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AD 838138

ESTABLISH MANUFACTURING METHODS TO UTILIZE EXPLOSIVES AS HIGH ENERGY SOURCE TO SPOT WELD METALS

TECHNICAL REPORT AFML-TR-68-185

June 1968

by

E. W. LaRocca
Aerojet-General Corporation

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Contract No. AF 33(615)-5354
MMP Project No. 9-802

Advanced Fabrication Techniques Branch
Manufacturing Technology Division
Air Force Materials Laboratory
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

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FOREWORD

This final report covers all work performed under Contract AF33(615)-5354, Project Number 9-802 from 1 July 1966 to 31 May 1968. The manuscript was released by the author in June 1968 for publica tion as an AFML Technical Report.

The program is under the technical direction of F.R. Miller, Advanced Fabrication Techniques Branch, Manufacturing Technology Div., (MATF), Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433.

A.E. Doherty, Manager, Advanced Materials Technology, Aerojet's New Product Development Department, was program manager. E.W. La Rocca, Engineering Specialist, was the engineer in charge of the project.

The project was conducted as part of the Air Force Manufacturing Methods Program. The prime objective of this program is to establish, on a timely basis, manufacturing processes, techniques and equipment for use in economical production of USAF materials and components.

This technical report has been reviewed and is approved.

JACK R. MARSH, Chief
Advanced Fabrication Techniques Branch
Manufacturing Technology Division
AF Materials Laboratory

ACKNOWLEDGEMENTS

The author wishes to acknowledge the work of other members of the New Product Development Department and the Ordnance Department for their assistance to the program. A.E. Doherty for program management: E.K. Henriksen for many helpful suggestions and contributions to design problems; L.H. Knop and N.G. Westerfield for much of the exploratory work; R.E. Pesante for his assistance in the camera studies; and H. Smith of the Chino Hills Facility, who prepared and fired the explosive charges.

ABSTRACT

By: E. W. LaRocca
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The formation of spot welds with explosive charges as high energy sources has been investigated, and methods of producing welds have been determined. Materials welded include aluminum alloy 2024-T3, Type 347 stainless steel, 17-7 precipitation hardening steel, titanium alloys 6Al-4V and 8Al-1 Mo-1V, in thicknesses ranging from 0.010-in. foil to 0.500-in. plate. Both similar metal and dissimilar metal welds have been successfully produced.

Explosives for application to the welding process included RDX, PETN, HMX, TNT, Dynamite, Tetryl, Detasheet, and some specially formulated explosives. The most success was obtained with a specially formulated mixture of ammonium perchlorate and nitroguanidine, which was capable of detonating in diameters as small as 0.150 in.

Conventional electrical resistance welds were fabricated for comparison. Tests showed that explosively formed welds were somewhat lower in strength than resistance welds, but the explosive welds in many cases showed superior axial and flexural fatigue lives.

Ultrasonic inspection of explosively formed spot welds by the C-scan process showed the characteristic feature of this type of weld to be annular or ring-shaped, with an unwelded area in the center of the weld. A theory of weld formation was derived that agreed with observations from the flash X-ray and framing camera studies.

It was concluded that welds made by cylindrical explosive charges applied to dimpled standoff sheets produce ring welds by symmetrical jetting action, but that such welds do not create stress concentrations that would affect weld behavior during fatigue tests.

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1. INTRODUCTION

This program, under Contract AF 33(615)-5354, was conducted to provide manufacturing or production methods for the spot welding of metals, utilizing explosives as high-energy sources. Specifically, the program was intended to determine and evaluate process parameters necessary for the successful production of metallurgically sound welds, to optimize these parameters, produce welds, and to compare the explosive welds with accepted electrical (resistance) welds.

1.1 MATERIALS

Materials for weld specimens were selected to include representative high-strength alloys of aluminum, titanium, and steel. The material thicknesses ranged from 0.010-in. foil to 0.500-in. plate. Their weld characteristics, for both resistance and explosive welds, were evaluated using strength tests (lap shear), dye penetrant inspections, C-scan ultrasonic inspections (for explosive welds only), and axial and flexural fatigue tests.

1.2 TEST PROCEDURES

In the absence of specifications governing explosive spot welds, Specification MIL-W-6858 (applicable to conventional spot welds) was used as a guide for specimen size, weld diameters, and minimum lap shear strength requirements of explosive welds. This specification was also used as a standard for the resistance welds.

1.3 EXPLOSIVES

The program included testing and evaluating a group of explosives of various energies for application to the production of spot welds. Tests were conducted on many military and commercial explosives and several improvised formulations that were developed exclusively for spot welding applications.

2. EXPLORATORY AND FOUNDATIONAL STUDIES

2.1 LITERATURE SURVEY

A literature survey was conducted to determine likely parameters for the production of spot welds. While considerable research has been published (References 1 through 6) on flat-plate welding and cladding, at the initiation of the program little information was available on the effects of small, concentrated explosive loads on the welding of metals. Some obvious parameters were (1) the velocity of sound in each material, (2) density relationships between materials to be joined, (3) detonation velocity and pressure of the explosive used, and (4) the methods of introducing high-pressure pulses to laminar materials.

Considerable information was available on the sound velocity and density relationships for metals. The product of the sonic velocity (c) and the density (ρ) is defined as the "acoustic impedance" or the "characteristic impedance" (Reference 7). If two metal plates are placed one on the other and the top plate receives a pulse producing an elastic wave in the materials (at normal incidence), then conditions at the interface are such that reflection may occur. For incident plane compression, the reflected stress (σ_R) is a function of the characteristic impedances through the following relationship:

$$\sigma_R = \sigma_1 \frac{\rho_2 c_2 - \rho_1 c_1}{\sum(\rho c)}$$

where,

σ_1	=	original incident stress intensity
$\rho_1 c_1$	=	impedance of first medium
$\rho_2 c_2$	=	impedance of second medium
$\sum(\rho c)$	=	sum of both impedances

If the absolute value of the characteristic impedance of the first medium is greater than that of the second medium, compressive stresses are reflected as tensile stresses. If improper impedance matching is employed, reflected stresses can conceivably separate the plates in contact, which is contrary to the welding requirement. As in the electrical analogy to shock dynamics, the maximum power transferred from a generator to a receiver occurs when the impedances of botb are matched. It has long been known that the effect also occurs in shock loaded systems, so efforts during this program have been to employ as the top plate (adjacent to the explosive charge) a material having the same, or lower, impedance than the lower plate. This rule has been found to generally hold and will be discussed further in the report.

2.2 PRELIMINARY WELDING

Methods were studied of introducing concentrated shock loads to thin sheets and plates. In keeping with the conventional appearance and function of spot welds, the use of cylindrical charges was obvious. Preliminary experimental work involved the use of an orifice plate (Figure 1). The workpiece was a double strip of aluminum (seen projecting from the left side of the orifice plate) and resting on a large steel block that served as an anvil. The welding charge was contained in the transparent vertical cylinder with a blasting cap taped to the top. The charge holder was the steel block with six holes of various diameters, known as orifices, and the charge was simply placed into one of the orifices.

Figure 2 shows other examples of orifice plates. Cylinder A contains one orifice and is of such a length that the orifice is actually a firing chamber. Cylinder B was employed for tests with water as the pressure transmitting medium; water was placed in the vertical hole and the charge occupied the horizontal cavity. A plain, flat orifice plate is shown as C in the figure. The charge holder, anvil, and workpieces were held together in a hydraulic press (Figure 3). Tests based on this arrangement were used to formulate the initial parameters of the spot welding process. Studies of welds made from sheets of 0.063-in.-thick aluminum alloy 2024-0 (annealed) material were instrumental in outlining the basic mechanisms of explosive spot welding.

The predominant feature of the process is the axial symmetry of the system that results in circular weld patterns. It was discovered during many preliminary tests that the plain, flat-ended, cylindrical charges produce weld areas that are not full circles, but rather ring areas with unwelded central circular areas. Various charge configurations were attempted to avoid ring welds and to produce full circle welds. Some of these charge configurations are shown in Figures 4 and 5.

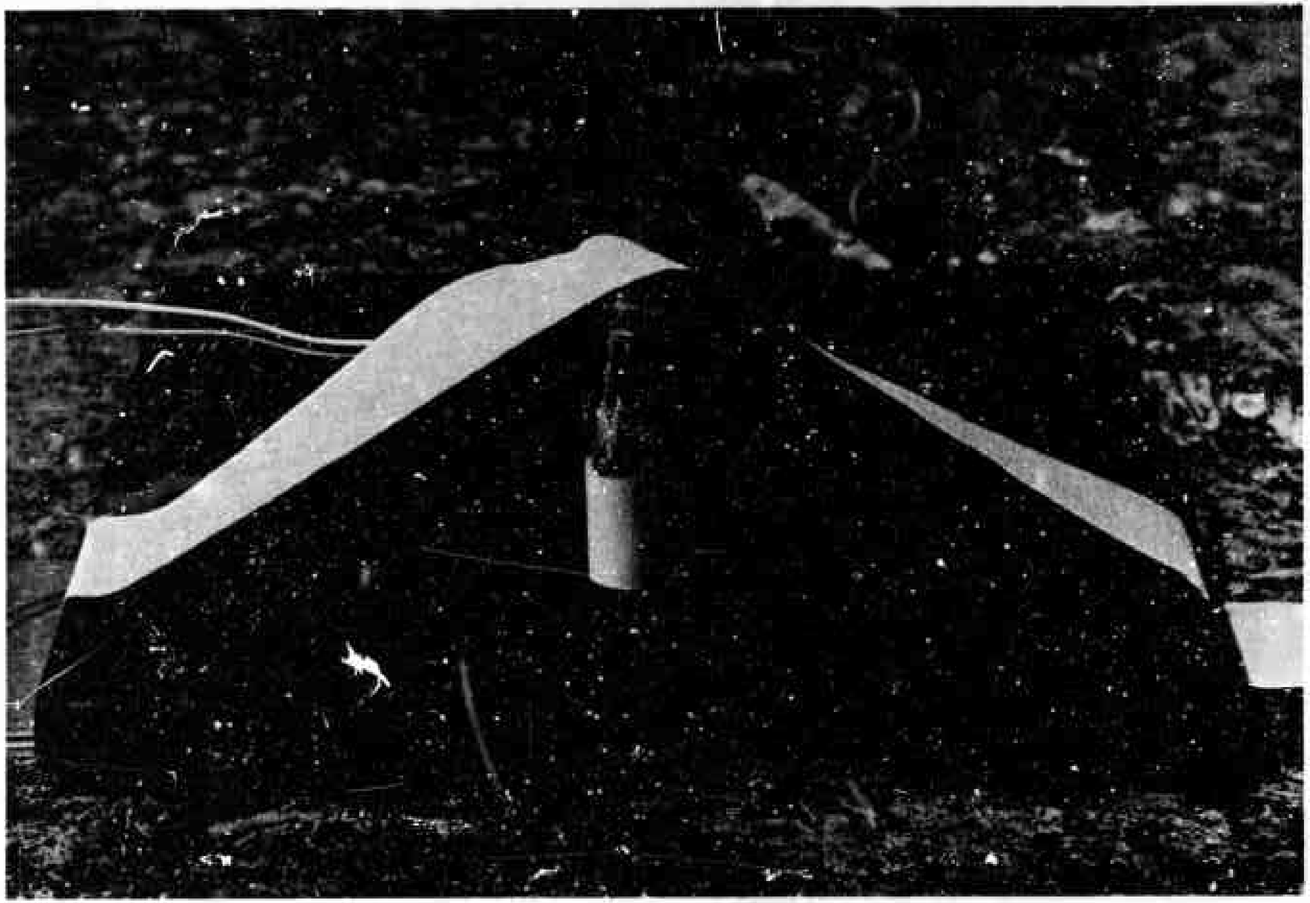

Figure 1. Manually Operated Tooling Setup for Explosive Spot Welding.

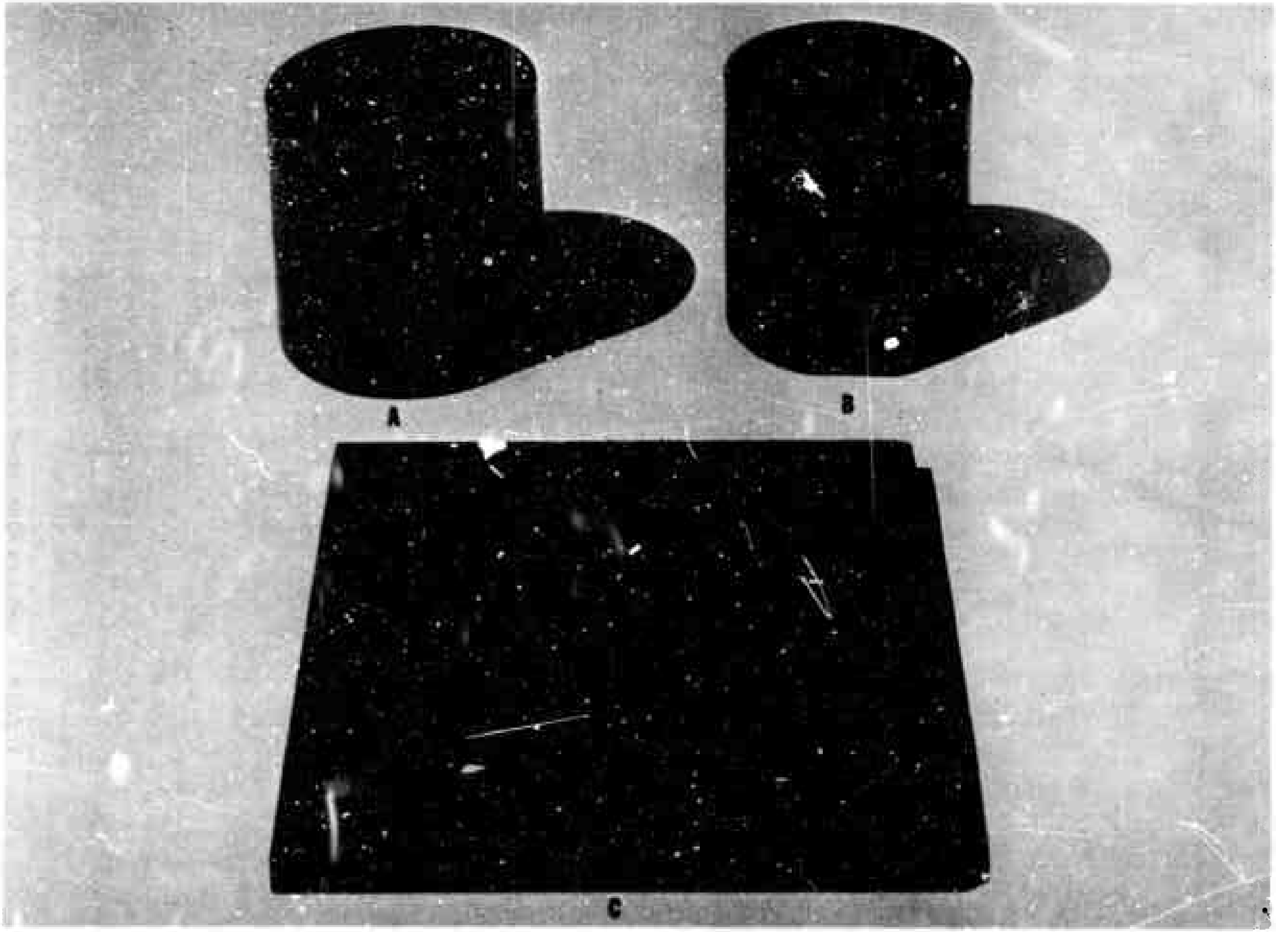

Figure 2. Orifice Plates.

Figure 3. Press Operated Tooling for Explosive Spot Welding.

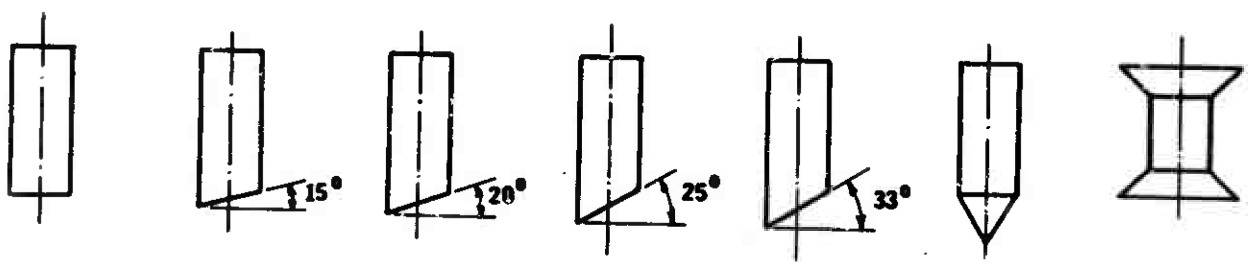

Figure 4. Charge Geometries.

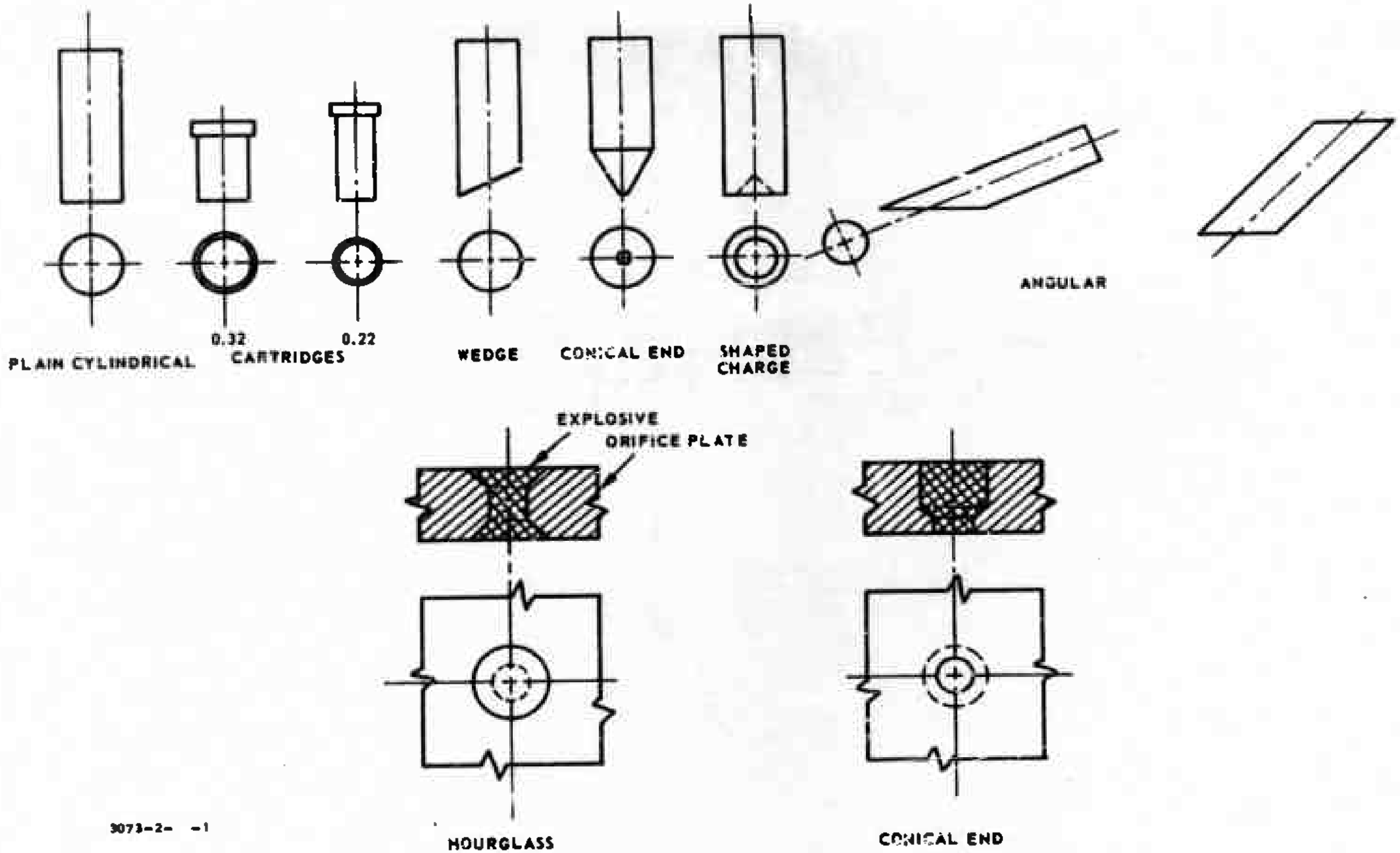

Figure 5. Charge Configurations.

The charge geometries shown include:

- Flat-ended cylinders
- Wedged cylinders with ends cut at angles of 15°, 20°, 25°, and 33° relative to the parallel faces of the cylinders
- Cylinders with conical ends
- Cylinders combined with two cones to produce hourglass shapes
- Cylinders with shaped-charge faces

The use of orifice plates other than those containing cylindrical charge cavities was attempted, and various plate arrangements are shown in Figure 6. Combinations of charges and orifice plates produced welds of varying degrees of soundness, but the predominant feature of sound welds continued to remain a ring area.

2.3 EXPLOSIVES USED FOR WELDING

A variety of explosives, pure and in compounds, was used during the welding program. Pure explosives are explosives that were used in the form supplied by the manufacturers, and mixed explosives are blends of explosives, formulated specifically for the welding program.

The following pure explosives have been used:

- Nitroguanidine
- Ammonium perchlorate
- Dynamite (Hercules 60/40 and Trojan 70C)
- TNT, flaked and granulated
- Composition C-4
- PETN
- Tetryl

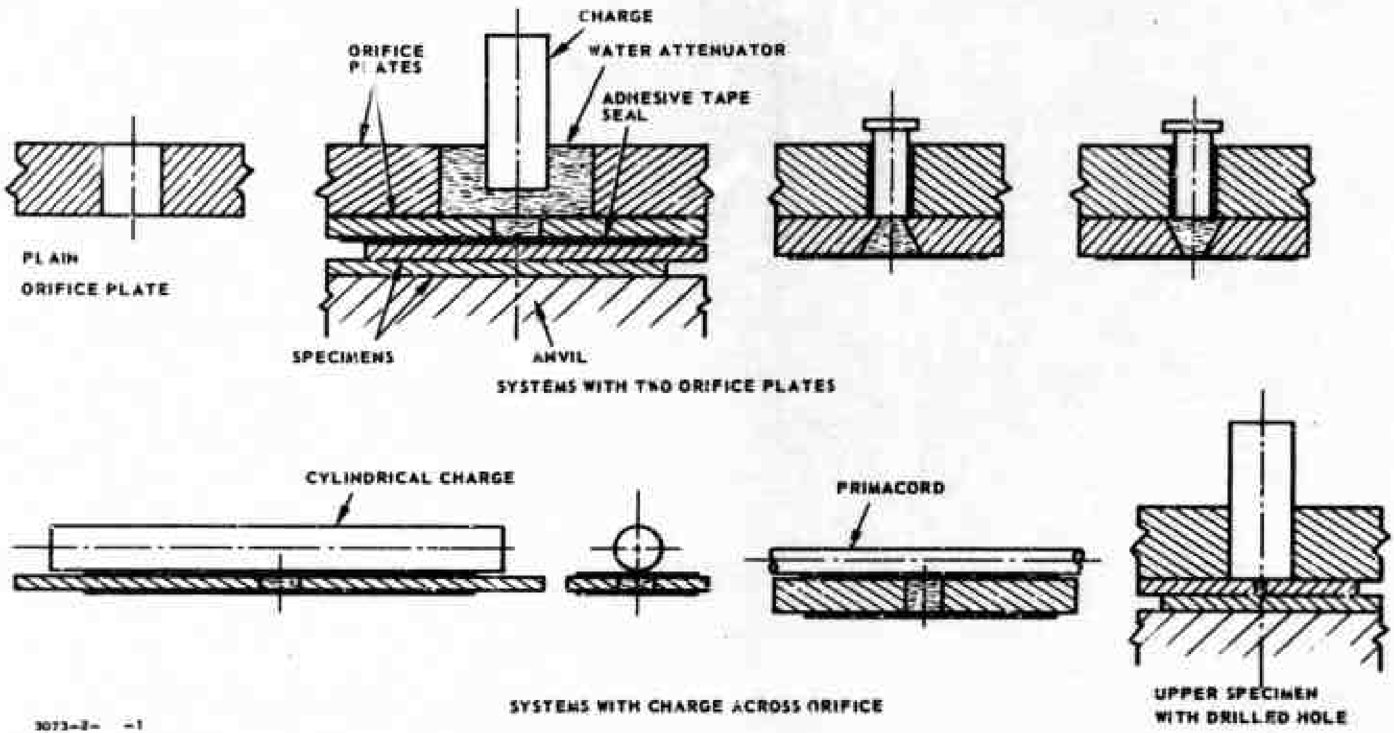

Figure 6. Orifice Plate Arrangements.

- RDX
- HMX
- H-6
- Detasheet, Types C and D
- Primacord, 100 and 40 gr/ft

The following mixtures were formulated and tested:

- 115 ammonium perchlorate/97 nitroguanidine
- 50/50 PETN/nitroguanidine
- 60/40 PETN/nitroguanidine
- 60/40 RDX/nitroguanidine
- 60/40 PETN/ammonium perchlorate
- 16% ammonium perchlorate/84% nitroguanidine

The 16% (by weight) ammonium perchlorate/84% nitroguanidine mix was developed specifically for spot welding applications and was so successful that it was used to provide almost all the production welds. The derivation of this particular mixture, which was designated AP/NG, is given in Appendix I. For various reasons, most commercial explosives were soon eliminated from the program; the most important reasons were (1) they produced severe deformation of the weld panel surfaces, or (2) their detonation velocities were too high to be effective as weld promoters. Many explosives were found to possess critical detonation diameters in excess of the charge diameters required and could not be consistently detonated. The AP/NG mix, however, was capable of consistent detonation in diameters as small as 0.15 in., confined only in plastic or paper straws.

2.4 DETONATORS

Detonation for production of welds was initiated by several commercial detonators. Among the more successful detonators employed were the following:

- T24E1
- D114G1
- MK 70
- MK 71

These detonators were found to be interchangeable without noticeable differences in behavior. All detonators were approximately 3/16-in. in diameter, approximately 3/8 in. long, and could be consistently detonated by a low-voltage (9 v) dry battery.

2.5 DETONATION VELOCITY MEASUREMENTS

Critical diameter tests were made with pure nitroguanidine and with ammonium perhclorate/nitroguanidine mixtures, at various densities and blasting cap sizes. The explosive was loaded into plastic or paper tubes, 4 in. long with 0.020-in. wall thickness, and with internal diameters varying from 0.150 to 0.610 in. After pressing the explosive to the desired density, each tube was fitted with a detonator and fired. Results of these tests showed that the AP/NG mix could be detonated in charges as small as 0.150 in. in diameter, while the pure nitroguanidine could be detonated only in charges larger than 0.250 in.

The charges (so-called "rate sticks") were cylindrical, and were formed by pressing the explosive to the desired density in thin-walled acetate tubes of the appropriate diameter. To maintain uniform density, the charge was loaded in 11 equal increments to a total charge length of 5-1/2 in., with a 1/2-in. space left for the detonator. A typical test setup is shown in Figure 7. The rate stick, A of Figure 7, with the detonator at the top end was assembled vertically onto a 1- by 1-in. block of Plexiglas, 2-1/4 in. high, which is shown as C in Figure 7. A shield or buffer plate, B, consisting of a 4-in. square sheet of 1/16-in. Plexiglas was inserted between the charge and the transparent column to prevent the products of detonation from fogging the Plexiglas.

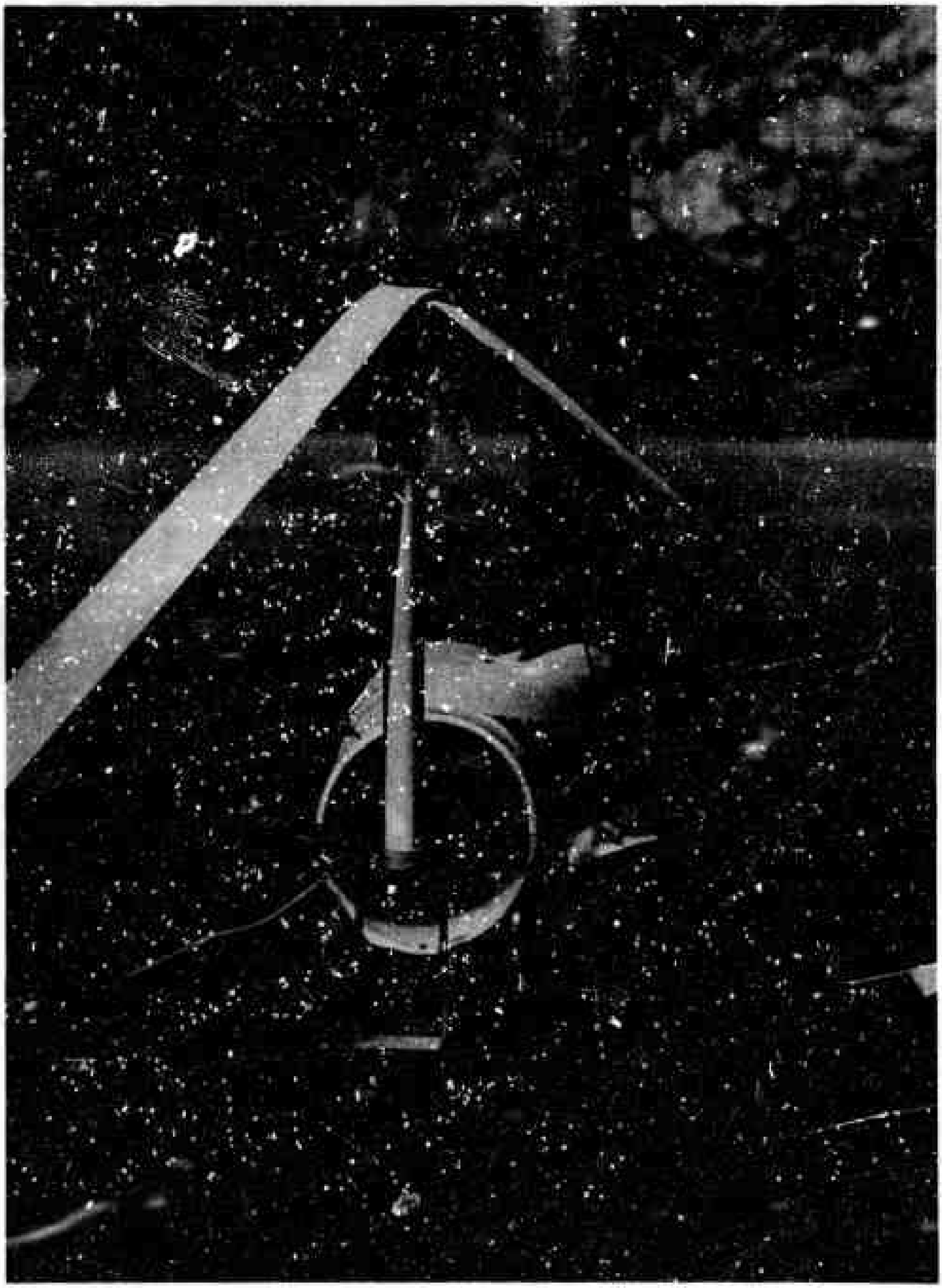

Figure 7. Typical Test Setup
A. Rate Stick C. Plexiglas Column
B. Shield Plate D. Argon Bomb

When the charge was fired, the detonation wave moved downward and attained the detonation velocity that is characteristic for that particular charge density and diameter. Upon its arrival at the Plexiglas, the detonation wave transmitted pressure through the interface and a shock wave was propagated through the Plexiglas column. The detonation wave was sufficiently luminous to be recorded on film. The shock wave in the Plexiglas was made visible by backlighting produced by the argon bomb, D in the figure.

The events were recorded with a Beckman and Whitley Model 194 continuously writing streak camera, shown in Figure 8. The record consists essentially of a film strip with dark streaks, the outline of which forms a wedge-shaped or sloping pattern; a reproduction of a representative film is shown in Figure 9. The slopes represent the ratios between the propagation velocities of the recorded events and the velocity of the film. The propagation velocities are calculated from the measured slopes and the known film velocity. Results of these tests for the AP/NG mix are shown in Figure 10.

2.6 FRAMING CAMERA STUDIES

Framing camera and flash X-ray photographic tests were undertaken to determine the phenomena that occurred during the welding process, so that possible parameters for closing the centers of ring welds could be established. It was also believed that this information would define the welding areas in relation to the shock front. In this regard, the tests were designed to determine whether lateral motion between weld specimens was conducive to welding, and to determine the extent of such a motion if it occurs.

Twenty-four framing camera tests were conducted for this study, using a Beckman and Whitley Model 189 framing camera. Figure 11 (Views A through I) illustrate the various test configurations used to observe shock wave phenomena. Plexiglas was used in all tests because it provided an excellent medium for photographically observing the shock waves. Holes that were match-drilled in both the upper and lower Plexiglas plates made it possible to observe lateral motion between the two plates. Light from an exploding bridgewire, magnified by a Fresnel lens, provided backlighting for all tests. Table I is a record of the test setup and the camera speed, delay, and time lapse between frames.

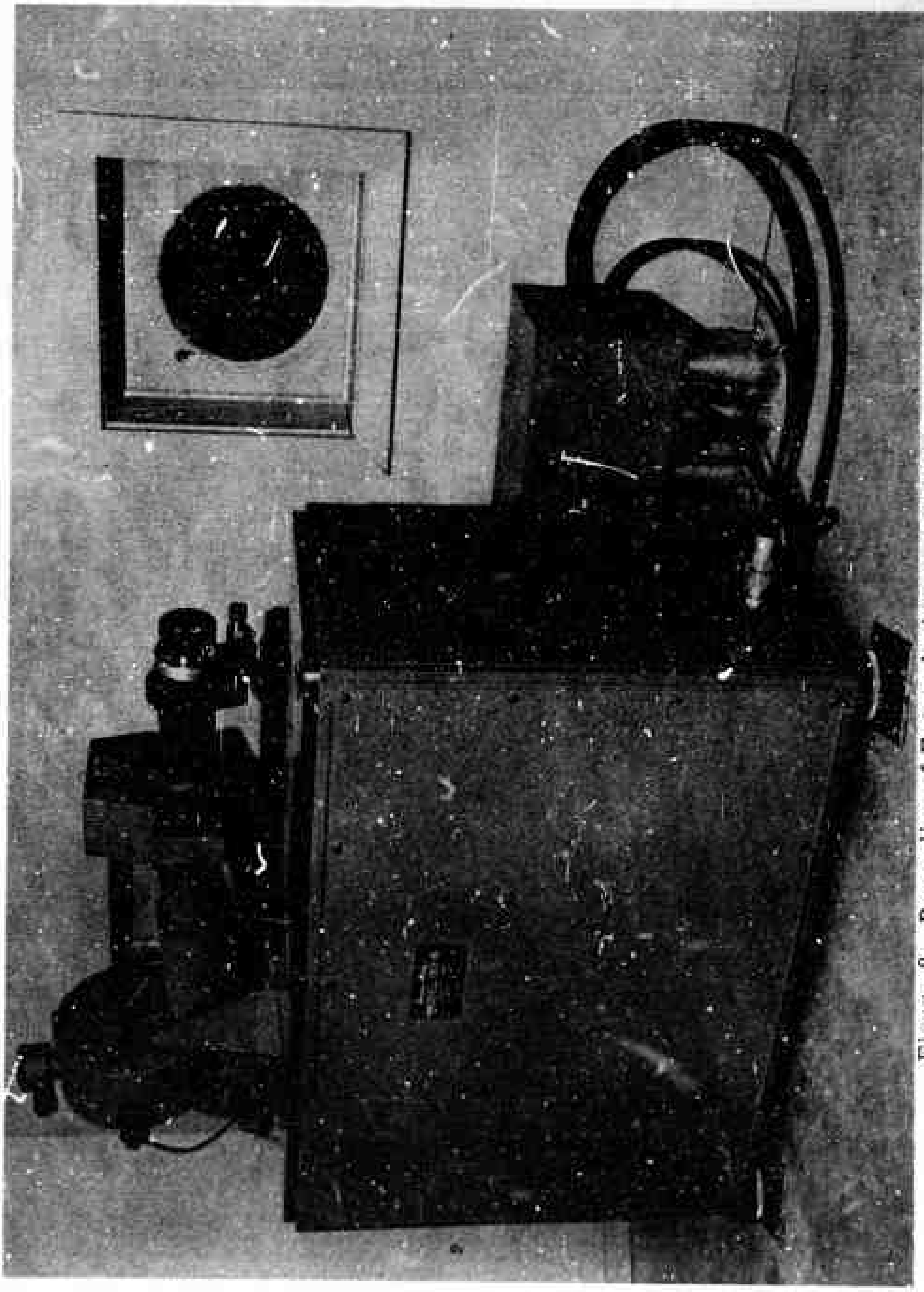

Figure 8. Recording of Events by Means of Beckman & Whitley Model 194 Continuous Writing Streak Camera.

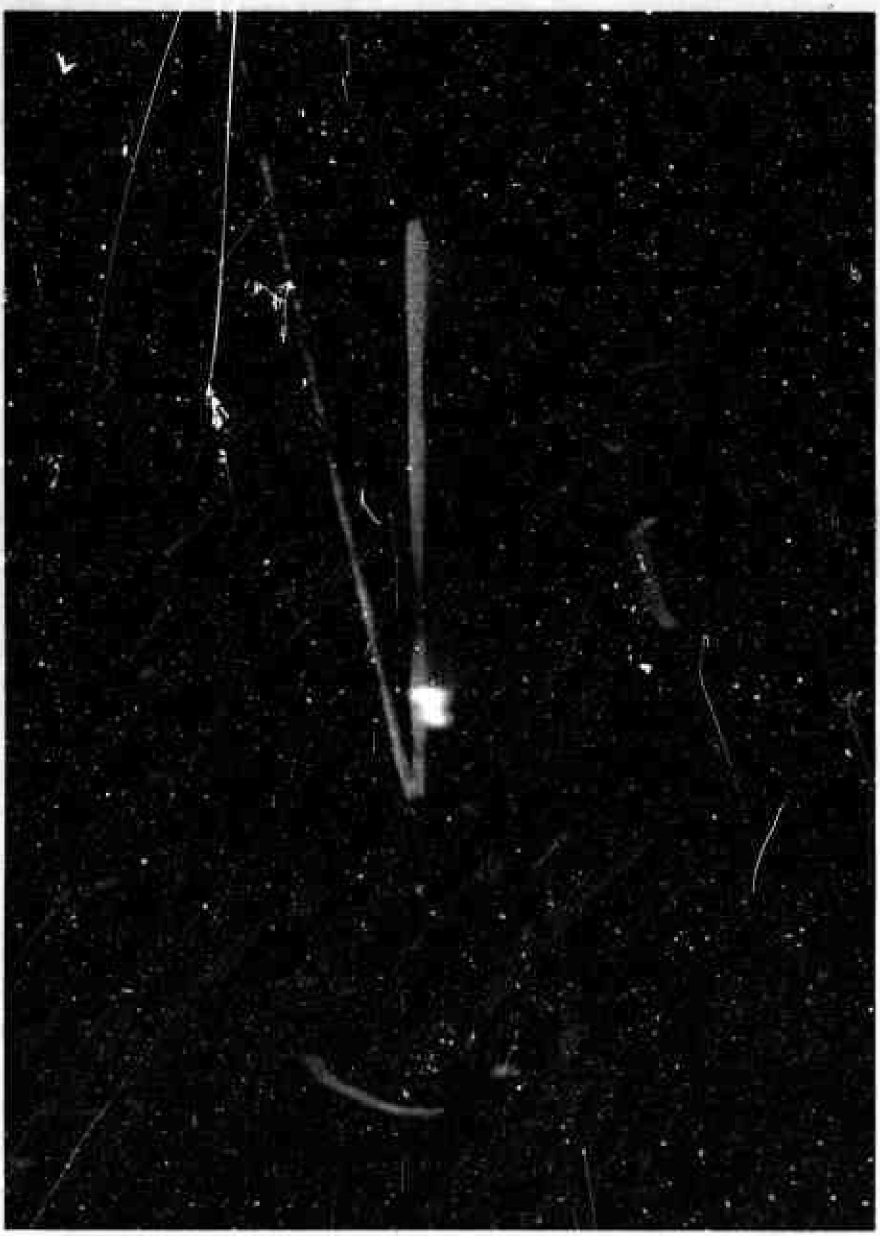

Figure 9. Reproduction of a Representative Streak Film.

