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HUGHES AIRCRAFT COMPANY
GROUND SYSTEMS
FULLERTON, CALIFORNIA

NASA CR 70935

FACILITY FORM 602

N66-19615
(ACCESSION NUMBER)

41
(PAGES)

CR 70935
(NASA CR OR TMX OR AD NUMBER)

(THRU)
1
(CODE)
16
(CATEGORY)

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 2.00

Microfiche (MF) .50

ff 653 July 65

RE-ORDER NO. 65-897

FR 65-10-257

LASER WELDING OF COATED MAGNET WIRE

J. R. Shackleton and L. J. Martin

Hughes Aircraft Company

FINAL REPORT

P.O.# CU-326020

17 November 1965

The Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

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I. INTRODUCTION

The objective of this program is to demonstrate the capabilities of Laser microwelding for terminating coated magnet wire.

This report describes the equipment and technique used to perform Laser welds of #36 and #40 "polythermaleze" coated magnet wire to stainless steel and gold plated nickel terminals without using conventional methods for stripping the coated magnet wire.

II. SUMMARY

The following remarks summarize the findings of this program:

1. Good high strength welds were made between the desired terminal materials.

2. Low strength welds could be detected visually by the necking down of the wire adjacent to the weld.

3. One off-center shot was necessary to vaporize insulation; a second on-center shot fused the metals together.

4. All of the "T" weld breaks occurred in the heat affect zone, indicating good fusion.

5. Necking down of the wire is undoubtedly caused by variations in heat input into the weld, excessive heat causing excessive fusion and necking down. In both types of welds there was a more severe dropoff on the extreme value chart on #40 wire than for #36, indicating that with finer wire more precise Laser control is necessary.

6. Consistently high strength welds can be obtained by (a) rejecting welds showing a neckdown of the wire and rewelding or (b) a very precisely controlled Laser so that excess fusion and necking down do not occur.

III. EXPERIMENTAL APPARATUS

The apparatus used on this program consisted of:

1. A Hughes Model 202 Laser Microwelder (Figure 1)

2. A holding fixture to support the parts of the specimen during the welding operation (Figure 2)

3. A Dillon Model M Testing Machine equipped with a variable pull rate mechanism and Hunter Spring Company Model L1000-M 0 - 1000 gm reading range indicator head (Figure 3).

A. The Welding Machine

The Laser Microwelder was a Hughes Aircraft Company Model 202. It is shown in Figure 1 (64-01-243). This unit was specifically prepared to perform the microwelding operation for laboratory studies. Basically, any Laser unit consists of three elements -- the power supply, the Laser itself, and the special optics required to adapt the Laser unit to the specific function. A mechanical contrivance is, of course, necessary to hold things together. In this instrument all of these items are integrated into the unit shown, complete with a series of interlocks, all necessary controls, a micropositioning table and a work light.

The power supply uses a capacitor discharge design. This power supply is capable of storing 1200 joules. The controls for the power supply are conveniently located on a panel at the rear of the work surface. The storage capacitor switches are located on the left (hidden), and the charging voltage control and indicator are on the right of the Laser head.

The Laser head, the metal cylinder above the work table, carries sighting and focusing optics and a shutter. The unit is designed so that sighting is done through the ruby crystal; both surfaces of the ruby crystal were made partially transmitting. This design was used because it permits positioning and depth of focus while at the same time minimizing supplementary hardware that would complicate experimental programs. This design results in some of the Laser light being transmitted backward toward the eyepiece. The shutter is a safety device incorporated to prevent the operator from being injured by the Laser flash. The shutter is in the interlock system so that the Laser cannot be fired unless the shutter is closed.

The output power from the Laser is rated at one joule minimum with 750 joules of excitation.

The entire volume in which the Laser beam is exposed is enclosed by a blue tinted safety shield which protects the eyes of the operator from high intensity reflections. These shields are hinged to allow access to the work area and are also in the interlock system.

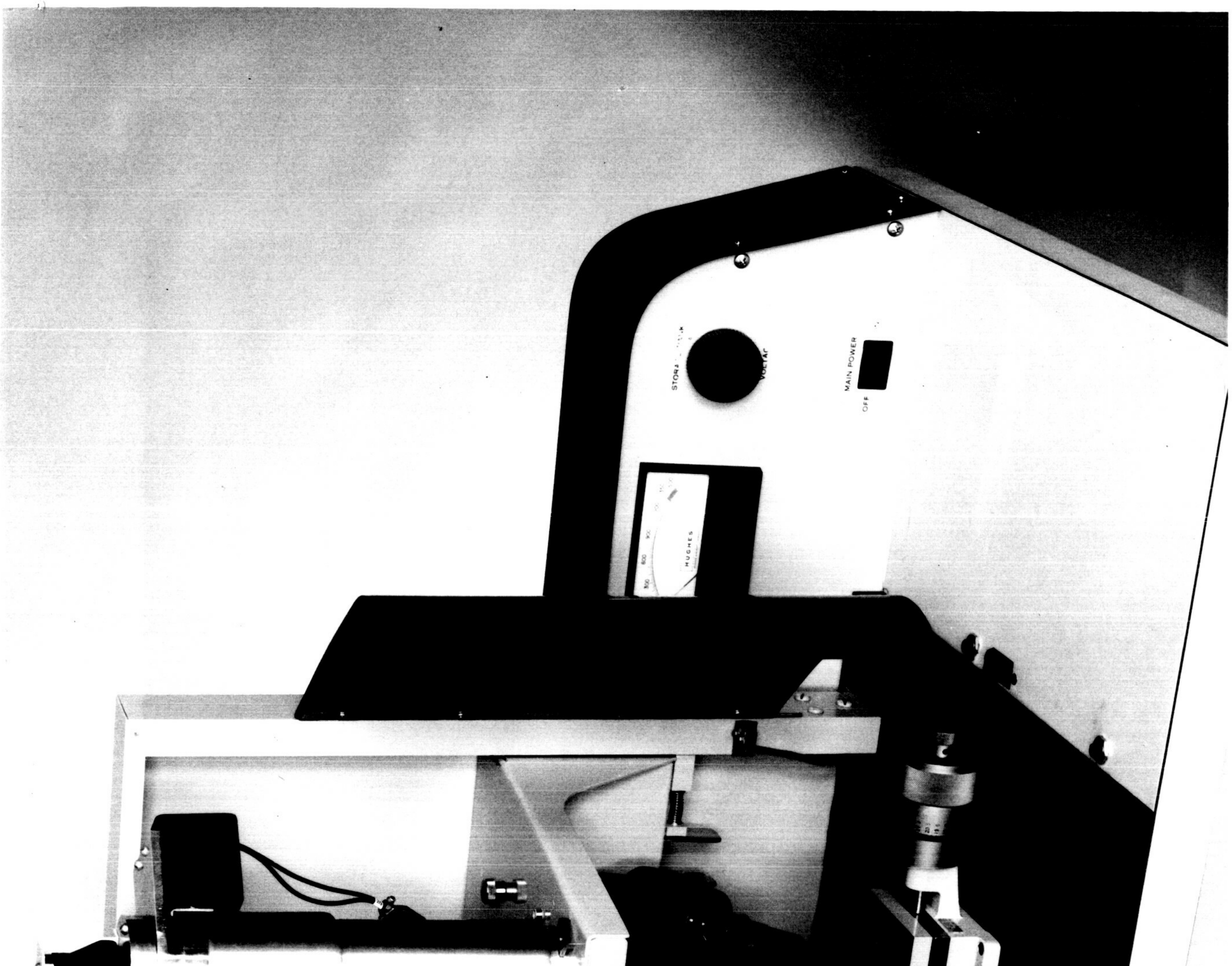

Figure 1

An auxiliary cooling system was incorporated and attached to the cooling fitting on the Laser head. This cooling system consists of a supply of dry nitrogen (nominally 40 cu ft/hr) and a heat exchanger to cool the gas to -150°C. This cooling system was required to increase the repetition rate of welding.

B. The Assembly Fixture

The holding fixture is shown, disassembled, in Figure 2 (65-11-053). It is constructed of two pieces of perforated board held together by bolts. The top board has elongated openings through which the Laser beam is focused and fired. The grey strips on this board are sponge rubber pads which press the pieces, to be welded, together. The bottom board has two series of four shallow grooves milled in its surface. These grooves receive and orient the nickel wire or stainless steel tee terminals. The fine copper wire specimens are laid across the nickel or stainless steel terminals, and the top board is fastened in place. Before final tightening of the assembly bolts, the fine wire is pulled taut.

C. The Testing Machine

The testing machine used to perform the pull strength tests is shown in Figure 3 (65-11-052). The base machine is Dillon Model M Universal Testing Machine (1) modified by mounting a Hunter Spring Model L-1000M force gage (2) on the indicating head. The lower jaws are automatic gripping jaws from a Hunter Spring Company Model TJH Testing Machine. This lower jaw is always used to grip the copper wire. The upper specimen fitting has been specially made to hold the gold plated nickel wire or the stainless steel terminal at an angle of 45° with respect to the direction of head travel.

The head travel rate used in these tests was one inch per minute.

IV. TEST SPECIMENS

The test specimens were made by forming a weld at the 90° intersection of the copper wire and the terminal specimen. The specimen terminals were 303 stainless steel tees with

