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MAGNETIC FORMING COIL DESIGN AND DEVELOPMENT

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REPUBLIC AVIATION CORPORATION
MANUFACTURING RESEARCH

FINAL REPORT

PERIOD JUNE 17, 1963 – MARCH 31, 1964

MANUFACTURING ENGINEERING DIVISION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

CONTRACT: NAS 8-5435

NASA FINAL REPORT
March, 1964

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Republic Aviation Corporation
Manufacturing Research Department

RAC 2214

63-69-1

Magnetic forming coils were used successfully to corrective form weld induced contour distortion in NASA produced welded sidewall panels removed from 33 foot diameter Saturn Booster subassemblies.

FOREWORD

This Final Summary Report covers the work performed under Contract NAS 8-5435, Control Number TP3-82458, S/1 (2F), from June 17, 1963 to March 31, 1964. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the National Aeronautics and Space Administration.

This contract with Republic Aviation Corporation at Farmingdale, New York was initiated by the National Aeronautics and Space Administration Manufacturing Engineering Division at the George C. Marshall Space Flight Center, Huntsville, Alabama.

Mr. F. Smith is the Project Engineer, Mr. N. Inman performed the electromagnetic analysis and designed the magnetic coils. Mr. R. Dippel assisted in tool and equipment design and Mr. G. Pfanner was responsible for overall supervision of the program. Messrs. R. Schwinghammer and E. Foster coordinated the program on behalf of the George C. Marshall Space Flight Center.

Approved by: Robert W. Hussa
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Manufacturing Research Engineer

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T. F. Imholz, Chief
Manufacturing Rsch. Engr.

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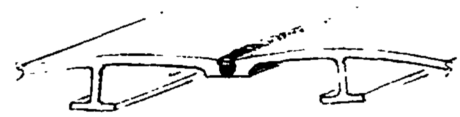
INTRODUCTION

Research in capacitor discharge metal forming is conducted in the Manufacturing Research Laboratories of Republic Aviation Corporation with two capacitor bank installations operable to 39,000 and 155.000 joules respectively. This report covers magnetic forming experiments which were conducted with this equipment under contract NAS 8-5435, "Magnetic Forming Coil Design and Development." Work conducted prior to the contract had established that metal movement in relatively thick high strength aluminum plate (.500" thick 5456-H323 aluminum alloy with 35,000 psi yield) was possible without high magnetic coil mass, and was obtainable within the energy of the capacitor bank installations on hand.

The objective of the contract was to develop coils and techniques for the corrective forming of panels which have distortions such as occur in welding. There are two kinds of distortion which are typically associated with the area about a weld.

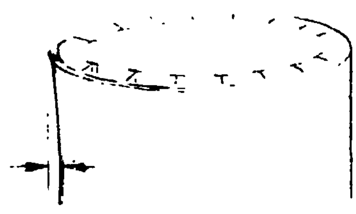
Inward

Circumferentially along the weld line



This type of deformation is locally about the weld region. The greatest deviation is at the weld, but continues to include the first T on either side. Such T's are thereby not in correct position or angulation for assembly of splash baffles.

Longitudinal bow of the weld line



This type of contraction occurs in conjunction with the above weld area distortion.

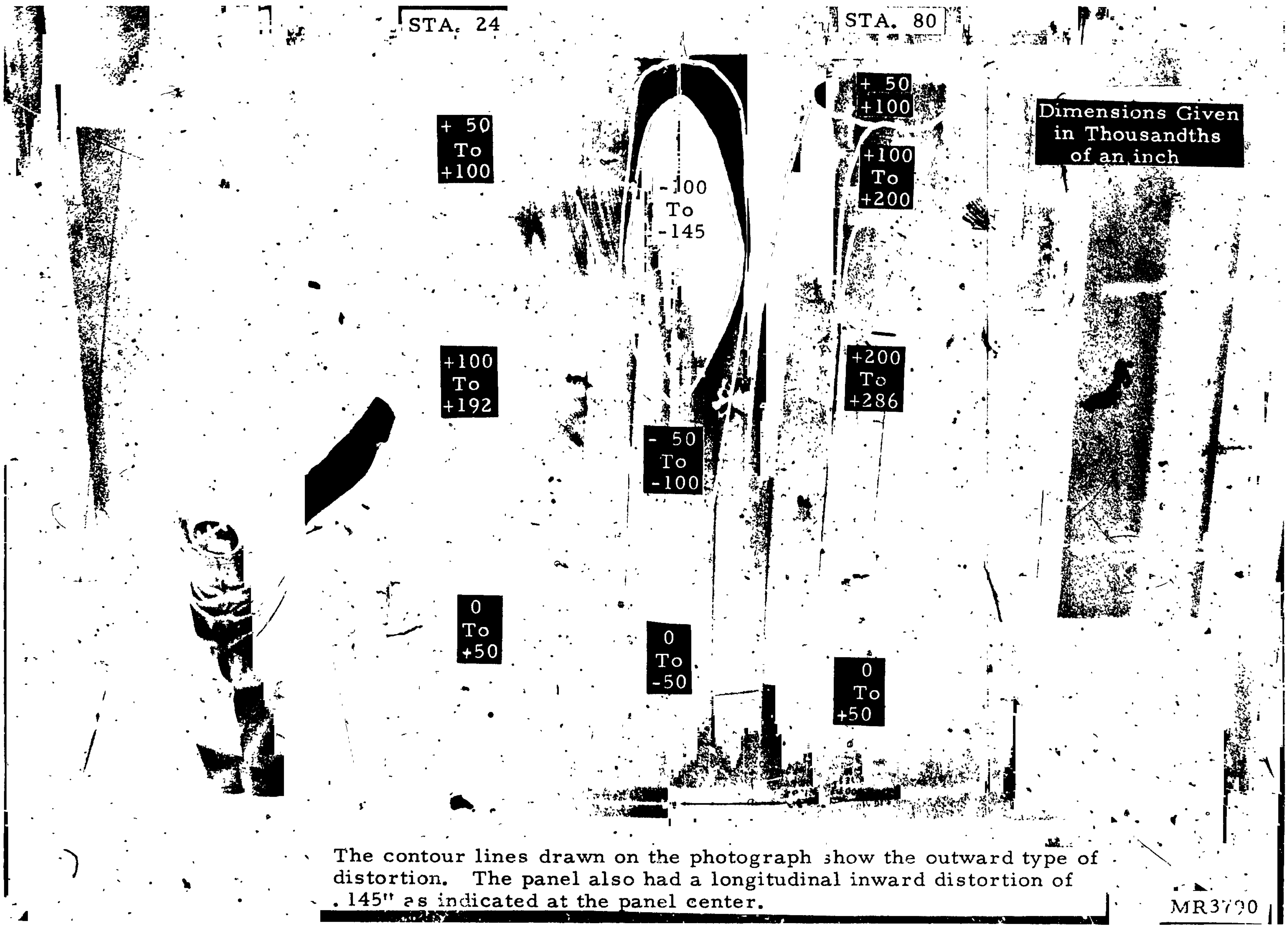
Outward

This distortion begins at a distance at the tee stiffeners adjacent to the welds and carries for a distance of 4 to 6 stiffeners (2 to 3 feet). The outward type of distortion is not as common to all panels as is the inward distortion but also appears associated with the weld

Much of the experimental work was conducted with two integrally stiffened panels received from MSFC. A photograph of panel 1 is shown in Figure 1. The panels are identified in the report as Panel 1 and Panel 2 in reference to the order in which they were received. Work actually began with Panel 2, a slightly smaller panel than #1. Panel 2 had both of the inward distortion effects at the weld to a rather serious degree (See Figure 9), whereas Panel 1 was inwardly distorted only in the longitudinal direction at the weld. However, Panel 1 had a considerable amount of the less usual outward distortion centered 2 feet away from the weld, in both longitudinal and circumferential directions.

During the first seven months of the nine month period of the contract, monthly progress reports were issued which contain records of the experiments performed. The work of the final two month period (February and March 1964) is included in this final report. The work reported in the first seven progress reports is summarized, but not repeated in this final report. For convenient reference, an index by work subject is included.