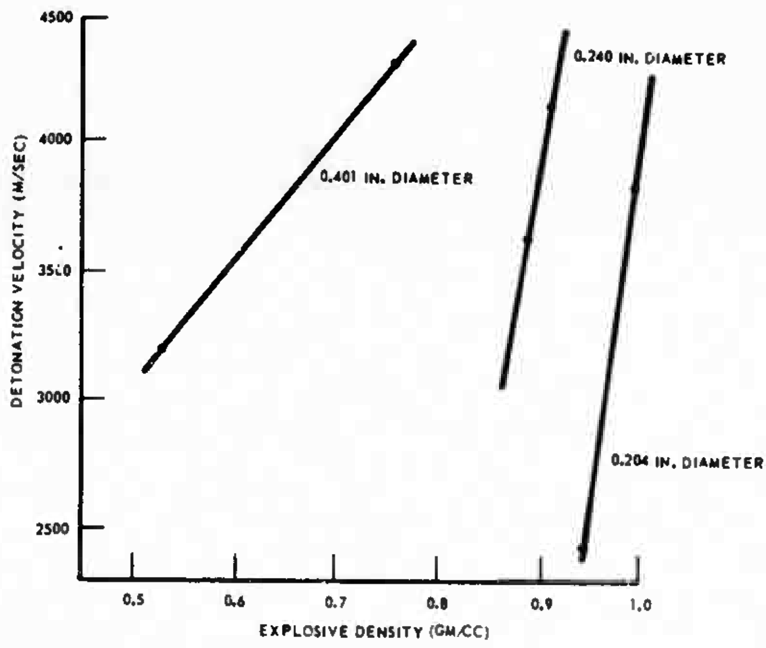

Figure 10. Detonation Velocity Studies of AP/NG Mix.

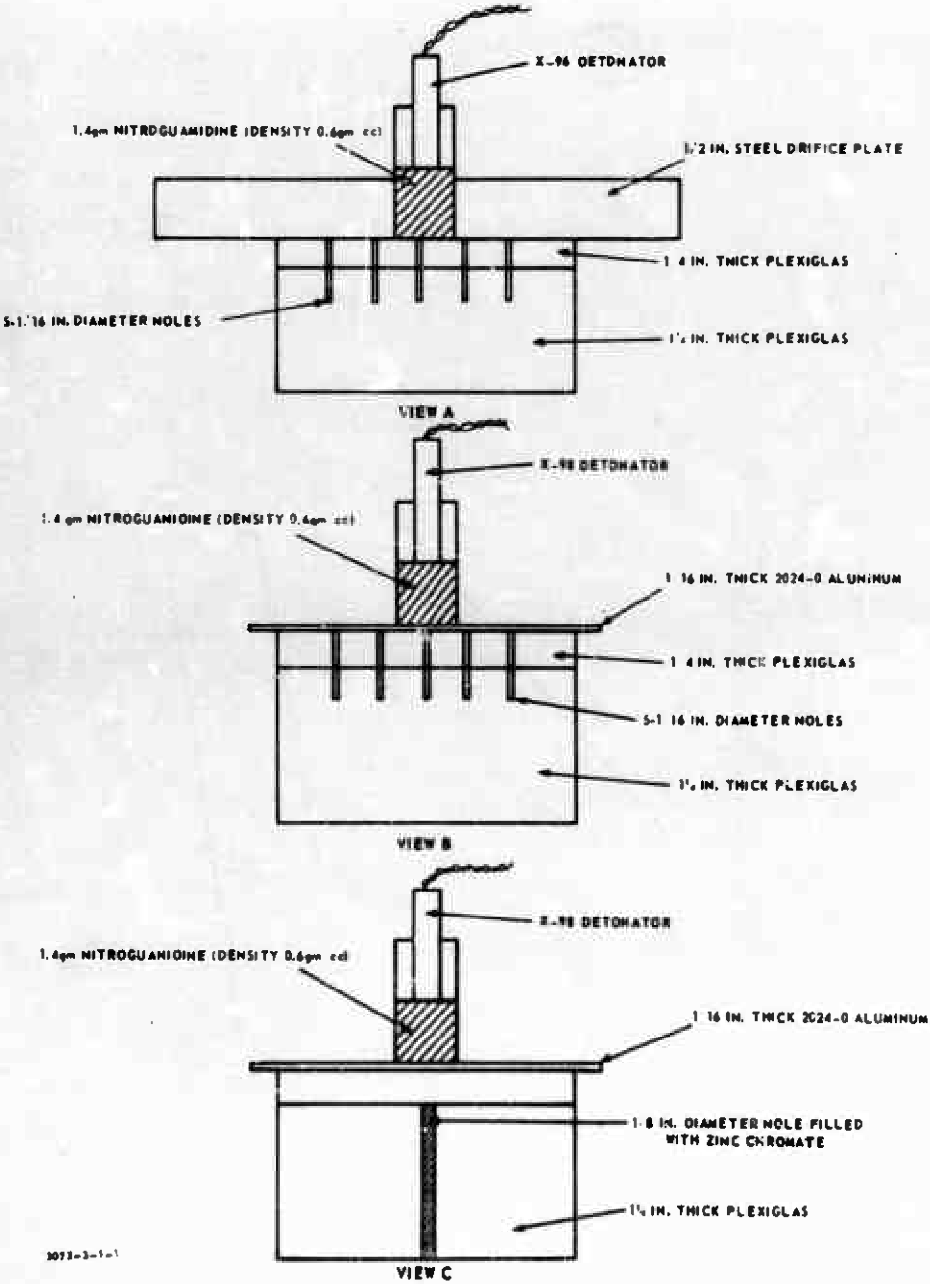

Figure 11. Charge and Target Configurations for Shock Wave Photography (Sheet 1 of 3).

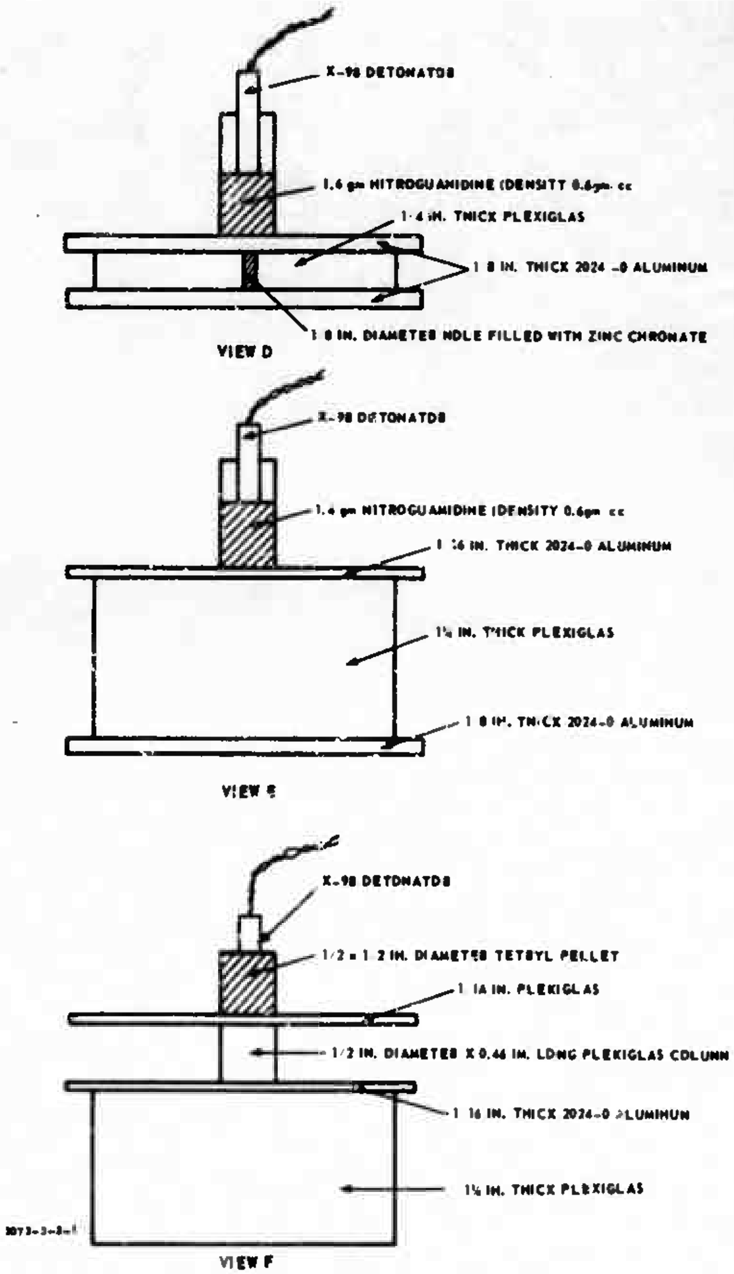

Figure 11. Charge and Target Configurations for Shock Wave Photography (Sheet 2 of 3).

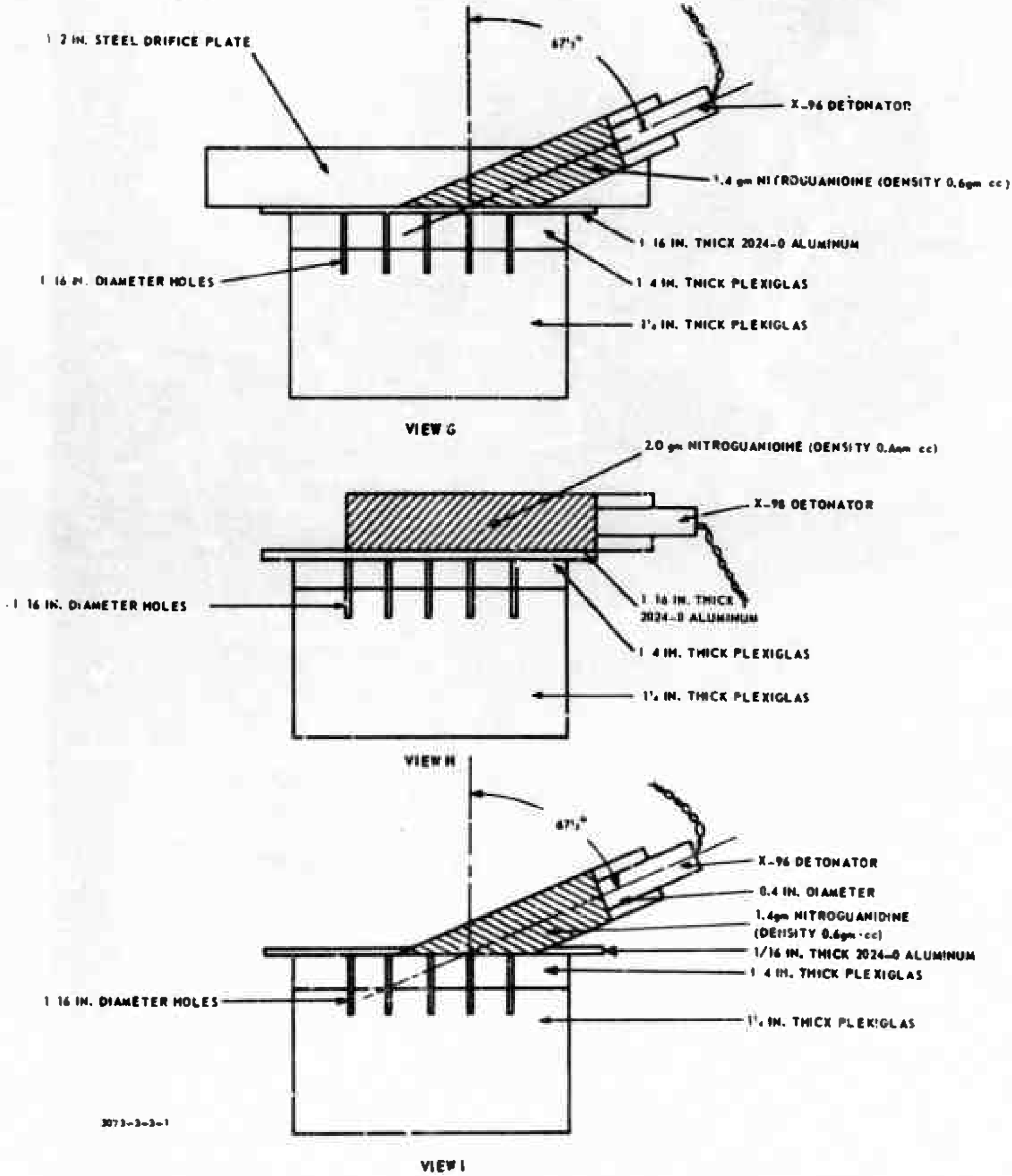

Figure 11. Charge and Target Configurations for Shock Wave Photography (Sheet 3 of 3).

Table I. Data for Framing Camera Records.

Test Number	Test Setup (Figure 3)	Camera (rotation per sec)	Camera Delay (msec)	Time Between Frames (msec)
2238	View A	2003	421	2.1
2239	View A	2001	401	2.1
2240	View A	3999	170	1.05
2241	View A	3992	159	1.05
2242	View A	3998	159	1.05
2243	View B	3998	159	1.05
2244	No Record		-	-
2245	View C	4002	159	1.05
2246	View C	3996	159	1.05
2247	View B	4002	159	1.05
2248	View D	5000	107	0.84
2249	View D (no hole in Plexiglas)	5011	100	0.84
2250	View E	4000	159	1.05
2251	View E	4002	152	1.05
2252	View F	3998	157	1.05
2253	View F	4001	140	1.05
2254	View F	3999	170	1.05
2255	View F	4000	166	1.05
2256	View G	4003	159	1.05
2257	View I	4001	159	1.05
2258	View H	3997	159	1.05
2259	View G	4002	159	1.05
2260	View I	4003	159	1.05
2261	View I	4001	159	1.05
2262	View G	3998	159	1.05

Photographic records of Tests 2245, 2250, 2256, 2257, and 2258 are included as Figures 12 through 16. The record of Test 2245 (Figure 12) is an excellent example of a normal shock wave. The shock wave entered the Plexiglas directly under the explosive charge and traveled down through the Plexiglas until it struck the top of the test stand, which reflected the wave back into the Plexiglas. Figure 12 clearly shows the reflection of the shock wave at the two outer edges of the Plexiglas.

The record of Test 2250 (Figure 13) is another excellent example of the shock wave emerging from the 0.063-in.-thick 2024-0 aluminum alloy sheet into the Plexiglas medium. The symmetrical wave entered the Plexiglas in one frame, and in the next frame a breakup of the Plexiglas is visible. Fracturing of the Plexiglas is visible as a dark area behind the shock wave; the shock wave traveled completely through the Plexiglas and was reflected back by the 1/8-in.-thick aluminum alloy bottom sheet. Breakup of the Plexiglas following the reflected compression wave is shown in Frames 13 through 16, and 19 through 22 of Figure 13.

The record of Test 2256 (Figure 14) is an example of a shock wave configuration produced by a 67-1/2° angular charge that was contained in a steel orifice plate; this particular charge configuration had shown some promise of producing a closed-center spot weld. The shock wave in this case moved laterally as well as vertically, and at the intersection of the two Plexiglas plates a compressive reflected wave was introduced.

The record of Test 2257 (Figure 15) is another example of a 67-1/2° angular charge, but without the confinement of the steel orifice plate. The results were similar to the previous test, but in this test the lateral displacement of the shock wave was less pronounced.

The record of Test 2258 (Figure 16) shows the shock wave pattern produced by a cylindrical charge detonated laterally along the surface of the 0.063-in.-thick aluminum alloy sheet. The shock wave was principally produced in the upper 1/4-in.-thick Plexiglas, and reflected by the lower 1-1/4-in.-thick Plexiglas. However, the shock penetrated and moved laterally in the lower Plexiglas, but it was very weak; the shock in the upper, thinner, Plexiglas was very prominent, as evidenced by the amount of breakup in the upper plate.

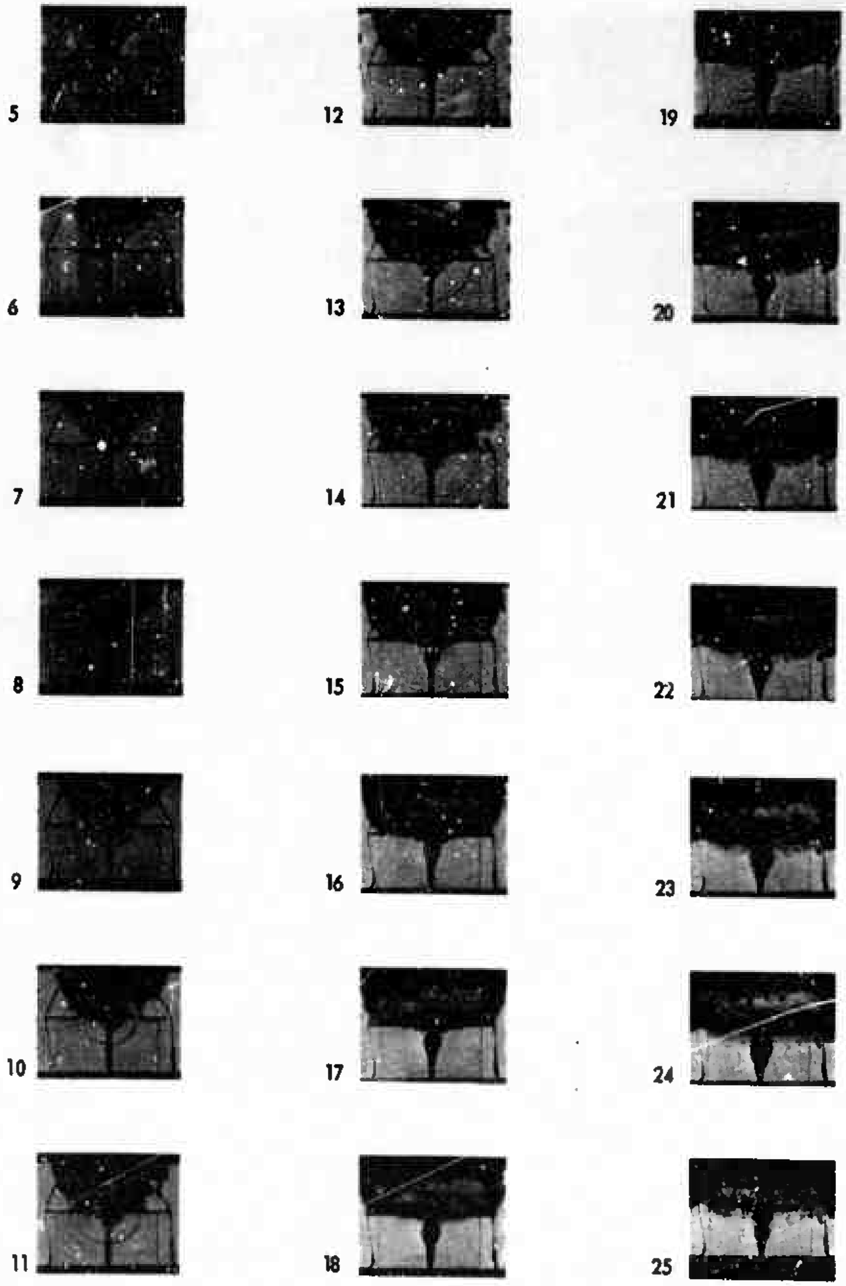

Figure 12. Shock Wave Propagation, Test No. 2245, Configuration 3c, Frames 5 through 25.

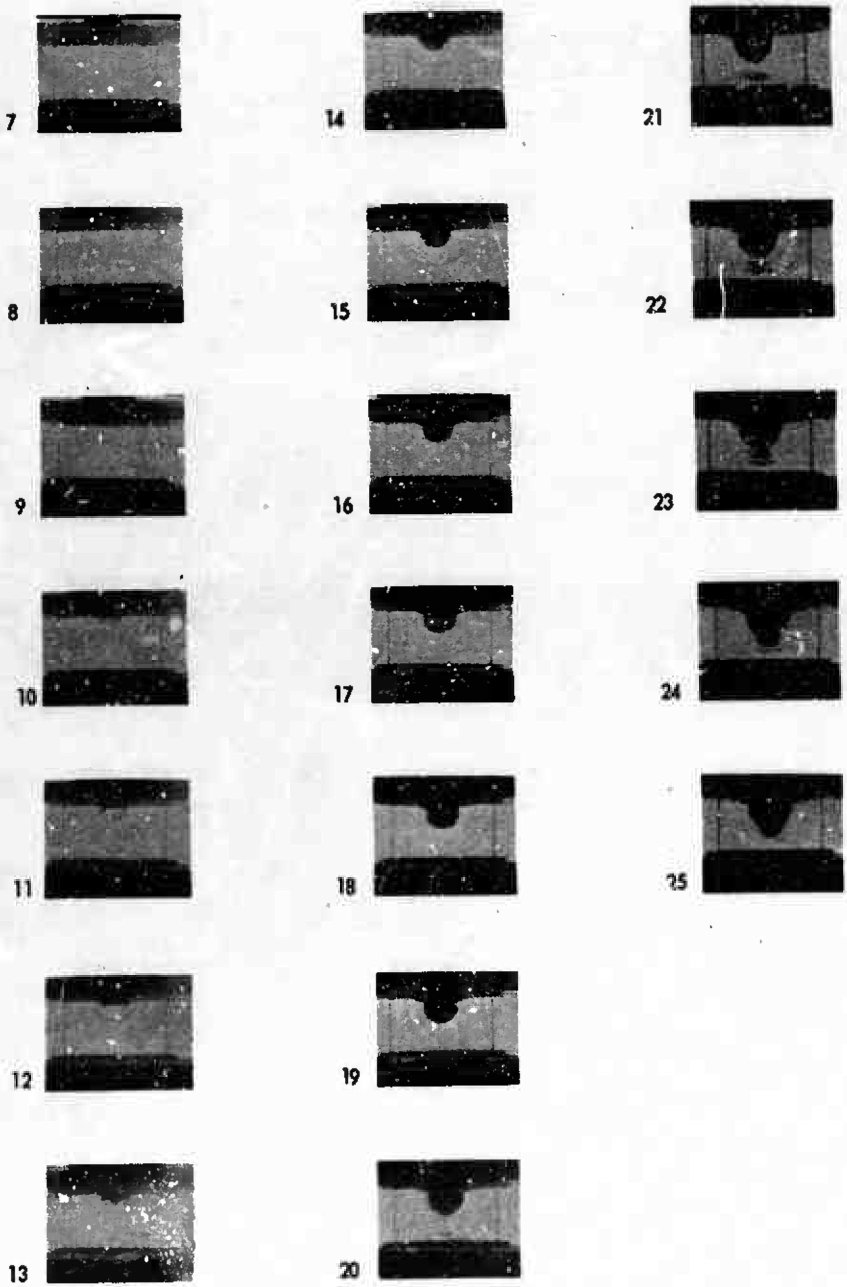

Figure 13. Shock Wave Propagation, Test No. 2250, Configuration 3e, Frames 7 through 25.

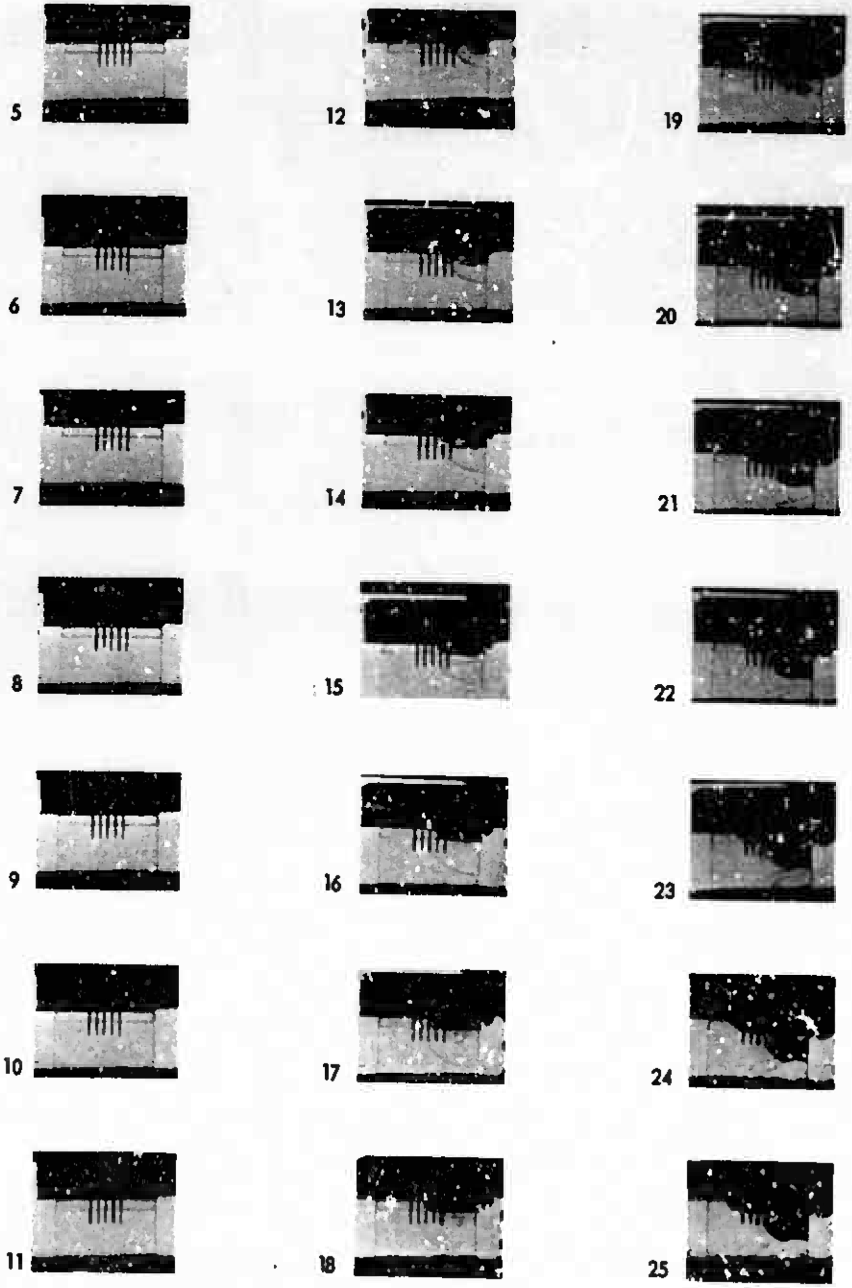

Figure 14. Shock Wave Propagation, Test No. 2256, Configuration 3g, Frames 5 through 25.

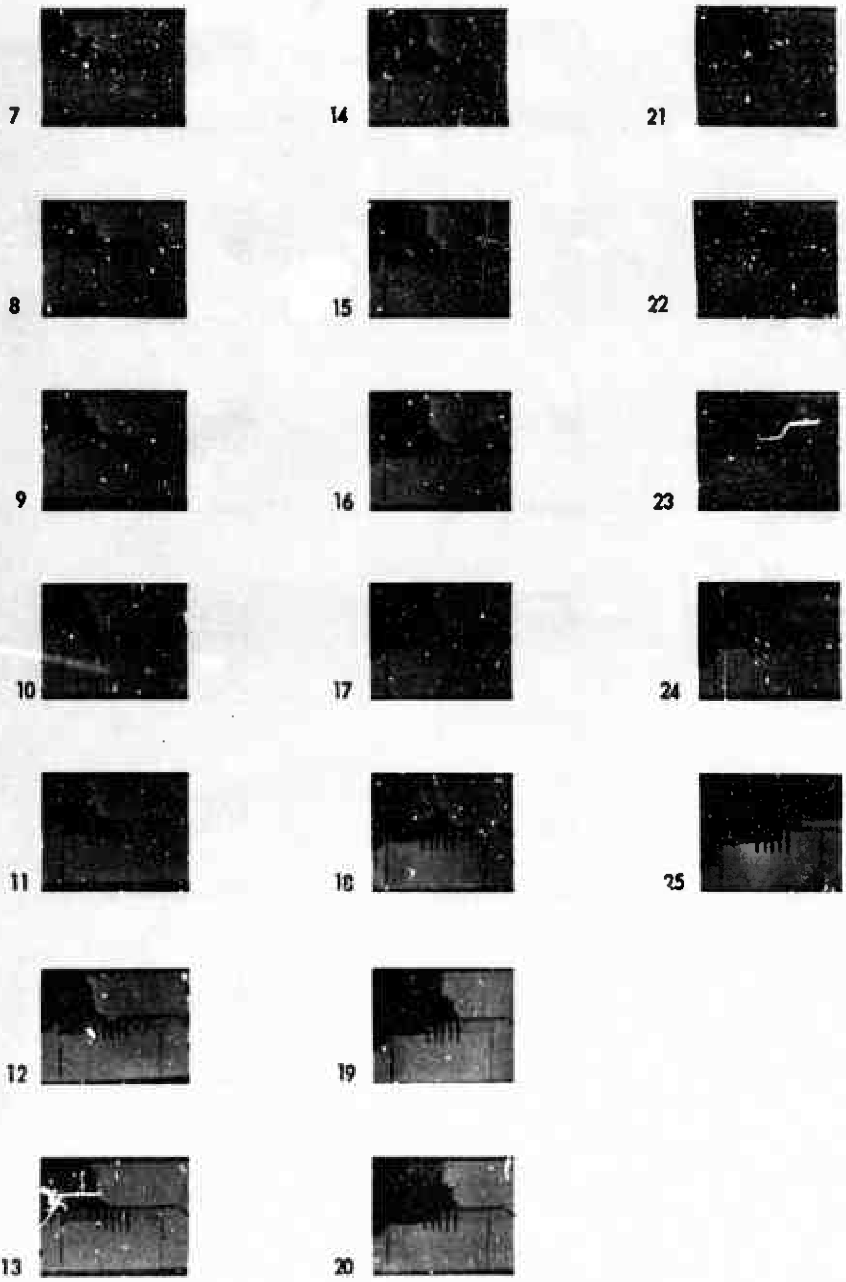

Figure 15. Shock Wave Propagation, Test No. 2257, Configuration 3i, Frames 7 through 25.

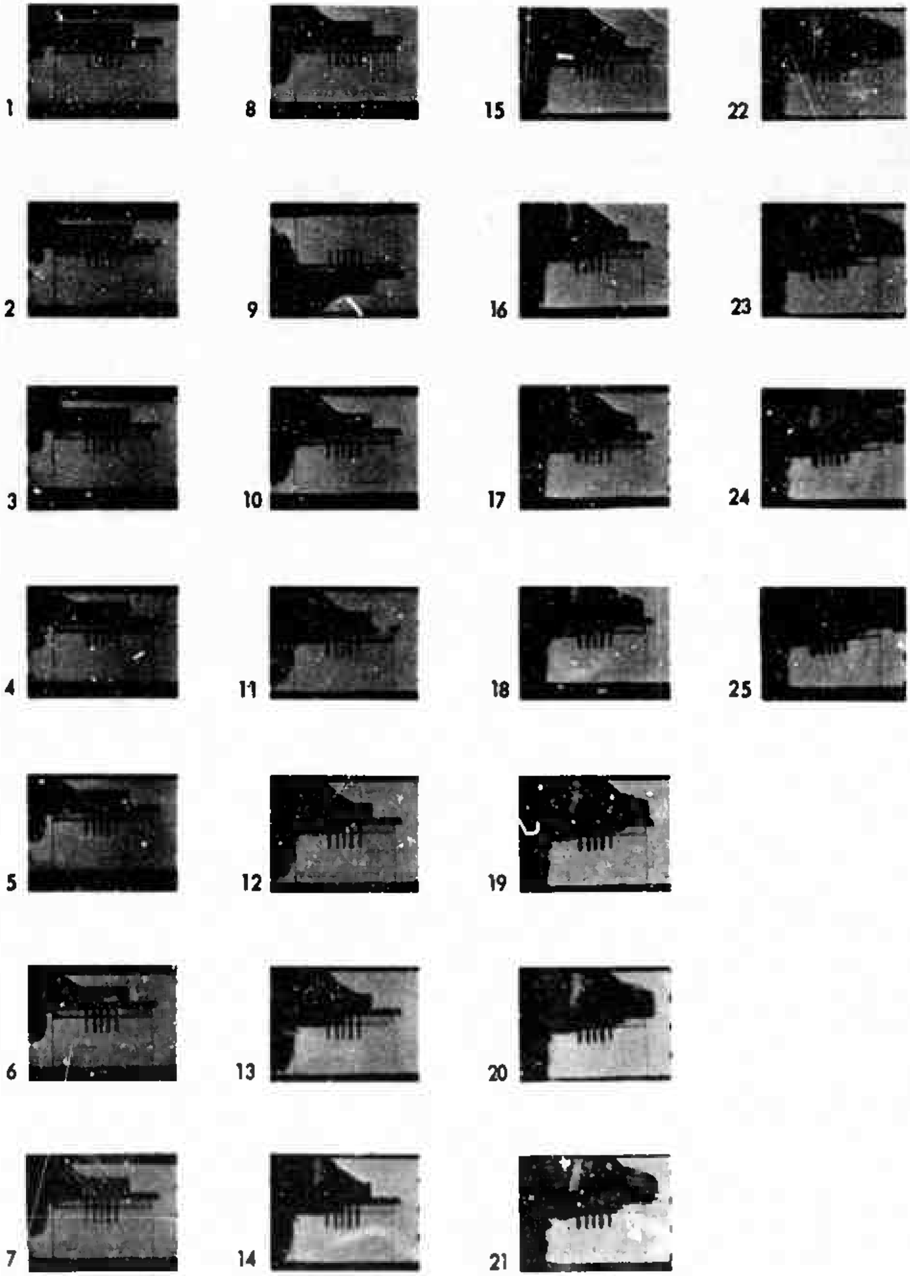

Figure 16. Shock Wave Propagation, Test No. 2258, Configuration 3h, Frames 1 through 25.

2.7 FLASH X-RAY STUDIES

To supplement the framing camera studies, six flash X-ray photographs were taken to determine the presence of motion during the welding process. Figure 17 is a diagram of the general test arrangement, and Figure 18 illustrates the explosive charge configuration. To record any possible motion of weld specimens during the explosive process, six 2- by 3-in. panels of 0.063-in. aluminum alloy 2024-0 sheet were machined with concentric circular grooves forming a "bull's-eye" target in the center of each panel. The grooves were then filled with lead-tin solder to show up clearly on the X-ray film.

To provide reference points for possible motion, a static X-ray picture was obtained prior to each test. It was found that the 1/2-in.-thick Plexiglas anvil that was used to support the test specimens considerably reduced the clarity of the X-ray picture. However, if the anvil was omitted, the specimens were deformed by direct contact with the detonating system to the extent that data would have been questionable; therefore, only anvil-supported specimens were evaluated. An example of the photographs obtained before and during the welding is shown in Figure 19.

Measurements of the target inner ring 0.220 in. in diameter showed that an outward movement of 0.030 in. occurred during a time span of 7 to 10 μsec. This 7- to 10-μsec interval represents the time lapse between Frames 2 and 4 on the X-ray photograph. Measurements on a ring with a diameter of 0.650 in. indicated that an outward movement of 0.060 in. occurred during the same time interval, which shows that radial flow velocity increases rapidly with distance from the center.

The time delay for the flash X-ray tubes, in relation to the firing pulse input to the X-98 detonator, was determined hy three individual timing tests; these timing tests utilized the same explosive setup shown in Figure 18 with the exception that weld specimens were replaced by DuPont T1 targets. The DuPont T1 target was a normally open switch that was closed by the shock wave as it progressed through the end closure. The delay times of the three tests were as follows:

Test 1	-	47 μsec
Test 2	-	45 μsec
Test 3	-	47 μsec

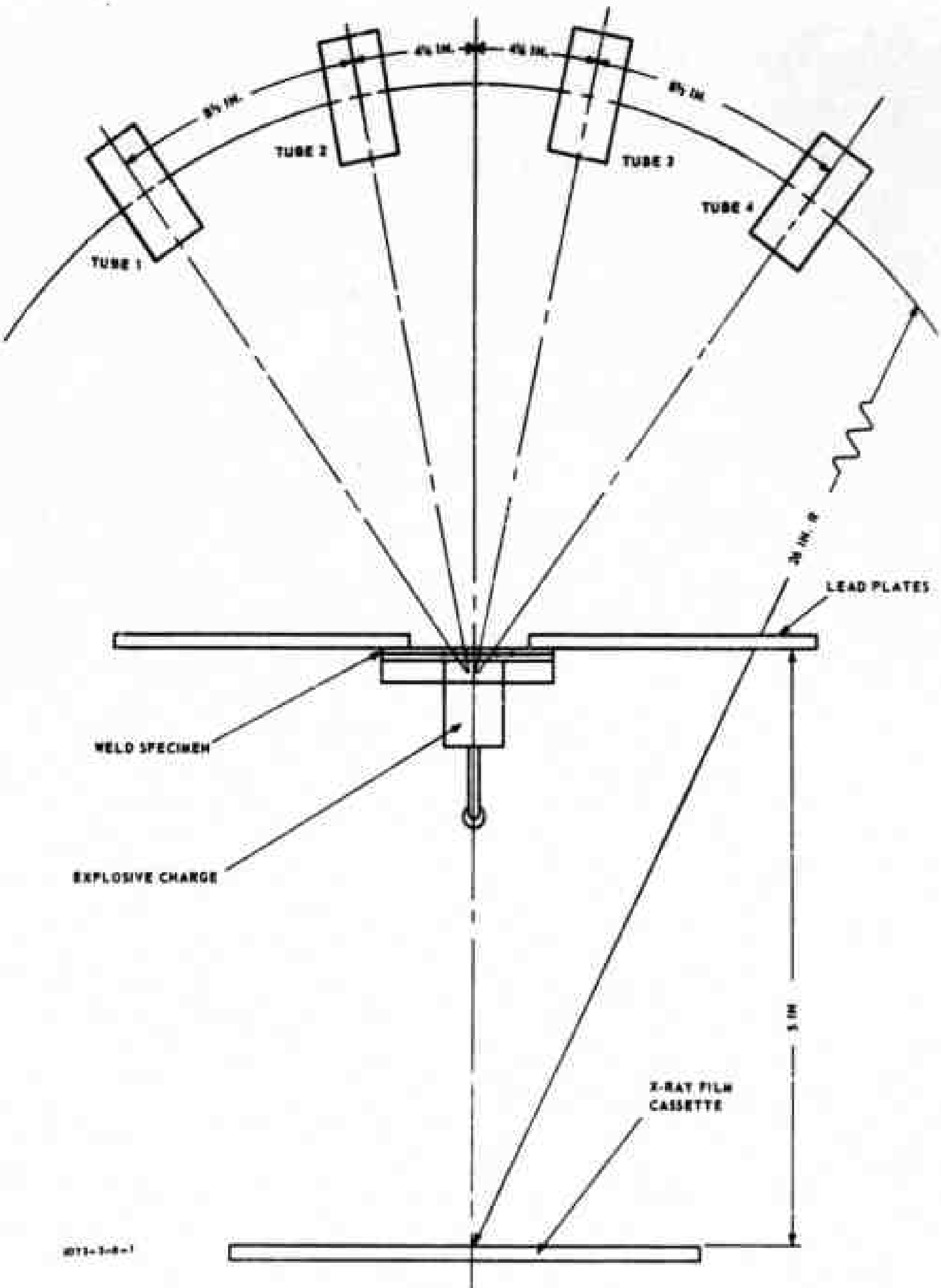

Figure 17. Setup for Flash X-Ray Photography.

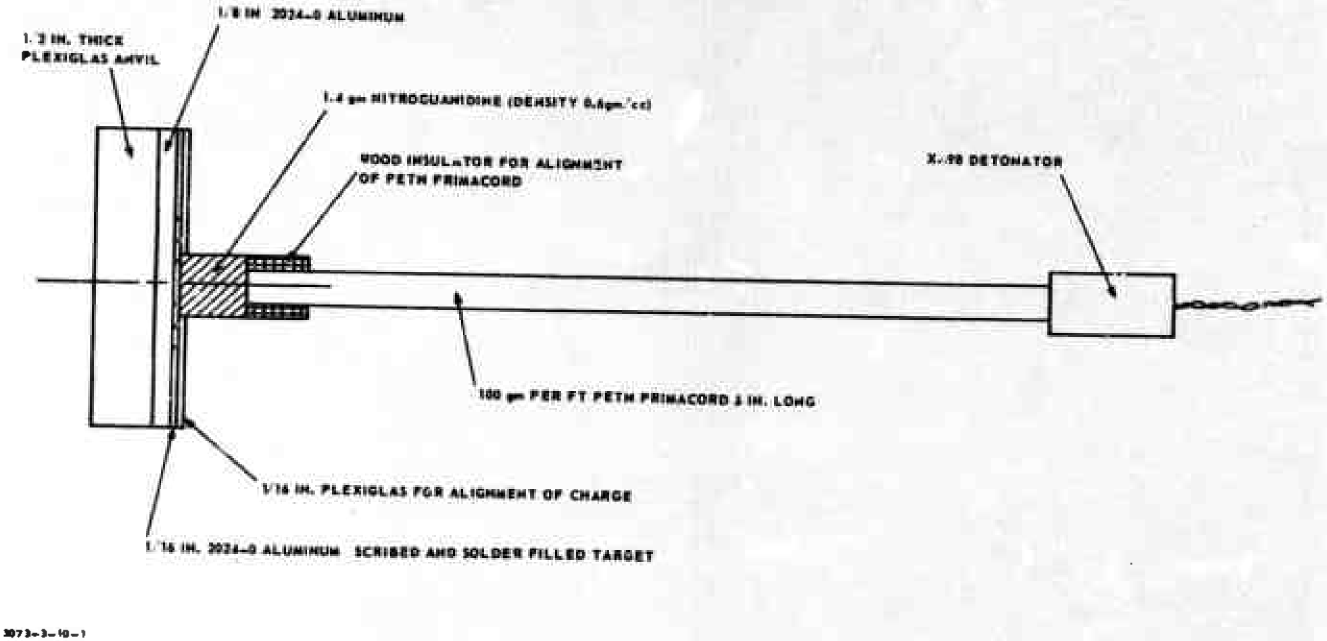

Figure 18. Arrangement of Explosive Charge and Target for Flash X-Ray Photography.

