ASSESSING THE EFFECTS OF GMAW-PULSE PARAMETERS ON ARC POWER AND WELD HEAT INPUT

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By
Andrew Paul Joseph, B.S.

The Ohio State University
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Masters Examination Committee:
Dr. Dave F. Farson, Advisor
Dr. Richard W. Richardson

Approved by

Dave Farson
Advisor
Graduate Program
Welding Engineering
ABSTRACT

Pulsed gas metal arc welding (GMAW-Pulse) combines the low spatter levels of spray transfer with the low heat input of globular and short circuit transfer. The drawback of GMAW-Pulse is the large number of variables that must be adjusted to produce a stable arc. Synergic (one knob) control has made the application of complicated pulse waveforms simple for the welding operator. However, the use of these complicated preset waveforms has created problems in determining arc power for estimating welding heat input. Three basic types of electrical measurements are readily available for determining arc power. In this report, they are referred to as RMS power, average power, and average instantaneous power. Depending on the method of measurement, large variations of the measured arc power and subsequently estimated heat input can occur.

Liquid nitrogen calorimetry was used to find the arc efficiency and actual heat input to welds made with GMAW-Pulse. Bead-on-plate welds on mild steel coupons were made using 0.045" ER 70S-6 wire with 90% Argon – 10% CO₂ shielding gas. Arc voltage and current were measured using high-speed data acquisition, and high-speed video was used to maintain constant 1/8" arc length throughout testing. The heat input to the coupons found by calorimetry was
compared to the estimated heat input from the three types of arc power calculations. It has been shown that the most appropriate method to estimate heat input for GMAW-Pulse was through the use of an Average Instantaneous Power calculation. RMS Power (the product of RMS current and RMS voltage) estimates a heat input that was approximately 10% higher than actual. Average Power calculated as the product of average voltage and current predicted a heat input that was approximately 12% lower than actual.

Once the most appropriate method of measuring power and estimating heat input was found, an investigation into the effects of individual pulsing parameters on heat input, dilution, and penetration at constant wire feed speeds was conducted. Pulsing parameter variation in the normal operating regime used in industry gave up to a 17% variation in the power and heat input for welds at a given wire feed speed. The variations produced very little if any changes in bead shape, penetration, and dilution. Some subtle differences in bead shape (reduced papillary width) were produced by pulse waveforms that operated outside of the normal operating regime.
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VITA

November 3, 1971 ........................................... Born - Columbus, Ohio

2001 .......................................................... B.S. Welding Engineering,
Ohio State University

1999 – Present .............................................. Graduate Fellow,
The Edison Welding Institute,
Columbus, Ohio.

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CHAPTER 1

INTRODUCTION

Gas Metal Arc Welding (GMAW) [1] is widely used for joining many types of ferrous and non-ferrous metals. The process uses a continuously fed consumable wire electrode and an open arc in a locally gas-shielded atmosphere between the wire and the work piece. Heat from the arc melts the work and the consumable electrode, forming a molten pool on the work. Metal is transferred from the wire to the pool in several different forms depending on the arc current levels.

To ensure arc stability, arc length must be maintained relatively constant. This requires matching wire feed speed with the wire burn-off rate (a.k.a. melting rate). Also, the metal transfer should be of the spray type to minimize short-circuiting and spatter. During spray transfer, metal droplets are much smaller than the diameter of the electrode as they are transferred through the arc to the molten pool. With sufficient arc length, the droplets are transferred in a “free flight” fashion, with no physical contact between the wire and the molten pool. When GMAW is used with Direct Current in the Electrode Positive polarity (DCEP) and an argon rich shielding environment, spray transfer is achieved
above a critical current level that is known as the spray transition current. This current level is dependent on wire material, wire diameter and shielding gas. Appendix A lists spray transition current levels for steel electrodes.

Below the spray transition current, globular metal transfer occurs where molten drops two or three times the wire diameter grow until they are transferred through a short circuit, or by gravity. Globular transfer is less desirable than spray transfer due to the uncontrollable nature of the drop size (which may cause difficulties for out of position welding) and the spatter that occurs as a result of the short circuit.

At current levels well below spray transition current levels, short circuit transfer occurs. This type of transfer produces a small fast freezing weld pool that is well suited for low heat input requirements (thin sheet, bridging gaps, and out of position welding). Metal is transferred from the electrode to the work only during a period when the electrode is in contact with the weld pool. No metal is transferred across the arc gap.

Spray transfer is very desirable due to its low spatter levels and controllable drop size and direction. However, high current levels are required to establish spray transfer. Materials that are sensitive to higher energy inputs, such as quenched and tempered steels and thin gauge materials, cannot be welded in this mode. Out of position welding is also difficult with spray transfer since the molten pool is large and very fluid.
1.1 Pulsed Gas Metal Arc Welding

Pulsed gas metal arc welding (GMAW-Pulse) combines the advantages of spray transfer with the lower heat input of globular and short circuit transfer. GMAW-Pulse uses a high current pulse for a finite period of time followed by a low current background period. The low current level background period primarily maintains the arc, while the high current level peak pulse forms and transfers one or more drops from the electrode (see Figure 1.1). The drops are typically 1 to 1.2 times larger than the electrode. The alternating waveform of high and low currents transfers a series of drops, resulting in spray type transfer at an average current level that would normally produce the less desirable globular transfer. Typically GMAW-Pulse is used to lower the average current (and therefore heat input) in out of position applications or thin sheet. [1]
Figure 1.1 - Current waveform for GMAW-Pulse.

The drawback to GMAW-Pulse is the additional variables that must be manipulated to produce a stable arc. Trial and error approaches to pulse parameter selection are costly and can result in an unsatisfactory weld due to the arc instabilities. For example, at a given wire feed speed, the pulse magnitude (pulse amplitude and duration) must form and detach at least one droplet with each pulse. If the pulse magnitude is too small, droplets will not detach and the metal transfer will become unstable. Also, the average current as determined by
all of the parameters must produce a burn off rate equal to the wire feed speed to maintain a constant arc length. Any error in the balance between wire feed speed and burn off rate can cause burn back or stubbing of the electrode. The difficulties of selecting appropriate parameters can lead to weld defects and operator frustration.

Early GMAW-Pulse machines had a limited selection of adjustable pulsing parameters. Typically, combining two separate power supplies produced a pulsing effect. The background current was supplied by a DC power supply, while the peak current was provided by a half wave rectified Alternating Current (AC) power supply connected in series with the DC power supply. Peak and background current could be independently adjusted although pulsing frequency was fixed at power line frequency (50 - 60Hz). Solid-state circuitry has since improved markedly, allowing the pulsing parameters to be adjusted independently. Having the freedom to independently adjust the pulsing variables, as well as the flexibility to adjust variables like ramp rates and overshoot of the current pulse, has made it extremely difficult for an operator to quickly develop pulsing parameters for a particular application. [2]

1.2 Synergic Power Supplies

The solution to the problem of developing pulsing parameters has come in the form of "synergic" power supplies. The word synergic means working
together, and in the context of pulsed welding, it means that the individual pulse parameters are coordinated with the wire feed rate to generate a stable arc.

A synergic power supply simplifies the use of GMAW-Pulse technology by using pre-programmed pulse parameter algorithms developed by the power supply manufacturer. With synergic control, the relationship between wire feed rate and pulse parameters is based on electrode size, material and shielding gas is programmed into the control logic of the welding power supply at the factory. The operator simply specifies the electrode size, material and shielding gas being used, selects a wire feed speed, and the pulsing parameters are automatically set based on a pre-programmed pulse parameter algorithm. Some research concerning the selection of pulsing parameters and development of control algorithms has taken place [3 – 7] and most, if not all, power supplies in the marketplace today have preprogrammed algorithms available for a variety of material/shielding gas combinations [8 – 10].

Synergic power supplies have simplified the use of GMAW-Pulse technology and this technology has become more widely used in industry. However, the use of complicated waveforms has brought on new problems in terms of measuring and specifying critical weld variables. Voltage, current, arc power and heat input are common welding parameters called out in welding procedures. Depending on the method of measurement, large variation in the measured values of these quantities can occur under practical conditions.
1.3 Objectives

Typically, non-pulsing DC GMAW voltage and current are measured as average or Root Mean Square (RMS) quantities. Pulsing waveforms can be measured using the same methods, but produce results that lead to inaccurate calculations of arc power and subsequently heat input. Incorrect estimates of heat input can lead to many problems including an undesirable microstructure or failure of the weld joint. The first objective of this project was to compare methods for measuring and calculating power and heat input using electrical measurements for GMAW-Pulse welding, and determine which method is the most appropriate for estimating heat input to a weld.

The second objective was to determine the effects of different pulse parameter algorithms on arc power, heat input, penetration and dilution for several commercially available power GMAW-Pulse power supplies. Each of these power supplies had significantly different pulse parameter algorithms and the effects of the pulsing parameters on heat input, dilution, and penetration at a fixed wire feed speed were determined.

Also, a state of the art commercially available GMAW-Pulse power supply that had three different algorithms available for a particular wire feed speed was evaluated. Each algorithm was tested across a range of wire feed speeds, and the resulting heat input, dilution, and penetration was reported and compared to the other commercial power supplies.
CHAPTER 2

MEASUREMENT OF VOLTAGE, CURRENT, POWER AND HEAT INPUT

Correct measurement of GMAW-Pulse power and heat input is required throughout the rest of this study. Since power and heat input are usually estimated through the measured voltage and current, it is important to measure these parameters correctly, and also to correctly determine their relationship to the true power and heat input.