The coils, coil holders, damping and attaching device employed during the program were shipped to MSFC. Two sets of transmission lines (not used) without terminations on one end to permit adaptation to a MSFC bank were also shipped. A shipment list describing these items is included in the report.



PANEL 1 MOUNTED IN VERTICAL FIXTURE PRIOR TO CORRECTIVE FORMING

FIGURE 1

RESULTS AND CONCLUSIONS

1. The practicality of using magnetic coils, which are simply attached to workpieces by vacuum or mechanical fasteners, for corrective forming has been demonstrated. The process has the advantage of being operable in relatively inaccessible regions. Another major advantage of the process is that contact between the forming coil and workpiece is obtained by the inertia effect of the high energy forming impulse rather than by structure. By use of damping device attachment of the coil by means such as vacuum or fasteners, the forming forces are transmitted to the workpiece after forming begins and such forces are of much lower amplitude and, consequently, of longer duration. In summary, the completed work demonstrates in a general way that the magnetic forming technique can be used to reform relatively heavy gage aluminum components "in the field".

2. With regard to the specific problem of contour correction discussed in this report, the process can be conducted safely and reliably. Deformation calibrations can be established for particular workpiece and energy conditions for any particular coil and capacitor bank.

3. The tooling manufactured during the program adequately demonstrates the practicality of the process and can be effectively used. For actual use, improvements such as reduced coil heatup and simplified coil positioning should be made.

4. Corrective forming of longitudinal and cylindrical inward distortion of the weld region sections was accomplished using 4 inch diameter magnetic coils operating at energy levels between 6000 and 12,000 joules, without visible damage to either workpiece or coil. Longitudinal error of .230" and cylindrical error of .205" were brought within a $\pm$ .030" tolerance.

5. Corrective forming of moderately severe distortion (from .050" to .100" beyond engineering drawing tolerance) outside the weld zone where the skin thickness is .200" can be accomplished using 4 inch and 12 inch diameter magnetic coils operating at 3000 to 6000 joule discharge levels, without deleterious effect upon the workpiece or coil.

Where more excessive distortion exists (.100" to .250" beyond engineering drawing tolerance) and higher energy discharges (above 6000 joules) are required, correction is only partially successful, because of concave distortion produced in the machined flat surfaces (away from the coil face).

6. Damping of the 4" coil was effectively achieved with an air cylinder so that the restraining force at discharge levels up to 12,000 joules (the highest energy used) did not distort the tee stiffeners to which the coil was attached.

7. Damping of the 12" coil was effectively achieved with a loose fitting piston.

8. The vacuum attachment with 8 vacuum cups was adequate to adhere the 12" coil to the smooth outer panel surface at discharge levels up to 8000 joules. Vacuum attachment of the 4" coil with 2 vacuum cups remained secure up to 8000 joules. The discharge level whic' vacuum adhesion will withstand is dependent upon the rigidity (or lack of overall movement) of the workpiece.

9. The work output (deformation) per discharge energy was essentially equal for the 240 uf and 960 uf capacitor banks, although frequency differed by a factor of two. The portable MSFC bank produced deformation several times greater with the same forming coils.

10. A 4 inch diameter, 10 turn coil has the capability of accepting 17,000 joules on a single shot basis without damage.

11. A 12 inch diameter, 40 turn coil has the capability of accepting 48,000 joules on a single shot basis without damage.

12. The hardness of the encapsulating epoxy should be selected to be a compromise to have adequate resistance to softening due to coil heating yet to be resilient enough to avoid failure due to the discharge impulse.

13. Coil heating becomes significant at high coil output, and coil cooling appears advisable to obtain greater result in less time and avoid softening of the encapsulating epoxy.

14. The combination of the u[illegible] f epoxy impregnated glass [illegible]oth tape achieved satisfactory turn to [illegible]rn bonding of the coil in that [illegible]ilures do not occur between turns at less than twice the discharge energ[illegible] evels which can be considered in avoiding over localized forming.

SUMMARY OF PREVIOUS WORK (June 1963 - January 1964)

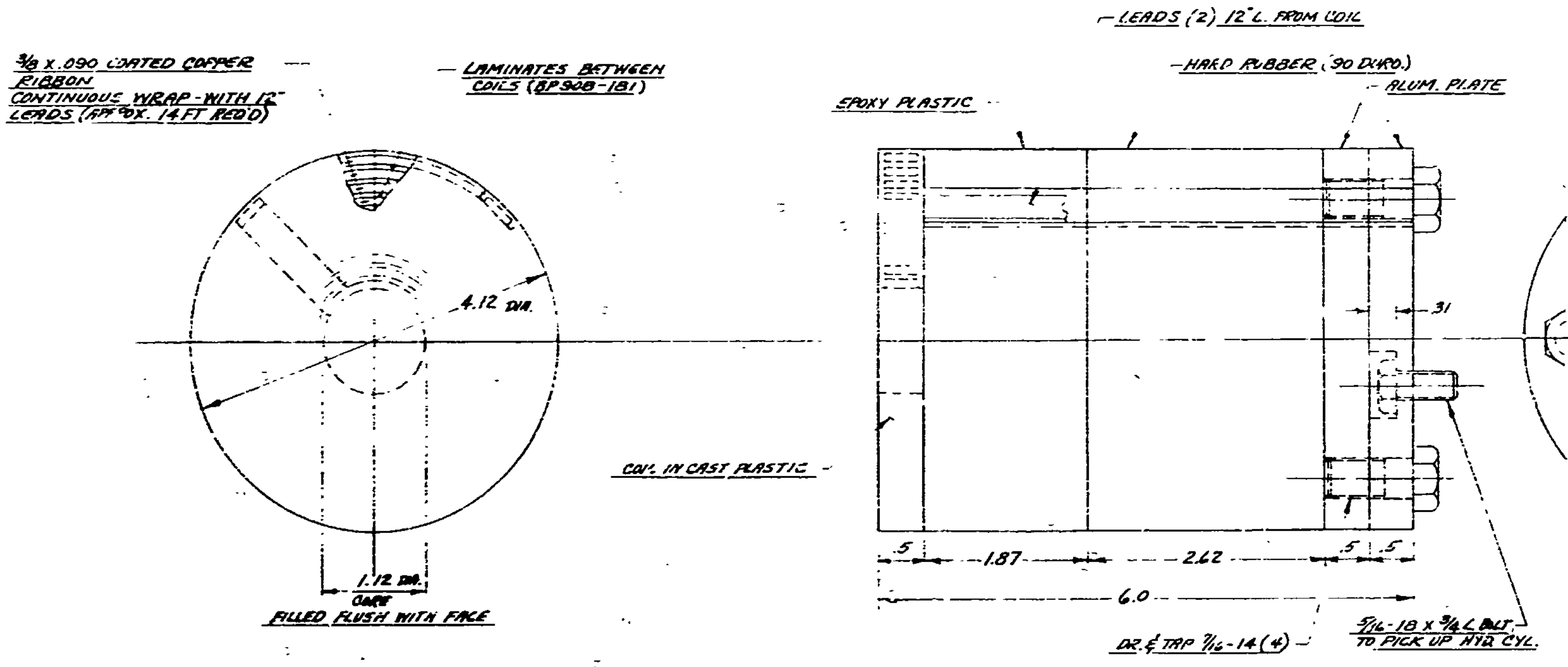
The work conducted during the prior period of the contract, June 17, 1963 to January 31, 1964 has been reported in Progress Reports 1 through 7. This previous work is summarized in less detail below under several work headings, and references are made to supporting data in the Progress Reports.

1. Development of forming coils and coil holders

There were requirements for two types of forming coils to be designed and made for the experimental magnetic forming work. One had to be small enough to enter within the 4.18 inch opening made by the machined tee stiffeners on the inner panel surface. A second coil, specified to be 12 inches in diameter, was to be used on the outer panel surface. For manufacturing simplicity and strength, the coils made were circular, flat and rigid, and comprised of .090" x .38" triple formvar insulated rectangular wire. The turns were insulated by interleaving epoxy impregnated glass cloth, which was also used to encase the completely wound coil. The glass cloth used was chosen after a series of lap shear tests had been made to determine the most efficacious bonding material available. Report #2 describes the tests and results. The small coil included 10 turns, and was approximately 4 inches in diameter, while the 12 inch diameter coil included 40 turns. Figure 2 contains drawing of both coils and describes the manner of manufacture.