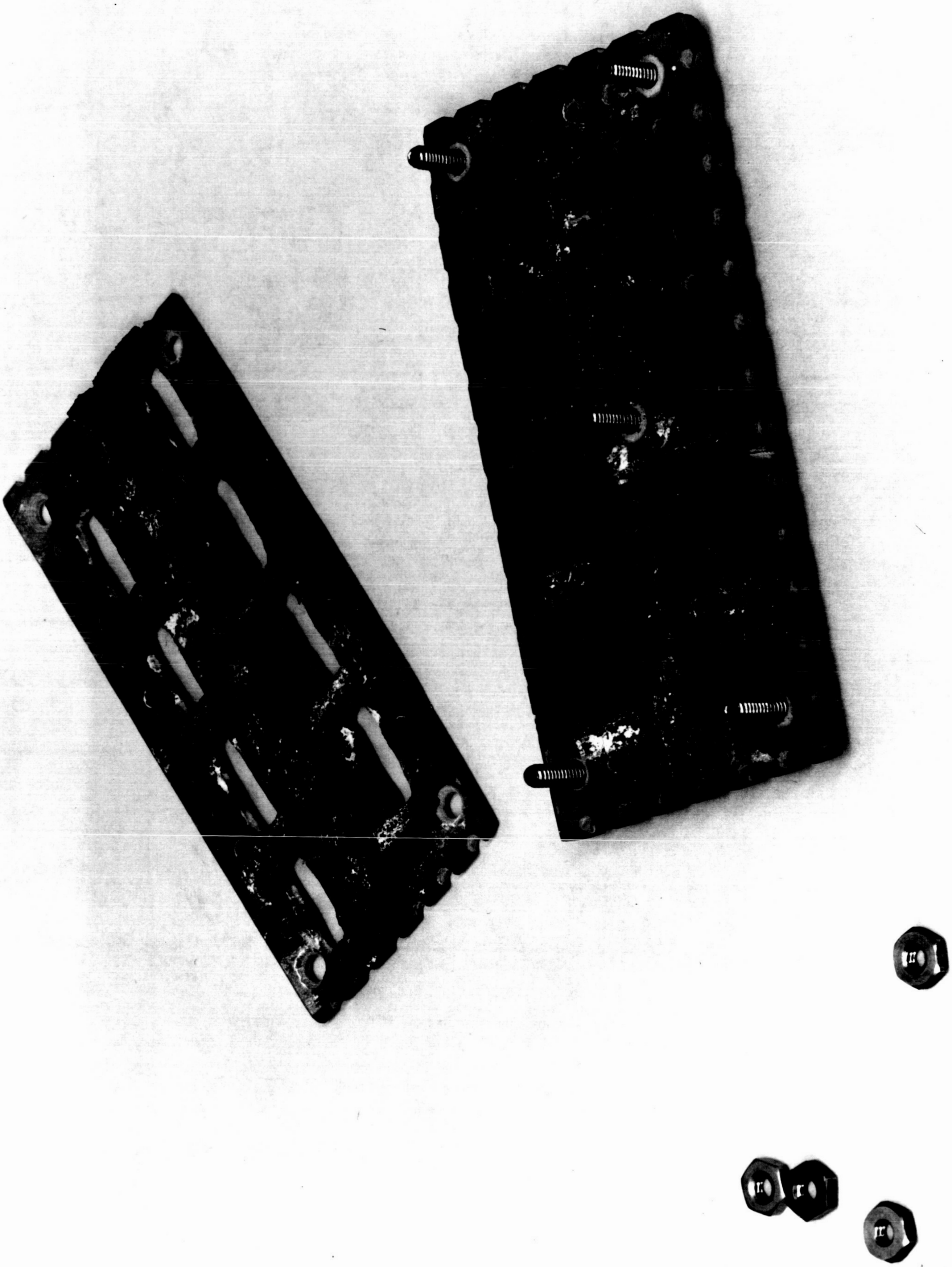

Figure 2

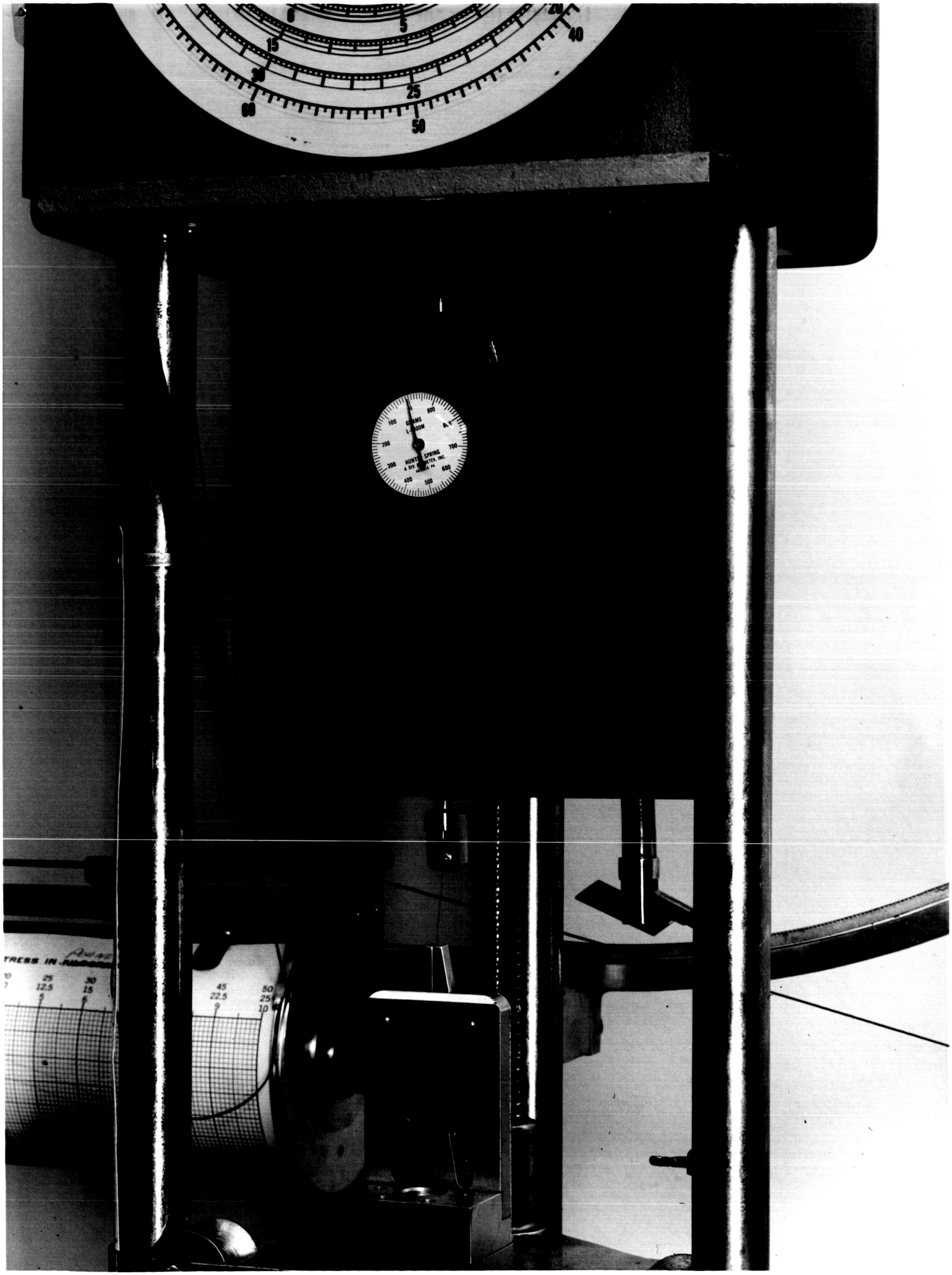

Figure 3

a cross section of .025 inch at the point of weld and 3/4 inch lengths of .020 gold plated nickel wire. The copper wire was #36 and #40 wire. The combinations of these terminals and wire sizes produce four series of specimens designated T36, T40, W36 and W40. All specimen materials and parts were supplied by the Jet Propulsion Laboratories, Inc. After welding, the copper was cut off, leaving a 3/4 inch length of copper wire to be gripped in the testing machine.

V. PROCEDURE FOR MAKING THE WELDS

At the present stage of the development of the Laser welding process and Laser microwelding equipment, the procedure is not amenable to the development of rigorous weld schedules. Today, the accomplishment of Laser microwelds is largely dependent on operator skill. From experience with the machine, the operator can estimate the general power level for the trial welds. From the way the machine performs on the trial welds, adjustments are made until satisfactory welds are made. In no case on this program was it necessary to exceed four trial welds to adjust the machine for a new wire-terminal combination.

The criterion for the proper setting of weld energy is the degree of melt. Insufficient energy produces "dry" or semi-dry welds. Too much energy produces more than adequate melt, excessive necking down of the copper wire and a large amount of metal evaporation, resulting in a large pit at the point of fusion rather than a nice flow.

The controls available for machine adjustment are:

1. Energy storage capacitance variable from 200 to 1400 microfarads.

2. Capacitor charging voltage variable from 0 - 1350 volts.

3. Coolant flow rate.

The primary controls are capacitance and voltage. These establish the luminous energy available to pump the ruby. Although the capacitance influences the luminous pulse time, the control is not adequate to study pulse duration effects. The storage capacitance control is best considered as just an energy storage range switch.

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The voltage control is the continuous control on the amount of energy stored in the capacitor bank.

The coolant flow rate affects the operating temperature of the ruby. Since Laser action is strongly dependent on operating temperature, this control has a profound effect on energy output and pulse repetition rate. Without adequate cooling, it would be necessary to wait at least five minutes between flashes in order to achieve repeatability. With adequate cooling, the rate may be increased to two flashes per minute (with this machine which has an upper limit on repetitive rate set by capacitor charging time).

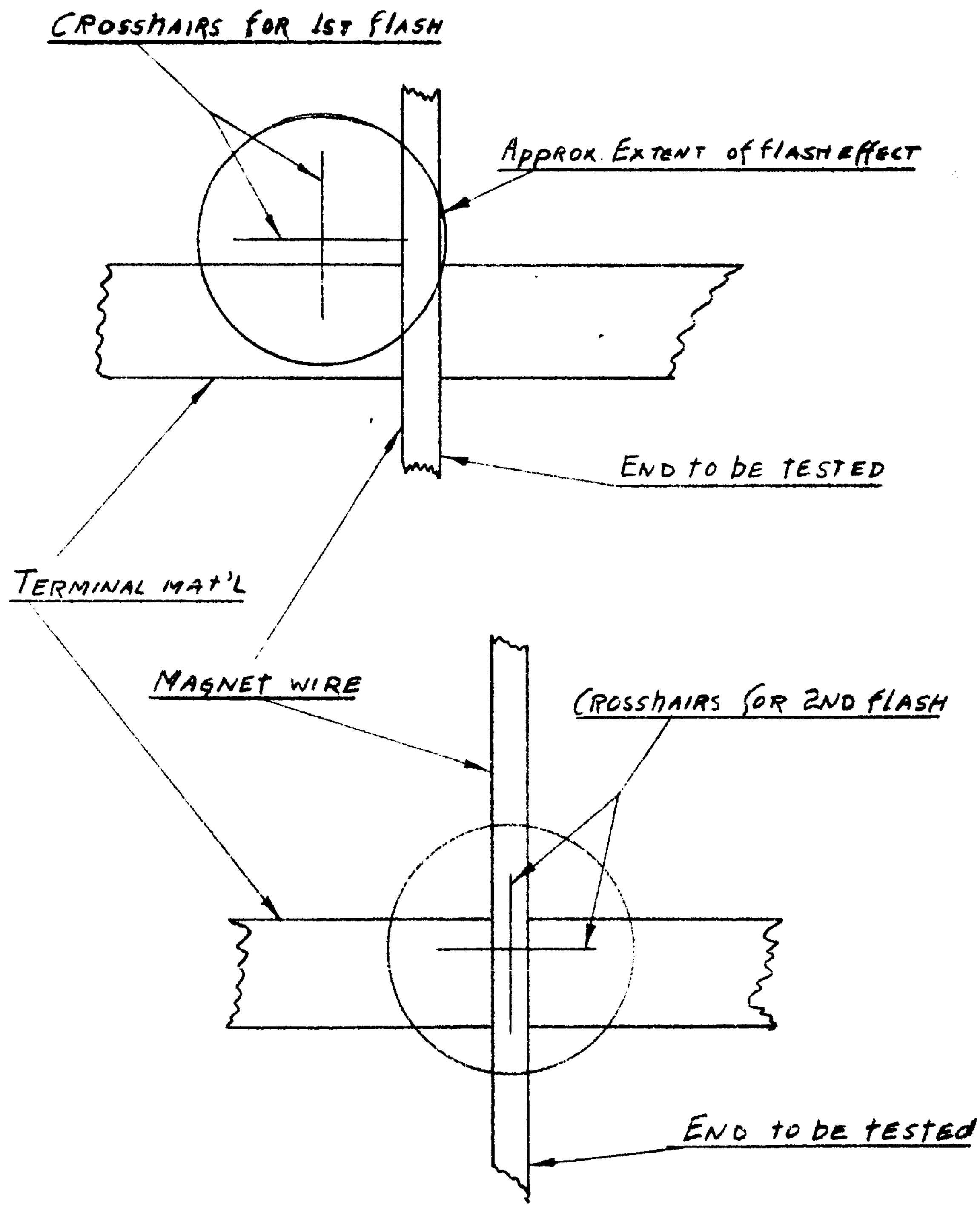
Laser welding is accomplished by focusing the flash of the Laser at the point at which it is desired to heat the work. It was found advantageous to form the weld in two separate Laser flashes. The first flash, focused adjacent to the eventual weld, accomplished the stripping of the insulation from the wire. The second flash, focused at the point of weld, caused actual metal flow. The site picture used in making these two flashes is shown in Figure 4. It will be noted in Figure 4 that an effort was made to locate the weld toward the top edge of the terminal. This was done as a precaution against burning off the wire when the weld was made. The reasoning was that if a "burn-off" did occur there would be enough wire material left to be welded without having to disassemble the holding fixture. In actual practice, there were very few "burn-offs" and when they did occur the holding fixture did not hold the loose end in contact with the terminal, such that disassembly was required.

