52	1.47	1.46	1.48
24	500	0.11	0.13	0.19	0.29	0.22	0.24	0.29	0.38	0.24	0.25	0.30	0.38	0.16	0.17	0.21	0.29
	700	0.21	0.20	0.23	0.29	0.41	0.40	0.42	0.47	0.52	0.50	0.52	0.57	0.54	0.52	0.52	0.57
	900	0.43	0.39	0.38	0.41	0.73	0.68	0.67	0.69	0.93	0.88	0.86	0.87	1.04	0.98	0.96	0.97
	1100	0.78	0.71	0.67	0.66	1.17	1.09	1.04	1.03	1.47	1.38	1.33	1.31	1.67	1.58	1.52	1.49
26	500	0.12	0.09	0.11	0.15	0.28	0.25	0.26	0.30	0.35	0.31	0.31	0.35	0.32	0.28	0.28	0.31
	700	0.23	0.17	0.15	0.16	0.49	0.42	0.39	0.40	0.65	0.58	0.54	0.54	0.72	0.64	0.60	0.59
	900	0.47	0.38	0.32	0.30	0.82	0.72	0.66	0.63	1.07	0.97	0.90	0.86	1.23	1.12	1.05	1.01
	1100	0.83	0.71	0.61	0.56	1.27	1.14	1.04	0.98	1.62	1.48	1.38	1.31	1.87	1.73	1.62	1.54
28	500	0.17	0.10	0.06	0.06	0.39	0.31	0.26	0.25	0.51	0.42	0.37	0.36	0.53	0.44	0.39	0.37
	700	0.30	0.19	0.12	0.08	0.60	0.49	0.41	0.37	0.82	0.70	0.61	0.56	0.94	0.81	0.72	0.67
	900	0.55	0.41	0.30	0.23	0.95	0.80	0.69	0.61	1.25	1.10	0.98	0.90	1.46	1.30	1.18	1.09
	1100	0.92	0.75	0.61	0.50	1.41	1.23	1.08	0.97	1.81	1.62	1.47	1.35	2.11	1.92	1.76	1.64

Legend

Chamber Pressure (pounds per square inch absolute)

Travel Speed (inches per minute)

Wire Speed (inches per minute)

Voltage (volts)