WELD ALLOYING IMPROVEMENT WITH SQUARE TYPE CURRENT WAVES ON ALTERNATING-CURRENT TUNGSTEN-ARC INERT-GAS-SHIELDED WELDING

by

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I. INTRODUCTION

This study was undertaken to establish the degree of alloying of aluminum and an aluminum-silicon alloy into a fusion weld by the alternating-current tungsten-inert-gas-shielded arc using various current wave shapes. The work was with the fusion welded closure of an aluminum-silicon alloy bonded aluminum-clad uranium-metal fuel element. Wave shapes from an asymmetric amplitude and 180 degrees out of phase third harmonic distorted sine wave to a virtually square symmetrical wave were used in the study. In addition, the study was to establish for the optimum current wave shape, the open-circuit voltage that would produce a stable arc without superimposed continuous high-frequency current stabilization. From the data developed in the study it would then be possible to select the most desirable current wave shape and open-circuit voltage for the design of future alternating-current welding power supplies.

From previous studies it has been determined that the wave shape of the alternating welding current influences the degree of alloying. In addition, the use of series current wave balancing capacitors was shown to be beneficial by increasing the power in the reverse polarity half cycle (6, p. 36). The end result of these effects was the maintaining of a more uniform temperature in the weld.

All previous work was performed with an Alcoa 1100 alloy aluminum cladding and a modified[1] Alcoa A-13 (AlSi) alloy braze. Since the previous studies were reported, the

[1] The exact composition of the brazing alloy, the limits of each element in the alloy and the assembly techniques are Atomic Energy Commission Confidential Classified information.

aluminum cladding has been changed to an Alcoa X-8001 which contains approximately one per cent nickel and the addition of nickel to the brazing metal. The nickel additive makes homogeneous alloying much more difficult and the combined alloys in the weld have a tendency to crack at the closure point (7, p. 24).

II. ELECTRIC ARC PHENOMENA

The electric arc is composed of very complex phenomena. In arc welding there are very few of the phenomena which affect the welding or are of major interest. Arc welding of all types employs a high pressure arc starting at essentially a point and ending on a plane. The polarity of the point to plane arc determines its shape and thus the heat concentration on the plane or work piece.

With the point or electrode negative and the work piece positive the arc has a hemispherical shape (6, p. 15), Figure 1, producing a small very intensely heated spot on the work piece from electron bombardment (5, p. 343).

When the electrode is positive and the work piece negative, the arc has a cone shape (6, p. 15), Figure 2, producing a broad low intensely heated spot from positive ion bombardment (5, p. 302), exclusive of the intensely heated cathode spot which has a very small portion of the total energy. Considerable material is removed from the solid surface of the work piece by positive ion bombardment. The areas from which surface material is being removed from the solid metal is shown as the bright spots in Figure 2. In the welding of the highly reactive metals such as aluminum, magnesium and similar metals, advantage is taken of the cathode sputtering produced on solid metal by the positive ion bombardment, to remove surface oxides and produce a cleaner weld with uniform penetration. The oxides act as a thermal barrier (6, p. 15-22).

The electrical characteristics of a constant length arc in a particular gas (16, p. 298-S) and with a finite current are determined by the electrode materials, relative electrode dimensions and the polarity in relation to the electrode dimensions. If the electrode is tungsten and the work piece is aluminum with a shielding gas of five parts by volume of argon to seven of

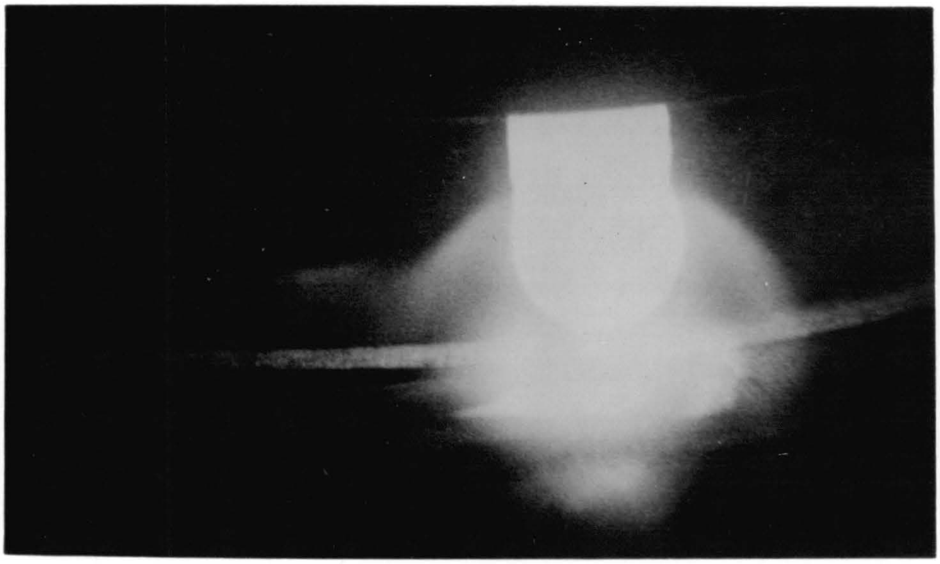


FIGURE 1

Arc Shape with Electrode Negative

165 amp, 5/32" zirconium-tungsten electrode
5-7 argon-helium volume gas ratio, balanced current

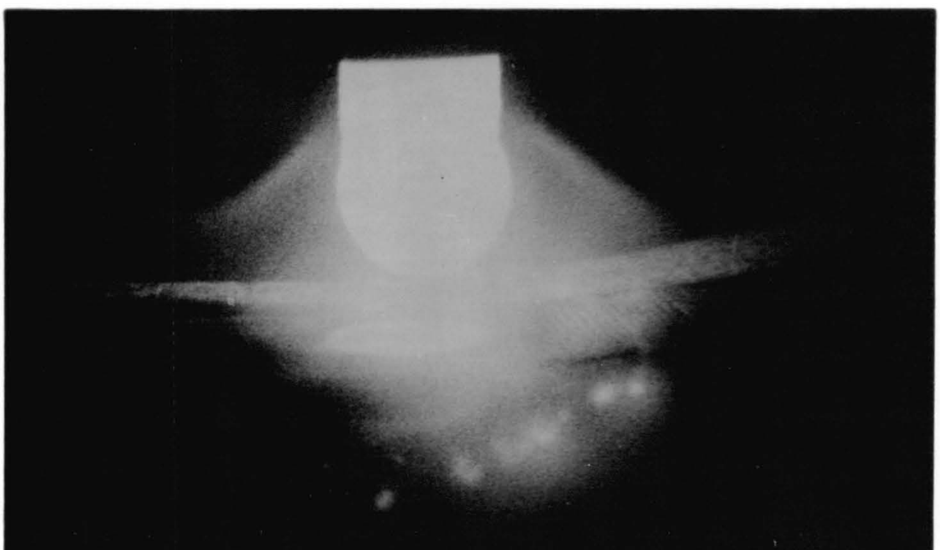


FIGURE 2

Arc Shape with Electrode Positive

helium for a capacitor balanced square wave of current of 200 amperes RMS the arc drop will be 8 volts with the electrode negative and the work piece positive. With the electrode positive and the work piece negative the arc drop will be 20 volts. If the capacitors are removed, the current, during the half cycle the electrode is positive, will be small compared to when the electrode is negative, Figure 23. This phenomenon is called rectification in welding.

Rectification is ever present (1, p. 521) when arc welding with alternating current even though the electrode and work piece are of the same material, the difference in physical dimensions will affect the electron emission relationship between them. The use of series capacitors (19) in the welding current circuit is the common method of eliminating rectification. Rectification has two effects on welding and its associated equipment. The first is the reduction of energy in the half cycle when the electrode is positive. The second is the saturation effect on the magnetic cores in the welding power supply. This is particularly so in the saturable reactor type units (7, p. 22).

In an electric arc the heat generated at the positive end is approximately twice that generated at the negative end when the negative electrode is a refractory material (1, p. 521). In addition the unit energy density at the cathode, excluding the cathode spot, is low due to the large area covered. Therefore, in the case of the tungsten-alternating-current arc in which there is rectification, the half cycle the work piece is negative is essentially eliminated as a heat source.

At the end of each half cycle in an alternating-current arc there is a very brief period in which the current may be zero depending on the rate of rise of the reversing voltage and the external circuit constants. During this period the ionization is decreasing which decreases the conductivity of the arc column. In addition the temperature of the new cathode is dropping rapidly. As the voltage reverses, the arc conductivity that existed just before the instant of zero current must be re-established. Also the polarities of the space charges that exist at the old anode and cathode must be reversed. The voltage to re-ignite the arc is consequently higher than the arc burning voltage. The process of re-ignition may be considered as a race between the rising recovery voltage and the forces of de-ionization and temperature drop (17, p. 1398), (18, p. 413). The potential drop at the start of the re-ignition period is largely concentrated in the space adjacent to the new cathode, the major portion of the arc being free of potential gradient (10, p. 926). This is caused by the cathode spot being thermal electron emission limited. In a circuit with a high ratio of inductance to resistance, arc re-ignition is improved, for at zero current the voltage approaches a maximum and the distributed capacitance in the inductance can cause the recovery voltage to reach a peak value double that of the open-circuit voltage (3, p. 854), (10, p. 926). This rise of voltage is shown in Figure 23 in which the restrike potential is 125 volts for an 80 volt RMS sine wave open-circuit potential which produces a maximum potential of 113 volts. The use of high values of inductance that produce time constants of more than one half second adversely affects the programming of short weld cycles.

As the recovery voltage reverses and the current passes through zero the forces of de-ionization, temperature drop, neutralization and reversal of the space charges at the electrode surfaces cause the arc to re-establish always as a glow discharge requiring a higher arc voltage than for the true arc (5, p. 355). At the transition from the glow discharge to the true arc, the arc voltage drops suddenly to that required for the true arc. The transition is shown as a discontinuity in the current trace just after the current passes through zero as the electrode becomes positive, Figures 23-35.

In welding with the tungsten-inert-gas-shielded arc the problem of arc re-ignition becomes very critical when the work piece is aluminum with its high thermal conductivity. The arc restrikes at a low voltage when the tungsten is negative because of the refractory nature and high electron emission characteristic of tungsten. The arc restrikes at a high voltage when the aluminum is negative because of the high thermal conductivity and low thermal electron emission characteristics of aluminum. This is shown in Figure 23 with the high value of restrike voltage with its wide separation when the electrode goes positive. Figure 3 shows a family of curves taken on an unbalanced current unit which has an open-circuit voltage, the voltage before the arc is ignited, that is sinusoidal and a sinusoidal welding current, Type III. The electrode was pure tungsten, the work piece aluminum and argon shielding gas. In this case the 100 volts was not enough to produce positive arc re-ignition and 150 volts was just on the safe side. If the voltage is not high enough to equal or exceed the voltage to restrike the arc when the electrode is positive, the arc will then go out or conduct only when the electrode is negative (6, p. 29). In addition, as the welding current approaches zero a similar condition exists and a glow discharge will form if the recovery voltage is not high enough or if the cooling and deionization rates are too high.

As the sine current wave is distorted toward a narrow high peaked wave by a high value of 180 degrees out of phase third harmonic, the open-circuit voltage required for positive arc re-ignition increases to 165 volts. Conversely as the sine current wave is distorted towards a square wave the open-circuit voltage required for positive arc re-ignition decreases.

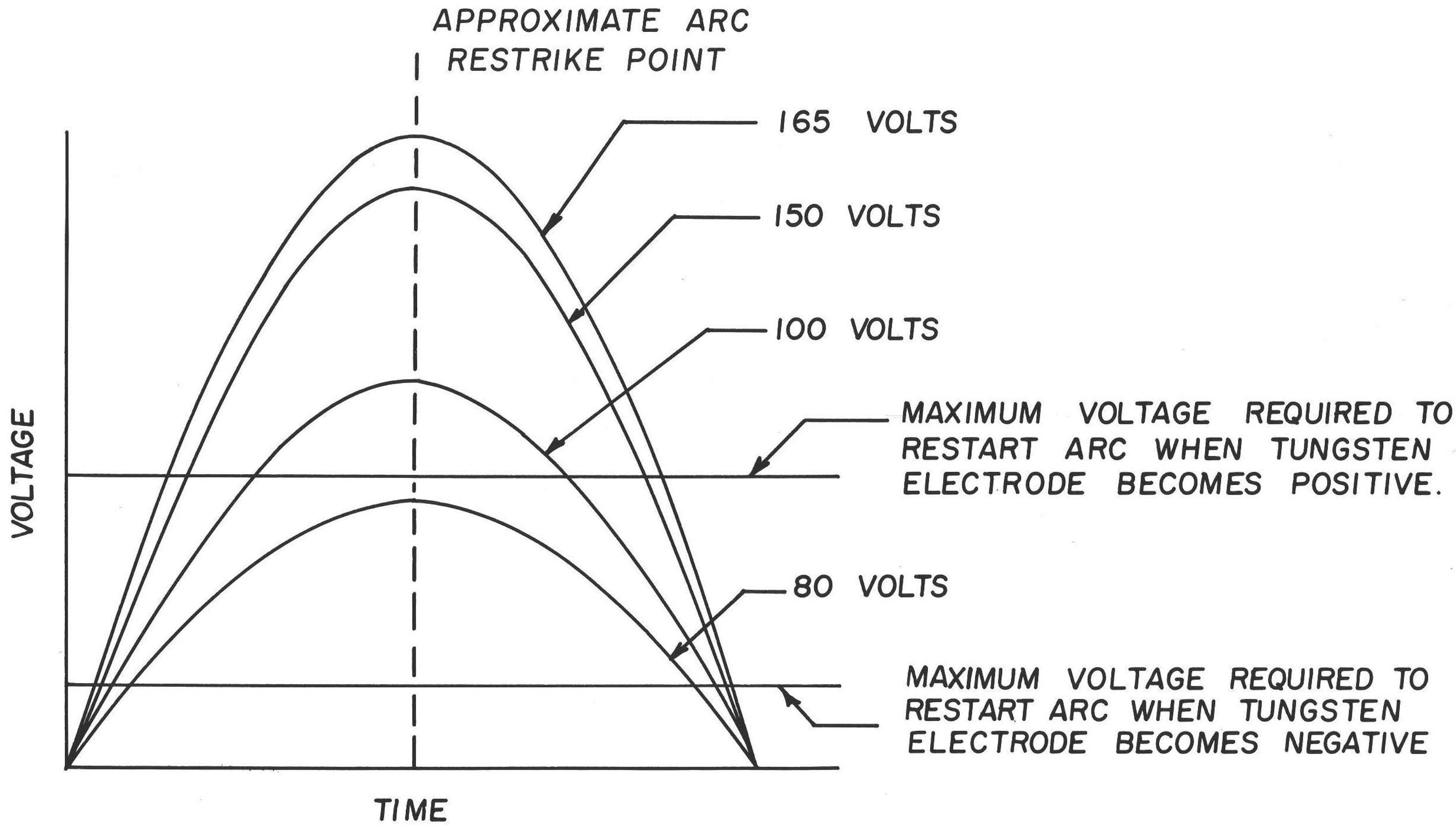


FIGURE 3

Transformer Voltage Characteristics

III. FUSION WELD CLOSURES

In Figure 4 is shown the unwelded type of male and female closures of the alsi-bonded aluminum-clad uranium-metal fuel element used in the study. A section through the zone to be fusion welded is shown in Figure 5.