The procedure of forming the weld toward one edge of the terminal produced butt type welds to the non-functional end of the wire which appeared to be very satisfactory.

The cut off end of weld T36-22 (Appendix Plate 1) appears on the side of the terminal. Efforts to produce this weld consistently were not successful.

In a few cases, it was necessary to use more than two bursts to perform a weld. These cases were dominantly in forming the welds with the #40 wire. These exceptional cases were caused by problems in the holding fixture. The sponge rubber pads (particularly one of the pads) were not able to hold the wire taut.

Microexplosions, caused by the evaporation of some of the metal, physically moved the wire away from the point of weld.



SITE PICTURES USED IN MAKING WELDS FOR TERMINATING MAGNET WIRE

FIGURE 4

By "chasing" the wire with the welder sometimes a weld could be accomplished; other times no weld could be made. This difficulty is believed to be due to the design of the holding fixture and not attributable to the Laser. Weld #T36-6 on Appended Plate 1 shows evidence of where the wire has been moved during the welding operation and subsequently welded in the new position.

VI. STRENGTH TESTING

The specimens were mounted in the testing machine such that the more rigid element (the tee or the nickel wire) was held at a 45^{o} angle with respect to the direction of head travel. The head travel rate was one inch per minute.

VII. DATA

The data accumulated on this program are presented in the following four tables. Some comments on the data appear in Appendix 2.

Pull Strength of Laser Welds / T-36

PROGRAM: TERMINATION of MAGNET WIRE - JPL / PO #CU326020

TEST GEOMETRY: TORSION-SHEAR

UNITS: GRAMS

CONFIGURATION: #36 Cu WIRE to STAINLESS STEEL TERMINAL

SPEC #	PULL STR	FAILURE LOCAT.	COMMENTS
1	No Test	Heat Aff Zone	OPERATOR ERROR
2	250	"	TERMINAL LOST
3	220	"	
4	280	"	
5	330	"	
6	320	"	
7	No Test	"	OPERATOR ERROR
8	300	"	
9	260	"	
10	200	"	TERMINAL LOST
11	280	"	" "
12	210	"	
13	[redacted]	"	
14	315	"	
15	240	"	
16	310	"	
17	280	"	
18	300	"	
19	300	"	
20	320	"	
21	290	"	
22	300	"	
23	290	"	
24	285	"	
25	145	"	
26	255	"	
27	315	"	
28	325	"	
29	150	"	DAMAGED IN HANDLING
30	260	"	

FORM 703

HUGHES AIRCRAFT CO.

ANALYSIS
PREPARED BY J R Shackleton 15 Nov 65
CHECKED BY

MODEL

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Pull Strength of Laser Welds / T-36

PROGRAM: TERMINATION of MAGNET WIRE – JPL / PO #CU326020
TEST GEOMETRY: TORSION–SHEAR
UNITS: GRAMS
CONFIGURATION: #36 Cu Wire to STAINLESS STEEL TERMINAL

SPEC #	PULL STR	FAILURE LOCAT.	COMMENTS
31	290	HEAT AFFECTED ZONE	
32	290	"	
33	190	"	
34	240	"	
35	240	"	
36	270	"	
37	280	"	
38	50	WELD	
39	255	HEAT AFFECTED ZONE	
40	300	"	
41	235	"	
42	295	"	
43	300	"	
44	205	"	
45	300	"	
46	225	"	
47	NO TEST	"	OPERATOR ERROR
48	140	"	
49	225	"	
50	265	"	

FORM 703

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MODEL

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Pull Strength of Laser Welds / T-40

PROGRAM: TERMINATION of MAGNET WIRE - JPL / PO #CU326020
TEST GEOMETRY: TORSION-SHEAR
UNITS: GRAMS
CONFIGURATION: #40 Cu WIRE to STAINLESS STEEL TERMINALS

SPEC #	PULL STR	FAILURE LOCAT.	COMMENTS
1	100	HEAT AFFECTED ZONE	
2	10	"	
3	60	"	
4	55	"	
5	95	"	
6	60	"	
7	60	"	
8	15	"	
9	45	"	
10	80	"	
11	100	"	
12	105	"	
13	70	"	
14	100	"	
15	105	"	
16	95	"	
17	115	"	
18	—	—	BROKE IN HANDLING
19	75	"	
20	110	"	
21	105	"	
22	80	"	
23	~~70~~ 75	"	
24	85	"	
25	70	"	
26	90	"	
27	—	—	"
28	100	"	
29	45	"	
30	90	"	

FORM 703

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MODEL

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Pull Strength of Laser Welds / T-40

PROGRAM: Termination of Magnet Wire – JPL / PO #CU326020
TEST GEOMETRY: Torsion–Shear
UNITS: Grams
CONFIGURATION: #40 Cu wire to Stainless Steel Terminals

Spec #	Pull Str	Failure Locat.	Comments
31	90	Heat Affected Zone	
32	—	—	Broke in Handling
33	110	"	
34	80	"	
35	65	"	
36	20	"	
37	95	"	
38	85	"	
39	60	"	
40	80	"	
41	100	"	
42	20	"	
43	95	"	
44	90	"	
45	80	"	
46	85	"	
47	95	"	
48	105	"	
49	95	"	
50	100	"	
51	90	"	

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PULL STRENGTH OF LASER WELDS - W-36

PROGRAM: TERMINATION OF MAGNET WIRE - JPL / PO #CU326020
TEST GEOMETRY: TORSION-SHEAR
UNITS: GRAMS
CONFIGURATION: #36 Cu WIRE to Au PLTD .020 NICKEL WIRE

SPEC #	PULL STR	FAILURE LOCAT.	COMMENTS
1	135	HEAT AFFECTED ZONE	
2	140	"	
3	195	"	
4	175	"	
5	—	—	BROKE IN HANDLING
6	225	"	
7	—	—	" " "
8	215	"	
9	210	WELD	
10	145	"	
11	105	"	
12	230	"	
13	190	"	
14	100	"	
15	120	HEAT AFFECTED ZONE	
16	140	"	
17	155	"	
18	200	WELD	
19	225	HEAT AFFECTED ZONE	
20	210	"	
21	115	WELD	
22	180	"	
23	35	"	
24	140	"	
25	85	"	
26	—	—	LOST
27	10	WELD	
28	250	HEAT AFFECTED ZONE	
29	15	WELD	
30	160	"	

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FORM 703

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MODEL
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Pull Strength of Laser Welds - W-36

PROGRAM: TERMINATION of MAGNET WIRE - JPL / PO# CU326020
TEST GEOMETRY: TORSION-SHEAR
UNITS: GRAMS
CONFIGURATION: #36 Cu WIRE to Au PLTD .020 NICKEL WIRE

SPEC #	PULL STR	FAILURE LOCAT.	COMMENTS
31	25	WELD	
32	125	HEAT AFFECTED ZONE	
33	—	—	BROKE WHILE HANDLING
34	210	"	
35	135	"	
36	205	"	
37	130	"	
38	40	WELD	
39	230	HEAT AFFECTED ZONE	
40	160	"	
41	110	WELD	
42	155	"	
43	135	HEAT AFFECTED ZONE	
44	195	WELD	
45	230	HEAT AFFECTED ZONE	
46	15	WELD	
47	165	HEAT AFFECTED ZONE	
48	110	WELD	
49	140	"	
50	145	"	

FORM 703

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MODEL

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Pull Strength of Laser Welds / W-40

PROGRAM: TERMINATION of MAGNET WIRE - JPL / PO #CU326020
TEST GEOMETRY: TORSION-SHEAR
UNITS: GRAMS
CONFIGURATION: #40 CU WIRE to GOLD PLTD. .020" NICKEL WIRE

SPEC #	PULL STR	FAILURE LOCAT.	COMMENTS
1	25	HEAT AFFECTED ZONE	
2	100	"	
3	65	"	
4	70	"	
5	—	—	BROKE IN HANDLING
6	90	"	
7	30	"	
8	30	"	
9	45	"	
10	10	"	
11	5	"	
12	55	"	
13	—	—	BROKE IN HANDLING
14	0	"	
15	50	"	
16	10	"	
17	—	—	LOST
18	70	"	
19	30	"	
20	15	"	
21	40	"	
22	10	"	
23	—	—	BROKE IN HANDLING
24	55	"	
25	—	—	
26	40	"	
27	40	"	
28	70	"	
29	5	"	
30	0	WELD	

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Pull Strength of Laser Welds / W-40

PROGRAM: TERMINATION of MAGNET WIRE - JPL / PO #CU3260[illegible]
TEST GEOMETRY: TORSION-SHEAR
UNITS: GRAMS
CONFIGURATION: #40 Cu wire to Au pltd. .020 Nickel wire

SPEC #	PULL STR	FAILURE LOCAT.	COMMENTS
31	90	Heat Affected Zone	
32	80	"	
33	20	"	
34	70	"	
35	10	"	
36	5	"	
37	90	"	
38	—	—	BROKE IN HANDLING
39	85	"	
40	95	"	
41	40	"	
42	55	"	
43	15	"	
44	75	"	
45	50	"	
46	50	"	
47	25	"	
48	95	"	
49	10	WELD	
50	50	Heat Affected Zone	

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ANALYSIS
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MODEL

PULL STRENGTH ~~of Laser Welds~~ WIRE

PROGRAM: TERMINATION of MAGNET WIRE – JPL / PO# CU326020
TEST GEOMETRY: ~~TENSION SHEAR~~ TENSILE
UNITS: GRAMS
CONFIGURATION: TEST of WIRE

SPEC #	PULL STR	FAILURE LOCAT.	COMMENTS
	#36 Cu WIRE		
1	360		
2	380	AT GRIPS	
3	315		
4	380		
5	350		
6	370		
AVE	359		
	#40 Cu WIRE		
1	130	AT GRIPS	NOT TRUE TEST (specimens 1–7)
2	140	"	
3	130	"	
4	140	"	
5	135	"	
6	140	WIRE	
7	140	AT GRIPS	
AVE	136		

Appendix 1

The following eight plates are photographs of the experimental welds performed in work against P.O.# CU-326020.

