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QUALITY WELD PARAMETERS FOR MICROWELDING TECHNIQUES AND EQUIPMENT

Prepared under Contract No. NAS 8-21326 by
W. R. Hutchinson and L. G. Hall

MARTIN MARIETTA CORPORATION

For

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER
Marshall Space Flight Center, Alabama

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(Final Report)

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Prepared under Contract No. NAS 8-21326 by
MARTIN MARIETTA CORPORATION
Orlando, Florida

For

Quality and Reliability Assurance Laboratory

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

ABSTRACT

A limited amplitude, controlled decay (LACD) welding concept developed at the Martin Marietta Corporation, Orlando Division, was optimized on this program to improve the weldability of component lead materials of electronic modules. During this study it was observed that the weldability of OFHC copper could be significantly improved by welding to nickel wire instead of ribbon with the stipulation that the nickel wire must always be the larger of the two. Of the materials evaluated in this program, kovar, nickel, dumet, and OFHC copper, the LACD process improved welding ranges by a factor of 2 to 4X.

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FOREWORD

This report was prepared for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama 35812, under MSFC Contract No. NAS 8-21326.

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SUMMARY

A new welding process conceived and reduced to practice by the Martin Marietta Corporation, was optimized and evaluated on NASA contract NAS 8-21326. Evaluation was achieved by comparing results obtained on a standard and a limited amplitude, controlled decay modified welder. A series of typical component lead materials were tested including kovar, nickel, dumet, and OFHC copper. Preliminary and final qualification tests were run to establish valid weldability comparisons for both welding processes.

The limited amplitude, controlled decay welding process consists of building or modifying a standard capacitor discharge welder to control the shape of the weld pulse. By insertion of a variable impedance in the primary circuit, pulse amplitude, pulse length, and current decay can be selectively controlled. Thus the name limited amplitude, controlled decay was selected and the abbreviation, LACD. The modified welding equipment is pictured in Figure A.

Since the effect of impedance on weldability needed a most thorough investigation, the effect of varying impedance versus watt-seconds was investigated at three isopressures. Representative isopressures were selected from previously run standard isostrength diagrams. A complete watt-second weldability range was established for approximately eight impedance settings at each of the three selected isopressures. Both welding processes were tested on each of 12 materials combinations.

The LACD welding concept improved the weldability of all materials combinations investigated, except the OFHC copper to nickel ribbon combinations, by providing a better match to the power supply. Based on optimum scale utilization, an improvement of from 2x to 4x was achieved. For instance, 0.017 kovar which had a normal welding range of 2 to 3 watt-seconds at a pressure of 5.5 pounds on the low scale, was satisfactorily welded in the range of 50 to 100 watt-seconds on the high scale of the LACD modified welder.

During the program, a brief academic study was completed when it was observed that OFHC copper wire appeared to be more weldable to nickel wire than to nickel ribbon. OFHC copper welding ranges of 30 watt-seconds were easily achieved using nickel wire and the LACD welding concept. The mass relationship of the copper to nickel wires was mathematically correlated to the observed LACD, delta watt-second welding range.

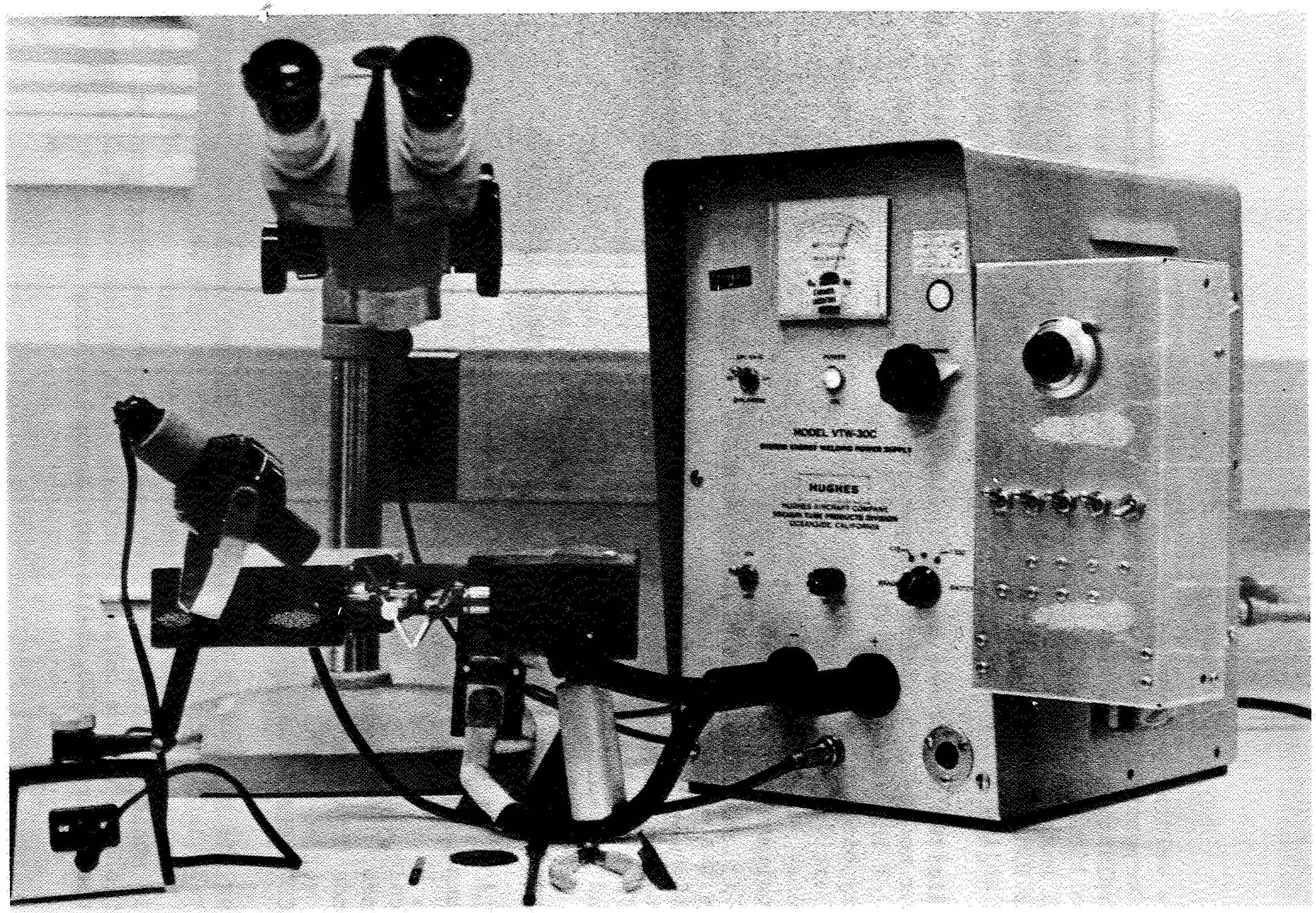


Figure A. Limited Amplitude, Controlled Decay
Welding Equipment

No deviation from NASA materials specifications is required except the stipulation that a nickel barrier layer is mandatory on any gold plated copper surface such as dumet. Also the presence of gold plating thickness in excess of 50 to 150 microinches restricts the weldability range of dumet.

I. INTRODUCTION

Welding was difficult in the early days of structural fusion welding because neither the power supply nor the welding electrodes were truly matched to the job requirements. If an arc was generated and a bare rod fused, a weld was made. Power supplies and welding electrodes have improved until, today, both equipment and electrodes are tailor made for the job, and in the field of microwelding, welding equipment is undergoing evolutionary changes. Component lead materials have already been limited to a select few by NASA specification.

The need for higher density electronic packaging has caused the use of modular packaging and welded circuitry. This, in turn, requires reliable welding procedures through control of welding equipment, welding processes, and component lead materials. The proper match of welding equipment and the component lead is necessary to satisfy manufacturing tolerances. Neither the equipment nor the lead material may vary beyond certain acceptable limits to produce a satisfactory weld. Consideration of possible human error helps establish the limitations which must be set on equipment and material.

Over the past six to eight years, a wide variety of lead material and welding equipment have been used. It was not uncommon to require more than one set of welding parameters for specific material combinations when two or more welding machines were used. Today, welding equipment and component lead material have been improved considerably, but a small deviation from established welding parameters will still produce a defective weld. This is due to an improper equipment to material match, accentuated by variation of material from lot to lot. In the case of 0.017 inch diameter kovar, the present production welding range is close to 1 watt-second; 0.020 inch diameter dumet is 2 to 3 watt-seconds; while nickel is somewhat higher. With such limitations a small human error can easily cause a defective weld. New shipments of components and aging of the equipment have caused problems at the Martin Marietta Corporation. Welding parameters have had to be re-established more than once when trouble occurred.

Even with normal Quality Control procedures a potential hazard exists if a mixed lot of components should go undetected to the production floor. A more tolerant welding system to allow for normal variations induced by the equipment, material, and the human element is required. Such a system was conceived and the feasibility established at the Orlando Division. Preliminary tests have demonstrated an order of magnitude improvement in weldability.

This study was designed to improve reliability of microwelding by demonstrating an improved welding concept employing capacitor discharge welding equipment. The concept provides the basis for design of a new power supply or the modification of typical, commercial grade, capacitor discharge welding machines. This new welding concept, LACD, expands the weldability of component lead materials.

II. DEVELOPMENT

The LACD welding concept was developed to provide a better match of the capacitor discharge microwelding power supply to the varity of component lead materials required in the fabrication of welded electronic modules. LACD provides limited peak current and controlled current decay. Limitation of peak current reduces expulsion. Addition of resistance into the primary circuit of the capacitor discharge welder, permits a better match of power to individual component lead weld joints, and provides a greater scale utilization of the specific power supply. Evaluation of the LACD concept was performed by comparing results achieved on a standard power supply with those achieved on the LACD modified welding power supply. Development and evaluation are described in three sections: 1) LACD Circuit Optimization, 2) Preliminary Evaluation, and 3) Final Evaluation.

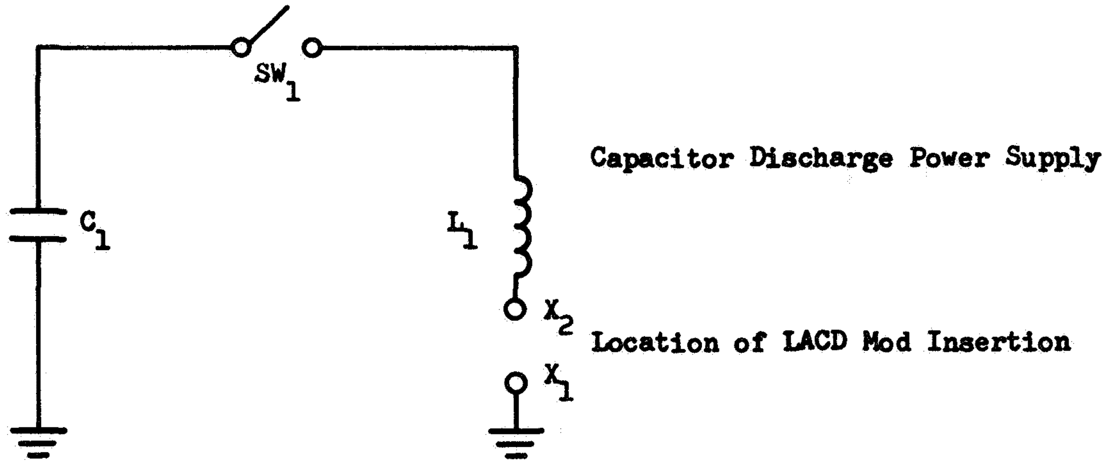
A. LACD CIRCUIT OPTIMIZATION

1. Circuit

Figure 1 shows the schematic of a capacitor discharge power supply and a schematic of the LACD modification circuit which was incorporated into the Hughes power supply at locations X1 and X2. The components shown were selected to provide minimum drift due to temperature change. A resistance check of the circuit, after making up to 50 welds at maximum welding power, showed a change of less than one half of one percent, as indicated in Table I.

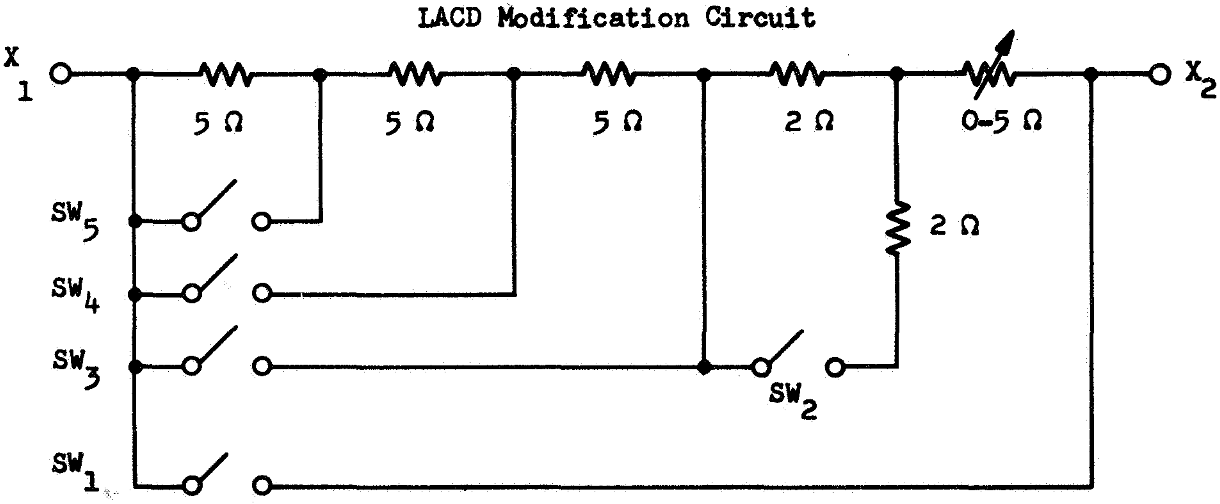
2. Pulse Control

An oscilloscope trace of the weld pulse obtained by use of the LACD modification is shown in Figure 2. The shortest of the three pulses shown is produced by a standard power supply, the intermediate length weld pulse is produced by addition of high inductance, and the longest weld pulse is produced by the LACD modification. The LACD weld pulse is the smallest in amplitude and greatest in pulse length. A calibration of the weld pulse was made as it varied with added internal resistance. This is shown in Table II and in Figure 3. The addition of resistance significantly increases weld pulse length. Since the most effective portion of the weld pulse occurs during the first 63 percent decay period, it may be seen that the maximum effective increase in pulse length at this decay point occurs with an internal resistance of 10 ohms. At this point, the LACD weld pulse is essentially 12.5 milliseconds



C_1	Capacitor Bank
SW_1	Mercury Switch
L_1	Primary of Output Transformer

LACD Modification Circuit



Rheostat	0-5 Ω	150 Watt
Resistance	5 Ω	40 Watt
	2 Ω	40 Watt
Switches	S_1 to S_5	DPST 32A

Figure 1. Schematic of LACD Modification

TABLE I

LACD Impedance Test

(Performed at a power setting of 100 W-s)

Setting at Start	5 ohms	10 ohms	20 ohms
Test Welds Performed	Measured Value	Measured Value	Measured Value
0	5.00	10.00	20.00
10	5.00	10.00	20.00
20	5.00	10.00	20.00
30	5.00	10.00	20.00
50	5.02	9.98	19.97

Repetitive LADC impedance checks made after 0, 10, 20, 30, and 50 welds with a weld rate of one every 2 1/2 seconds.