It is desirable, from a corrosion and dependability standpoint, to produce a weld that is completely alloyed in all its portions and free of voids, pipes and cracks. Shown in Figure 6 is a weld section with the desired alloying. In addition, fine surface smoothness and uniform weld width are also required. A pair of welds removed from the ends of a randomly selected single fuel element is shown in Figure 7.

In order to have a uniform base on which to determine weld quality, all welds were made with the same width across the end, overhang over the cladding wall, and depth down the cladding wall.

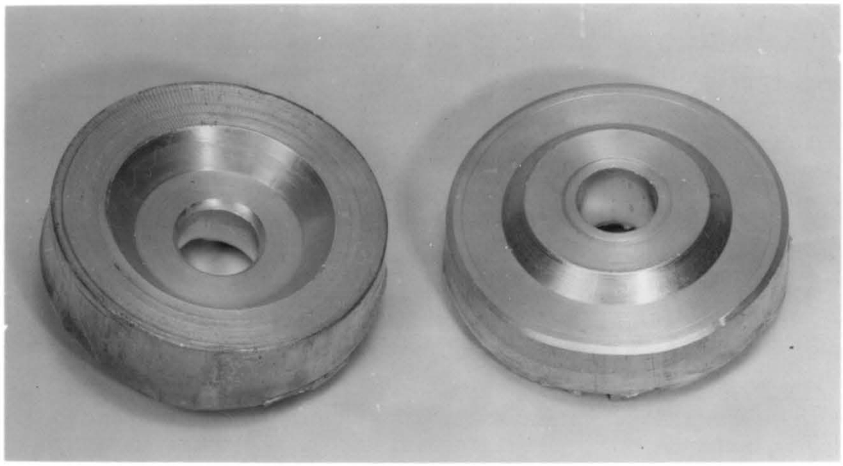
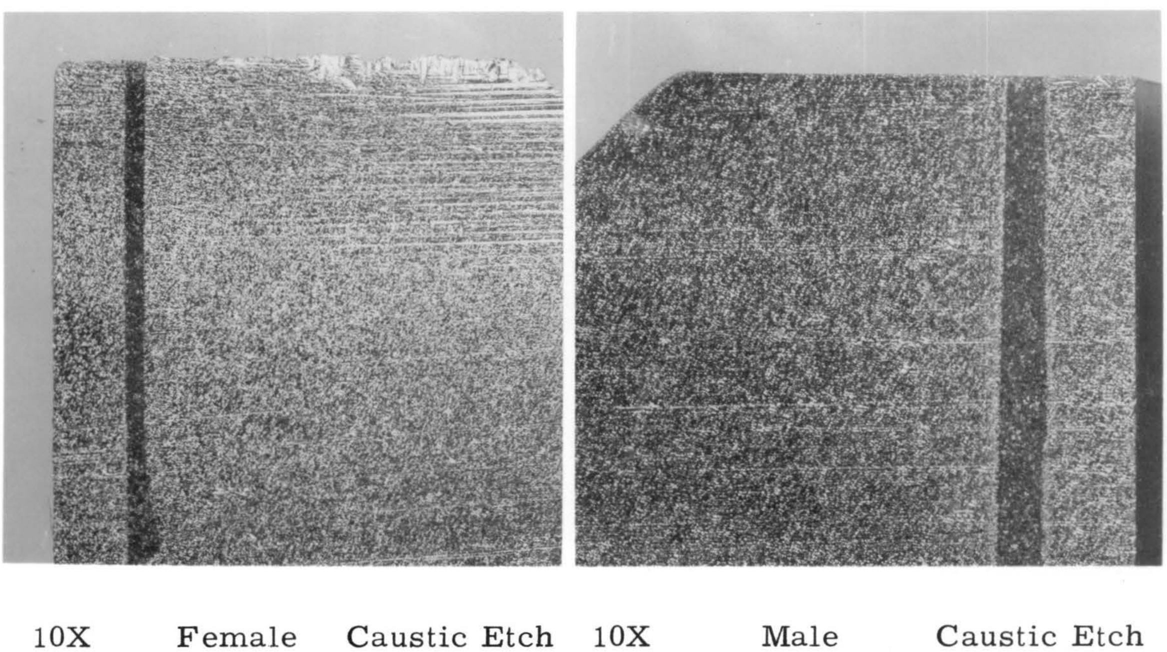


FIGURE 4

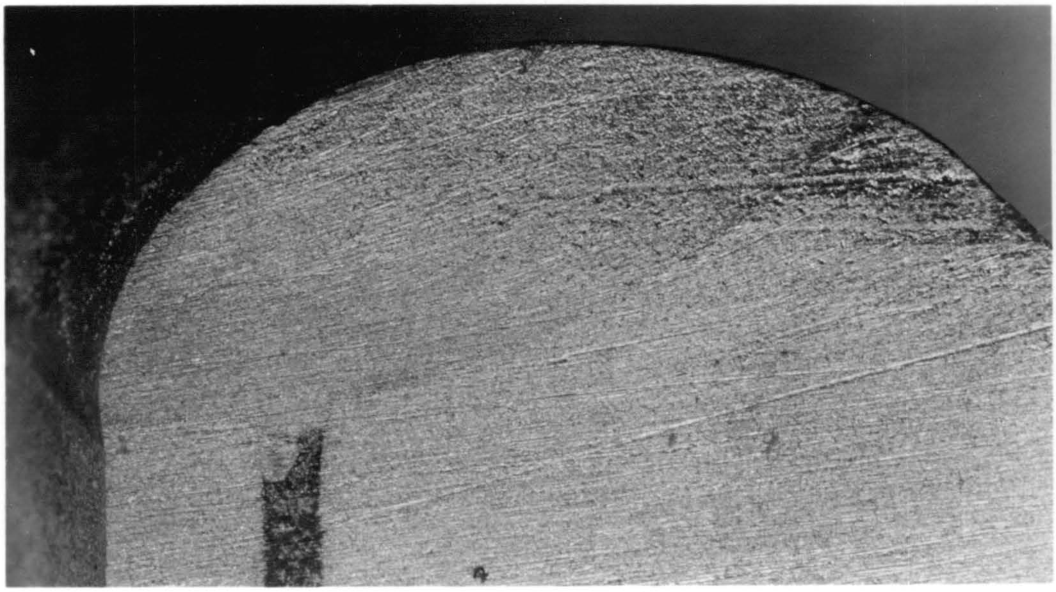
1-1/4X Unwelded Closures



10X Female Caustic Etch 10X Male Caustic Etch

FIGURE 5

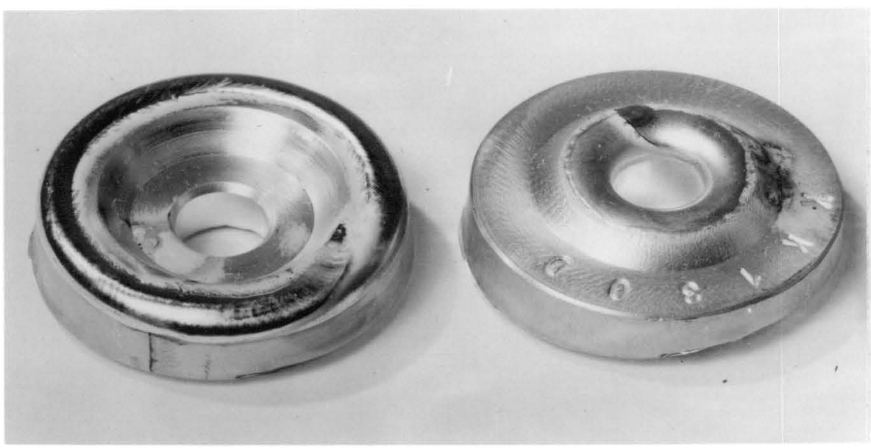
Unwelded Closure Sections



20X Caustic Etch

FIGURE 6

Weld Section with Desirable Alloying



1-1/4X

FIGURE 7

Welded Closures

IV. SHIELDING GASES

A 5-7 argon-helium volume ratio was used for all the tests, with the same flow rate being maintained for all welds. This ratio was selected on the basis of weld alloying improvement, depth to width ratio increase, cleanliness of the weld surface and increased welding speed as compared to argon.

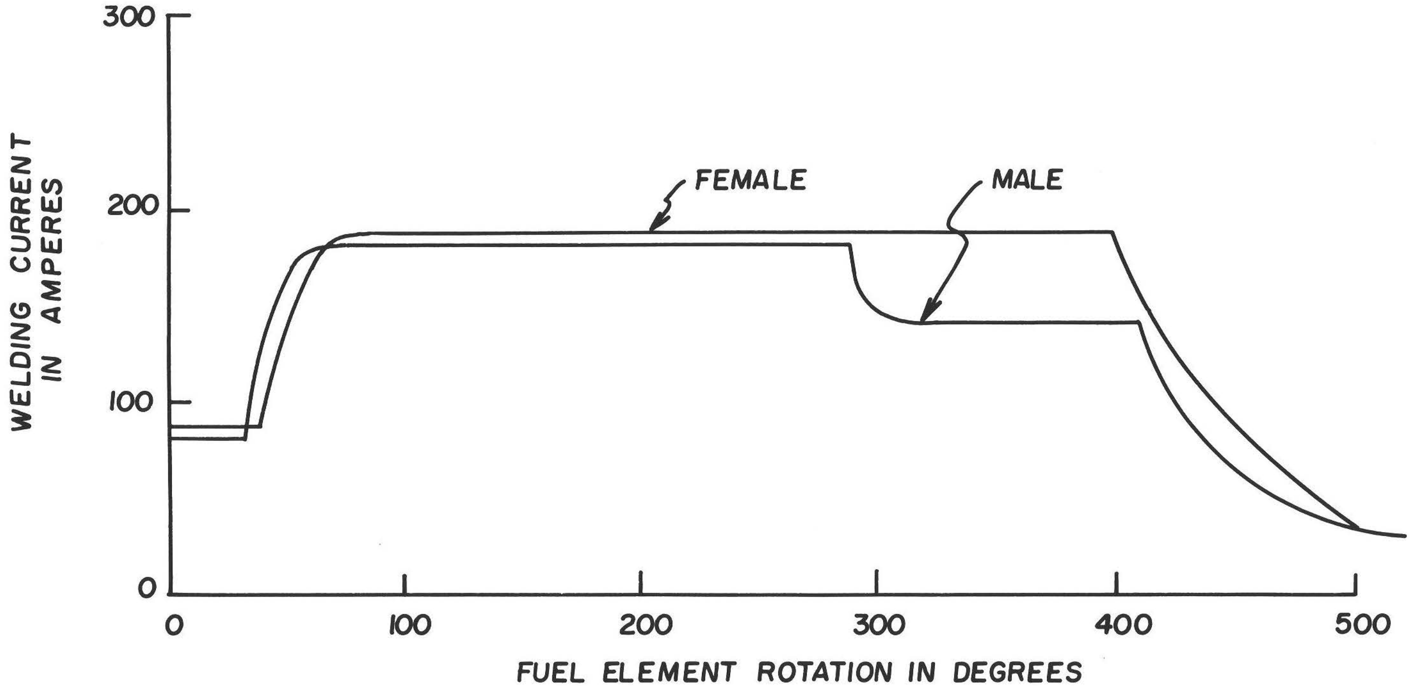


FIGURE 8

Semi-Automatic Welding Machine Current Programs

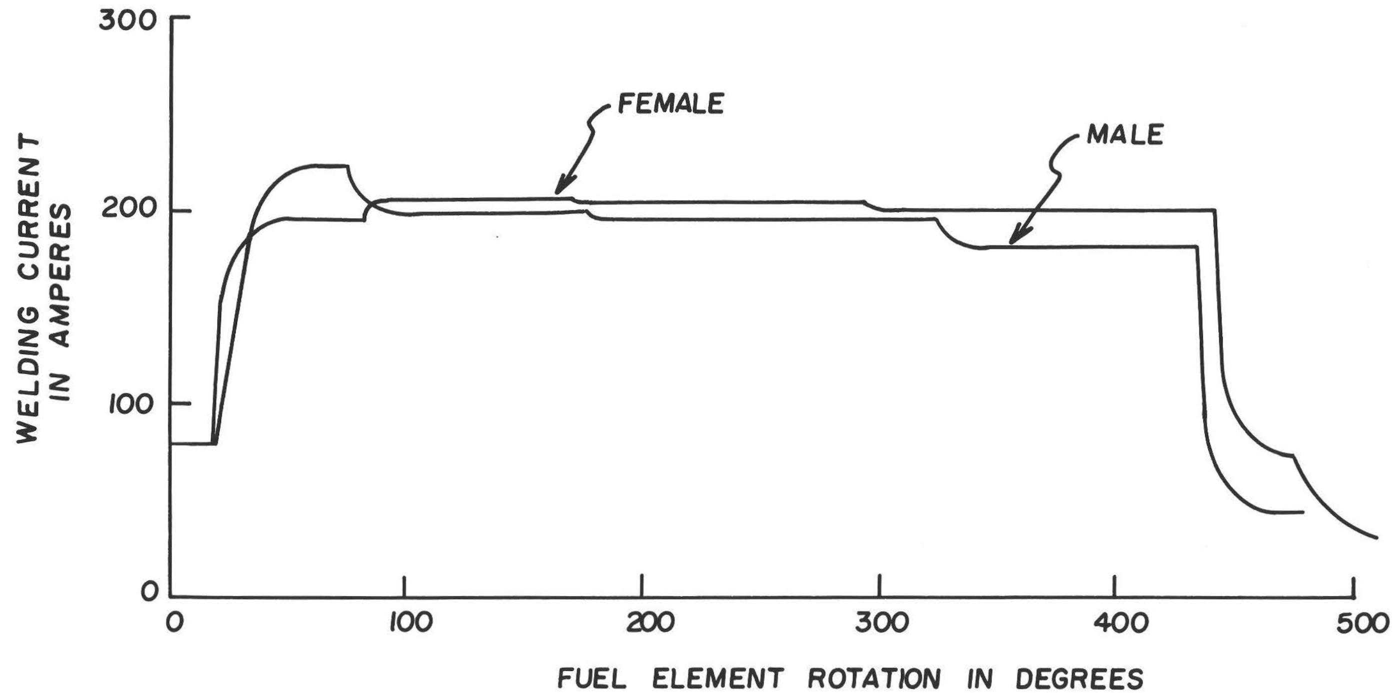


FIGURE 9

Fully Automatic Machine Welding Current Programs

V. WELDING CURRENT

The welding machines and power supplies available for performing the tests were developed over a period of years and varied from a semi-automatic machine in which the operator placed the work piece in a fixture and pressed the button to initiate the welding cycle to fully automatic machines in which the work pieces are conveyorized in for welding and out after welding. The semi-automatics were originally designed without current programming and had a current decay at the end of the weld. These units were subsequently modified to produce the current programs shown in Figure 8. The fully automatics were designed with seven steps of current programming in order to produce smooth arc starting, a weld of uniform dimensions and a closure point of the same dimension as the weld. The current programs are shown in Figure 9.

The current programs for Type I and II current waves, Figure 10, started at full welding current and near the closure point of the weld an air operated device was actuated to decay the current rapidly. For the Type III current wave the programs are shown in Figure 8, while for the Type IV to XI inclusive, the current programs are shown in Figure 9.

VI. CURRENT WAVE SHAPES

From previous work (6, p. 53-55) (7, p. 3) (8, p. 25-30) it has been established that there is definitely a relationship between the alloying produced in a fusion weld closure of an alsi-bonded aluminum-clad uranium-metal fuel element and the current wave shape of the alternating current used to produce it. In order to obtain as broad a sampling as possible, current wave shapes from all but two types of welding power supplies tested were used for comparison. Types I and II were not used in this test as previous work indicated that they were completely unsatisfactory (6, p. 41-46). The types of current wave shapes used in this and the previous tests are shown in Figure 10.