The welds were made between #36 and #40 polythermaleze coated copper wire and gold plated .020 nickel wire and 303 stainless steel tee terminals.

Each series of welds is coded as follows:

1. T-36 #36 copper wire to 303 SS tee terminals
2. T-40 #40 copper wire to 303 SS tee terminals
3. W-36 #36 copper wire to nickel wire
4. W-40 #40 copper wire to nickel wire

Within the series each weld is serial numbered to allow later correlation between weld appearance and pull strength.

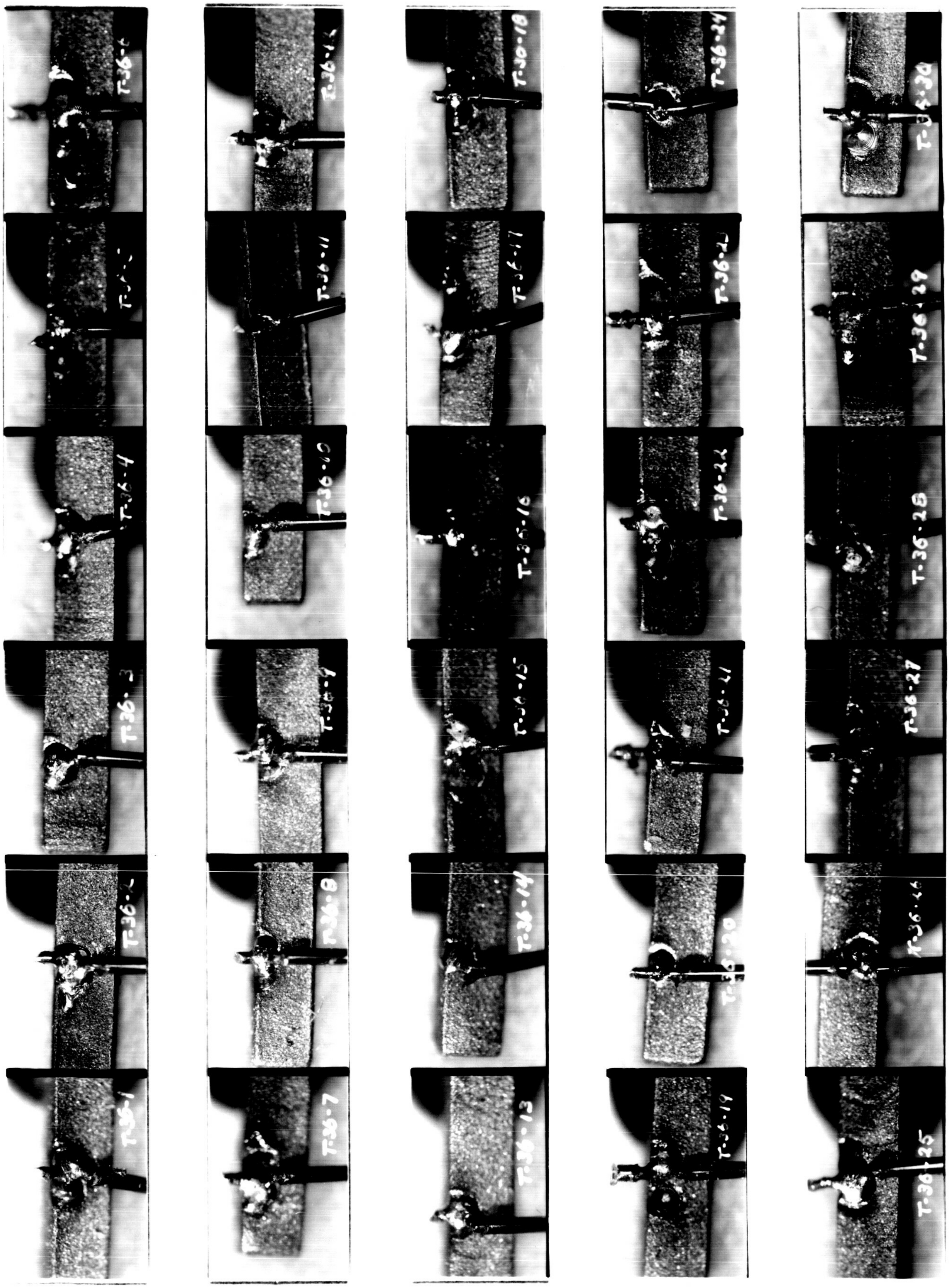
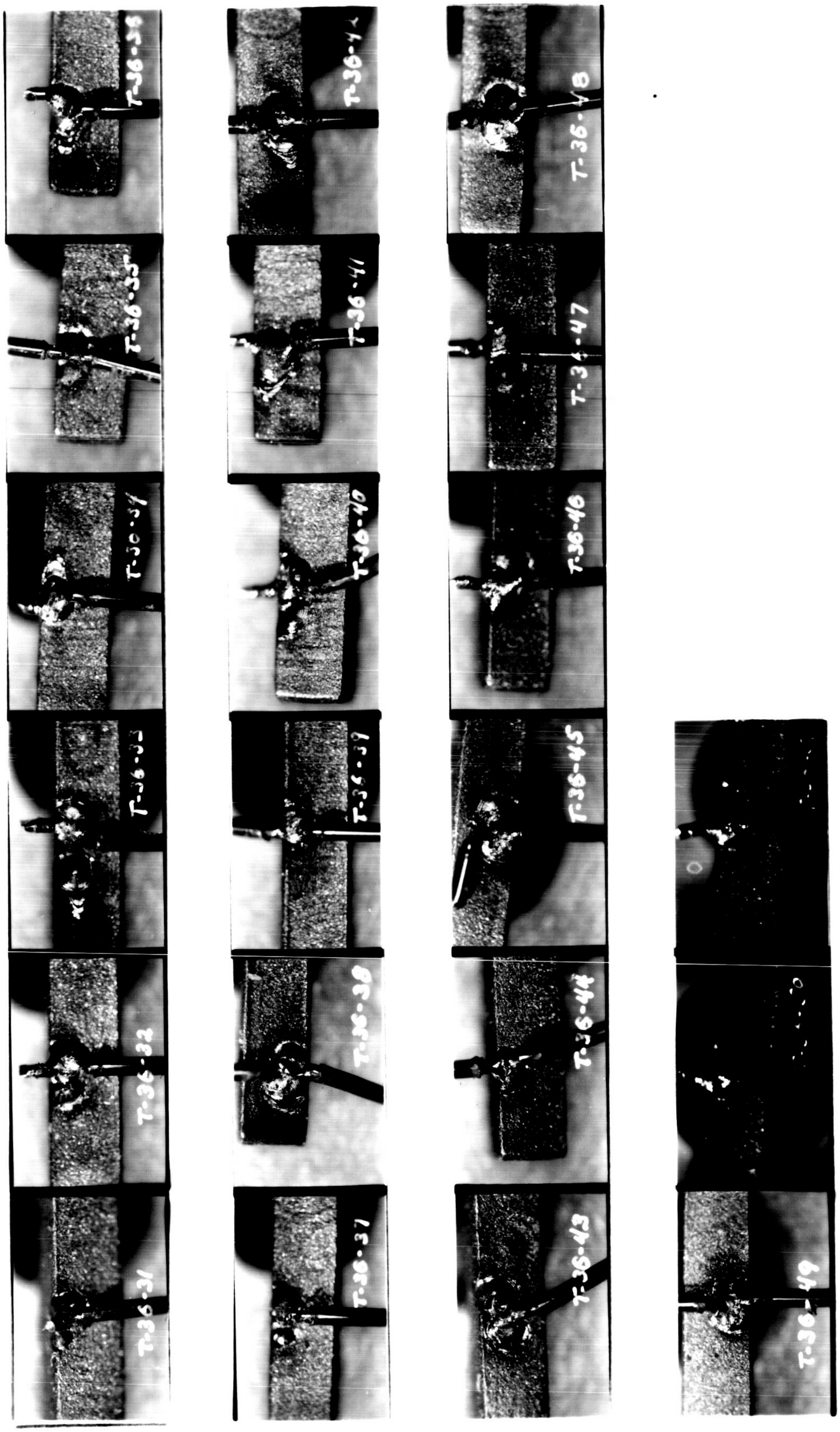


PLATE 1


T-36-31
T-36-32
T-36-37
T-36-38
T-36-40
T-36-41
T-36-43
T-36-45
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T-36-47
T-36-49