Alinco Resistance Tester, Model No. 101-5 B. F., used to make resistance checks. Initial calibration tests were made with a Wheatstone Bridge.

against 3.1 milliseconds for the standard power supply. Thus the effective weld pulse length may be increased up to four times the length of the conventional weld pulse. Test data was obtained on a Type 564 Tektronix Storage Oscilloscope.

B. PRELIMINARY EVALUATION

The evaluation of the LACD concept versus the standard welding concept was performed on a series of materials normally used in electronic circuit modules as follows:

1 0.010 x 0.020 inch nickel (bare) to 0.017 and 0.025 inch kovar (Au)

2 0.010 x 0.020 inch nickel to 0.025 and 0.032 inch nickel (bare)

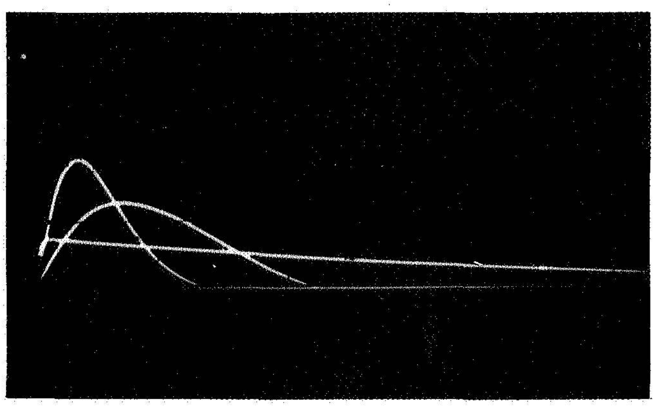
3 0.010 x 0.020 inch nickel to 0.020 and 0.032 inch dumet (Au) with Ni barrier

4 0.010 x 0.020 inch nickel to 0.020 inch dumet (Au) without Ni barrier

5 0.010 x 0.020 inch nickel to 0.010 x 0.025 inch nickel (bare)

6 0.010 x 0.020 inch nickel to 0.020 and 0.032 inch OFHC Cu (Au)

7 0.025 and 0.032 inch nickel wire to 0.020 inch OFHC Cu (Au) (not required by contract)



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Scale: 2 ms/cm

Figure 2. Oscilloscope Traces of Welding Current

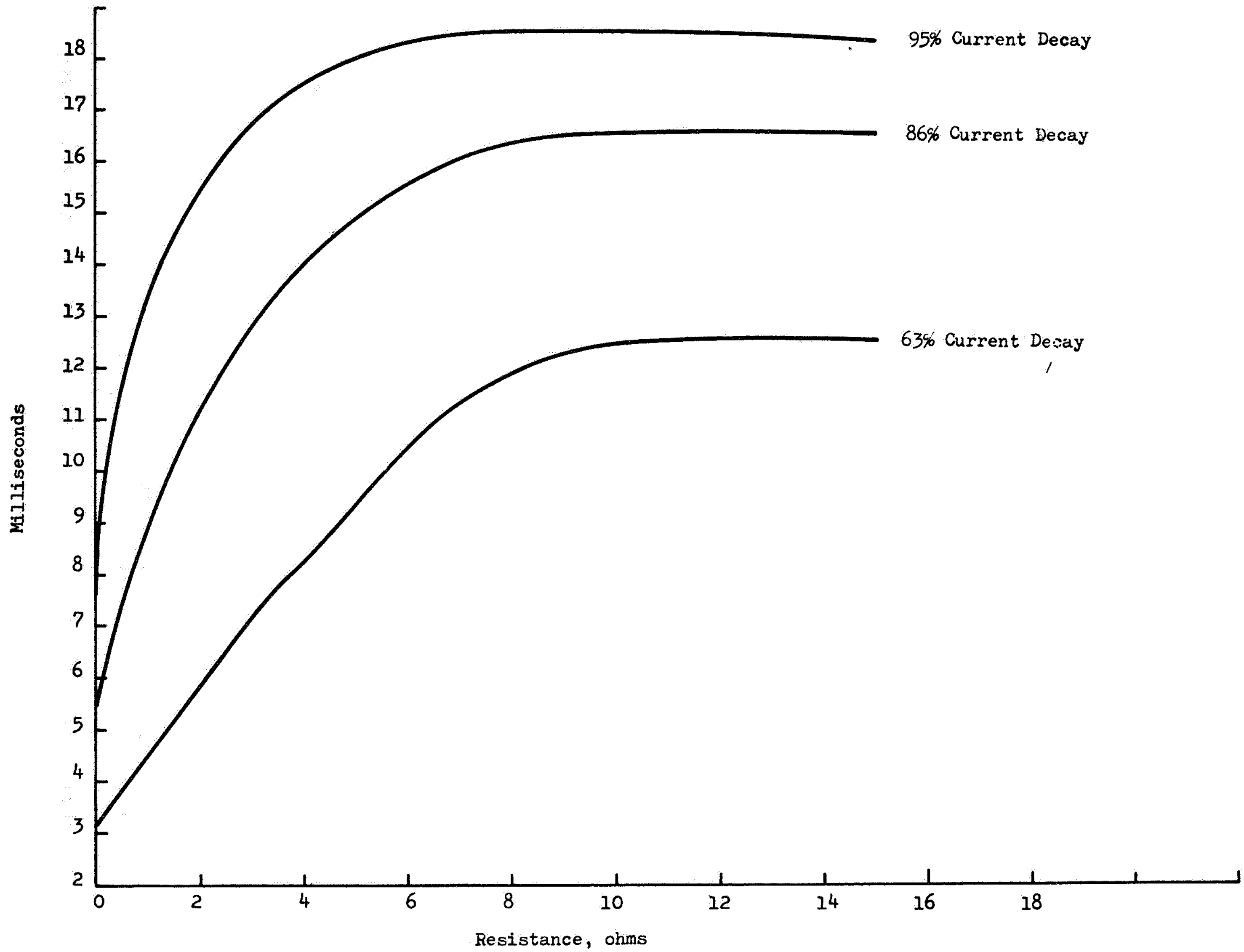


Figure 3. LACD Weld Pulse Time Versus Changing Primary Resistance

Table II

Weld Pulse Length Versus
Added Primary Resistance

(in milliseconds)

Current Decay	0 Ω	2 Ω	4 Ω	5 Ω	6 Ω	7 Ω	8 Ω	9 Ω	10 Ω	15 Ω
63%	3.0	6.5	8.3	9.3	10.5	11.0	12.0	12.0	12.5	12.5
86%	5.4	11.2	14.0	14.5	15.5	15.7	16.3	16.5	16.5	16.5
95%	7.5	15.5	17.5	18.0	18.5	18.5	18.5	18.5	18.0	18.3

Obtained on a Type 564 Tektronix Storage Oscilloscope

Exploratory welds have been made with nickel ribbons of INCO alloys 200, 205, and 270. All of these alloys meet military specification requirements. Since alloy 205 is the industry standard for electronic components, it was used for the bulk of the work. Where welds or welding ranges could not be achieved with alloy 205, INCO Ni alloy 270 was used.

A preliminary evaluation and past conventional welding data indicate that the best results are obtained at 5.5 pounds pressure for 0.017 inch diameter gold plated kovar. Some work was done at 2 pounds pressure to see how the LACD concept would function at low welding pressures. This is desirable when small, notched welding electrodes are required for welding in restricted locations.

Impedance settings used were from 2 to 16 ohms (in 2 ohm increments) for each selected welding pressure. Maximum spread in watt-second settings were sought. The lower watt-second setting developed strengths meeting the 60 percent pull strength of the weakest material used in the particular weld study. Two upper limits were established by using one or more of the following methods:

1 Determine the setting just below expulsion which would still meet the 60 percent strength requirement.

2 Determine the watt-second setting where neither component lead penetrated the other more than 50 percent of the thickness or diameter of the smaller lead.

3 Determine the watt-second setting where maximum setdown did not exceed 35 percent of the combined thickness of the two materials being welded.

Welding electrodes representing all conventional types were explored for compatibility with the LACD pulse control system. Test results indicated no significant deviation in compatibility from the existing conventional unmodified weld power supply. This was performed on the weldability of OFHC copper. Electrode types explored were RWMA Classes 1 and 2 of group A, and Classes 13 and Moly, of group B.

1. Standard Versus LACD Modified Welder

A series of tests was run while varying the internal resistance at typical welding pressures of 4, 5.5, and 8 pounds. An occasional series of tests was performed at 2 and 10 pounds. Preliminary data were established at maximum and minimum welding currents at which welds would meet NASA requirements. A total of five welds were made at the extremes and three welds at one or two watt-second intervals between these extremes. This basic data is shown in the appendix. Results of these tests are plotted in Figure 4 showing one isopressure diagram of one size of each material at its optimum welding pressure. The welding range increased significantly as primary impedance was increased. The largest spread in welding current is summarized in Table III for each of the welding pressures investigated. It was observed that maximum welding range was achieved with LACD when the maximum weld current was 100 watt-seconds. The minimum welding current is essentially 100 watt-seconds minus the welding ranges shown in Table III. Figures 5 through 9 show typical isostrengths plotted at a pressure of 5.5 pounds. Standard welder and LACD modified welder pull strength were plotted from a minimum strength of 60 percent of the tensile of the lower strength lead to the maximum watt-second level, where acceptable welds are limited by 35 percent total deformation, 50 percent setdown, expulsion, or loss of strength below the 60 percent strength level. These figures show significantly increased welding ranges with the LACD process. To evaluate the possible affects of LACD on weld join strength, the strength data shown in plots of Figure 5 through 9 were examined.

The total number of acceptable weld joints over the complete welding range was averaged and is shown in Table IV in the strength average columns. The number of weld joints averaged is shown in the population columns. The LACD to standard strength ratio was obtained and is shown in the last column. In each case, LACD shows no significant decrease in welding strength except in the welding of 0.032 inch nickel wire to 0.010 x 0.020 inch nickel ribbon where a loss of 5 percent is indicated.

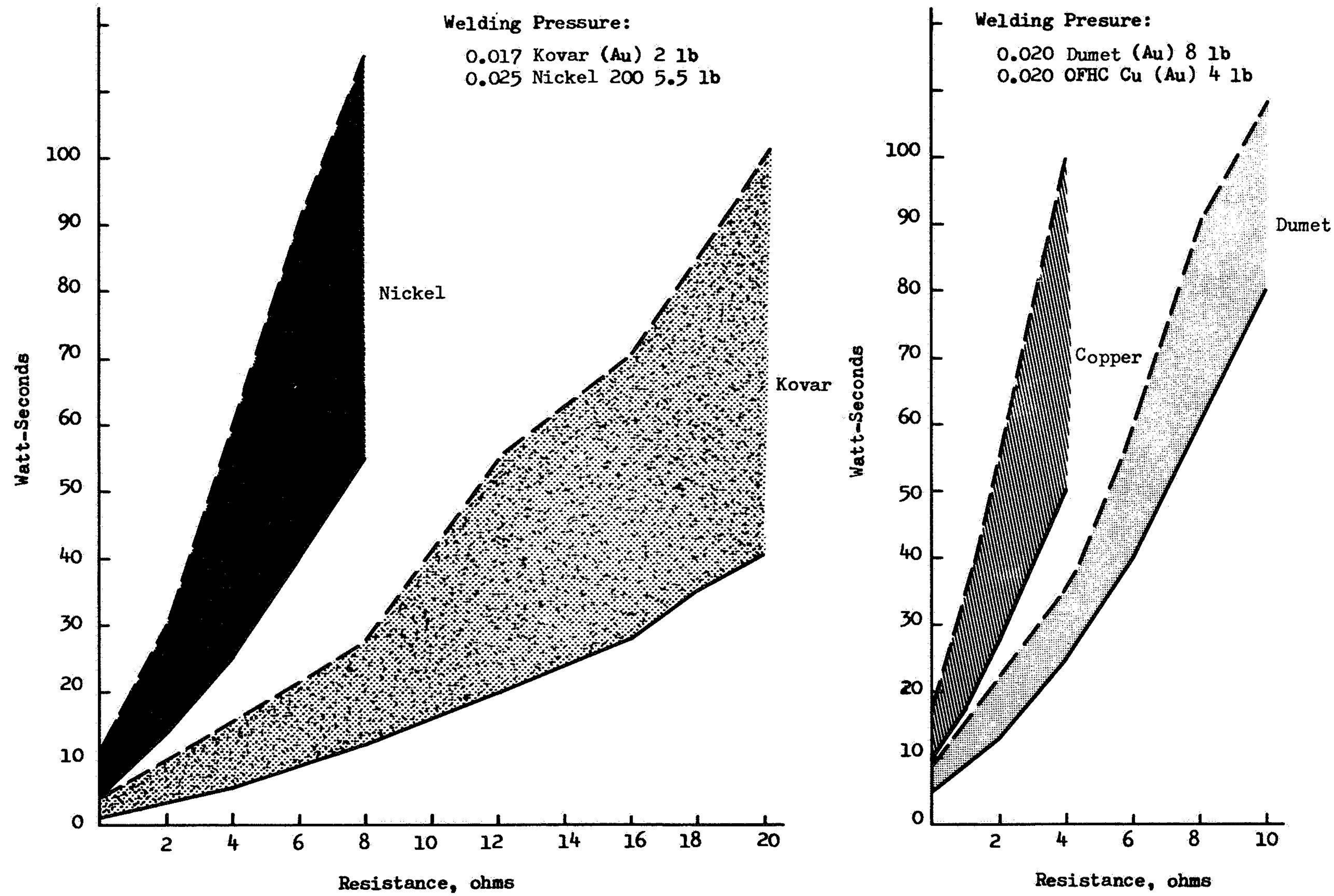


Figure 4. Improved Welding Range with LACD Impedance

Table III. Preliminary Data, Comparative Δ Watt-Second Welding Ranges of Standard Versus LACD Modified Equipment

Welding Pressure	2 lb		4 lb		5.5 lb		8 lb		10 lb	
Equipment Condition	Std	LACD	Std	LACD	Std	LACD	Std	LACD	Std	LACD
17 Kovar (Au)	3	60	1.5	50	1	45	0	40		
25 Kovar (Au)			6	88	3	72.5	7	77.5		
25 Ni 200			6	30	6	32	8	30		
32 Ni 205			1	35	1	25	2	20		
10 x 25 Ni 200	0	20	3	33	1	20	0	10		
20 Dumet (Au)										
No Ni flash			0	5						
With Ni flash			2	30	2	25	4	28		
32 Dumet (Au)			5	45	4	40	7	35		
With Ni flash										
16 OFHC Cu (Au)	1	0			0	0				
20 OFHC Cu (Au)							None		0	5
12 x 31 Ni 270 (1)			0	10	0	20				
20 OFHC Cu (Au)										
20 Ni "A"			0	0	0	0	0	0		
25 Ni 200			3	30	5	23	2	15		
32 Ni 205			7.5	50	9	50	8.5	45		

Note:

Welded to 10 x 20 Ni 205 except last group of 20 OFHC Cu (Au) which is welded to 20 Ni "A", 25 Ni 200, and 32 Ni 205 as specified.