The Type I current wave is produced by the commercially available saturable reactor type units without current wave balancing.

The Type II current wave is produced by using series current balancing capacitors in the welding current circuit of the unit used for Type I.

The Type III current wave is produced by the commercially available moveable coil type units with series current balancing capacitors.

The Type IV current wave is produced by custom designed and fabricated units with series current wave balancing capacitors.

The Types V to XI current waves inclusively are produced by custom designed and fabricated units with series current wave balancing capacitors.

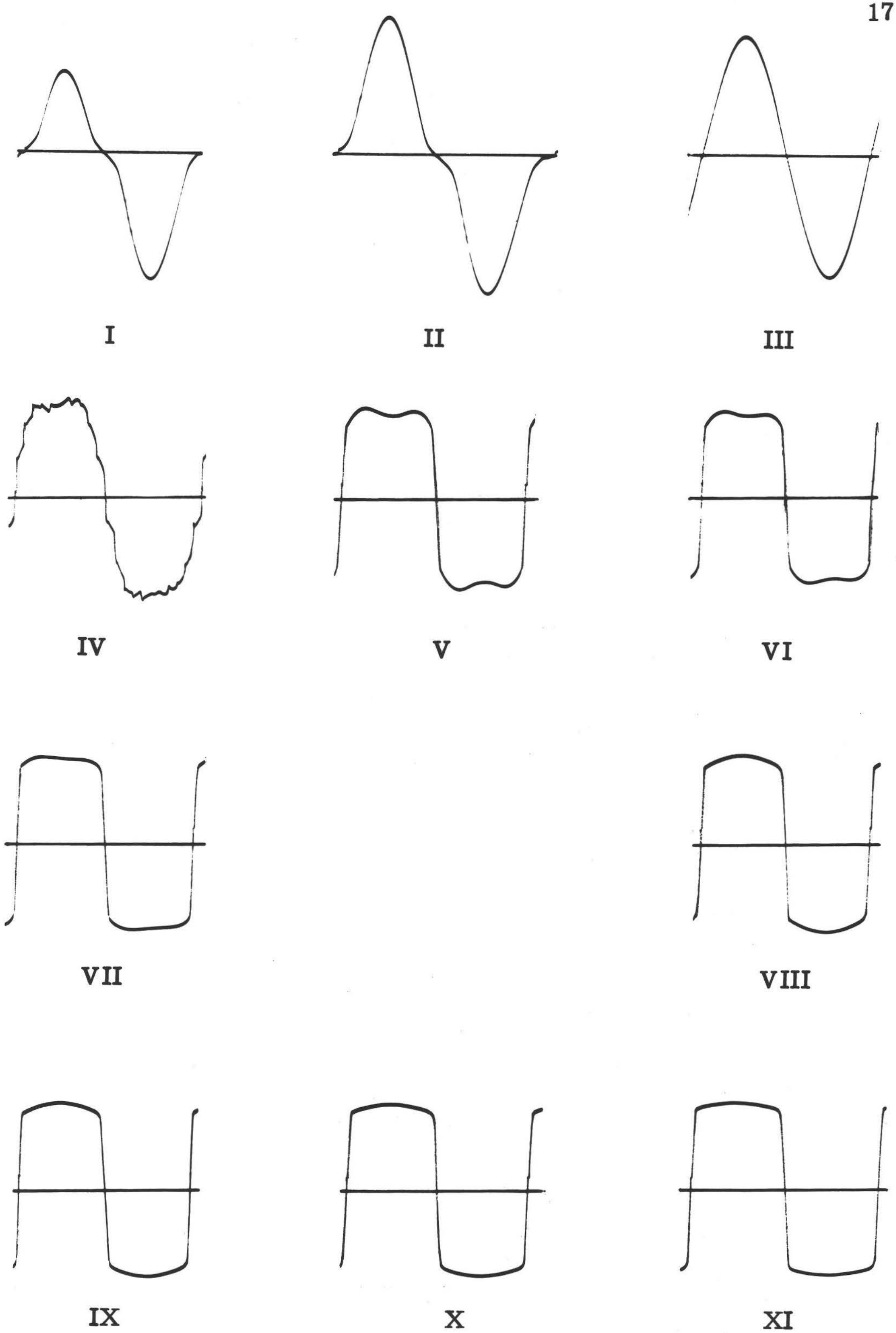


FIGURE 10

Current Wave Shapes Investigated

For all saturable reactor type devices the current wave shape appears to change as the current changes from minimum to maximum or maximum to minimum. The wave shape that occurs at minimum current becomes the crest of the wave as the current is increased. In Figure 11 is shown the variation in current wave shape of a wave similar to the Type VII wave with the current varying from minimum to maximum. If all of the ordinates were to the same scale, the exact ordinates of the 35 ampere wave would appear on the crest of the 300 ampere wave. This means that as the amplitude of a square wave increases the form factor approaches unity. The maximum current wave shape apparent variation can be reduced by using shorter and/or multiple current ranges. The current range below 100 amperes was used in arc starting and crater filling and produced no adverse effect on weld quality.

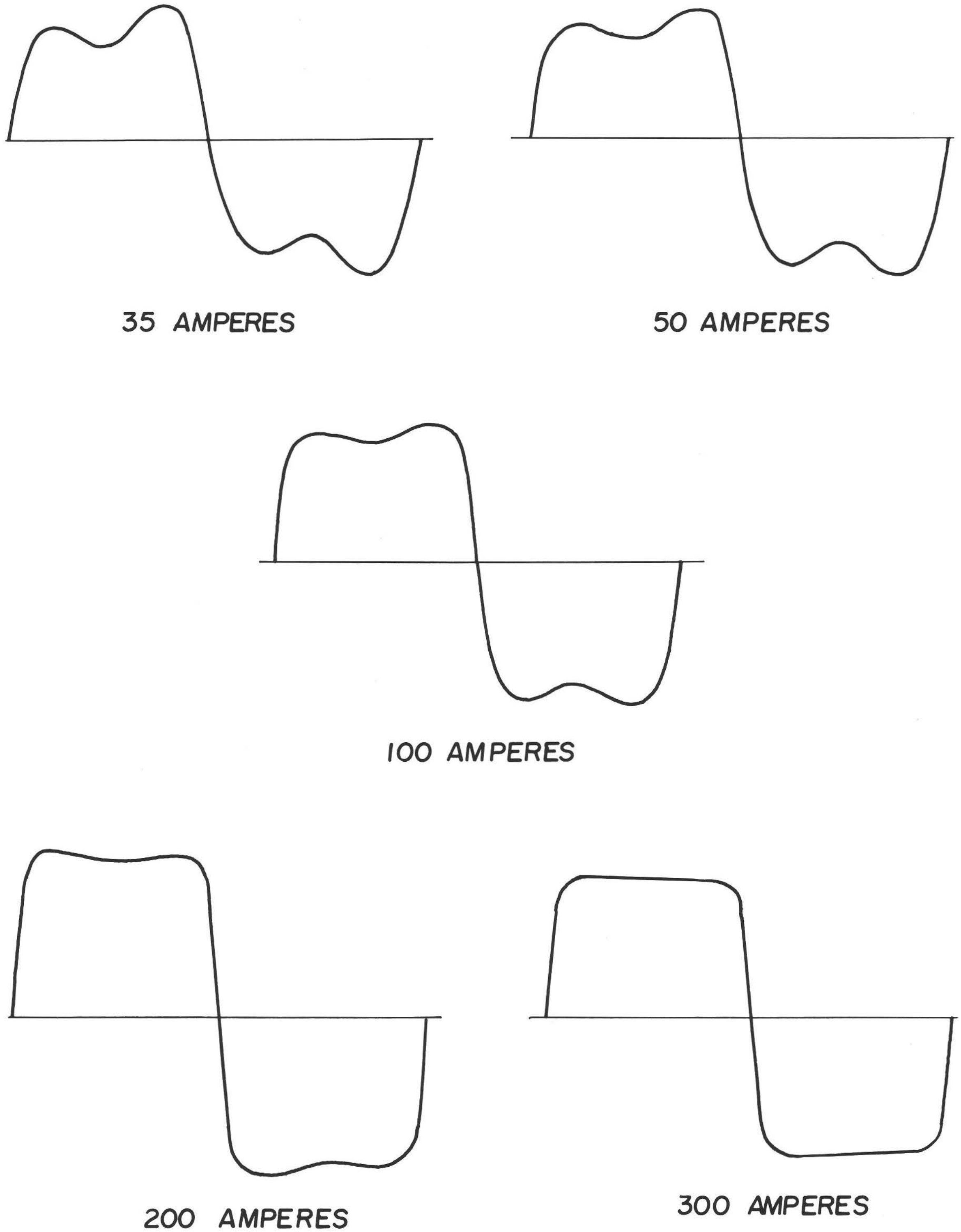


FIGURE 11

Type VII Current Wave Shape Variation
with Change in Current

VII. WELD CLASSIFICATION

The following weld classification system was developed in order to be able to place a numerical value on the weld quality of a sample lot of 100 welded closures from one end of a fuel element. The 100 welded closures are sectioned through the end of the crater filling period, polished with 240X grit belt and caustic etched. This produces 400 welds for classification purposes.

To each class is assigned a digit equal to the class number. The largest digit, 5, was assigned to Class V welds so that a slight change in the number of the poorest welds would produce the greatest change in the weld quality number. Upon completion of reading the total weld section surfaces, the total of each class is multiplied by the assigned digit. These totals are added and the new total is divided by the number of classes. The division by the number of classes reduces the weld quality number to a smaller more easily handled number. The quotient produced is a measure of weld quality; the smallest number possible being 80 for all perfect welds, and the largest number 400 for all bad welds. In all welds there must be no evidence of reduction of the residual cladding thickness by the welding.

CLASS I. Excellent. A weld in which the alloying throughout the weld section is complete and there is no evidence of localized silicon concentration in the weld or heat affected zone, Figure 12.

CLASS II. Good. A weld in which there is complete alloying in the weld from the braze to the surface of the weld equal to the thickness of the residual can or tube cladding. There may be points of localized silicon concentration as long as the incremental in line total of complete alloying is equal to the residual cladding thickness, Figure 13.

CLASS III. Fair. The same as Class II except that the incremental in line total must be at least one-half the residual cladding thickness, Figure 14.

CLASS IV. Poor. The same as Class III except that the incremental in line total must be less than one-half of the residual cladding and must be greater than 0.005 inches. In addition, this class includes all welds in which there is a continuous path of decreasing silicon concentration from the braze to the surface of the weld. This path must become invisible at the surface of the weld, Figure 15.

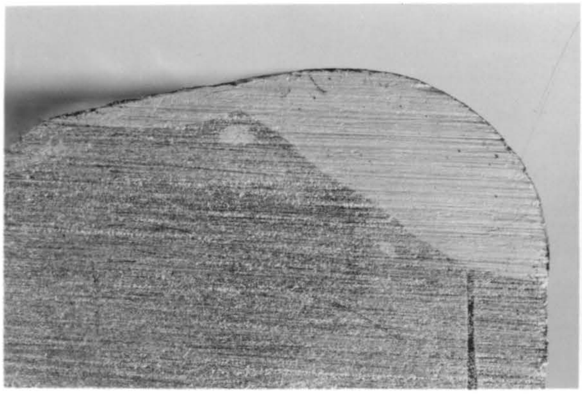
CLASS V. Bad. A weld in which there are: 1, massive areas of silicon concentration that are continuous from the braze to the surface; 2, continuous path of silicon concentration from the braze to the weld surface; or 3, in which 1 and 2 come to 0.005 inches or less of the weld surface, Figure 16.

CLASS VI. Internal Cracks. Cracks occurring in the interior of the weld at mainly the closure point and not being visible on the weld surface, Figure 17.

CLASS VII. Spots. Localized high silicon spots occurring on the surface of the weld and extending to the braze in a continuous column, Figure 18.

CLASS VIII. High Silicon Quarters. Where the spots are so close together that it is impractical to count them. They are classified on nearest fourth of the circumferential weld distance they cover.

Classes VI and VII are not included in the calculations as their frequency of occurrence is very erratic compared to other classes. Class VIII was not included as it occurred only in the second group of material.



10X Caustic Etch

FIGURE 12

Class I Weld

10X Caustic Etch

FIGURE 13

Class II Weld

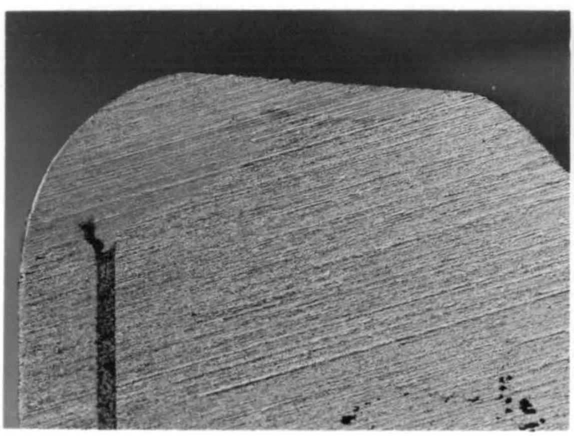


FIGURE 14

Class III Weld

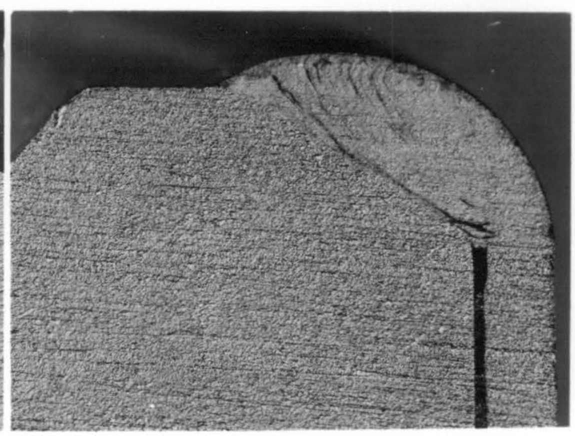
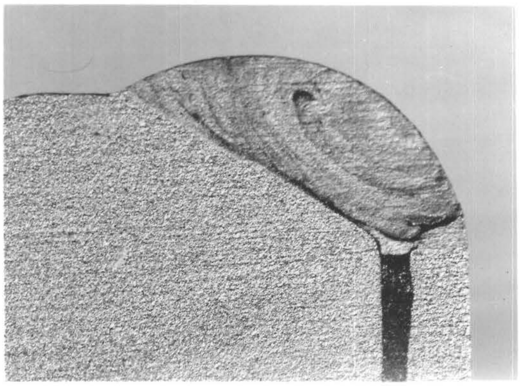