PLATE 2

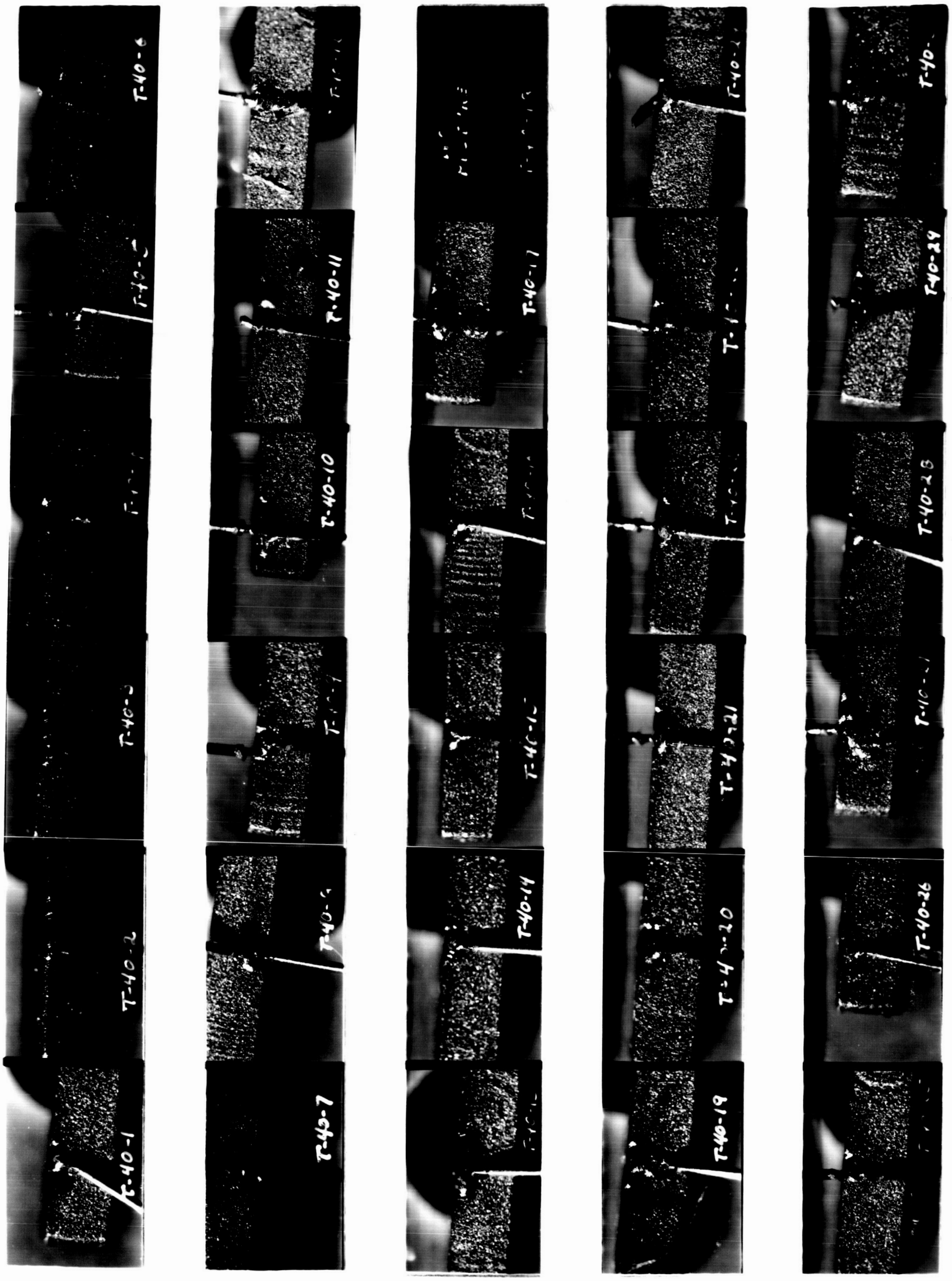


PLATE 3

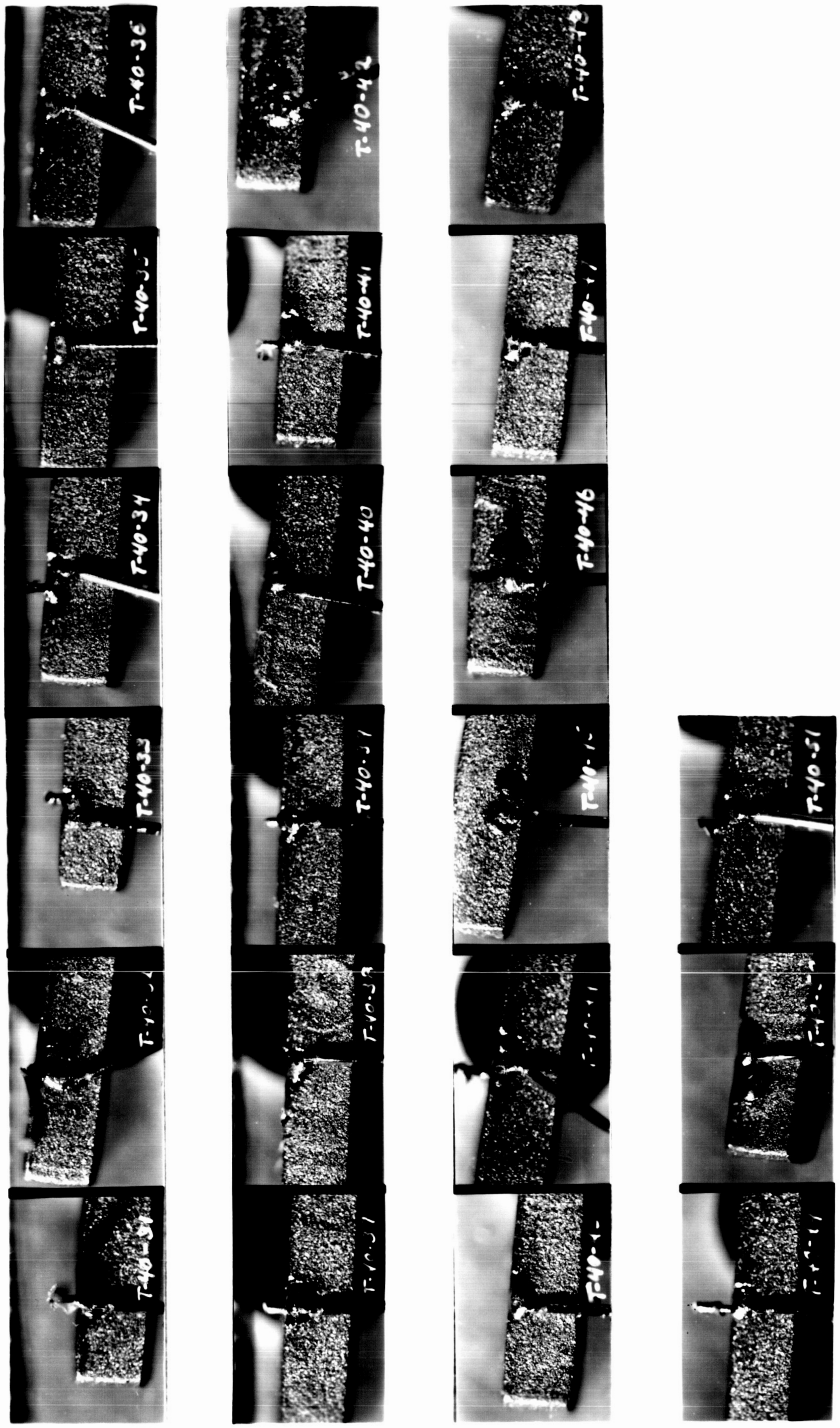


PLATE 4

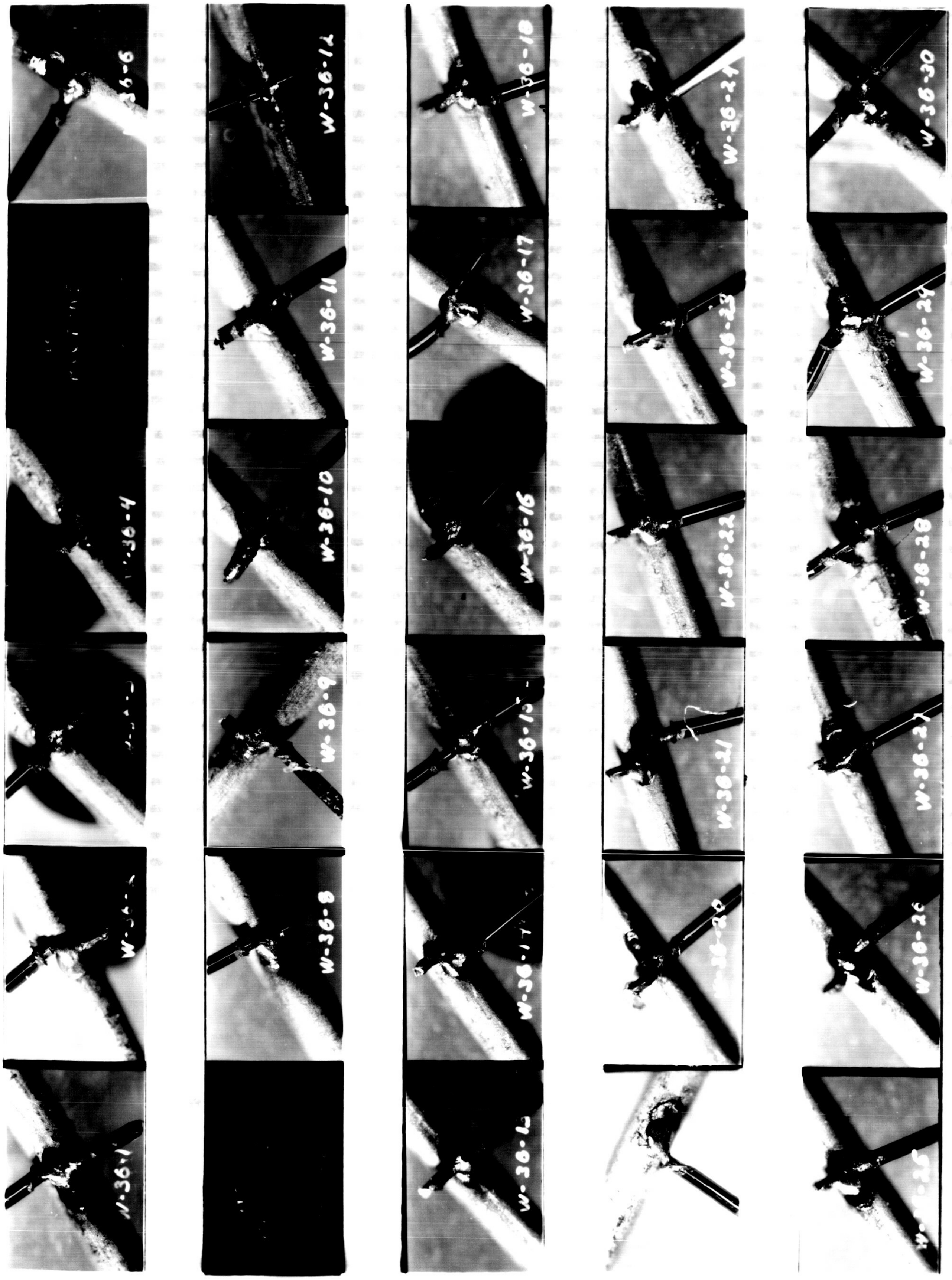

W-36-1
W-36-8
W-36-9
W-36-10
W-36-11
W-36-12
W-36-16
W-36-17
W-36-18
W-36-21
W-36-22
W-36-23
W-36-24
W-36-26
W-36-27
W-36-28
W-36-30