2.1 Electrical measurements

Before making any digital measurements of a pulsed waveform, sampling frequency must be addressed. If the sampling frequency of the measurement equipment is too low, aliasing can occur. Aliasing occurs when the sampling rate does not give a true picture of the event. An example of aliasing can be seen in Figure 2.1. The sampling frequency is approximately the same as the pulsing frequency, resulting in a wave that incorrectly represents the true event [11]. To prevent aliasing, sample frequency should be at least twice the frequency of
interest, and preferably 10 times the frequency to adequately capture the waveform.

Figure 2.1 - Aliasing resulting from too low of a sampling frequency.

2.2 Calculating Power

When current and voltage are measured over a period of time at a particular sampling frequency, their magnitude can be summarized as the arithmetic average or root mean square (RMS). Average power may be calculated as the product of the arithmetic mean or RMS values of voltage and current, or by averaging the products of individually sampled values of voltage and current. The difference in calculated power can be substantial depending on which method is used. [11]

Average power calculated from the arithmetic means of current and voltage is
\[ P_{AV} = I_{AV} \cdot V_{AV} \]  

(1)

where \( I_{AV} = \frac{\sum I_i}{n} \) and \( V_{AV} = \frac{\sum V_i}{n} \). RMS power is given by

\[ P_{RMS} = I_{RMS} \cdot V_{RMS} \]  

(2)

where \( I_{RMS} = \sqrt{\frac{\sum I_i^2}{n}} \), and \( V_{RMS} = \sqrt{\frac{\sum V_i^2}{n}} \).

On the other hand, power calculated using the instantaneous voltage and current samples is given by

\[ P_{NAR} = \sum_{i=1}^{n} \frac{I_i \cdot V_i}{n} \]  

(3)

where \( n \) is the sample number using a large sampling rate (i.e. at least 10 times the pulse frequency to prevent aliasing). Instantaneous power can be described as the average of all of the instantaneous power values measured during a weld.

In order to find instantaneous power, measurement equipment capable of storing the product of individual voltage and current readings is necessary.

### 2.3 Calculating Heat Input

Heat input is a principal variable in heat flow and is useful for predicting weld bead morphology, weld and heat affected zone microstructures, and mechanical properties. The ratio of energy entering the base metal per unit time to the weld travel speed is
\[ H = \frac{P}{S} \]  \hspace{1cm} (4)

where \( H \) is heat input, \( P \) is arc power as calculated in section 2.2, and \( S \) is welding speed.

The theoretical heat input defined in equation (4) does not take into account any energy losses that are common to arc welding. The theoretical heat input represents the total energy generated by the arc, which can be different from the energy input to the work by the arc and the molten filler metal during welding. Energy losses such as convection and radiation losses to the environment, resistance and conduction losses at the contact tip, surrounding gas cup and unmelted electrode are quantified by arc or thermal efficiency \( \eta \). The true heat input to the work, \( H_{\text{net}} \), is

\[ H_{\text{net}} = \frac{P \cdot \eta}{S} \]  \hspace{1cm} (5)

where \( \eta \) is thermal efficiency. Thermal efficiencies have been measured to vary from 62% to 85% [11 - 13] for GMAW, whereas efficiencies can range as high as 90% for submerged arc welding and down to 45% for plasma arc welding [1]. Each of the formulas above for heat input and power are summarized in Table 2.1.
\[
H_{\text{ms}} = \frac{P \cdot \eta}{S} \\
I_{av} = \frac{\sum I_i}{n} \\
P_{av} = I_{av} \cdot V_{av} \\
V_{av} = \frac{\sum V_i}{n} \\
P_{\text{rms}} = I_{\text{rms}} \cdot V_{\text{rms}} \\
I_{\text{rms}} = \sqrt{\frac{\sum i^2}{n}} \\
P_{\text{inst}} = \frac{\sum I_i \cdot V_i}{n} \\
V_{\text{rms}} = \sqrt{\frac{\sum v^2}{n}}
\]

\( P = \text{power}, \ \eta = \text{efficiency}, \ S = \text{travel speed}, \ I = \text{current}, \ V = \text{voltage} \)

Table 2.1 - Calculations for Heat Input and Power

2.4 Determination of the Correct Power Measurement for Heat Input

Calculations

For a constant voltage process, such as GMAW in the spray mode, calculated power and heat input are *virtually* unaffected by the type of measurement used for voltage and current. This is due to the fact that the non-pulsed voltage and current waveform is essentially constant with only a minor ripple as the result of arc behavior and electrical characteristics of the welding power supply. For example, 3-phase rectified power supplies have an inherent constant ripple that is sufficiently characterized by an average current and voltage (generally accompanied by a standard deviation). Since the waveform is almost constant, calculation of heat input with RMS voltage and current values
will closely match the calculations with the average values, with an increased variance as the standard deviation of the average current and voltage increases.

GMAW in the short circuit transfer mode is characterized by large fluctuations in current and the frequency. Even so, it can be shown that as long as the ratio of arc time to short circuit time is constant, then the long-term average current is constant irrespective of frequency [14, 15]. As long as the sample time is greater than 0.5 seconds, it is valid to quote the average current and ignore the detailed waveform produced by short circuit welding. Thus, the average current and voltage appropriately determine heat input for short circuit welding.

GMAW-Pulse adds a new challenge to measuring voltage and current. As mentioned in Chapter 1, a pulse of high current controls droplet detachment and provides directional transfer of droplets of weld metal to the work piece. The alternating high current pulse and low current background comprise a waveform with an average current below the spray transition current while maintaining spray transfer qualities, improving transfer stability and out of position welding. The pulsed waveform causes a significant change in the voltage and current over time, and a subsequent change in the heat input delivered to the part compared to a constant voltage GMAW weld. The calculated heat input can vary quite significantly depending on whether average, instantaneous or RMS measurement methods are used. It is important to use the correct measurement to ensure proper heat input calculations.
A review of the technical literature shows that some debate has taken place concerning the most accurate method to obtain power and heat input measurements for pulsed waveforms. Needham [14, 15], Melton [16], and Dilthey and Killing [17] suggest that the mean values of voltage and current should be used for power (and subsequently heat input) calculation. According to Needham, the burn-off rate, which must be matched to the wire feed speed, is proportional to average current.

Dilthey and Killing measured the cooling time of the weld bead by immersing thermocouples in the weld metal. The cooling time from 800°C to 500°C was measured to determine the heat gained by the work piece. From this, they determined that the calculated average power more closely matched the measured heat input compared to RMS readings.

On the other hand, Sergeev, et al. [18] refers to instantaneous power as active power, and reports that RMS power is approximately 11% higher compared to instantaneous power. Sergeev claims that by using instantaneous power, energy parameters of the welding process are more accurately reflected since voltage and current surges as well as any phase shift between the two are accounted for. Sergeev also recommends a simple measuring unit that will properly determine instantaneous power.

More recently, Bosworth [11] also suggests that power delivered to the work should be measured as the product of instantaneous current and voltage values in order to estimate the correct heat input. Using a water calorimeter, Bosworth compared the mean power ($P_{AV}$) and instantaneous power ($P_{inst}$) to the
true heat input. Evaluation was accomplished via thermal efficiencies, showing that mean power ($P_{av}$) can give a thermal efficiency greater than 105%, (which is obviously not possible). Thermal efficiencies calculated using instantaneous power ($P_{inst}$) ranged from 70 – 75%, which is in agreement with efficiencies from other researchers [12]. According to Bosworth, the use of RMS voltage and current measurements for assessing pulsed current heat input is not recommended because these measurements will also produce artificially high heat inputs.

In addition, Fuerschbach [19] claims that heat inputs based on temperature measurements adjacent to the weld rely on assumptions that are difficult to verify about the heat flow in that area. Direct calorimetric measurements are more reliable.

2.4.1 Heat Input Confirmation Testing for GMAW-Pulse

Due to the large amount of disagreement concerning which method of calculating power and heat input is most accurate, a set of confirmation experiments was designed and carried out. These tests were intended to determine which method of power measurement most precisely determines the true heat input to the part. The tests were modeled after Smartt’s heat transfer experiments for GMAW and Gas Tungsten Arc Welding using a liquid nitrogen calorimetric system [12, 20].