Backup data for this table is contained in Section VII.

(1) Weld only to 20 OFHC Cu (Au)

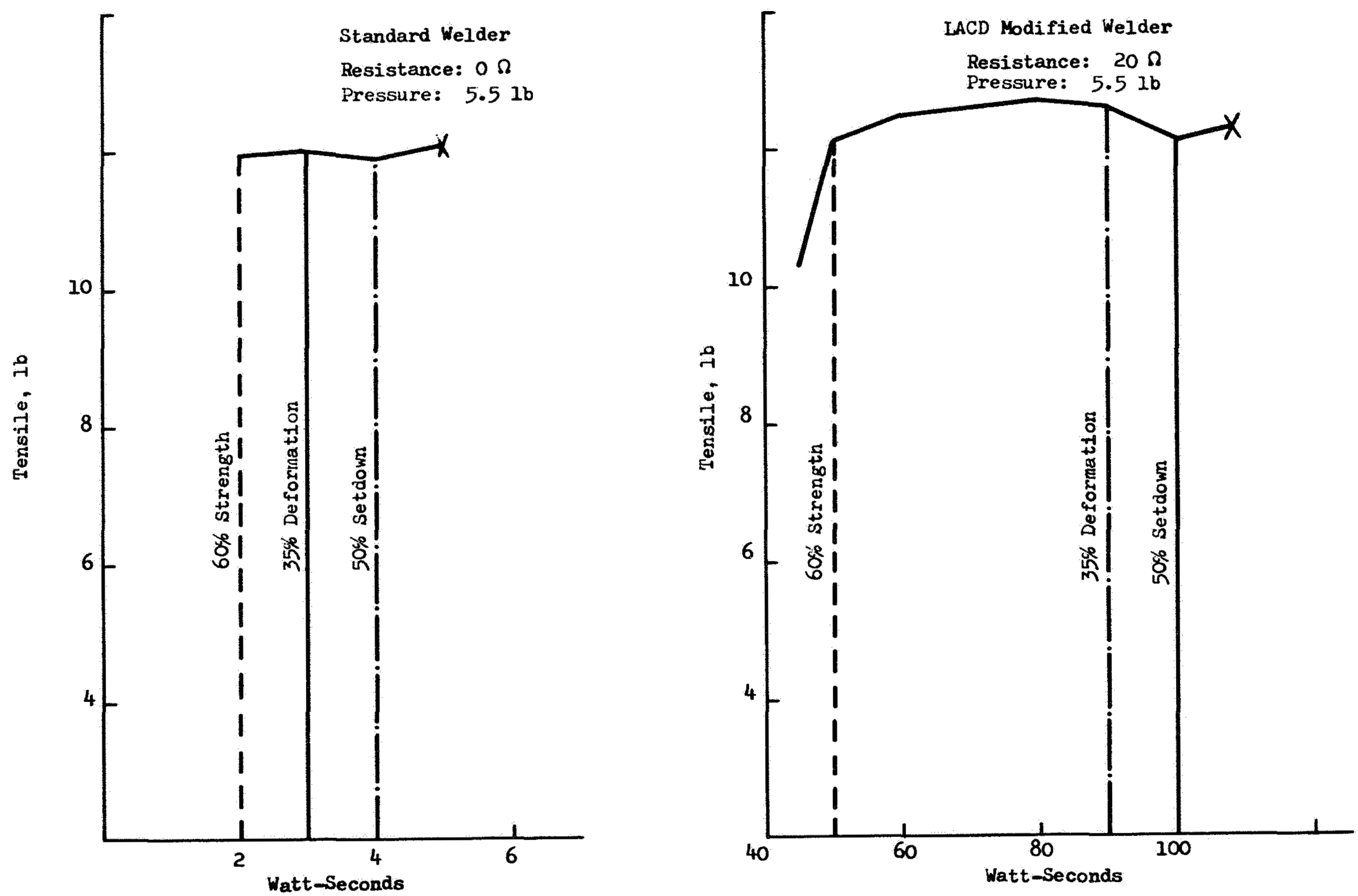


Figure 5. Isostrength Data - 0.017 Kovar (Au) to 0.010 x 0.020 Ni205

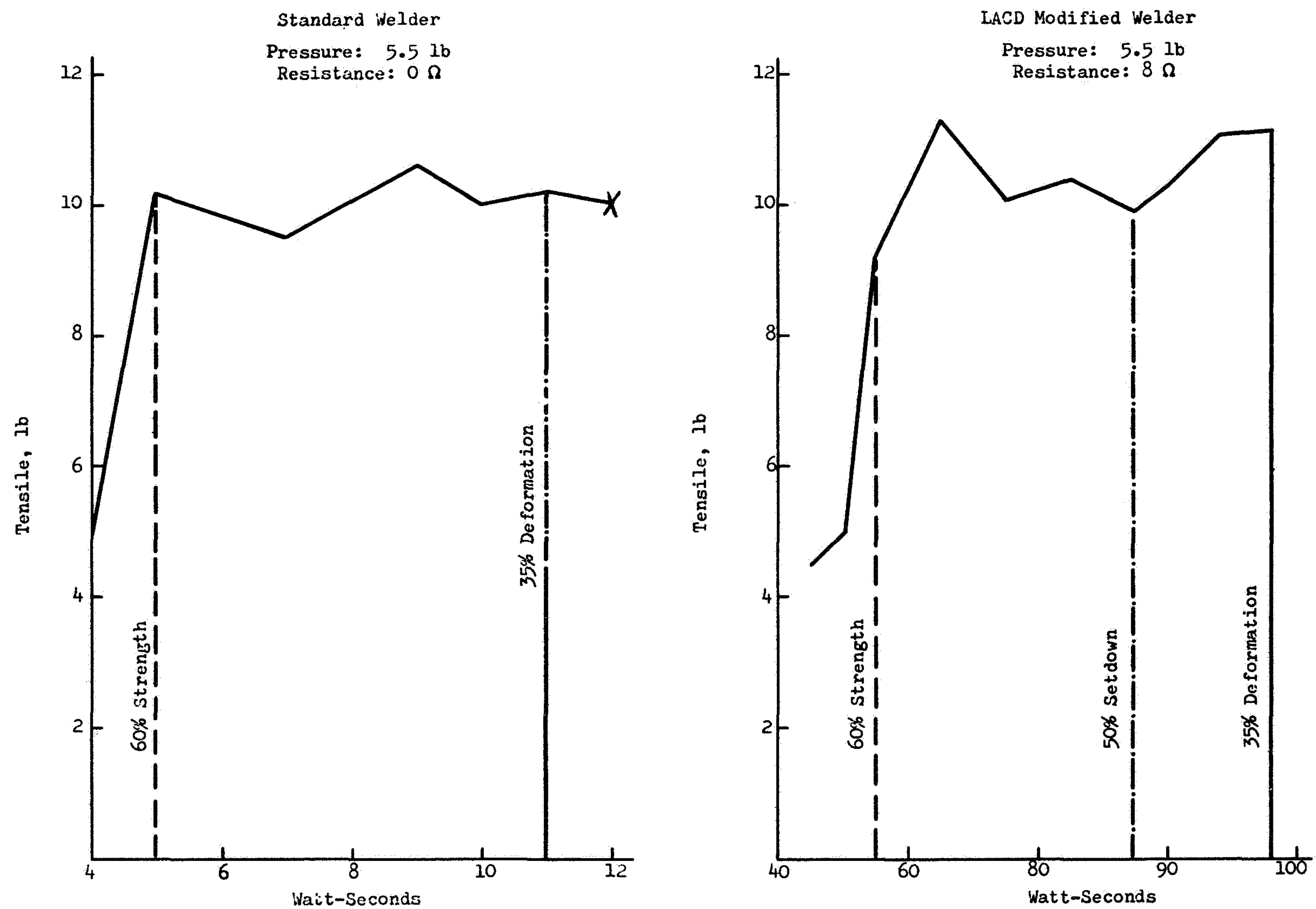


Figure 6. Isostrength Data - 0.025 Ni200 to 0.010 x 0.020 Ni205

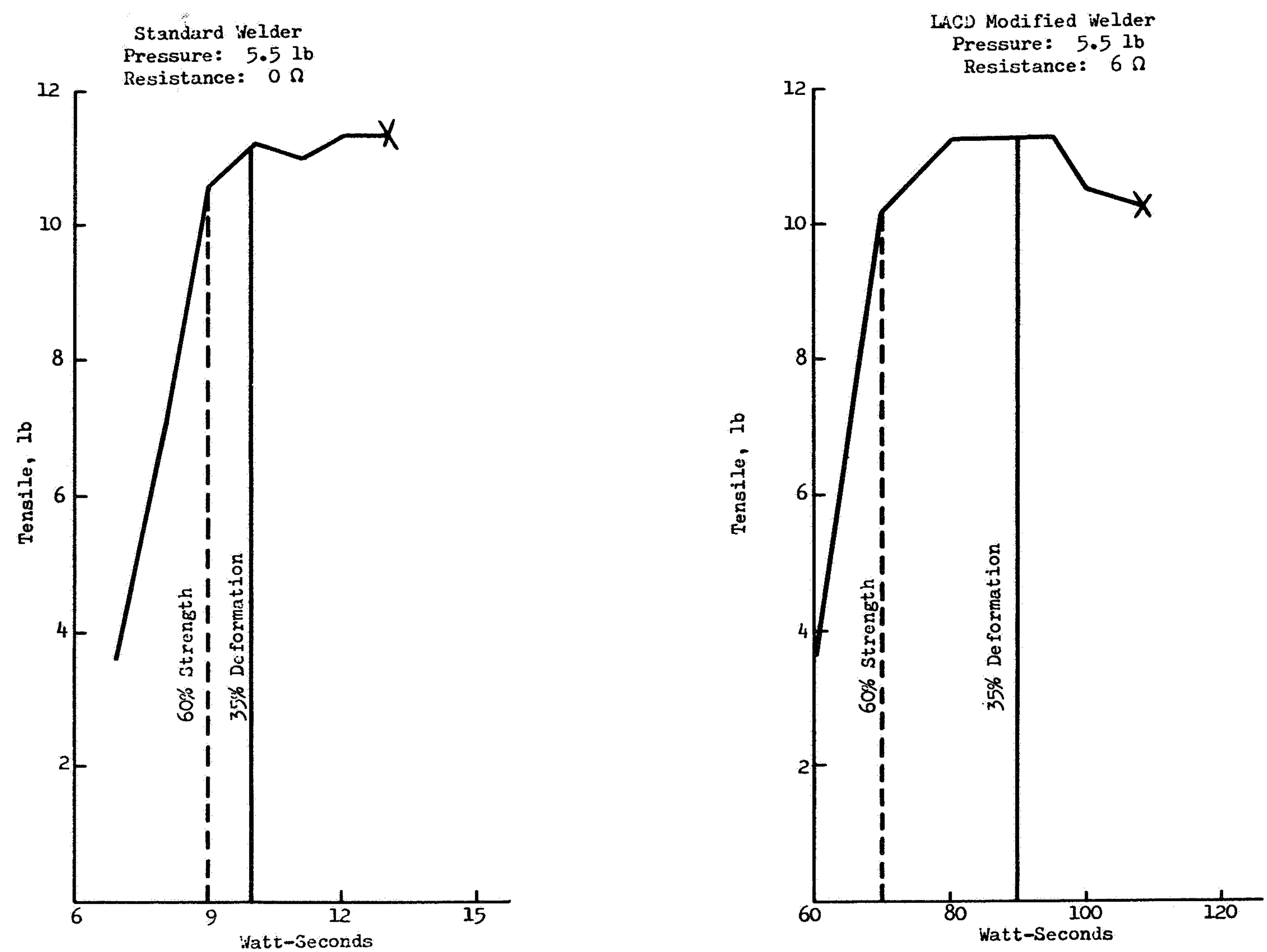


Figure 7. Isostrength Data - 0.010 x 0.025 Ni200 to 0.010 x 0.020 Ni205

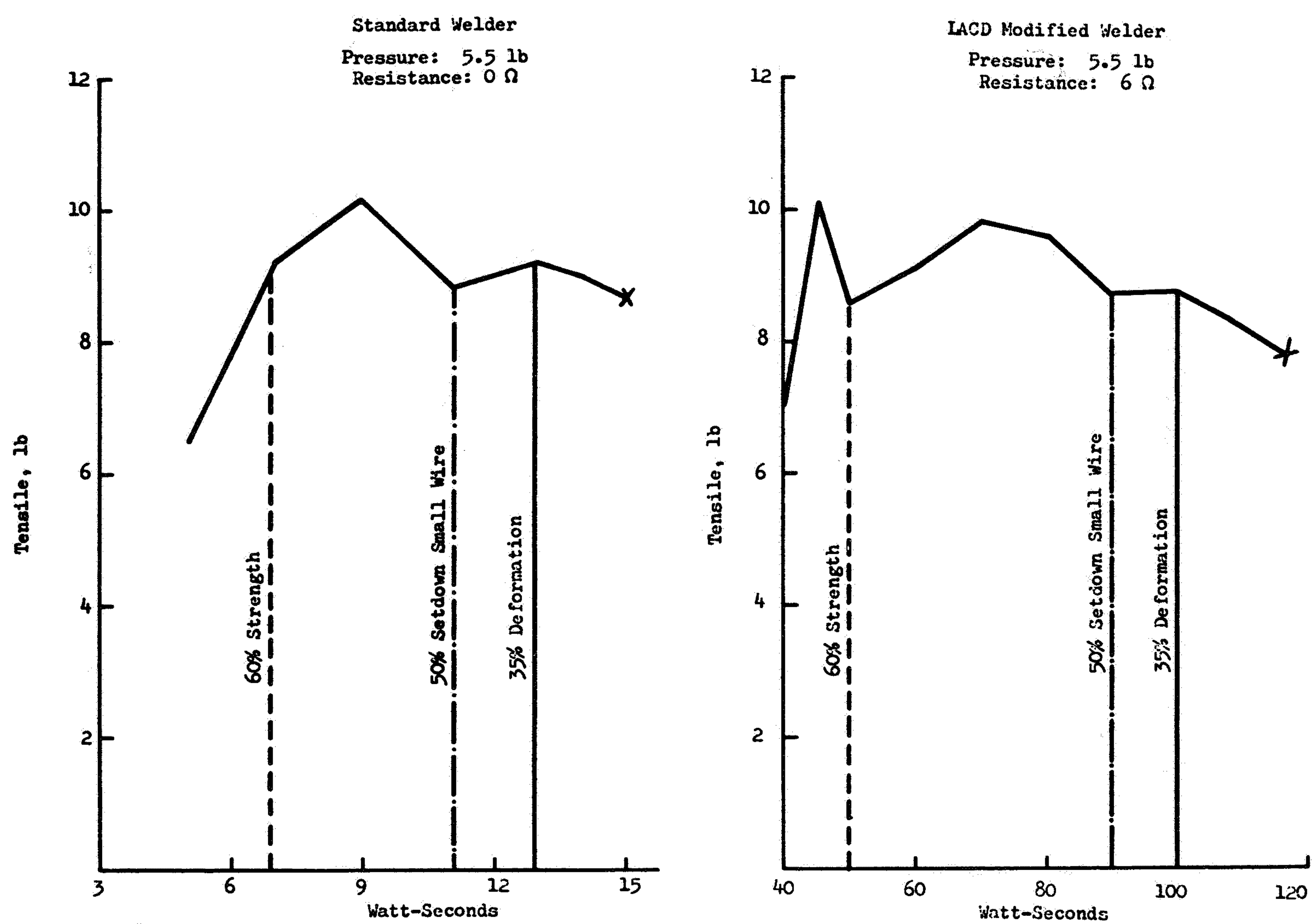


Figure 8. Isostrength Data - 0.032 Dumet (Au) to 0.010 x 0.020 Ni205

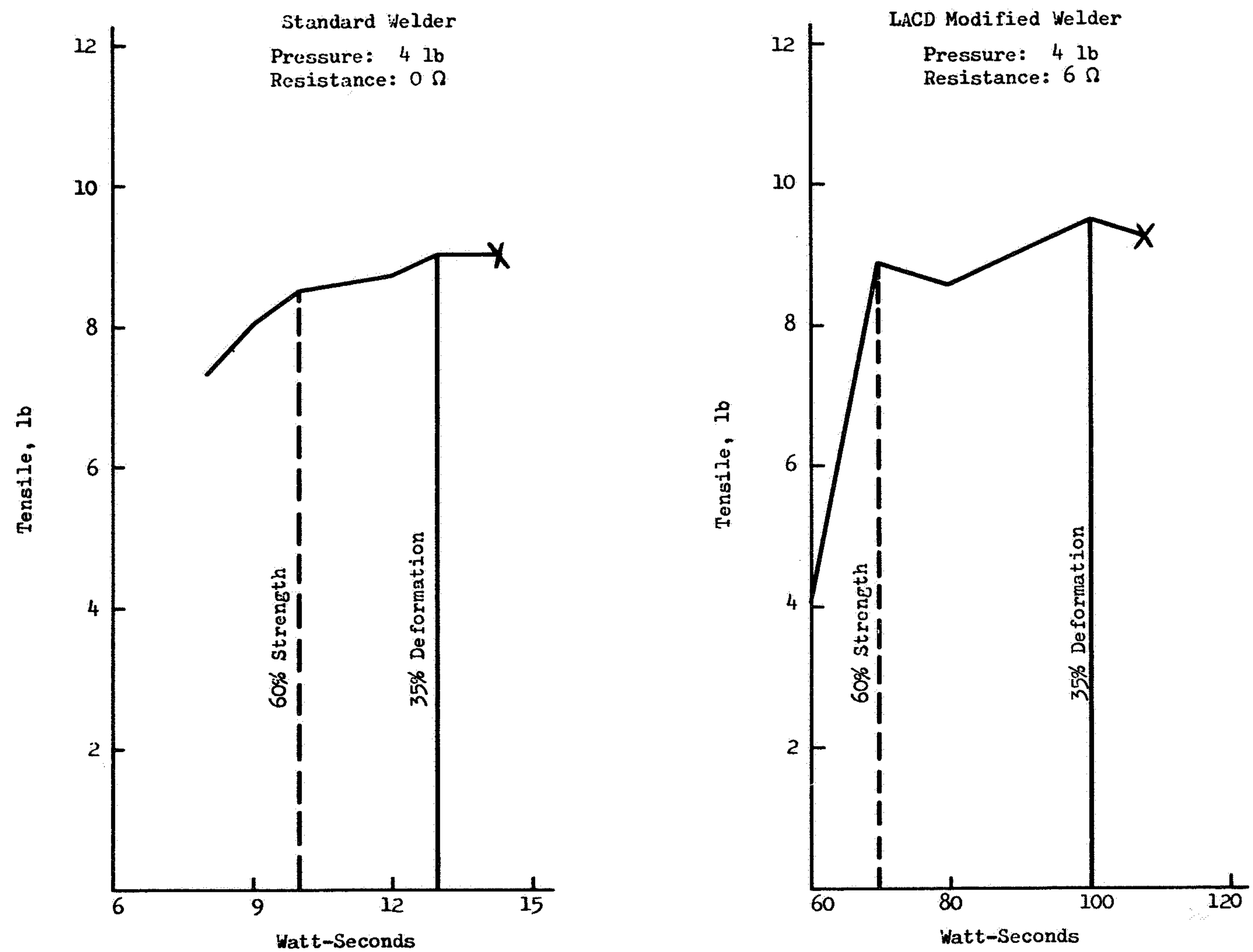


Figure 9. Isostrength Data - 0.020 OFHC Cu (Au) to 0.025 Ni200

Table IV

Average Joint Strengths of Complete Welding Range, Standard and LACD Modified Equipment

(Welding Pressure: 5.5 lb)

Materials Mils	Standard Welder		LACD Mod Welder		LACD/Standard Strength Ratio
	Strength Avg	Population	Strength Avg	Population	
17 Kovar (Au) 10 x 20 Ni 205	10.0 lb	6 (1)	10.5 lb	15 (1)	1.04
25 Kovar (Au) 10 x 20 Ni 205	9.8 lb	9	9.9 lb	21	1.01
10 x 25 Ni 200 10 x 20 Ni 205	10.9 lb	6	11.0 lb	9	1.01
25 Ni 200 10 x 20 Ni 205	10.1 lb	15	10.2 lb	15	1.01
32 Ni 205 10 x 20 Ni 205	11.1 lb	6	10.5 lb	12	0.95
20 Dumet (Au) 10 x 20 Ni 205	9.6 lb	6	9.8 lb	9	1.02
32 Dumet (Au) 10 x 20 Ni 205	9.4 lb	12	9.4 lb	15	1.00
20 OFHC Cu (Au) 25 Ni 200	8.7 lb	9	9.1 lb	12	1.04
20 OFHC Cu (Au) 32 Ni 205	9.2 lb	12	9.5 lb	18	1.03
20 Silver (bare) 10 x 20 Ni 205	5.3 lb	5	5.9 lb	10	1.13

(1) Information obtained from welding ranges established on isostrengths such as shown in Figures 5 through 9, etc.

2. Copper Nickel Weldability

During the preliminary evaluation of standard versus LACD modified equipment, it was observed that the copper to nickel ribbon series shows poor weldability. This was based on the use of the RWMA No. 2 welding electrode used as a Martin Marietta standard for welding electronic modules. A welding range was achieved on welding OFHC copper to 10 x 20 Ni 205 nickel ribbon by the standard process when the copper mass was smaller than that of the Ni bus as with 0.016 OFHC copper (Au), but not with 0.020 OFHC copper(Au). It was possible to weld 0.020 OFHC copper (Au) to a larger cross-sectional ribbon 12 x 31 Ni 270 at single points, but still could not establish a welding range. The LACD welding process produced welding ranges with all of these combinations except the 0.016 OFHC copper (Au) to 10 x 20 Ni 205 where only welds were achieved at single watt-second settings at an impedance setting at 4 ohms and 10 ohms. It was observed that significantly improved welding ranges were achieved on welding 0.020 OFHC copper (Au) to a ribbon of larger cross-section or by welding a smaller copper wire to