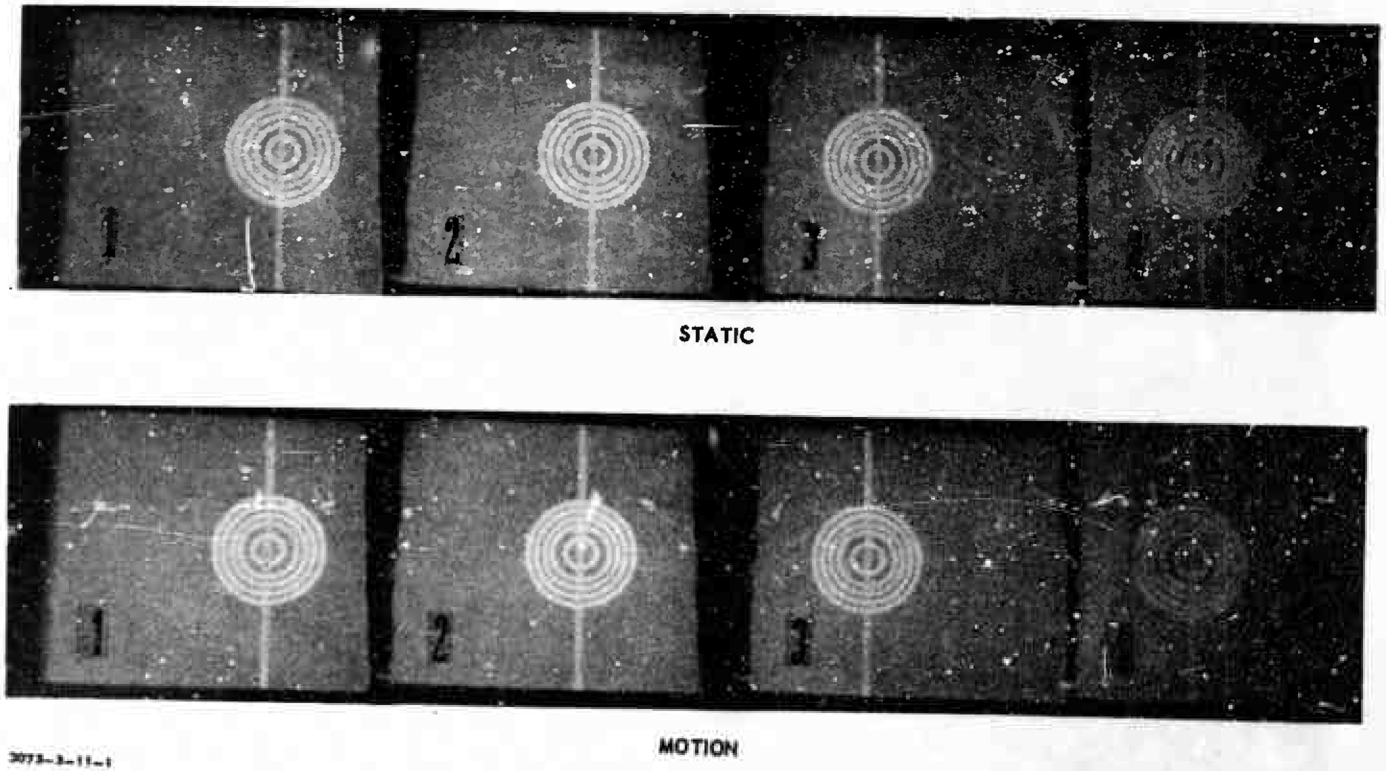

Figure 19. Samples of Flash X-Ray Records Taken Before the Detonation and During the Period of Detonation.

These delay times represent the elapsed time from detonator firing pulse until the shock wave generated by the explosive charge entered the top aluminum specimen. Based on these results, the first tube of the flash X-ray assembly was set to trigger at 47 μsec, and the second tube at 50 μsec. The times were varied on the third and fourth tubes between tests. Two different times were used for each tube; 53 and 55 μsec for the third tube, and 57 and 60 μsec for the fourth tube. Because motion occurred after the second frame on the X-ray film, it was apparent that the motion trailed the shock wave by approximately 3 μsec. This is also evident in the framing camera photographs, where a shock wave is shown entering the Plexiglas in one frame, and two frames later, approximately 2 μsec, the breakup of the Plexiglas becomes evident.

2.8 DISCUSSION OF TEST RESULTS

It was concluded from framing camera photographs and X-ray records that relative motion between spot welded sheets does occur. This motion appears to result from lateral or horizontal displacement, which is produced by the powerful vertical (downward) compression of the shock wave and the subsequent pressure effects of the detonation gases. In the framing camera photographs, this motion was indicated by the breakup and fracturing of the Plexiglas panels; in the flash X-rays it was evidenced by movement of the solder-filled rings. It appeared evident that this relative motion is a requisite of the welding process because earlier welding experiments repeatedly showed that no welding occurred when there was no standoff between weld sheets constrained by hold-down devices, which eliminated movement. Therefore, it was concluded that the weld was produced by lateral motion between the weld sheets. In the case of spot welds, the shock pressure was applied over a limited and concentrated area, usually of circular or near-circular shape; in this case, there appeared to be an outward movement over most of the area, apparently radiating from a fixed source. At the source of motion and in its immediate surroundings there was no motion and consequently no welding. The fact that the shock wave was spherical supports this concept; at any point removed from the shock wave axis, the wave had a radial component supporting the outward expanding motion while at the center itself the wave had only a tangential component.

2.9 USE OF DIMPLES FOR STANDOFF

Exploratory studies indicated that a positive hold-down pressure, which kept the weld sheets in contact, was a requisite for weld attainment, yet a standoff between the sheets at the weld junction was also necessary. The most successful solution for these requirements was to form a dimple in the top weld sheet. Both flat and spherical dimples, as shown in Figure 20, were tested, and it was found that weld strength varied with dimple height (or standoff) hut not consistently.

Many tests were made to evaluate the effects of the dimple standoff. The first test series kept all weld parameters constant, except varied the standoff. Then the charge length was varied and the series was repeated. Finally, the two series were repeated with the same standoffs and the same two charge lengths, but with a new charge diameter. In each case, the weld sample (in the form of lap shear specimens) was pulled in tension and the strength of the weld was measured in pounds. In many cases, the weld deformation (defined as the vertical deflection from the top surface to the center of the weld) was measured as an indication of the explosive effects on the sheet material.

This test program was applied to (1) welding Type 347 stainless steel together, and (2) welding 6Al-4V titanium alloy together. The explosives tested were nitroguanidine and C-2 sheet explosive. The results are presented in Tables II through VII, and Figures 21 through 28. The data cover tests with flat and spherical dimple geometries, but the majority of tests were with the flat dimple. The data for the spherical dimple are listed in Tables III and VI, and are shown graphically as curves A-6 and B-6 in Figures 23 and 27. The corresponding curves for the flat dimples are also reproduced for comparison. It is apparent that, for a given standoff, the spherical dimple produced a higher weld strength. A numher of test specimens examined after lap shear tests are shown in Figures 29 and 30. The weld nuggets show considerable uniformity, both in weld texture and shape. These and similar examples were instrumental in deriving the final theory of spot weld formation.

2.10 THEORY OF FORMATION OF RING WELDS

An analysis of the production of ring welds based on the dimple concept was undertaken. Based on this analysis, it is now believed that ring welds are formed as shown in Figure 31, when a dimple cavity is used for a standoff. If the diameter of the explosive charge exceeds the dimple gap, shown as

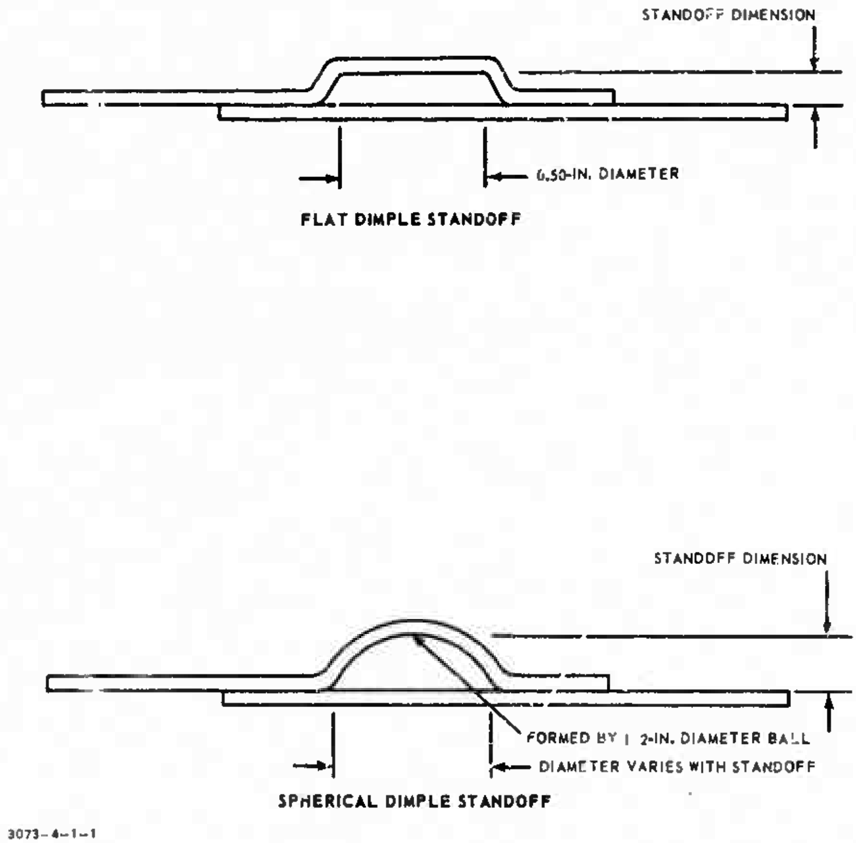

Figure 20. Dimple Configurations for Standoff.

Table II. Effect of Variation in Explosive Charge Size and Plate Standoff on Weld Strength.

Type 347 stainless steel, 0.063 in., welded to itself.
Explosive: Nitroguanidine of density 0.69 gm/cc.

Explosive Charge Weight (gm)	Explosive Charge Diameter (in.)	Explosive Charge Length (in.)	Specimen Standoff (in.)	Weld Strength (lb)	Curve No.
3.0	0.41	2.00	0.015	1400	A-1
|	|	|	0.015	3500	|
|	|	|	0.020	4080	|
|	|	|	0.025	3950	|
|	|	|	0.030	3420	|
|	|	|	0.035	3935	|
|	|	|	0.040	3900	|
|	|	|	0.045	4220	|
|	|	|	0.050	3375	|
|	|	|	0.060	3200	|
|	|	|	0.075	2950	|
1.5	|	1.00	0.015	2575	A-2
|	|	|	0.025	3275	|
|	|	|	0.030	2200	|
|	|	|	0.035	3300	|
|	|	|	0.035	3450	|
|	|	|	0.040	2400	|
|	|	|	0.040	3580	|
|	|	|	0.050	4075	|
|	|	|	0.060	3050	|
|	|	|	0.070	3125	|

Standoff produced by the flat dimple.

Table III. Effect of Variation in Explosive Charge Size and Plate Standoff on Weld Strength and Vertical Deflection.

Type 347 Stainless Steel, 0.063 in., welded to itself.
Explosive: Nitroguanidine of density 0.69 gm/cc.

Explosive Charge						
Weight (gm)	Diameter (in.)	Length (in.)	Vertical Deflection (in.)	Specimen Standoff (in.)	Weld Strength (lb)	Curve No.
2.00	0.31	2.00	0.058	0.015	2875	A-3
				0.015	1850	
				0.025	1400	
			0.065	0.025	2500	
			0.066	0.035	2875	
				0.035	2500	
				0.045	2500	
			0.056	0.045	1850	
				0.055	2300	
			0.073	0.055	2700	
			0.085	0.065	1800	
				0.065	2350	
				0.075	2900	
			0.096	0.075	3225	
1.00		1.00		0.015	2040	A-4
				0.025	2100	
				0.035	2140	
				0.045	1920	
				0.055	1420	
				0.065	2540	
				0.075	1700	
				0.015*	2375	
				0.025*	2500	
				0.035*	2550	
				0.045*	2500	A-6
				0.055*	2575	
				0.065*	2300	
				0.075*	2900	

Standoff produced by the flat dimple, except as noted by *.

* Standoff produced by the spherical dimple.

Table IV. Effect of Variation in Plate Standoff on Weld Strength and Vertical Deflection.

347 Stainless Steel, 0.063 in., welded to itself.
Explosive: Type C-2 Detasheet
Attenuator: 1/8-in.-thick zinc chromate.

Explosive Charge						
Weight (gm)	Diameter (in.)	Length (in.)	Vertical Deflec-tion (in.)	Specimen Standoff (in.)	Weld Strength (lb)	Curve No.
0.45	0.31	3 Layers	0.038	0.015	2575	A-5, A-8
			0.031	0.025	2350	
			0.043	0.035	1825	
			0.047	0.045	3400	
			0.046	0.055	500	
			0.067	0.075	2750	

Standoff produced by the flat dimple.

Table V. Effect of Variation in Explosive Charge Size and Plate Standoff on Weld Strength.

6Al-4V titanium, 0.063 in. thick, welded to itself.
Explosive: Nitroguanidine of density 0.69 gm/cc.

Explosive Charge			Specimen	Weld	
Weight (gm)	Diameter (in.)	Length (in.)	Standoff (in.)	Strength (lb)	Curve No.
3.0	0.41	2.00	0.015	1850	B-1
			0.025	1400	
			0.025	3200	
			0.030	1675	
			0.030	3600	
			0.035	2300	
			0.035	1350	
			0.040	3300	
			0.040	2500	
			0.045	3500	
			0.050	3575	
			0.050	3500	
			0.055	3900	
			0.060	3500	
1.5		1.00	0.015	700	B-2
			0.025	2500	
			0.030	2605	
			0.040	3005	
			0.050	2775	
			0.050	2800	
			0.050	3500	
			0.060	2705	
			0.070	2815	

Standoff produced by the flat dimple.

Table VI. Effect of Variation in Explosive Charge Size and Plate Standoff on Weld Strength and Vertical Deflection.

6Al-4V Titanium, 0.063 in., welded to itself.
Explosive: Nitroguanidine of density 0.69 gm/cc

Explosive Charge Weight (gm)	Diameter (in.)	Length (in.)	Vertical Deflection (in.)	Specimen Standoff (in.)	Weld Strength (lb)	Curve No.
2.00	0.31	2.00	0.054	0.015	1175	B-3, B-7
				0.025	1500	
			0.055	0.025	1350	
				0.035	2300	
			0.059	0.035	2100	
				0.045	2750	
			0.075	0.045	3100	
				0.055	2450	
			0.071	0.055	400	
				0.065	2850	
				0.065	2500	
				0.075	2000	
			0.084	0.075	1950	
1.00		1.00		0.035	1240	B-4
				0.045	960	
				0.055	840	
				0.065	200	
				0.075	1480	
				0.025*	2150	B-6
				0.035*	2150	
				0.045*	2175	
				0.055*	2250	
				0.065*	2450	
				0.075*	1250	

Standoff produced by the flat dimple except as noted by *.

* Standoff produced by ½-in.-diameter ball.

Table VII. Effect of Variation of Plate Standoff on Weld Strength and Vertical Deflection.

6Al-4V titanium, 0.063 in., welded to itself.
Explosive: Type C-2 Detasheet.
Attenuator: 1/8-in. thick zinc chromate.

Explosive Charge			Vertical Deflection (in.)	Specimen Standoff (in.)	Weld Strength (lb)	Curve No.
Weight (gm)	Diameter (in.)	Length (in.)				
0.45	0.31	3 Layers	0.041	0.015	1650	B-5, B-B
|	|	|	0.046	0.025	1550	|
|	|	|	0.055	0.035	1825	|
|	|	|	0.055	0.045	1475	|
|	|	|	0.054	0.065	2150	|
|	|	|	0.065	0.075	1125	|

Standoff produced by the flat dimple.

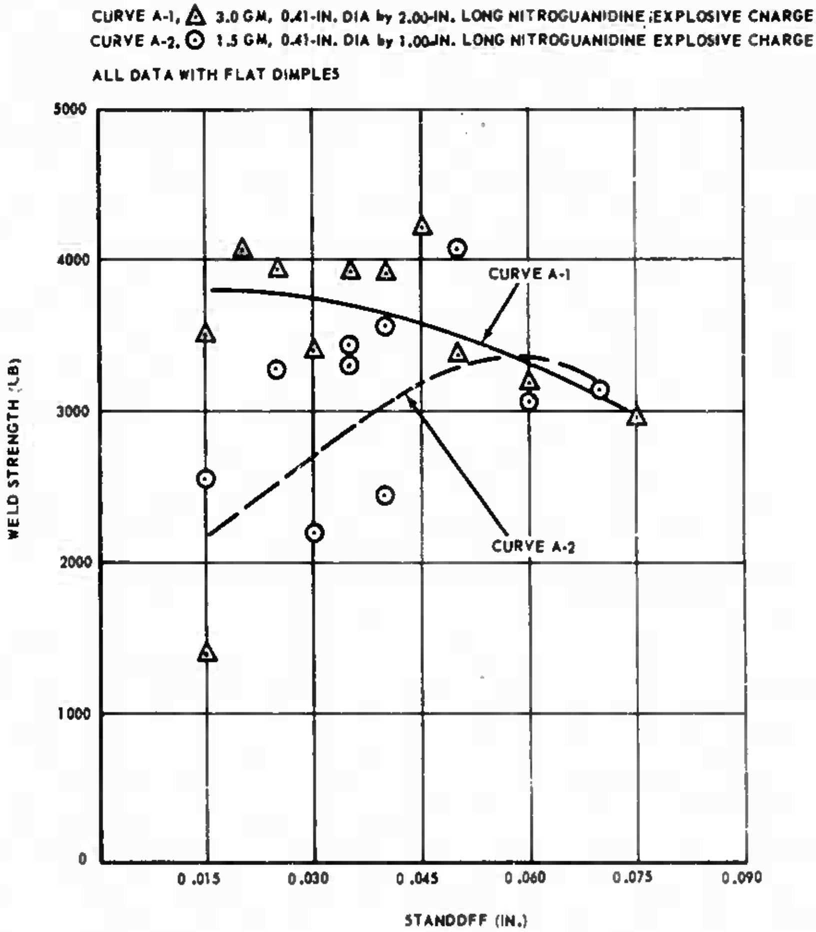

Figure 21. Weld Strength vs Standoff for Type 347 Stainless Steel 0.063 in. Thick. (a)

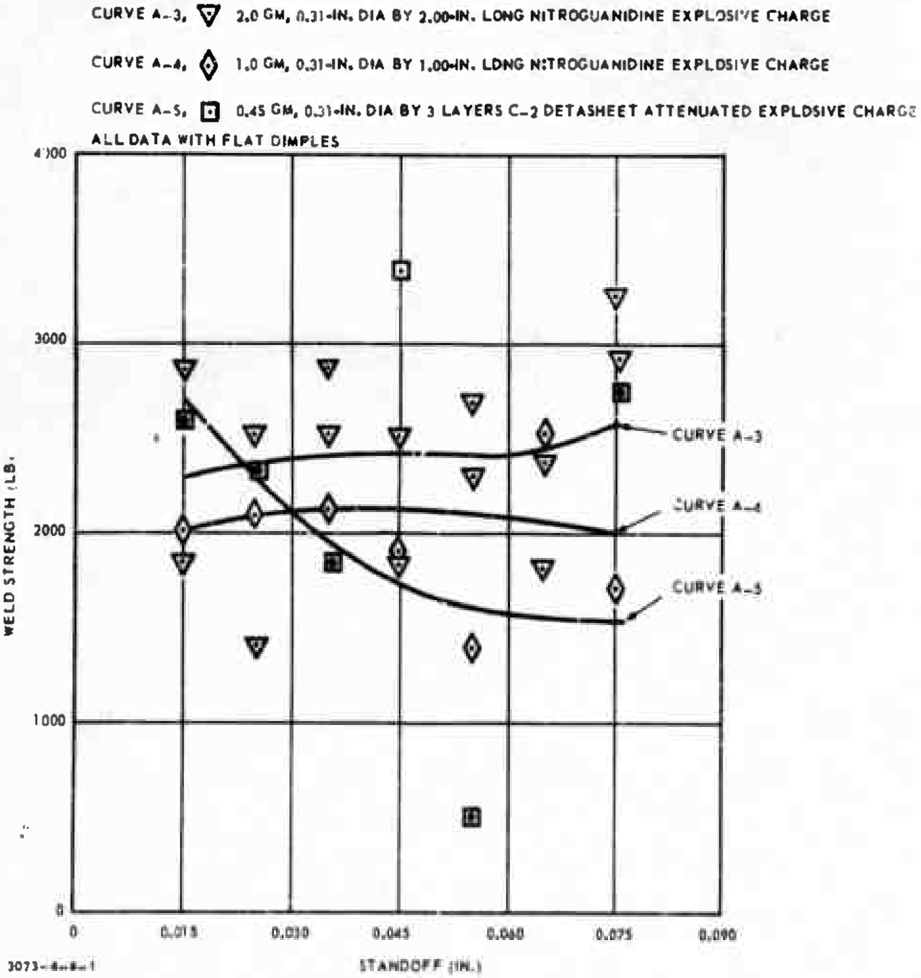

Figure 22. Weld Strength vs Standoff for Type 347 Stainless Steel 0.063 in. Thick. (b)

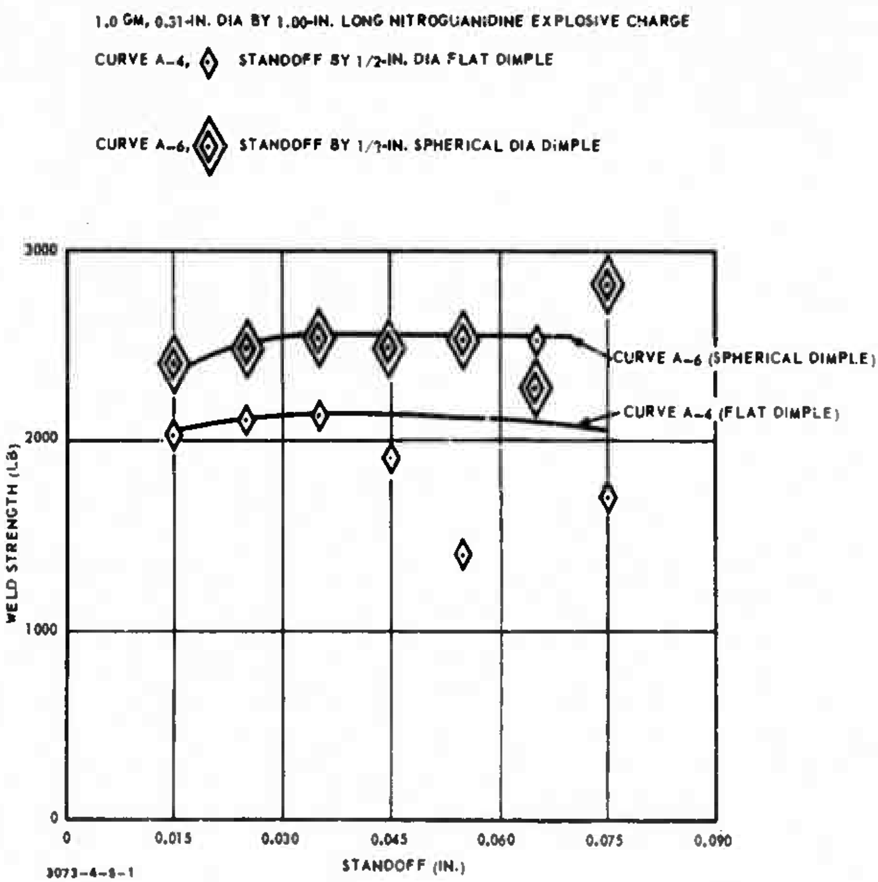

Figure 23. Weld Strength vs Standoff for Type 347 Stainless Steel 0.063 in. Thick (Comparison Between Dimple Geometries).

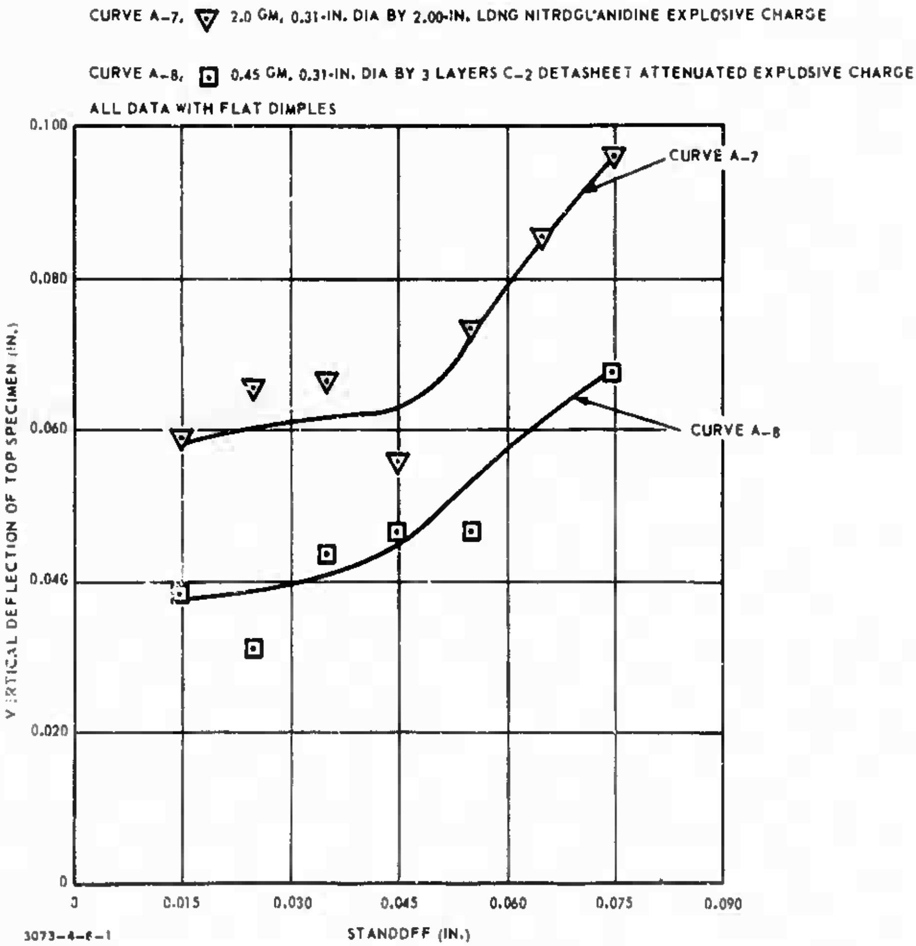

Figure 24. Vertical Deflection vs Standoff for Type 347 Stainless Steel 0.062 in. Thick.

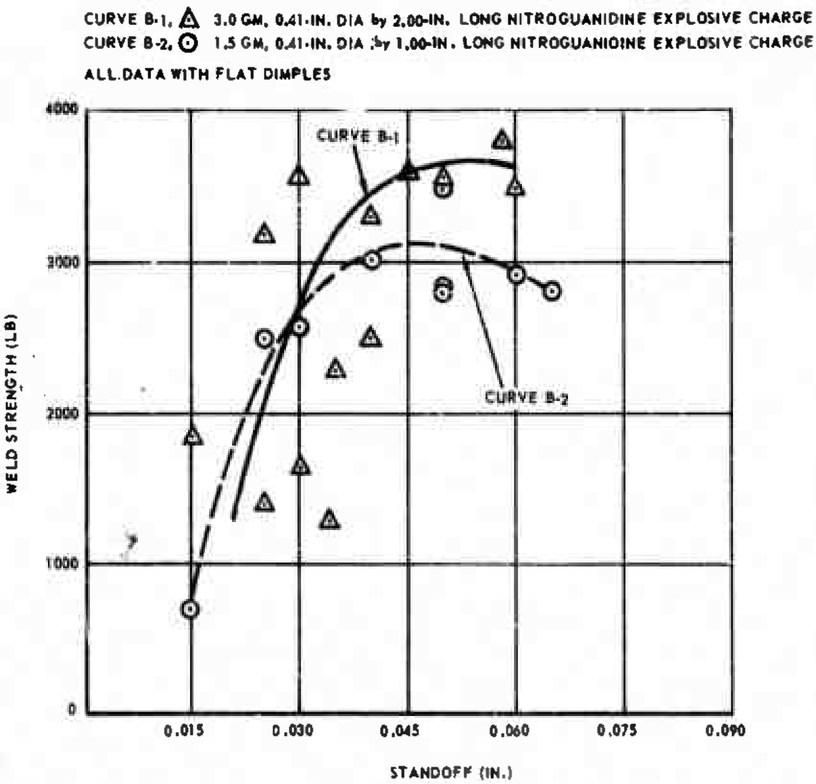

Figure 25. Weld Strength vs Standoff for 6Al-4V Titanium 0.063 in. Thick (a).

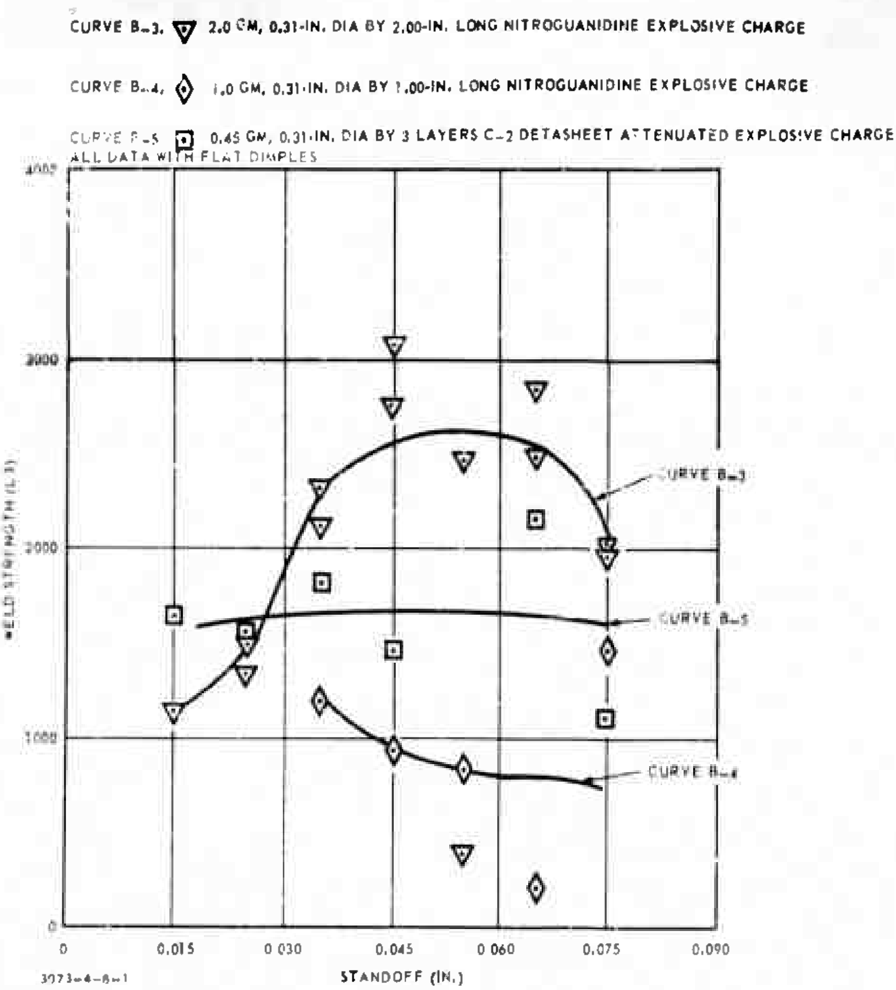

Figure 26. Weld Strength vs Standoff for 6Al-4V Titanium 0.063 in. Thick (b).

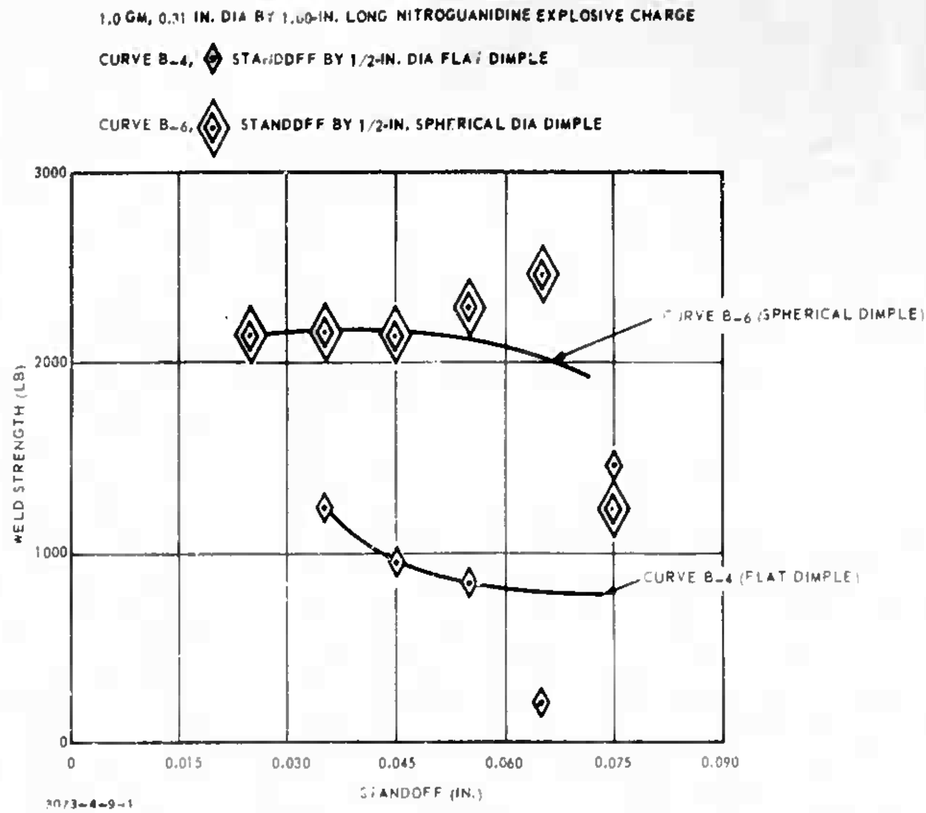

Figure 27. Weld Strength vs Standoff for 6Al-4V Titanium 0.063 in. Thick (Comparison Between Dimple Geometries).

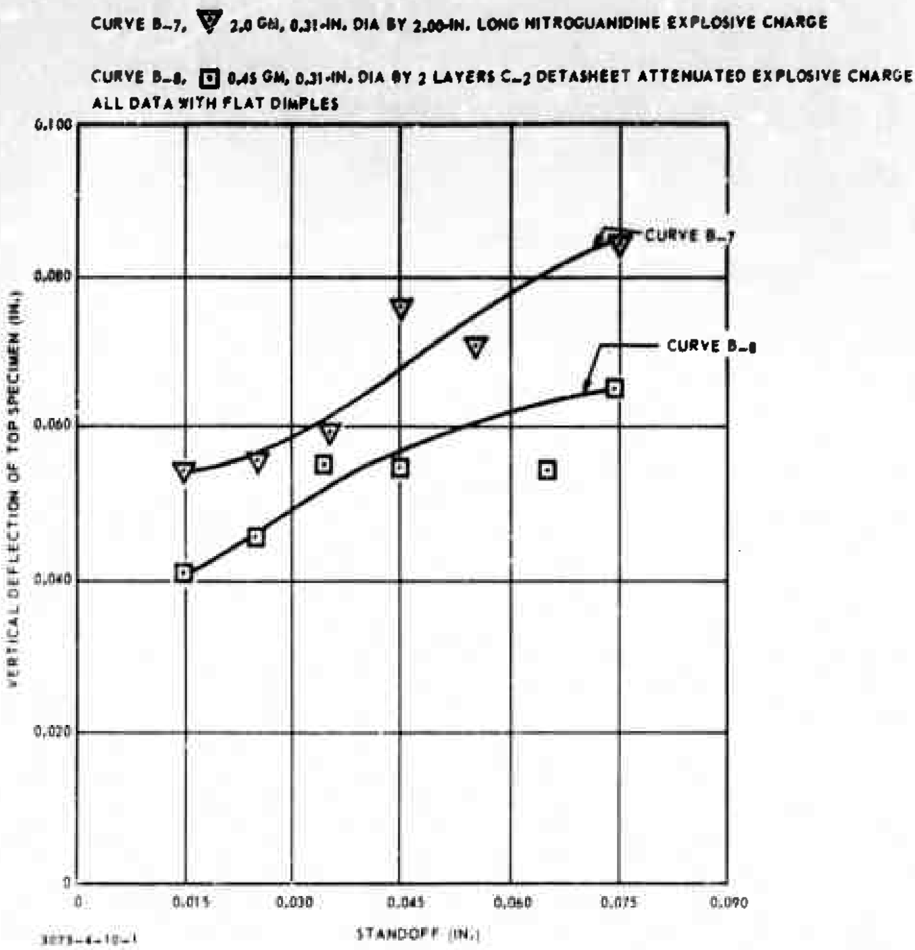

Figure 28. Vertical Deflection vs Standoff for 6Al-4V Titanium 0.063-in. Thick.

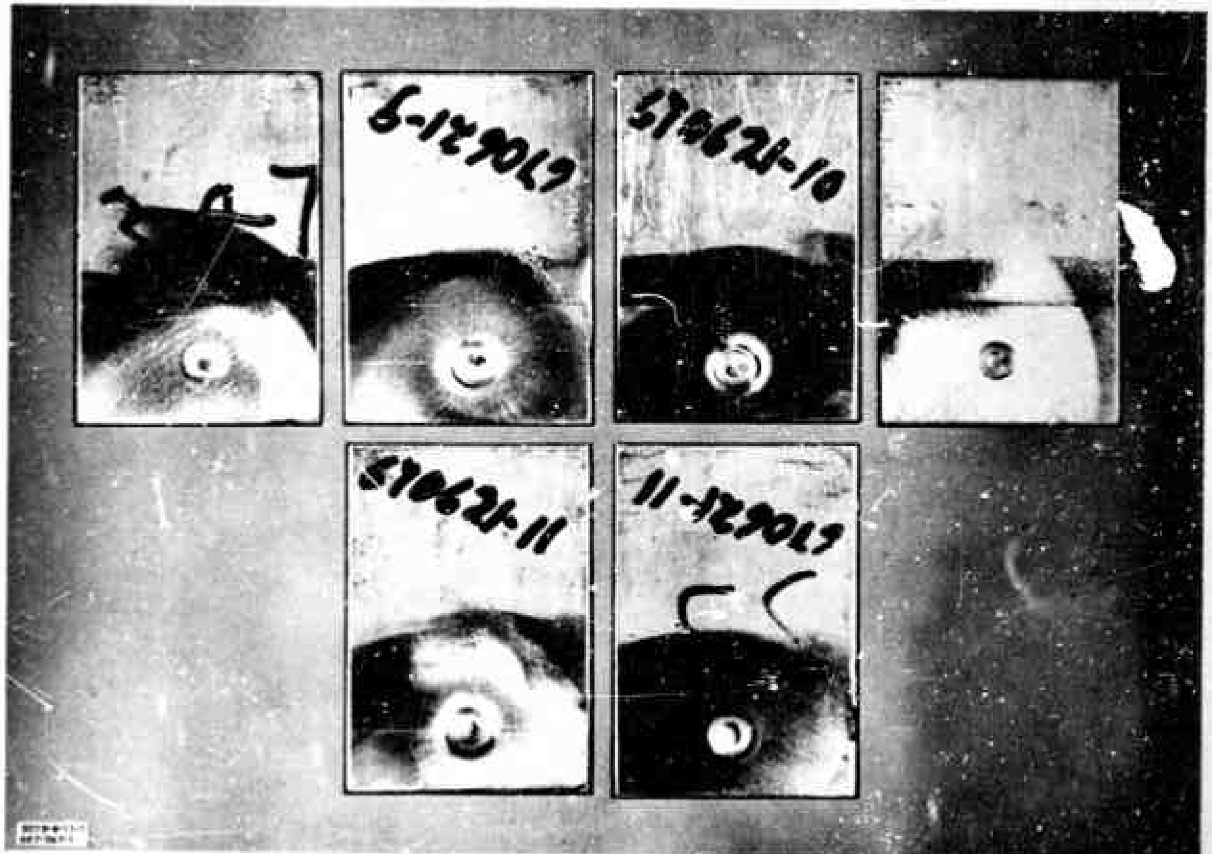

Figure 29. Examples of Type 347 Stainless Steel Specimens Welded with Spherical Dimples (a).