FIGURE 15

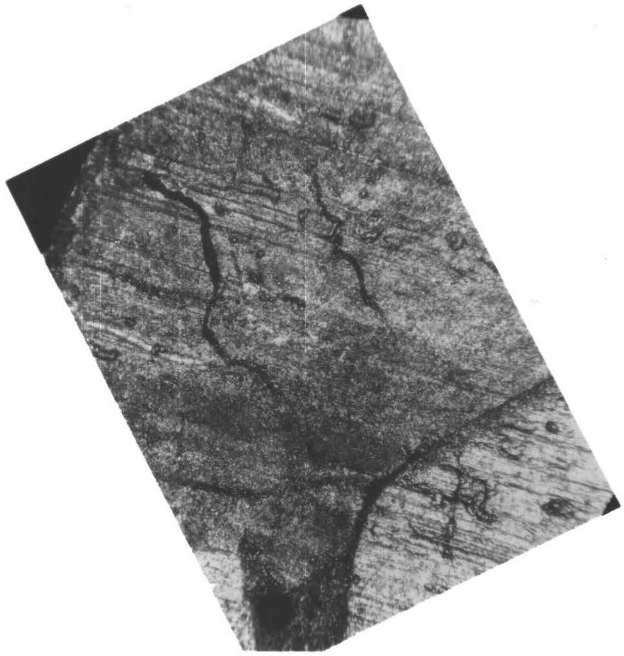
Class IV Weld



10X Caustic Etch

FIGURE 16

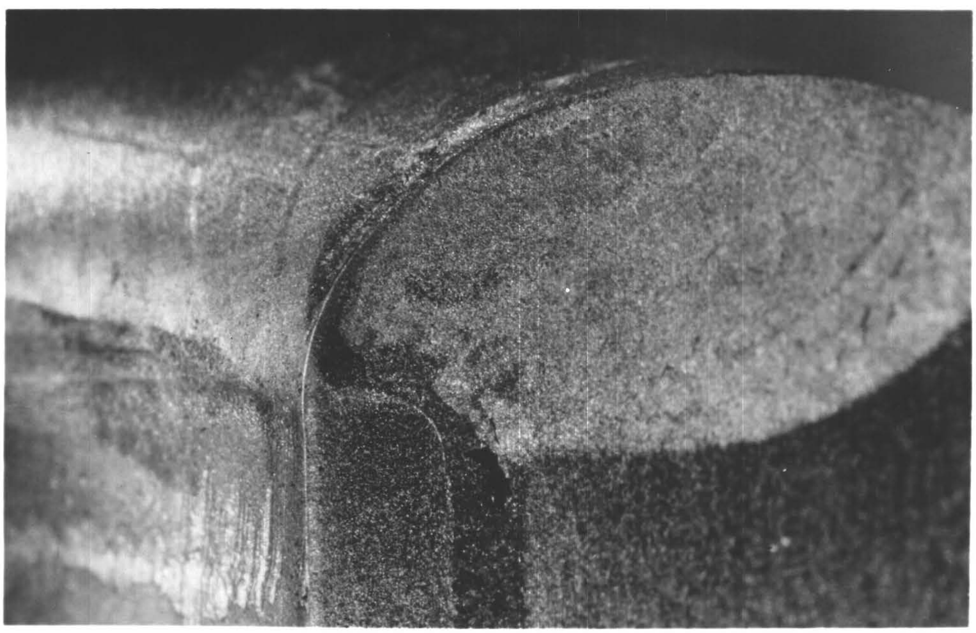
Class V Weld



50X Caustic Etch

FIGURE 17

Class VI Weld



20X Caustic Etch

FIGURE 18

Class VII Weld

VIII. CURRENT WAVE SHAPE EVALUATION

The assembly process of AlSi-bonded aluminum-clad uranium-metal fuel elements is a very complex process which is Atomic Energy Commission Classified Confidential. There are many factors that affect the quality and analysis of the braze. In canning a group of material for some finite test it is virtually impossible to control all of the factors that affect the particular condition being studied. Statisticians have studied the assembly process intensively and have come to the conclusion that it is virtually impossible to apply statistics to the findings of a welding test and give the result any real meaning.

Due to reasons beyond control, it was not possible to obtain enough identical uranium cores for testing so that all of the required pieces could be canned at the same time with the same equipment and crews. In addition to the finished material required, enough uranium cores must be started through the preparation process to take care of the shrinkage occurring at preparation, canning and facing.

On the basis of the foregoing a decision was made to can the material for the test in two groups.

To further complicate the problem, though its extent was not known at the time, the cladding material had been changed recently from 1245 alloy, which is essentially pure aluminum, to X-8001 which contains approximately one per cent nickel. It was known at this time that the addition of nickel to the aluminum made the alloying in the weld more difficult but nothing was known of the effect of varying concentrations. With the 1245 cladding all of the machining scraps were converted into A-13 brazing metal. This practice was continued with the advent of the X-8001 cladding material which increased the nickel content in the braze metal.

The first canning group of material produced good welds and normal weld quality correlation with known current wave shapes.

In Table I is shown the variation in quality of the mating surfaces of a group of Type IV current wave weld sections from canning No. 2 indicating that the weld quality correlation around a single weld and throughout a lot is not good and that the male weld is more difficult to produce than the female (8, p. 28-30). Throughout the second canning group there was no complete over-all weld quality correlation and some of the data reversed known relationships.

In the reading of the weld sections it was discovered that there was a difference in the aluminum grain size and darkness of the silicon matrix. The matrixes were uniform throughout each of the two cannings. In Figure 19 is shown the micro-structure of the first canning and in Figure 20 the second. The results of chemical examination of the welds and brazes and spectrographic analysis of the cladding are shown in Table II, showing that the nickel concentration in the second canning was greater than the first by a factor of two. The correlation between the weld quality of the two canning groups is in agreement with recent work on the effect of nickel content on weld quality (13, p. 2).

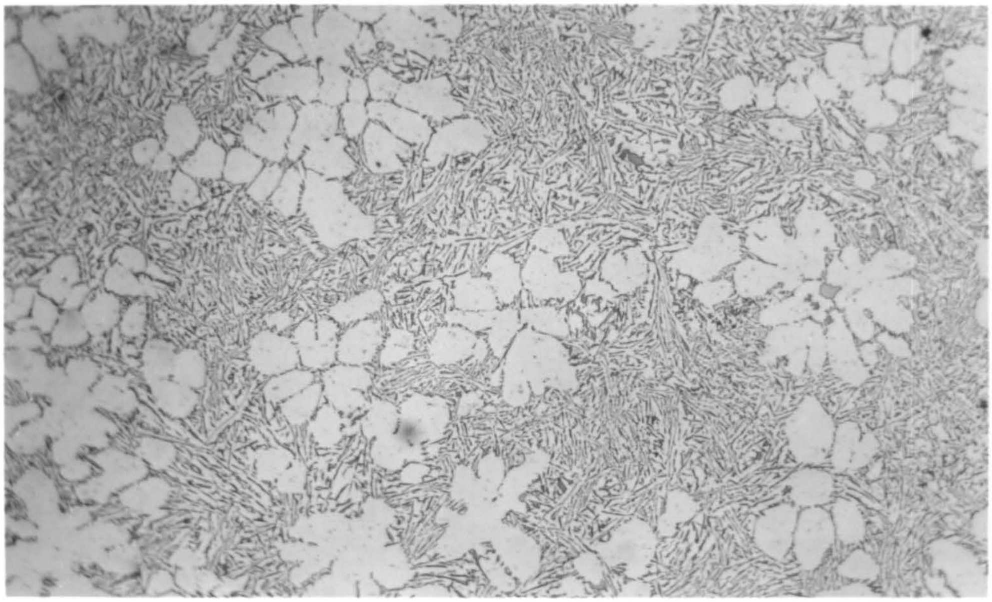
The most popular welding power supplies available are saturable reactor type devices. In saturable type devices the shape of the current wave is directly proportional to the inductance. From this it is obvious that the more square the wave shape the higher the cost of the unit because of the additional KVA of magnetic core assembly required.

Mating Surface Weld Class Variation
Lot No. 7

PC No.	Male End: Mating Surfaces at Weld Closure — Start	Male End: Mating Surfaces at Weld Closure — End	Male End: Mating Surfaces at Weld Midpoint — Start	Male End: Mating Surfaces at Weld Midpoint — End	Female End: Mating Surfaces at Weld Closure — Start	Female End: Mating Surfaces at Weld Closure — End	Female End: Mating Surfaces at Weld Midpoint — Start	Female End: Mating Surfaces at Weld Midpoint — End
D	II	IV	IV	IV	II	III	I	II
E	IV	IV	IV	III	III	I	III	IV
F	IV	IV	IV	II	II	I	IV	IV
G	IV	III	III	III	I	III	IV	IV
H	III	IV	IV	II	III	II	IV	IV
I	IV	III	IV	IV	IV			III
J	IV	IV	III	IV	V			IV
K	IV	III	IV	II	IV	I	V	V
L	III	IV	IV	III	IV	IV	II	II
M	III	IV	IV	IV	III	II	IV	I

TABLE I

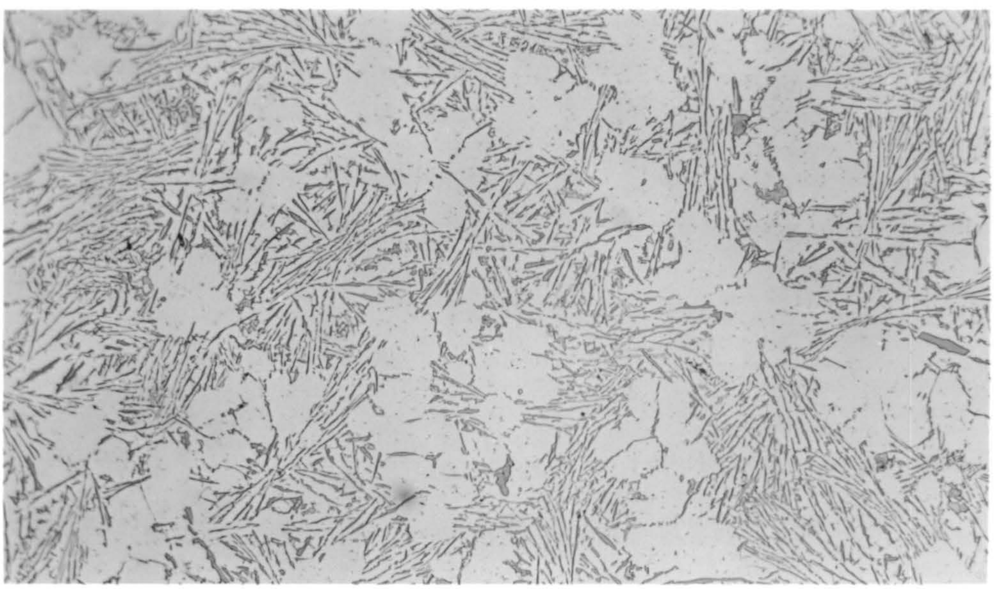
Mating Surface Weld Variation
Type IV Current Wave



250X 0.5% HF Etch

FIGURE 19

Braze Microstructure Canning No. 1



250X 0.5% HF Etch

FIGURE 20

Braze Microstructure Canning No. 2

CANNING NO. 1

Component	Silicon	Nickel
Braze	19.82%	0.27%
Weld Bead	0.45%	0.58%
Cladding		Medium to Strong

CANNING NO. 2

Braze	14.81%	0.43%
Weld Bead	0.38%	1.09%
Cladding		Medium to Strong

TABLE II

Metal Analysis

This study was made to determine first the current wave shape that would produce the best alloying in the weld and second the open-circuit voltage required to produce good arc starting and a stable arc during welding and crater filling.

Within the limits of available equipment the current wave shapes were selected to give a uniform distribution of shapes between the two limits from a narrow high peaked wave with rectification to virtually a square wave shown in Figure 10.

In making the welds for these tests every effort was made to produce all welds with the same dimensions. This is theoretically possible but in actual practice any slight variation in thickness of the aluminum mass changes its value as a heat sink and thus changes the width of the weld. For a constant value of current, as the mass decreases the weld widens, and conversely, narrows as it increases.

The current programming was arranged to produce a circumferential weld of uniform width for the average fuel element. This is complicated, for reasons not known, by the circumferential weld width variation of consecutive pieces on any one machine. It is not caused by current and arc voltage variation.

Experience has shown that in order to obtain accurate data on weld quality the welds produced on at least one hundred pieces must be examined and sectioned diametrically through the closure point on the weld. The reason for the one hundred pieces is that some undesirable conditions occur only once in this number of pieces. The point of sectioning is required as the cracks in the internal structure of the weld occur mainly at this point (7, p. 24).

Though a vast amount of work has been done by many people on the problem of alloying the braze into a homogeneous weld, there is nothing definitely known as to why alloying is not complete. Recent work indicates that a constant temperature in the weld will produce virtually complete alloying in the weld (14) (15). The melting point of the cladding is 655° C and the brazing metal 585° C. There is no detectable difference within 1° C of the melting point of the A-13 braze metal and the A-13 plus 0.5 per cent nickel.

Previous work (7, p. 21) has shown that it is much more difficult to produce complete alloying of the male weld than for the female weld. In support of this is the welding rate for the male weld is exactly one third that of the female weld. Any increase in the welding speed above that used on either the male or female welds decreases their quality (8, p. 22).

In early work (6, p. 53) it was found when comparing the weld quality of welds produced with Types I, II and III current wave shapes that as the current wave shape changed from a Type I towards a Type III the weld alloying improved. The improvement in weld quality by the elimination of rectification has been found by others (12). Also the surface roughness decreases. In Figure 21 is shown the alloying that occurred in one third of the welds produced with the Type I current wave and Figure 22 the surface roughness[2]. The welds were made at 23.5 inches per minute with argon shielding gas. The Type III current wave with the identical technique produces satisfactory weld quality. From this it was theorized that the increments of heat per unit time were more uniform as the current wave widened and its maximum value decreased. Oscillograms[3] of arc power, current and voltage for current wave Types I, II and III are shown

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2 High speed motion pictures show the corrugations in the weld surface forming as the current started to decay when the electrode is positive.

3 All oscillograms were taken with 200 amperes RMS in order to make a direct comparison of the power produced in each half cycle by each type of current wave.

15X Caustic Etch

FIGURE 21

Weld Alloying Produced by Type I Current Wave
165 amp, argon shielding gas, 6 rpm

2X

FIGURE 22

Weld Surface Produced by Type I Current Wave
165 amp, argon shielding gas, 6 rpm

in Figures 23, 24 and 25. In going from an unbalanced Type I to a balanced Type II current wave the oscillograms show that the maximum power in a half cycle changes from the half cycle the electrode is negative to the half cycle the electrode is positive. There is no visible change in the width of the valley between the power pulses. This indicates that any gain in weld quality is due to the increased power in the half cycle the electrode is positive maintaining a more uniform temperature in the weld. There is a large reduction in the surface corrugations of the weld (6, p. 46).

Comparing the oscillograms of the Type II and Type III current waves shown in Figures 24 and 25 there is a definite reduction in the width of the valley between the power pulses. This is evidenced in the weld quality improvement between the two types (6, p. 53).

Further improvement is shown in the reduction of the valley between the power pulses of Types III and IV current waves shown in Figures 25 and 26. Also, the power pulses are developing flat tops indicating that a more uniform temperature is occurring in the welds.

One form of square current wave types is shown in Figures 27, 28 and 29. A comparison of the Type IV with these, Types V, VI and VII, shows that in the latter there is a major reducion in the width of the valley between the power pulses. The tops of the power pulses are further broadened and flattened producing a more uniform temperature in the weld.

In Figures 30, 31, 32 and 33 is shown a second form of square waves. A comparison of the previous type of square waves with these shows that the valleys between the power pulses are identical. There is a difference in the contour of the tops of the two forms.