The 4 inch diameter coils were used singly and in pairs on either side of a tee stiffener. Since these coils were to be used on the inner panel surface between the tee stiffeners, they had to be supported beyond the height of the stiffeners. Holders were designed to make attachment to the stiffeners while guiding the coil along the machined bays between the tee stiffeners, and to contain the coil during its recoil movement following discharge. The coils were encapsulated in epoxy plastic which was molded to a piston-like shape. They were attached, in turn, to one inch diameter air cylinders, operating at 90 psi, which provided damping action to recoil, and returned the coil face to the workpiece. The coil and air cylinder were supported within a micarta cylinder, which fastened to the tee stiffeners. Figures 3, 4 and 5 illustrate the single and tandem coils and holders.

The 12 inch diameter coil was intended for forming against the outer surface of the panel, which offers no means of support for the coil or holder (such as the tee stiffeners of the inside surface). This coil was also encapsulated in epoxy plastic to make a piston-like shape, and was loosely placed in a closed-end cylinder, containing captive air. Since there was little clearance between the walls of the cylinder and the sides of the coil body, the movement of the coil on recoil built up air pressure, stopping the coil motion, and actually returning the coil face to the workpiece. The cylinder holder was attached to slides, providing coil location on the panel surface, and the whole assembly was fastened to eight vacuum cups, which secured it to the smooth panel surface. See photograph in Figure 6. It was possible to move the coil in the cylinder five feet longitudinally along the panel surface without relocating the vacuum cups. Discharges up to 8000 joules were possible without disengagement of the vacuum cups. A drawing of the vacuum attachment are shown in Figure 7.



4" DIA. 10 TURN COIL

MANUFACTURING NOTE:
COIL LAMINATED AS FOLLOWS.
1ST 3 TURNS - 3 LAMINATES
NEXT 4 TURNS - 1 LAMINATE
LAST 3 TURNS - 3 LAMINATES

Manufacturing P
4" Diameter 10 T

1. Wrap wire and BP908-181 epoxy im
equivalent, for 10 turns.

2. Apply Scotchweld EC1386 Adhesive (
both coil faces, filling voids.

3. Oven cure for 1 hour at 350°F, usin
coil surface.

4. Wrap coil completely using BP908-1
nated glass cloth.

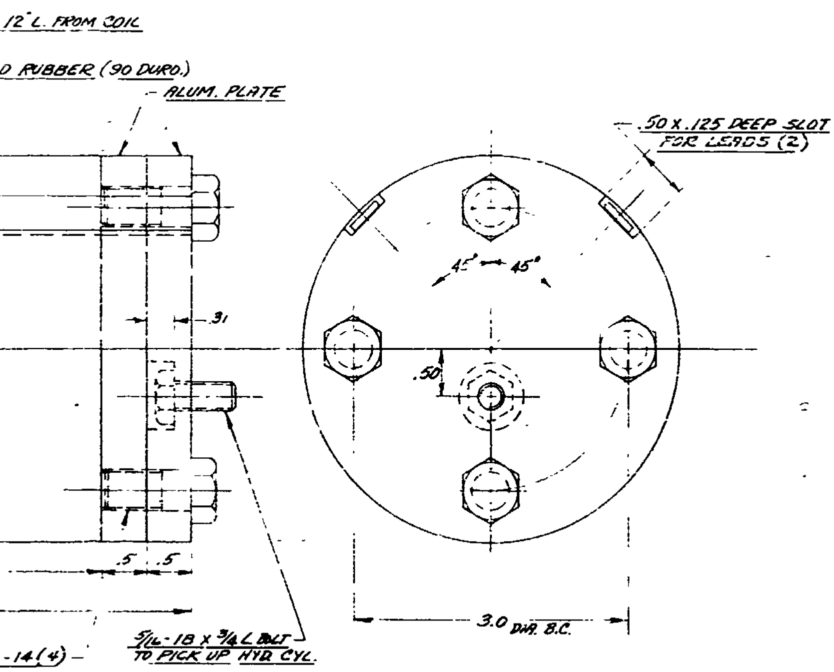
5. Oven cure for 90 minutes at 325°F.