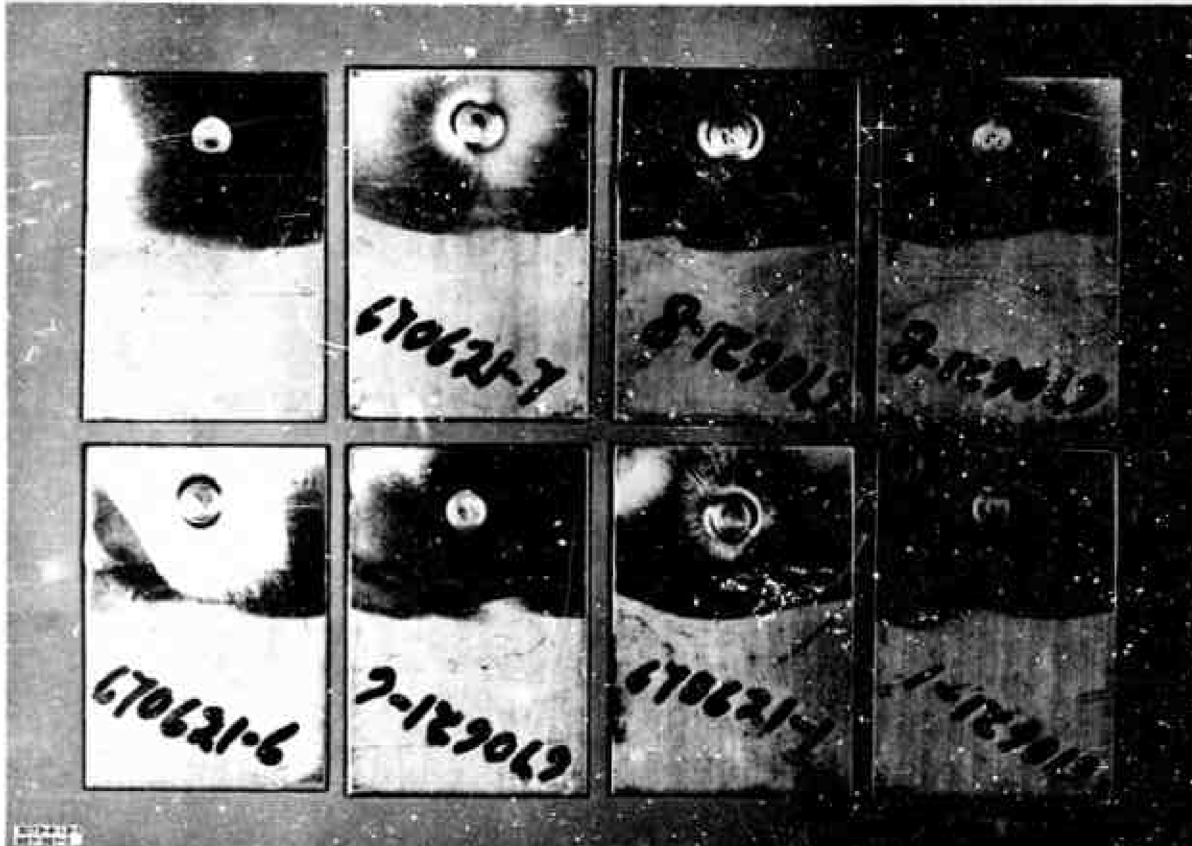

Figure 30. Examples of Type 347 Stainless Steel Specimens Welded with Spherical Dimples (b).

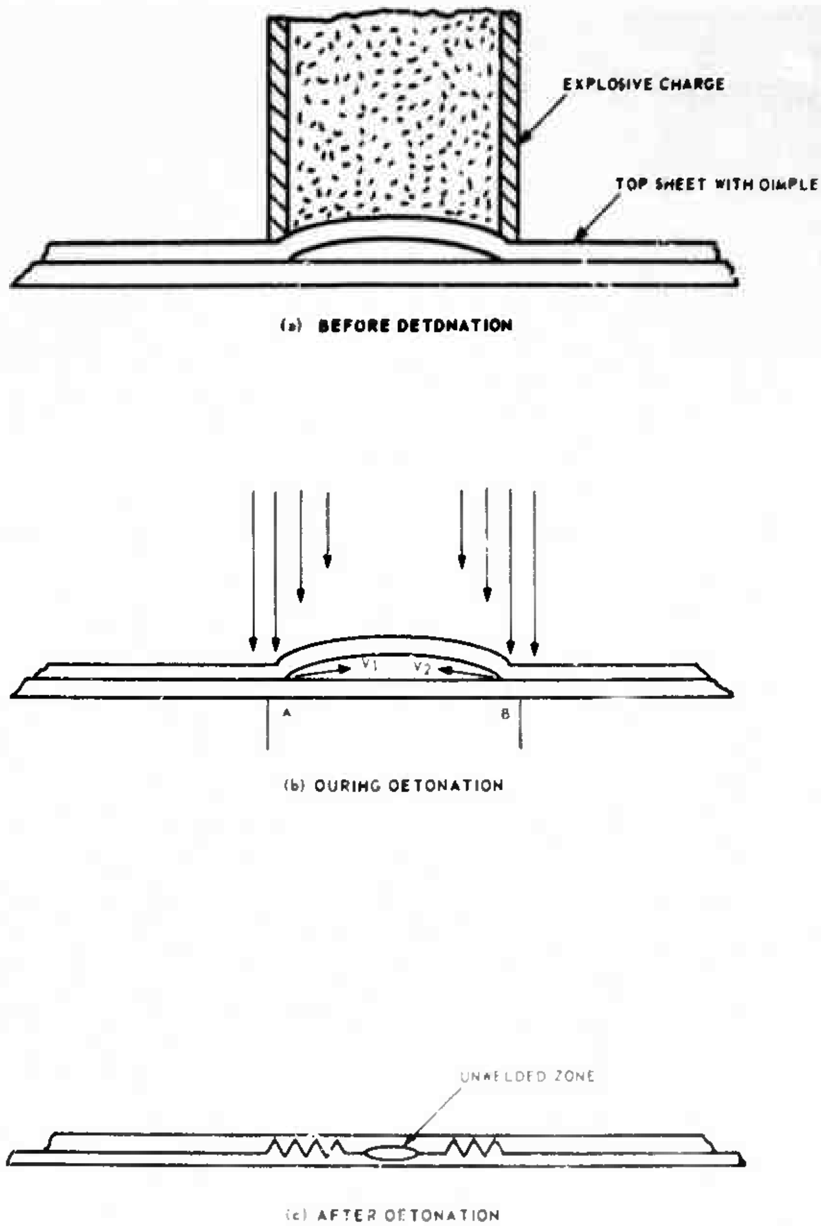

Figure 31. Ring-Weld Mechanism.

the distance AB in Figure 31(b), then jetting is symmetrically produced across the dimple because of the circular geometry. However, jets V_1 and V_2 (shown in the same figure) will meet at the center and cancel each other, producing an unwelded zone in the center of the dimple cavity. It may be concluded that under these conditions a dimple will always produce a ring weld. Ring welds may also form without dimple standoffs if charge diameters are large, so that the area of metal beneath the charge is free to vibrate to the extent that a standoff is produced by sheet flexure.

If the charge diameter is smaller than the dimple gap, no weld or only a weak weld is possible. This concept has been difficult to demonstrate because the critical detonation diameter of most explosives (in general) is larger than the dimple gaps employed. It was possible to derive this analysis only after the formulation of an optimized AP/NG mix, which is described in Section 2.3. Results of the flash X-ray studies in Section 2.7 confirm this analysis. It was shown that radial metal flow increased rapidly with distance from the center of the weld, or essentially that the greatest metal velocity occurs at the ring area and decreases as the center is approached. This is in keeping with the above hypothesis and describes the acceleration of the jet, which decreases as it approaches the weld center, eventually reducing the velocity to zero when it collides with an opposing jet.

3. PRODUCTION OF WELDS

3.1 MATERIALS AND COMBINATIONS

The materials utilized for the weld program and their thicknesses and Rockwell hardness values were as follows:

- 6Al-4V Titanium, 0.010 in., Rockwell 37C
- 6Al-4V Titanium, 0.060 in., Rockwell 34C
- 6Al-4V Titanium, 0.125 in., Rockwell 34C
- 8Al-1 Mo - 1V Titanium, 0.060 in., Rockwell 35C
- 17-7 PH, 0.060 in., Rockwell 88B

- 17-7 PH, 0.125 in., Rockwell 90B
- 17-7 PH, 0.375 in., Rockwell 85B
- Type 347, 0.010 in., Rockwell 81B
- Type 347, 0.060 in., Rockwell 89B
- Type 347, 0.500 in., Rockwell 82B
- Alclad 2024-T3, 0.060 in., Rockwell 74B
- Alclad 2024-T3, 0.125 in., Rockwell 78B

The actual combinations of welds produced explosively are shown in Table VIII, while those produced by resistance (electric) welding are shown in Table IX.

3.2 WELD DETAILS

As a compromise to Specification MIL-W-6858, all weld panels were standardized to 1-1/4 in. widths, and each panel was 3 in. long; this allowed an overlap area equal to the width. All specimens cut from sheet material were sheared so that the long dimension of the test panel was parallel to the rolling direction of the sheet, in accordance with the specification.

All explosive charges were confined in thin-walled aluminum alloy 3003-H14 tubes, and contained in 1/2-in.-thick aluminum blocks so that the charges were presented to the weld sheets perpendicularly. Weld sheets were held down by a tube having a C-shaped section, straddling the charge, in the hydraulic press shown in Figure 3.

Dimples were produced in top sheets by forcing a small steel ball into the top sheet to a controlled depth. This provided the standoff described in Section 2.9. However, all standoff dimple heights were standardized at 0.035 in. because this dimension appeared to serve all materials equally well. For example, in the case of the 0.010-in. 6Al-4V titanium foil (shown as Series 1 in Table VIII, a 1/4-in.-diameter ball was used. For Series 4, using the 17-7 PH alloy, a 3/8-in.-diameter ball was found to provide a dimple yielding optimum welds. For Series 2, using the 1/8-in. titanium alloy, dimpling by ball produced bowing of the sheet and prevented welding. Because it was known that flat sheets are necessary for welds, the dimple was machined by a 1/2-in.-diameter ball end mill for optimum welds. Similarly, for Series 9 welds, the titanium top sheet was dimpled by a 1/2-in. end mill.

Table VIII. Alloy Combinations Explosively Welded.

Series	Top Sheet Alloy	Top Sheet Thickness (in.)	Bottom Sheet Alloy	Bottom Sheet Thickness (in.)
1	Ti 6-4	0.010	Ti 6-4	0.010
2	Ti 6-4	0.125	Ti 6-4	0.125
3	17-7 PH	0.060	17-7 PH	0.060
4	17-7 PH	0.060	17-7 PH	0.375
5	Ti 8-1-1	0.060	Ti 8-1-1	0.060
6	2024-T3	0.125	2024-T3	0.125
7	347 SS	0.060	347 SS	0.060
8	17-7 PH	0.060	Ti 6-4	0.060
9	Ti 6-4	0.060	347 SS	0.500
10	2024-T3	0.060	347 SS	0.500
11	2024-T3	0.060	17-7 PH	0.125
12	2024-T3	0.060	347 SS	0.010

Table IX. Alloy Combinations Resistance Welded.

Series	Top Sheet Alloy	Top Sheet Thickness (in.)	Bottom Sheet Alloy	Bottom Sheet Thickness (in.)
13	Ti 6-4	0.010	Ti 6-4	0.010
14	Ti 6-4	0.125	Ti 6-4	0.125
15	17-7 PH	0.060	17-7 PH	0.060
16	17-7 PH	0.060	17-7 PH	0.375
17	Ti 8-1-1	0.060	Ti 8-1-1	0.060
18	2024-T3	0.125	2024-T3	0.125
19	347 SS	0.060	347 SS	0.060

Surface finish was important to good weld production. Except for the aluminum alloy 2024-T3, which was an Alclad alloy, wirebrushing mating surfaces prior to welding was satisfactory. Alclad surfaces were cleaned with acetone and the 1/2-in. Type 347 stainless steel, shown as bottom plates in Series 9 and 10 couples, was ground to a 120-grit finish on a wet belt.

Charges were hand loaded to produce a density of 0.8 gm/cc for each charge. Details of each explosively welded combination were as follows:

Series 1	Standoff	0.035 in.
	Dimple Ball Size	1/4 in.
	Explosive	100% Nitroguanidine
	Charge Diameter	3/8 in.
	Charge Length	1 in.
Series 2	Standoff	0.035 in.
	Dimple Ball Size	1/2-in. ball end mill
	Explosive	AP/NG mix
	Charge Diameter	1/2 in.
	Charge Length	2 in.
Series 3	Standoff	0.035 in.
	Dimple Ball Size	1/4 in.
	Explosive	AP/NC
	Charge Diameter	1/2 in.
	Charge Length	2 in.

Series 4	Standoff	0. 035 in.
	Dimple Ball Size	3/8 in.
	Explosive	PETN
	Charge Diameter	1/2 in.
	Charge Length	2 in.
Series 5	Standoff	0. 035 in.
	Dimple Ball Size	5/16 in.
	Explosive	AP/NG
	Charge Diameter	1/2 in.
	Charge Length	2 in.
Series 6	Standoff	0. 035 in.
	Dimple Ball Size	3/8 in.
	Explosive	AP/NG
	Charge Diameter	1/2 in.
	Charge Length (no hold down required)	1 in.
Series 7	Standoff	0. 035 in.
	Dimple Ball Size	3/8 in.
	Explosive	AP/NG
	Charge Diameter	1/2 in.
	Charge Length	2 in.

Series 8	Standoff	0.035 in.
	Dimple Ball Size	5/16 in.
	Explosive	AP/NG
	Charge Diameter	1/2 in.
	Charge Length	2 in.
Series 9	Standoff	0.035 in.
	Dimple Ball Size	1/2-in. end mill
	Explosive	AP/NG
	Charge Diameter	1/2 in.
	Charge Length	2 in.
Series 10	Standoff	0.035 in.
	Dimple Ball Size	3/8 in.
	Explosive	100% Nitroguanidine
	Charge Diameter	1/2 in.
	Charge Length	1 in.
Series 11	Standoff	0.035 in.
	Dimple Ball Size	3/8 in.
	Explosive	100% Nitroguanidine
	Charge Diameter	1/2 in.
	Charge Length (no hold down required)	3/4 in.

Series 12	Standoff	0.035 in.
	Dimple Ball Size	3/8 in.
	Explosive	100% Nitroguanidine
	Charge Diameter	1/2 in.
	Charge Length (no hold down required)	3/4 in.

3.3 TEST SCHEDULES

Twenty to twenty-five sets of weld joints of each configuration shown in Table VIII were prepared using the production setups described in Section 3.2, and identified as Series 1 through 12. Series 13 through 19, electrical resistance welds, were fabricated in accordance with Appendix II and MIL-W-6858. All welds were measured for nugget diameter and dye-penetrant inspected. From each series, 5 specimens were selected for lap shear tests to determine weld tensile strengths. Explosively welded panels were then subjected to a C-scan ultrasonic inspection. After examination of the C-scan records, 10 specimens were selected for tension-tension fatigue tests, and three specimens for flexural fatigue tests.

Axial fatigue tests were conducted at 1800 cycles per minute, in a tension-tension mode, with a load ratio of 0.05 so that the minimum tensile load was 5% of the maximum tensile load. Two specimens were tested at each of five stress levels in an effort to produce fatigue curves covering up to one million cycles. Flexural fatigue tests were conducted at the same rate and at three load levels in an effort to produce data up to and including one million cycles.

4. TEST RESULTS

4.1 DYE-PENETRANT TESTS

All welded joints were subjected to dye-penetrant inspection procedures and examined for flaw indications. All resistance welds showed no surface defects (predictably) because resistance spot welding of these materials presented no new problems, and considerable skill as well as knowledge has been accumulated for the process.

Explosively welded joints were generally without surface defects except for joints fabricated with aluminum alloy top sheets. A summary of these results is shown in Table X. Series 6 joints, composed of 0.125-in. alloy 2024-T3 sheets, showed occasional surface cracks resulting from excessive flow of the top sheet material. Series 10, 11, and 12 joints, with top sheets of the same material, showed center pitting in a majority of cases; this pitting appeared to be somewhat deeper in Series 10 joints, those made with aluminum top sheets and 1/2-in. stainless steel bottom plates, and may be caused by a jetting effect from the detonators.

4.2 C-SCAN ULTRASONIC TESTS

C-scan ultrasonic records are included in Appendix III of this report. Interpretation of these records showed that the welds were ring-shaped; some were more completely formed than others. The records shown in Appendix III have numerical designations for each specimen inspected; these numbers served as identification of specimens selected for fatigue testing. Only those welds showing completed ring configurations were selected for axial fatigue tests; other specimens were either not used, or, in case of shortages, used for flexure tests.

4.3 LAP SHEAR TESTS

In most cases, at least five weld joint specimens from each series were tested for shear strength. A summary of these tests is shown in Table XI. All resistance welds exceeded the strength requirements of MIL-W-6858 while four out of twelve explosively welded joints did not. However, when welds composed of different materials for top and bottom sheets were examined, these welds exceeded the minimum requirements for the weaker material (as required by the specification).

4.4 AXIAL FATIGUE TESTS

Axial tension-tension fatigue results are shown in Appendix IV. Logarithmic graphs of loads versus cycles to failure are shown in Figures 32 through 41. Figures 32 through 38 are graphical comparisons of explosive and electrical welds of the same materials (e.g., Figure 32 shows Series 1 and Series 13 welds on the same graph). All specimens were made from 0.010-in. 6Al-4V titanium foil, but Series 1 welds were explosively fabricated while Series 13

Table X. Results of Dye-Penetrant Tests of All Welded Joints.

Series	Top Sheet Alloy	Top Sheet Thickness (in.)	Bottom Sheet Alloy	Bottom Sheet Thickness (in.)	Weld Method	Weld Diameter (in.)	Specification Minimum Diameter (in.)	Dye-Penetrant Indications
1	6-4 Ti	0.010	6-4 Ti	0.010	Explosive	3/8	0.060	None
2	6-4 Ti	0.125	6-4 Ti	0.125	↓	1/2	0.280	None
3	17-7 PH	0.060	17-7 PH	0.060	↓	7/16	0.200	None
4	17-7 PH	0.060	17-7 PH	0.375	↓	1/2	0.200	None
5	8-1-1 Ti	0.060	8-1-1 Ti	0.060	↓	1/2	0.200	None
6	2024-T3	0.125	2024-T3	0.125	↓	1/2	0.280	Occasional surface cracks
7	347 SS	0.060	347 SS	0.060	↓	1/2	0.200	None
8	6-4 Ti	0.060	17-7 PH	0.060	↓	1/2	0.200	None
9	6-4 Ti	0.060	347 SS	0.500	↓	1/2	0.200	None
10	2024-T3	0.060	347 SS	0.500	↓	9/16	0.200	Center pits, 7 out of 17
11	2024-T3	0.060	17-7 PH	0.125	↓	9/16	0.200	Center pits, 4 out of 18
12	2024-T3	0.060	347 SS	0.010	Explosive	1/2	0.200	Center pits, 15 out of 18
13	6-4 Ti	0.010	6-4 Ti	0.010	Resistance	3/16	0.060	None
14	6-4 Ti	0.125	6-4 Ti	0.125	↓	15/32	0.280	None
15	17-7 PH	0.060	17-7 PH	0.060	↓	3/8	0.200	None
16	17-7 PH	0.060	17-7 PH	0.375	↓	1/2	0.200	None
17	8-1-1 Ti	0.060	8-1-1 Ti	0.060	↓	3/8	0.200	None
18	2024-T3	0.125	2024-T3	0.125	↓	9/16	0.280	None
19	347 SS	0.060	347 SS	0.060	Resistance	3/8	0.200	None

Table XI. Results of Lap Shear Tests of Both Explosively Welded and Resistance Welded Test Specimens.

Series	Top Sheet Alloy	Top Sheet Thickness (in.)	Bottom Sheet Alloy	Bottom Sheet Thickness (in.)	Weld Method	Lap Shear Strength (lb) 1	2	3	4	5	Average	Specification
1	Ti 6-4	0.010	Ti 6-4	0.010	Explosive	175	200	175	175	200	185	265
2	Ti 6-4	0.125	Ti 6-4	0.125	↓	4325	4350	5930	3675	5030	4660	7700
3	17-7 PH	0.060	17-7 PH	0.060	↓	2600	2900	2500	2600	2650	2650	2595
4	17-7 PH	0.060	17-7 PH	0.375	↓	1000	3250	2625	9275	10,000+**	Indeterminate	2595
5	Ti 8-1-1	0.060	Ti 8-1-1	0.060	↓	1100	1550	1125	1000	1350	1225	3900
6	2024-T3	0.125	2024-T3	0.125	↓	2700	2500	3100	3900	2850	3010	2650
7	347 SS	0.060	347 SS	0.060	↓	2425	2750	2725	3250	3250	2880	2595
8	17-7 PH	0.060	Ti 6-4	0.060	↓	975	1400	1375	1075	1050	1175	(2595)
9	Ti 6-4	0.060	347 SS	0.500	↓	1775	1800	3175	3575	-	2580	(3900)
10	2024-T3	0.060	347 SS	0.500	↓	5100	5050	3250	4100	4400	4380	(840)
11	2024-T3	0.060	17-7 PH	0.125	↓	4000	3800	4175	4500	4625	4220	(840)
12	2024-T3	0.060	347 SS	0.010	Explosive	1250*	1250*	1225*	1225*	975*	1185	(195)
13	Ti 6-4	0.010	Ti 6-4	0.010	Resistance	600	500	400	500	700	540	265
14	Ti 6-4	0.125	Ti 6-4	0.125	↓	9000	8000	9000	9000	8500	8700	7700
15	17-7 PH	0.060	17-7 PH	0.060	↓	3800	3800	3300	3800	3800	3800	2596
16	17-7 PH	0.060	17-7 PH	0.375	↓	6250*	6000*	6500*	6100*	7000*	6370	2595
17	Ti 8-1-1	0.060	Ti 8-1-1	0.060	↓	4400	4700	4500	4600	4500	4540	2650
18	2024-T3	0.125	2024-T3	0.125	↓	3500	3775	3725	-	-	3670	2650
19	347 SS	0.060	347 SS	0.060	Resistance	3800	3900	3800	3700	3900	3820	2595

*Specimen broken in parent material. no weld failure.

**No failure at limit of testing machine.

( )Based on strength of weaker member.

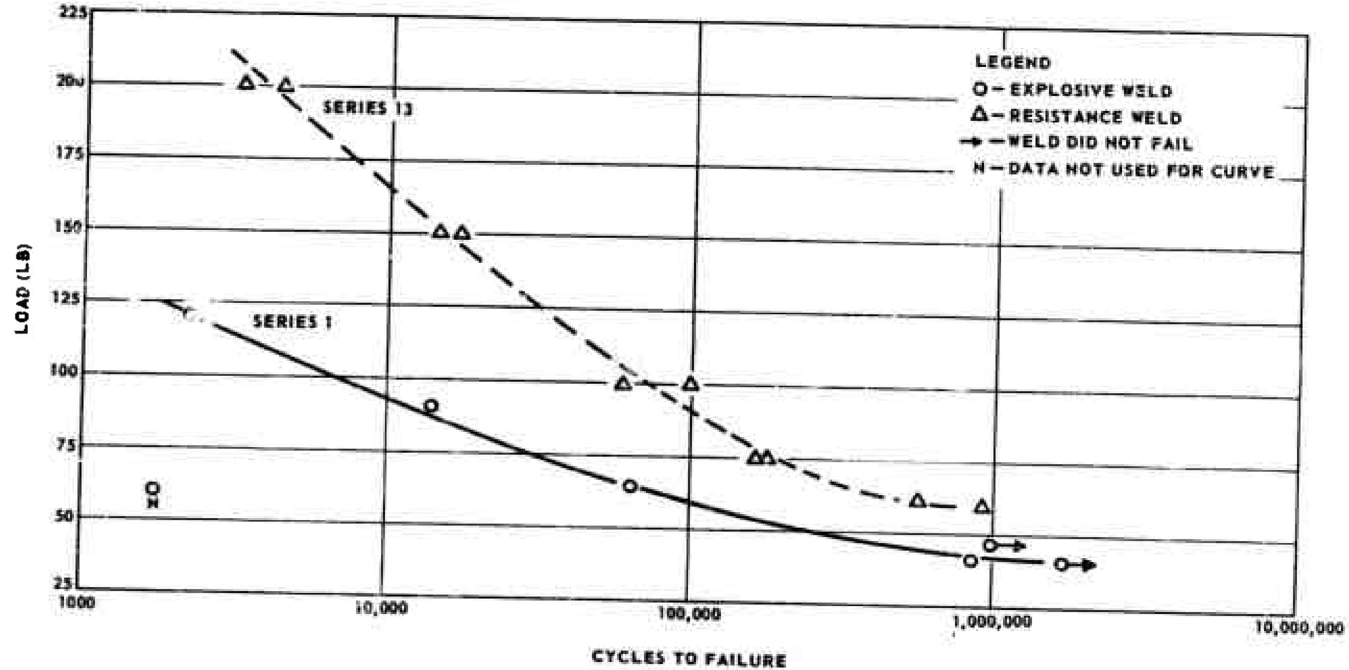

Figure 32. Weld Strength Comparison of Same Materials (a).

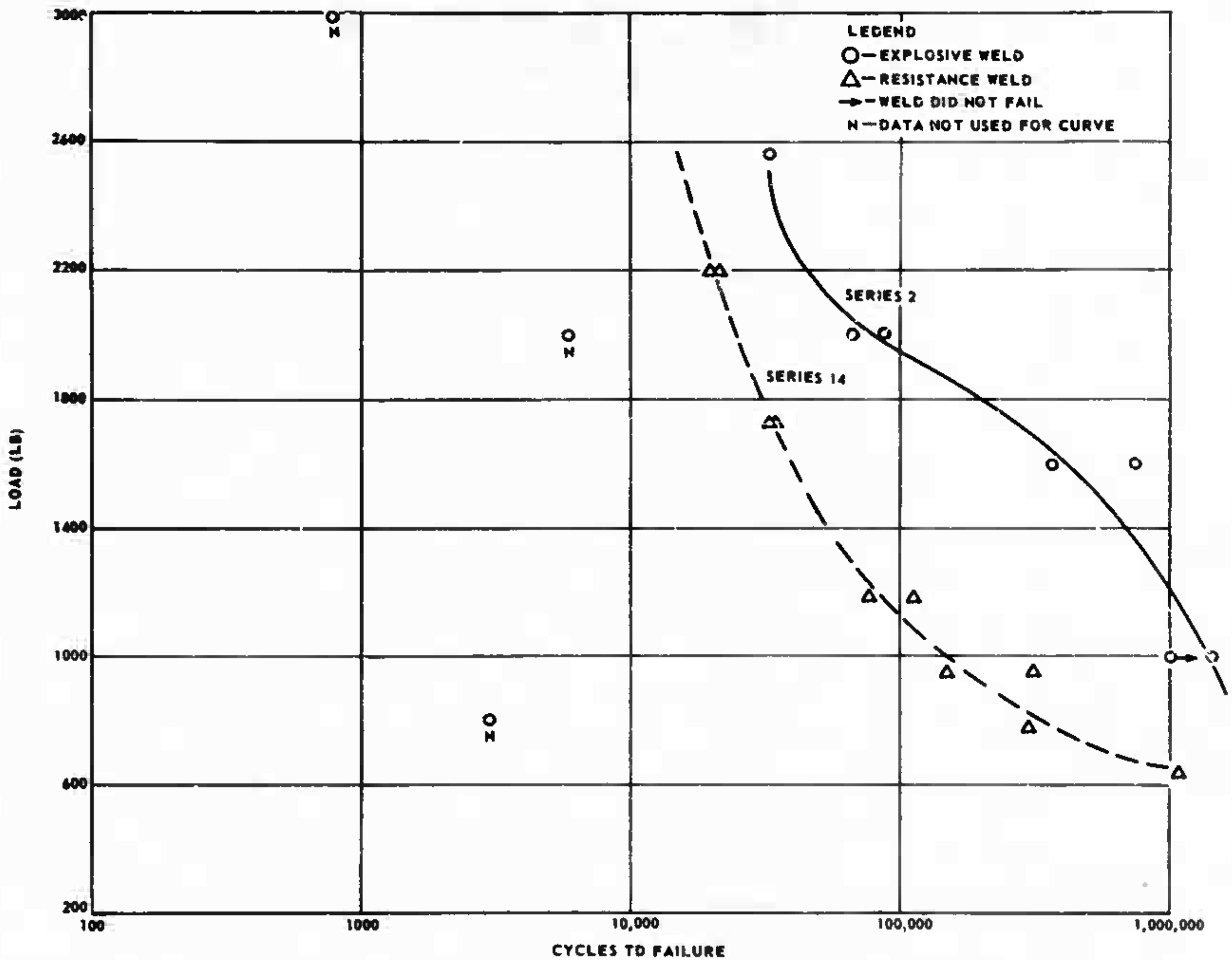

Figure 33. Weld Strength Comparison of Same Materials (b).

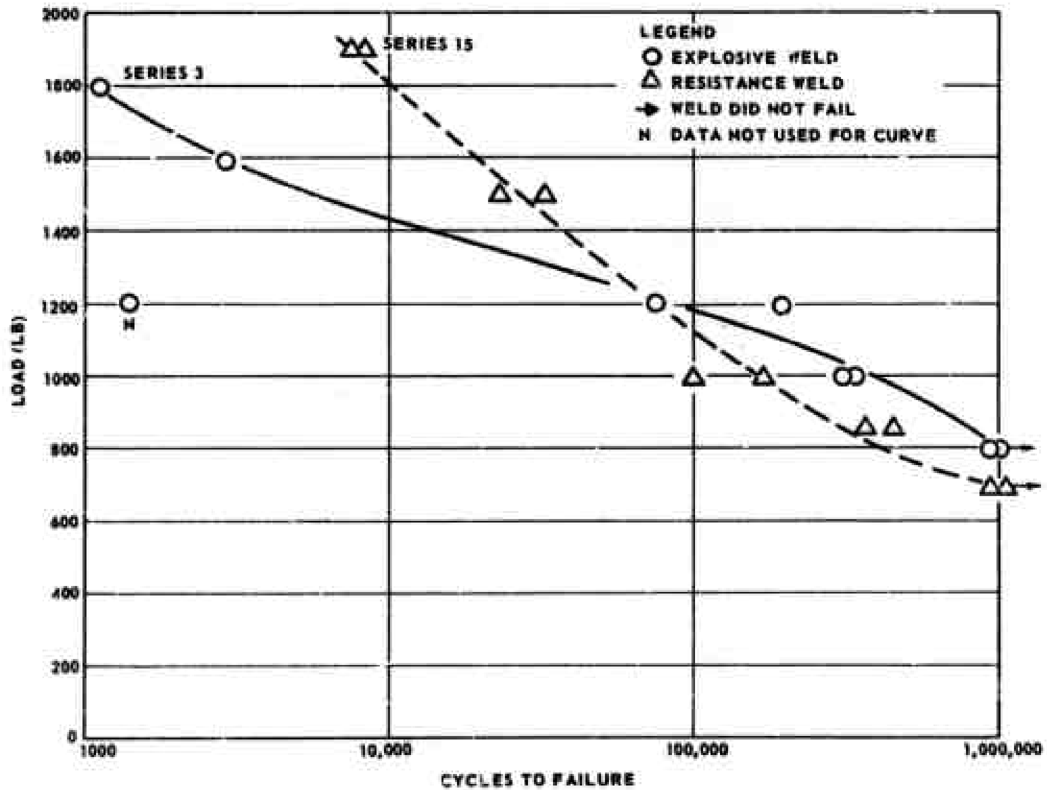

Figure 34. Weld Strength Comparison of Same Materials (c).

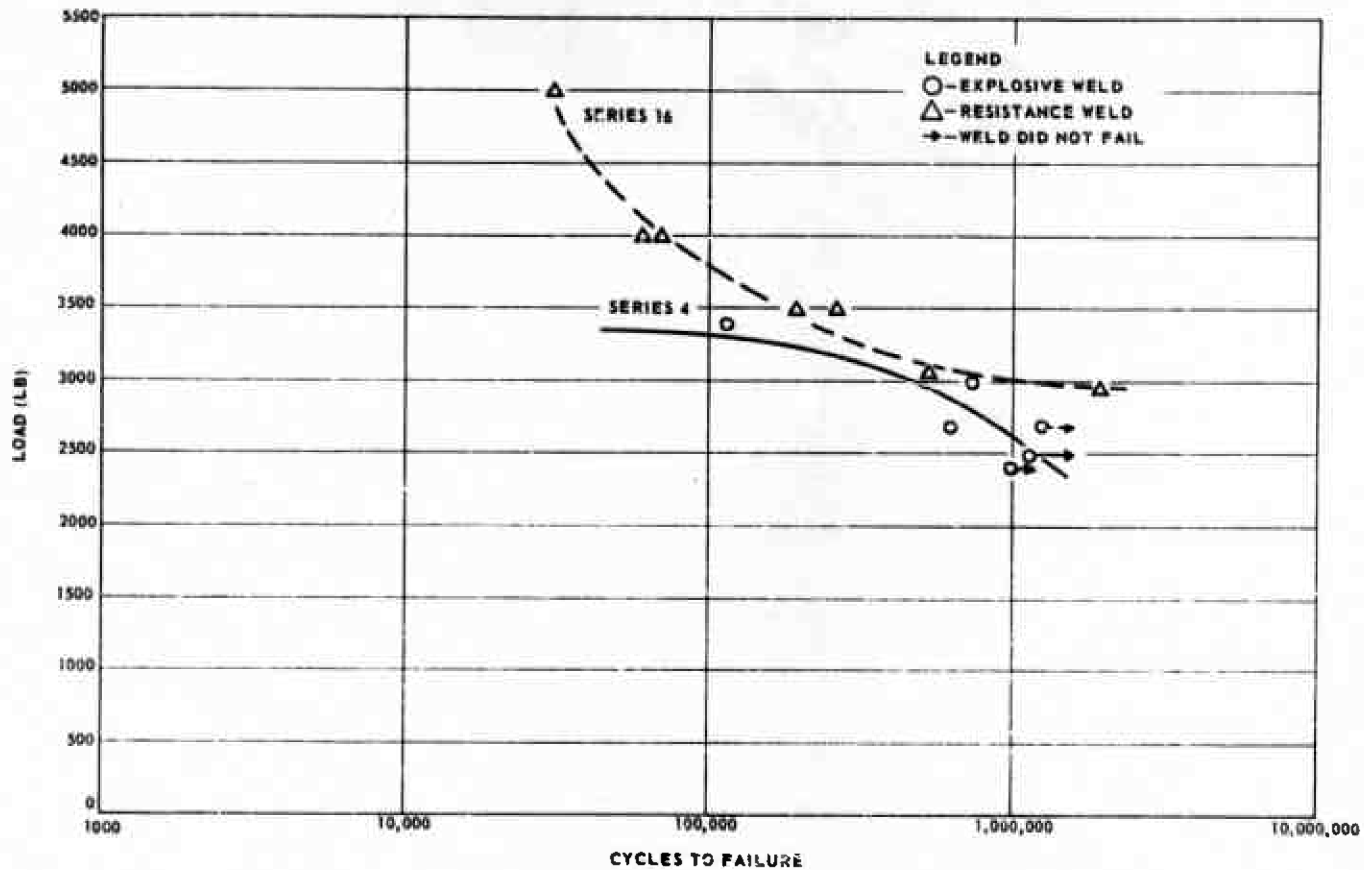

Figure 35. Weld Strength Comparison of Same Materials (d).

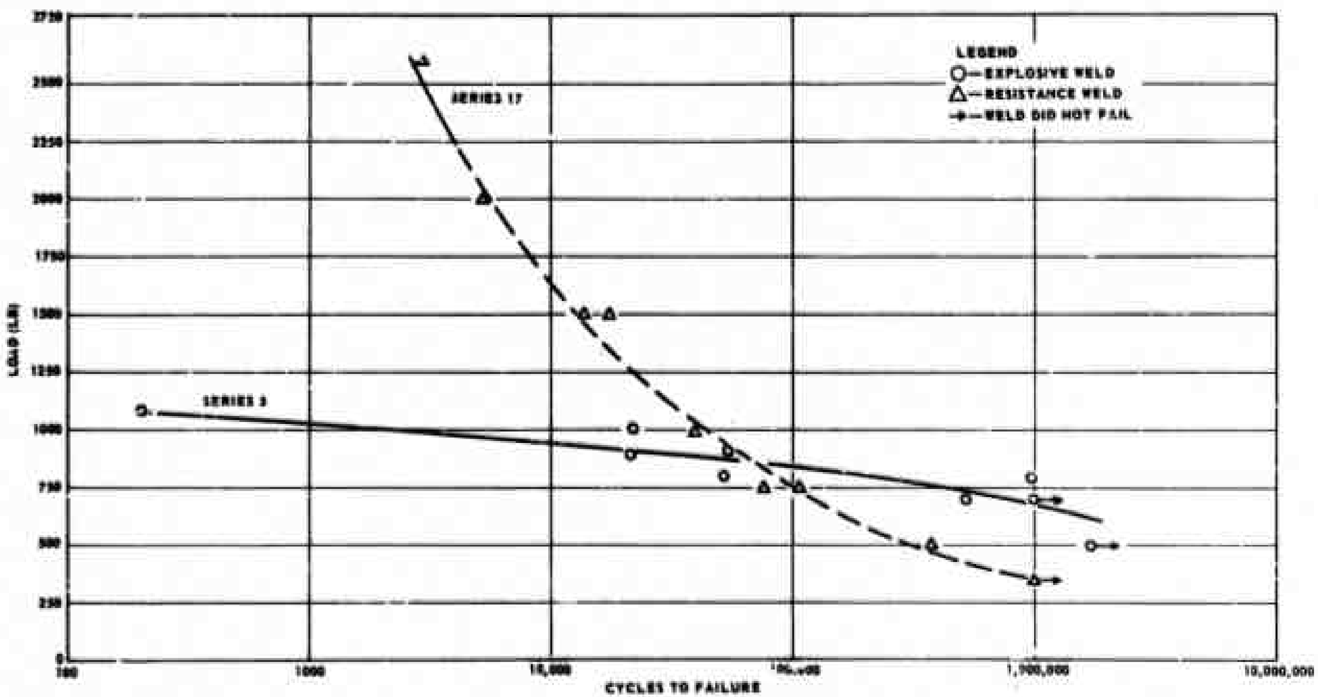

Figure 36. Weld Strength Comparison of Same Materials (e).