a given 10 x 20 nickel 205 ribbon size. To further evaluate this relationship, three nickel wire diameters (0.020, 0.025, and 0.032) were each welded to three OFHC copper (Au) wire diameters (0.010, 0.016, and 0.020). Table III shows the results with the standard and LACD modified welders. On welding 0.020 OFHC (Cu) to the largest diameter nickel wire of 0.032 diameter. Watt-second welding ranges as high as 7.5 watt-seconds were obtained with the standard power supply at 4 pounds pressure, 9 watt-seconds at 5.5 pounds pressure, and 8.5 watt-seconds at 8 pounds pressure. The LACD modified welding equipment produced welding ranges of essentially 50 watt-seconds at each of the three welding pressures. The actual usage of moly welding electronics (recommended to achieve optimum heat match on welding OFHC copper) produced LACD welding ranges as high as 70 watt-seconds. Plotting the LACD welding ranges versus the square of the ratio of nickel to copper diameters provided the results shown in Figure 10. A family of curves is indicated. The possibility of predicting welding ranges for the selected nickel to copper diameter appears highly feasible. An OFHC copper to nickel mass relationship may be selected to achieve the desired LACD welding watt-second range.

C. FINAL EVALUATION

The LACD modified welder was compared to the standard welder by comparing qualified welding ranges and photomicrographs of the cross-sectioned weld joints. The LACD weld pulses were correlated to the emitted infrared pulse during welding.

1. Comparison of Standard Versus LACD

Qualification tests were performed to substantiate the weld improvement obtained by the LACD process over the standard process during the preliminary study. The extent of improvement, in most cases, remained unchanged even though both the standard and LACD weldability ranges were somewhat smaller than was observed in the preliminary data. The qualification test established firm upper and lower watt-second limits at which sound welds could be made, for the standard and LACD processes. A total of 50 welds was made at all limits, meeting NASA criteria for a sound weld.

When either limit failed to meet quality requirements by as few as one weld in a series of 50, the limit was moved to a more conservative setting and the qualification test rerun. The qualified welding limits established for both the standard and LACD welding processes are shown in Table V. Ten materials combinations are listed. Approximately 130 qualification tests were run to successfully complete the listed 113 qualification test results specifying maximum and minimum welding currents. This amounts to some six to seven thousand welds.