PLATE 5

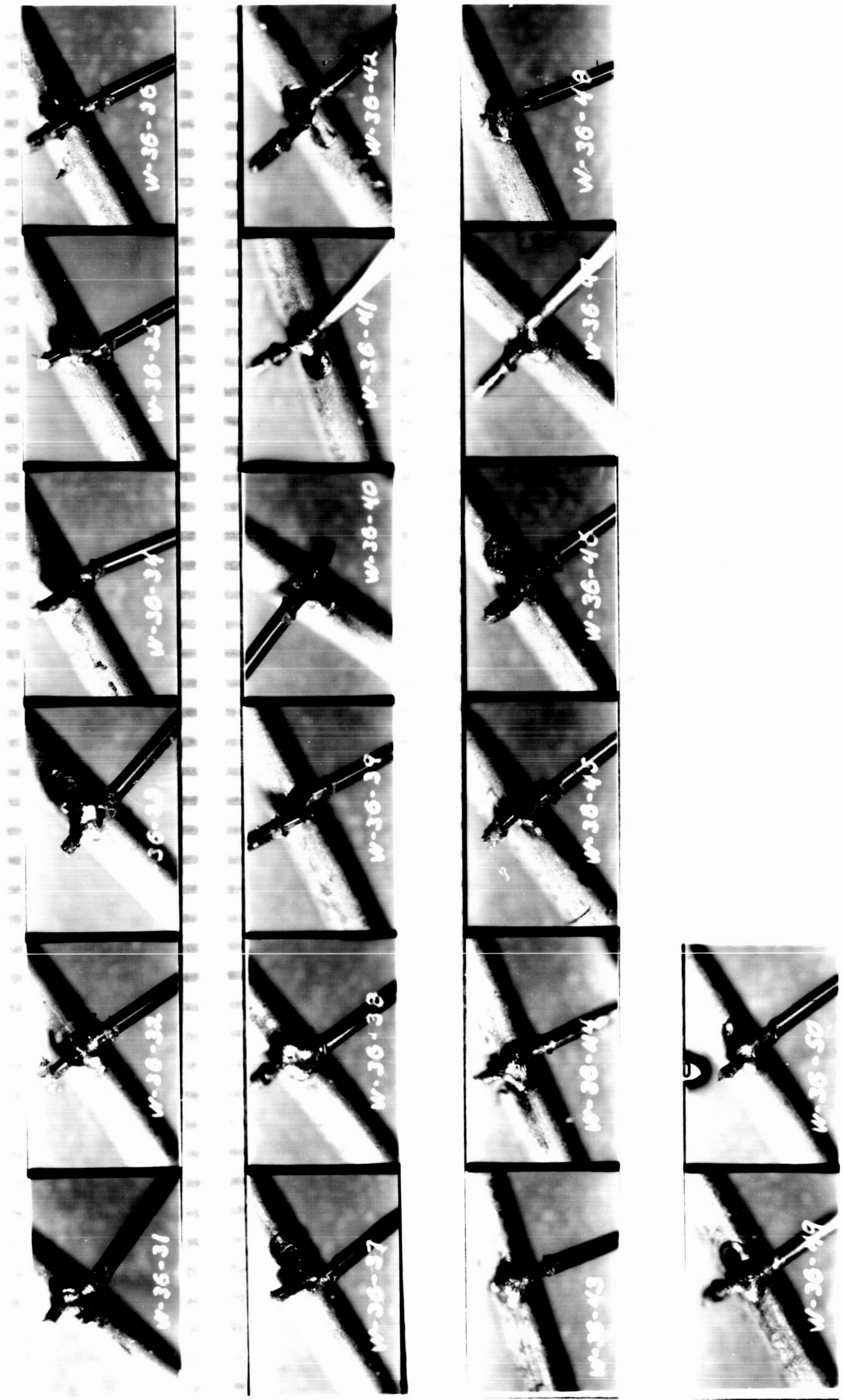


PLATE 6

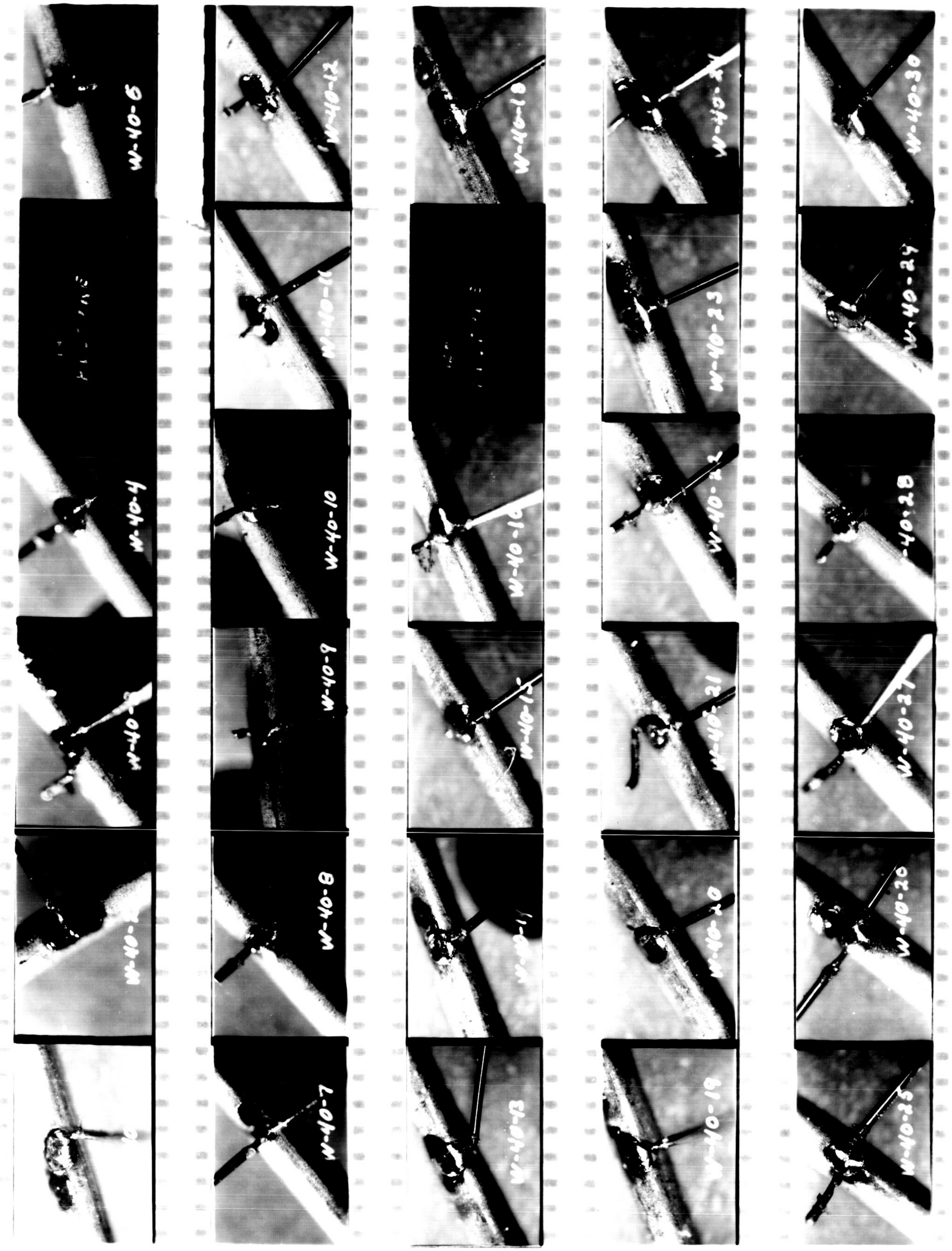


PLATE 7

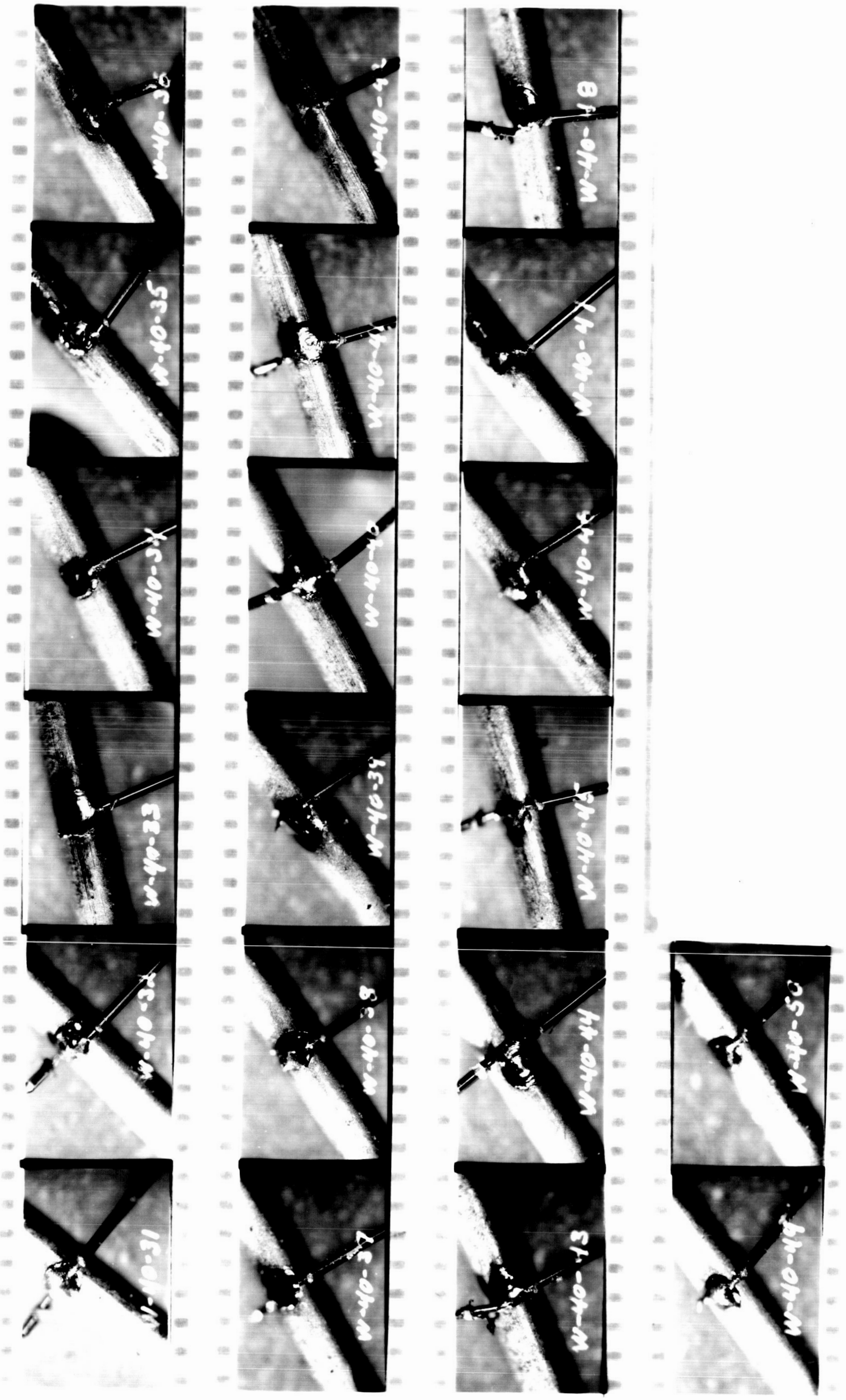


PLATE 8

Appendix 2

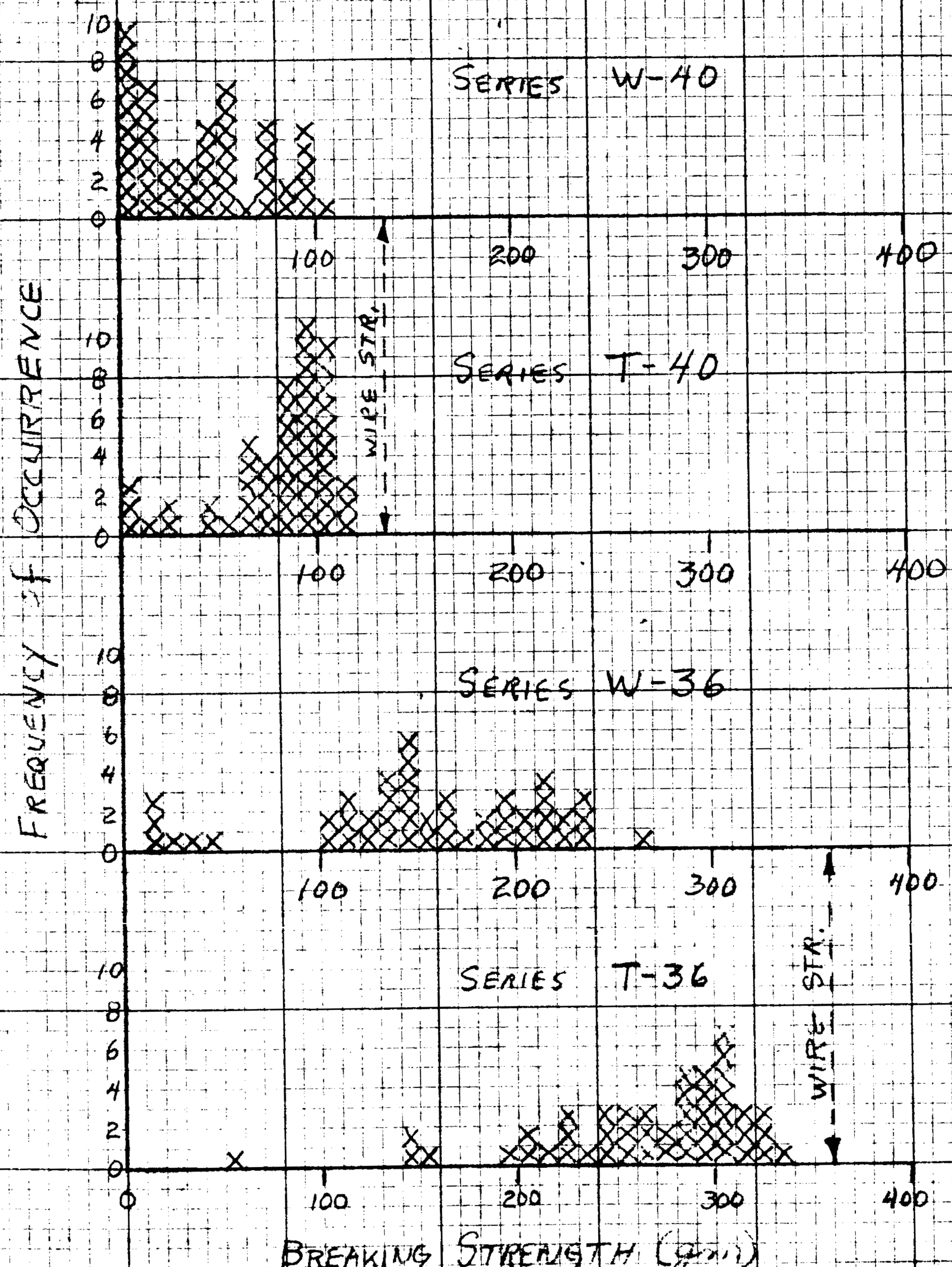
Preliminary Study of Results

Inspection of the data was performed by the construction of the histograms (strength value observed versus the number of times observed) shown in Figure A2-1. Since none of these histograms resembles a normal distribution and two of them, the T34 series and the T40 series, show the skewness typical of data that should be handled by "extreme-value" statistics (1) (this is also justified on theoretical grounds) this method of analysis was applied to all four series of tests. The results of this analysis are shown graphically in Figures A2 - A5. In most cases, these graphs show a main sequence (also visible in the histograms) and then a few stragglers.