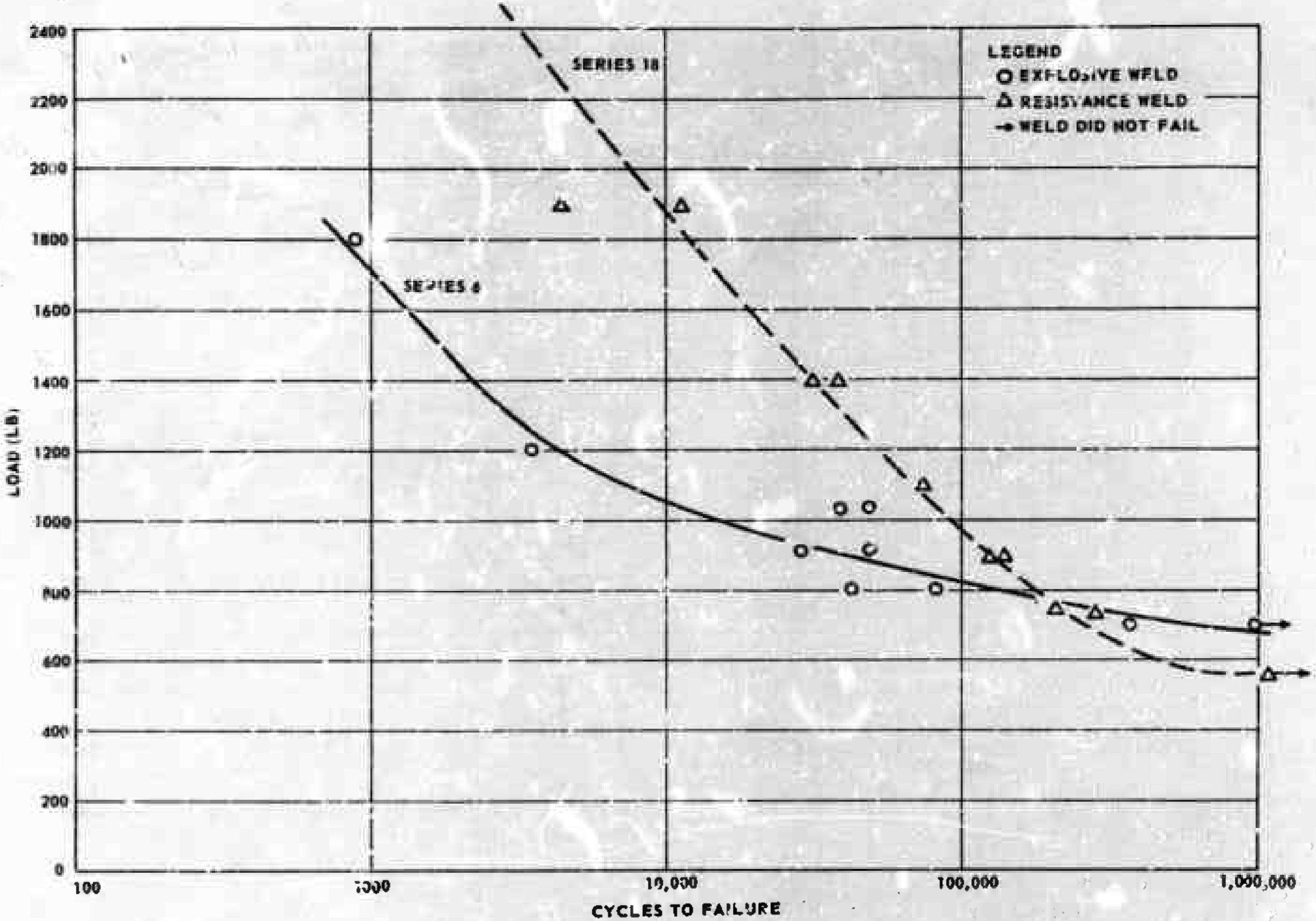

Figure 37. Weld Strength Comparison of Same Materials (f).

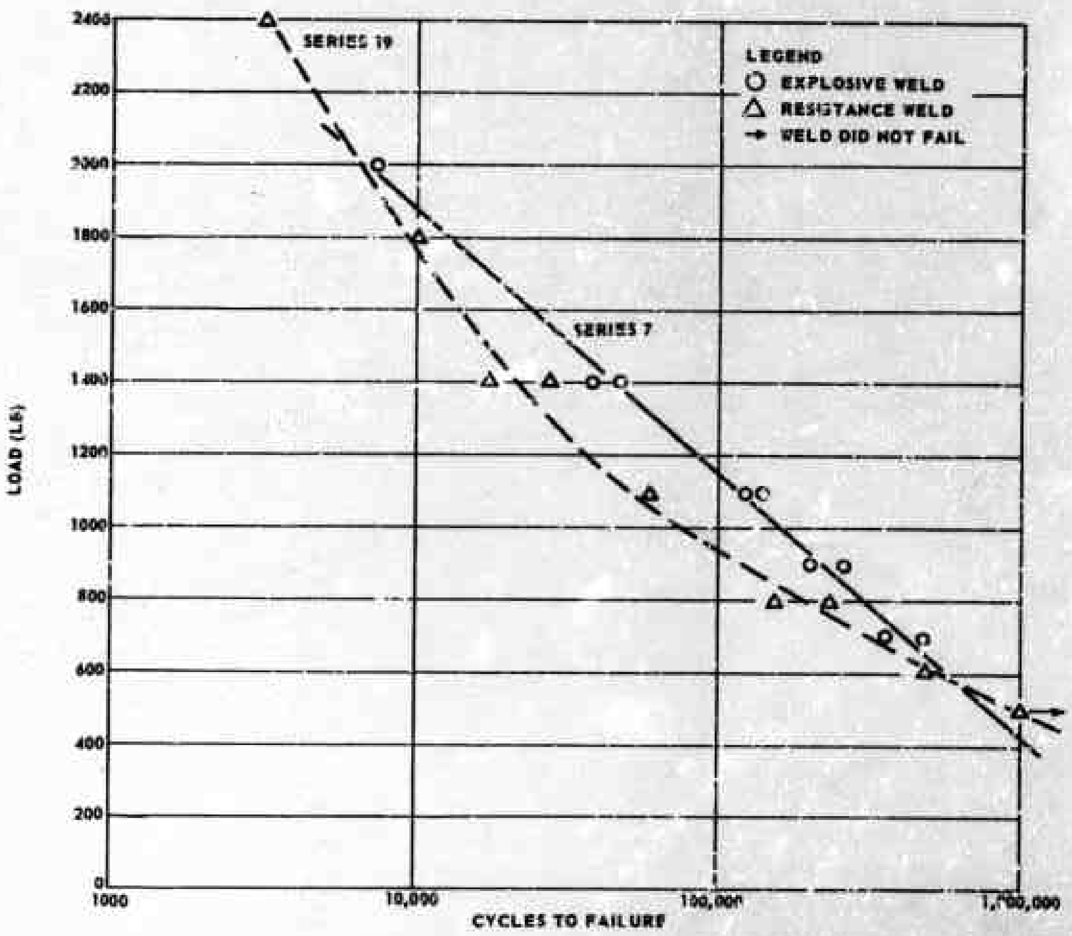

Figure 38. Weld Strength Comparison of Same Materials (g).

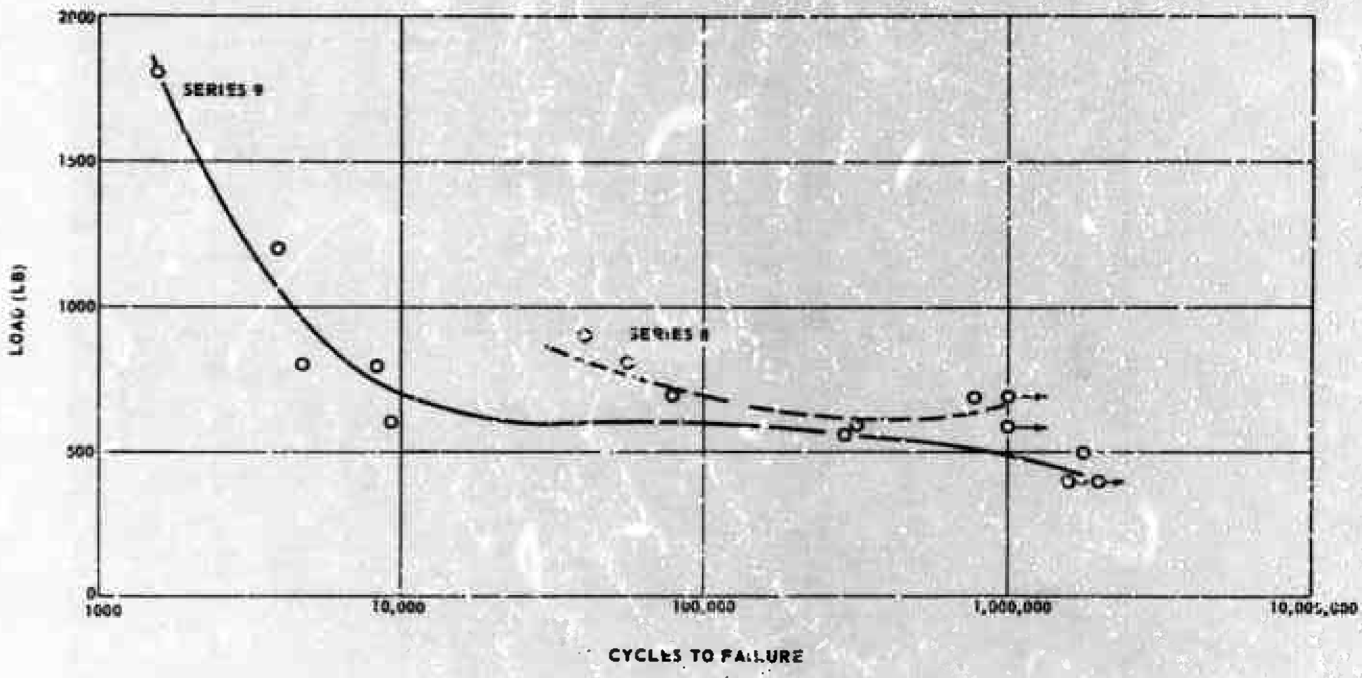

Figure 39. Weld Strength Comparison of Explosively Formed Welds (Dissimilar Welds and Dissimilar Thicknesses.)

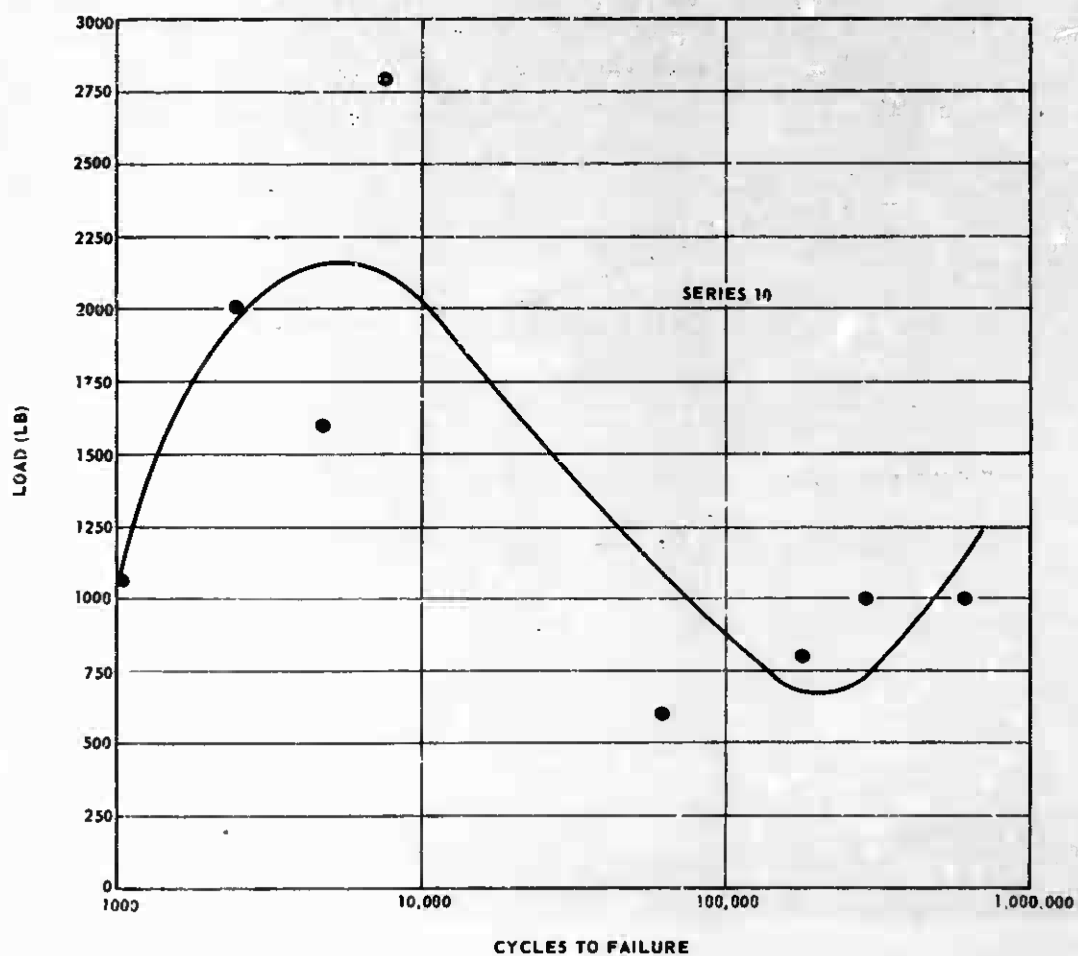

Figure 40. Variation of Series 10 Material (a).

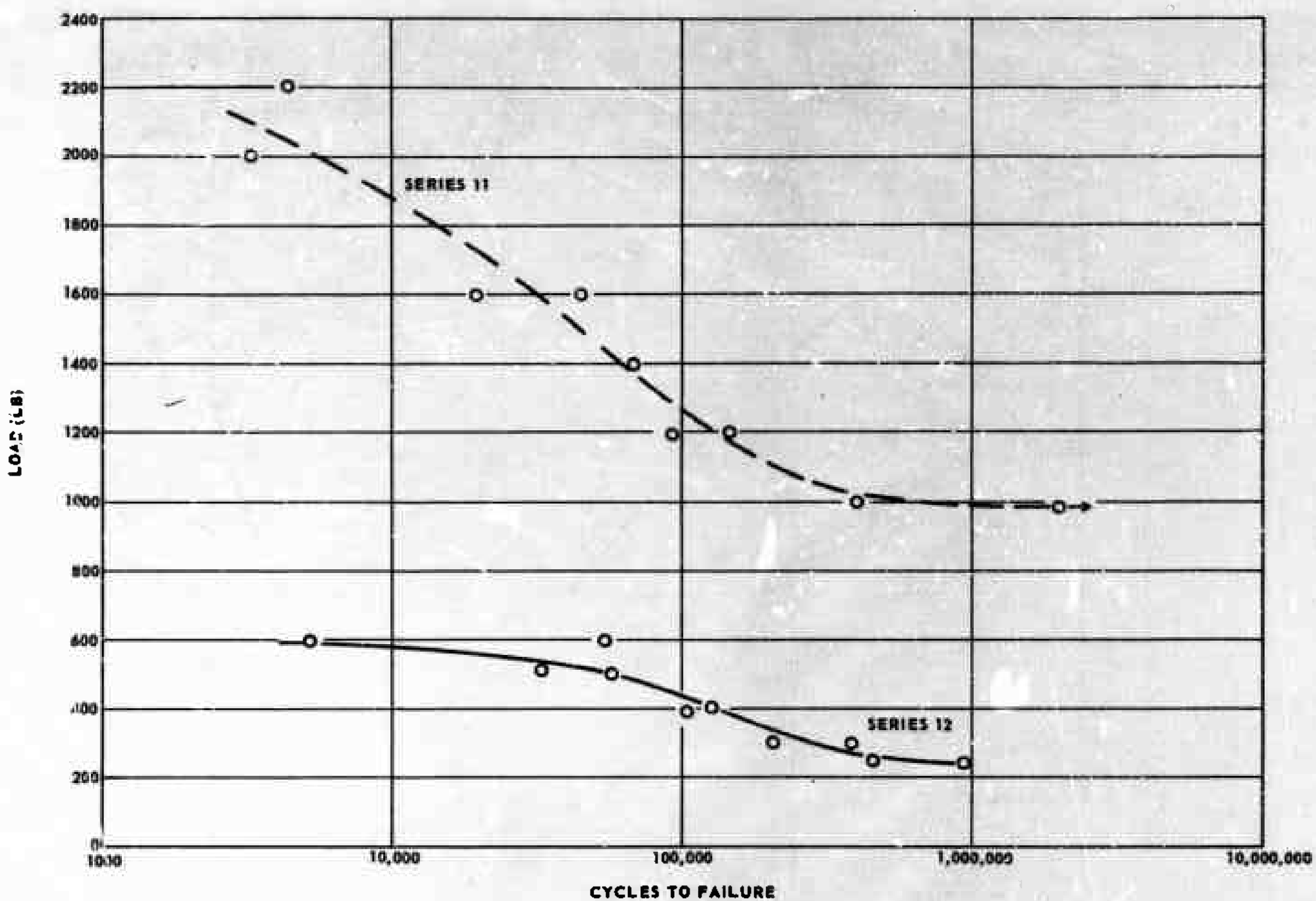

Figure 41. Weld Strength Comparison of Type 347 Stainless Steel and 17-7 PH Alloy Welded to Same Thickness of Aluminum Alloy.

welds were made by resistance methods. Figure 39 is a comparison of dissimilar metals and dissimilar thicknesses, while Figure 40 shows the variations obtained in Series 10 material in which the dye penetrant tests had shown central pitting. Figure 41 shows the comparison in strength levels between stainless steel (Type 347) foil and 0.125-in. 17-7 PH alloy welded to the same thickness of aluminum alloy.

4.5 FLEXURAL FATIGUE TESTS

Samples of both explosive and resistance welds were flexure tested using a Krouse Testing Machine. Welded panels were flexed from zero to the maximum bending moment reported in Table XII. Because of the differing thicknesses of materials tested, the value of the moment arm was varied to provide reasonable loads and deflections for each set of speciments; the values ranged from 3.15 in. for Series 4 and 9 welds (with thick bottom plates) to 2.40 in. for Series 13 (foil) welds.

Except for Series 1 and 13 welds, flexure tests were conducted at a standard load rate of 1800 cycles per minute. Series 1 and 13 welds were fabricated from 0.010-in. material and at 1800 cycles resonance occurs in the thin sheets and results in complex stress distributions. Therefore, load rates for these foil welds were reduced to 900 cycles per minute.

A summary of test results is shown in Table XII. Logarithmic graphs of bending moment versus cycles to failure are shown in Figures 42 through 52. Figures 42 through 48 are graphical comparisons of explosive and electrical welds of the same materials (described in Paragraph 4.4), while Figure 49 shows dissimilar metals and dissimilar thicknesses. Figure 50 shows the wide variation in Series 10 material, which was previously observed during axial fatigue tests; the poor quality of Series 10 welds, (0.060-in. aluminum alloy on 0.500-in. stainless steel) is readily observed in the C-scan records shown in Appendix III.

5. TECHNICAL DISCUSSION

5.1 IMPEDANCE EFFECTS

The characteristic impedance has been one of the fundamental parameters associated with shock phenomena. Empirically, it has always appeared necessary to explosively weld or clad from the lower-impedance material to the higher-impedance material. From the following list of materials

Table XII. Flexural Fatigue Tests

Specimen No.*	Load (lb)	Moment Arm (in.)	Maximum Bending Moment (in.-lb)	Cycles to Failure	Comments
1-11	0.315	2.44	0.77	585,600	
1-12	0.44	2.44	1.07	59,400	
1-13					Weld Broken during Machining
2-1	33.9	2.98	101.0	165,100	
2-2	42.9	2.98	127.8	338,200	
2-4	25.9	2.98	77.2	1,433,700	
3-12	22.9	2.98	68.2	172,700	
3-13	19.9	2.98	59.3	458,000	
3-14	14.9	2.98	44.4	1,670,000	Discontinued
4-15	14.9	3.15	46.9	1,927,000	Discontinued
4-16	22.9	3.15	72.1	206,000	
4-17	18.9	3.15	59.5	1,175,200	
5-2	16.9	2.80	47.3	1,091,100	Discontinued
5-3	19.9	2.80	55.7	101,300	
5-11	21.9	3.08	67.5	0	Failed on Loading
6-4	23.9	3.08	73.6	13,200	
6-11	17.9	3.08	55.1	59,200	
6-13	11.9	2.95	35.1	2,000,000	Discontinued
7-1	17.9	3.08	55.1	207,600	
7-2	18.9	3.08	58.2	169,400	
7-8	22.9	3.08	70.5	100,300	
8-5	19.9	3.08	61.3	258,500	
8-9	24.9	3.08	76.7	82,800	
8-12	16.9	3.08	52.1	558,900	
9-13	22.9	3.15	72.1	0	Failed on Loading
9-15	10.9	3.15	34.3	465,900	
9-16	14.9	3.15	46.9	0	Failed on Loading
10-1	11.9	3.10	36.9	163,100	
10-14	5.9	3.15	18.6	3,700	
10-15	3.9	3.15	12.3	2,195,100	Discontinued
11-5	11.9	3.08	36.7	12,400	
11-6	8.9	3.08	27.4	58,800	
11-15	5.9	3.08	18.2	1,591,000	Discontinued
12-14	0.69	2.45	1.69	47,400	
12-16	0.44	2.52	1.11	288,300	
12-17	0.378	2.50	0.95	2,453,000	Discontinued
13-11	0.315	2.60	0.32	15,600	
13-12	0.19	2.40	0.46	1,000,000	Discontinued
13-13	0.253	2.40	0.61	1,000,000	Discontinued
14-11	33.9	2.98	101.0	642,500	
14-12	42.9	2.98	127.8	[illegible]	
14-13	25.9	2.98	77.2	[illegible]	
15-11	[illegible]	3.15	62.7	129,800	
15-12	22.9	3.08	70.5	110,300	
15-13	14.9	3.08	45.9	472,400	
16-11	22.9	2.93	67.1	52,100	
16-12	14.9	3.00	44.7	822,800	
16-13	18.9	3.08	58.2	125,400	
17-11	16.9	3.08	52.1	51,500	
17-12	11.9	3.08	36.7	148,000	
17-13	9.9	3.08	30.5	430,800	
18-11	23.9	3.08	73.6	319,900	
18-12	28.9	3.08	89.0	155,500	
18-13	35.9	3.08	110.6	211,200	
19-11	22.9	3.08	70.5	30,800	
19-12	18.9	3.08	58.2	60,200	
19-13	17.9	3.08	55.1	63,700	

* 1-11 means Series I Specimen 11.

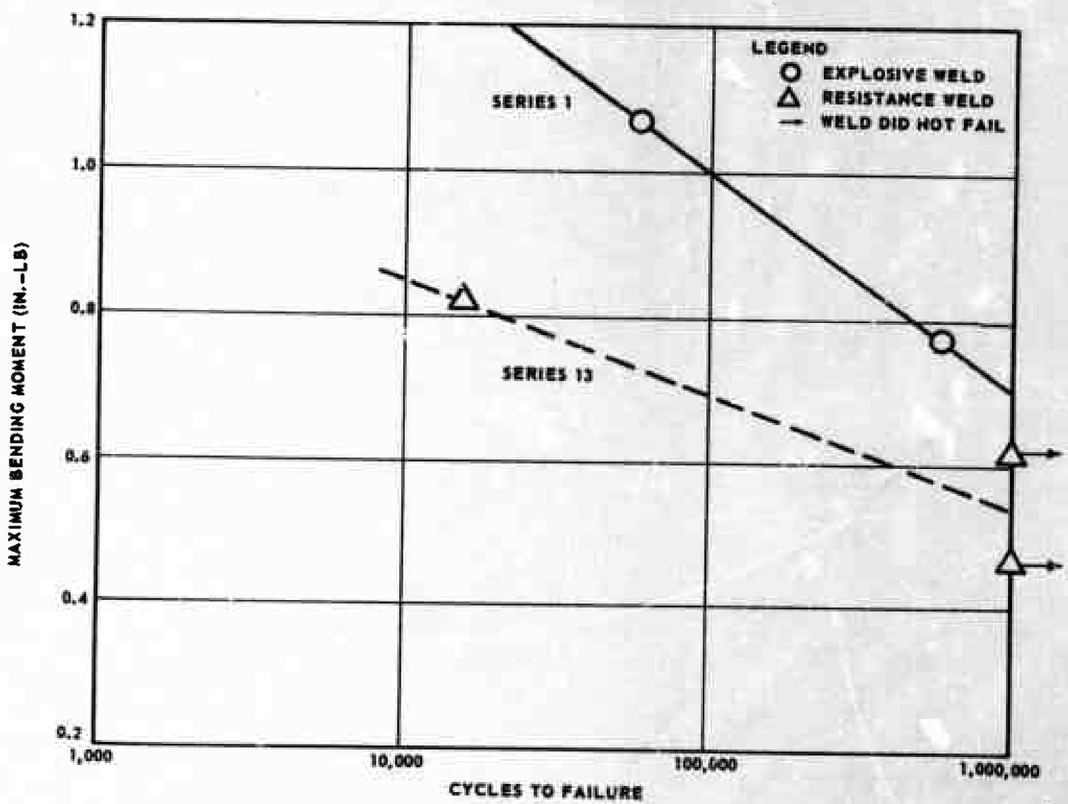

Figure 42. Weld Strength Comparison of Same Materials (h).

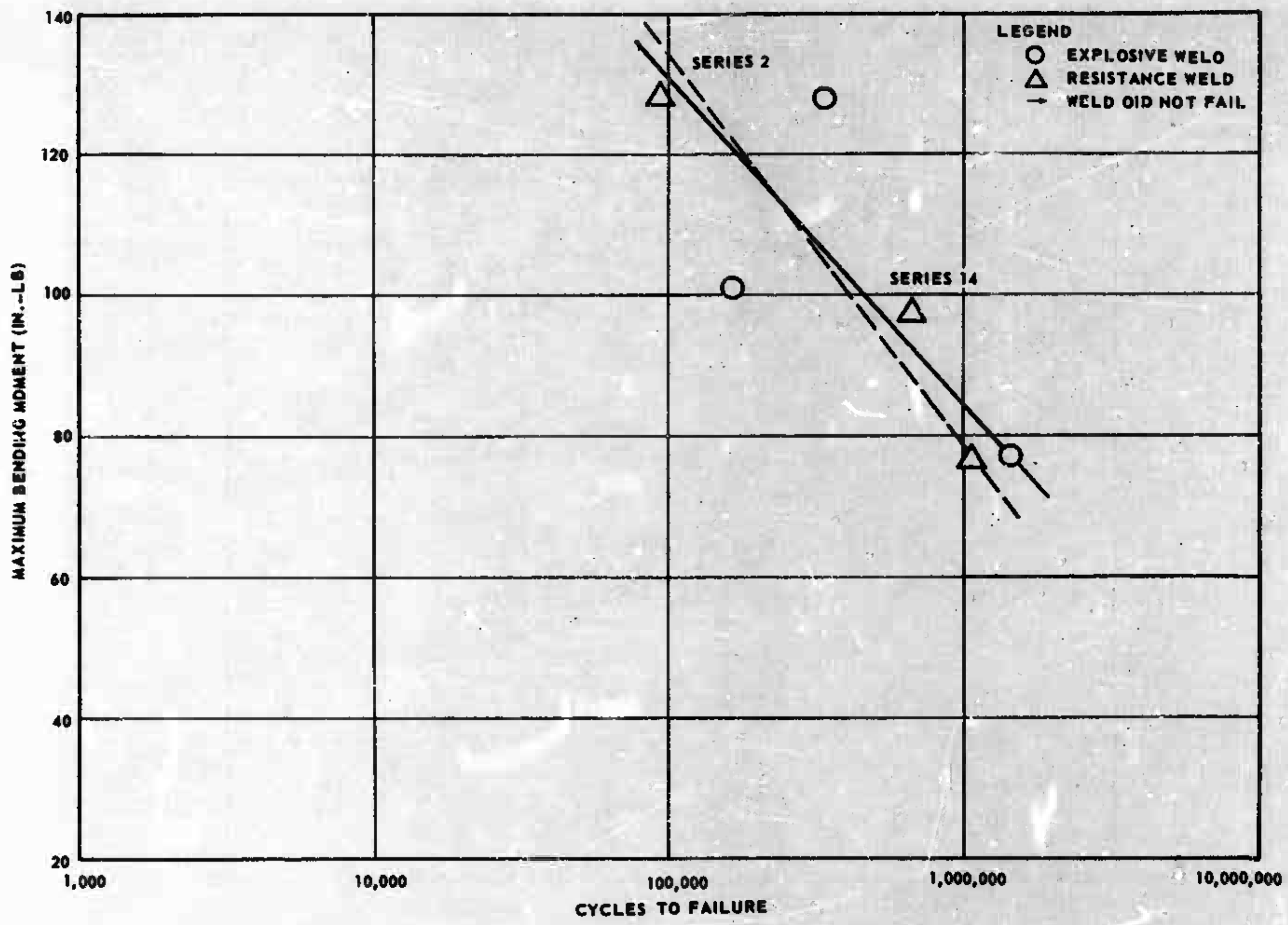

Figure 43. Weld Strength Comparison of Same Materials (i).

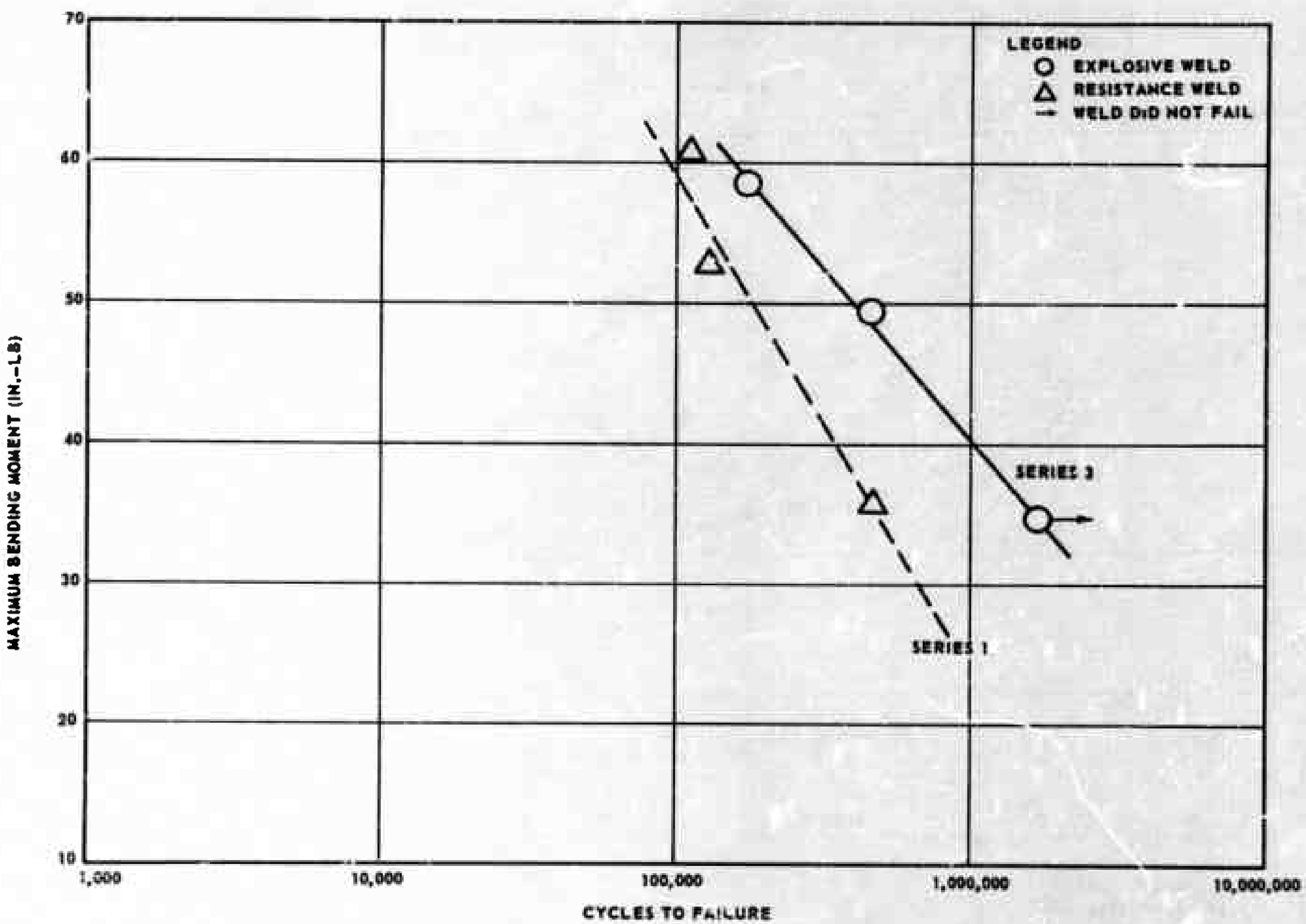

Figure 44. Weld Strength Comparison of Same Materials (j).

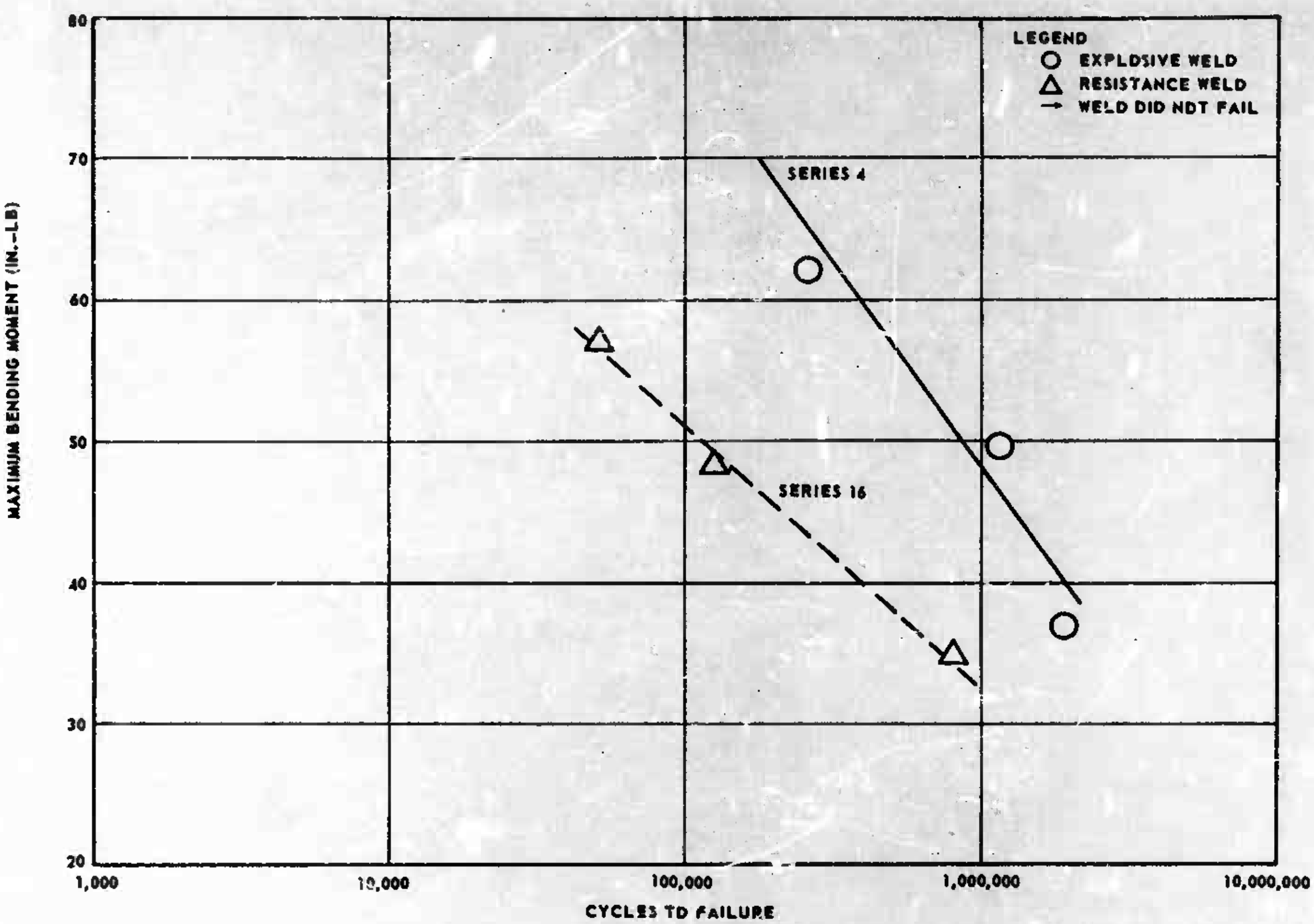

Figure 45. Weld Strength Comparison of Same Materials (k).

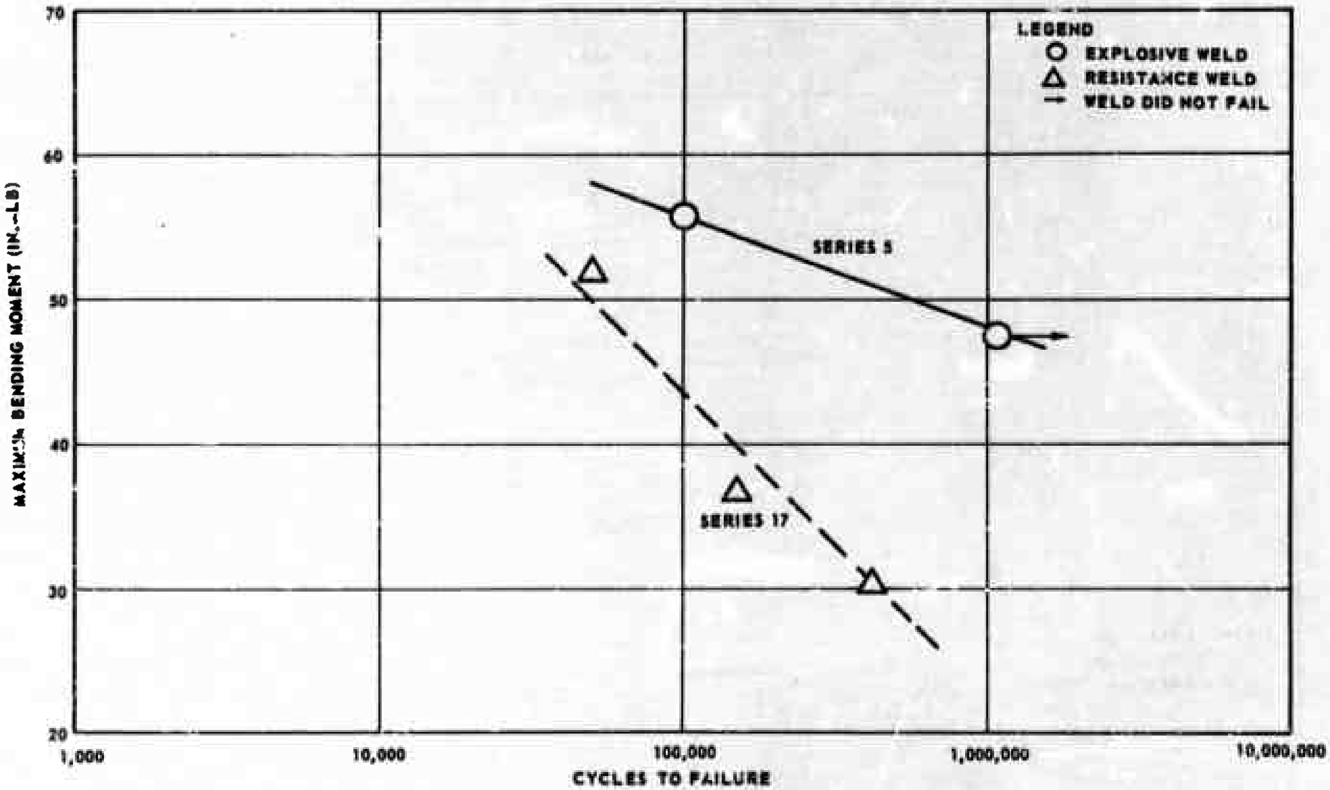

Figure 46. Weld Strength Comparison of Same Materials (1).

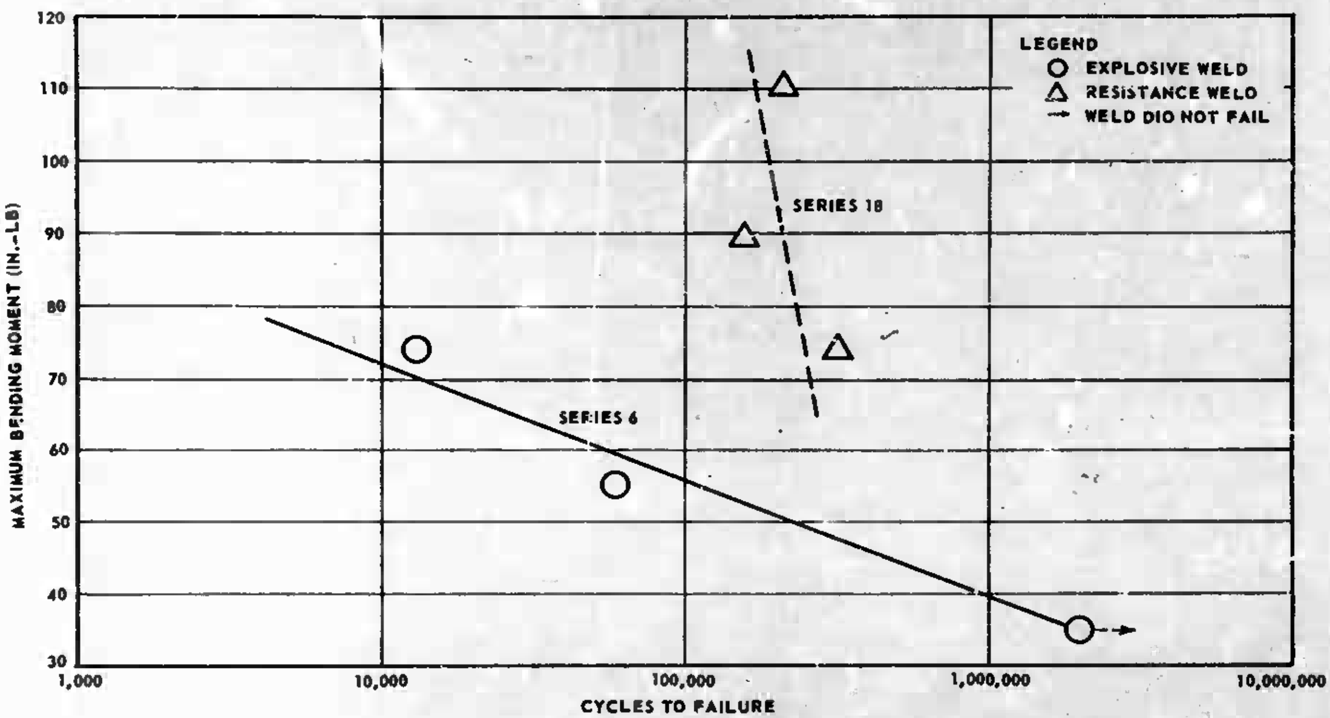

Figure 47. Weld Strength Comparison of Same Materials (m).