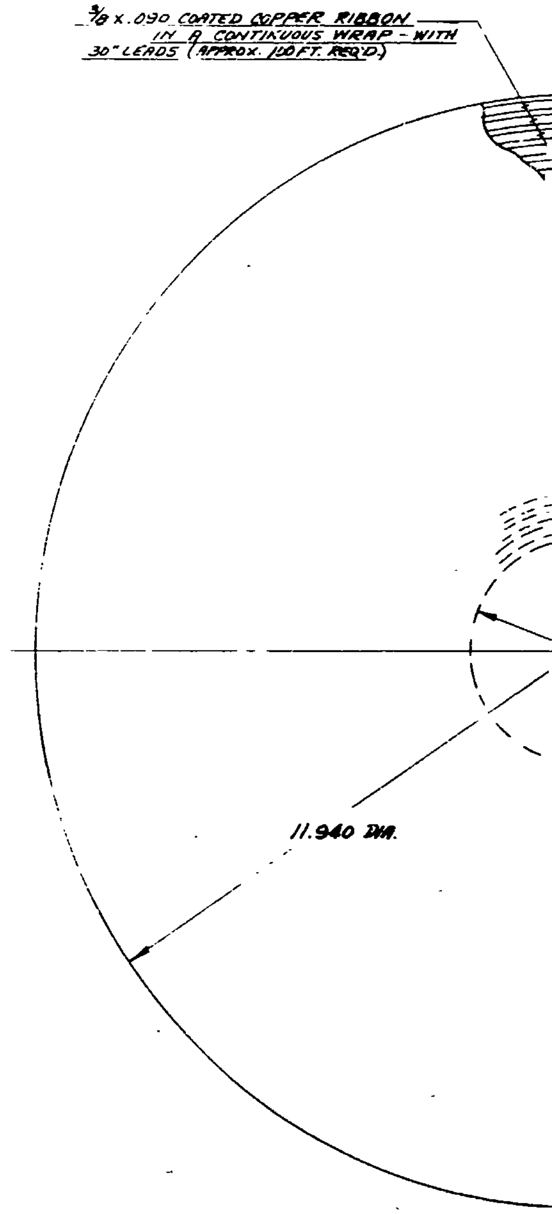
6. Encapsulate coil using epoxy resin*

*51% (by weight)	Epirez 5091 (J
43.8%	LP3 Thiokol
5.2%	Diethylenetriam

7. Cement 90 Duro. Rubber block to co
resin adhesive (as in #6 above) and

8. Cement aluminum plate to rubber bl
(as in #6 above) and room temperatu





Manufacturing Procedure
4" Diameter 10 Turn Coil

1. Wrap wire and BP908-181 epoxy impregnated glass cloth strip, or equivalent, for 10 turns.

2. Apply Scotchweld EC1386 Adhesive (Minnesota Mining & Mfg.) to both coil faces, filling voids.

3. Oven cure for 1 hour at 350°F, using pressure plates against each coil surface.

4. Wrap coil completely using BP908-181 (or equivalent) epoxy impregnated glass cloth.

5. Oven cure for 90 minutes at 325°F.

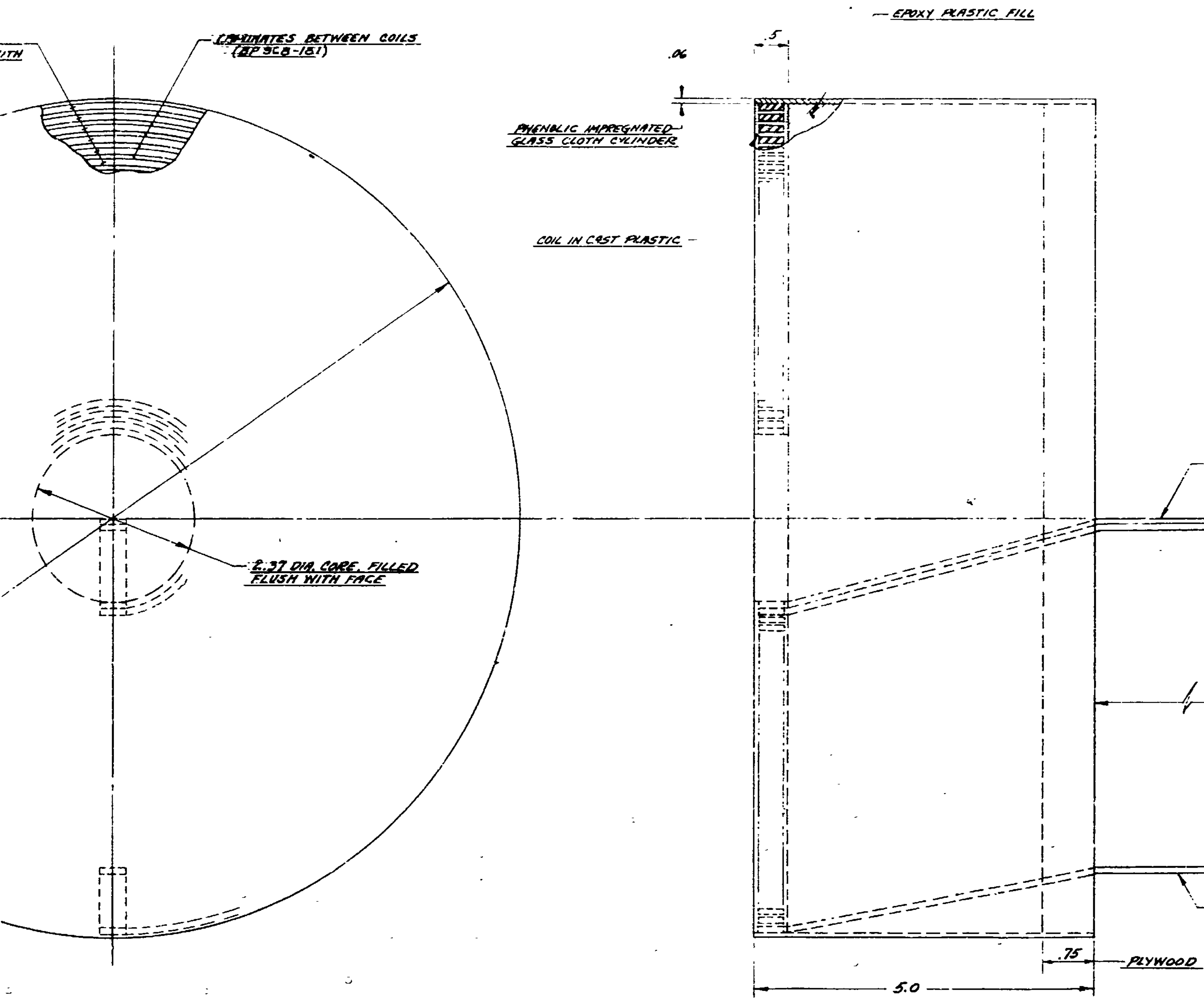
6. Encapsulate coil using epoxy resin*, and room temperature cure

   *51% (by weight) Epirez 5091 (Jones - Dabney Company)
   43.8% LP3 (Thiokol Chemical)
   5.2% Diethylenetriamine

7. Cement 90 Duro. Rubber block to cured epoxy face, using epoxy resin adhesive (as in #6 above) and room temperature cure.

8. Cement aluminum plate to rubber block, using epoxy resin adhesive (as in #6 above) and room temperature cure.

FIGURE



12" DIA. 40 TURN COIL

MANUFACTURING NOTE:
COIL LAMINATED AS FOLLOWS
1ST 3 TURNS - 3 LAMINATES
2ND 3 TURNS - 2 "
NEXT 28 TURNS - 1 "
35,36,37 TURNS - 2 "
LAST 3 TURNS - 3 LAMINATES

E 2

Manufacturing Procedure
12" Diameter 40 Turn Coil

1. Wrap wire and BP908-181 epoxy impregnated glass cloth strip, or equivalent, for 40 turns.

2. Oven cure for 90 minutes at 325°F, using pressure plates against each coil surface.

3. Apply Scotchweld EC1386 Adhesive (Minnesota Mining & Mfg.) to both coil faces, filling voids.

4. Oven cure for 1 hour at 350°F, using pressure plates against each coil surface.

5. Wrap coil completely using BP908-181 (or equivalent) epoxy impregnated class cloth, applying (3) laminates on each coil face, and (10) laminates (strips) around outer periphery, and enclosing the entire coil with (1) covering layer.

6. Oven cure for 90 minutes at 325°F, using pressure plates against each coil surface.

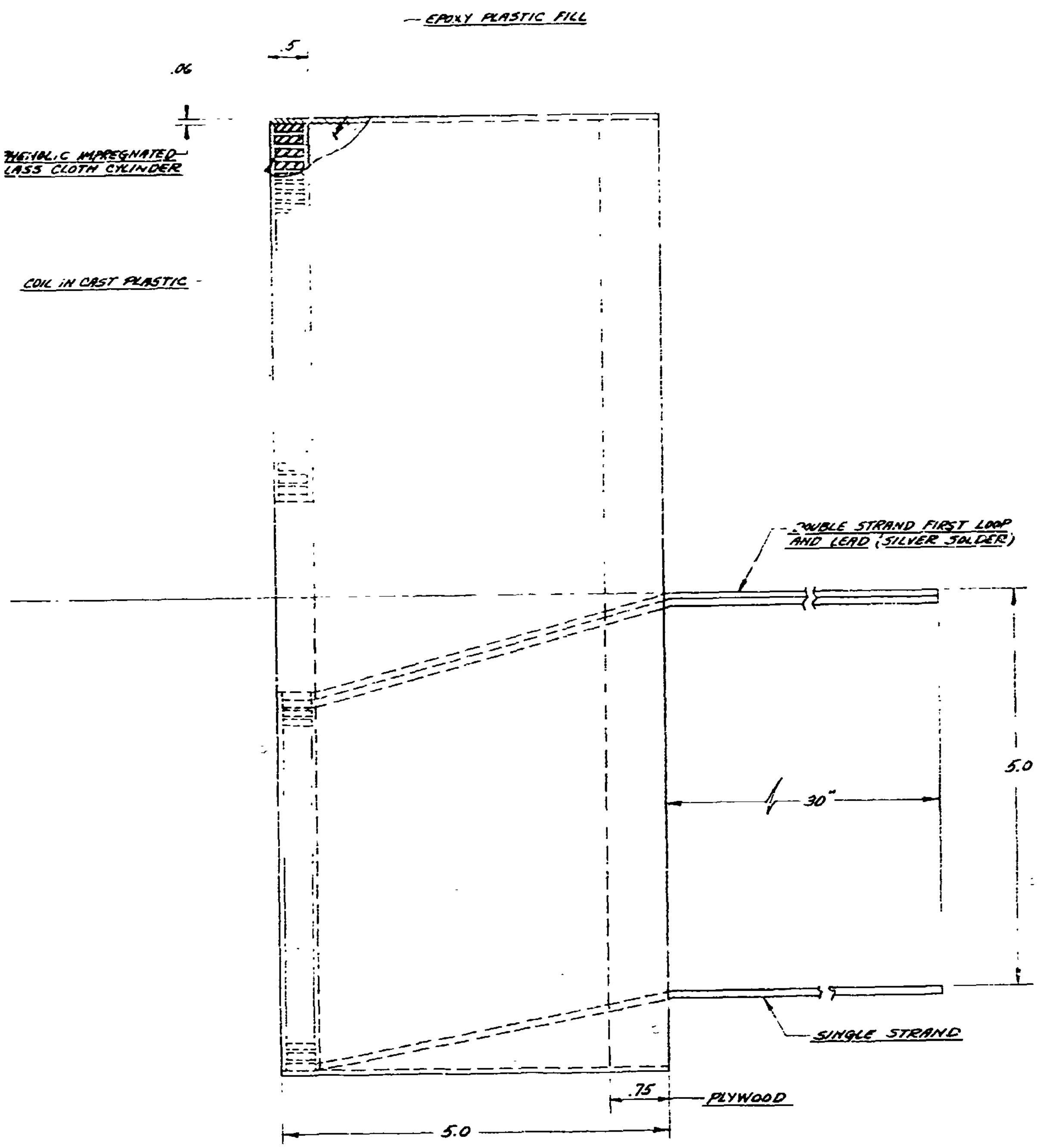
7. Locate coil within phenolic impregnated glass-cloth cylinder (see (10) below for manufacturing instructions) and encapsulate coil using epoxy resin*, and room temperature cure.