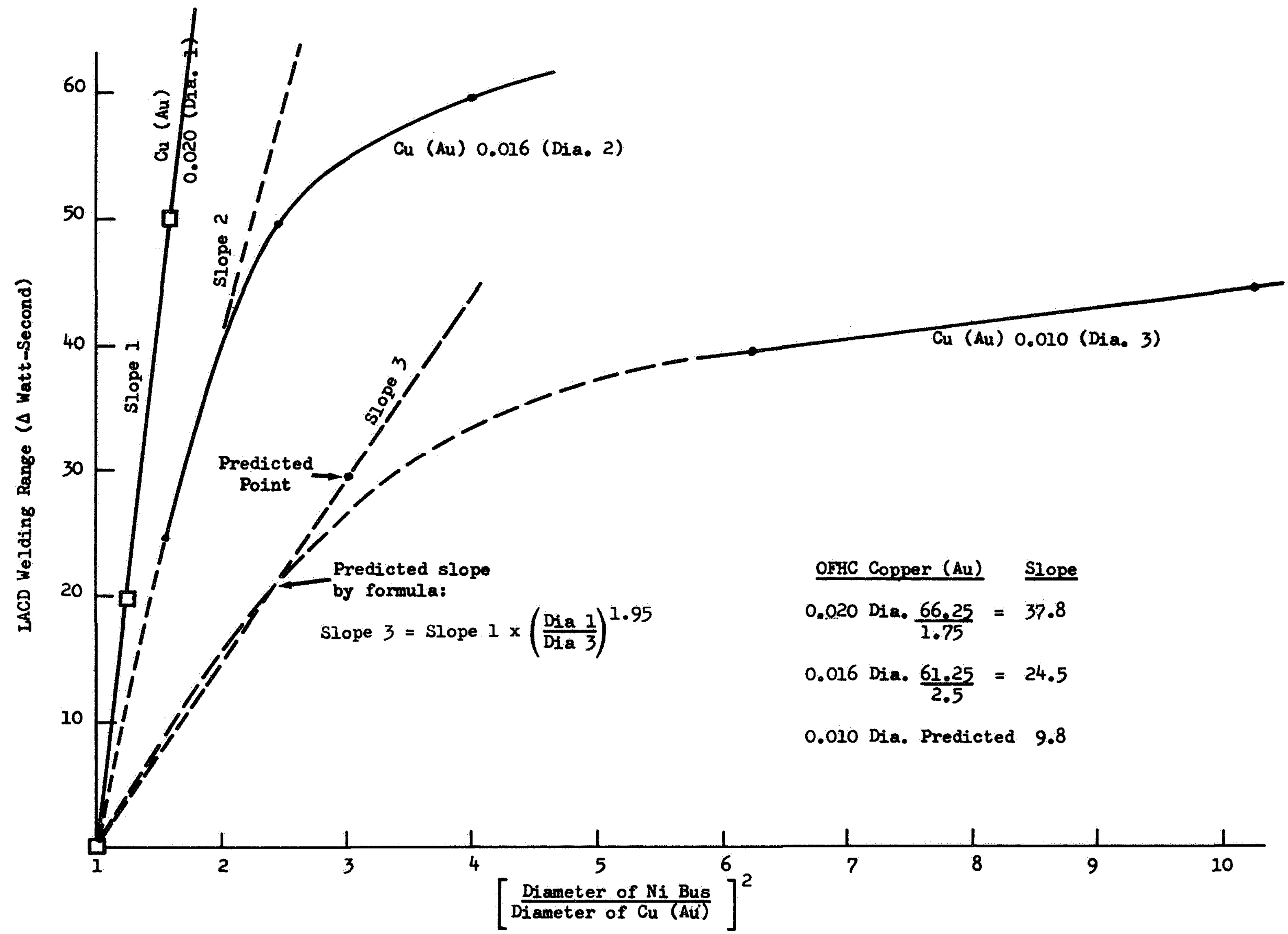


Figure 10. Correlation of LACD Welding Range with the Ni/Cu Mass Relationship

TABLE V

Welding Parameters and Welding Range, Standard and LACD Modified Hughes Power Supply

Materials Combinations		Standard Power Supply				LACD Modified Power Supply							
		Low Power Scale, 0-15 W-s				Low Power Scale, 0-15 W-s				High Power Scale, 0-100 W-s			
	Pressure	Ohms	Watt-seconds			Ohms	Watt-seconds			Ohms	Watt-seconds		
mils	lb	Ω	Min.	Max.	Range	Ω	Min.	Max.	Range	Ω	Min.	Max.	Range
17 Kovar(Au)	2	0	2	4	2	4.5	7	15	8	21	50	100	50
X	4	0	2	3.5	1.5	5.25	8.5	15	6.5	21	55	100	45
10x20 Ni 205	5.5	0	2	3	1	4.75	8	15	7	20	50	100	50
	8	0	2	3	1	4	8	13	5	18	50	90	40
25 Kovar(Au)	4	0	2	6	4	2.5	5	15	10	14	35	100	65
X	5.5	0	3	6	3	2	5	15	10	12	27.5	100	72.5
10x20 Ni 205	8	0	3	6	3	2	6	15	9	13	40	100	60
10x25 Ni 200	2	0	>5.5	6	0	1.4	12	15	3	9.5	80	100	20
X	4	0	7	8.5	1.5	1.1	13	15	2	8.5	90	100	10
10x20 Ni 205	5.5	0	>8.5	9	0	0	0	0	0	7.5	95	100	5
25 Ni 200	4	0	4.5	6	1.5	2	11	15	4	11.25	75	100	25
X	5.5	0	5	7	2	1.5	9.5	15	5.5	10	80	100	20
10x20 Ni 205	8	0	6	8	2	1	12	13	1	9	90	100	10
32 Ni 205	4	0	4.5	6	1.5	2	10.5	15	4.5	10	65	100	35
X	5.5	0	5	7	2	1.5	11	15	4	10	85	95	10
10x20 Ni 205	8	0	7	8.5	1.5	1	12	15	3	8	85	100	15
20 Dumet(Au) X 10x20 Ni 270	12	0	5.5	6	0.5	1.5	13	14.5	1.5	9.25	85	100	15
32 Dumet(Au) X 10x20 Ni 270	12	0	> 6.5	7	0	0	0	0	0	7.5	80	100	20
20 OFHC(Au) X 25 Ni 200	4	0	10.5	13	2.5	0	0	0	0	6	70	100	30
20 OFHC(Au) X 32 Ni 205	4	0	12.5	17.5	5	0	0	0	0	4	50	100	50
20 Ag (bare)	5.5	0	12.5	12.5	0					4	80	90	10

Qualification welding ranges were obtained on all materials combinations evaluated by the LACD process except for the copper to ribbon combinations. All were welded using the RWMA No. 2 welding electrode. Two materials combinations showed zero welding ranges, on evaluation by the standard process, in addition to the copper to ribbon combinations. See Table V. Zero welding range is defined as a welding range less than one-half watt-second. These materials for which a welding range could not be established on qualification testing were: 1) 0.032 inch diameter gold plated dumet, and 2) 0.020 inch diameter bare silver wire.

Direct comparison of the welding range obtained by the standard welder on the low power scale and the welding range obtained with the LACD modified welder on the high power scale shows an exaggerated improvement. To compare these data it is necessary to convert to percent values. All welding ranges derived from the qualified data which were developed on the low scale (0 to 15 W-s) and reported in columns 1 and 2, are divided by 15. All welding ranges developed on the high scale (0 to 100 W-S) and reported in column 3, are divided by 100. These values represent the percentage of the lower and upper watt-second scale utilized by the welding range, and are expressed as percent scale utilization in Table VI, columns 4, 5 and 6. These values show that the LACD process has produced a significant improvement over that obtained by the standard process. A LACD improvement factor may be expressed as a ratio of these percentage values, ie, the LACD scale utilization percent divided by the standard scale utilization percent. LACD improvement factors are shown in Table VI, columns 7 and 8.

The greatest improvement in weldability is indicated by the LACD improvement factor on the dumet wires to nickel ribbon combinations. This is followed by kovar wire to nickel ribbon combinations, and then the nickel wire to nickel ribbon combinations. Improvement factors obtained with 0.020 inch diameter OFHC (Au) wire to nickel wire combinations show one improvement factor somewhat lower than that achieved on the nickel wire to ribbon and one value somewhat higher. In all cases the LACD improvement factors were 1.8 or greater. In case of the 1.8 value for 0.020 OFHC (Au), the standard power supply watt-second range on the low power scale was 2.5 watt-seconds, on the high power scale the welding range obtained with the LACD modified welder was 30 watt-seconds. This is 5 watt-seconds higher than the welding range obtained on the 0.025 inch diameter nickel to 0.010 x 0.020 inch nickel ribbon combination, and 5 watt-seconds less than the welding range obtained with the 0.035 inch diameter nickel to 0.010 x 0.020 nickel ribbon combination.

A requirement generated in another Martin Marietta division required a quick look at joining silver wire to nickel ribbon. Weld joints could

TABLE VI

LACD Improvement Factor, Optimum Welding Range, Standard and LACD Modified Equipment

			Optimum Welding Range Δ W-s			Optimum Scale Utilization %			LACD Improvement Factor	
Column Number			1	2	3	4	5	6	7	8
Equipment Condition			Std.	LACD Modified		Std.	LACD Modified		LACD Modified	
Power Scale			Low	Low	High	Low	Low	High	Low	High
Material mils	Pressure lb Std.	Pressure lb LACD	Scale 0-15 W-s	Scale 0-15 W-s	Scale 0-100 W-s	$\frac{\text{Col. 1}}{15}$	$\frac{\text{Col. 2}}{15}$	$\frac{\text{Col. 3}}{100}$	$\frac{\text{Col. 5}}{\text{Col. 4}}$	$\frac{\text{Col. 6}}{\text{Col. 4}}$
17 Kovar(Au)	2	2	2	8	50	13.3	53.3	50	4	3.8
25 Kovar(Au)	4	5.5	4	10	72.5	26.7	66.7	72.5	2.5	2.7
10x25 Ni 200	4	2	1.5	3	20	10	0	20	0	2
25 Ni 200	5.5	(1)	2	5.5	25	13.3	36.7	25	2.8	1.9
32 Ni 205	5.5	4	2	4.5	35	13.3	30	35	2.3	2.6
20 Dumet(Au)	12	12	0.5	1.5	15	3.3	10	15	3	4.5
32 Dumet(Au)	12	12	0	0	20	0	0	20	0	∞
20 OFHC(Au) x 25 Ni 200	4	4	2.5	0	30	16.7	0	30	0	1.8
20 OFHC(Au) x 32 Ni 205	4	4	2.5	0	50	16.7	0	50	0	3
20 Ag (bare)*	5.5	5.5	0	0	10	0	0	10	0	∞

*Based on limited data test run

(1) 5.5 lbs on Low Power Scale and 4 lbs on High Power Scale

be achieved at 12.5 watt-seconds at a pressure of 5.5 pounds, meeting the 60 percent minimum strength level without spitting. However, defective welds were obtained at settings only one-quarter watt-second above or below this value. The LACD modified welder produced consistently good weld joints over a welding range of 10 watt-seconds, from 80 to 90 watt-seconds, with a LACD impedence setting of 4 ohms. These were not qualified results but were based on a preliminary study involving approximately 200 welds.

The qualification test data recorded in Table V and additional qualification test data have been evaluated to determine the minimum and maximum watt-second settings which can be used for the welding of two or more material combinations. These combinations are shown in Table VII as Combo-set 1, Combo-set 2, and Combo-set 3. Essentially, Combo-sets one through three are weldable by the standard power supply as well as the LACD modified welder. The same was found to be true for wire to ribbon material combinations, 0.025 inch diameter kovar (Au) to ribbon, and nickel wire to ribbon combinations. The ranges over which these sets can be welded are shown for pressures of 4, 5.5, and 8 pounds. In the case of Combo-set 1, the joint welding range was improved by LACD modified weld equipment by a factor of 4 to 1. No advantages were achieved using the LACD modified welder on Combo-sets 2 or 3 since the improvement factor has a value of less than one. This appears to be due to the divergents of the welding ranges with increased resistance. The LACD monoparametric improvement factor was calculated as the ratio of scale utilization percentages as shown at the bottom of Table VII.

2. Metallographic Examination

Cross-sectioned welding joints were made of all material combinations at the minimum and maximum watt-second settings on welds from the standard welder and the LACD modified welder. Figures 11, 12, and 13 show representative photomicrographs of the maximum power settings of one of each of the two materials diameters investigated, and for each type of materials welded. Each weld met all NASA requirements for strength, deformation, setdown, and expulsion. No significant difference was observed in the general appearance of these sectioned specimens from the standard welder or the LACD modified welder. Examination of the photomicrographs shows the weld joint interface and grain size to be identical. Some slight grain enlargement is apparent in both types of weld joints but no significant difference can be seen. Photomicrographs for OFHC copper (Au) show the lower welding limit of one materials combination (Figure 13, views c and d). These reveal somewhat less deformation and lower bonding area.

Metallurgical studies have shown that sound bonds were obtained on welding kovar to nickel, nickel to nickel, and dumet core to nickel. At the minimum acceptable strength levels, the dumet lead is bonded to the nickel ribbon by copper braze. In all other material combinations a true weld was observed by the appearance of recrystallization across the weld joint interface.

TABLE VII. MONOPARAMETRIC WELDING RANGE
STANDARD VERSUS LACD

Set of Materials Combinations mils	Pressure (lb)	Standard Power Supply				LACD Modified Welder				LACD M/I* Factor
		Ohms	Watt-seconds Min.	Watt-seconds Max.	Range R_1	Ohms	Watt-seconds Min.	Watt-seconds Max.	Range R_2	$0.15 \times \frac{R_{2\,max}}{R_{1\,max}}$ **
<u>Combo - Set 1</u>										
17 Kovar (Au)										
10x20 Ni 205	4	0	2	3.5	1.5	21	60	100	40	
	5.5	0	3	3	0	20	60	100	40	4.0
25 Kovar (Au)	8	0	3	3	0	19.5	65	100	35	
10x20 Ni 205										
<u>Combo - Set 2</u>										
25 Ni 200										
10x20 Ni 205	4	0	4.5	6	1.5					
	5.5	0	5	7	2	5.5	85	95	10	0.75
32 Ni 205	8	0	7	8	1					
10x20 Ni 205										
<u>Combo - Set 3</u>										
25 Kovar										
10x20 Ni 205	4	0	4.5	6	1.5	10	70	70	0	0
25 Ni 200	5.5	0	5	6	1	10	85	85	0	
10x20 Ni 205	8	0	0	0	0					
32 Ni 205										
10x20 Ni 205										