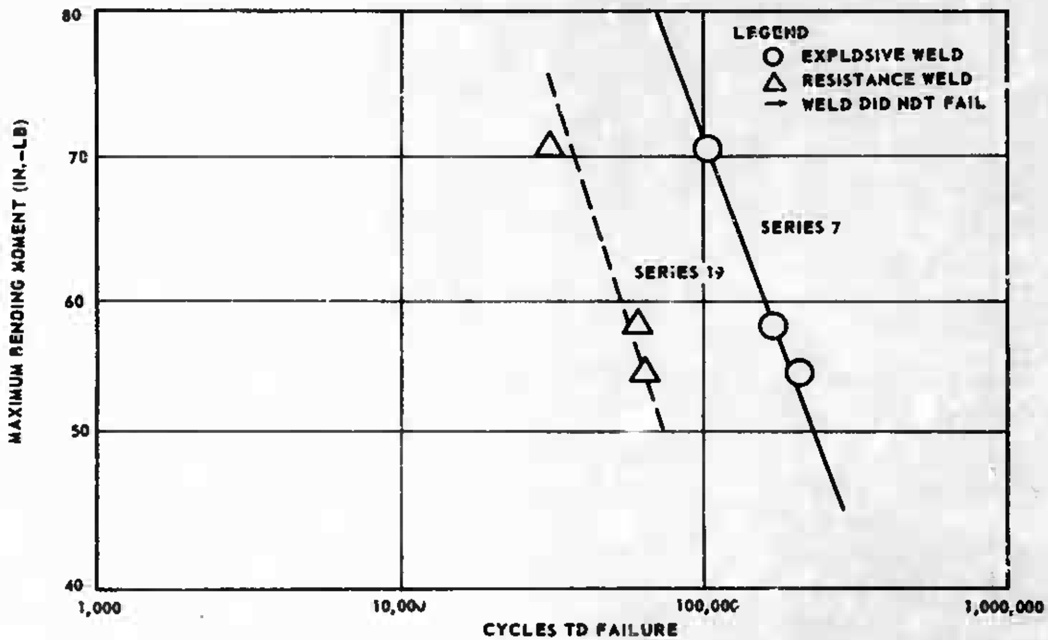

Figure 48. Weld Strength Comparison of Same Materials (n).

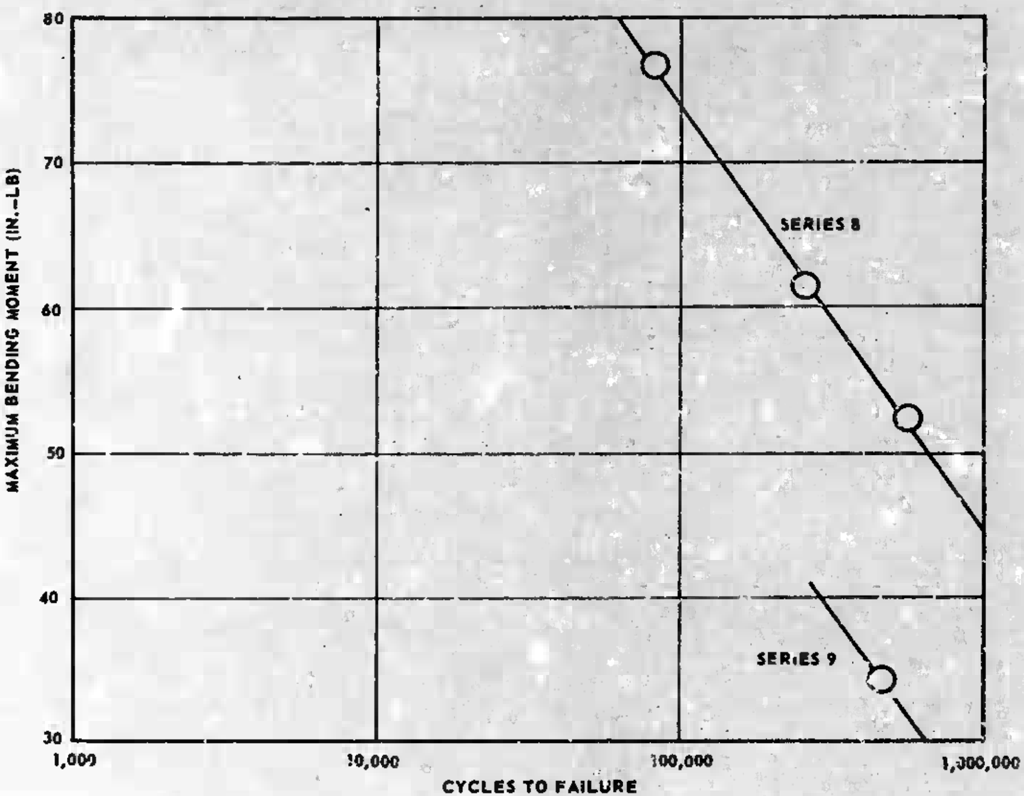

Figure 49. Weld Strength Comparison of Dissimilar Metals of Dissimilar Thicknesses.

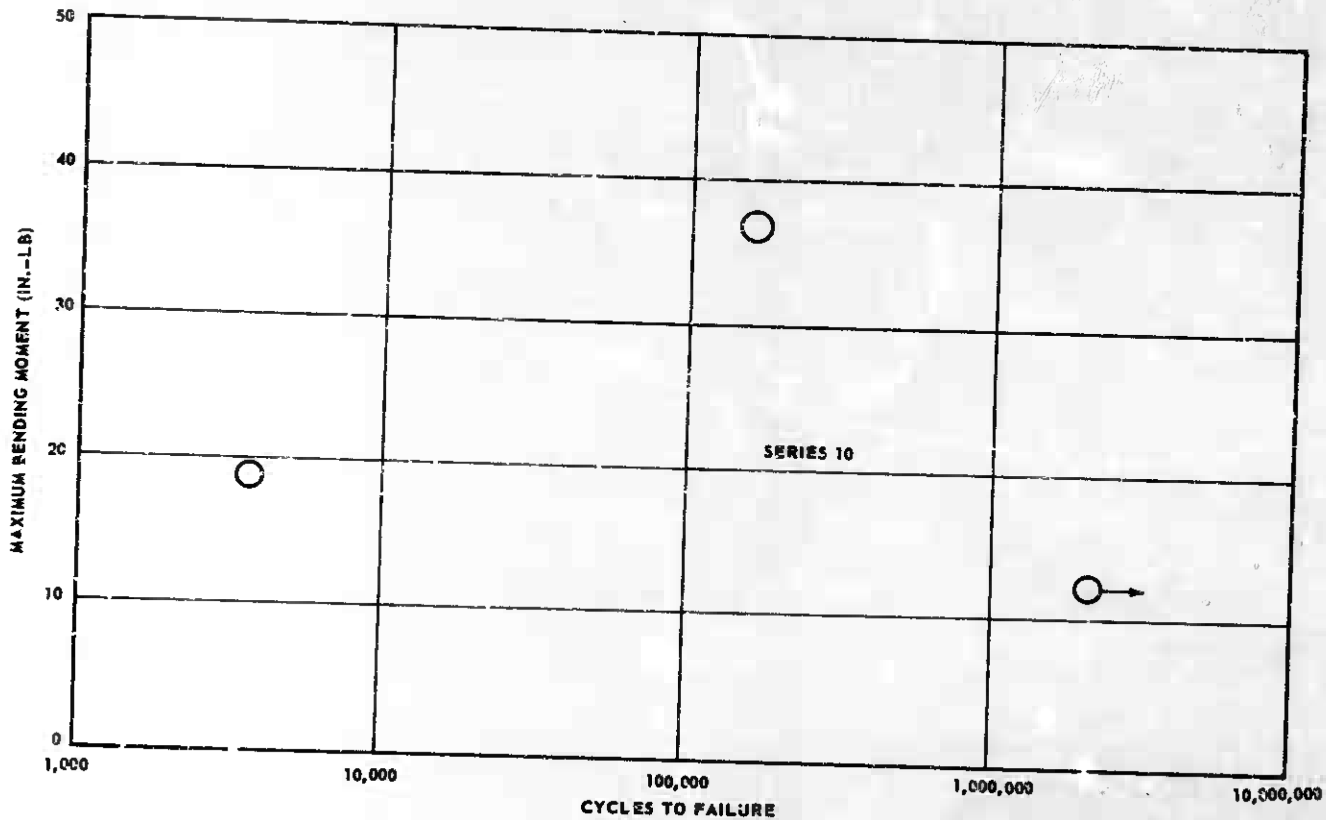

Figure 50. Variation of Series 10 Material (b).

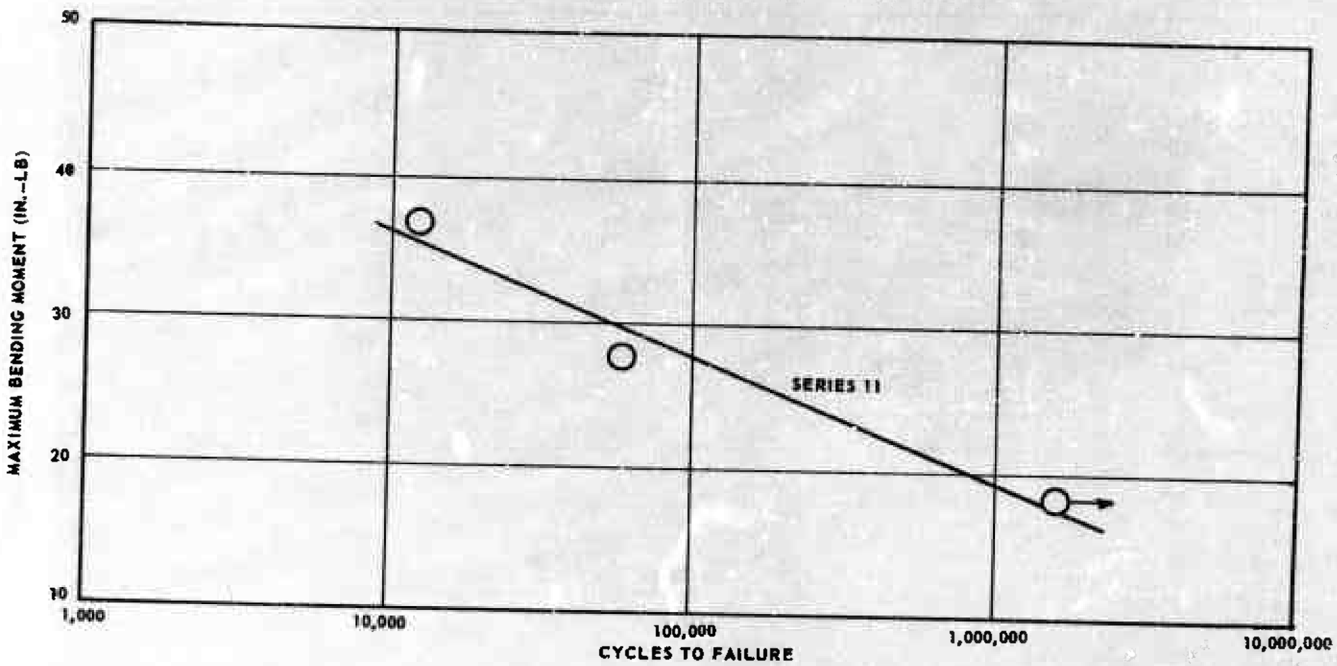

Figure 51. Flexural Characteristics of Series 11 Material.

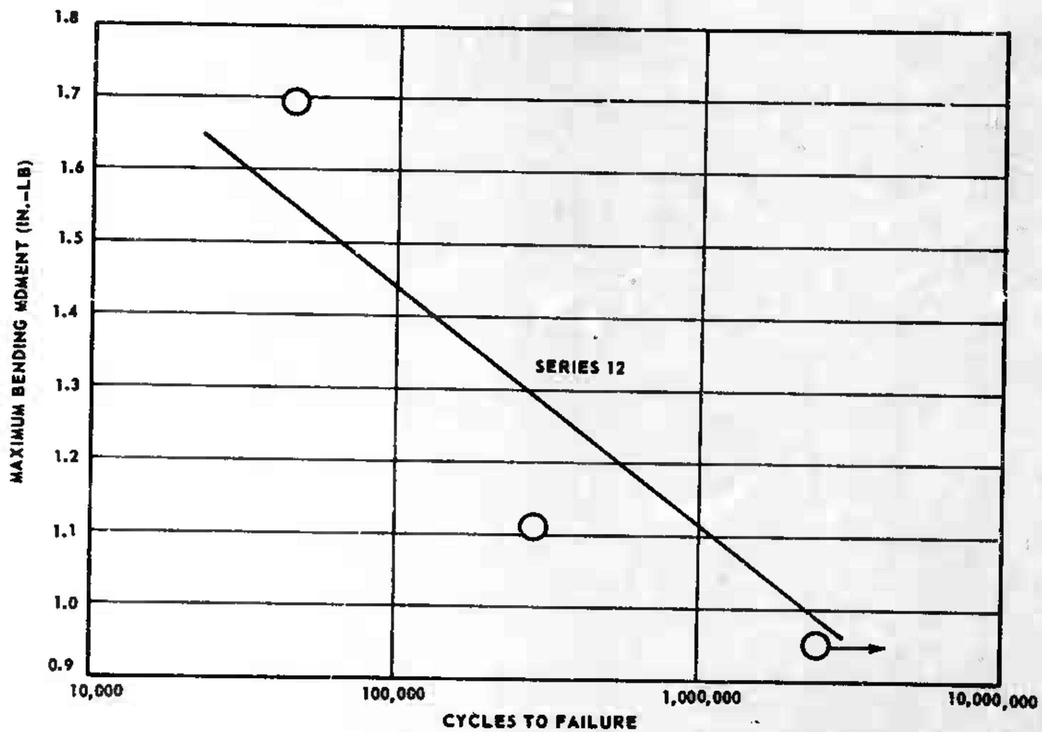

Figure 52. Flexural Characteristics of Series 12 Material.

(arranged in order of increasing impedance) it would be possible to weld from the lower value to the higher (i. e., materials higher in the list should be capable of being welded explosively to those below them).

Material	Impedance (lb-sec/cu in.)
Aluminum Alloys	50
Titanium Alloys	85
Stainless Steels	145
Plain Carbon Steels	150

An exception to this rule was found in welding the materials forming Series 8 spot welds (i. e., 6Al-4V titanium and 17-7 PH steel, both 0.060 in. thick). It was found that a couple composed of a titanium alloy top sheet with a steel bottom sheet produced marginal welding (if at all) and strong welds were obtained when the sheet positions were reversed. Attempts to weld the titanium top sheet to the stainless steel lower sheet by substituting a titanium anvil for the conventional steel anvil were not successful.

In the Series 9 welds (0.060-in. 6Al-4V titanium and 0.500-in. Type 347 stainless steel), the impedance transfer rule was obeyed. It is apparent that impedance matching alc is not sufficient to determine the weldability of two different materials, but a correction term for the thickness of the weld sheets must also be considered.

5.2 AXIAL FATIGUE RESULTS

It is apparent from the axial fatigue test data that resistance welds generally show higher shear strength values under static testing, while explosively formed welds do not appear to be impaired by the ring weld configuration (especially at low stress levels).

The curves shown in Figures 32 through 41 have been drawn to a "best fit" pattern. They are from a "least squares" analysis by an Aerojet computer program, and are not necessarily ideal fatigue curves. Anomalies are apparent in Figure 40, Series 10 welds, with 0.060-in. top sheets of 2024-T3 welded to 0.500-in. Type 347 stainless steel bottom plates. The sinusoidal nature of the curve, obtained by a best fit of a higher-order logarithmic equation, implies that the welding process for this combination was very erratic and subject to more variation than the other welds considered; the static lap shear tests generally showed the welds capable of withstanding 5000 lb in tension.

Series 2 welds, made from 0.125-in. 6Al-4V titanium alloy, proved to be stronger in fatigue than their resistance-welded counterparts, although some welds did not conform to the normal or expected distribution. Conversely, titanium alloy 8Al-1 Mo-1V, showed stronger welds (at least up to 100,000 cycles) in the resistance-weld counterparts, as shown in Figure 36. The same characteristic can be observed in the comparison between Series 6 and Series 18 welds with 0.125-in. sheets of 2024-T3 (Figure 37); a crossover point occurs at approximately 200,000 cycles, after whicb the explosive welds appear to be superior to the resistance welds.

It appears that explosively formed ring welds are not detrimental to the fatigue life of the weld. Strength levels of welds may be somewhat lowered because an explosive weld is essentially a surface phenomenon and does not show much penetration. But, explosive welds are not as susceptible to stress concentrations, nor do they show any decided notch sensitivity, as resistance-welded counterparts.

5.3 FLEXURAL FATIGUE RESULTS

With the exception of Series 6 and 18 welds (0.125 in. aluminum joints), it is apparent from Figures 42 through 48 that explosively formed welds are not as sensitive to flexural fatigue as resistance welds; in most cases explosive welds are stronger. As discussed in Paragraph 5.2, this strength may be due to tbe absence of notch sensitivity; presumably because tbere are no subsurface metallurgical defects (e.g., microcracks or porosity) inherent in resistance welds (where the actual melting occurs). It is equally apparent, however, that not all welds have been optimized by this study. Series 9 welds, shown in Figure 49 and recorded in Table XII, show a weakness in the process in that specimens actually failed on loading of the panels in the test fixture.

5.4 WELDING CRITERIA

With few exceptions, strong spot welds can be attained when welding dissimilar metals if the impedance matching rule is obeyed. A standoff between welding sheets has been required, which produces ring welds with unwelded centers.

Standoffs are also required for welding similar metal sheets together. For all materials welded, it has been observed that sheet flatness is mandatory in all areas adjacent to the dimple standoff to ensure that the sheets are in contact, which aids welding. Mechanically wirebrushed surfaces are adequate if the surface finish is at least as smooth as that produced by a 120-grit grinding belt.

Cylindrical charges of explosives must be presented to the weld specimens perpendicularly, or skewed ring welds of low contact area and low strength are produced. However, in the case of low yield strength materials such as aluminum, the combination of a cylindrical charge over a dimple tends to produce a shaped-charge effect in the center of the weld, which reduces the strength of the weld.

Hold-down devices are necessary to promote contact of workpieces and to ensure the axial presentation of the charge. An exception to this was observed in the welding of aluminum, which required no hold-down pressure, presumably because the force of detonation was sufficient to produce contact with low yield strength materials.

5.5 EXPLOSIVES FOR SPOT WELDING

The characteristics of explosives applicable for spot welding must include (1) low detonation velocities, (2) small critical detonation diameters, and (3) low brisance.

It has been theorized that detonation velocities lower than the acoustic velocities of the metals being welded are required because higher velocities produce unstable jetting and cause damage to the metals. Nitroguanidine has been used by Aerojet for joining low yield strength materials, but stronger materials require higher energies. The addition of ammonium perchlorate to nitroguanidine resulted in an explosive mixture of higher energy but with no significant increase in detonation velocity, and also fulfilled the requirements for the small critical diameter and low brisance.

The requirement that the critical diameter of the explosive be small is necessary so that large amounts of explosive can be avoided and to keep weld diameters reasonably small. Explosives of high brisance must be avoided to prevent fragmenting of the panels intended to be joined.

The AP/NG mix described elsewhere in this report is recommended for explosive spot welding. Detonators must be included in the overall aspects of explosive welding. Large detonators or very high energy ignition sources should be avoided because of their contributions to surface deformation.

5.6 DESIGN OF A SPOT WELDING MACHINE

Three different concepts of an explosive spot welding machine have been designed. Preliminary layouts of these concepts are shown in Drawings 1310-67-0001 through -0003, and reproductions of the drawings are included in this report as Appendix V. The three models consist of two different basic configurations, bottom loading or top loading, according to the manner in which the explosive charge is introduced to the area to be welded. They also show three different methods of operation of the breech mechanism -- air operated, cam operated, and gas pressure operated. The combinations shown are as follows:

Model AGC-1	Bottom loaded, air operated
Model AGC-2	Bottom loaded, cam operated
Model AGC-3	Top loaded, gas pressure operated

Two methods were considered for ignition -- by firing pin or electrical detonator. Detonators with mechanical firing pins are considerably less expensive than electrical detonators, and the firing pin method of initiation was incorporated in the design of Model AGC-3. Electric detonators, while more expensive than stab-type, require no moving mechanical parts and this type was incorporated in the design of Model AGC-1.

For economy and safety it is necessary that neither the exploding charge nor the fragments produced by the charge case or cartridge directly contact any metal surface of the machine, because this surface would be severely damaged after repeated impacts. For this reason all three models show an empty chamber surrounding the actual charge, and the cartridge is located by means of its rear part. It is apparent that a minimum distance between the charge and the nearest metal surface be maintained. On the other hand, the necessity for welding close to a vertical wall provides an upper limit for that same dimension. Construction and testing of a model would be required to fix these dimensions.

6. CONCLUSIONS AND RECOMMENDATIONS

Conclusions reached after consideration of the results of this program are as follows:

a. Explosive spot welds approach resistance welds in static lap shear tests and, in welds of dissimilar metals, may surpass them.

b. Although formed as rings with unwelded areas in the centers, explosive spot welds are not as sensitive to stress concentration factors because of the ring formation, and show very high fatigue resistance.

c. Ring welds are not necessarily areas of weakness with regard to axial or flexural fatigue.

Because the explosive spot welding process is a surface welding process, it is believed that an increase in weld area would increase the static lap shear strengths. It is recommended that methods of eliminating the ring and producing solid area welds be developed, if the process is intended to compete with electrical resistance welds.

REFERENCES

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3. Carpenter, S., et al, "Relationship of Explosive Welding Parameters to Metal Properties and Geometry Factors," First International Conference of the Center for High Energy Forming, June 1967.

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5. Bahrani, A. S., and B. Crossland, "Explosives and Their Use in Engineering," Metals and Materials (British Institute of Metals), Vol. 2, No. 2, February 1968, and Vol. 2, No. 3, March 1968.

6. Holtzman, A. H., and G. R. Cowan, "Bonding of Metals With Explosives," Welding Research Council Bulletin, No. 104, April 1965.

7. Kolsky, H., "Stress Waves in Solids," Oxford University Press, 1954.

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Appendix I

DERIVATION OF AP/NG MIX

Nitroguanidine ($CH_4N_4O_2$) is an oxygen-deficient explosive whose power relative to TNT is about 105%. Oxygen-rich compounds may be added to nitroguanidine to improve the oxygen balance, and a considerable selection of materials and proportions is available for this purpose. Previous experience has shown that the ammonium perchlorate-nitroguanidine mixture is easy to handle, inexpensive, and effective in welding or cladding low-strength alloys. However, previous mixtures consisting of approximately 50% explosive and 50% oxidizer were found to be extremely oxygen-rich and probably not representative of the optimum explosive for this particular application. Therefore a new mixture was formulated.

For the new mixture the theoretical products of detonation were assumed to be CO, H_2, H_2O, N_2, and HCl. After first satisfying the chlorine requirement, the hydrogen was balanced to produce 75% water and 25% free hydrogen. This stoichiometry was selected to optimize the yield of the explosive in a manner similar to that used to optimize propellant mixtures, and the calculations are as follows:

$$a\ NH_4ClO_4 + b\ CH_4N_4O_2 \longrightarrow b\ CO + c\ H_2O + d\ H_2 + e\ N_2 + a\ HCl$$

where,

Chlorine:	$a = a$
Carbon:	$b = b$
Hydrogen:	$2c+2d+a = 4a+4b$
Nitrogen:	$2e = a+4b$
Oxygen:	$4a+2b = b+c$
and	$c = 3d$ by definition

The following equation is obtained by proper solution of these equations:

$$0.174\ NH_4ClO_4 + CH_4N_4O_2 \rightarrow CO + 1.696\ H_2O + 0.565\ H_2 + 2.087 N_2$$

$$+ 0.174\ HCl$$

The new mixture therefore consists of 20 gm of ammonium perchlorate and 104 gm of nitroguanidine, or approximately 16% oxidizer in place of the 50% previously used. Power calculations based on the characteristic-product method show the new mixture is now 125% relative to TNT, and a net increase in explosive energy has been achieved.

Appendix II

RESISTANCE WELDING SCHEDULES

Resistance welding was accomplished in accordance with the schedules contained on the following pages.

Aerojet-General Corp.
Downey, California

Date ____________
Schedule No. C-3
Revision No. 00

Federal Spot Weld Schedule

Machine Type FC-4A-48
Serial No. 16792
KVA 150
Control Type GE-CR-7503
Throat 50" x 14

	Upper Sheet	Lower Sheet
Material	Stainless steel	
Condition	Ti 6Al-4V	
Thickness	0.010	0.010
Preparation		

Transformer: Series ☐ Parallel ☒

PRESSURE SETTINGS

High Weld: 38
Low Weld: 0 — Low ☐ High ☒
Slow Approach: 32
High Return: 18
Low Return: 0 — Low ☐ High ☐

HEAD CONTROLS

Weld 21
Forge ____

Deflection Control
Weld Force ______ #
Forge Force ______ #

Slow Approach
On ☒ Off ☐

Tip Dress ☐
Operator ☒
Weld ☒
No Weld ☐

PANEL CONTROL SETTINGS

Heat Range: 40
Heat Vernier: 30

Repeat ☐ Non Repeat ☐
Pulse Cycles: 2
Weld Cycles: 2
Norm — Low Frequency
Plus 1 Cycle

Squeeze Time: 20
Hold Time: 35
Off Time: 35
Tailing Time Switch: 0
Tailing Heat: 0
Forge Time: 0
Tap Switch
Pot: 0

FORGE TIME

Forge: On ☐ Off ☒
Tailing: On ☐ Off ☒

Normal ☒
Antipolarity ☐
Positive ☐
Negative ☐

FIRING PATTERN

Preheat: 0 — Cycles: 0 — On ☐ Off ☒
Postheat: 0 — Cycles: 0 — On ☐ Off ☒
Chill: 0

	Upper Electrode	Lower Electrode
Material	Copper	Copper
RWMA Class	1	1
Diameter	5/8 in.	5/8 in.
Radius	6 in.	6 in.
Profile	STD	STD
Cooling	INT	INT

Part Name Test
Part No. 6-4-010
Specification MIL-W-6858C

Remarks:

Summary of Test Results

Internal Quality: Accept ☐ Reject ☐
Surface Condition: Accept ☐ Reject ☐

	Shear Strength	Nugget Diameter
Specification Req.	205 #/S	0.060 In.
Actual Average	______ #/S	______ In.
Actual Minimum	______ #/S	______ In.
Actual Range	______ #/S	
Actual Variation	______ %	

Remarks:

Indentation (Average): Upper ______ % Lower ______ %

Penetration (Average): Upper ______ % Lower ______

Operator ____________
Weld Engineer ____________
Quality Control ____________
Quality Engr. ____________

Date
Lab. Technician ____________
Met. Lab. Engr. ____________
Government ____________

Schedule No. Series 13

Aerojet-General Corp.
Downey, California

Date ______
Schedule No. C-5
Revision No. 00

Federal Spot Weld Schedule

Machine Type FC-4A-48
Serial No. 16792
KVA 150
Control Type GE-CR 7503
Throat 50 x 14

	Upper Sheet	Lower Sheet
Material	Ti 6Al-4V	
Condition		
Thickness	0.125	0.125
Preparation	Wire Brush	

Transformer: Series ☐ Parallel ☒

PRESSURE SETTINGS

- High Weld: 46
- Low Weld: 0 (Low ☐ High ☒)
- Slow Approach: 34
- High Return: 20
- Low Return: 0 (Low ☐ High ☒)

HEAD CONTROLS

Weld 24
Forge 0

Deflection Control
Weld Force ______ #
Forge Force ______ #

Slow Approach
On ☐ Off ☐

Tip Dress ☐
Operator ☒
Weld ☒
No Weld ☐

PANEL CONTROL SETTINGS

- Heat Range: 40
- Heat Vernier: 27
- Repeat ☐ Non Repeat ☒
- Pulse Cycles: 5
- Weld Cycles: 7
- Norm / Low Frequency / Plus 1 Cycle
- Squeeze Time: 20
- Hold Time: 40
- Off Time: 55
- Tailing Time Switch: 0
- Tailing Heat: 0
- Tap Switch
- Forge Time
- Pot

FORGE TIME

Forge: On ☐ Off ☒
Tailing: On ☐ Off ☒

Normal ☒
Antipolarity ☐
Positive ☐
Negative ☐

FIRING PATTERN

	Preheat	Postheat
	0	0
Cycles	0	0
	On ☐ Off ☒	On ☐ Off ☒

Chill 0

	Upper Electrode	Lower Electrode
Material	Copper	Copper
RWMA Class	III	III
Diameter	5/8 in.	5/8 in.
Radius	6 in.	6 in.
Profile	STD	STD
Cooling	INT	INT

Part Name Test
Part No. 6-4-125
Specification MIL-6858

Remarks:

Summary of Test Results

Internal Quality: Accept ☐ Reject ☐
Surface Condition: Accept ☐ Reject ☐

	Shear Strength	Nugget Diameter
Specification Req.	5950 #/S	.280 In.
Actual Average	______ #/S	______ In.
Actual Minimum	______ #/S	______ In.
Actual Range	______ #/S	
Actual Variation	______ %	

Remarks:

Indentation (Average) Upper ______ % Lower ______ %

Penetration (Average) Upper ______ % Lower ______

Operator ______
Weld Engineer ______
Quality Control ______
Quality Engr. ______

Date
Lab. Technician ______
Met. Lab. Engr. ______
Government ______

Schedule No. Series 14

Aerojet-General Corp.
Downey, California

Date ____
Schedule No. C-2
Revision No. 00

Federal Spot Weld Schedule

Machine Type FC-4A-48
Serial No. 16792
KVA 150
Control Type GE-CR 7503
Throat 50 x 14

	Upper Sheet	Lower Sheet
Material	17-7 PH	17-7 PH
Condition		
Thickness	0.060	0.060
Preparation	With Solvent	With Solvent

Transformer: Series ☐ Parallel ☒

PRESSURE SETTINGS

- High Weld: 45
- Low Weld: 0 — Low ☐ High ☐
- Slow Approach: 40
- High Return: 24
- Low Return: 0 — Low ☐ High ☐

HEAD CONTROLS

Weld 28
Forge 0

Deflection Control
Weld Force ____ #
Forge Force ____ #

Slow Approach
On ☐ Off ☒

Tip Dress ☐
Operator ☒
Weld ☒
No Weld ☐

PANEL CONTROL SETTINGS

- Heat Range: 40
- Heat Vernier: 34

Repeat ☐ Non Repeat ☒

- Pulse Cycles: 3
- Weld Cycles: 5

Norm — Low Frequency — Plus 1 Cycle

- Squeeze Time: 20
- Hold Time: 30
- Off Time: 35
- Tailing Time Switch: 0
- Tailing Heat: 0
- Forge Time: 0 — Tap Switch
- Pot: 0

FORGE TIME

Forge: On ☐ Off ☒
Tailing: On ☐ Off ☒

Normal ☒
Antipolarity ☐
Positive ☐
Negative ☐

FIRING PATTERN

	Preheat	Postheat
	0	0
Cycles	0	0
Chill	0	
On	☐	☐
Off	☒	☒

	Upper Electrode	Lower Electrode
Material	Copper	Copper
RWMA Class	III	III
Diameter	5/8 in.	5/8 in.
Radius	6 in.	6 in.
Profile	STD	STD
Cooling	INT	INT

Part Name Test
Part No. 17-7-060
Specification MIL-6858

Remarks:

Summary of Test Results

Internal Quality: Accept ☐ Reject ☐
Surface Condition: Accept ☐ Reject ☐

	Shear Strength	Nugget Diameter
Specification Req.	210 #/S	200 In.
Actual Average	____ #/S	____ in.
Actual Minimum	____ #/S	____ in.
Actual Range	____ #/S	
Actual Variation	____ %	

Remarks:

Indentation (Average) Upper ____ % Lower ____ %

Penetration (Average) Upper ____ % Lower ____

			Date
Operator ____		Lab. Technician ____	
Weld Engineer ____		Mat. Lab. Engr. ____	
Quality Control ____		Government ____	____
Quality Engr. ____			

Schedule No. Series 15

Aerojet-General Corp.
Downey, California

Date ________
Schedule No. C-6
Revision No. ________

Federal Spot Weld Schedule

Machine Type FC-4A-48
Serial No. 16792
KVA 150
Control Type GE-CR-7503
Throat 50 x 14

	Upper Sheet	Lower Sheet
Material	17-7 PH	17-7 PH
Condition	Sheet plate	
Thickness	0.060	0.375
Preparation	Sand	

Transformer: Series ☐ Parallel ☒

PRESSURE SETTINGS

High Weld: 44
Low Weld: 0 — Low ☐ High ☒
Slow Approach: 30
High Return: 22
Low Return: 0 — Low ☐ High ☒

HEAD CONTROLS

Weld 24
Forge 0

Deflection Control
Weld Force ____ #
Forge Force 0 #

Slow Approach
On ☒ Off ☐

Tip Dress ☐
Operator ☒
Weld ☒
No Weld ☐

PANEL CONTROL SETTINGS

Heat Range: 40
Heat Vernier: 38

Repeat ☒ Non Repeat ☐

Pulse Cycles: 4
Weld Cycles: 6

Norm ◯ Low Frequency
Plus 1 Cycle

Squeeze Time: 20
Hold Time: 50
Off Time: 50

Tailing Time Switch: 0
Tailing Heat: 0

x Top Switch Forge Time
◯ Pot

FORGE TIME

Forge: On ☐ Off ☒
Tailing: On ☐ Off ☒

Normal ☒
Antipolarty ☐
Positive ☐
Negative ☐

FIRING PATTERN

Preheat: 0; Cycles 0
Postheat: 0; Cycles 0
Chill: 0

On ☐ Off ☒ — On ☐ Off ☒

	Upper Electrode	Lower Electrode
Material	Copper	Copper
RWMA Class	II	II
Diameter	5/8 in.	5/8 in.
Radius	6 in.	6 in.
Profile	STD	STD
Cooling	INT	INT

Part Name Test
Part No. 17-7-060-375
Specification MIL-W-6858

Remarks:

Summary of Test Results

Internal Quality: Accept ☐ Reject ☐
Surface Condition: Accept ☐ Reject ☐

	Shear Strength	Nugget Diameter
Specification Req.	____ #/S	____ In.
Actual Average	____ #/S	____ In.
Actual Minimum	____ #/S	____ In.
Actual Range	____ #/S	
Actual Variation	____ %	

Remarks:

Indentation (Average) Upper ____ % Lower ____ %

Penetration (Average) Upper ____ % Lower ____

Date

Operator ________
Weld Engineer ________
Quality Control ________
Quality Engr. ________

Lab. Technician ________
Met. Lab. Engr. ________
Government ________

Schedule No. Series 16

Aerojet-General Corp.
Downey, California

Date ______
Schedule No. C-4
Revision No. 00

Federal Spot Weld Schedule

Machine Type FC-4A-48
Serial No. 16792
KVA 150
Control Type GE-CR-7503
Throat 50 x 14

	Upper Sheet	Lower Sheet
Material	Ti 8Al-1Mo-1V	Ti 8Al-1Mo-1V
Condition		
Thickness	0.060	0.060
Preparation	With solvent	

Transformer: Series ☐ Parallel ☒

PRESSURE SETTINGS

42 High Weld

0 Low Weld — Low ☐ High ☒

32 Slow Approach

22 High Return

0 Low Return — Low ☐ High ☒

HEAD CONTROLS

Weld 23
Forge 0

Deflection Control
Weld Force ____ #
Forge Force ____ #

Slow Approach
On ☒ Off ☐

Tip Dress ☐
Operator ☒
Weld ☒
No Weld ☐

PANEL CONTROL SETTINGS

48 Heat Range
28 Heat Vernier

Repeat ☐ Non Repeat ☐

4 Pulse Cycles
4 Weld Cycles

Norm / Low Frequency / Plus 1 Cycle

20 Squeeze Time
40 Hold Time
35 Off Time

0 Tailing Time Switch
0 Tailing Heat

0 Forge Time
Tap Switch
0 Pot

FORGE TIME

Forge: On ☐ Off ☒
Tailing: On ☐ Off ☒

Normal ☒
Antipolarity ☐
Positive ☐
Negative ☐

FIRING PATTERN

Preheat 0, Cycles 0 — On ☐ Off ☒
Postheat 0, Cycles 0 — On ☐ Off ☒
Chill 0

	Upper Electrode	Lower Electrode
Material	Copper	Copper
RWMA Class	III	III
Diameter	5/8 in.	5/8 in.
Radius	6 in.	6 in.
Profile	STD	STD
Cooling	INT	INT

Part Name Test
Part No. 8-1-1-060
Specification MIL-W-6858

Remarks:

Summary of Test Results

Internal Quality: Accept ☐ Reject ☐
Surface Condition: Accept ☐ Reject ☐

	Shear Strength	Nugget Diameter
Specification Req.	3000 #/S	0.200 In.
Actual Average	____ #/S	____ In.
Actual Minimum	____ #/S	____ In.
Actual Range	____ #/S	
Actual Variation	____ %	

Remarks:

Indentation (Average) Upper ____ % Lower ____ %

Penetration (Average) Upper ____ % Lower ____

Date

Operator ______
Weld Engineer ______
Quality Control ______
Quality Engr. ______

Lab. Technician ______
Met. Lab. Engr. ______
Government ______

Schedule No. Series 17

Aerojet-General Corp.
Downey, California

Date ______
Schedule No. C.6
Revision No. ______

Federal Spot Weld Schedule

Machine Type FC.4A.48
Serial No. 16792
KVA 150
Control Type GE
Throat 53 x ___

	Upper Sheet	Lower Sheet
Material	Alum	
Condition	2024 T3	
Thickness	0.125	0.125
Preparation		

Transformer: Series ☐ Parallel ■

PRESSURE SETTINGS

62 — High Weld
0 — Low Weld (Low ☐ High ☐)
40 — Slow Approach
30 — High Return
0 — Low Return (Low ☐ High ☐)

HEAD CONTROLS

Weld 36
Forge 60

Deflection Control

Weld Force ______ #
Forge Force ______ #

Slow Approach

On ☐ Off ■

Tip Dress ☐
Operator ■
Weld ■
No Weld ☐

PANEL CONTROL SETTINGS

60 — Heat Range
27 — Heat Vernier

Repeat ☐ Non Repeat ■

5 — Pulse Cycles
5 — Weld Cycles

Norm — Low Frequency — Plus 1 Cycle

20 — Squeeze Time
50 — Hold Time
50 — Off Time
7 — Tailing Time Switch
70 — Tailing Heat

Tap Switch Forge Time — Pot

FORGE TIME

Forge: On ■ Off ☐
Tailing: On ■ Off ☐

Normal ☐
Antipolarity ☒
Positive ☐
Negative ☐

FIRING PATTERN

Preheat 0 — Postheat 0
Cycles 0 — Cycles 0
Chill 0
On ☐ Off ■ — On ☐ Off ■

	Upper Electrode	Lower Electrode
Material		
RWMA Class		
Diameter	5/8 in.	5/8 in.
Radius	8 in.	8 in.
Profile		
Cooling	Water	Water

Part Name ______
Part No. ______
Specification ______

Remarks:

Summary of Test Results

Internal Quality: Accept ☐ Reject ☐
Surface Condition: Accept ☐ Reject ☐

	Shear Strength	Nugget Diameter
Specification Req.	______ #/S	______ In.
Actual Average	______ #/S	______ In.
Actual Minimum	______ #/S	______ In.
Actual Range	______ #/S	
Actual Variation	______ %	

Remarks:

Indentation (Average) Upper ______ % Lower ______ %

Penetration (Average) Upper ______ % Lower ______

Date

Operator ______
Weld Engineer ______
Quality Control ______
Quality Engr. ______

Lab. Technician ______
Met. Lab. Engr. ______
Government ______

Schedule No. Series 18

Aerojet-General Corp.
Downey, California

Date ______
Schedule No. C-1
Revision No. 00

Federal Spot Weld Schedule

Machine Type FC-4A-48
Serial No. 16792
KVA 150
Control Type GE-CR-7503
Throat 50 x 14

	Upper Sheet	Lower Sheet
Material	Stainless Steel	Stainless Steel
Condition	347	347
Thickness	0.060	0.060
Preparation	As received	

Transformer: Series ☐ Parallel ☒

PRESSURE SETTINGS

- High Weld: 44
- Low Weld: 0 — Low ☐ High ☒
- Slow Approach: 40
- High Return: 22
- Low Return: 0 — Low ☐ High ☒

HEAD CONTROLS

Weld 28
Forge 0

Deflection Control
Weld Force ______ #
Forge Force ______ #

Slow Approach
On ☐ Off ☒

Tip Dress ☐
Operator ☒
Weld ☒
No Weld ☐

PANEL CONTROL SETTINGS

- Heat Range: 40
- Heat Vernier: 34
- Repeat ☐ Non Repeat ☒
- Pulse Cycles: 3
- Weld Cycles: 5
- Norm / Low Frequency / Plus 1 Cycle
- Squeeze Time: 20
- Hold Time: 30
- Off Time: 35
- Tailing Time Switch: 0
- Tailing Heat: 0
- Tap Switch Forge Time: 0
- Pot: 0

FORGE TIME

Forge: On ☐ Off ☒
Tailing: On ☐ Off ☒

Normal ☒
Antipolarity ☐
Positive ☐
Negative ☐

FIRING PATTERN

	Preheat	Postheat
	0	0
Cycles	0	0
On	☐	☐
Off	☒	☒

Chill: 0

	Upper Electrode	Lower Electrode
Material	Copper	Copper
RWMA Class	III	III
Diameter	5/8 in.	5/8 in.
Radius	6 in.	6 in.
Profile	STD	STD
Cooling	INT	INT

Part Name Test
Part No. 347-060
Specification MIL-6858

Remarks:

Summary of Test Results

Internal Quality: Accept ☐ Reject ☐
Surface Condition: Accept ☐ Reject ☐

	Shear Strength	Nugget Diameter
Specification Req.	2110 #/S	0.200 In.
Actual Average	______ #/S	______ In.
Actual Minimum	______ #/S	______ In.
Actual Range	______ #/S	
Actual Variation	______ %	

Remarks:

Indentation (Average) Upper ______ % Lower ______ %

Penetration (Average) Upper ______ % Lower ______

Operator ______
Weld Engineer ______
Quality Control ______
Quality Engr. ______

Date
Lab. Technician ______
Met. Lab. Engr. ______
Government ______

Schedule No. Series 19

Appendix III

C-SCAN TEST RECORDINGS

The ultrasonic C-scan records are contained in the following pages.