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2.4.1.1 Experimental Procedure

A liquid nitrogen calorimeter was constructed using a 16 quart insulated cooler as a dewar for liquid nitrogen and a high accuracy, high capacity scale. The scale was a Mettler Toledo Wildcat 30 kg portable bench scale with a digital readout accurate to 0.001Kg (Figure 2.2) and was used to measure the change in weight of the dewar as liquid nitrogen boiled off. Temperature of the liquid nitrogen was measured for calculations using a resistance thermocouple. Prior to any testing, the dewar was filled with approximately 20 pounds (approximately ¾ full) of liquid nitrogen. The weight of the cooler and liquid nitrogen together was allowed to stabilize at a constantly decreasing rate as the liquid nitrogen boiled off. The rate at which the liquid nitrogen boiled off at ambient temperature was termed the normal evaporation rate. The amount of energy to take an unwelded coupon from ambient temperature to liquid nitrogen temperature was also found. The calorimeter data was calibrated by using steel coupons equalized at various temperatures. The amount of heat energy was measured with the calorimeter and compared to the theoretical heat energy based on the known heat capacity of steel. Appendix B contains the calorimeter calibration data.
Bead on plate welds were made in the flat position using a Lincoln Powerwave 455 GMAW-Pulse power supply. Welds were made in the Constant Voltage (CV) mode, and using the power supply’s synergic GMAW-Pulse program for the wire and gas used. Filler material used was ER70S-6 uncoated steel wire with a diameter of 1.2mm (.045\"). Base material was low alloy carbon steel with a thickness of 12.7mm (.5\>). Coupon dimensions were 6.35cm (2.5\") by 15.24 cm (6\"), and one weld was made per coupon to ensure no preheat effects were experienced from previous welds. Welding torch travel and weld angles were both 0\". The coupons were elevated from the fixture by four cap screws (Figure 2.3) at a distance of 1\" above the fixture, minimizing the heat lost.
via conduction during welding. The coupons were clamped using a quick release mechanism which permitted rapid transfer of the welded coupon to the liquid nitrogen dewar. The quick release clamps minimized the time for convection losses to the surrounding air following welding. Shielding gas used throughout this test consisted of 90% Argon - 10% CO₂ at 40 CHF.

Figure 2.3 – Quick Release Fixture.

Voltage was measured between the contact tip of the welding gun and the fixture (see Figure 2.3). This allowed voltage measurements as close to the arc as possible to most accurately measure the arc voltage. [21] Current was
measured using a Hall effect current sensor, and the wire feed speed of the electrode was measured using a tachometer-based pick up. A National Instruments PCI E data acquisition card in combination with a laptop PC was used to acquire voltage, current, and wire feed speed data, and display the results in a graphical format (Figure 2.4). Average and RMS voltage and current as well as average instantaneous power were also displayed. The sampling rate was 4500 Hz to prevent aliasing.

Figure 2.4 – Data Acquisition Display Showing Voltage, Current, Wire Feed Speed (upper), and Instantaneous Power Traces (lower).
The data acquisition system measurements were compared to a calibrated digital oscilloscope. Several measurements were taken and synchronized with both the oscilloscope and the data acquisition system, and subsequently compared. Appendix C contains the actual comparison data.

Since arc length has a direct effect on arc voltage, it was necessary to maintain a constant arc length throughout the testing. A high-speed video camera was used to provide accurate measurement of arc length. A 940 ±5 nm optical filter was used to allow viewing of the metal transfer without using laser back lighting (see Figure 1.1). Arc length was adjusted to 3.2 mm (0.125 in.) using the known wire diameter as a reference dimension in the video image. The 3.2-mm (0.125-in.) arc length was measured as the distance from the electrode tip to the weld pool surface at the moment of drop detachment.

One five-inch weld bead was deposited per base material coupon. Welds were made at wire feed speeds of 100, 200, 300, 400, and 500 IPM with respective travel speeds of 5, 10, 15, 20, and 25 IPM to maintain a constant wire feed speed / travel speed ratio. This gave a constant weld deposit area of 0.032 in² (20.6 mm²) throughout testing. Immediately after welding (1-3 seconds), the welded coupon was removed from the fixture and transferred to the liquid nitrogen dewar. The initial weight was recorded, and after an equilibration period of 10 minutes, the final weight was recorded. The difference between the initial and final weights of the liquid nitrogen is proportional to the heat content of the welded coupon.
2.4.1.2 Results and Discussion

The heat input to the weld coupons using the liquid nitrogen calorimeter was found using the following equations [12,20]:

\[
\text{Normal Evaporation (J) = weight change due to ambient evaporation over the testing period (g) x 47.66 cal/g x 4.184 J/cal}
\]

\[\text{Negative Heat Input (J) = weight change from room temperature to liquid nitrogen temperature (g) x 47.66 cal/g x 4.184 J/cal}\]

\[
\text{True Heat Input (J) = total weight change from welded coupon (g) x 47.66 cal/g x 4.184 J/cal} - \text{Normal evaporation (J)} - \text{Negative heat input (J)}
\]

where 47.66 cal/g is the heat of vaporization of liquid nitrogen.

The heat input to the weld coupons (equation 4) was calculated based on either average, RMS, or average instantaneous power (AIP), equations (1), (2), and (3) respectively. The heat input from the liquid nitrogen calorimetry tests and the calculated heat input are listed in Table 2.2. Table 2.2 shows a significant difference between the measured heat input and the calculated heat input for GMAW-Pulse welds and the CV welds at low wire feed speeds. At high wire feed speeds, the CV welds had almost identical measured heat inputs. This was due to the current level being above the spray transition current, and subsequently spray transfer with no short-circuiting occurred.
<table>
<thead>
<tr>
<th>WFS</th>
<th>Measured Heat Input from Calorimeter (KJ/in)</th>
<th>Calculated Heat Input from Average Voltage and Current (KJ/in)</th>
<th>Calculated Heat Input from RMS Voltage and Current (KJ/in)</th>
<th>Calculated Heat Input from Average Instantaneous Power (KJ/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>15.7</td>
<td>22.9</td>
<td>25.0</td>
<td>22.0</td>
</tr>
<tr>
<td>200</td>
<td>15.0</td>
<td>22.7</td>
<td>25.4</td>
<td>22.0</td>
</tr>
<tr>
<td>300</td>
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<td>400</td>
<td>17.2</td>
<td>23.5</td>
<td>23.5</td>
<td>23.5</td>
</tr>
<tr>
<td>500</td>
<td>18.6</td>
<td>22.7</td>
<td>22.7</td>
<td>22.7</td>
</tr>
<tr>
<td>GMAW-P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>15.7</td>
<td>18.1</td>
<td>28.6</td>
<td>22.0</td>
</tr>
<tr>
<td>200</td>
<td>15.7</td>
<td>18.9</td>
<td>26.5</td>
<td>22.3</td>
</tr>
<tr>
<td>300</td>
<td>15.0</td>
<td>18.4</td>
<td>24.7</td>
<td>21.6</td>
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<td>400</td>
<td>15.0</td>
<td>17.8</td>
<td>22.9</td>
<td>20.8</td>
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<tr>
<td>500</td>
<td>13.9</td>
<td>13.3</td>
<td>22.0</td>
<td>20.6</td>
</tr>
</tbody>
</table>

Table 2.2 – Comparison of Measured and Calculated Heat Input Values.

The differences between the GMAW-Pulse heat input values for a given wire feed speed shown in Table 2.2 can be explained in two ways. First, the differences between the calculated heat input based on the three types of power calculations exist due to the method in which the individual voltage and current measurements are manipulated. The 300, 400 and 500 ipm wire feed speed CV welds show very little difference between these three measurements since their waveform was not pulsed and not short-circuiting. However, since the GMAW-Pulse waveform is pulsed, the heat inputs based on arc power differ. Second, the difference between the measured heat input and the calculated heat inputs can be attributed to thermal efficiency:
\[ \text{Thermal efficiency(\%)} = \frac{\text{True Heat Input (J)}}{\text{Calculated Heat Input (based on arc power)}} \times 100\% \] (9)

Thermal efficiency accounts for the amount of energy that does not enter the welded coupon, but rather is lost to other places (surrounding air, unmelted electrode, contact tip, gas nozzle, etc.). Table 2.3 lists the calculated thermal efficiencies for each wire feed speed, as well as the average thermal efficiency for each of the three types of measurements.

<table>
<thead>
<tr>
<th></th>
<th>WFS (in/min)</th>
<th>Average Power (%)</th>
<th>RMS Power (%)</th>
<th>Average Instantaneous Power (AIP) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>100</td>
<td>68.6</td>
<td>62.8</td>
<td>71.6</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>66.2</td>
<td>59.2</td>
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<td></td>
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<td>400</td>
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<td>Average</td>
<td></td>
<td>71.8</td>
<td>69.3</td>
<td>72.8</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>WFS (in/min)</th>
<th>Average Power (%)</th>
<th>RMS Power (%)</th>
<th>Average Instantaneous Power (AIP) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMAW-P</td>
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<td>86.9</td>
<td>54.9</td>
<td>71.5</td>
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<tr>
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<td>81.5</td>
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<td>69.3</td>
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<tr>
<td></td>
<td>400</td>
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<td></td>
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<tr>
<td>Average</td>
<td></td>
<td>82.4</td>
<td>60.7</td>
<td>70.2</td>
</tr>
</tbody>
</table>

Table 2.3 – Calculated Thermal Efficiencies.

As stated previously, published thermal efficiency data shows efficiencies for GMAW that range from 62 to 85%. The CV welds have efficiencies ranging from 69% to 72%, showing excellent agreement with published data. It is
important to note that the CV welds above 300 IPM have nearly identical efficiencies due to their non-pulsing nature.

Previous literature for GMAW-Pulse shows efficiencies between 70 and 75%. From the thermal efficiency data in Table 2.3, it can be seen that the heat input for the GMAW-Pulse welds based on AIP yields an efficiency of 70.2%. This was in excellent agreement with previously published data, and indicated that the most appropriate method of estimating heat input for GMAW-Pulse was accomplished through the use of AIP.