*51 %	(by weight)	Epirox 5091 (Jones - Dabney Co.)
43.8%		LP3 (Thiokol Chemical)
5.2%		Diethylenetriamine

8. Cement plywood backing to epoxy face, using epoxy resin adhesive (as in #7 above) and room temperature cure.

9. Pot ply[…]
using e[…]

10. Manufa[…]
a)
b)
c)
d)



URN COIL

'S FOLLOWS
LAMINATES

LAMINATES

Manufacturing Procedure
12" Diameter 40 Turn Coil

1. Wrap wire and BP908-181 epoxy impregnated glass cloth strip, or equivalent, for 40 turns.

2. Oven cure for 90 minutes at 325°F, using pressure plates against each coil surface.

3. Apply Scotchweld EC1386 Adhesive (Minnesota Mining & Mfg.) to both coil faces, filling voids.

4. Oven cure for 1 hour at 350°F, using pressure plates against each coil surface.

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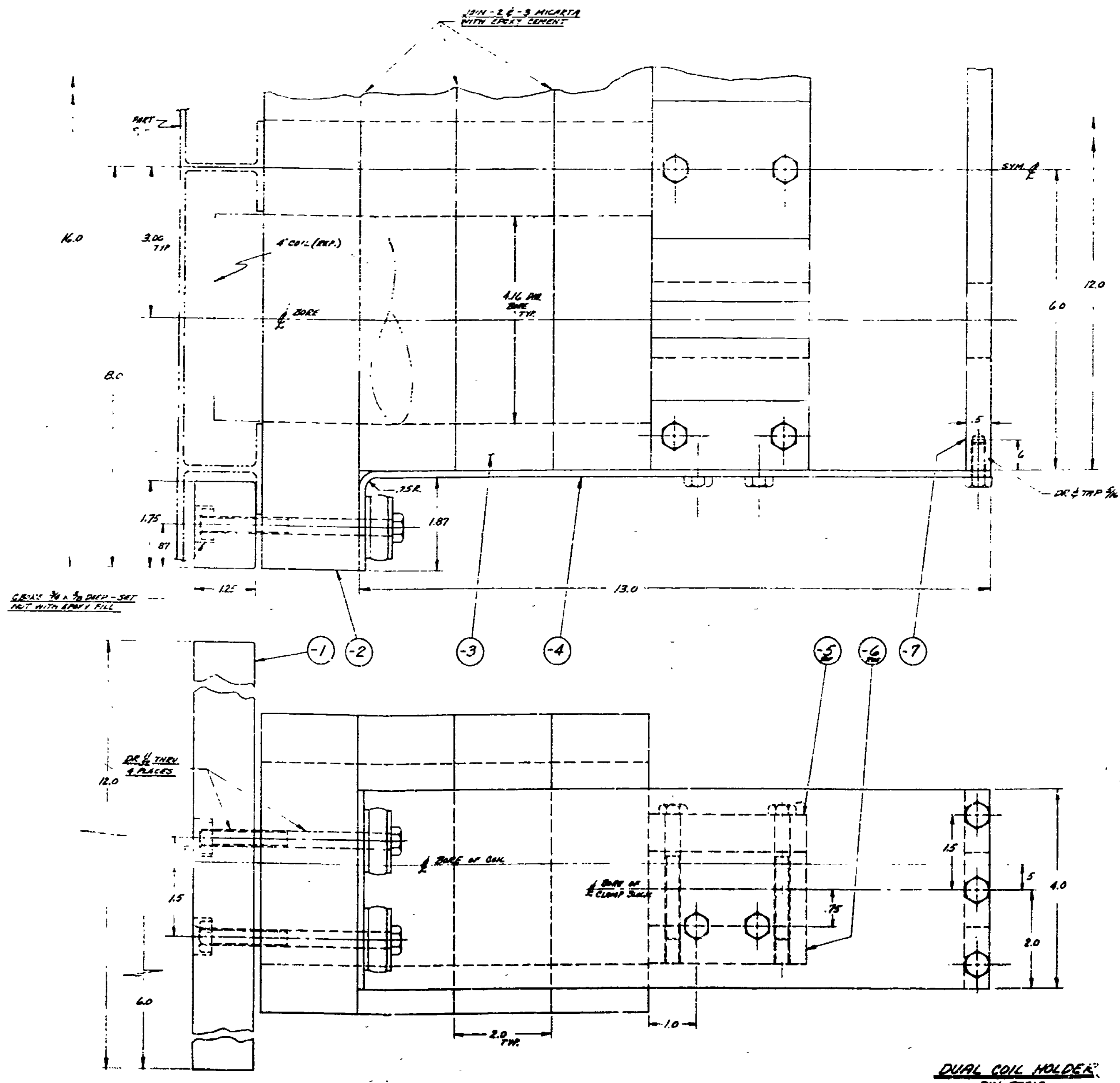
*51 % (by weight)	Epirex 5091 (Jones - Dabney Co.)
43.8%	LP3 (Thiokol Chemical)
5.2%	Diethylenetriamine

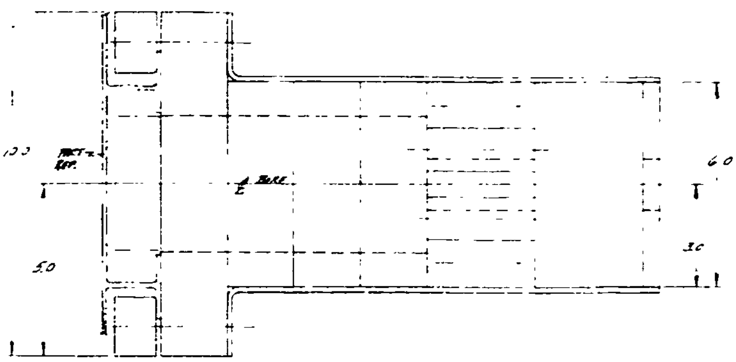
8. Cement plywood backing to epoxy face, using epoxy resin adhesive (as in #7 above) and room temperature cure.

9. Pot plywood backing to phenolic impregnated glass cloth cylinder using epoxy resin adhesive and room temperature cure.

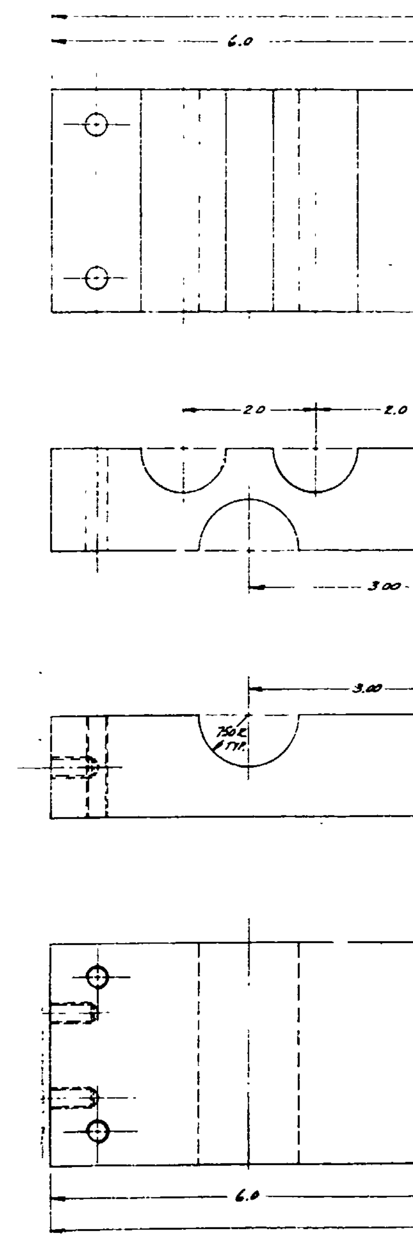
10. Manufacture phenolic impregnated glass cloth cylinder as follows:
    a) wrap tightly 6 turns of Sunform F1760 (Sun Chemical) or equivalent phenolic impregnated glass cloth 6" wide around 11.70" diameter mandrill.
    b) cover wrap glass cloth with Mylar adhesive tape
    c) oven cure for 3 hours at 350°F
    d) remove from mandrill and peel outer wrap, including Mylar tape covering.