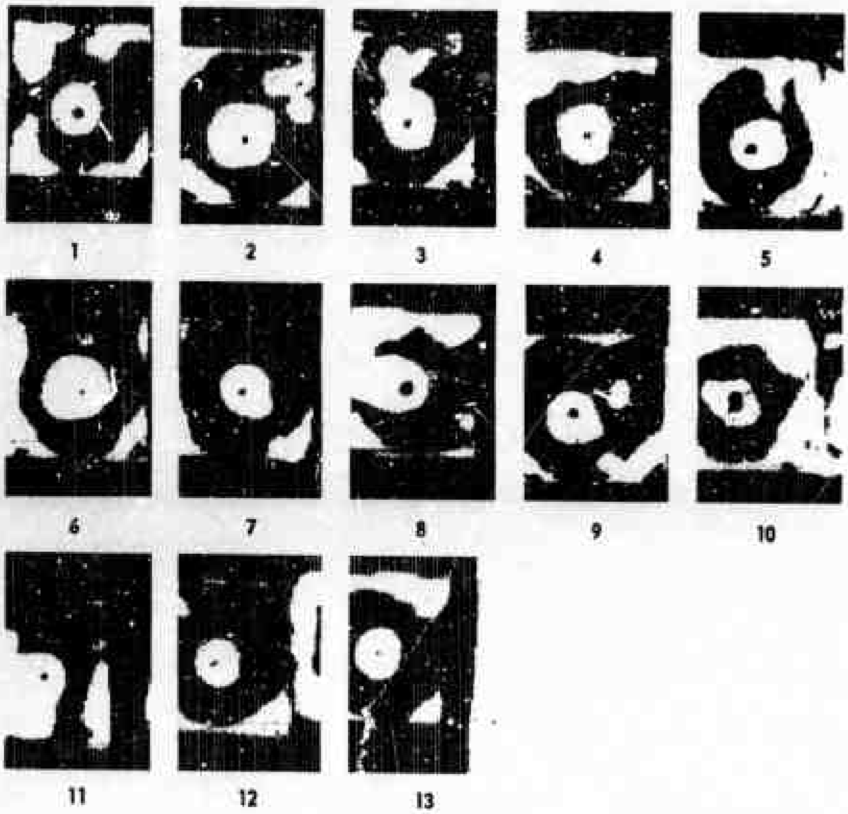


Figure 53. C-Scan Record of Series 1 Welds.

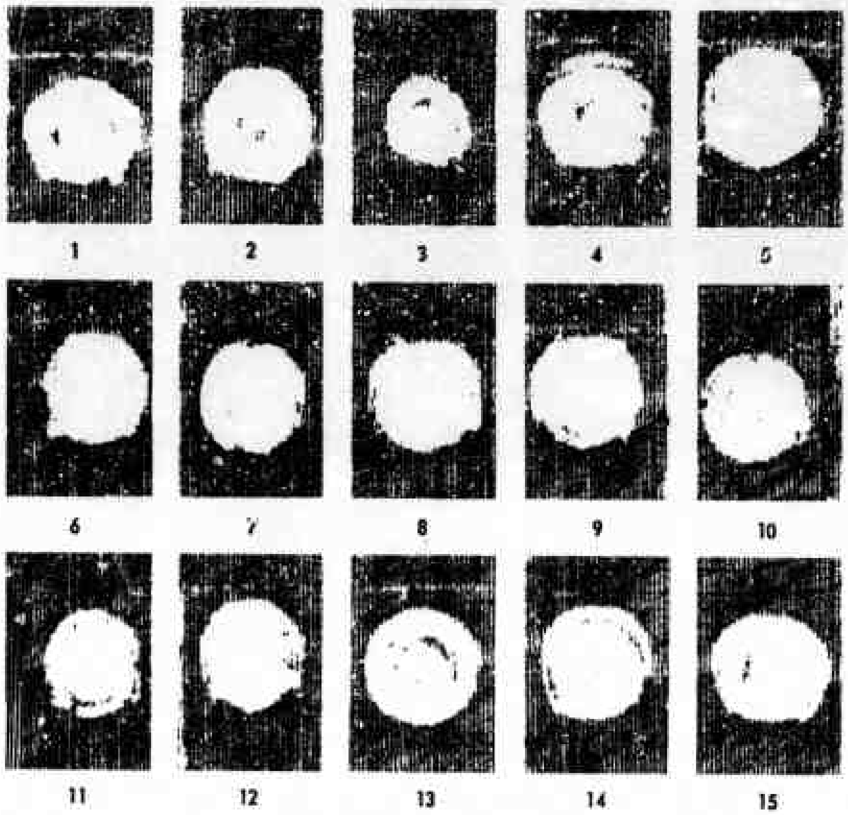


Figure 54. C-Scan Record of Series 2 Welds.

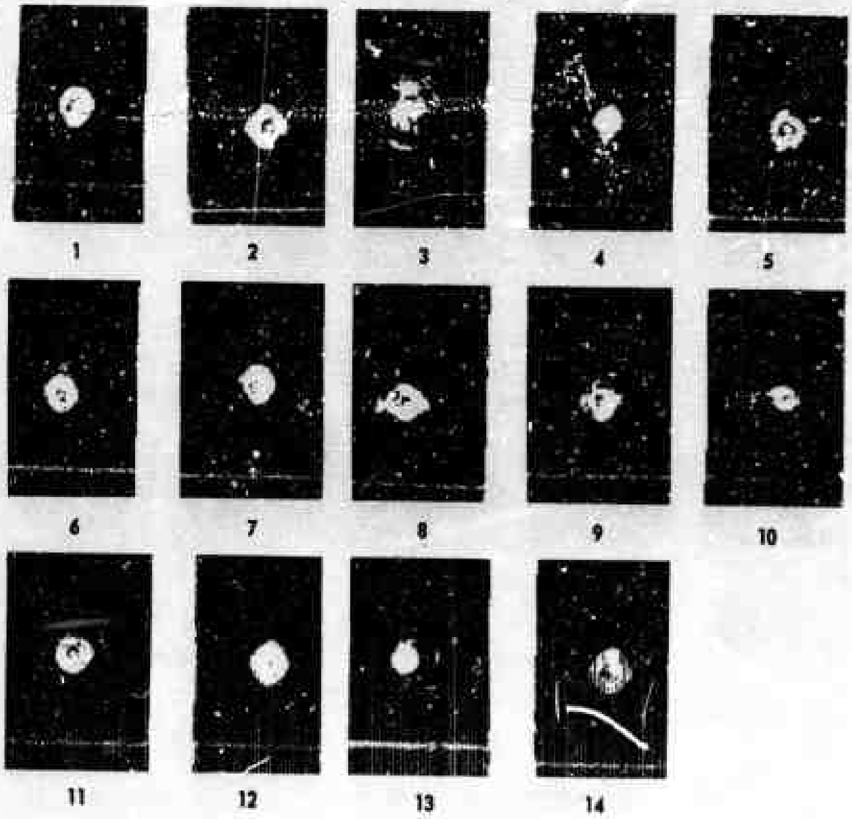


Figure 55. C-Scan Record of Series 3 Welds.

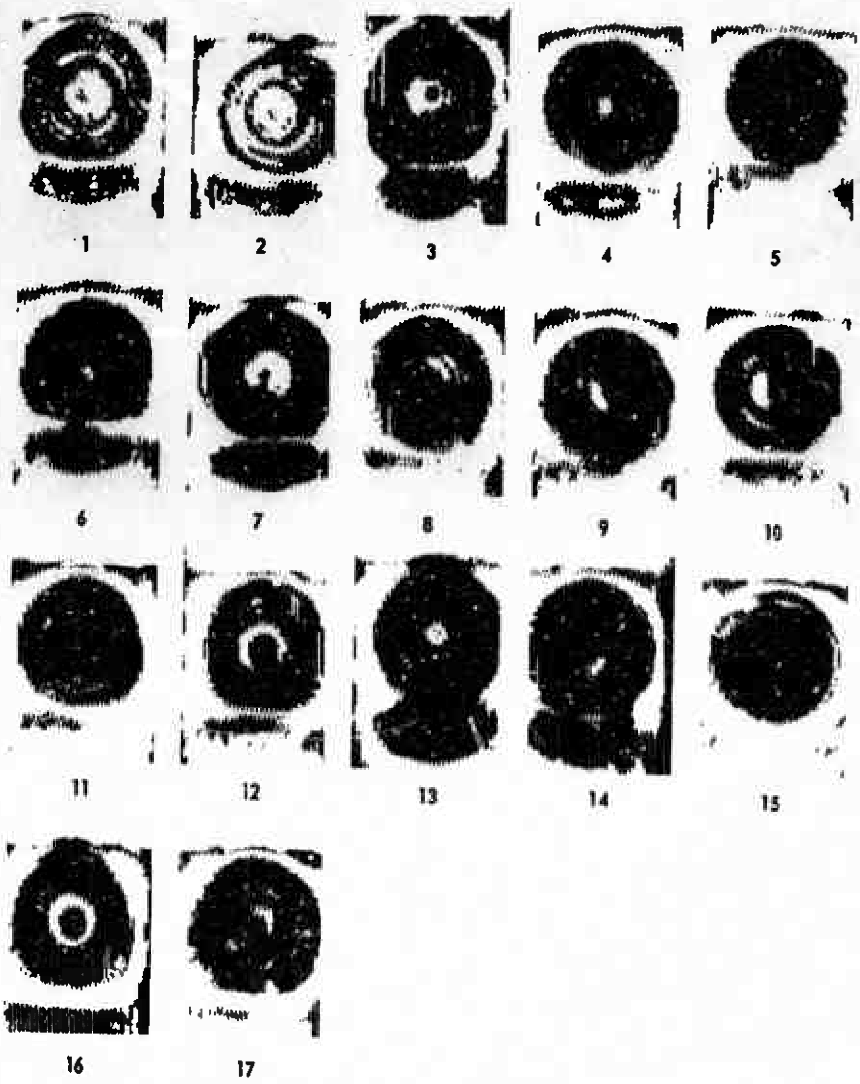


Figure 56. C-Scan Record of Series 4 Welds.

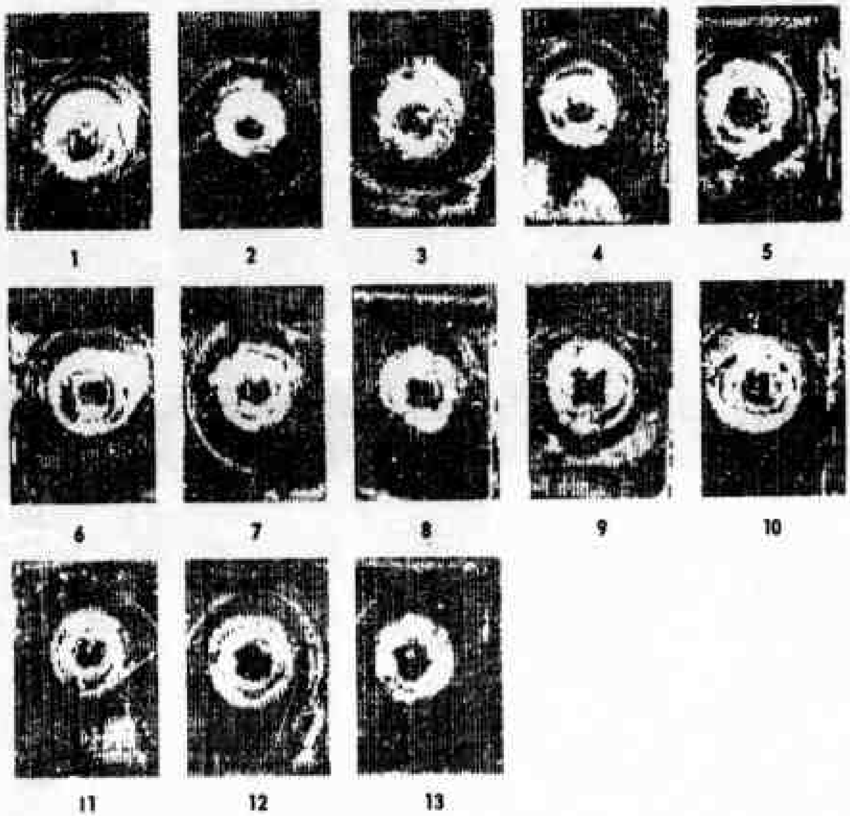


Figure 57. C-Scan Record of Series 5 Welds.

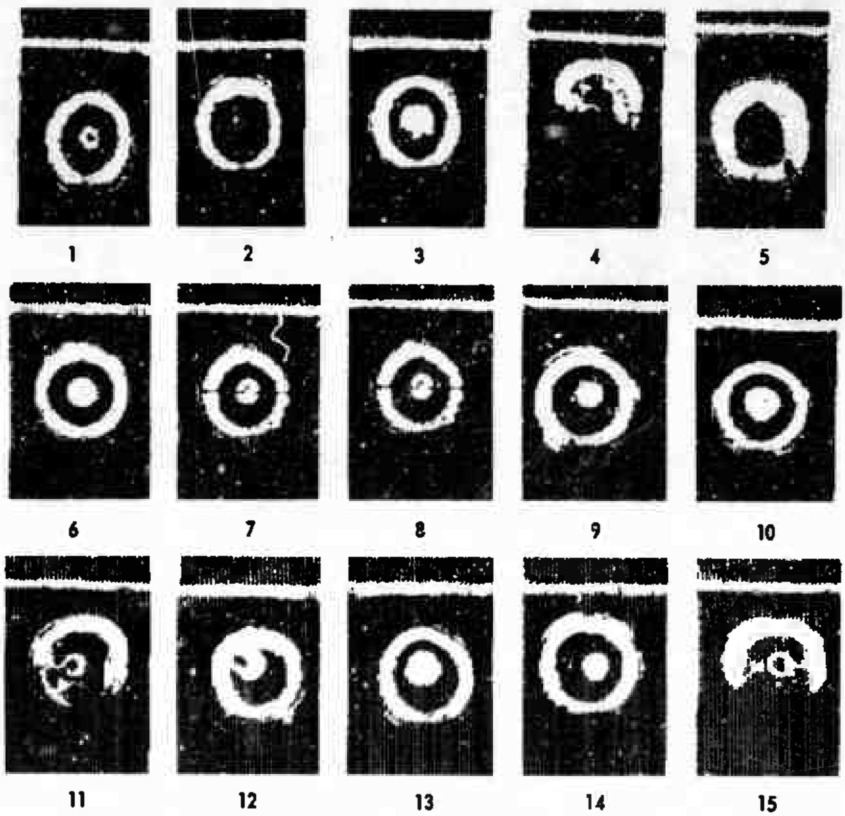


Figure 58. C-Scan Record of Series 6 Welds.

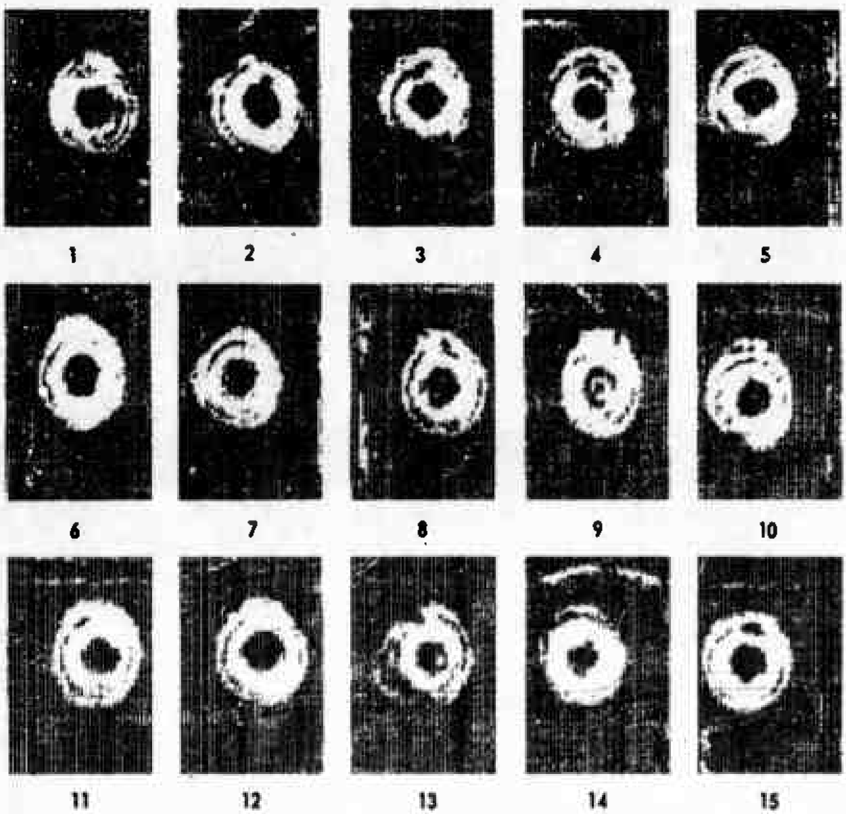


Figure 59. C-Scan Record of Series 7 Welds.

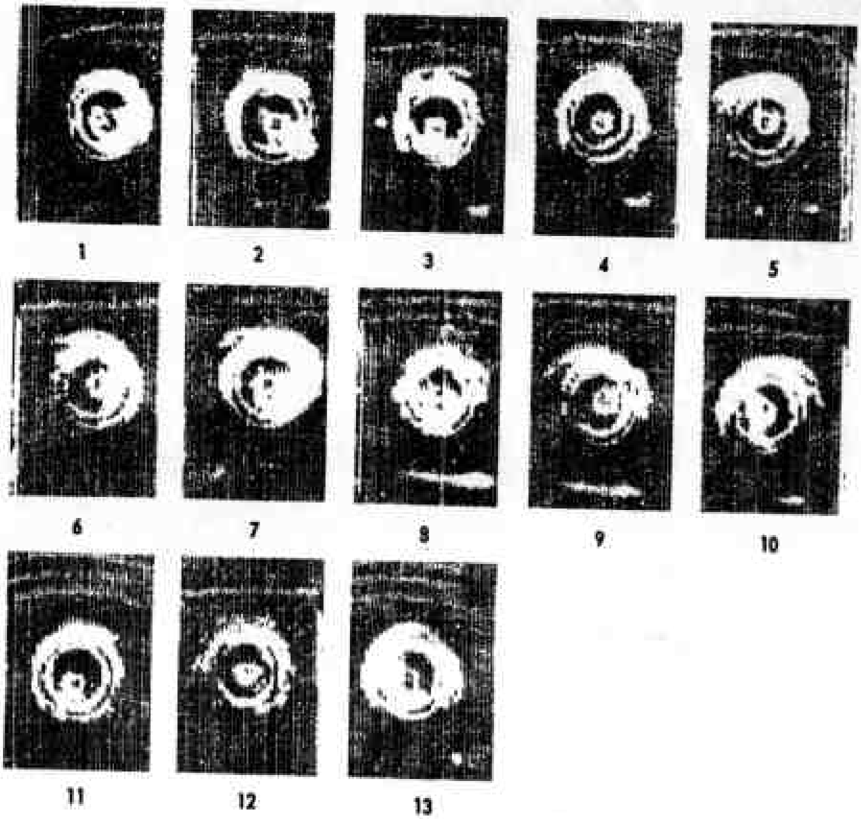


Figure 60. C-Scan Record of Series 8 Welds.

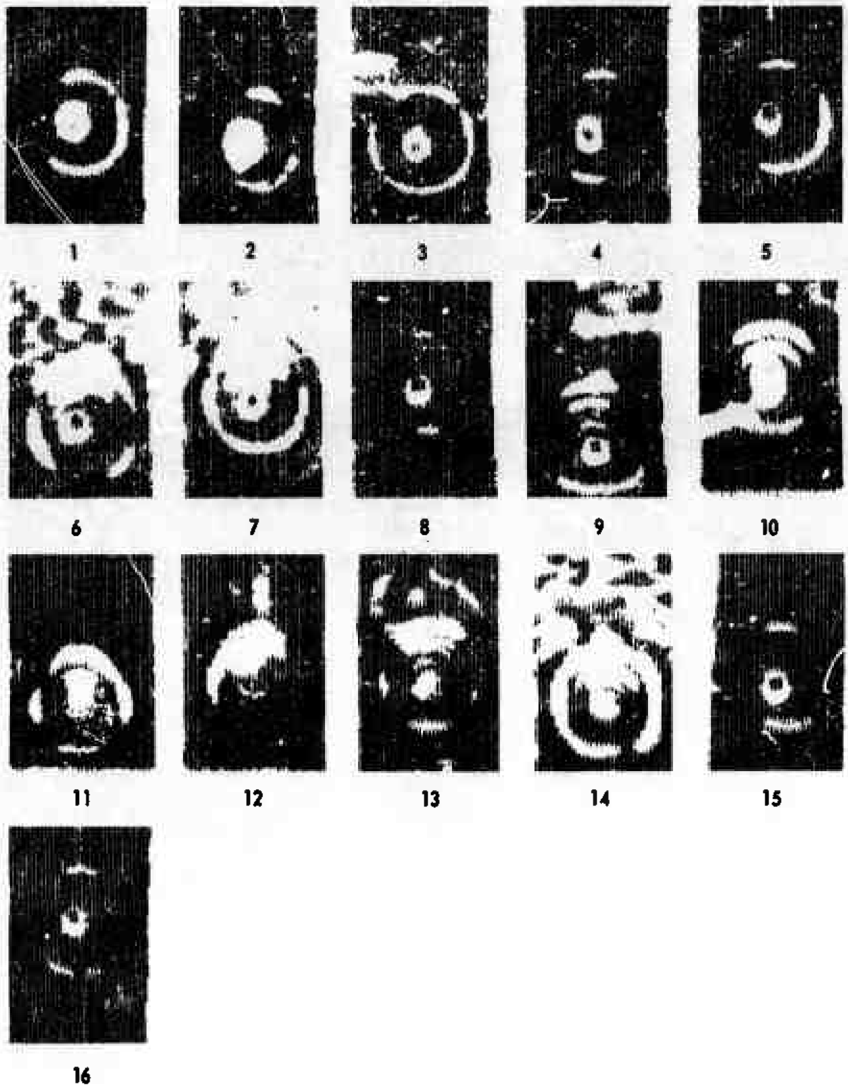


Figure 61. C-Scan Record of Series 9 Welds.

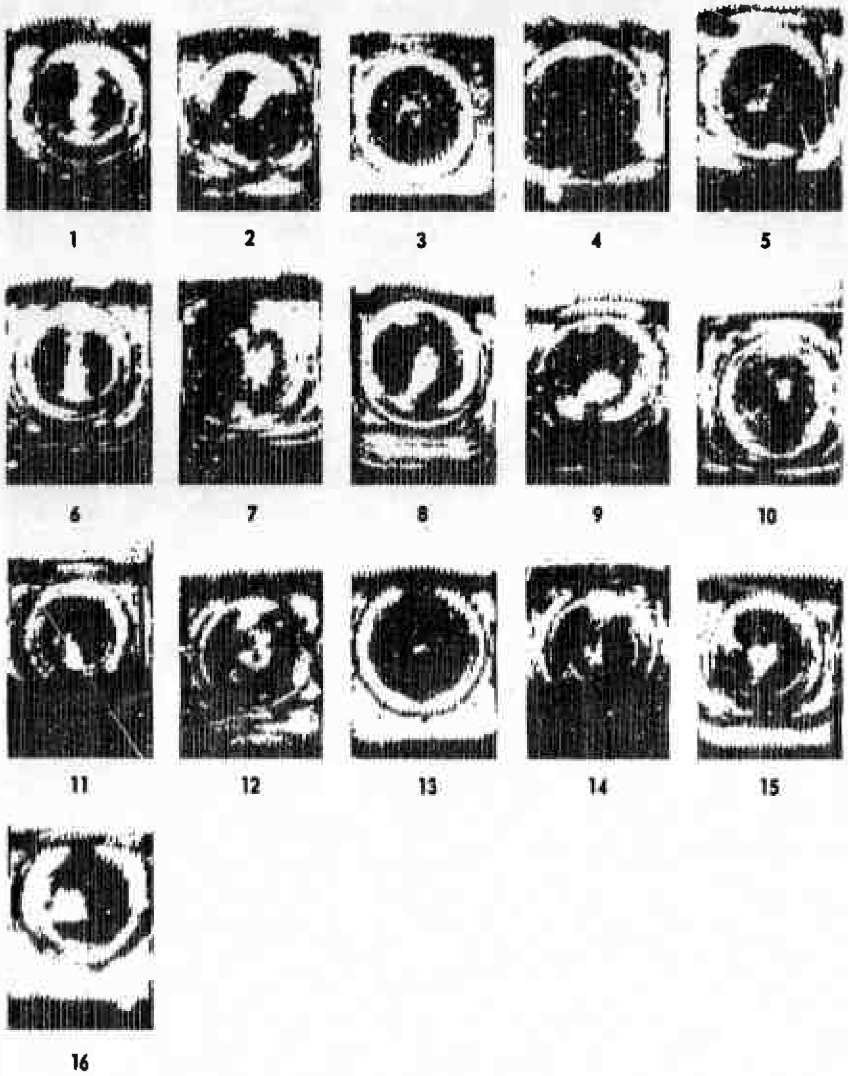


Figure 62. C-Scan Record of Series 10 Welds.

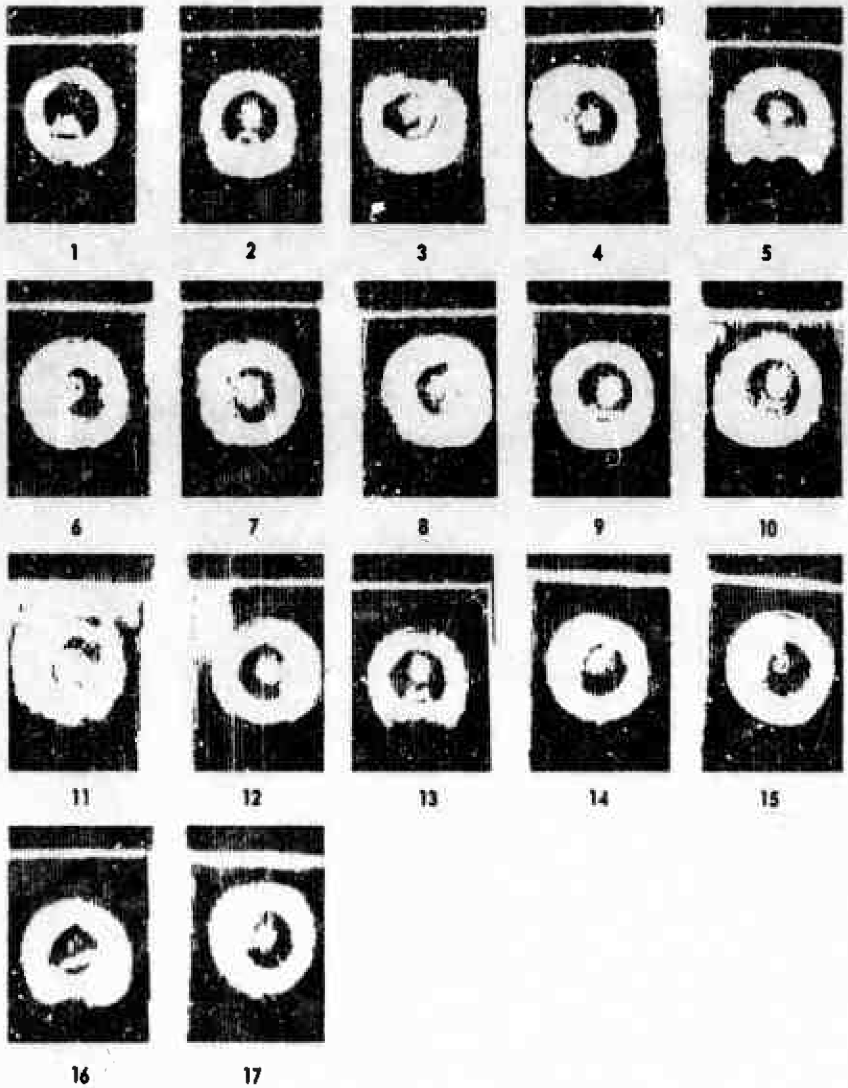


Figure 63. C-Scan Record of Series 11 Welds.

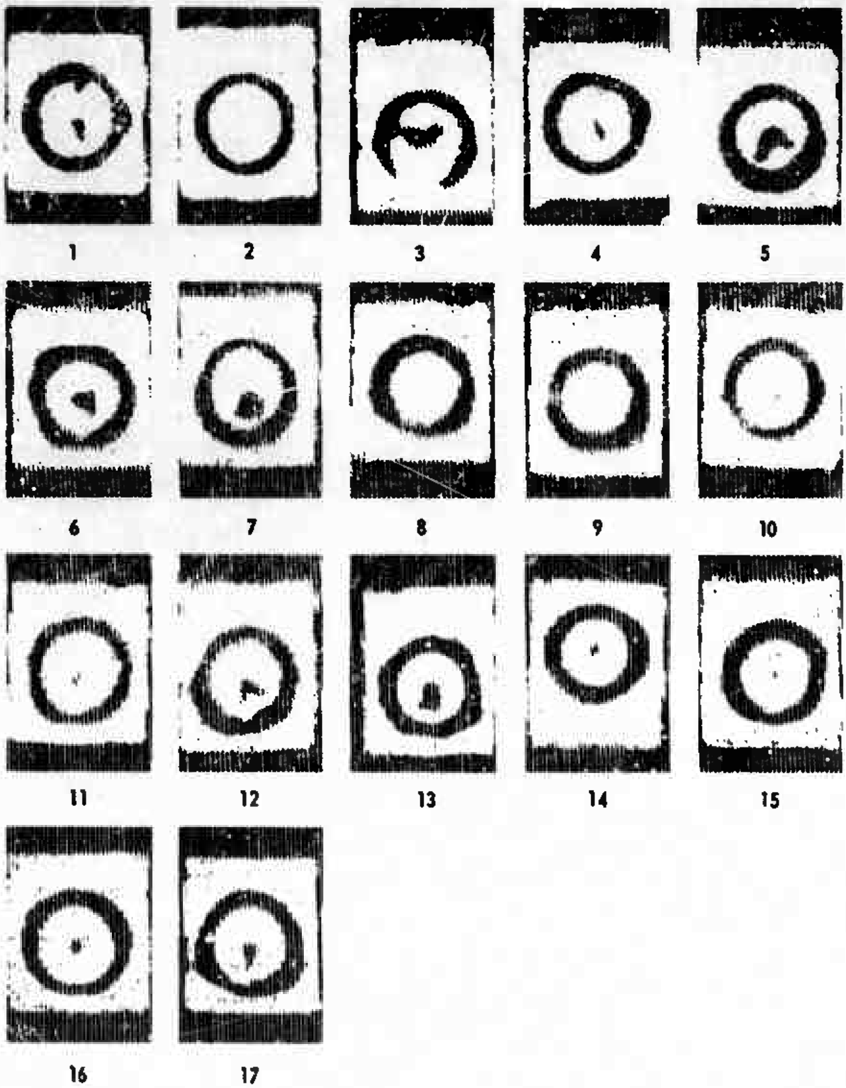


Figure 64. C-Scan Record of Series 12 Welds.

Appendix IV

AXIAL FATIGUE TEST RESULTS

The results of the axial fatigue tests are contained in the following tables.

Table XIII. Axial Fatigue Test Results, Series 1.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	120	6	0	Failed on installation
2	120	6	2,200	
3	90	5	14,200	
4	60	3	1,700	
5	60	3	0	Failed on installation
6	60	3	0	Failed on installation
7	60	3	65,400	
8	40	2	1,697,400	Discontinued
9	40	2	844,200	
10	50	3	1,000,000	Discontinued

Note 1: Load Ratio: 0.05

Note 2: Material: 6-4 Titanium; Nominal Thickness: 0.010 in.

Table XIV. Axial Fatigue Test Results, Series 2.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
5	1000	50	1,451,600	
6	2000	100	88,400	
7	3000	150	800	
8	2000	100	6,100	
9	1600	80	363,800	
10	2500	125	33,100	
11	1600	80	765,200	
12	2500	125	33,300	
14	1000	50	1,000,000	Discontinued
15	2000	100	67,100	

Note 1: Load Ratio: 0.05

Note 2: Material: 6-4 Titanium; Nominal Thickness: 0.125 in.

Table XV. Axial Fatigue Test Results, Series 3.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	1600	90	0	Fractured on loading
3	1800	90	1,100	
4	1200	60	1,400	
5	800	40	1,000,900	
6	1000	50	309,500	
7	1200	60	197,500	
8	1000	50	332,700	
9	1200	60	70,300	
10	1600	80	2,900	
11	800	40	1,072,900	Discontinued

Note 1: Load Ratio: 0.05

Note 2: Material: 17-7; Nominal Thickness: 0.060 in.

Table XVI. Axial Fatigue Test Results, Series 4.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
4	2400	120	1,000,000	Discontinued
5	3000	150	757,600	Failed in parent metal away from weld
6	3800	190	300	
8	3400	170	113,500	
9	3400	170	500	
10	3000	150	900	
11	2500	125	0	Failed on loading
12	2500	125	1,142,800	Discontinued
13	2700	135	1,285,000	Discontinued
14	2700	135	627,100	

Note 1: Load Ratio: 0.05

Note 2: Material: 17-7; Nominal Thickness: 0.375/0.060 in.

Table XVII. Axial Fatigue Test Results, Series 5.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	500	25	1,700,000	Discontinued
4	900	45	20,800	
5	700	35	512,500	
6	1100	55	200	
7	800	40	50,800	
8	700	35	1,000,000	Discontinued
9	900	45	54,100	
10	800	40		Specimen overloaded on installation
12	800	40	988,900	
13	1000	50	22,700	

Note 1: Load Ratio: 0.05

Note 2: Material: 8-1-1 Titanium; Nominal Thickness: 0.060 in.

Table XVIII. Axial Fatigue Test Results, Series 6.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	1800	90	900	
2	1200	60	3,500	
3	900	45	49,600	
5	900	45	29,500	
6	800	40	42,800	
7	700	35	369,000	
8	700	35	1,000,000	Discontinued
9	800	40	81,100	
10	1050	52	49,000	
12	1050	52	39,400	

Note 1: Load Ratio: 0.05

Note 2: Material: 2024-T3; Nominal Thickness: 0.125 in.

Table XIX. Axial Fatigue Test Results, Series 7.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
4	900	45	203,600	
5	1400	70	47,700	
6	2000	100	7,500	
7	1100	55	141,200	
9	700	35	482,600	
10	1400	70	38,400	
11	1100	55	127,400	
12	900	45	258,100	
14	2000	100	0	Failed on Loading - very small weld area
15	700	35	354,600	

Note 1: Load Ratio: 0.05

Note 2: Material: 347 Stainless; Nominal Thickness: 0.060 in.

Table XX. Axial Fatigue Test Results, Series 8.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	600	30	1,011,900	Discontinued
2	900	45	40,300	
3	800	40	31,000	
4	900	45	3,200	
6	700	35	78,900	
7	700	35	1,000,000	Discontinued
8	800	40	0	Failed on loading
10	800	40	56,000	
11	600	30	318,100	
13	700	35	781,300	

Note 1: Load Ratio: 0.05

Note 2: Material: 6-4/17-7; Nominal Thickness: 0.060 in.

Table XXI. Axial Fatigue Test Results, Series 9.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	1800	90	1,600	
3	1200	60	4,000	
4	800	40	4,700	
5	800	40	8,400	
6	400	20	1,619,000	Discontinued
7	600	30	0	Failed on loading
9	600	30	9,400	
10	500	25	1,848,500	
11	400	20	2,115,300	Discontinued
12	600	30	290,100	

Note 1: Load Ratio: 0.05

Note 2: Material: 6-4/347; Nominal Thickness: 0.500/0.060 in.

Table XXII. Axial Fatigue Test Results, Series 10.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
2	--	---	--	Failed in handling
3	2800	140	7,600	
4	1600	80	4,700	
5	2000	100	2,500	
7	1000	50	1,000	Off center weld
8	1000	50	258,300	
9	1000	50	0	Specimen overloaded on installation
10	1000	50	609,400	
11	800	40	179,400	
12	600	30	64,400	

Note 1: Load Ratio: 0.05

Note 2: Material: 2024/347; Nominal Thickness: 0.060/0.500 in.

Table XXIII. Axial Fatigue Test Results, Series 11.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	2200	110	0	Failed during installation
2	2200	110	4,400	
4	1600	80	19,300	
7	1200	60	147,400	Parent metal away from weld
8	1200	60	93,300	Parent metal away from weld
9	1000	50	2,211,000	Discontinued
10	1000	50	401,400	Parent metal away from weld
12	1600	80	45,600	Parent metal away from weld
13	2000	100	3,200	Weld break
14	1400	70	69,700	Parent metal away from weld

Note 1: Load Ratio: 0.05

Note 2: Material: 2024/17-7; Nominal Thickness: 0.060/0.125 in.

Table XXIV. Axial Fatigue Test Results, Series 12.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	600	30	52,700	
3	600	30	5,100	
4	400	20	127,600	
5	400	20	107,700	
6	300	15	208,300	
7	300	15	393,100	
10	500	25	30,300	
11	500	25	54,300	
12	250	13	461,300	
13	250	13	933,700	

Note 1: Load Ratio: 0.05

Note 2: Material: 2024/347; Nominal Thickness: 0.060/0.010 in.

Table XXV. Axial Fatigue Test Results, Series 13.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	200	10	4,500	
2	150	8	14,400	
3	100	5	60,000	
4	60	3	580,000	
5	75	4	163,900	
6	60	3	924,100	
7	100	5	103,800	
8	150	8	17,500	
9	75	4	174,700	
10	200	10	3,700	

Note 1: Load Ratio: 0.05

Note 2: Material: 6-4 Titanium; Nominal Thickness: 0.010 in.

Table XXVI. Axial Fatigue Test Results, Series 14.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	2200	110	20,200	
2	1700	85	36,600	
3	1200	60	113,100	
4	950	48	316,600	
5	800	40	305,300	
6	1700	85	33,300	
7	1200	60	77,800	
8	2200	110	21,300	
9	950	48	151,900	
10	650	33	1,066,300	Discontinued

Note 1: Load Ratio: 0.05

Note 2: Material: 6-4 Titanium; Nominal Thickness: 0.125 in.