* based on scale utilization

** $\frac{R_2}{100} \div \frac{R_1}{15}$

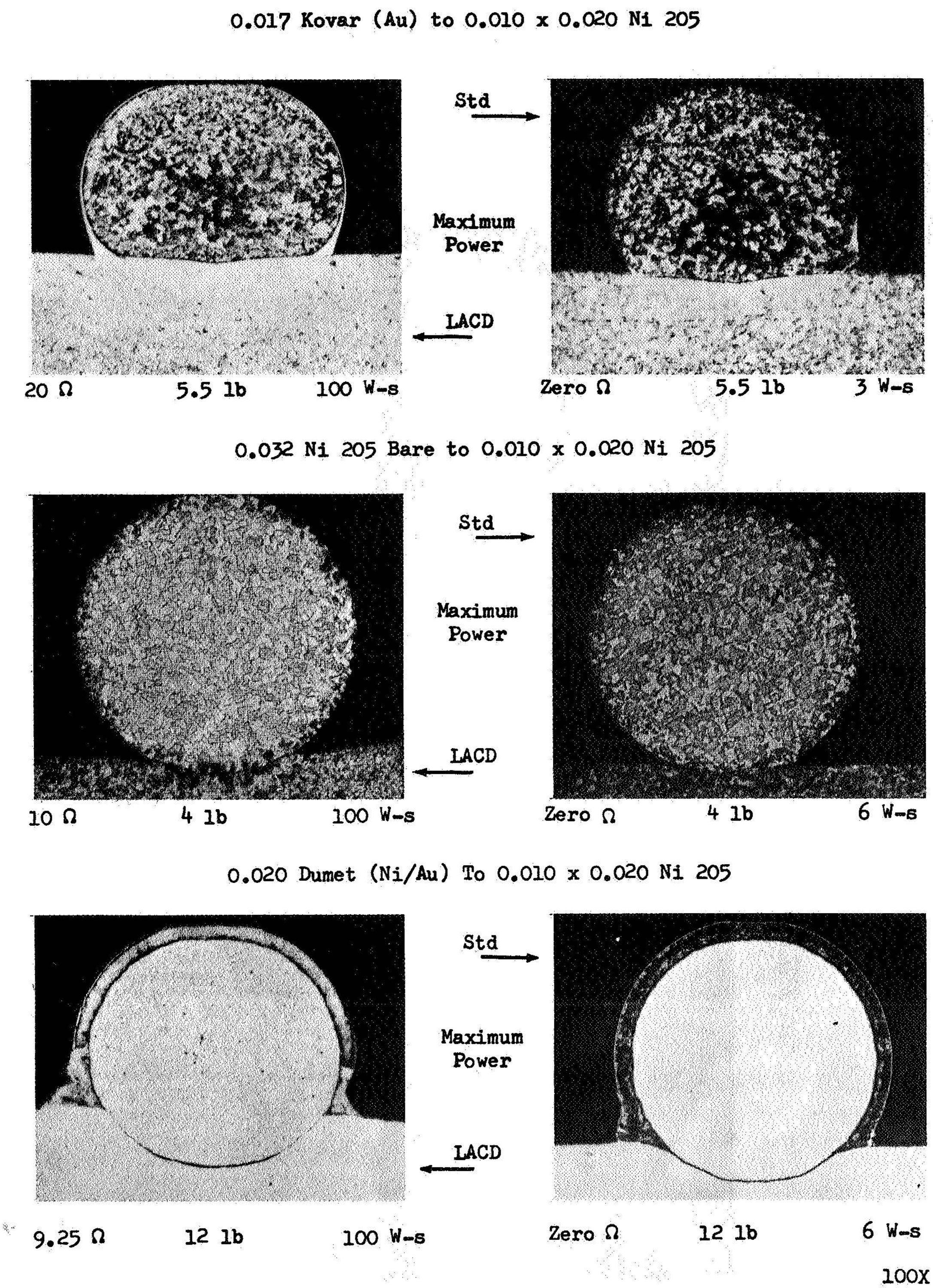


Figure 11. Representative Photomicrographs of Lead Materials (Note comparative grain growth and penetration)

0.010 x 0.025 Ni 200 to 0.010 x 0.020 Ni 205

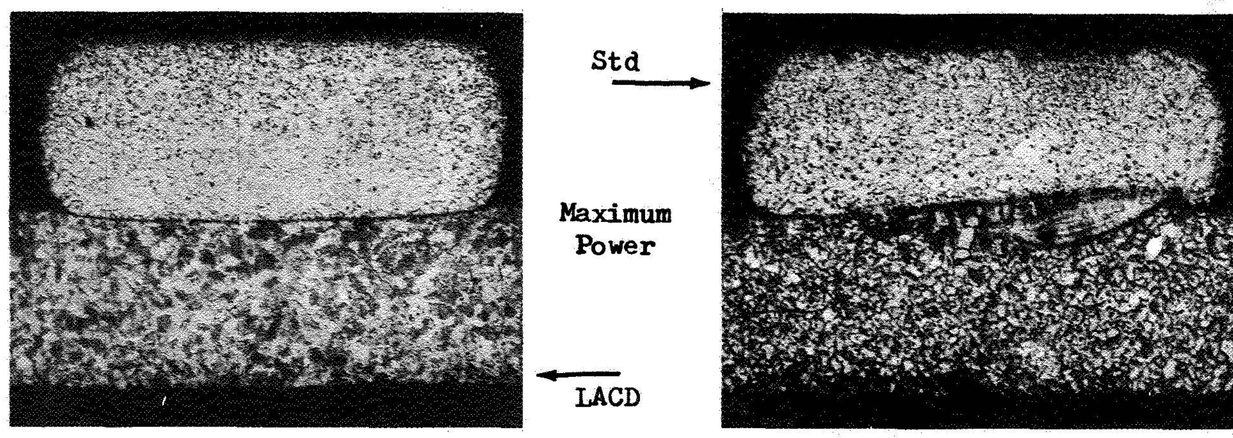


Figure 12. Photomicrographs of Ribbon to Ribbon Welds (Note comparable grain growth)

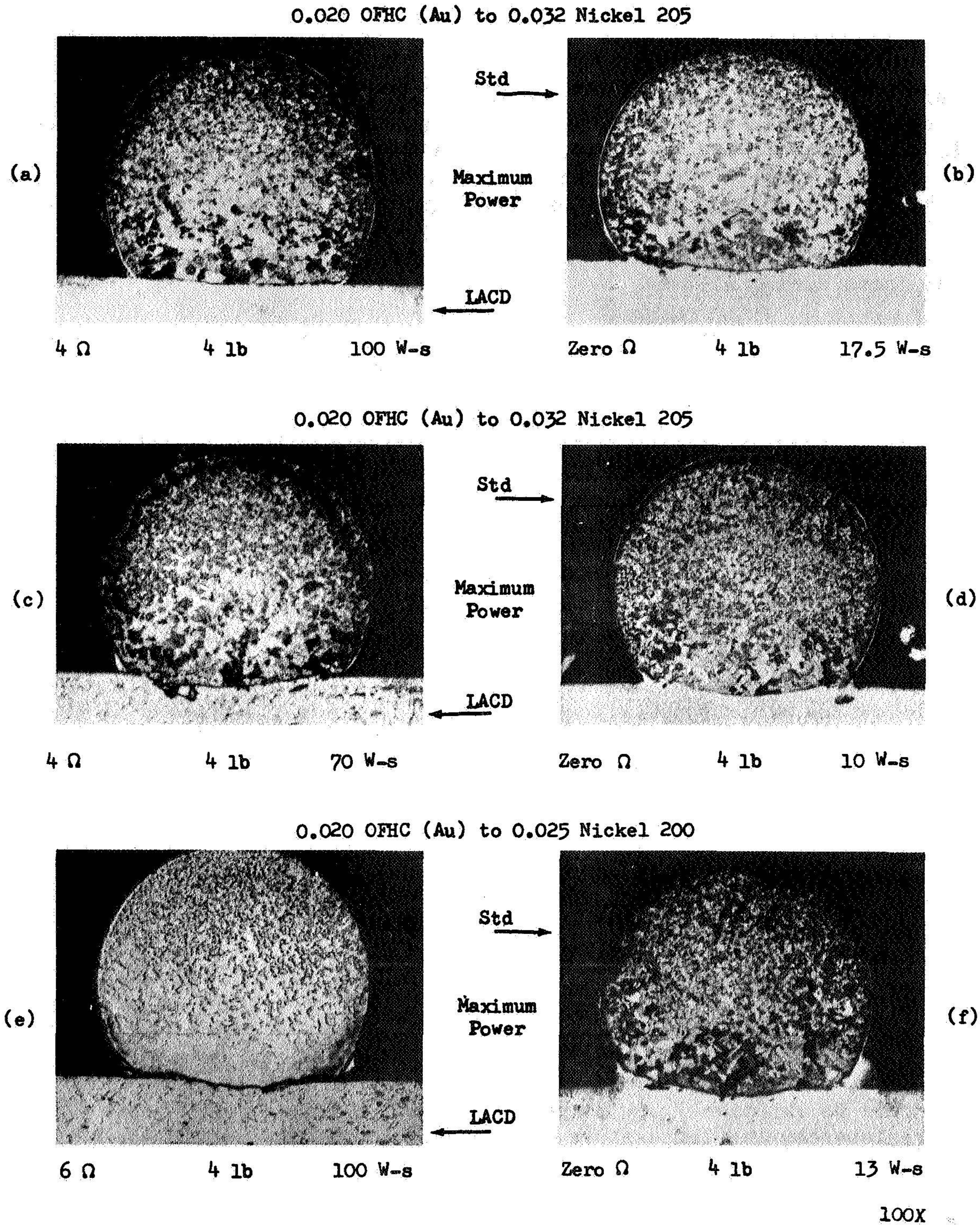


Figure 13. Photomicrographs of OFHC Copper (Au) to Nickel Wire (Note comparative grain coarsening obtained by both standard and LACD processes)

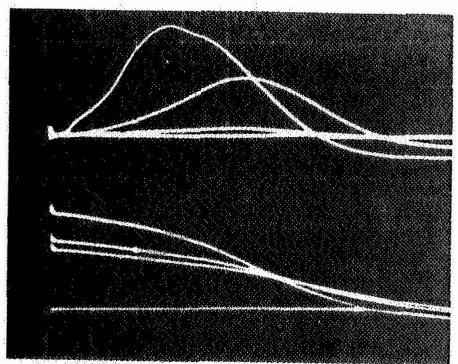
In the case of the nickel ribbon to ribbon welds, the weld area occurred off-center. Sectioning of the weld joint parallel to the axis of the smaller ribbon showed the weld to be approximately five mils off center with a 65 percent bond area. Polishing of two identical ribbon to ribbon weld joints on perpendicular planes approximately five mils on either side of theoretical center showed a sound weld nugget in one and the absence of a weld in the other. Special care was taken during the preparation of the welding electrodes at the welding pressure to assure parallel electrode faces during welding.

Visual inspection of the mating electrodes at 20X confirmed proper flat parallel seating at welding pressure. The off-centered weld appears to be caused by shunting or seeking the shortest current path toward the heels of the welding electrodes. The welding electrode configuration was modified to provide more uniform current density across the weld joint, as specified in this report.

3. Infrared Weld Pulse Evaluation

Oscilloscope traces were made of the welding current pulse and the infrared pulse resulting from the weld (Figure 14). A dual trace was made for each materials combination investigated. These show the maximum and minimum qualification weld settings obtained at the welding pressure of 5.5 pounds with an additional trace made at a welding current somewhat below the minimum qualification setting. Since the emitted IR is directly related to the temperature of the welding joint, it may be seen that the heating rate varies with the amplitude of the weld pulse. As the watt-second power setting is increased, the heating rate increases. The IR traces in the oscilloscope patterns show the effect of the physical properties of component lead base materials. The kovar IR traces (Figure 14, views a and b) are generally symmetrical with a gradual rise and drop in welding temperature. The elimination of the weld joint interface on melting does not appear to significantly affect heat generation in the kovar weld joint. In the case of nickel and dumet, views c through f, tendencies exist for the IR traces to occur more promptly. In fact, in views c and f, the IR traces rise more rapidly on welding dumet than the temperature decay of the weld joint, showing the effect of the loss of weld joint interface on melting. As this contact resistance is eliminated, the only resistance left is that of the molten weld joint. Since this is relatively low with respect to the initial weld joint interface resistance, the temperature of the weld joint declines.

(a)

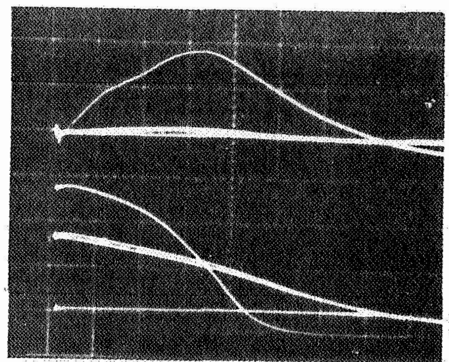


5

0.017 Kovar (Au) to 0.010 x 0.020 Ni 205
5.5 lb, 20 Ω; 100 W-s, 75 W-s, and 50 W-s

IR Pulse

Current Pulse

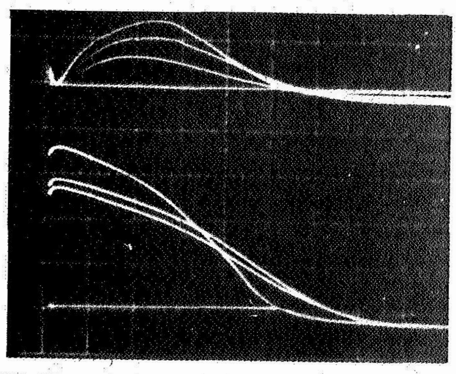


(b)

7

0.025 Kovar (Au) to 0.010 x 0.020 Ni 205
5.5 lb, 12 Ω; 100 W-s, 27.5 W-s, and 25 W-s

(c)

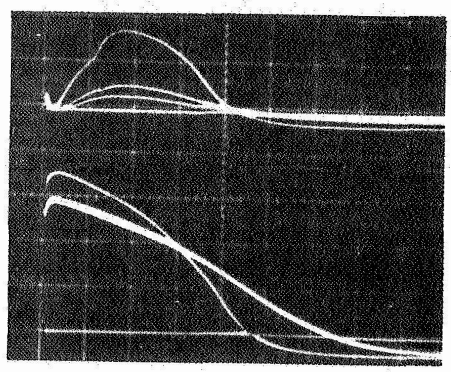


11

0.025 Nickel to 0.010 x 0.020 Ni 205
5.5 lb, 11.25 Ω; 100 W-s, 75 W-s, and 62.5 W-s

IR Pulse

Current Pulse

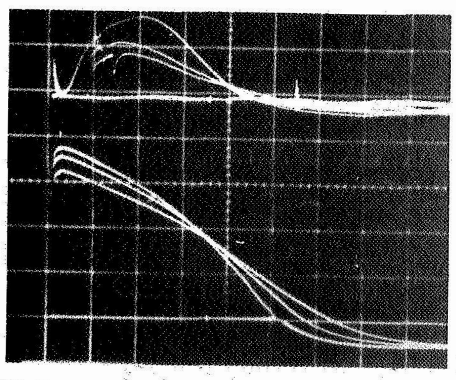


(d)

13

0.032 Nickel to 0.010 x 0.020 Ni 205
5.5 lb, 10 Ω; 100 W-s, 65 W-s, and 60 W-s

(e)