Heat input based on RMS power and average powers are 60.7% and 82.4%, respectively. This indicates that heat input estimates based on RMS power will tend to be high, and will not produce accurate quantitative relationships with respect to weld properties. Likewise, heat input estimates based on average power will tend to be low.

2.4.1.3 Graphical Interpretation

When the GMAW-Pulse calculated heat input is plotted against the measured heat input (solid lines in Figure 2.4), it can be seen that average power yields a calculated heat input that is closest to the measured heat from calorimetry, indicating that the thermal efficiency is very high. Heat input based on RMS power is just the opposite. The thermal efficiency is lower than previous literature suggests it should be and the slope is higher than the true heat input.
The CV welds (dashed lines in Figure 2.5) show an overall higher heat input compared to the GMAW-Pulse welds. This result was expected for the wire feed speeds higher than 300 IPM because current is above the spray transition level. Below 200 IPM, short-circuiting and globular transfer modes lowered the heat input.

Since heat input based on AIP has a slope that very closely matches the measured heat input and corresponds to a thermal efficiency of 70 – 75%, calculating heat input using AIP was determined to be the most appropriate method of estimating heat input to a weld.

Figure 2.5 - Graphical analysis of true heat input vs. calculated heat input.
2.5 Mathematical Analysis

Thermal conditions in and near the weld must be maintained within specific limits to control properties such as microstructure, mechanical properties, residual stresses and distortion. Power is the physical quantity of interest to determine the thermal conditions (or heat input). The equation for average instantaneous power is as follows:

\[ P_{av} = \frac{1}{T} \int_0^T i(t) \cdot v(t) dt \]  \hspace{1cm} (10)

We are interested in the average of the power because our interest is heat input which is averaged over some length of time.

Some researchers have used RMS current and RMS voltage to define power based on the assumption that resistance, R, is not time varying. Under this assumption:

\[ v(t) = i(t)R \]  \hspace{1cm} (11)

Using \( I_{RMS} = \sqrt{\frac{1}{T} \int_0^T i^2(t) dt} \) and substituting equation (11) into equation (10) gives

\[ P_{av} = I_{RMS}^2 R \]  \hspace{1cm} (12)

Furthermore, if \( R \) is constant and

\[ V_{RMS} = I_{RMS} R \]  \hspace{1cm} (13)

then

\[ P = I_{RMS} V_{RMS} \]  \hspace{1cm} (14)
where \( V_{\text{rms}} = \frac{1}{T} \int_{0}^{T} v(t) \, dt \). However, Figure 2.6 shows a plot of resistance and voltage vs. time for a small portion of a GMAW-Pulse weld. Resistance clearly varies with time, thus making the assumptions that resistance is false and equation 16 an invalid expression for arc process power.

![Graph showing voltage and resistance over time](image)

**Figure 2.6 – Voltage and Resistance vs. Time for a GMAW-Pulse Weld.**

Some researchers have also used average current and average voltage as a substitute for AiP as follows:

\[
P = I_i V_{av}
\]  

(15)
where \( I_{av} = \frac{1}{T} \int_{0}^{T} i(t) dt \) and \( V_{av} = \frac{1}{T} \int_{0}^{T} v(t) dt \). As long as \( i(t) \) and \( v(t) \) are constant, equation 15 is valid. Under conditions where \( i(t) \) and \( v(t) \) are time varying, such as pulsed current welding, equation 15 is not valid. A simple proof of this can be seen using the following example:

Figure 2.7 – Current and Voltage Trace for Typical Square Wave Pulse.

Calculating average power and average voltage according to Table 2.1:

\[
I_{av} = \frac{400}{2} + \frac{40}{2} = 220 \text{ Amps}
\]

\[
V_{av} = \frac{25}{2} + \frac{20}{2} = 22.5 \text{ Volts}
\]

\[
P_{av} = I_{av} \cdot V_{av} = 220 \cdot 22.5 = 4950 \text{ Watts}
\]
Calculating Average Instantaneous Power according to Table 2.1:

\[ P_{\text{INST}} = \frac{400 \cdot 25}{2} + \frac{40 \cdot 20}{2} = 5400 \text{ Watts} \]

Clearly average power and Average Instantaneous Power are not equal for the condition where I and V are time varying.

2.6 Conclusions

1. The most appropriate method to calculate heat input is the Average Instantaneous Power.

2. Power calculated from RMS measurements of voltage and current is inaccurate because resistance of the arc varies. It calculates a heat input that is approximately 10% higher than actual.

3. Power calculated from average voltage and current yields a heat input that is approximately 12% lower than actual.
CHAPTER 3

EFFECTS OF PULSE PARAMETERS ON HEAT INPUT, DILUTION AND PENETRATION

Once the ability to appropriately calculate the heat input to a weldment was found, an investigation into the effects of pulsing parameters on heat input was carried out. Some literature that has been published uses pulse parameters at varying wire feed speeds to yield a particular dilution and/or penetration [7, 22 - 26]. There has been no work published which suggests that pulsing parameter selection has a significant effect on heat input for a constant deposit area weld. An investigation was conducted to determine to what extent pulsing parameters affect heat input, base metal dilution and weld penetration under constant welding conditions.

3.1 Explanation of Individual GMAW-Pulse Parameters

GMAW-Pulse parameters can be broken down into two groups based on their influence on the wire burn off rate: primary and secondary. The primary pulsing parameters include peak current (Ip), background current (Ib), pulse
width (tp) and frequency (f). Some basic rules have been established for the selection of values for the primary pulsing parameters. The following rules are recommended as a guideline for initial parameter selection (see Figure 3.1):

- Peak current (Ip) – must be high enough to provide sufficient force to pinch droplets from the tip of the filler wire and propel the drops across the arc. In other words, Ip must be greater than the spray transition current level, which is dependent on wire material, wire diameter and shielding gas. Appendix A lists spray transition currents for steel.

- Pulse width (tp) – together with Ip; largely determine the peak energy, which ultimately will control the number of drops detached for one pulse. Most researchers specify “one drop per pulse” as the ideal condition. [3-10] More than one drop per pulse typically indicates a transition to spray transfer and is due to a pulse width that is too long. Less than one drop per pulse usually indicates that the pulse width is too short.

- Background current (Ib) - maintains a stable arc. No droplets are transferred to the weld pool at this current, and the weld pool begins to solidify. Ib is set at a level that is low enough to allow solidification to begin, but high enough to prevent stubbing or short-circuiting of the filler wire into the weld pool. When welding sheet metal, Ib should be set as low as possible, whereas when welding thick materials, Ib should be set higher.
- Frequency (f) – is proportional to wire feed speed and controls burn off rate. In some synergic control power supply algorithms (where pulsing parameters are adjusted according to a preset schedule based on the wire feed speed that has been selected), frequency is used to adjust arc length in the form of a "trim" knob. More sophisticated pulse parameter algorithms adjust frequency as well as some or all of the other primary parameters.

![Diagram of Pulse Parameter Primary Variables]

Figure 3.1 – Pulse Parameter Primary Variables

It should be noted that although the functions of the primary parameters are listed independently, the functions are interrelated. It is very difficult to adjust only one parameter without having an effect on the other variables.

The secondary group of pulsing parameters contains parameters such as: ramp up rate, overshoot, ramp down style (i.e. exponential, linear, logarithmic, etc.), ramp down rate, ramp down time, step off current, step off time, and
undershoot. Figure 3.2 shows the secondary variables in a single pulse. Many if not all of these parameters are fixed in most pulse parameter algorithms due to the obvious complexities that can arise if they are adjustable.

![Diagram of pulse parameter variables](image)

Figure 3.2 – Pulse Parameter Secondary Variables.

### 3.2 Power Supply Review

Given the large number of variables available, an assessment of industrial approaches toward pulse parameter selection was necessary. The review focused on the state of the art approaches for pulse parameter selection taken by power supply manufacturers. Four power supplies from four different manufacturers were characterized and will be called power supply A, B, C, and D.
to maintain objectiveness. Each power supply had synergic (one knob) control. Appendix D contains an index of the available algorithms for each power supply.

3.2.1 Experimental Procedure

Each power supply that was used could store several synergic algorithm programs corresponding to different material/shielding gas combinations. The common synergic algorithm among all of the power supplies was 0.045" steel wire and some combination of argon – CO₂ shielding gas. Therefore it was decided to concentrate the testing using 0.045" ER70S-6 wire and 90% Argon – 10%CO₂, which all of the power sources supported.

A constant deposit area test matrix was used to systematically characterize each approach towards pulse parameter selection (Table 3.1). As shown in this table, a constant wire feed speed to travel speed ratio (WFS/TS) of 20 was maintained for a constant weld deposit area. Travel speed was incrementally increased from 5 to 25 ipm in 5 ipm increments. The corresponding wire feed speed was 20 times the travel speed. This matrix covered the entire current range of each power supply.
<table>
<thead>
<tr>
<th>Travel Speed (ipm)</th>
<th>Wire Feed Speed (ipm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>200</td>
</tr>
<tr>
<td>15</td>
<td>300</td>
</tr>
<tr>
<td>20</td>
<td>400</td>
</tr>
<tr>
<td>25</td>
<td>500</td>
</tr>
</tbody>
</table>

Constant: ER70S-6 1.2 mm (0.045") wire
90% Argon – 10% CO₂ shielding gas at 40 CFH
0 degree push travel angle
0 degree work angle
1/8-in. arc length
3/4-in. contact tip-to-work distance

Table 3.1 - Test Matrix for the Power Supply Review.