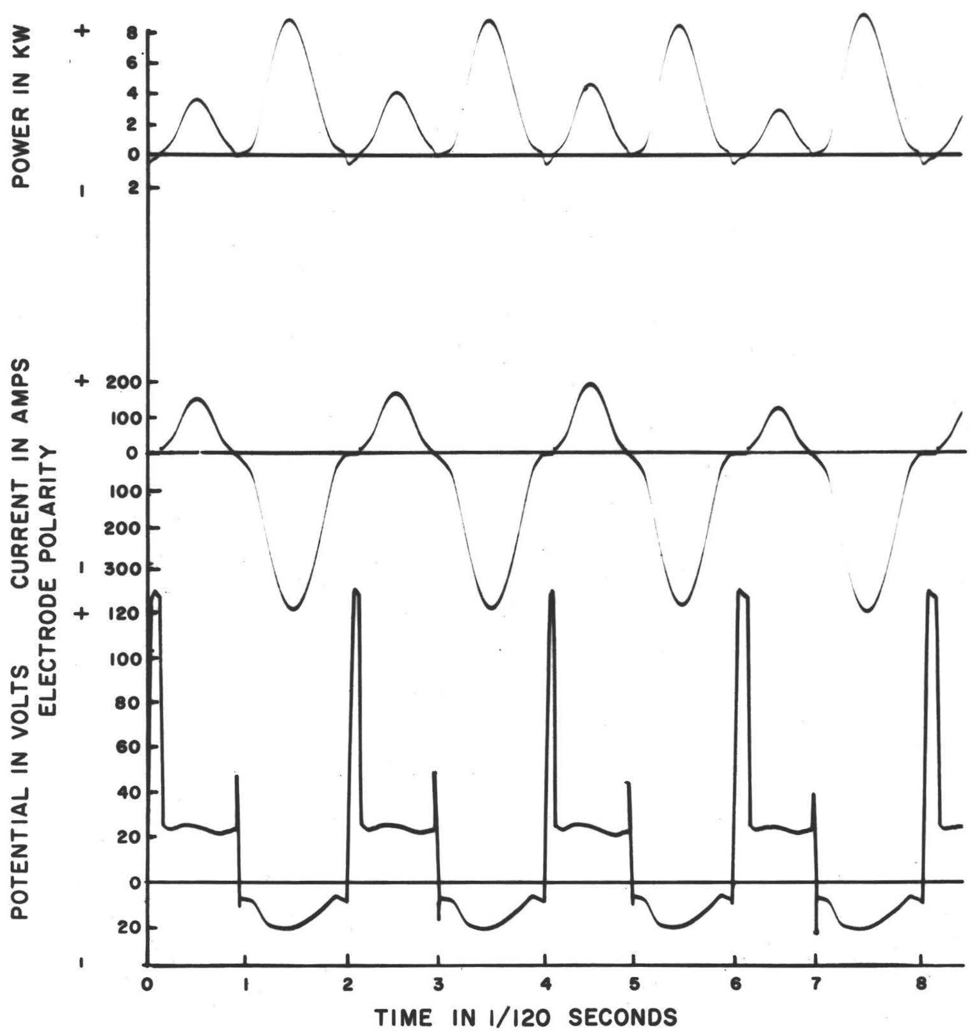
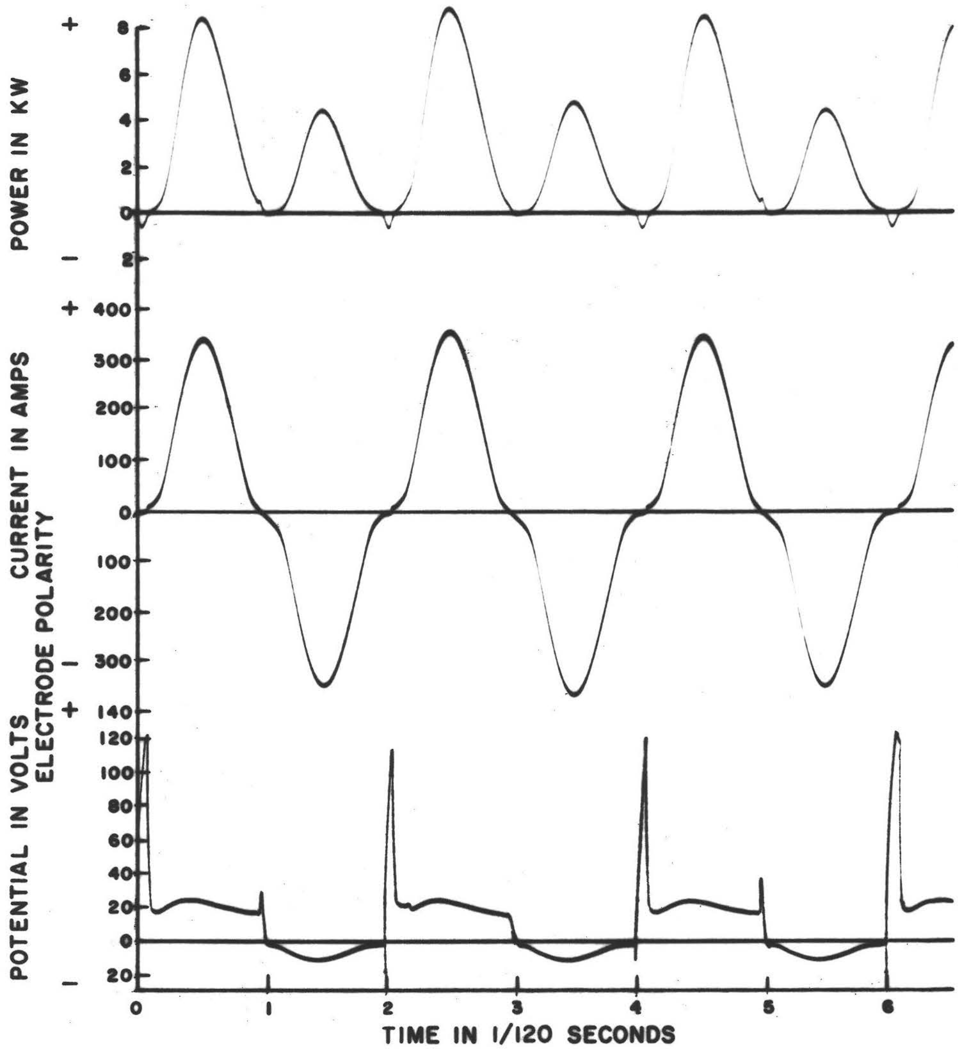