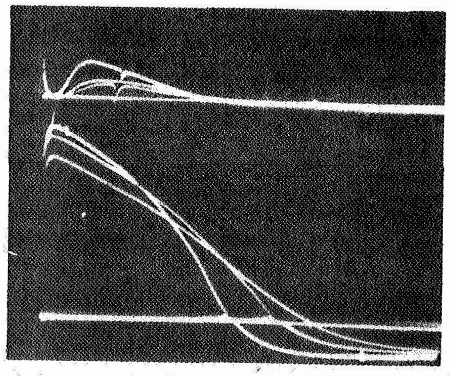


15

0.020 Dumet (Au) to 0.010 x 0.020 Ni 205
5.5 lb, 9.25 Ω; 100 W-s, 85 W-s, and 70 W-s

IR Pulse

Current Pulse



(f)

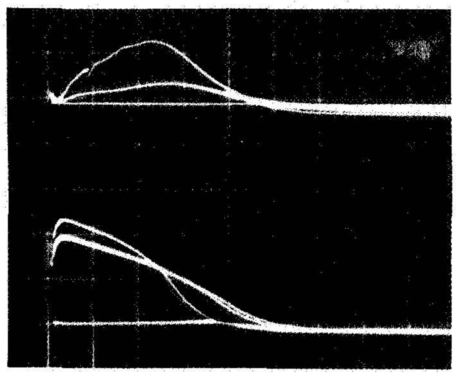
17

0.032 Dumet (Au) to 0.010 x 0.020 Ni 205
5.5 lb, 7.5 Ω; 100 W-s, 80 W-s, and 60 W-s

Scale: 2ms/cm

Figure 14. Oscilloscope Traces of Weld Current and Infrared Pulses

(g)

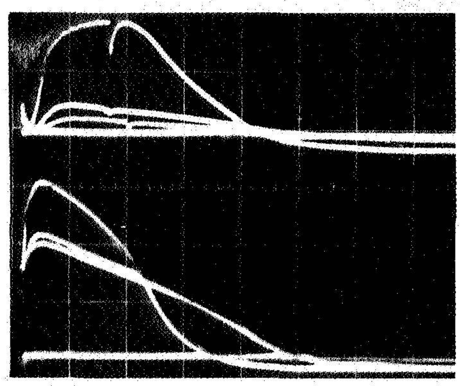


21

0.020 OFHC Cu (Au) to 0.025 Ni 200
5.5 lb, 6 Ω; 100 W-s, 70 W-s, and 65 W-s

IR
Pulse

Current
Pulse

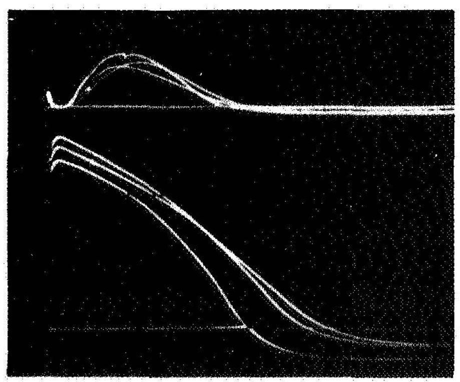


(h)

23

0.020 OFHC Cu (Au) to 0.032 Ni 205
5.5 lb, 4 Ω; 100 W-s, 50 W-s, and 40 W-s

(i)



IR
Pulse

Current
Pulse
9

0.010 x 0.025 Nickel to 0.010 x 0.020 Ni 205
5.5 lb, 8.5 Ω; 100 W-s, 90 W-s, and 80 W-s

Scale: 2ms/cm

Figure 14. Oscilloscope Traces of Weld Current and Infrared Pulses (cont)

III. DISCUSSION

The LACD modification has a demonstrated capability of shaping the weld pulse, limiting amplitude, and controlling current decay. Use of the LACD impedance setting in conjunction with the watt-second setting provides complete control of pulse shape, amplitude, and power. This has provided significant improvement in the weldability of all materials except the copper to ribbon combinations. However, the substitute 0.020 OHFC copper (Au) to two different nickel wire diameters of 0.025 and 0.032 inch showed improvements in weldability of 1.8 and 3.0, respectively. The joining of 0.020 silver lead material to 0.010 x 0.020 nickel ribbon was accomplished on a limited number of test welds over a welding range of 10 watt-seconds with the LACD modified welder.

During this program, welding parameters and conditions were tailored to "production conditions". The welding head was placed in a horizontal position with the welding electrodes down, to give the operator optimum visibility. Similarly, RWMA No. 2 electrodes (reduced to 0.060 diameters straight shaft at the welding tip) were used to simulate the production need to weld a complete module at one welding station. This eliminates the potential production problem of mixed electrodes. As a result, some reduction in welding range is accepted in certain materials. For this reason the standard RWMA No. 2 welding electrodes were used during the welding of OFHC copper to nickel ribbon.

Welding of OFHC copper has always been difficult even with optimum electrode combinations. With RWMA No. 2 electrodes, no welds were made by the standard welder on either OFHC copper wire to 0.010 x 0.020 ribbon, although 0.020 OFHC copper could be welded to the larger 0.012 x 0.031 Ni 270 ribbon, and larger nickel wires during the preliminary survey. With LACD, preliminary welds could be made with all wire and ribbon nickel bus materials. Qualification was achieved on 0.020 OFHC copper to both of the larger diameter nickel wires with both standard and LACD modified welders equipped with RWMA No. 2 welding electrodes.

The relationship (developed using the LACD modified welder) of copper/nickel mass ratio to the weldability range strongly indicates the possibility of specifying wire diameters to achieve a desired weldability range. While more extensive testing would establish more precise data, preliminary data were sufficient to demonstrate the copper/nickel mass relationship to LACD weldability range.

The LACD concept has demonstrated the ability to weld all material combinations weldable by the standard welder. No special tolerance limits must be imposed on any of the component lead materials evaluated. However, the fact that both kovar lead diameters were welded at pressures of 4, 5.5, and 8 pounds over the same 40 watt-second welding range strongly indicates that diameter tolerances can be opened one more mil on the high side of 0.017 kovar and the lower side of 0.025 kovar.

The experience obtained from performing a few tests on three laboratory lots of dumet wire has indicated a significant narrowing of the weldability range with increased gold plating thickness due to the formation of "gold fuzz". Nominal gold plating thickness was 280 μin.

On welding the heavier gold plated dumet material, a porous spongy gold colored substance develops at the weld joint at the lower watt-second settings. This substance, termed "gold fuzz", is easily brushed off, or removed with a high velocity dry air blast. At higher watt-second settings the normal molten fillets alloy with or prevent the formation of the "gold fuzz". Fillets must be 50 to 90 percent of the smaller of the two joint materials to prevent "gold fuzz". Best results were obtained with 0.010 x 0.020 INCO nickel 270 ribbon as compared with the standard electronic grade 0.010 x 0.020 nickel 205.

A sample from one of the troublesome lots of dumet was sectioned, and measured 280 microinches of gold plating. Sample material clipped from production components showed much better weldability than laboratory material. Production sample clippings of 0.020 dumet (Au) showed a gold plating thickness of 60 to 90 μin. For the new LACD process as well as the old, gold plating thickness should be kept on the low side of the specified 50 to 150 microinches. Also, tests performed on gold plated dumet without a nickel barrier layer exhibited severely restricted weldability. This experience emphasizes the necessity of adhering to NASA plating specifications with no waiver permitted on the nickel barrier requirement on gold plated dumet.

Examination of the physical properties of the welded component has shown that the LACD welding process has not been detrimental to the weld. The effective duration of the LACD weld pulse is about three to four times as long as the weld pulse of the standard welder. The LACD weld pulse is 12 milliseconds at the 63 percent decay point and 18 milliseconds at the 95 percent decay point at maximum impedance setting. At a much lower impedance setting, the LACD 63 percent decay point may be as short as 6.5 milliseconds. No sensation of heat was detected by touch on holding the component of lead materials close to the welding electrodes while welding with the LACD process or on touching the leads immediately after welding. Metallurgical examination of cross-sectioned welds made by the LACD process shows the grain size of both component lead and nickel bus material remains unchanged as compared to similar maximum power welds made by the standard welder. Of ten materials combinations examined at a typical welding pressure of 5.5 pounds, only one showed an apparent loss of 5 percent of weld strength. The remaining nine materials combinations showed an equivalent or slightly higher weld joint strength when welded with the LACD process.

One problem encountered during the program is considered worth noting. The welding power supply developed irregular performance. Trouble shooting showed no evidence of fault in the equipment. All tubes were changed and capacitors checked. Monitoring of the power line with a Tektronix oscilloscope showed no irregularities at the time the welding power supply watt-second meter showed a sudden positive deflection. Even so, the problem was resolved by changing to another power line. Later discussion of the problem with personnel performing laser research in an adjacent laboratory revealed that pulsing of the laser causes a sudden momentary phase shift of the 60 cycle voltage at the moment of firing. This phase shift cannot be detected by an oscilloscope when the oscilloscope sweep is synchronized by the incoming line voltage.

IV. CONCLUSIONS

The results of this program have lead to the following conclusions:

1. The LACD welding concept has significantly increased the standard weldability range of all materials investigated except the copper to nickel ribbon combinations.

2. The LACD welding concept has improved the weldability, as shown below in decreasing order with only OFHC Cu welded to nickel wire.

LACD Improvement Factor	Weldability Range
Dumet (Au) wire	Kovar (Au) wire
Kovar (Au) wire	OFHC Copper (Au)
OFHC Copper (Au)	Nickel (bare) wire
Nickel (bare) wire	Dumet (Au) wire
Nickel (bare) ribbon	Nickel (bare) ribbon

3. The LACD welding concept controls weld pulse height, pulse length, and current decay.

4. The LACD welding concept does not degrade the physical properties of the weld joint except for a slight loss in tensile strength from 11.1 to 10.5 pounds on 0.032 nickel to 0.010 x 0.020 nickel ribbon. No change in grain size was detected.

5. The absence of the nickel barrier layer in gold plated dumet seriously degrades weldability.

6. Heavy gold plating produces "gold fuzz" when welding gold plated dumet. Heavy weld fillets prevents the formation of "gold fuzz".

7. Quality assurance criteria for inspection of weld joints shall remain the same as with standard welding equipment. Process control and equipment requirements are specified in Section VI.

8. Gold plated 0.010, 0.016 and 0.020 OFHC copper wire demonstrated excellent weldability when welded to nickel bus wire one to two gauges larger than the copper wire being welded.

9. The square of the copper to nickel mass relationship can be directly correlated to LACD weldability range.

V. RECOMMENDATIONS

These recommendations are based on the conclusions contained in Section IV.

1. The present MSFC 270B specification which establishes dimensions and plating thicknesses is adequate for producing satisfactory welds with the LACD concept, if strict adherence to the following is maintained:

   1 Nickel barrier layer is required on gold plated dumet wire or otherwise where gold comes in contact with a copper surface.

   2 Specified 50 to 150 microinches of gold on dumet leads is not exceeded.

2. When a "gold fuzz" problem is encountered, use a tightly bonded heavy weld fillet as restricted by Quality Assurance items 6 and 7 of Part C of Section VI.

3. Any OFHC copper lead material required for special circuits must be limited to 0.010 to 0.020 inch diameter with nickel bus wire one to two gauges larger than the copper wire to be welded. Larger copper wire requires proportionately larger nickel bus wire which is difficult to bend on a production line.

4. Perform additional studies on the mass ratio of copper to nickel to more precisely establish the relationship and permit an enlightened design of a weldable electronic module containing OFHC component leads.

5. Modify the existing capacitor discharge welders to the LACD welding concept.

6. In the modification of any capacitor discharge welder, the capacitor discharge leakage resistor must be no less than 1000 ohms, and preferably greater than 2000 ohms.

7. Welding electrodes should be prepared as shown in Figure 15 to assure uniform welding current through the weld joint.

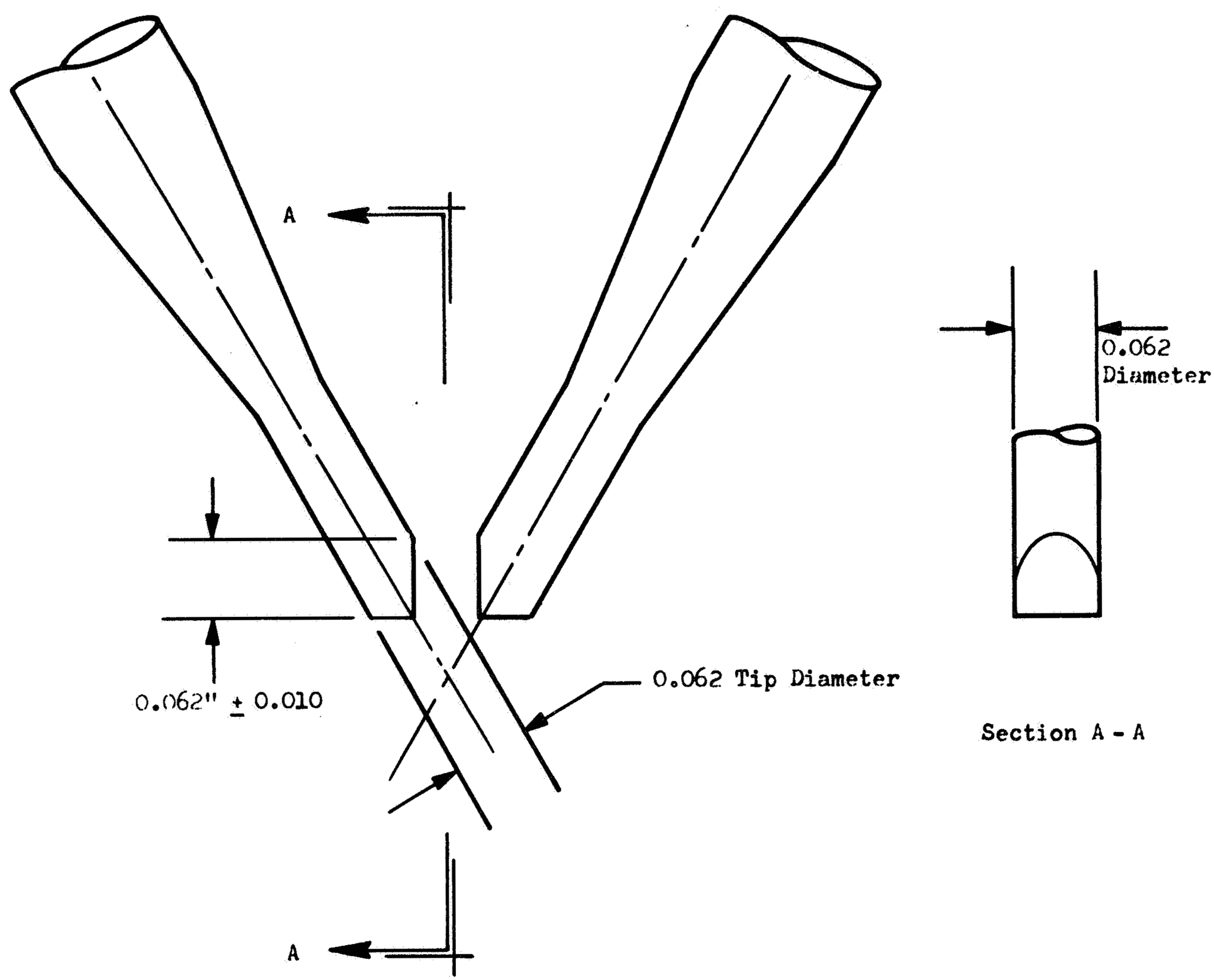


Figure 15. Electrode Tip Preparation

VI. SPECIFIC REQUIREMENTS

A. EQUIPMENT

The equipment required for this program consisted of a Hughes power supply, Model No. VTW-30C, modified with an impedance system as shown in Figure 1. The parts necessary to reconstruct the system are listed below.