Bead on plate tests were used to minimize the number of variables during testing, allowing the torch push angle and work angle to be fixed at 0°. All welds were made using a stationary straight machine welding gun and a linear table that moved the base material at a constant speed. This setup allowed the high-speed video equipment to be stationary and detached from the linear table, which prevents image distortion from the linear table vibration. All welds were made in the flat position. Each power supply was used in an identical setup condition (Figure 3.3). Contact tip to work distance was fixed at 3/4". Arc length was visually set to 1/8" using the H570 camera by adjusting each power supply's "trim" knob.
Figure 3.3 – Equipment Setup for Power Supply Testing

Filler material used for this work was ER70S-6 uncoated steel wire with a diameter of 1.2mm (.045\textapo). Base material was low alloy carbon steel 12.7mm (.5\textapo) thick. Coupon dimensions were 6.35 cm (2.5\textapo) by 15.24 cm (6\textapo) and one weld was made per coupon. This ensured that no preheat effects were experienced from previous welds. Welding torch travel and weld angles were both 0\textapo (Figure 3.4). Shielding gas used throughout this study was 90\% Argon - 10\% CO\textsubscript{2} at 40 CFH.
Figure 3.4 – Welding Fixture and Torch.

Data acquisition for each weld was analyzed using the same software (Figure 2.4) that was used for the liquid nitrogen calorimetric tests. The software allowed for accurate measurement of the four critical pulse parameter variables: peak current, background current, pulse width, and frequency.

3.2.2 Results and Discussion

Examination of each of the waveforms produced by the four welding power supplies yielded a few common results. One common finding was each
power supply produced a standard trapezoid waveform. Figure 3.5 shows the waveform for power supply B at 200 IPM, which illustrates the trapezoidal waveform. Another commonality was that none of the power supplies utilized a step off current.

![Welding Parameters Diagram](image)

**Figure 3.5 – Sample Waveform at 200 IPM.**

Graphs of peak current, background current, frequency and pulse width versus wire feed speed for each power source were produced and can be seen in Figures 3.6 through 3.9. Appendix E contains the numerical results for each of these graphs. Each of these graphs showed a general increase in each parameter with an increase in wire feed speed. This corresponded to an increase in the burn off rate to match the increase in wire feed speed. There were some
specific differences between pulse parameter selections as wire feed speed increased. The specific differences will be discussed below.

![Graph showing Peak Current (Ip) vs. Wire Feed Speed.](image)

**Figure 3.6 – Peak Current (Ip) vs. Wire Feed Speed.**
Figure 3.7 – Background Current (A) vs. Wire Feed Speed.

Figure 3.8 – Frequency (Hz) vs. Wire Feed Speed.
Figure 3.9 – Pulse Width ($tp$) vs. Wire Feed Speed.

Power Supply A had a pulse parameter algorithm that was fairly simple. Peak current and pulse width were left relatively constant throughout the entire range of wire feed speed. Frequency was increased proportionally with wire feed speed. It was assumed that background current was intended to be constant, but at wire feed speeds of 400 and 500 ipm the pulse frequency was so high that there was not enough time for the current to reach the low background level. This conclusion was verified based on the current trace shown in Figure 3.10. It appeared that if frequency was lower at the 400 and 500 ipm settings, the current would have been able to reach the same level as the 100, 200, and 300 ipm
settings. High-speed video revealed that the 500 ipm setting was very similar to spray transfer.

Figure 3.10 – Power Supply A Waveforms.

Power Supplies B and C have very similar pulse parameter algorithms. Peak current, background current, and frequency were all incrementally adjusted as wire feed speed increases as seen in Figures 3.11 and 3.12. Pulse width was held relatively constant. Despite the similarities in the primary pulse parameters, differences were seen in some of the secondary parameters. Power Supply B
had an exponential ramp down style, with a very slight undershoot. Power Supply C had a linear ramp down style (similar to Power Supply A), however it had a significant undershoot and overshoot. Figure 3.13 shows a magnified view of a single pulse found in Power Supply C, displaying the undershoot and overshoot. High-speed video showed a fairly consistent one drop per pulse throughout the range of wire feed speeds for both Power Supplies B and C.

Figure 3.11 – Power Supply B Waveforms
Figure 3.12 – Power Supply C Waveforms

Figure 3.13 – Power Supply C Undershoot and Overshoot.
Power Supply D had the most complicated pulse parameter algorithm.

Figure 3.14 shows the current and voltage traces. Peak and background current jumped from 100 to 200 IPM, but then are held constant. Frequency was incrementally increased in a fashion that was very similar to Power Supply B. The major difference compared to the other power supplies was found in pulse width. Pulse width started lower than the other power supplies and increased through the range of testing. High-speed video showed a consistent one drop per pulse with this power supply as well.

Figure 3.14 – Power Supply D Waveforms
Graphs of Average Instantaneous Power versus WFS and Heat Input (based on AIP) versus WFS were created to determine the effect of the various pulsing parameters on power and heat input (Figures 3.15 and 3.16). Figure 3.15 shows a general increase in AIP of all power supplies as wire feed speed was increased. The increase in power was expected and was necessary to match the required increase in burn off rate as wire feed speed was raised. Closer investigation showed a significant difference in AIP between each power supply algorithm at a constant wire feed speed. This difference in power was also seen as a difference in heat input (Figure 3.15).

![Graph showing AIP vs. Wire Feed Speed](image)

**Figure 3.15 - AIP vs. Wire Feed Speed (linear trend lines used).**
Figure 3.16 - Heat Input (based on AIP) vs. Wire Feed Speed.

At this point in the investigation, the differences in heat input at a given wire feed speed seen in Figure 3.16 may have been from several sources. One source may have been electrical differences between power supplies, such as inductance or resistance. Another difference may have been the actual pulsing parameters themselves. Noise, such as slight differences in arc length or any other experimental error, may also have played a part in creating the differences. The next part of the investigation will attempt to narrow the differences to one source.
3.3 Conclusions

1. The various pulse parameter algorithms used by the different power supply manufacturers resulted in as much as a 12% variation in heat input for a given wire feed speed.

2. There were many combinations of pulsing parameters that produced sound welds at each wire feed speed tested.

3. It was not entirely clear how much of the heat input variation was due to pulsing parameters and how much was power source characteristic dependant.

4. Further experiments are needed to decouple the pulse parameter and power source characteristic effects.
CHAPTER 4

SIMULATED PULSING PARAMETERS

After the commercial power supplies were characterized, significant differences in heat input for a fixed wire feed speed were produced. It was questioned whether or not the differences in heat input were based solely on differences in pulse parameters. The differences may have occurred in part due to differences in electrical characteristics between each of the power supplies, or simply due to experimental error. In order to eliminate power supply differences as a variable, each of the previously investigated waveforms were analyzed and reproduced on one power supply, thus eliminating any power supply variability.

4.1 Experimental Procedure

Reproduction of the waveforms was accomplished using Lincoln Electric's "Waveform Designer Pro" software (Figure 4.1) and Powerwave 455 pulsing power supply. The software gave full control of all of the primary pulsing parameters (highlighted in blue in Figure 4.1), as well as most of the secondary parameters. The parameters were programmed into the software, and then subsequently fine-tuned as necessary while welding to produce a constant 1/8"
arc length. The adjustments were necessary since the Lincoln Powerwave 455 pulsing power supply did not respond to certain pulse parameter algorithms the same way the tested power supplies responded.

Figure 4.1 – Lincoln Electric’s Waveform Designer Pro software.

Each waveform was copied as accurately as possible, including the four primary pulsing variables (lp, lb, tp, f), rise and fall rates, overshoot, and undershoot. The waveform of power supply D was impossible to completely reproduce due to a superimposed ripple in the current. This was not considered to be a problem because the basic waveform and pulse parameter algorithm
could be copied without losing the intent of the original waveform strategy. At this point in the experiment, it was considered to be more important to accurately maintain a 1/8" arc length than it was to precisely copy the waveforms of the other power supplies. Arc length has a large effect on heat input calculations and was fixed to match the previous power supply comparison. Thus, it was anticipated that some of the measurements might not be precisely the same as values found in Chapter 3.

Aside from the use of one power supply, all other equipment was the same as that used in the previous experiment. The linear slide and the high-speed video camera were again used to accurately measure a 1/8" arc length. Voltage and current were measured using the same data acquisition system at the same monitoring points.

For a baseline comparison, constant voltage (CV) welds were made using the same wire feed speed and travel speed increments. Voltage was adjusted to give a constant 1/8" arc length. The power supply and equipment setup was identical to that used for the simulated pulse parameter welds in order to maintain consistent measurements. The same wire feed speed / travel speed ratio and set points were also used (Table 4.1).
<table>
<thead>
<tr>
<th>Travel Speed (ipm)</th>
<th>Wire Feed Speed (ipm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
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<tr>
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</tr>
<tr>
<td>20</td>
<td>400</td>
</tr>
<tr>
<td>25</td>
<td>500</td>
</tr>
</tbody>
</table>

Constant: ER70S-6 1.2 mm (0.045") wire
90% Argon – 10% CO₂ shielding gas at 40 CFH
0 degree push travel angle
0 degree work angle
1/8-in. arc length
3/4-in. contact tip-to-work distance

Table 4.1 - Test Matrix for the Power Supply Review.