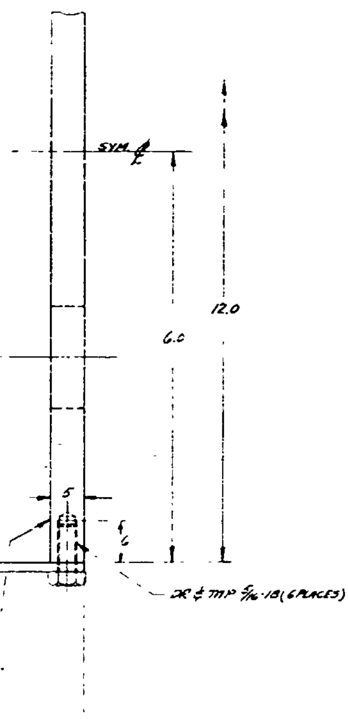


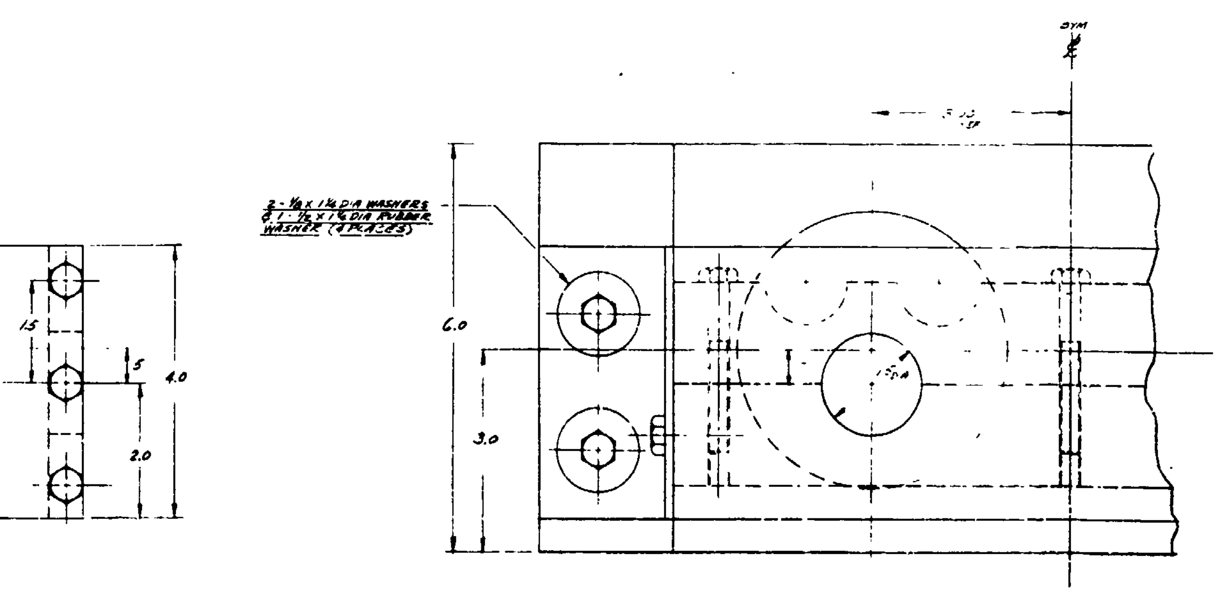
DUAL COIL HOLDER
FULL SCALE



SINGLE 4" DIA COIL HOLDER
IDENTICAL TO DUAL HOLDER
EXCEPT AS NOTED HERE
1/2" SCALE







DUAL COIL HOLDER
FULL SCALE

F

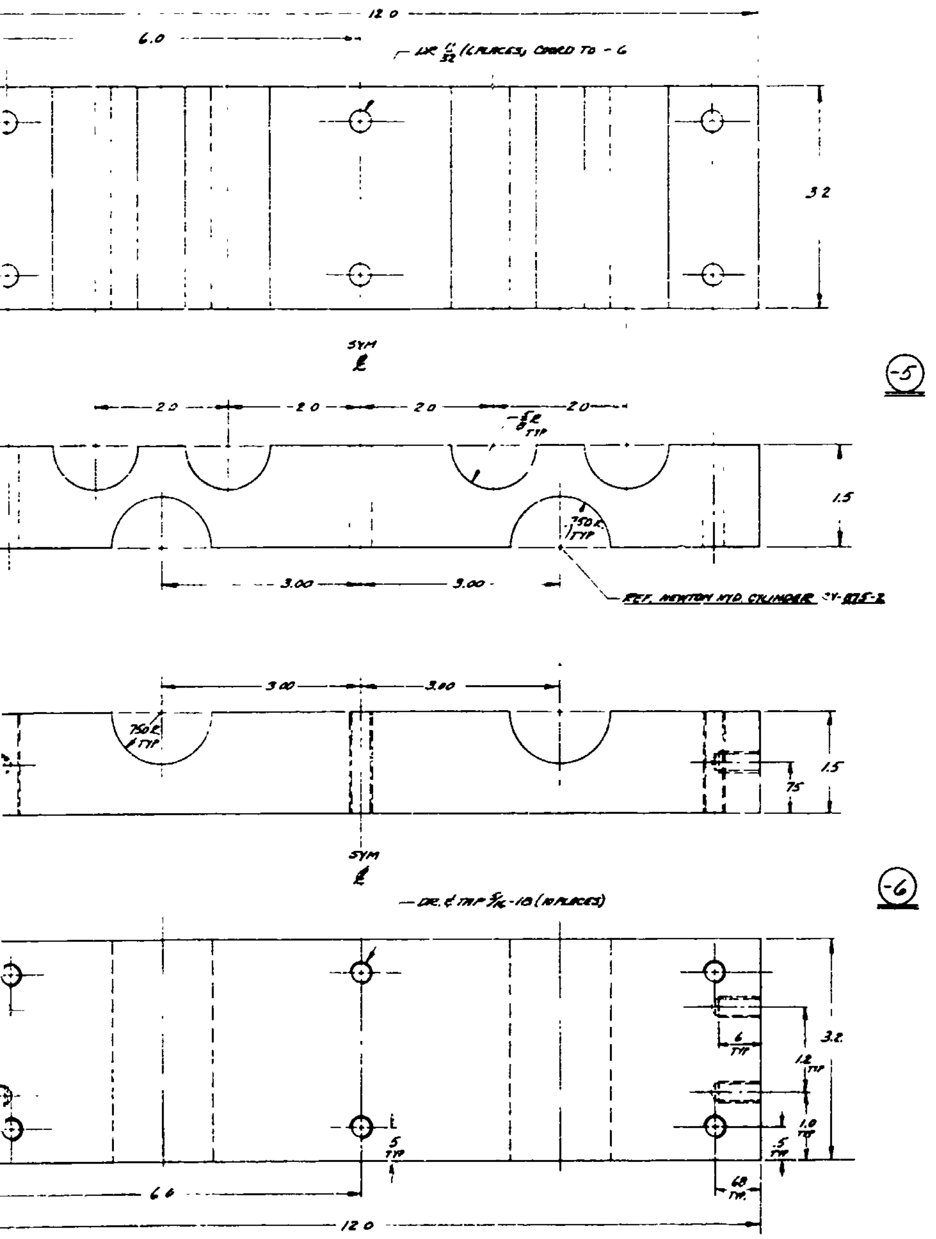
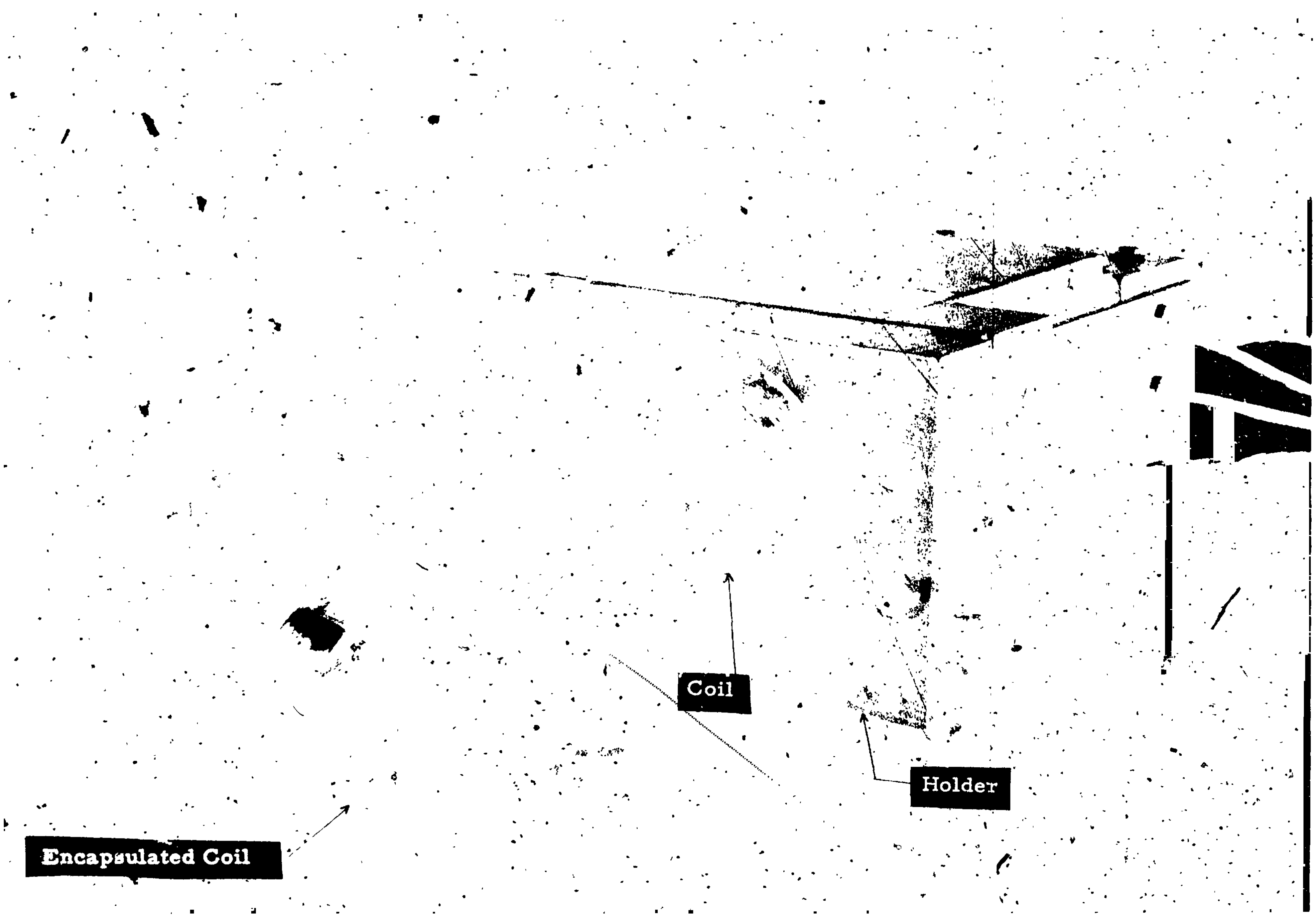