Item	Rating	Quantity Required
DPST switch	16 amp per contact	5
Rheostat	0-5 ohms, 150 watt	1
Resistors	2 ohms, 40 watt	2
Resistors	5 ohms, 40 watt	3

Interconnecting wiring is No. 10 gauge, insulated for 500Vdc minimum.

B. PROCESS CONTROL

To realize the most reliable and consistent results, strict attention must be observed regarding:

1 Welding electrode configuration

2 Welding electrode dressing

3 Welding electrode alignment.

The welding electrodes should be shaped as shown in Figure 15. This should be monitored as required to assure compliance. The number of welds per hour, welding pressure, and the formation of the tips will dictate the frequency of monitoring and reshaping.

The welding electrode dressing should be observed after each five welds. The electrodes are dressed with a non-residual contact burnishing tool and then polished with a sanding disc.

A non-residual contact burnishing tool such as #3-316 (P.K. Nevses Inc., P. O. Box 65, Arlington, Illinois), is satisfactory. A sanding disc of approximately 600 grit is recommended. The contact burnishing tool is pulled down between the two welding electrodes, maintained at welding pressure, to assure square and parallel electrode faces. This is repeated until all areas of both electrode faces show bright fresh metal. A sanding disc is then rotated 180 degrees between the two electrodes, maintained at welding pressure, for final polish. Electrodes are brushed with a dry clean acid brush to eliminate all dust. A blast of dry air will eliminate dust from the electrodes and the welding system. The included angle between the electrodes initially should be set at 60 degrees with a spacer tool, and both electrodes aligned fore and aft against a straight edge or block to assure face to face alignment. These directions are to be followed only after establishing that the two horizontal electrode holder arms are on the same horizontal axis (as most often utilized in manufacturing).

Weekly checks of the LACD modification unit are recommended at impedance settings at 5 ohms, 10 ohms, and 20 ohms.

C. QUALITY ASSURANCE

All LACD qualification weld joints and production welds must meet the following requirements. All visual inspection shall be performed at a magnification of 20X.

1) Welds must be 60 percent or above the tensile strength of the weakest of the two component lead materials.

2) Neither of the two lead materials may setdown into the other more than 50 percent of the thickness of the thinner material.

3) No weld shall be accepted if the thickness of the weld is reduced more than 35 percent of the total thickness of the two unwelded materials.

4) No weld shall be acceptable if there are visual indications of metal expulsion.

5) No spitting, expulsion, or cracking is permitted.

6) The fillet size of any kovar weld joint shall be restricted to 50 percent maximum of the smaller wire diameter.

7) The fillet size of any dumet, nickel, or copper lead to nickel bus material shall be restricted so as not to touch either welding electrode.

VII. PROGRAM DATA

This data was performed during the preliminary evaluation and is summed up in Table III.

TABLE VIII

Summary of Δ Watt-Second Welding Range for Preliminary LACD Evaluation
Welding Pressure, 5.5 lb

Material mils	Pressure lb	Limits	0Ω	2Ω	4Ω	6Ω	8Ω	10Ω	12Ω	14Ω	16Ω	18Ω	20Ω
17 Kovar (Au)	5.5		1	3	3	4	13	10	12.5	22.5	25	30	40
25 Kovar (Au)	5.5		3	10	14.5	28	42.5	57.5	72.5				
25 Ni 200	5.5		6	16	25	30	32						
32 Ni 205	5.5		1	2.5	2.5	15	10	25					
10x25 Ni 200	5.5		1	10	20	20							
20 Dumet (Au)													
no Ni flash	5.5		0	0	2.5	5	5	0					
with Ni flash	5.5		2	5	12.5	25	20	25					
32 Dumet (Au)													
with Ni flash	5.5		4	15	30	40							
16 OFHC Cu(Au)	5.5					0@7Ω							
20 OFHC Cu(Au)	5.5		None		→	→							
12x31 Ni 270(1)	5.5		0	10	20								
20 OFHC Cu(Au)	5.5												
20 Ni "A"	5.5		0	0	0		0						
25 Ni 200	5.5		5	10	25	23							
32 Ni 205	5.5		9	22.5	50								

(1) Only to 20 OFHC Cu (Au)

TABLE IX

Welding Range in ΔWatt-Seconds for Preliminary LACD Evaluation

Material mils	Pressure lb	Limits	0Ω	2Ω	4Ω	6Ω	8Ω	10Ω	12Ω	14Ω	16Ω	18Ω	20Ω
17 Kovar (Au)	2		3		9		15.5		35		42		60
	4		1.5	3	4	6.5	10	15	25	20	25	50	50
	5.5		1	3	3	4	13	10	12.5	22.5	25	30	40
	6		2	4	6	9	15	15	25	28	32.5	0	0
	8		0	3	6	7	12.5	17.5	30	25	40	45	
25 Kovar (Au)	4		6	13.5	23	43	65	88					
	5.5		3	10	14.5	28	42.5	57.5	72.5				
	8		7	14	25	45	65	77.5					
25 Ni 200	4		6	16	22.5	30	30						
	5.5		6	16	25	30	32						
	8		8	27.5	30	30							
32 Ni 205	4		1	4	5	0	20	35					
	5.5		1	2.5	2.5	15	10	25					
	8		2	5	10	15	20						
10x25 Ni 200	2		0	0	10	5	10	20					
	4		3	5	15	30	33						
	5.5		1	10	20	20							
	8		0	0	0	10	0	0					
	12		0	0	0	0	0						

TABLE IX

Welding Range in ΔWatt-Seconds for Preliminary LACD Evaluation (cont)

Material mils	Pressure lb	Limits	0Ω	2Ω	4Ω	6Ω	8Ω	10Ω	12Ω	14Ω	16Ω	18Ω	20Ω
20 Dumet (Au) no Ni flash	4		0	0	2.5	5	5	0					
20 Dumet (Au) with Ni flash	4 5.5 8		2 2 4	5 5 10	7.5 12.5 10	20 25 20	30 20 30	30 25 28					
32 Dumet (Au) with Ni flash	4 5.5 8		5 4 7	15 15 10	20 30 35	45 40 35							
16 OFHC Cu (Au)	2 5.5		1		0	0@7Ω			0				
20 OFHC Cu (Au)	8 10	None			5								
20 OFHC Cu (Au) to 12 x 31 Ni 270	4 5.5		0 0	10 10	10 20								

TABLE IX

Welding Range in ΔWatt-Seconds for Preliminary LACD Evaluation (cont)

Material mils	Pressure lb	Limits	0Ω	2Ω	4Ω	6Ω	8Ω	10Ω	12Ω	14Ω	16Ω	18Ω	20Ω
20 OFHC Cu (Au)	4						0						
20 Ni "A"	5.5		0	0	0		0						
	8		0										
20 OFHC Cu (Au)	4		3			30							
25 Ni 200	5.5		5	10	25	23							
	8		2		15								
20 OFHC Cu (Au)	4		7.5	27.5	50								
32 Ni 205	5.5		9	22.5	50								
	8		8.5	30	45@3Ω								

TABLE X

Establishment of Maximum-Minimum Welding Watt-Second Limits,
Preliminary LACD Evaluation

Material mils	Pressure lb	Limits	0Ω	2Ω	4Ω	6Ω	8Ω	10Ω	12Ω	14Ω	16Ω	18Ω	20Ω	22Ω
17 Kovar (Au) x 10x20 Ni 205	2	Max	4		15		27.5		55		70		100	
		Min	1		6		12		20		28		40	
	4	Max	4.5	8	12	17.5	25	35	50	55	65	90	95	116
		Min	3	5	8	11	15	20	25	35	40	40	45	50
	5.5	Max	3	6	7	11	23	25	30	45	55	65	90	
		Min	2	3	4	7	10	15	17.5	22.5	30	35	50	
	6	Max	4	8	13	20	30	35	50	60	70			
		Min	2	4	7	11	15	20	25	32	37.5			
	8	Max	3	8	15	20	30	40	60	65	85	95		
		Min	3	5	9	13	17.5	22.5	30	40	45	50		
25 Kovar (Au) 10 x 20 Ni 205	4	Max	8	17.5	30	55	80	108						
		Min	2	4	7	12	15	20						
	5.5	Max	6	15	22.5	40	60	80	100					
		Min	3	5	8	12	17.5	22.5	27.5					
	8	Max	10	20	35	60	85	100						
		Min	3	6	10	15	20	22.5						

TABLE X

Establishment of Maximum-Minimum Welding Watt-Second Limits,
Preliminary LACD Evaluation (cont)

Materials mils	Pressure lb	Limits	0Ω	2 Ω	4 Ω	6 Ω	8 Ω	10Ω	12 Ω	14 Ω	16 Ω	18 Ω	20 Ω	22 Ω
25 Ni 200 x 10x20 Ni 205	4	Max	11	27	60	85	106							
		Min	5	11	17.5	35	45							
	5.5	Max	11	30	60	70	87							
		Min	5	14	25	40	55							
	8	Max	15	45	75	106								
		Min	7	17.5	35	55								
32 Ni 205 x 10x20 Ni 205	4	Max	6	15	27.5	35	60	95						
		Min	5	11	22.5	35	40	60						
	5.5	Max	7	17.5	30	55	70	95						
		Min	6	15	27.5	40	60	70						
	8	Max	9	22.5	45	70	100							
		Min	7	17.5	35	55	80							
10x25 Ni 200 x 10x20 Ni 205	2	Max	6	17.5	35	45	65	90						
		Min	6	17.5	25	40	55	70						
	4	Max	9	22.5	45	80	108							
		Min	6	17.5	30	50	75							
	5.5	Max	10	30	60	90								
		Min	9	20	40	70								

TABLE X

Establishment of Maximum-Minimum Welding Watt-Second Limits,
Preliminary LACD Evaluation (cont)

Materials mils	Pressure lb	Limits	0 Ω	2 Ω	4Ω	6 Ω	8Ω	10 Ω	12 Ω	14 Ω	16 Ω	18 Ω	20 Ω	22 Ω
10x25 Ni 200 x 10x20 Ni 205	8	Max	0	0	0	90	0	0	0					
		Min	0	0	0	80	0	0	0					
	12	Max	0	0	60	0	0	0						
		Min	0	0	60	0	0	0						
20 Dumet (Au) No Ni Flash 10x20 Ni 205	4	Max	5	12.5	25	40	60	70						
		Min	5	12.5	22.5	35	55	70						
20 Dumet (Au) with Ni Flash 10x20 Ni 205	4	Max	7	17.5	30	55	85	108						
		Min	5	12.5	22.5	35	55	75						
	5.5	Max	7	17.5	35	60	75	100						
		Min	5	12.5	22.5	35	55	75						
	8	Max	9	22.5	35	60	90	108						
		Min	5	12.5	25	40	60	80						
32 Dumet (Au) with Ni Flash 10x20 Ni 205	4	Max	11	30	55	90								
		Min	7	15	35	45								
	5.5	Max	12	30	60	90								
		Min	7	15	30	50								
	8	Max	14	30	70	95								
		Min	7	20	35	60								

TABLE X

Establishment of Maximum-Minimum Welding Watt-Second Limits, Preliminary LACD Evaluation (cont)

Materials mils	Pressure lb	Limits	0 Ω	2 Ω	4 Ω	6 Ω	8 Ω	10 Ω	12 Ω	14 Ω	16 Ω	18 Ω	20 Ω	22 Ω
16 OFHC Cu (Au) x 10x20 Ni 205	2	Max	7		35			108						
		Min	6		35			108						
	5.5	Max				100 @7 Ω								
		Min				100 @7 Ω								
20 OFHC Cu (Au) x 10x20 Ni 205	8	None												
	10	Max			80									
		Min			75									
20 OFHC Cu (Au) x 12x31 Ni 270	4	Max	15	50	90									
		Min	15	40	80									
	5.5	Max	15	45	95									
		Min	15	35	75									

TABLE X

Establishment of Maximum-Minimum Welding Watt-Second Limits,
Preliminary LACD Evaluation (cont)

Materials mils	Pressure lb	Limits	0 Ω	2 Ω	4 Ω	6 Ω	8 Ω	10 Ω	12 Ω	14 Ω	16 Ω	18 Ω	20 Ω	22 Ω
20 OFHC Cu (Au)	4	Max/Min					90							
x	5.5	Max/Min	10	22.5	40		100							
20 Ni "A"	8	Max/Min	10											
20 OFHC Cu (Au)	4	Max	13			100								
x		Min	10			70								
25 Ni 200	5.5	Max	14	35	70	108								
		Min	9	25	45	85								
	8	Max	15		90									
		Min	13		75									
20 OFHC (Au)	4	Max	17.5	55	100									
x		Min	10	27.5	50									
32 Ni 205	5.5	Max	20	50	100									
		Min	11	27.5	50									
	8	Max	22.5	65	100 } @ 3 Ω									
		Min	14	35	55 }									

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