4.2 Results and Discussion

The simulated welds were made and are shown in Figures 4.2 – 4.5, and the constant voltage measurements are shown in Figure 4.6. When the simulated waveforms were compared directly with the actual waveforms from Chapter 3, there were some minor differences in both wave shape and current and voltage levels. These differences were considered irrelevant since the effect of the pulse parameter algorithm on heat input was being investigated, not how accurately the algorithm could be reproduced.
Figure 4.2 – Simulated Power Supply A Waveform.
Figure 4.3 – Simulated Power Supply B Waveforms.
Figure 4.4 – Simulated Power Supply C Waveform.
Figure 4.5 – Simulated Power Supply D Waveform.
Figure 4.6 – Constant Voltage Measurements.

Average Instantaneous Power was plotted against wire feed speed (Figure 4.7), and shows good correlation with the previous results shown in Figure 3.14. Power Supply A had the highest power, and Power Supply D had the lowest, with Power Supplies B and C somewhere in the middle. There was a significant difference in power between each simulated power supply algorithm at a constant wire feed speed.
Figure 4.7 – Average Instantaneous Power vs. Wire Feed Speed for Simulated Pulse Parameters (linear trend lines used).

Heat input (based on AIP) versus wire feed speed (Figure 4.8) also had excellent correlation to the actual power supply heat input graph (Figure 3.15). Power Supply A had the highest heat input, close to that of the CV weld. Power Supply D had the lowest heat input, approximately 17% lower at the 500 IPM setting.
Figure 4.8 – Heat Input (based on AIP) versus Wire Feed Speed for Simulated Pulse Parameters.

Figure 4.7 and 4.8 show that for any given wire feed speed, pulse parameters have a significant effect on power and heat input to the weldment. Power and heat input can vary as much as 17% due to nothing other than changing pulsing parameters. Since using parameter algorithms can have a sizeable effect on heat input, it may be possible that penetration and dilution can be controlled as well. When the pulsing parameters were compared to the constant voltage weld, most of the pulse parameter algorithms produce a lower heat input, which was expected.
4.3 Penetration and Dilution

Each simulated pulse parameter weld was cross-sectioned and dilution and penetration were measured. Figure 4.9 contains a macro photograph map of the cross sections. Since the shielding gas had a high concentration of argon, finger type penetration was exhibited. Although there were obvious changes in bead shape as wire feed speed was increased, there was very little difference in bead shape for any one wire feed speed.

<table>
<thead>
<tr>
<th>WFS</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>C</td>
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<tr>
<td>D</td>
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<tr>
<td>CV</td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

Figure 4.9 – Macro section Map.
Figure 4.10 is a graph of the penetration for each waveform at each wire feed speed. Penetration was measured from the base metal top surface to the bottom of the finger. There was an obvious increasing trend as wire feed speed increases, however penetration changes were relatively small at each wire feed speed. Despite some subtle differences at the higher wire feed speeds, no real trends were established.

![Penetration Graph](image)

Figure 4.10 - Penetration for the Simulated Pulse Parameters.

Dilution was measured by the following equation:

\[
\frac{(NA - DA)}{(NA)} \times 100\%
\]
where DA is Deposit Area and NA is Nugget Area. The results are shown in Figure 4.11. Similar to the penetration results, dilution increased as wire feed speed was increased. Dilution variations were small at each wire feed speed.

![Dilution for the Simulated Pulse Parameters](image)

**Figure 4.11 – Dilution for the Simulated Pulse Parameters.**

### 4.4 Conclusions

1. A difference of up to 17% in power and heat input was produced by different pulse parameter waveforms at any given wire feed speed, however there were very little if any changes in bead shape, penetration, and dilution.
2. Some subtle differences in bead shape, penetration, and dilution were produced that may have been due to the arc characteristics produced by different waveforms, i.e. some waveforms may have concentrated the arc more than others.

3. Further experiments are needed to investigate the maximum limits of heat input changes due to pulsing parameters in an attempt to find a relationship between bead shape, penetration, dilution and pulsing parameters.
CHAPTER 5
CONFIRMATION TESTING

Once the effects of varying pulse parameters at a fixed wire feed on power and heat input were found, it was desired to determine the boundary conditions. Tests were performed to investigate the minimum and maximum limits of heat input changes due solely to pulse parameter changes, and to determine if any relationship exists between pulsing parameters and bead shape, penetration, and dilution. Also, a state of the art commercially available power supply with the ability to adjust pulse parameters at a fixed wire feed speed was used to confirm the previous findings of this project.

5.1 Experimental Procedure

The boundary tests were conducted using the same equipment setup and test matrix that was used in previous tests with the exception of the pulse parameter algorithms. Two new pulse parameter waveforms were created using Lincoln’s Waveform Designer Pro software that were referred to as “High Peak” and “Low Peak”. These waveforms are similar to Power Supply D and A,
respectively, however they were much more exaggerated. All other parameters were set according to Table 5.1, which is identical to previous testing.

<table>
<thead>
<tr>
<th>Travel Speed (ipm)</th>
<th>Wire Feed Speed (ipm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>13</td>
<td>200</td>
</tr>
<tr>
<td>15</td>
<td>300</td>
</tr>
<tr>
<td>26</td>
<td>400</td>
</tr>
<tr>
<td>25</td>
<td>500</td>
</tr>
</tbody>
</table>

Constant: ER70S-6 1.2 mm (0.045") wire 90% Argon – 10% CO₂ shielding gas at 40 CFH 0 degree push travel angle 0 degree work angle 1/8-in. arc length 3/4-in. contact tip-to-work distance

Table 5.1 - Test Matrix for the Panasonic M5i 500.

5.2 Results and Discussion

The High Peak waveform was developed to represent a very high-energy pulse with a short pulse width (Figure 5.1). This type of waveform is sometimes referred to as a “hard arc” since it is very loud and has a constricted arc compared to a normal pulse. It was anticipated that the High Peak waveform would yield a low power and heat input since a majority of the pulse waveform was in the background region. The waveform from Power Supply D was the most similar waveform to the High Peak waveform. In order to match power with burn off rate, frequency was increased as wire feed speed was increased to a

65
level that yields a 1/8" arc length as viewed using high-speed video. The only exception to the algorithm was at the 100 IPM level. Peak current was lowered slightly to create a stable arc. At 200 IPM, the peak current was raised and then maintained at that level throughout subsequent increases in wire feed speed.

![Waveform Images]  
**Figure 5.1 – “High Peak” Waveforms.**

High-speed video revealed that the High Peak waveform was not optimized. Droplet transfer occurred during the background period. The molten drops were transferred in the form of a long stream similar to spray transfer. The long stream of molten material was violent and had residual drops that formed after the molten stream and were subsequently transferred to the pool. Figure 5.2 shows a sequence of high-speed video of a typical High Peak steady state transfer at 200 IPM wire feed speed. It was not possible to make a satisfactory
weld at the 500 IPM level due to the instability created from the extreme nature of the waveform.

<table>
<thead>
<tr>
<th>0.0 sec</th>
<th>0.9 sec</th>
<th>1.8 sec</th>
<th>2.7 sec</th>
<th>3.6 sec</th>
<th>4.5 sec</th>
<th>5.4 sec</th>
<th>6.3 sec</th>
<th>7.2 sec</th>
</tr>
</thead>
</table>

Figure 5.2– High Speed Video of High Peak Waveform.

The Low Peak waveform can be seen in Figure 5.3. This wave was designed to have the lowest peak current level possible with a low ramp up and ramp down rate. This type of waveform is typically referred to as a "soft arc" because the waveform is relatively quiet, and has a much wider and more spread out arc compared to a normal pulse. The waveform from Power Supply A was most similar to the Low Peak waveform. It was anticipated that this waveform would produce a high power level and heat input since it spent less time at the background current level compared to the High Peak waveform. The pulse parameter algorithm was very simple. As wire feed speed was increased, the frequency was also increased to yield a 1/8" arc length.
Figure 5.3 – "Low Peak" Waveforms.

Figure 5.4 shows a sequence of high-speed video clips from a typical steady state Low Peak waveform pulse at 200 IPM wire feed speed. Similar to the High Peak waveform, this waveform was not considered to be optimal. The long pulse produced a large drop that was transferred to the molten pool, however a second drop that was almost the same size followed the first drop. This condition was referred to as two drops per pulse, and was not considered to be optimal due to the high energy level required to transfer two drops.
Figure 5.4 – High Speed Video of “Low Peak” Waveform.

Average instantaneous power was plotted against wire feed speed (Figure 5.5). The AIP plot from the simulated waves test (Figure 4.7) was superimposed on Figure 5.5 as dotted lines. This allowed direct comparison of the power measurements. Figure 5.5 showed that the High Peak waveform was very efficient, with the trend very close to the lowest power waveforms. The Low Peak waveform had a very high power level, even slightly higher than the constant voltage power at the lower wire feed speeds. This was because the waveform produced two drops per pulse, and is not optimized properly.
Figure 5.5 – Average Instantaneous Power vs. Wire Feed Speed for Simulated Pulse Parameters (linear trend lines used).