FIGURE 3



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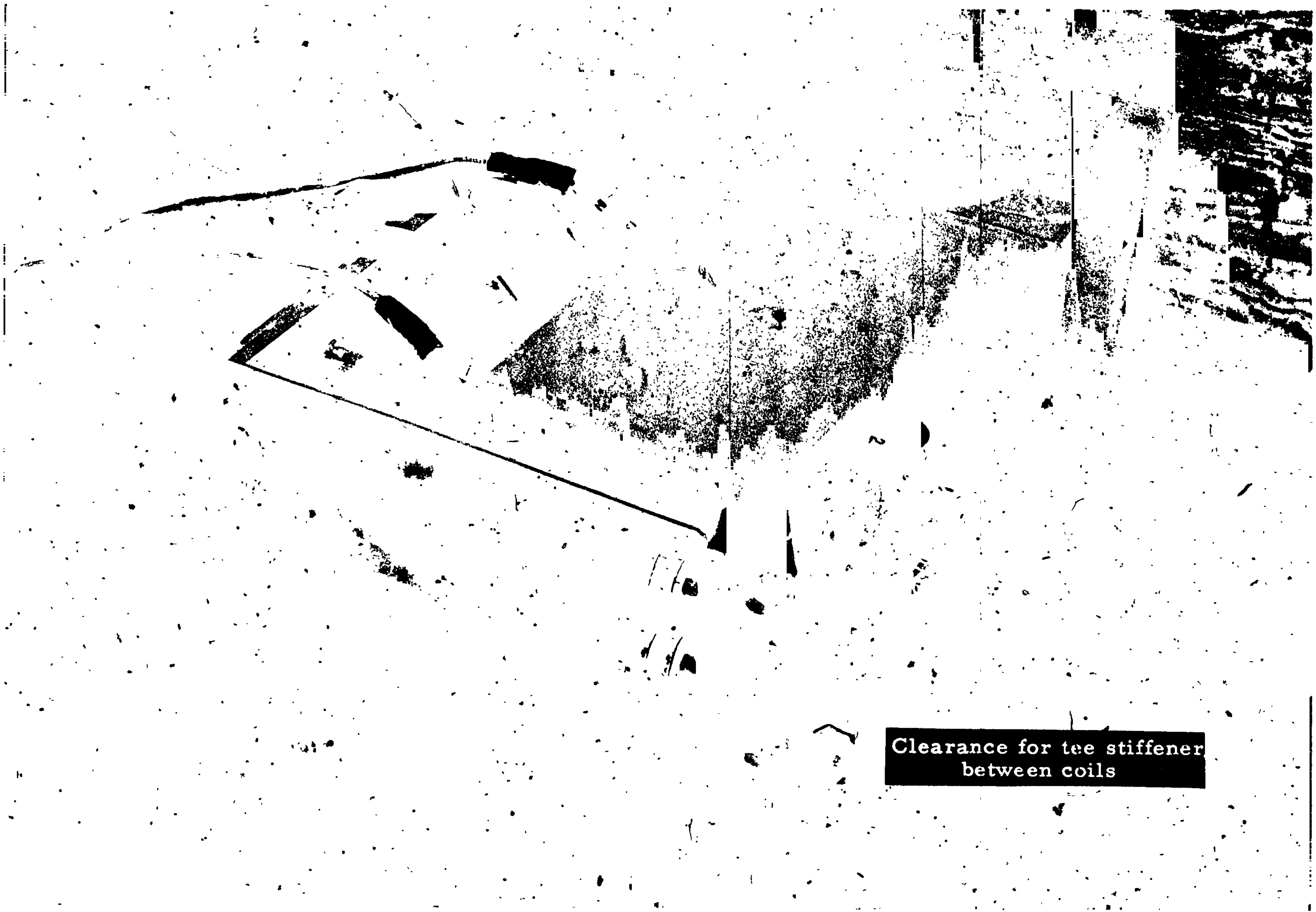
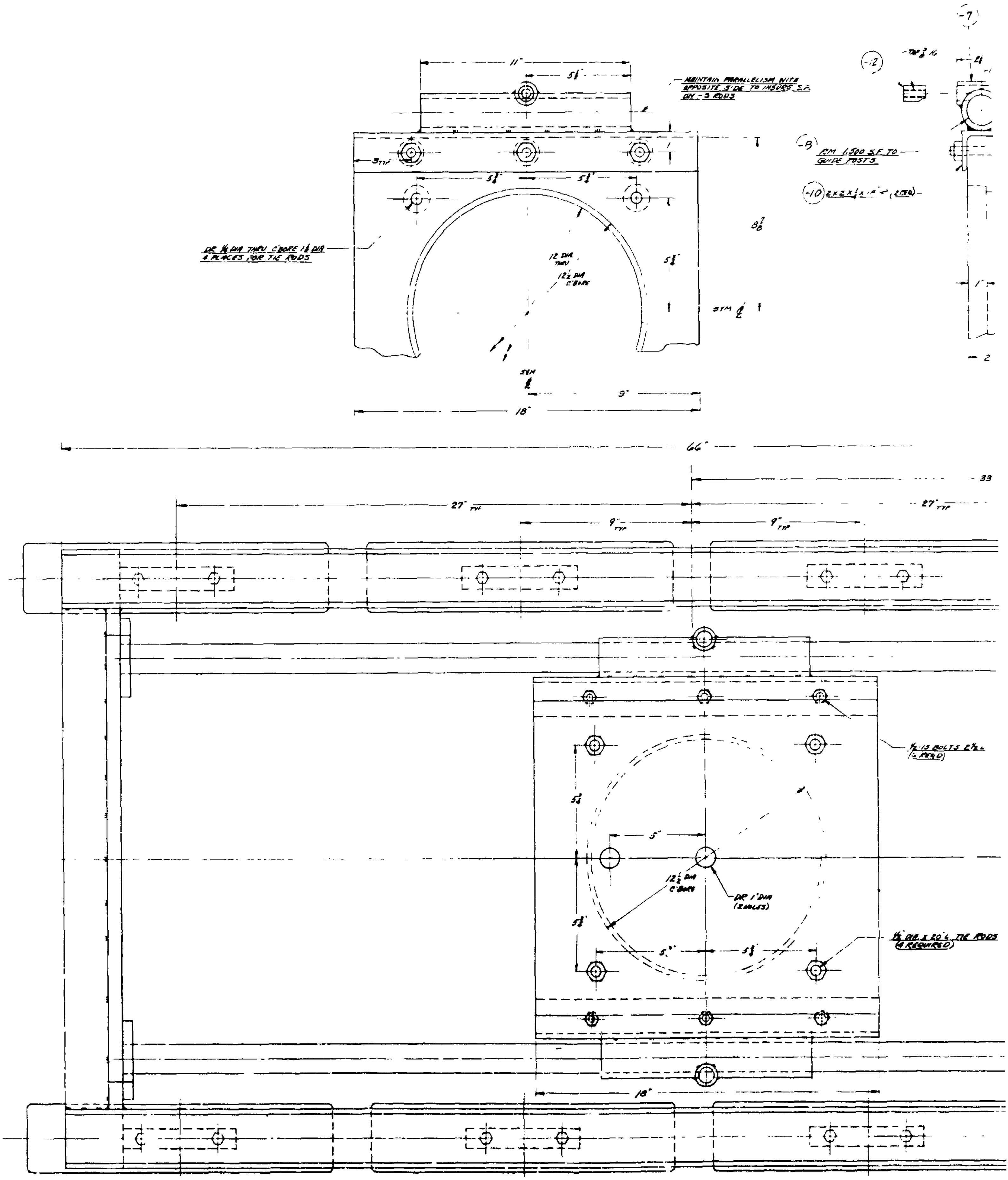
4 INCH 10 TURN COIL AND HOLDER
FIGURE 4