Further manipulation of the data is statistically illegitimate; however, it is believed that careful analysis of plates 1 through 8 for inspectable inadequacies of the weld combined with more careful handling of the test specimens to eliminate handling damage will remove the stragglers that appear in the distribution histograms. If this proves true, then the distribution of weld strengths will be greatly improved. The new distribution is suggested by the dotted line in Figure A2-2 where 98% of the welds would show a strength greater than 35 gm and a mean strength of about 90 gm.

(1) Gumbel, E. J., Probability Tables for the Analysis of Extreme-Value Data, N.B.S., App. Math Series 22

FIGURE A2-1



DISTRIBUTIONS of BREAKING STRENGTH
(HISTOGRAM FORM)

LASER microwelds - TERMINATION of MAGNET WIRE

REPORT FR65-10-257

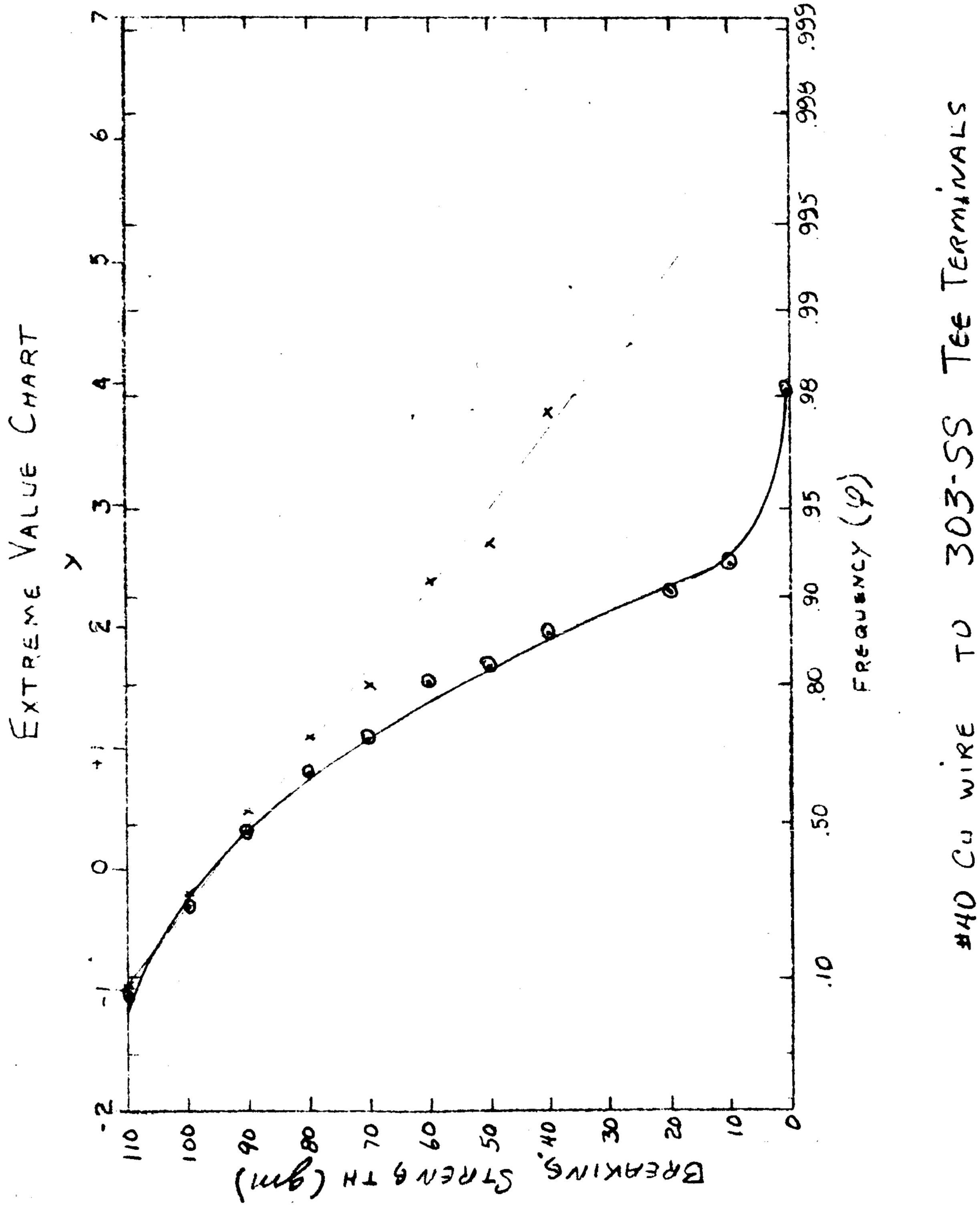
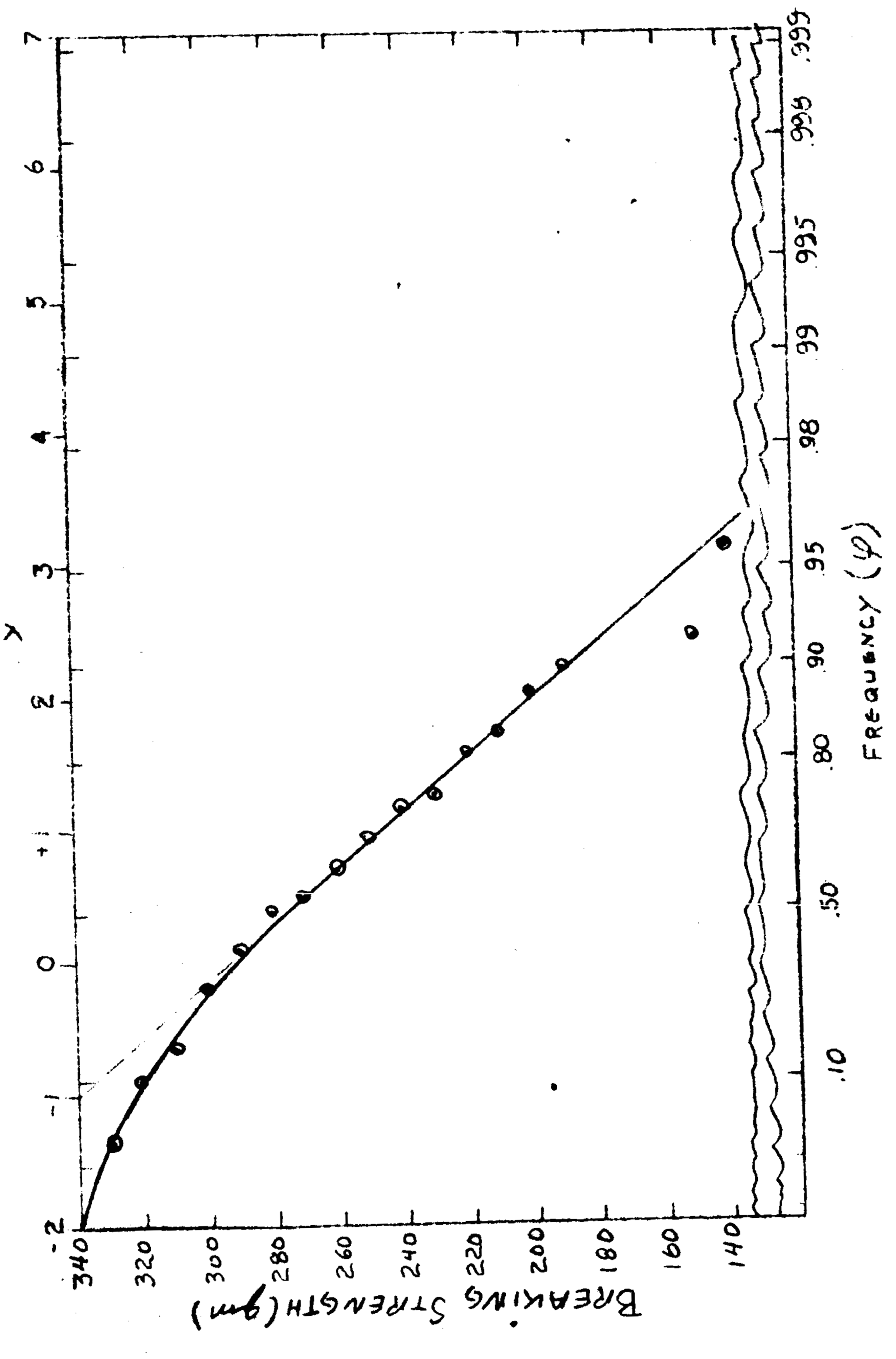