FIGURE 23

Type I Current Wave Arc Characteristics
200 amperes RMS



<u>FIGURE 24</u>

Type II Current Wave Arc Characteristics
200 amperes RMS

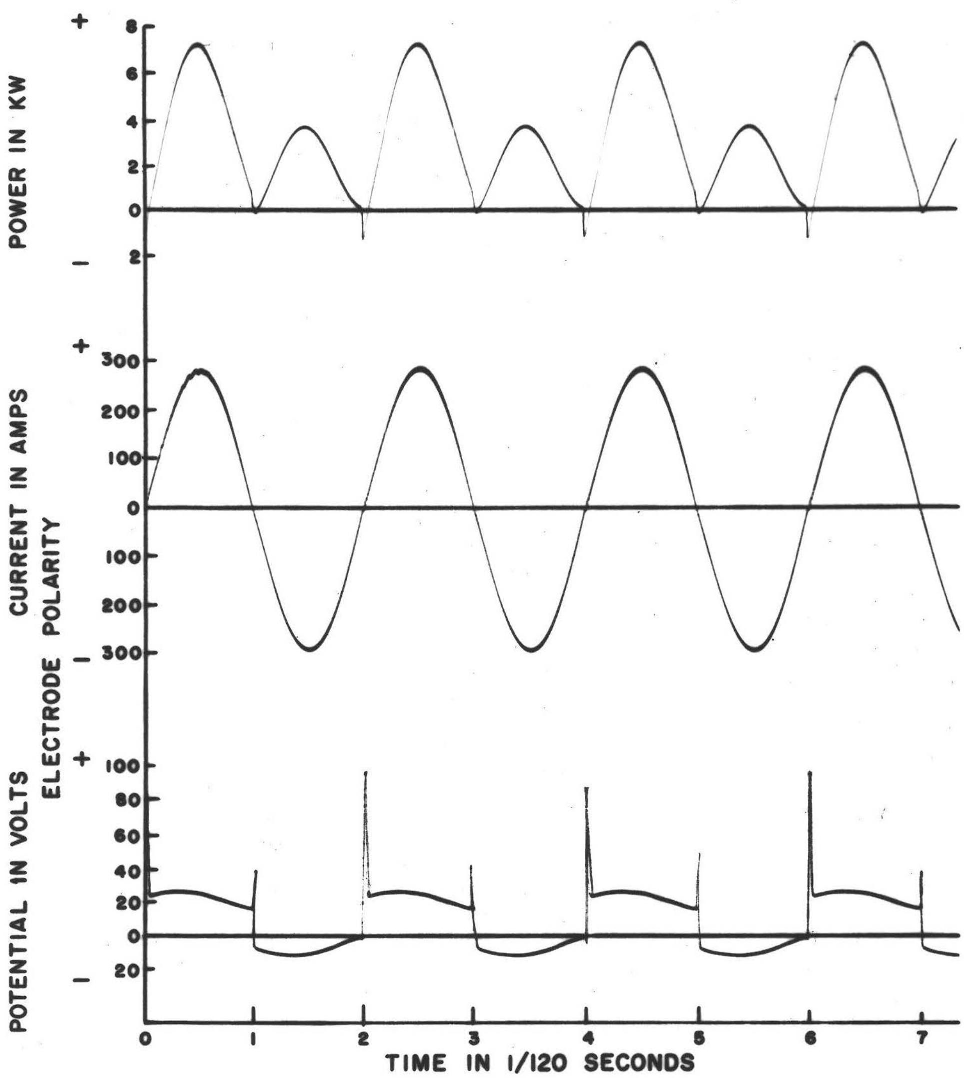


FIGURE 25

Type III Current Wave Arc Characteristics
200 amperes RMS

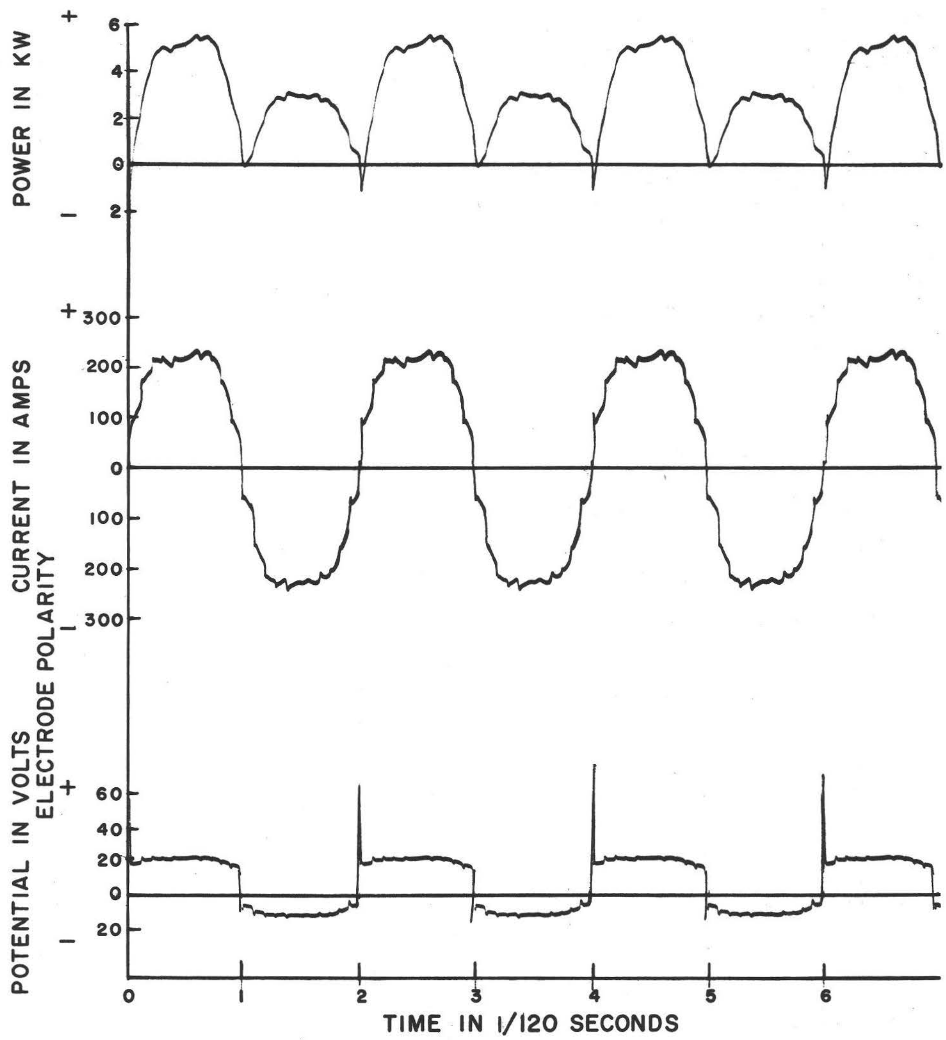


FIGURE 26

Type IV Current Wave Arc Characteristics
200 amperes RMS

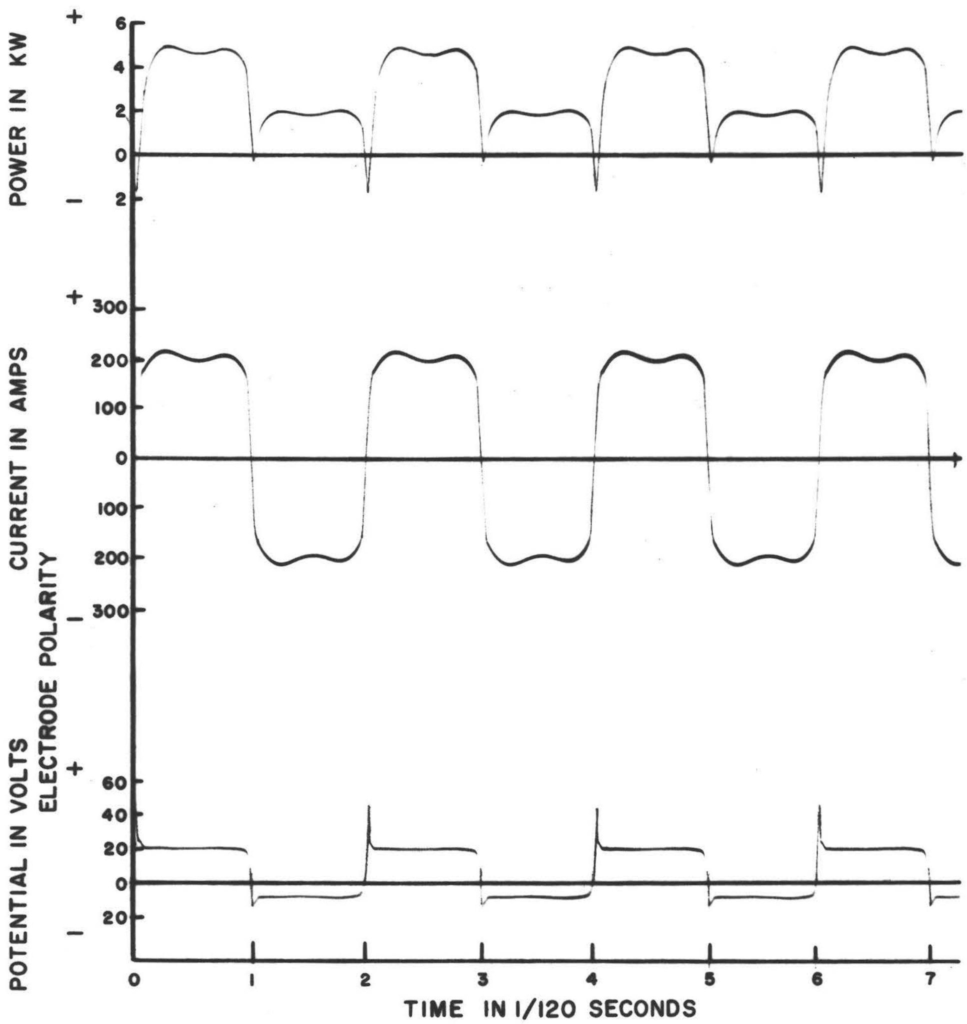
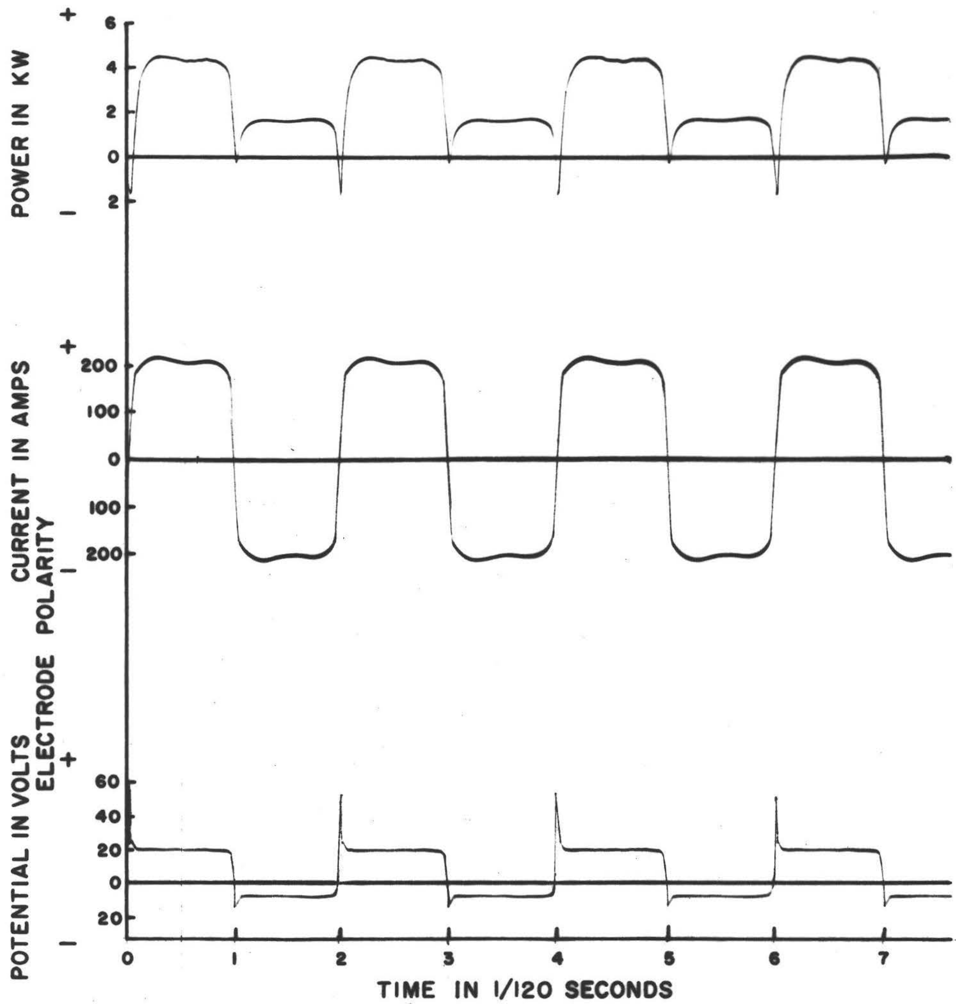