The heat input versus wire feed speed plot (Figure 5.6) shows that the Low Peak waveform had a very high heat input as was expected. The High Peak waveform did not produce the results that were expected. At the low wire feed speeds, the High Peak waveform had a very high heat input, decreasing as wire feed speed was increased. Only at the 300 and 400 IPM levels was the heat input as low as was expected.
5.3 Penetration and Dilution

The welds at 100 IPM, 200 IPM and 300 IPM were cross-sectioned and dilution and penetration were measured. Figure 5.7 shows a macro photograph map of the cross sections. Similar to the simulated waveform welds, finger type penetration was exhibited. Unlike the simulated waveforms welds, there appears to be a significant difference in the bead shape of welds. The Low Peak waveform produced an exaggerated papillary, or finger, compared to the High Peak waveform.
Figures 5.7 – Macro section Map for the High Peak and Low Peak Waveforms.

Figures 5.8 and 5.9 show the High Peak and Low Peak penetration and dilution. The penetration and dilution measurement from the simulated waveforms is also plotted as semitransparent areas for comparison. The penetration for high peak and low peak show a small difference in penetration at 100 and 300 IPM wire feed speeds, and show a large difference at the 200 IPM wire feed speed. This result was expected from the macro photograph as seen in Figure 5.7. The dilution follows the same trend. There was a small difference in dilution at the 100 and 300 IPM wire feed speed levels, and there is a large difference in dilution at the 200 IPM range. Although this data is not conclusive, it does show that there appears to be some relationship between pulse parameters and bead shape, penetration and dilution at the extreme boundaries for pulsing parameters.
Figure 5.8 – Penetration for the High Peak and Low Peak Waveforms.

Figure 5.9 – Dilution for the High Peak and Low Peak Waveforms.
5.4 State of the Art Commercial Power Supply

As part of the confirmation testing, a Panasonic HMII 500 pulsing power supply was acquired. This power supply had 3 pulsing modes available to the operator at any desired wire feed speed. The three modes were called "Hard pulse", "Soft pulse", and "Hybrid pulse". The manufacturer stated that the Soft pulse had a 'soft wide arc that produced good wetting', the Hard pulse had a 'moderate arc good for thin materials', and the Hybrid pulse had a 'very tight arc good for high speed welding on thin materials'.

5.4.1 Experimental Procedure

The Panasonic HMII 500 power supply was tested using the same setup as was previously used for the simulated waves to maintain consistency. Each of the 3 modes (Hard Pulse, Hybrid Pulse, and Soft Pulse) were tested according to Table 5.1. The same welding torch and electrical leads were used to ensure there was no change in the electrical characteristics of the testing setup.

5.4.2 Results and Discussion

Figures 5.10 – 5.12 show the waveforms produced by the Panasonic HMII 500 power supply in each of the three modes, Hard Pulse, Hybrid Pulse, and Soft Pulse respectively. It was very difficult to see any significant difference between
the three waveforms, however close examination showed that the frequencies are slightly different between the three at any given wire feed speed. The Hard Pulse had the highest frequency at each wire feed speed, the Soft Pulse had the lowest frequency, and the Hybrid Pulse had a frequency somewhere between the Hard Pulse and Soft Pulse waveforms. This was also evident during welding, as the differences in frequency could be heard as a higher pitch for high frequency and lower pitch for lower frequency.

![Waveform Diagrams](image)

Figure 5.10 – Panasonic HMl 500 “Hard Pulse” waveform.
Figure 5.11 – Panasonic HMII 500 “Hybrid Pulse” waveform.
Figure 5.12 – Panasonic HMII 500 “Soft Pulse” waveform

Magnification of the waveforms showed that the pulse widths were also slightly different. Figure 5.13 shows each of the pulsing modes at 300 IPM. The pulse width for the Hard Pulse was the shortest at each wire feed speed, the Soft Pulse was the longest, and the Hybrid pulse was between the Hard Pulse and the Soft Pulse. This result was expected because in order to have identical burn off rates, an increase in any parameter will require a proportional decrease in another parameter.
### Hard Pulse

<table>
<thead>
<tr>
<th>Parameter Display</th>
<th>Avg. Voltage</th>
<th>RMS Voltage</th>
<th>RMS Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V)</td>
<td>22.27</td>
<td>22.89</td>
<td>245.54</td>
</tr>
<tr>
<td>Current (A)</td>
<td>110.54</td>
<td>245.54</td>
<td></td>
</tr>
<tr>
<td>F.S. (Ipm)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Hybrid Pulse

<table>
<thead>
<tr>
<th>Parameter Display</th>
<th>Avg. Voltage</th>
<th>RMS Voltage</th>
<th>RMS Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V)</td>
<td>22.24</td>
<td>22.74</td>
<td>344.17</td>
</tr>
<tr>
<td>Current (A)</td>
<td>155.32</td>
<td>344.17</td>
<td></td>
</tr>
<tr>
<td>F.S. (Ipm)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Soft Pulse

<table>
<thead>
<tr>
<th>Parameter Display</th>
<th>Avg. Voltage</th>
<th>RMS Voltage</th>
<th>RMS Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V)</td>
<td>22.45</td>
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<td>252.85</td>
</tr>
<tr>
<td>Current (A)</td>
<td>174.57</td>
<td>252.85</td>
<td></td>
</tr>
<tr>
<td>F.S. (Ipm)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.13 – Magnified Panasonic HMII 500 waveforms at 300 IPM.
Average Instantaneous Power was plotted against wire feed speed (Figure 5.14) as solid lines, with the simulated waveform data plotted as dotted lines for reference. The power for each of the three welds is slightly lower than the lowest simulated waveform (Simulated D), which was expected due to the similarity between the Panasonic HMII 500 power supply waveform and the Simulated D waveform.

![Graph showing Average Instantaneous Power vs. Wire Feed Speed for Simulated Pulse Parameters](image)

Figure 5.14 – Average Instantaneous Power vs. Wire Feed Speed for Simulated Pulse Parameters (linear trend lines used).

The heat input (based on AIP) vs. wire feed speed (Figure 5.15) shows a small difference between the 3 pulsing modes. The Hard Pulse waveform
produced the highest heat input, while the Soft Pulse waveform produced the lowest heat input on average. The Hybrid Pulse waveform actually crossed from the highest heat input at 100 IPM to the lowest heat input at 500 IPM. In comparison to the Simulated Waveforms, the heat input was generally low as was expected due to the similarity between the HMII 500 power supply waveforms and the Simulated D waveform.

![Graph showing heat input vs. wire feed speed](image)

**Figure 5.15 – Heat Input (based on AIP) vs. Wire Feed Speed for the Panasonic HMII 500 Power Supply (linear trend lines used).**

### 5.4.3 Dilution

Each weld made by the Panasonic HMII 500 was cross-sectioned and dilution was measured. Figure 5.16 shows the macro section map for the welds.
The bead shapes were very similar to those seen in the previous experiments. There was an overall increase in finger type penetration and wetting as wire feed speed is increased, but there is very little difference in bead shape for any one wire feed speed.

<table>
<thead>
<tr>
<th>WFS</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
</tr>
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<tbody>
<tr>
<td>Hard</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hybrid</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.16 – Macro section Map for the Panasonic HMII 500 Power Supply.

Figure 5.17 shows dilution for each weld. Similar to previous results, there was an overall increase in dilution as wire feed speed is increased, while there was very little difference in dilution for any one wire feed speed.
5.5 Conclusions

1. It was found that up to a 17% change in arc power and heat input were produced by non-optimized pulsing parameters. The bead shapes of these welds had significant differences that warrant further investigation into the effects of slew rates on penetration and dilution.

2. Inside of the GMAW-Pulse operating regime normally used by industry, very little if any change in bead shape, penetration or dilution could be seen as a result of the changes in pulsing parameters.
CHAPTER 6

FUTURE WORK

The results from the High Peak and Low Peak waveforms produced a significant difference in the bead shape of the welds. These differences were probably due to differences in rise rates, fall rates, peak current level, or some combination of the three. Further investigation into the effects of these parameters on bead shape, penetration and dilution are necessary to refine the findings of this work.