Extreme Value Chart
y
-2
-1
0
+1
2
3
4
5
6
7
.10
.50
.80
.90
.95
.98
.99
.995
.998
.999
Frequency (φ)
110
100
90
80
70
60
50
40
30
20
10
0
Breaking Strength (gm)
#40 Cu wire to 303-SS Tee Terminals

Figure A2-2

EXTREME VALUE CHART



#36 CU WIRE TO 303-SS TEE TERMINALS

FIGURE A2-3

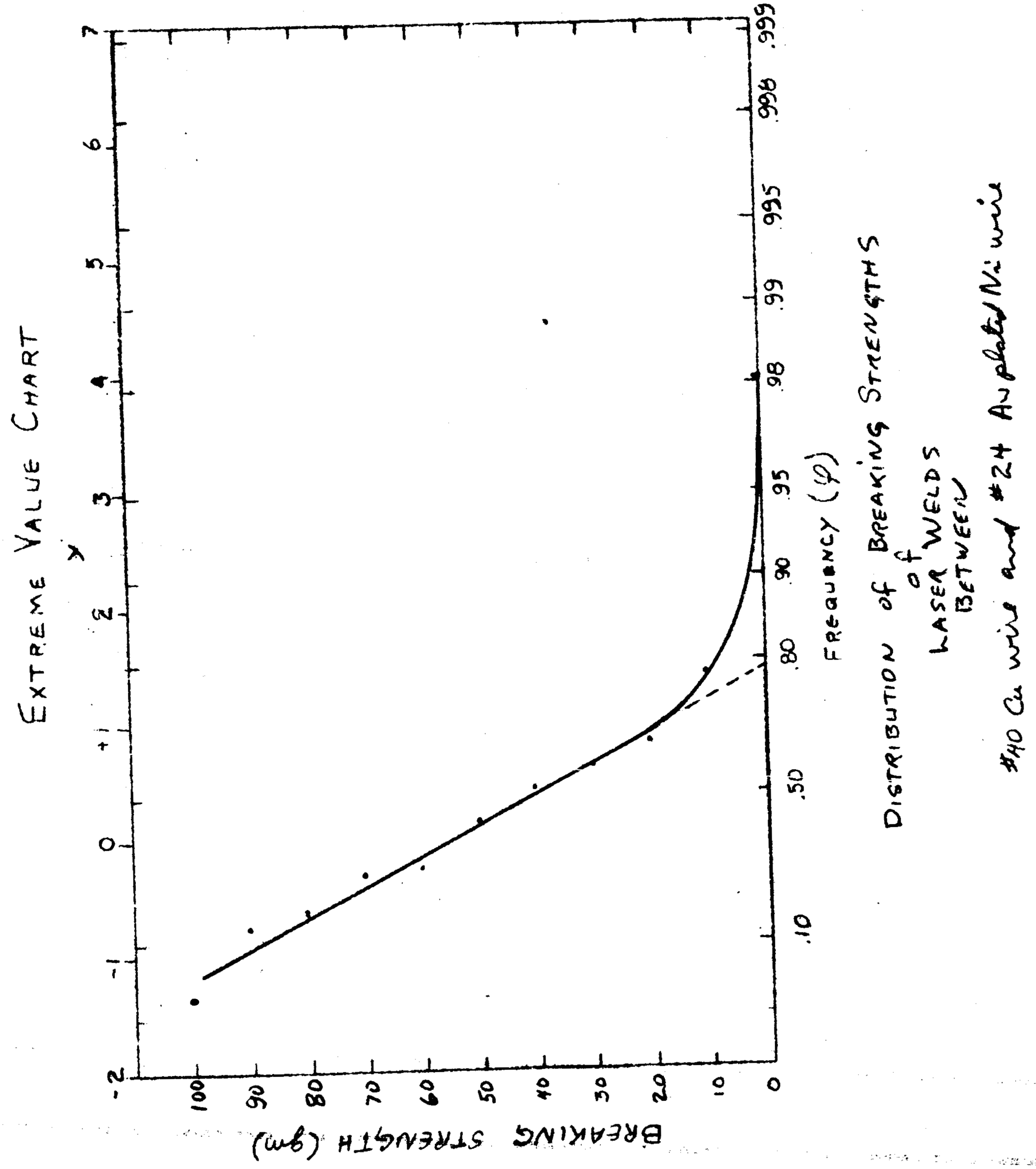
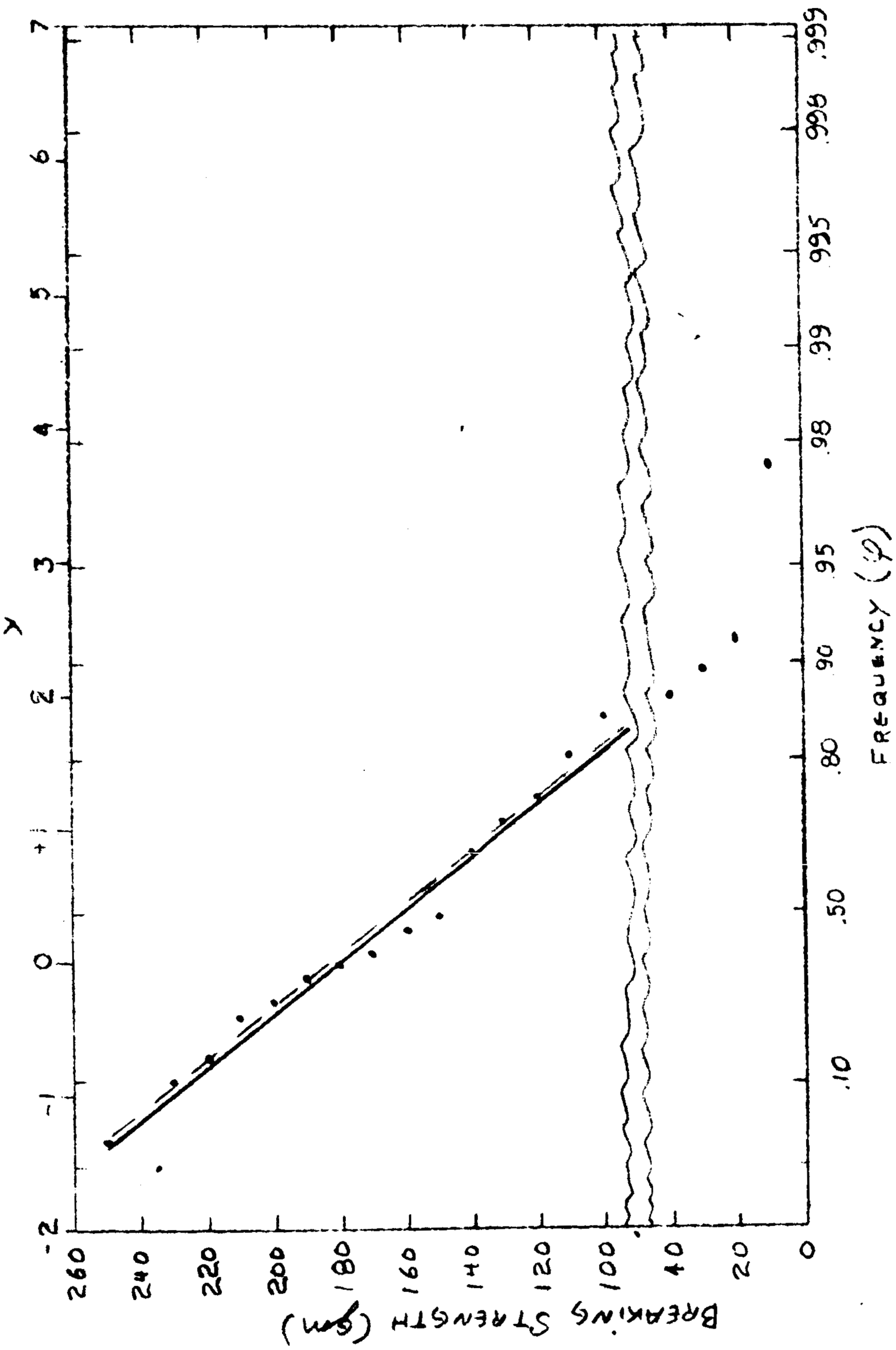

EXTREME VALUE CHART
y
-2
-1
0
+1
2
3
4
5
6
7
.10
.50
.80
.90
.95
.98
.99
.995
.998
.999
FREQUENCY (p)
100
90
80
70
60
50
40
30
20
10
0
BREAKING STRENGTH (gm)
DISTRIBUTION of BREAKING STRENGTHS of LASER WELDS BETWEEN
#40 Cu wire and #24 Au plated Ni wire

FIGURE A2-4

W 36

EXTREME VALUE CHART



#36 Cu WIRE TO #24 Au PLATED Ni WIRE

FIGURE A2-5