Table XXVII. Axial Fatigue Test Results, Series 15.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	1000	50	99,600	
2	1500	75	32,500	
3	1900	85	7,400	
4	1500	75	23,500	
5	700	35	1,000,000	Discontinued
6	1000	50	170,800	
7	850	43	451,600	
8	850	43	359,300	
9	700	35	1,144,500	Discontinued
10	1900	85	8,300	

Note 1: Load Ratio: 0.05

Note 2: Material: 17-7; Nominal Thickness: 0.060 in.

Table XXVIII. Axial Fatigue Test Results, Series 16.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	1800	90	773,300	Grip failure
2	3000	150	18,400	Grip failure
3	3000	150	512,100	
4	4000	200	70,600	
5	5000	250	30,200	
6	3500	175	258,200	
7	3000	150	1,958,500	
8	4000	200	64,000	
9	6000	300	0	Failed in grip on loading
10	3500	175	199,000	

Note 1: Load Ratio: 0.05

Note 2: Material: 17-7; Nominal Thickness: 0.060/0.375 in.

Table XXIX. Axial Fatigue Test Results, Series 17.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	2600	130	3,000	
2	2000	100	5,200	
3	1500	75	13,800	
4	1000	50	39,200	
5	750	38	102,800	
6	500	25	384,000	
7	350	17	1,000,000	Discontinued
8	350	17	1,000,000	Discontinued
9	750	38	73,600	
10	1500	75	17,300	

Note 1: Load Ratio: 0.05

Note 2: Material: 8-1-1 Titanium; Nominal Thickness: 0.060 in.

Table XXX. Axial Fatigue Test Results, Series 18.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	1400	70	38,500	
2	1900	85	4,500	
3	1100	55	77,600	
4	1400	70	31,300	
5	900	45	129,000	
6	900	45	122,700	
7	750	38	294,600	
8	750	38	208,300	
9	550	28	1,110,000	
10	1900	85	11,200	

Note 1: Load Ratio: 0.05

Note 2: Material: 2024-T3; Nominal Thickness: 0.125 in.

Table XXXI. Axial Fatigue Test Results, Series 19.

Specimen Number	Maximum Load (lb)	Minimum Load (lb)	Cycles to Failure	Remarks
1	2400	120	3,200	
2	1800	90	10,400	
3	1400	70	28,900	
4	1100	55	59,900	
5	800	40	234,300	
6	600	30	494,800	
7	500	25	996,500	
8	500	25	1,000,000	Discontinued
9	1400	70	17,900	
10	800	40	152,200	

Note 1: Load Ratio: 0.05

Note 2: Material: 347 Stainless; Nominal Thickness: 0.060 in.

Appendix V

EXPLOSIVE SPOT WELDING MACHINE DESIGNS

Reduced reproductions of Drawings Number 1310-67-0001 through -0003, Explosive Spot Welding Machine Models Number AGC-1, -2, and -3 are presented herein.

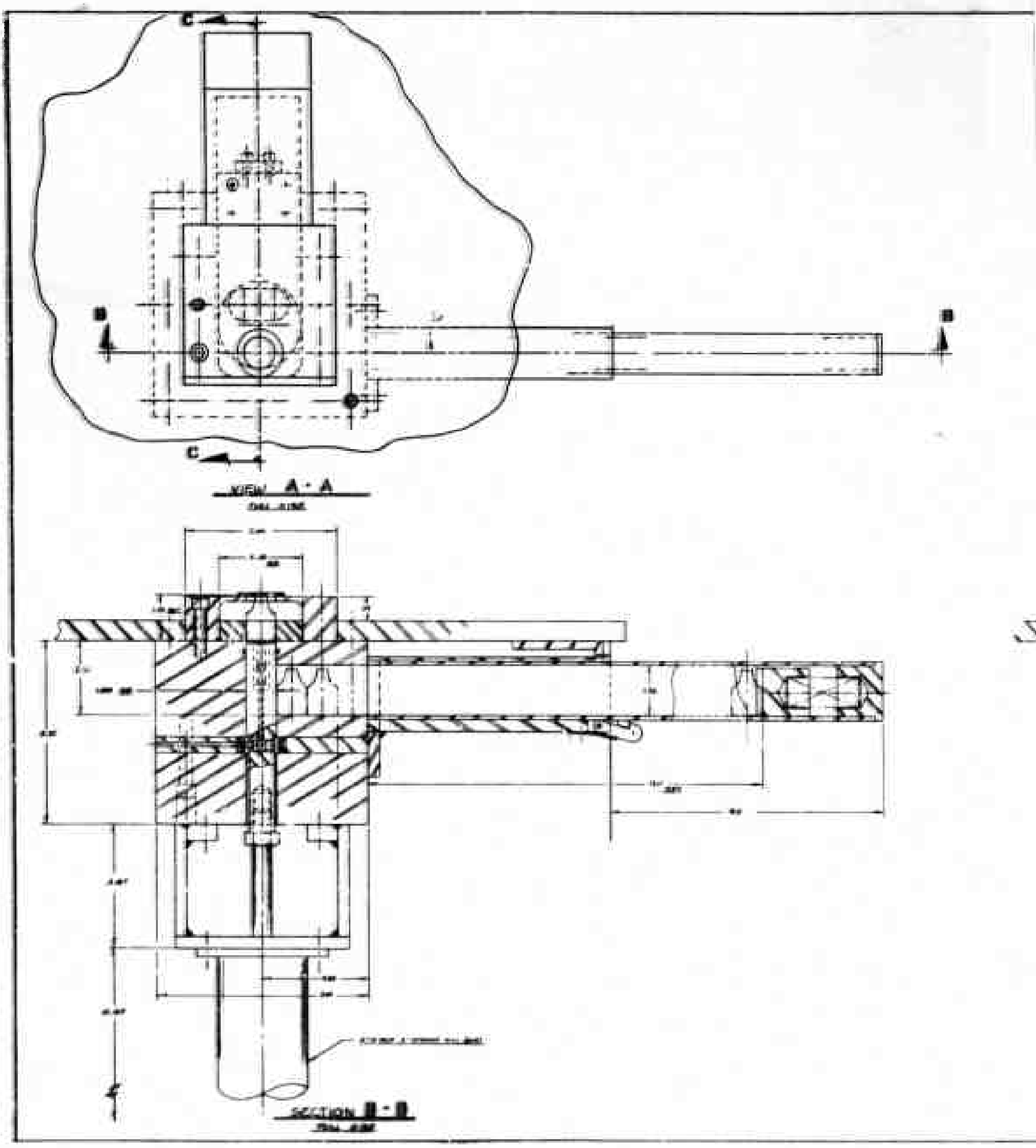
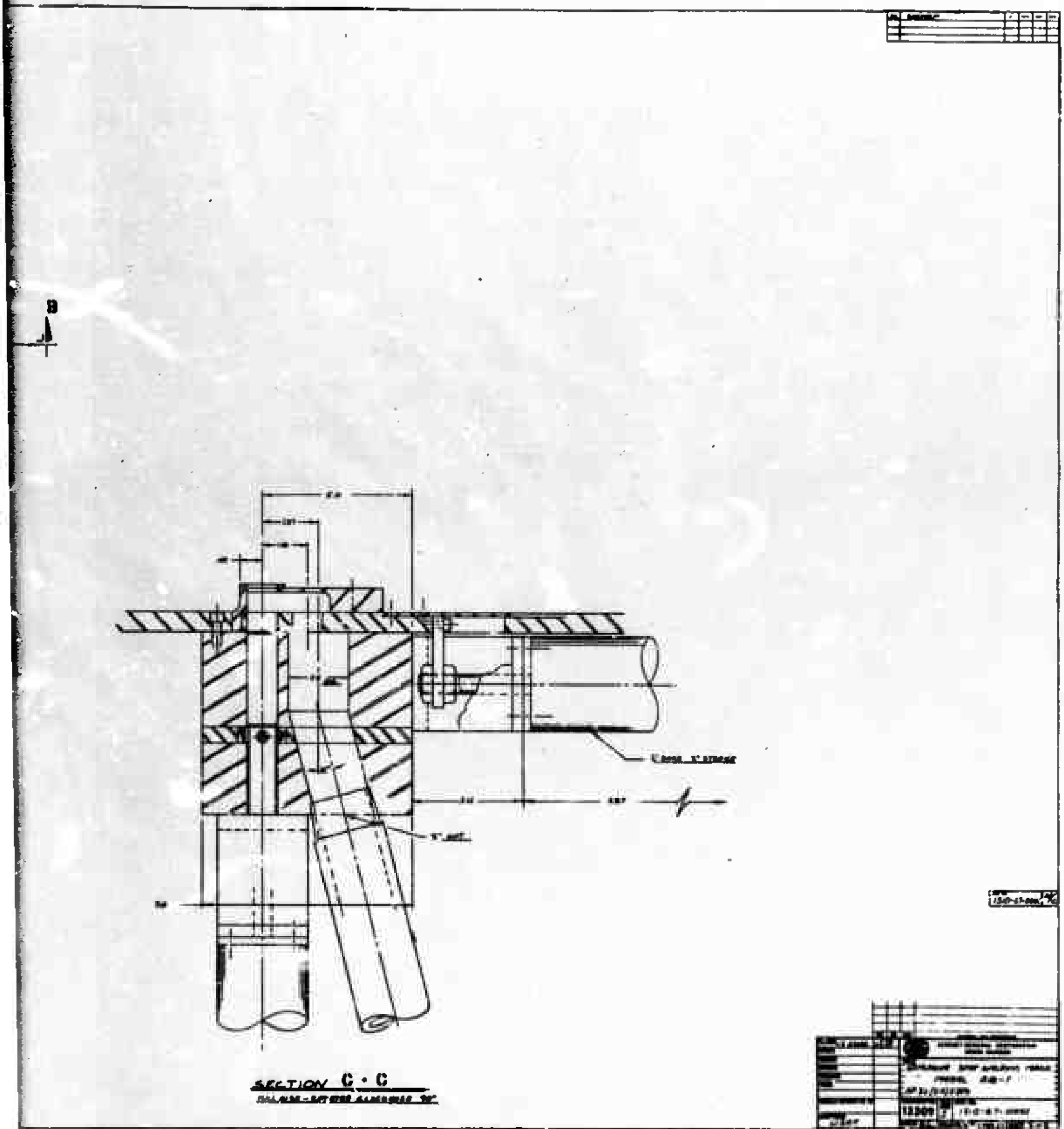


Figure 65. Model AG-1 Explosive Spo

A



xplosive Spot Welding Machine (Sheet 1 of 2).

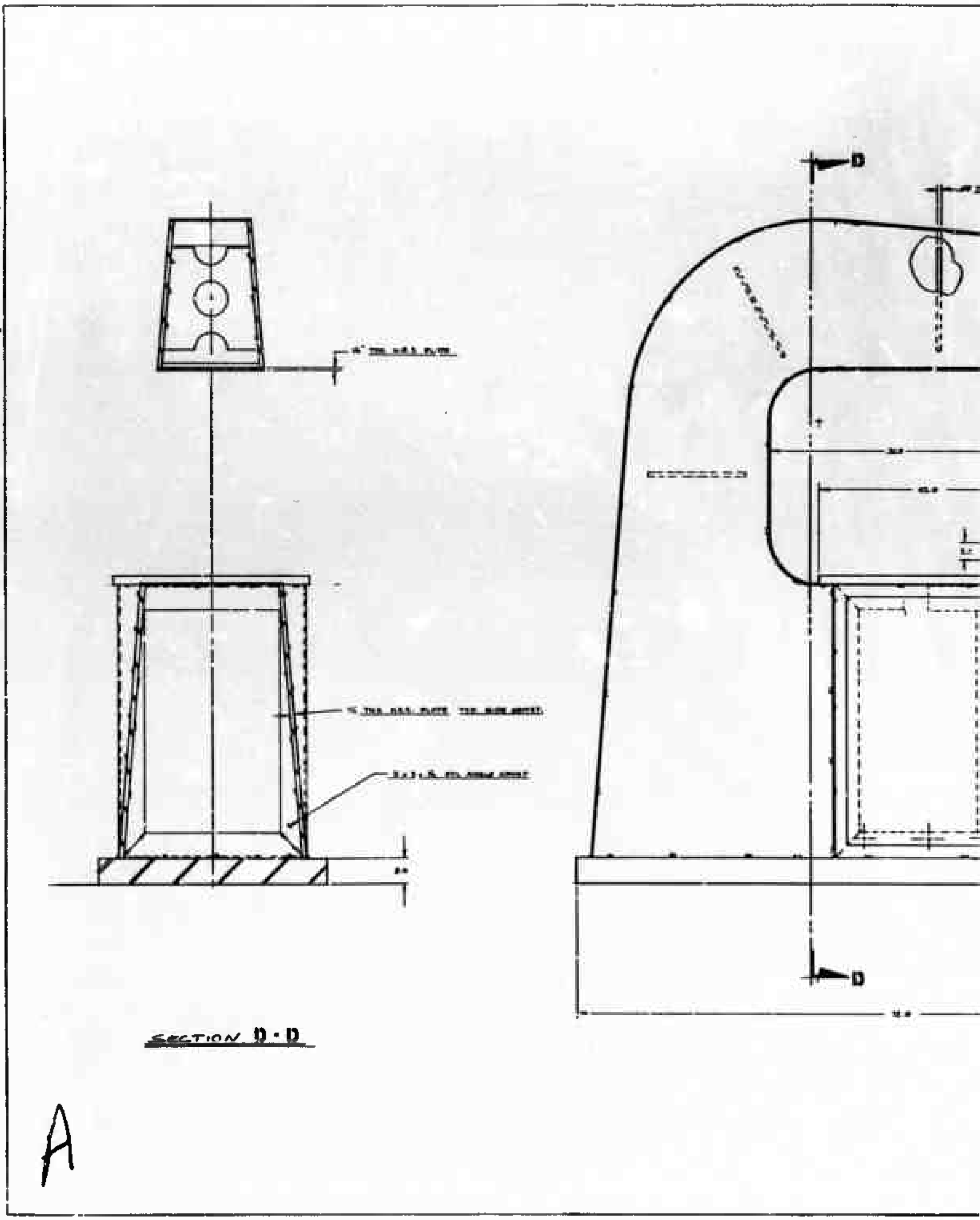
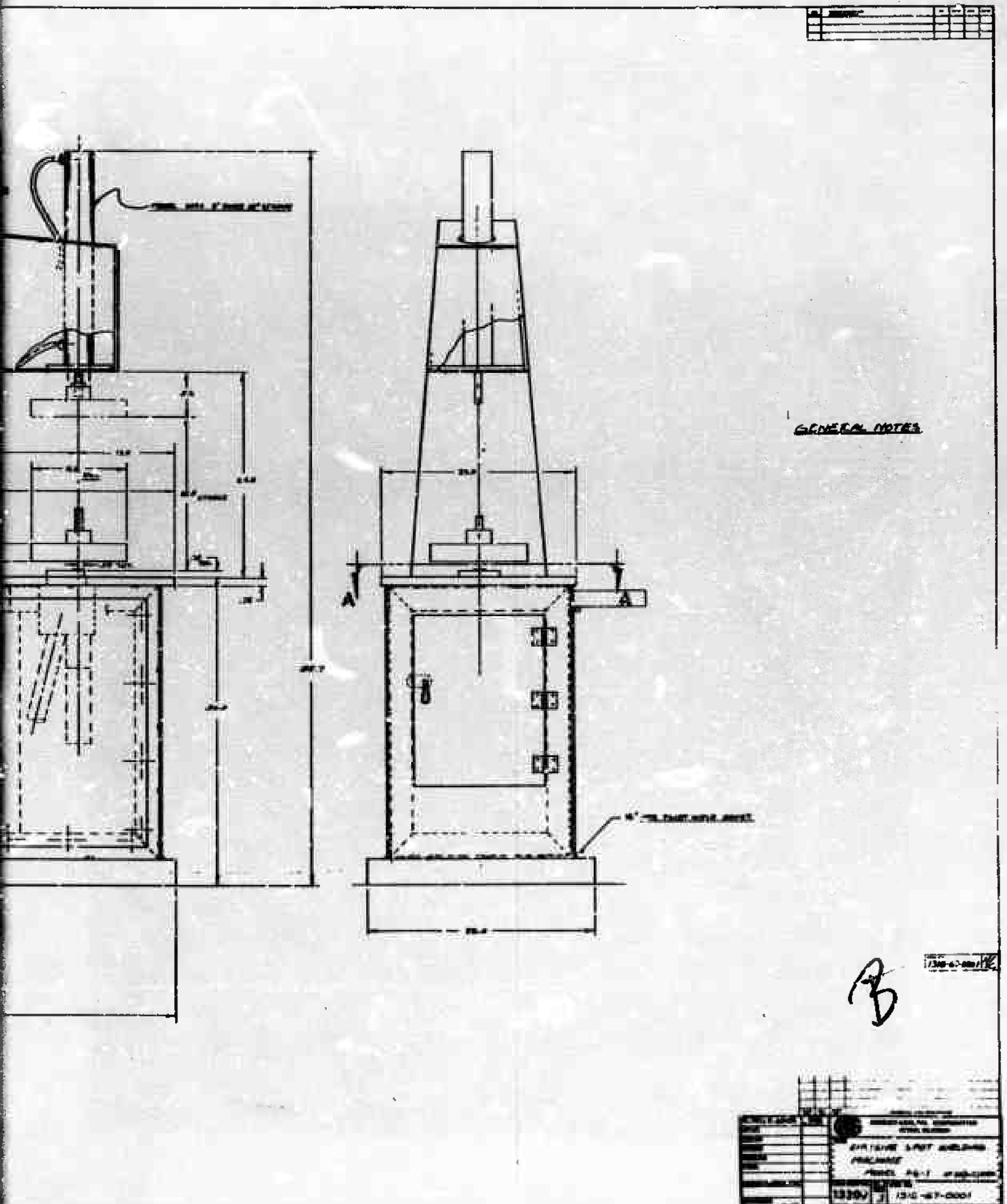


Figure 65. Model AG-1 Exp



osive Spot Welding Machine (Sheet 2 of 2).

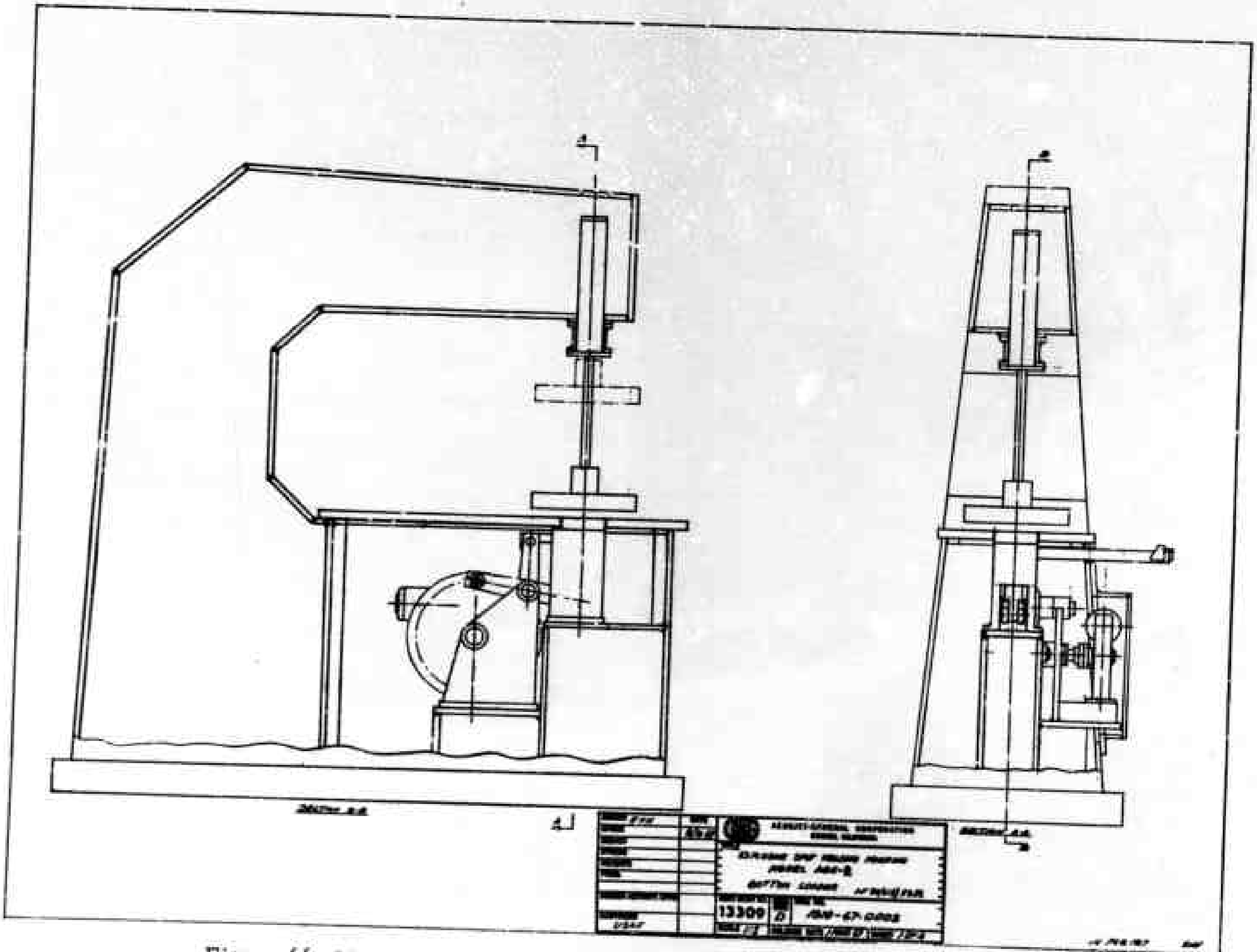


Figure 66. Model AGC-2 Explosive Spot Welding Machine (Sheet 1 of 4).

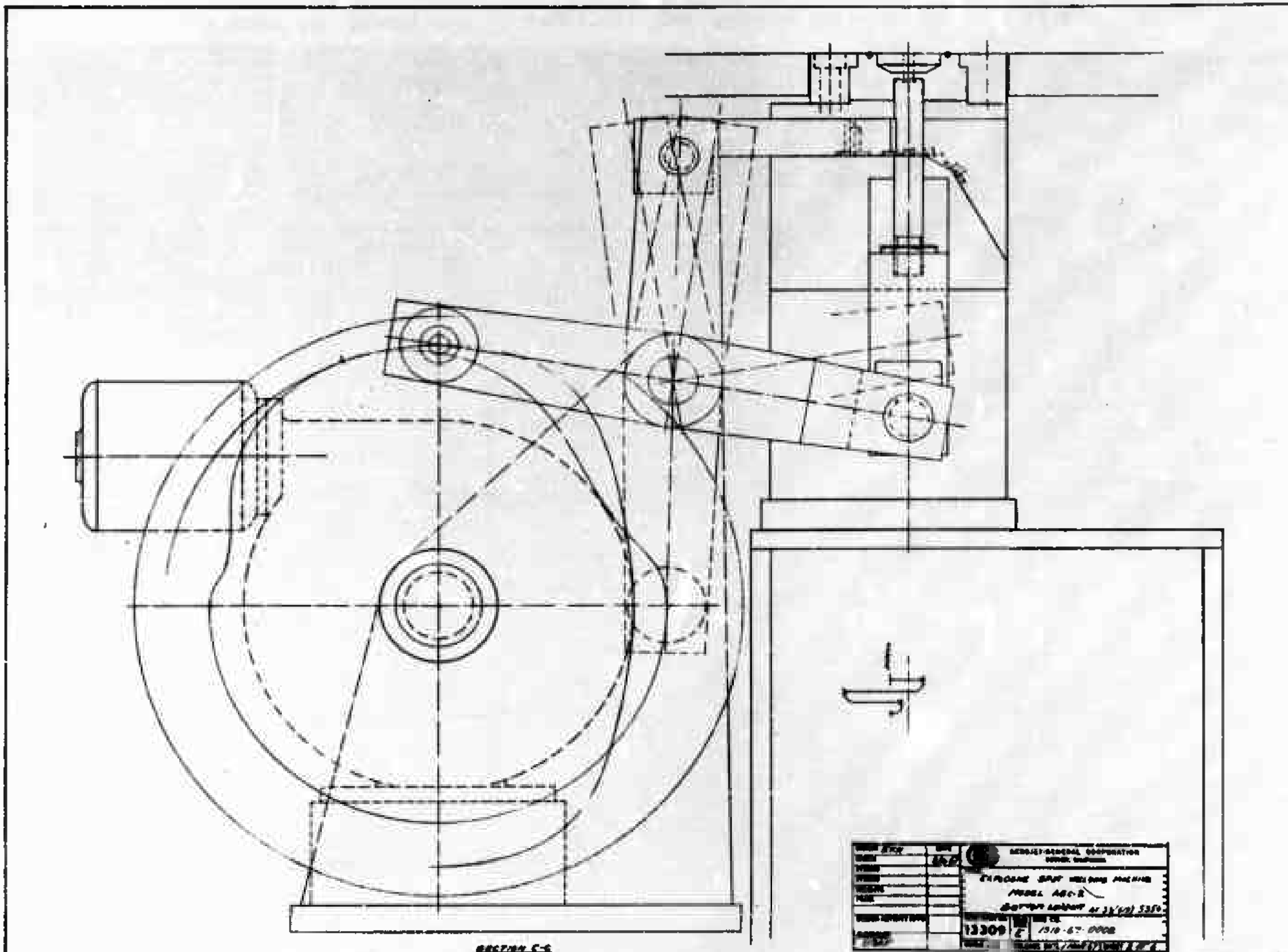


Figure 66. Model AGC-2 Explosive Spot Welding Machine (Sheet 2 of 4).

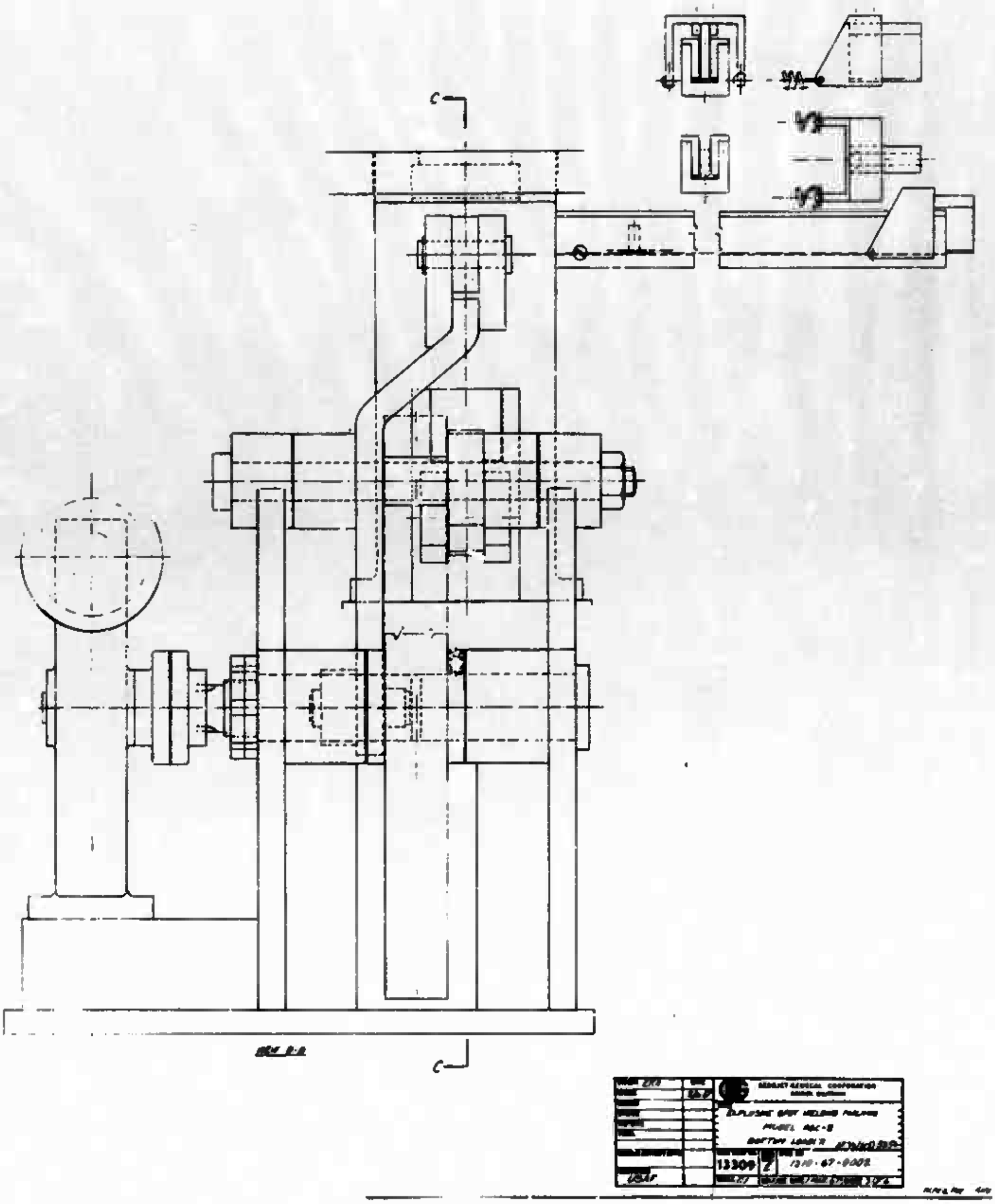


Figure 66. Model AGC-2 Explosive Spot Welding Machine (Sheet 3 of 4).

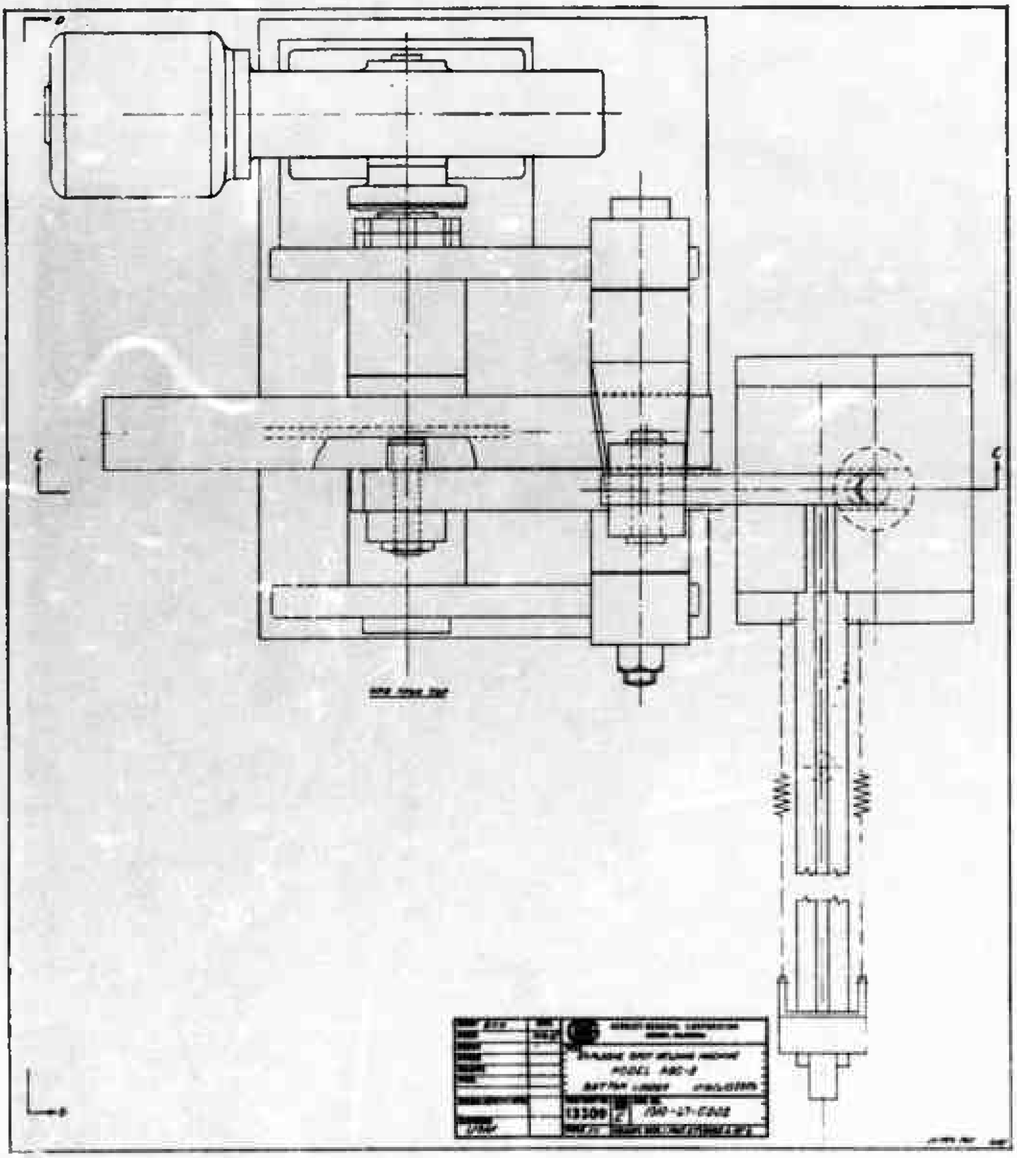


Figure 66. Model AGC-2 Explosive Spot Welding Machine (Sheet 4 of 4).

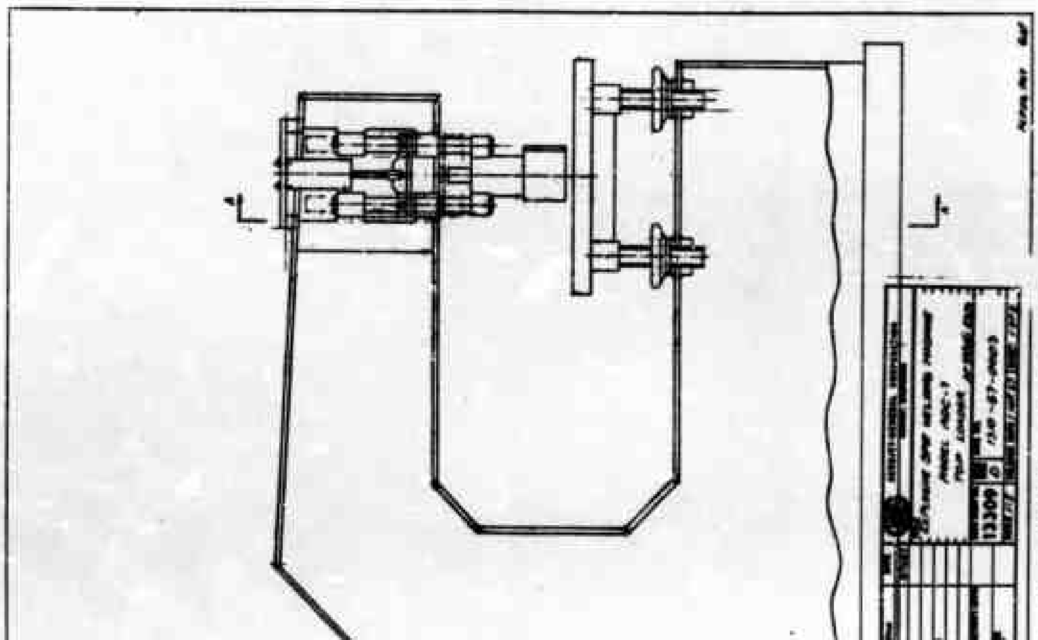


Figure 67. Model AGC-3 Explosive Spot Welding Machine (Sheet 1 of 2).

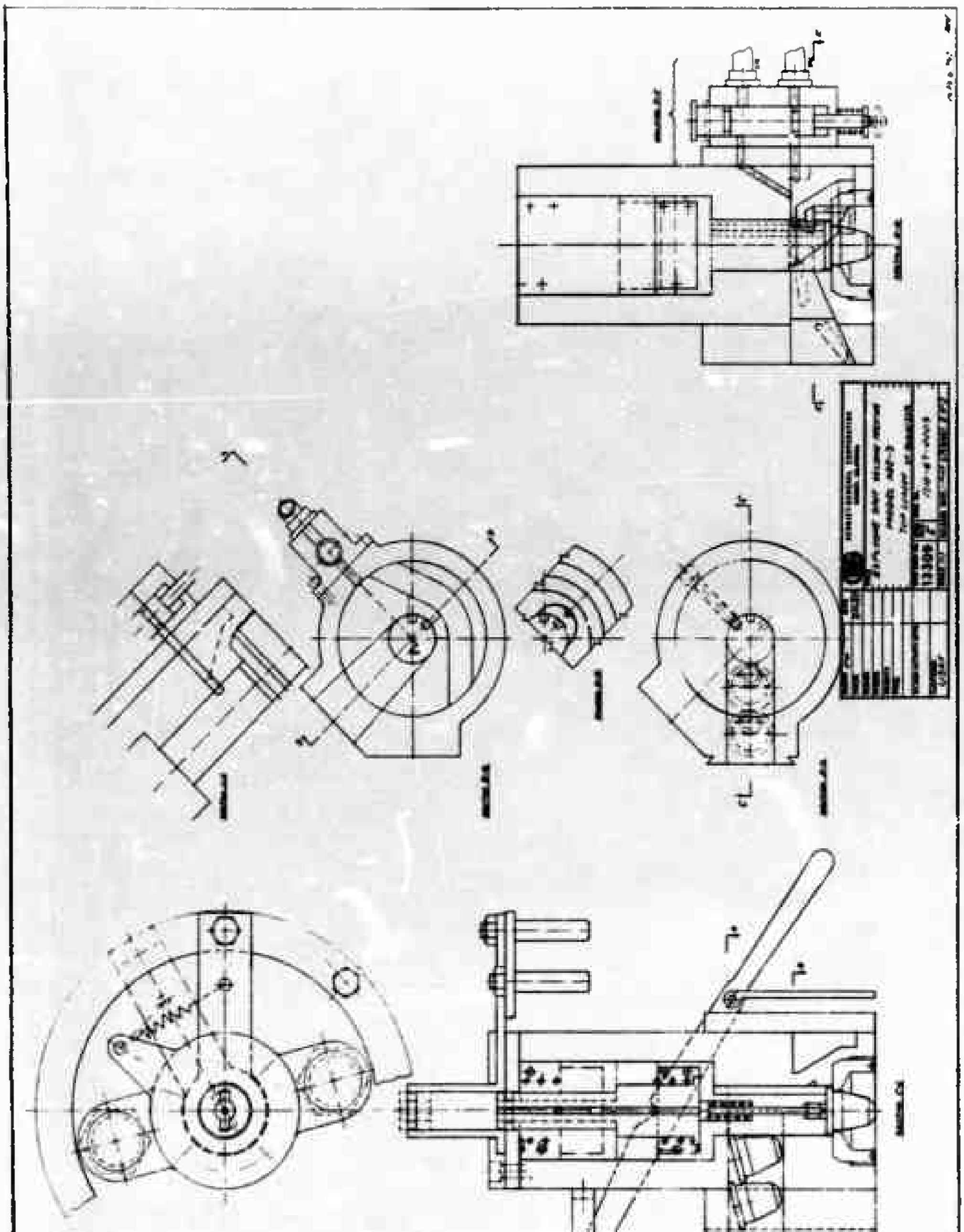


Figure 67. Model AGC-3 Explosive Spot Welding Machine (Sheet 2 of 2).

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1. ORIGINATING ACTIVITY (Corporate author) Aerojet-General Corporation 11711 Woodruff Avenue Downey, California 90241	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP None

3. REPORT TITLE ESTABLISH MANUFACTURING METHODS TO UTILIZE EXPLOSIVES AS A HIGH ENERGY SOURCE TO SPOT WELD METALS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Report for 1 July 1966 Through 31 May 1968

5. AUTHOR(S) (Last name, first name, initial)
LaRocca, Edward W.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1968	168	7

8a. CONTRACT OR GRANT NO. AF 33(615)-5354 b. PROJECT NO. MMP Project No. 9-802 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 1071-01(01)FP 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFML-TR-68-185

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13. ABSTRACT

The formation of spot welds with explosive charges as high energy sources has been investigated, and methods of producing welds have been determined. Materials welded include aluminum alloy 2024-T3, Type 347 stainless steel, 17-7 precipitation hardening steel, titanium alloys 6Al-4V and 8Al-1 Mo-1V, in thicknesses ranging from 0.010-in. foil to 0.500-in. plate. Both similar metal and dissimilar metal welds have been successfully produced.

Explosives for application to the welding process included RDX, PETN, HMX, TNT, Dynamite, Tetryl, Detasheet, and some specially formulated explosives. The most success was obtained with a specially formulated mixture of ammonium perchlorate and nitroguanidine, which was capable of detonating in diameters as small as 0.150 in.

Conventional electrical resistance welds were fabricated for comparison. Tests showed that explosively formed welds were somewhat lower in strength than resistance welds, but the explosive welds in many cases showed superior axial and flexural fatigue lives.

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Explosive welds						
Resistance welds						
Materials						
Aluminum						
Titanium						
Steel						
Explosives						
RDX						
PETN						
HMX						
TNT						
Dynamite						
Tetryl						
Detasheet						
Primacord						
Dimpled standoffs						

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