A second area where future work is warranted is in the area of transfer of pulsing parameters between two or more power supplies and/or configurations – dynamic parameter calibration. Many times it is necessary to transfer robust pulsing parameters between power supplies (i.e. replacement of an outdated machine, or starting a new product line). An example was seen in this research when trying to simulate parameters from commercially available power supplies. Simply using the same pulse parameters can cause problems since most power supplies have different electrical characteristics, and will not respond to the pulsing parameters in the same way. Separate welding configurations with the same power supply can also cause a similar effect due to electrical connection.
resistance and inductance. No literature to date has addressed this issue, and with the second generation of power supplies becoming cheaper and easily obtainable, this is rapidly becoming a major concern.
APPENDIX A

SPRAY TRANSITION CURRENT LEVELS FOR STEEL
<table>
<thead>
<tr>
<th>Wire Diameter (inches / mm)</th>
<th>Shielding Gas</th>
<th>Spray Transition Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.030 / 0.8</td>
<td>95% Argon – 5% O₂</td>
<td>145</td>
</tr>
<tr>
<td></td>
<td>98% Argon – 2% O₂</td>
<td>155</td>
</tr>
<tr>
<td></td>
<td>90% Argon – 10% CO₂</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>83% argon – 17% CO₂</td>
<td>170</td>
</tr>
<tr>
<td>0.035 / 0.9</td>
<td>95% Argon – 5% O₂</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>98% Argon – 2% O₂</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>90% Argon – 10% CO₂</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>83% argon – 17% CO₂</td>
<td>180</td>
</tr>
<tr>
<td>0.045 / 1.1</td>
<td>95% Argon – 5% O₂</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>98% Argon – 2% O₂</td>
<td>225</td>
</tr>
<tr>
<td></td>
<td>90% Argon – 10% CO₂</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>83% argon – 17% CO₂</td>
<td>250</td>
</tr>
</tbody>
</table>

Table A.1 – Spray Transition Current Levels for Steel. [*]
APPENDIX B

CALORIMETRY DATA
<table>
<thead>
<tr>
<th>Trial 1</th>
<th>Weight</th>
<th>Weight Lost</th>
<th>Minutes</th>
<th>Seconds</th>
<th>Total Time (s)</th>
<th>Change in Time</th>
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<td>12</td>
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<td>32</td>
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<td>19.72</td>
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<td>19.70</td>
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<td>0</td>
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<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td><strong>Average:</strong> 34.61</td>
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<table>
<thead>
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<th>Weight Lost</th>
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<th>Seconds</th>
<th>Total Time (s)</th>
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</tr>
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Table B.1 - Normal Evaporation Rate Data

88
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<th>Weight</th>
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<th>Minutes</th>
<th>Seconds</th>
<th>Total Time (s)</th>
<th>Change in Time</th>
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<td>66</td>
<td>34</td>
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<td>0.08</td>
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<td>50</td>
<td>170</td>
<td>34</td>
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<td>38</td>
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Table b.1 - Normal Evaporation Rate Data (continued)
<table>
<thead>
<tr>
<th>Name</th>
<th>Initial W (lb)</th>
<th>Final W (lb)</th>
<th>Change in W (lb)</th>
<th>Normal Change in W (lb)</th>
<th>Change Front Steel (lb)</th>
<th>E from Steel (J)</th>
<th>Theo, E (J)</th>
<th>Theo/Calc</th>
</tr>
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<td>1.18</td>
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<td>0.83</td>
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<td>6'-2</td>
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<td>0.77</td>
<td>69710.13</td>
<td>55988.06</td>
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<td>6'-3</td>
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<td>24.13</td>
<td>1.10</td>
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<td>0.75</td>
<td>67903.11</td>
<td>55448.68</td>
<td>0.82</td>
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<tr>
<td>12'-4</td>
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<td>27.44</td>
<td>1.74</td>
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<td>1.39</td>
<td>125727.90</td>
<td>110897.35</td>
<td>0.86</td>
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<tr>
<td>12'-5</td>
<td>3.46</td>
<td>25.34</td>
<td>1.70</td>
<td>0.35</td>
<td>1.35</td>
<td>122113.85</td>
<td>110260.01</td>
<td>0.90</td>
</tr>
<tr>
<td>12'-6</td>
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<td>23.36</td>
<td>1.66</td>
<td>0.35</td>
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<td>0.93</td>
</tr>
<tr>
<td>6'-7</td>
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<td>30.94</td>
<td>1.90</td>
<td>0.35</td>
<td>1.55</td>
<td>140184.10</td>
<td>145005.87</td>
<td>1.03</td>
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<tr>
<td>6'-8</td>
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<td>1.90</td>
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<td>1.55</td>
<td>140184.10</td>
<td>145005.87</td>
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<tr>
<td>12'-10</td>
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<td>23.96</td>
<td>3.48</td>
<td>0.35</td>
<td>3.13</td>
<td>282939.06</td>
<td>296541.49</td>
<td>1.06</td>
</tr>
<tr>
<td>6'-11</td>
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<td>199815.92</td>
<td>195537.79</td>
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<tr>
<td>6'-12</td>
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<td>2.21</td>
<td>199815.92</td>
<td>195537.79</td>
<td>0.98</td>
</tr>
<tr>
<td>12'-13</td>
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Table B.2 –Liquid Nitrogen Calorimeter Calibration Data
APPENDIX C
DATA ACQUISITION CALIBRATION DATA
<table>
<thead>
<tr>
<th>Voltage(channel 1)</th>
<th>Current (channel 2)</th>
<th>Trigger (channel 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 division = 20V</td>
<td>1 division = 300 A</td>
<td>5 volt trigger signal indicates</td>
</tr>
<tr>
<td>2 divisions = 40V</td>
<td>2 divisions = 600A</td>
<td>beginning of data acquisition</td>
</tr>
</tbody>
</table>

Figure C.1 – Test Verification at 100 IPM Travel Speed.
Voltage (channel 1)  |  Current (channel 2)  |  Trigger (channel 3)
1 division = 20V   |  1 division = 300 A   |  5 volt trigger signal indicates beginning of data acquisition
2 divisions = 40V  |  2 divisions = 600A   |  

Figure C.2 – Test Verification at 400 IPM Travel Speed.
<table>
<thead>
<tr>
<th>Voltage (channel 1)</th>
<th>Current (channel 2)</th>
<th>Trigger (channel 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 division = 20V</td>
<td>1 division = 300 A</td>
<td>5 volt trigger signal indicates</td>
</tr>
<tr>
<td>2 divisions = 40V</td>
<td>2 divisions = 600A</td>
<td>beginning of data acquisition</td>
</tr>
</tbody>
</table>

Figure C.3 – Test Verification at 250 IPM Travel Speed.
Voltage(channel 1)  | Current (channel 2)  | Trigger (channel 3)
---|---|---
1 division = 20V | 1 division = 300 A | 5 volt trigger signal indicates
2 divisions = 40V | 2 divisions = 600A | beginning of data acquisition

Figure C.4 – Test Verification at 600 IPM Travel Speed.
<table>
<thead>
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<th>Voltage (channel 1)</th>
<th>Current (channel 2)</th>
<th>Trigger (channel 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 division = 20V</td>
<td>1 division = 300 A</td>
<td>5 volt trigger signal indicates beginning of data acquisition</td>
</tr>
<tr>
<td>2 divisions = 40v</td>
<td>2 divisions = 600A</td>
<td></td>
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Figure C.5 – Test Verification at 100 IPM Travel Speed.
<table>
<thead>
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<th>Voltage (channel 1)</th>
<th>Current (channel 2)</th>
<th>Trigger (channel 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 division = 20V</td>
<td>1 division = 300 A</td>
<td>5 volt trigger signal indicates</td>
</tr>
<tr>
<td>2 divisions = 40V</td>
<td>2 divisions = 600A</td>
<td>beginning of data acquisition</td>
</tr>
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</table>

Figure C.6 – Test Verification at 400 IPM Travel Speed.
<table>
<thead>
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<th>Steel</th>
<th>.023, .030, .035, .045, .063</th>
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</thead>
<tbody>
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<td>.030, .035, .045, .063</td>
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<td>4043 Al</td>
<td>.023, .030, .035, .045, .063</td>
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<tr>
<td></td>
<td>5356 Al</td>
<td>.023, .030, .035, .045, .063</td>
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<tr>
<td></td>
<td>SiB</td>
<td>.023, .030, .035, .045</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power Supply B</th>
<th>Steel</th>
<th>1/16</th>
<th>Ar-O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>.035</td>
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</tr>
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<tr>
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</tr>
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<tr>
<td>SiB</td>
<td></td>
<td>.035</td>
<td>Ar</td>
</tr>
</tbody>
</table>

| Power Supply C | .035 Steel, Ar-O | .045 Steel, Ar-O |
|               | .035 Steel, Ar-CO2 | .045 Steel, Ar-CO2 |
|               | .035 309, Ar-CO2 | .045 309, Ar-CO2 |
|               | 3/64 5356 Al, Ar | .035 SiB, Ar |

| Power Supply D | Stainless/ Cr alloy | .035, .045, 1/16 |
|               | Steel |     |
|               | Soft Al |     |
|               | Hard Al |     |

Table D.1 - Available Syneric Algorithms for Each Power Supply
APPENDIX E

POWER SUPPLY WAVEFORM DATA
<table>
<thead>
<tr>
<th>WFS</th>
<th>Peak Current (amps)</th>
<th>Power Supply A</th>
<th>Power Supply B</th>
<th>Power Supply C</th>
<th>Power Supply D</th>
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</thead>
<tbody>
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<td>333</td>
<td>350</td>
<td>440</td>
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</tr>
<tr>
<td>200</td>
<td>343</td>
<td>375</td>
<td>420</td>
<td>522</td>
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</tr>
<tr>
<td>300</td>
<td>330</td>
<td>413</td>
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<td>527</td>
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</table>

<table>
<thead>
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<th>WFS</th>
<th>Pulse Width (milliseconds)</th>
<th>Power Supply A</th>
<th>Power Supply B</th>
<th>Power Supply C</th>
<th>Power Supply D</th>
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<table>
<thead>
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<th>Background Current (amps)</th>
<th>Power Supply A</th>
<th>Power Supply B</th>
<th>Power Supply C</th>
<th>Power Supply D</th>
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<table>
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<th>WFS</th>
<th>Frequency (hertz)</th>
<th>Power Supply A</th>
<th>Power Supply B</th>
<th>Power Supply C</th>
<th>Power Supply D</th>
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Table E.1 Pulse Parameters for each Power Supply
LIST OF REFERENCES