FIGURE 27

Type V Current Wave Arc Characteristics
200 amperes RMS



<u>FIGURE 28</u>

Type VI Current Wave Arc Characteristics
200 amperes RMS

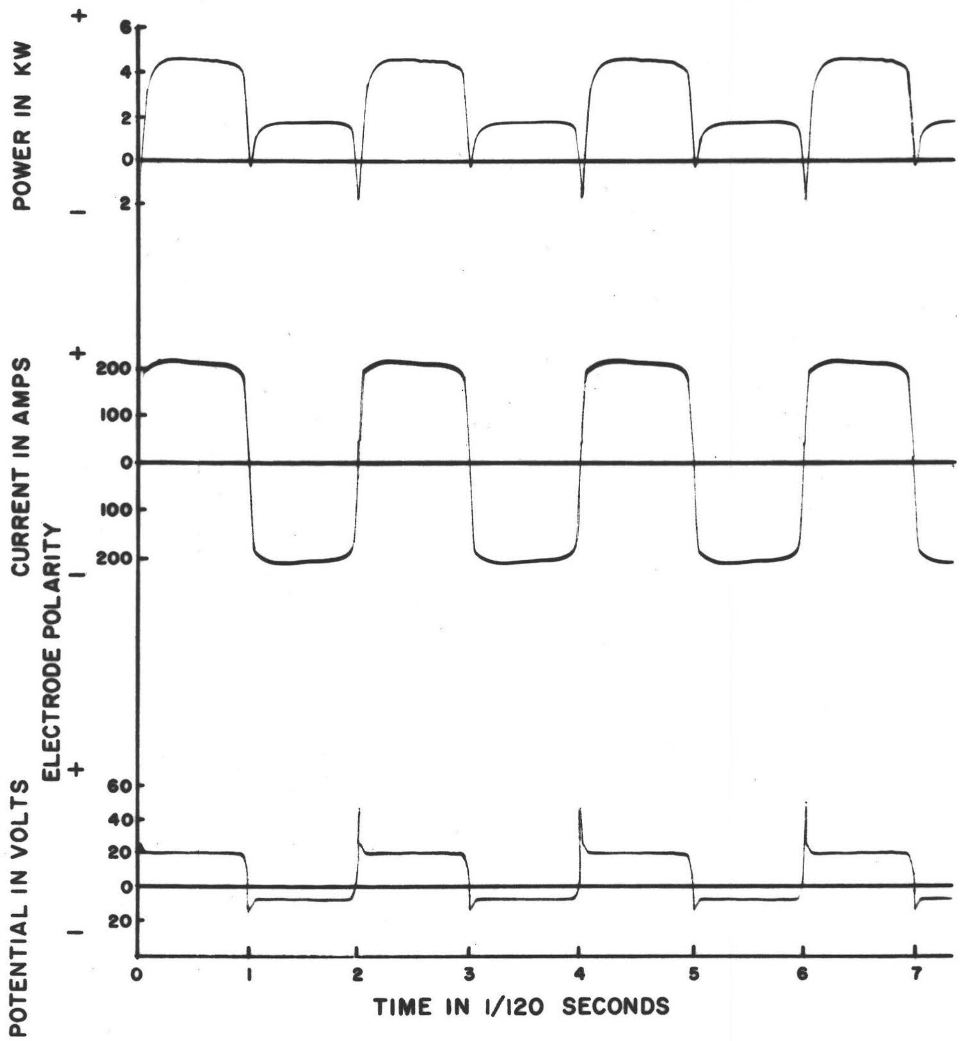


FIGURE 29

Type VII Current Wave Arc Characteristics
200 amperes RMS

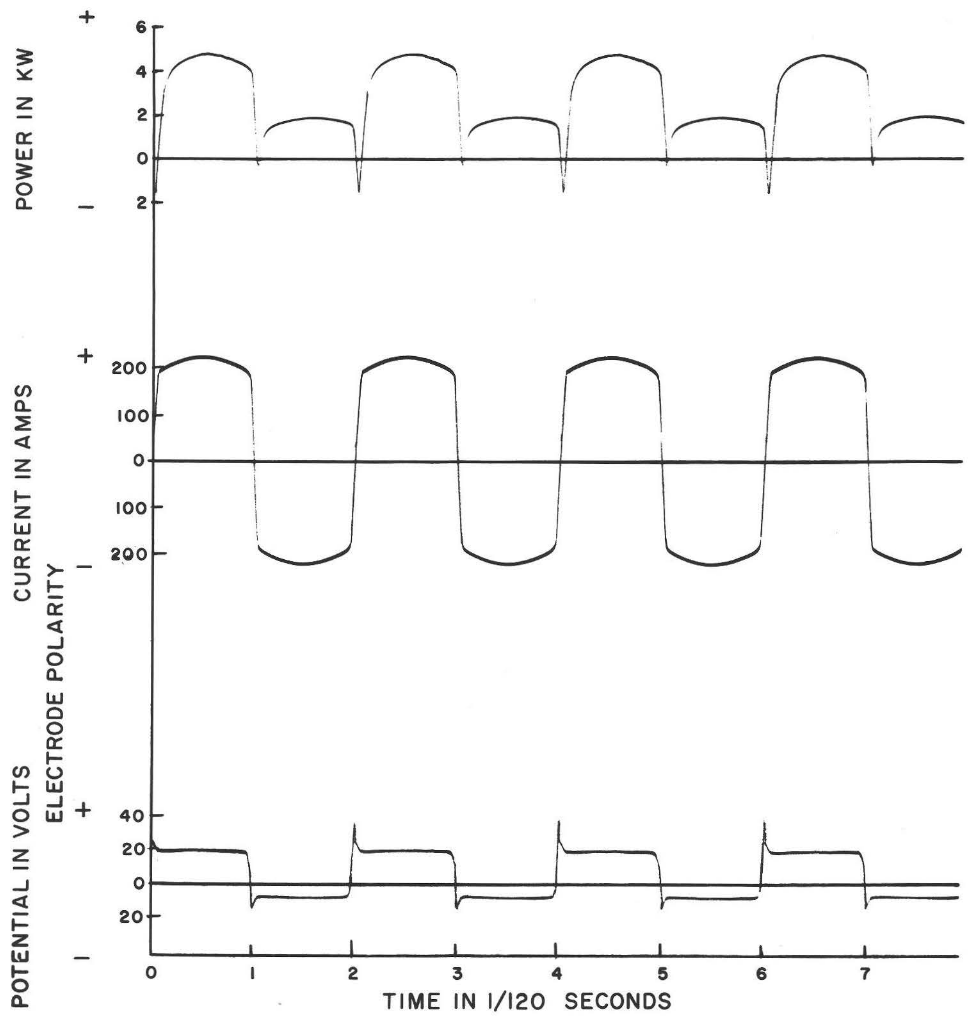


FIGURE 30

Type VIII Current Wave Arc Characteristics
200 amperes RMS

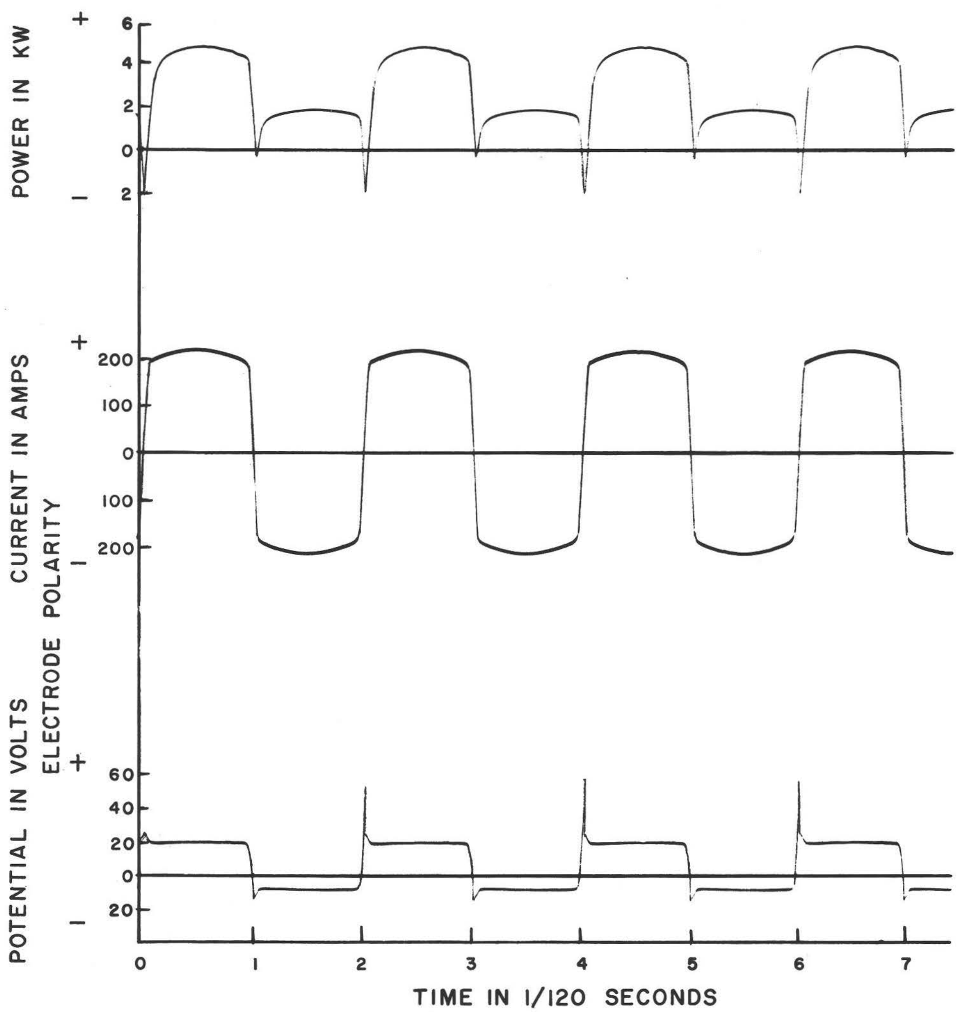


FIGURE 31

Type IX Current Wave Arc Characteristics
200 amperes RMS

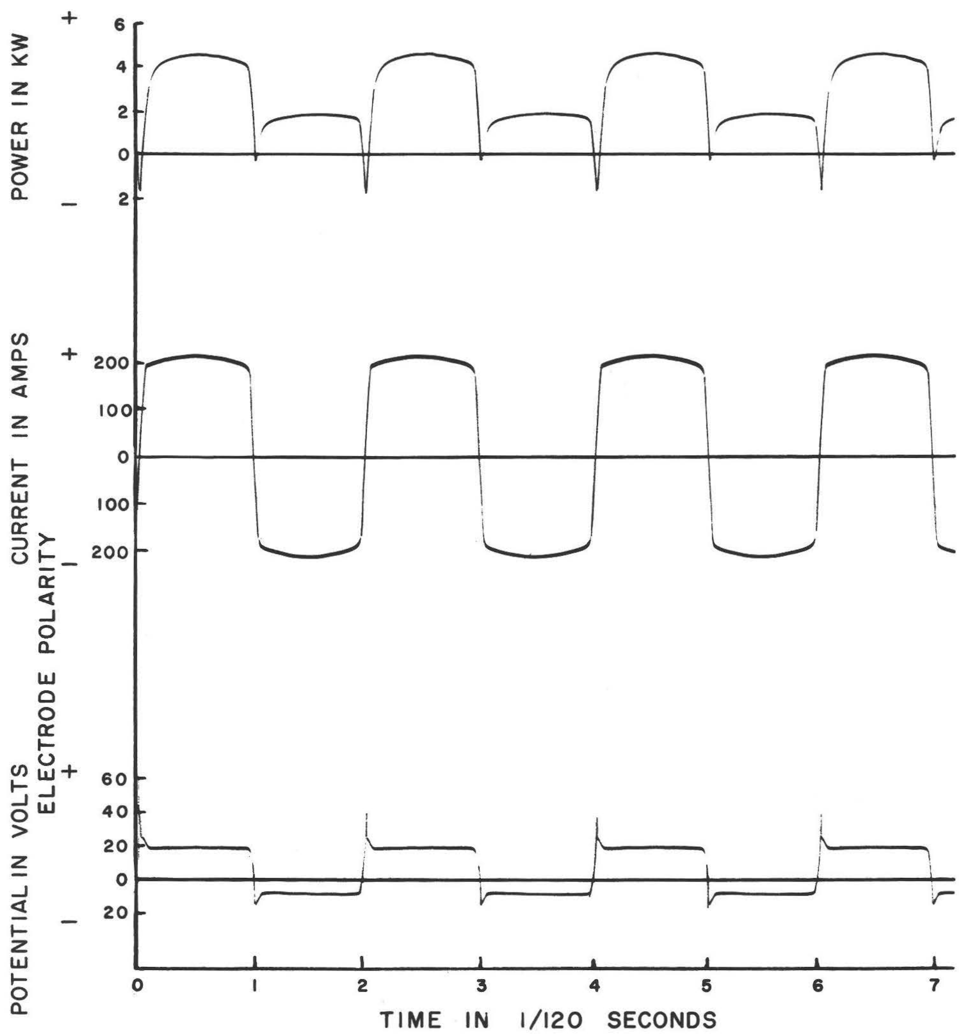


FIGURE 32

Type X Current Wave Arc Characteristics
200 amperes RMS

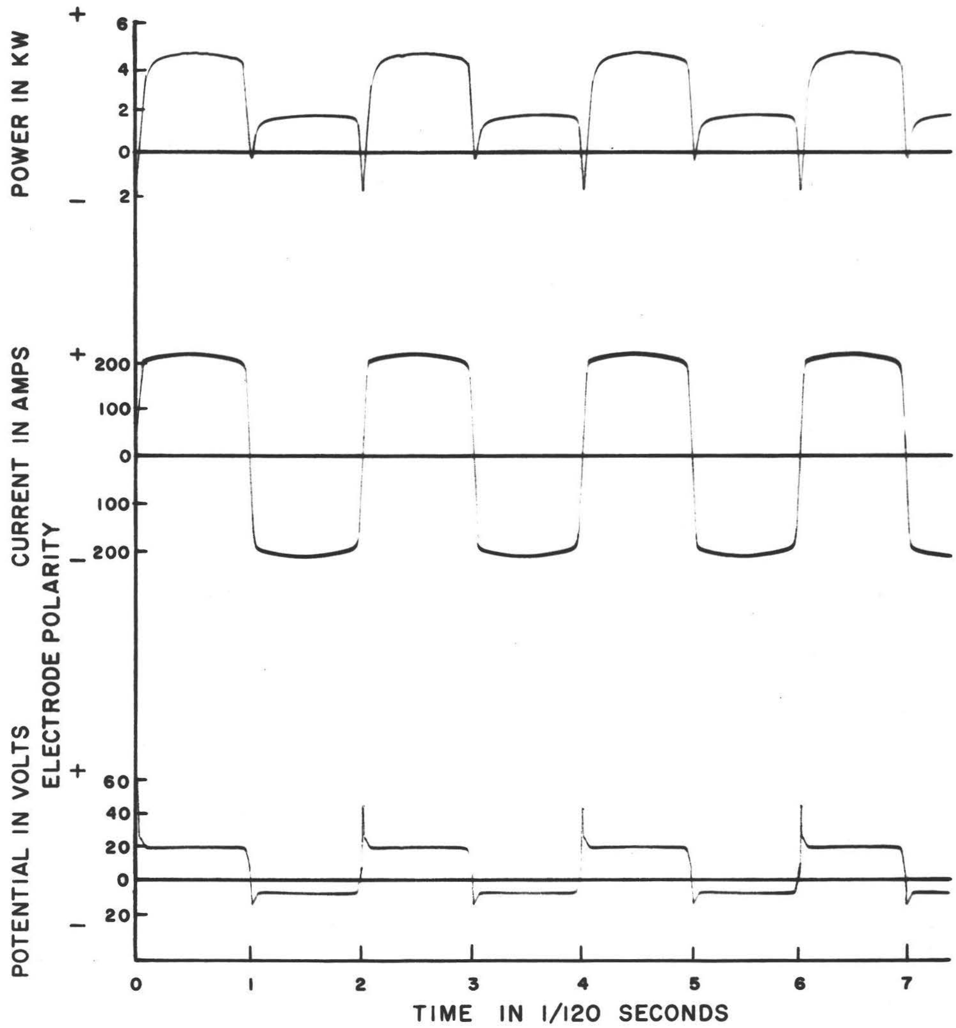


FIGURE 33

Type XI Current Wave Arc Characteristics
200 amperes RMS

Starting with the Type I current wave shape and including the Type XI there is a "negative" pulse of power as the polarity changes from the electrode positive to the electrode negative. Starting with the Type V and including the Type XI a "negative" pulse of power occurs as the electrode polarity changes from the electrode negative to the electrode positive. These pulses of "negative" power cannot be accounted for on any basis which included intrinsic arc phenomena (11). From calculations made using the known circuit constant of the watt galvanometer and its associated circuit about one-third of the "negative" power is produced by the inductance in the galvanometer current coil (4). The remainder is probably produced by circuit inductance in the watt galvanometer current circuit and reversal of the charges in the arc returning energy to the circuit. The difference in the amplitudes of the negative power pulses is produced by the difference in the amplitudes of the restrike potentials.

The effect of the "negative" power pulses is an "apparent" narrowing of the width of the power pulses. Since the current passing through the watt galvanometer is not the same as that passing through the current galvanometer and the inductance of the current galvanometer is negligible, the current trace is the true value. By multipling the corresponding ordinates of the current and voltage traces, the value of power can be found and is without any evidence of the "negative" power (8, p. 3). The exact alignment of the current and voltage traces can be made by aligning the discontinuity in the current trace with the crest of the restrike voltage when the electrode is positive.

In an attempt to develop a theoretical relationship between the welding current wave shape and its efficiency in alloying in a weld, numerous calculations[4] were made to see if some relationship would occur. This would require the use of a function that was independent of the small variations in current, voltage and power that occur in the arc. The first attempt was to use the form factor of the power pulses. In Table III are shown the comparison of the form factors of the power pulses for positive and negative electrode polarities. There is not a great enough difference in the values to produce a significant separation that could be used for evaluation. In Table IV are shown the form factors of the current wave shapes for each cycle of power. There is less separation than in the previous case.

A much better approach was developed by using the ratio of the power in a half cycle when the electrode is positive to the electrode negative. The tabulation of this data according to improving wave shape is shown in Table V showing that as the current wave squares up, the ratio increases from Type I to Type II then decreases from Type II to Type IV and then increases from Type V to Type XI, inclusive. The separation and trend are adequate for the evaluation. The change in trend between Types I and II is caused by the change from unbalanced to balanced current. The decrease between Types II and IV is very small percentage wise and may be caused by errors in the graphical solution. Increasing of the squareness of the current wave causes the ratio to decrease between types V and XI. Current wave Types IX and X appear to be interchanged by a comparison of the numerical value of the ratio but the trend indicates that they should be in this order as Type X is more square than Type IX. The reason is in all probability due to errors in the graphic method and calculations as the difference between the two is 0.78 per cent.

[4] All values of power were determined graphically from the power oscillogram trace, the instantaneous values of which were known by calibration.

Current Wave Type	Electrode Positive: Power in Kilowatts Average Value	Electrode Positive: Power in Kilowatts Effective Value	Electrode Positive: Form Factor	Electrode Negative: Power in Kilowatts Average Value	Electrode Negative: Power in Kilowatts Effective Value	Electrode Negative: Form Factor
I	1.798	2.27	1.262	4.02	5.17	1.283
II	3.51	4.68	1.332	1.835	2.44	1.330
III	4.20	4.79	1.141	2.20	2.52	1.145
IV	4.20	4.34	1.033	2.07	2.31	1.113
V	3.51	3.65	1.039	1.483	1.500	1.013
VI	3.22	3.38	1.048	1.280	1.310	1.023
VII	3.38	3.50	1.033	1.336	1.358	1.017
VIII	3.31	3.47	1.047	1.400	1.423	1.015
IX	3.46	3.58	1.035	1.375	1.400	1.018
X	3.45	3.55	1.030	1.373	1.398	1.017
XI	3.43	3.54	1.031	1.308	1.340	1.022

TABLE III

Wave Shape Half Cycle
Power Relationships

Current Wave Shape Type	Power Per Cycle in Kilowatts Average	Effective	Form Factor
I	2. 81	4. 00	1. 423
II	2. 67	3. 73	1. 396
III	3. 20	3. 82	1. 182
IV	3. 14	4. 81	1. 53
V	2. 50	2. 80	1. 12
VI	2. 25	2. 56	1. 138
VII	2. 36	2. 65	1. 122
VIII	2. 36	2. 65	1. 122
IX	2. 42	2. 72	1. 122
X	2. 41	2. 70	1. 122
XI	2. 37	2. 68	1. 13

TABLE IV

Current Wave Shape Power
Form Factor Relationship

Current Wave Type	Effective Power in Kilowatts Electrode Positive	Electrode Negative	Total Per Cycle	Ratio Effective Power Electrode Positive to Electrode Negative
I	2.27	5.17	4.00	0.44
II	4.68	2.44	3.73	1.92
III	4.79	2.52	3.82	1.90
IV	4.34	2.31	4.81	1.88
V	3.65	1.50	2.80	2.43
VIII	3.47	1.423	2.65	2.44
IX	3.58	1.40	2.72	2.56
X	3.55	1.398	2.70	2.54
VI	3.38	1.31	2.56	2.58
VII	3.50	1.358	2.65	2.58
XI	3.54	1.34	2.68	2.66

TABLE V

Current Wave Shape Half Cycle
Effective Power Relationship

The results of the pulse power ratio and weld evaluation are shown in Table VI tabulated according to the ratio of the effective power with the electrode positive to the effective power with the electrode negative. There is good correlation between Types III and IV as the weld quality number for both the male and female weld decreases. Also both are from the same canning group. The larger weld quality number indicates the male weld is more difficult to produce and is in agreement with previous work (8, p. 28-30). Types IV and V show an increase in weld quality numbers. However, Type IV is from the canning group that produced poor weld correlation and Type V is from the canning group that produced good weld correlation, indicating that the difference is not significant. This is substantiated by a review of Appendix III which shows that there is a major improvement in the items that are very serious, such as bad welds and cracks. Also the male weld quality number is larger than the female indicating it is a poorer weld, which is in agreement with previous work. A comparison of Types V and VIII indicates that according to the power pulse ratio the Type VIII produces the best weld while the weld quality number indicates the Type V. Since both were welded from the same canning group that produces good weld correlation and the numbers are so close together they will both produce welds of virtually the same quality. In addition the male weld quality numbers are larger than the female, as expected.

Comparing the power pulse ratios and weld quality numbers for Types VIII, IX and X there is a definite improvement in weld quality from Type VIII to Type X as shown by the correlation between ascending power pulse ratios and the descending weld quality numbers. Also the male weld quality numbers are larger than the female, as expected.

Current Wave Type	Ratio Effective Power Electrode Positive to Electrode Negative	Weld Quality Number	Canning Number	Welding Speed in Inches Per Minute
I	0.44			7.5
				25.3
II	1.92			7.5
				25.3
III	1.90	M 258	2	14.3
		F 233		42.4
IV	1.88	M 230	2	17.8
		F 215		52.9
V	2.43	M 276	1	17.8
		F 222		52.9
VIII	2.44	M 275	1	17.8
		F 259		52.9
IX	2.56	M 245	1	17.8
		F 211		52.9
X	2.54	M 212	1	17.8
		F 183		52.9
VI	2.58	M 265	2	17.8
		F 250		52.9
VII	2.58	M 250	2	17.8
		F 259		52.9
XI	2.66	M 293	2	17.8
		F 231		52.9

M = Male Weld
F = Female Weld

TABLE VI

Half Cycle Power Ratio
Weld Quality Relationship

The comparison between Types X and VI indicates a good correlation between the power ratios but a reverse correlation between the weld quality numbers. This is as expected as they are from different canning groups. A review of the data in Appendixes III and IV indicates that for most items Type X is a better weld than Type VI. However, from the previous findings and data it can be concluded from the power pulse ratio correlations that Type VI current wave produces a better weld than Type X. In addition, the male weld quality numbers are larger than the female, as expected.

A comparison of Types VI, VII and XI brings forth some unusual facts. The weld quality numbers indicate that the quality of the welds produced by Type VII should be better than that produced by Type VI but the power ratios indicate that they should be the same. The data in Appendixes III and IV generally indicate that the Type VII wave weld is better than the Type VI. An inspection of the power trace of the oscillograms in Figures 28 and 29 indicates that there is a difference in flatness of the tops of the power pulses of the two wave types and should not have the same power pulse ratios. In addition the weld quality number for the male weld is greater than the female indicating proper correlation. Thus it can be stated that though there is a measurable difference in the weld quality produced by the two current wave types as indicated by the weld quality number, the difference is very small.

A comparison of Types VII and XI current wave shapes indicates from the power pulse ratios that there is very good correlation but from the weld quality numbers the condition is reversed. An examination of the complete weld quality data, Table VII, indicates that the total spots and total high silicon quarters agree with the power pulse ratios and with the relationship between the male and female weld quality. From

Lot No.	Pieces in Lot	Wave Shapes Types	Weld Quality Number	Total Spots	Total High Silicon Quarters
8M	104	III	258	18	189
8F			233	7	88
7M	103	IV	230	197	132
7F			215	149	72
4M	102	V	276	87	
4F			222	23	
1M	105	VIII	275	26	
1F			259	58	
2M	106	IX	245	33	
2F			211	47	
3M	107	X	212	49	
3F			183	39	
5M	106	VI	265	546	42
5F			250	123	37
6M	101	VII	250	237	86
6F			259	34	64
0M	102	XI	293	67	84
0F			231	21	25

M = Male Weld
F = Female Weld

TABLE VII

Complete Weld Quality Tabulation

the previous data, the power pulse ratios and knowing the weldability of the material involved, it can be concluded that a Type XI current wave will produce a better weld than a Type VII but that the difference in quality cannot be established.

From a complete examination of the data it can be concluded that as an alternating-inert-arc-welding-current wave approaches a square wave that the quality of the fusion weld produced on an AlSi-bonded aluminum-clad uranium-metal fuel element will improve a measurable amount.

IX. OPEN-CIRCUIT-VOLTAGE WELDING-SPEED SHIELDING-GAS-RATIO RELATIONSHIPS

Dependency of the arc on open-circuit voltage for stable operation was discovered early in the study of parameters affecting the weld quality of AlSi-bonded aluminum-clad fuel elements (6, p. 27-33). For the Type III current wave, it was found when using argon as a shielding gas, currents of 150 to 175 amperes, 3/16-inch zirconium-tungsten alloy electrodes, a welding speed of 42.4 inches per minute and series current wave balancing capacitors that 100 open-circuit volts maintained good arc stability. Using a 5 to 7 argon-helium ratio shielding gas and all other parameters the same, the arc was difficult to start and had a tendency to go out during crater filling.

In evaluating the open-circuit voltage required to produce a stable arc with the Type XI current wave and a 3/16-inch zirconium-tungsten electrode, it was discovered that an arc that was stable at a welding speed of 17.8 inches per minute would go out at a welding speed of 52.9 inches per minute (8, p. 15-17). In Table VIII are tabulated the results of the tests showing the dependency of a stable arc on welding speed, open-circuit voltage and shielding gas ratio. It will be noted that with 100 open-circuit volts, argon shielding gas and a welding speed of 52.9 inches per minute that the arc was unstable with superimposed high frequency and stable without.

In Figures 23 and 24 are shown the effects of low open-circuit voltage on the third harmonic distorted sine current waves. The voltage cannot rise fast and high enough to re-ignite the arc without a discontinuity in the current. The arc was high frequency stabilized. Also, as the current nears the end of the pulse the arc tries to go out and the extinguishing voltage rises trying to maintain it. The low open-circuit

Open Circuit Volts	Shielding Gas Volume Ratio		High Frequency Stabilization		Arc Stability							
					17.8 In/Min				52.9 In/Min			
	Argon	Helium	Yes	No	Unstable	Almost Stable	Stable	Very Stable	Unstable	Almost Stable	Stable	Very Stable
80	x			x				x	x			
	x		x		x				x			
	5	7	x		x							
90	x			x					x			
	5	7	x		x							
95	x			x						x		
	5	7	x				x					
100	x		x							x		
	x			x							x	
	5	7	x				x					
105	x			x								x
	5	7	x				x					
	5	7		x	x							
110	5	7		x			x					
	3	9		x	x							
120	5	7		x						x		
	3	9		x					x			
125	5	7		x							x	
	3	9		x					x			
130	5	7		x								x
	3	9		x								x

TABLE VIII

Type XI Current Wave - Arc Stability Relationships for Variable Gas Ratios voltage also produces variable height and therefore variable areas of the current pulses. The combination of the variable heights and variable pulse widths produces a continuously varying temperature in the welds.

The time after zero current that a glow discharge exists approaches zero as the open-circuit voltage increases and the current wave shape squares up. When the electrode becomes positive the time that the glow discharge exists approaches zero as the wave shape squares up, which is shown in Figure 10 by the discontinuities in some of the current traces as the current rises above zero. The discontinuities are caused by there not being enough electrons and positive ions available at that instant to support a true arc. During the period of transition enough heat is added by particle acceleration from the rising voltage for a true arc to form. When the refractive tungsten electrode becomes negative there are enough electrons available to essentially form a continuous true arc. This is shown in Figure 10 as no discontinuities are recorded as the current increases below the zero axis. From theoretical considerations there must always be a finite time after the voltage starts increasing from zero that a glow discharge exists (5, p. 355). That a glow discharges does exist but is not shown in the current trace is shown by the peaks on the voltage traces after the point of zero current, Figures 26 to 33.

With increasing open-circuit voltage and squaring up of the current wave the extinguishing voltage required to maintain the arc at the end of the pulse is at least as great as the burning voltage. This is shown in the voltage trace of Figures 26 to 33 with the end of the voltage trace having a round corner. In Figures 23 to 25 the extinction voltage is shown as a definite spike indicating there is not enough voltage available to maintain a true arc.

The results of the tests indicated that an open-circuit potential of 130 volts would produce the required arc stability with all the gas ratios tested. This value was used throughout the tests on the Types V to XI, inclusively, current wave shapes producing excellent arc stability with a 5-7 argon-helium shielding gas ratio. The reason for this is that the maximum restrike voltage occurs at virtually zero current.

Equipment limitations allowed maximum open-circuit potentials of 80 volts for Types I and II and 100 volts for Type III current wave shapes. Type IV had a constant open-circuit potential of 165 volts.

The use of a high open-circuit voltage to maintain a stable arc has the following advantages:

1. Minimum radio frequency interference problems when using high frequency for arc starting only.
2. The high frequency stabilization tends to produce a weld with a rougher margin and surface.
3. The arc is more stable having less tendency to wander, producing a smoother weld.
4. The arc starts more quickly and smoothly.

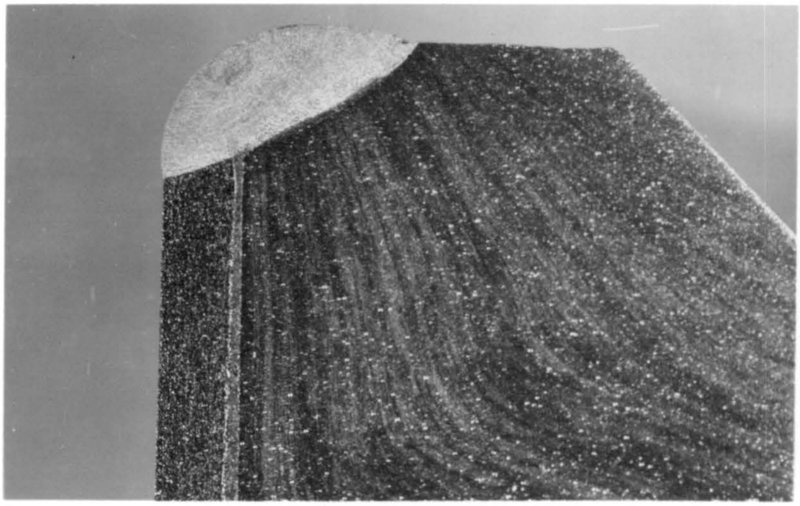
X. CONCLUSIONS

The improvement of fusion weld alloying with square type current waves in the closure weld of AlSi-bonded aluminum-clad uranium-metal fuel elements has been established. Alloying improves as the current wave shape changes from an asymmetrical 180 degree out of phase third harmonic distorted sine wave towards a symmetrical square wave.

It has been demonstrated that there is a positive agreement between the ratio of the power pulse with the electrode positive to the power pulse with the electrode negative and the weld quality number showing that alloying in the weld improves as the current wave shape changes towards a square wave. Also that weld alloying can be measured by a number.

The area covered by the arc on the plane of any finite point to plane setup is directly proportional to the current. From the test results it can be stated that as the temperature in the weld is held more constant and concentrated by a more constant value of current in each pulse, that weld alloying improves. This is supported by work in progress (14)(15) with direct current straight polarity using argon and helium shielding gases. Sections of representative welds are shown in Figures 34 and 35. The weld shown in Figure 34 was produced with argon and the one in Figure 35 with helium. The argon weld is a Class II weld and the helium a Class I. There was no evidence to indicate that the weld quality throughout a lot for either gas would be less than shown.

The relationship between welding speed, shielding gas ratios and the open-circuit voltage required to produce a stable arc without the use of high frequency stabilization has been demonstrated. It has also been shown that the use of a superimposed high-frequency current will contribute to an unstable arc condition with open-circuit voltages that will produce a stable arc.

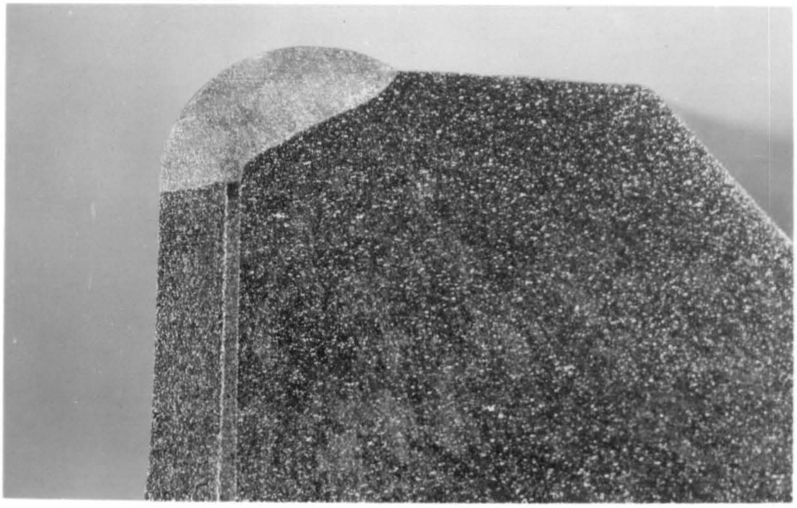


10X Caustic Etch

FIGURE 34

Weld Produced with Direct Current Straight Polarity and Argon Shielding Gas

150 amp, 12-1/2 rpm



10X Caustic Etch

FIGURE 35

Weld Produced with Direct Current Straight Polarity and Helium Shielding Gas

100 amp, 12-1/2 rpm

In changing the shielding gas mixture from a pure argon towards a pure helium the open-circuit voltage required to maintain arc stability with and without superimposed high-frequency current increases.

From the test results it can be stated that the more desirable characteristics for a welding power supply to fusion weld the closure of an AlSi-bonded aluminum-clad uranium-metal fuel elements with the alternating-current-tungsten-inert-gas-shielded arc are:

1. A balanced square current wave shape that is as good as Type XI, Figure 10.
2. Open-circuit potential of 130 volts for argon-helium mixtures of up to 3 argon - 9 helium by volume.

XI. ADDENDUM

Work with square type current waves has just started at other sites. The first results reported are with hand welding (9). The results are:

1. Substantial decrease in the amount of shielding gas per unit length of weld of 3003 aluminum.
2. Sound welds in 1/4 inch thick 3003 aluminum without tungsten inclusions as determined by X-ray examination.
3. More stable current during welding compared to conventional units.

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XIII. APPENDIX

GENERAL ELECTRIC
COMPANY
RESEARCH LABORATORY

P. O. Box 1088 ...... Schenectady, New York... Telephone
DIckens 6-8771

VIA AIR MAIL

January 12, 1960

Mr. Thomas B. Correy
Senior Engineer, Materials Engineering
Fuels Preparation Department
Hanford Atomic Products Operation
RICHLAND, WASHINGTON

Dr. Cobine and I have discussed your problem relating to oscillogram of inert gas arcs.

We are unable to account for this on any basis which involves intrinsic arc phenomena. A possible explanation may be that what you are seeing represents induced voltage because of inductive elements in your cirucit.

It seems to us quite significant that the "negative" power is observed when the rate of change of current is greatest. It is possible that the effect would disappear if the leads to the arc were rearranged, or if the external circuit impedance could be made more resistive.

s/

C. J. Gallagher
Liaison Scientist-General Physics
RESEARCH APPLICATION DEPARTMENT

CJG:ea

cc: JD Cobine

APPENDIX I

HATHAWAY INSTRUMENTS, INC.

5800 East Jewell Ave., Denver 22, Colorado

Your Ref: A. E. C. Purchase Order HA-60-88-1019
Our Ref: A 5371

February 2, 1960

General Electric Company
Hanford Atomic Products Operation
Fuels Preparation Department
Richland, Washington

Attention: Thomas B. Correy, Senior Engineer
Materials Engineering

Gentlemen:

Your letter of January 7, 1960, with various questions concerning watt oscillograms, has been studied by our engineering department and we regret this delay in answering. Comments from our engineering department are as follows and we hope they will be helpful to you.

1. Inasmuch as the watt galvanometer is an instantaneous resolution device, it records algebraically the product of voltage and current. Investigation of your records shows that the current lags the voltage in all cases at cross over, producing a negative current and a positive voltage, hence negative power.
2. It is noted that the negative power trace occurred only at positive peak voltage surges. We have drawn no conclusion from this as we do not have information on your input.
3. The phase angle between voltage and current may be caused by a large inductive load with surges back to the line at cross over and production of a negative power trace.
4. As nearly as we can tell from the oscillogram, the galvanometers are functioning as they should.

Yours very truly,

J. E. Carson
Assistant Sales Manager

JEC:jp

APPENDIX II

Lot No.	Excellent I	Good II	Fair III	Poor IV	Bad V	Internal Cracks VI
	Individual Weld Section Quality Number of Each Class Per Lot					
1M	12	89	52	226	25	15
1F	49	101	73	164	34	7
2M	36	101	111	160	3	4
2F	94	106	93	112	4	9
3M	70	116	86	105	16	
3F	140	125	83	45	19	1
4M	18	52	114	214	12	4
4F	84	74	64	150	17	1
5M	4	45	74	213	31	48
5F	76	54	61	179	33	10
6M	10	45	29	207	29	79
6F	53	49	58	188	44	16
7M	5	68	58	185	19	22
7F	108	75	55	111	42	17
8M	6	106	73	190	19	11
8F	56	135	43	151	21	3
0M	10	36	25	316	9	4
0F	103	80	48	128	10	31

APPENDIX III

WELD QUALITY TABULATION

Lot No.	Surface Penetrations by Silicon in Spots Per Weld: 1	2	3	4	5	6	7 or more	General High Silicon in 1/4 of the Circumference of the Weld: 1	2	3	4
1M	6	7	2								
1F	7	7	3	4	1		1				
2M	8	6	3	1							
2F	2	4	7		2	1					
3M	11	6	6	1							
3F	4	2	4	2	1						
4M	17	14	12	8	1	1					
4F			2	1		1	1				
5M	4	13	13	11	14	17	49	3	15	3	
5F	4	7		8	3	2	6	8	8	3	1
6M	11	16	10	15	9	5	4	16	25	4	2
6F	6	2	4		1		1	31	13	1	1
7M	1	1	12	11	5	9	5	19	30	7	8
7F	3	5	5	4	6	9	3	12	12	4	6
8M	1	1	1	3			3	22	30	13	17
8F			1	1				22	25	4	1
0M	7	7	6	2	4			23	15	1	7
0F	7	2	2	1				19	3		

APPENDIX IV

WELD QUALITY TABULATION

Current Wave Type	Maximum Power in Kilowatts Electrode Polarity		Average Maximum Power in Kilowatts	Ratio Maximum Power Electrode Positive to Electrode Negative
	Positive	Negative		
I	3.59	8.82	6.2	0.44
II	8.55	4.52	6.54	1.92
III	7.57	3.68	5.63	1.90
IV	5.37	3.18	4.28	1.88
V	4.90	1.98	3.44	2.43
VI	4.56	1.71	3.14	2.58
VII	4.63	1.75	3.19	2.58
VIII	4.80	1.89	3.35	2.44
IX	4.70	1.82	3.26	2.56
X	4.56	1.82	3.19	2.54
XI	4.53	1.72	3.18	2.66

APPENDIX V

HALF CYCLE MAXIMUM POWER RELATIONSHIPS

ALUMINUM COMPANY OF AMERICA
New Kensington, Pa.

February 11, 1960

Mr. Thos. B. Correy,
Sr. Engineer
Materials Engineering
General Electric Company
3706 Building, 300 Area
Richland, Washington

Dear Mr. Correy:

Thank you for the copy of your paper entitled "Development of an Improved Current Wave Shape Alternating Current Welding Power Source". We have examined this report and congratulate you for a well organized and informative paper. The description of the quality classification by means of photomicrographs is good.

As you know, we have purchased Type HDW Square Wave Welder from the Hevi-Duty Electric Company. This machine is single phase and has open circuit voltage connections for 80, 105 and 165. Current capacity for this machine is 35-150/100-300.

Many of the applications we have for this equipment are in a different category than the field in which you are working, and we cannot comment on many of your conclusions. However, we observed several characteristics that may be of interest.

(1) When operating with the 170 volt tap, there is no change in current value with or without continuous high frequency with argon and helium.

(2) When using 200 amperes, the current is a constant value even when the arc sounds uneven. Even with the balanced wave machine with a sinusoidal current wave, there is some variation when the arc sounds uneven.

(3) One of the cost factors in which most of our customers are interested in is the gas usage. We found it is possible to weld with a substantial decrease in gas flow, and still obtain a quality weld in 3003 aluminum.

APPENDIX VI

To Mr. Thos. B. Correy Date Feb. 11, 1960 Sheet No. 2

(4) It is possible to produce high quality welds in 1/4 3003 aluminum plate. An X-ray examination of the weld shows a sound weld with no tungsten inclusions.

(5) All the evaluation to date has been done manually. The welding operator finds it possible to do a superior job with this power source.

Very truly yours,

ALUMINUM COMPANY OF AMERICA
Alcoa Process Development Labs

s/

C. R. DIXON

CRD:as

cc: Seattle Sales Office