MR3714

TANDEM 4" COILS AND HOLDER
FIGURE 5

12" COIL ASSEMBLY AND VACUUM SUPPORT FIXTURE
FIGURE 6



MAINTAIN PARALLELISM WITH OPPOSITE SIDE TO INSURE S.F. ON -3 RODS
DR 3/4 DIA THRU C'BORE 1 1/4 DIA 4 PLACES, FOR TIE RODS
RM 1.500 S.F. TO GUIDE POSTS
-12
-8
-10
-7
11"
18"
9"
66"
33
27" TYP
9" TYP
1/2-13 BOLTS 2 1/2 L (6 REQ'D)
DR 1" DIA (2 HOLES)
3/4 DIA x 20 L TIE RODS (4 REQUIRED)

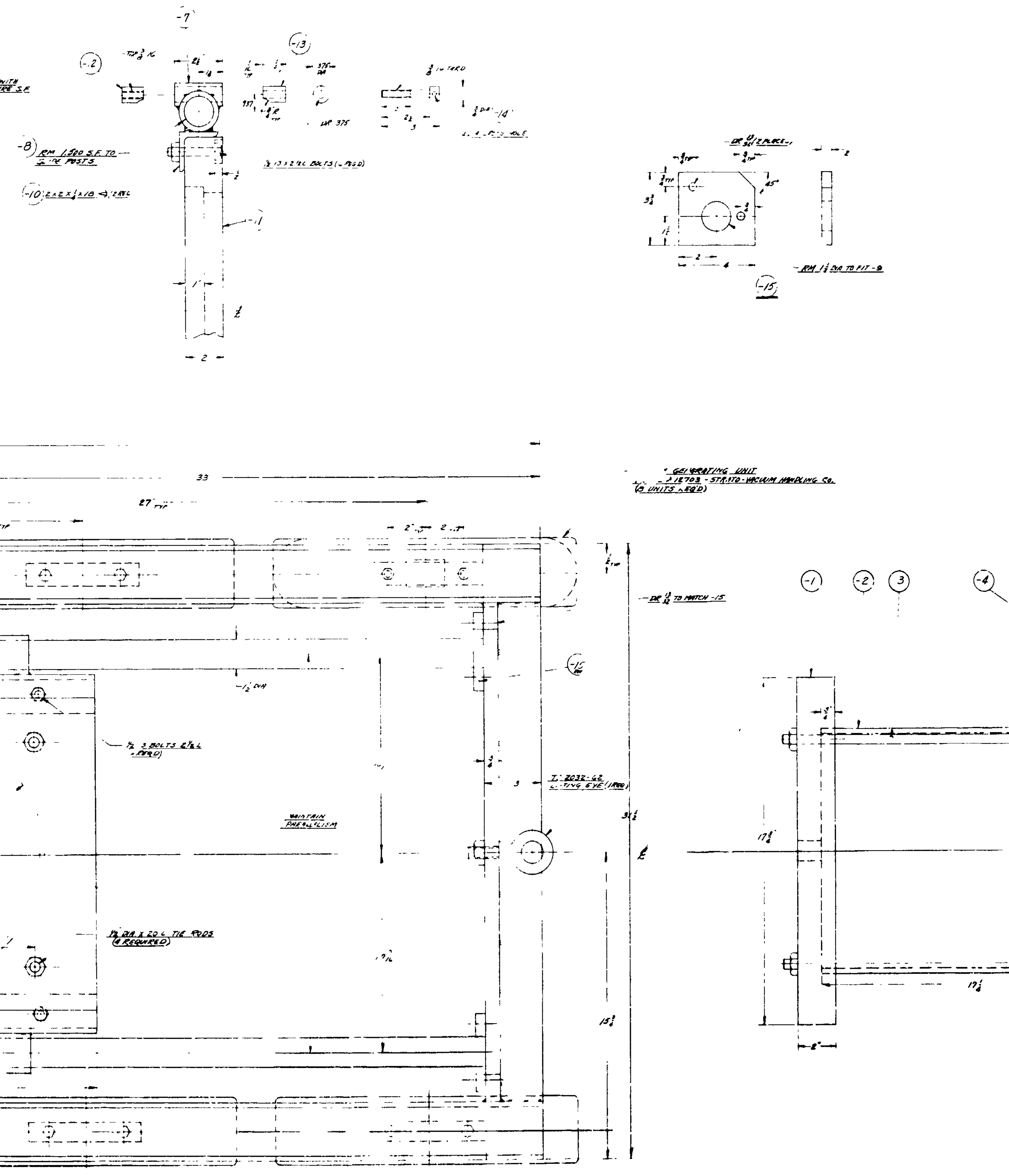
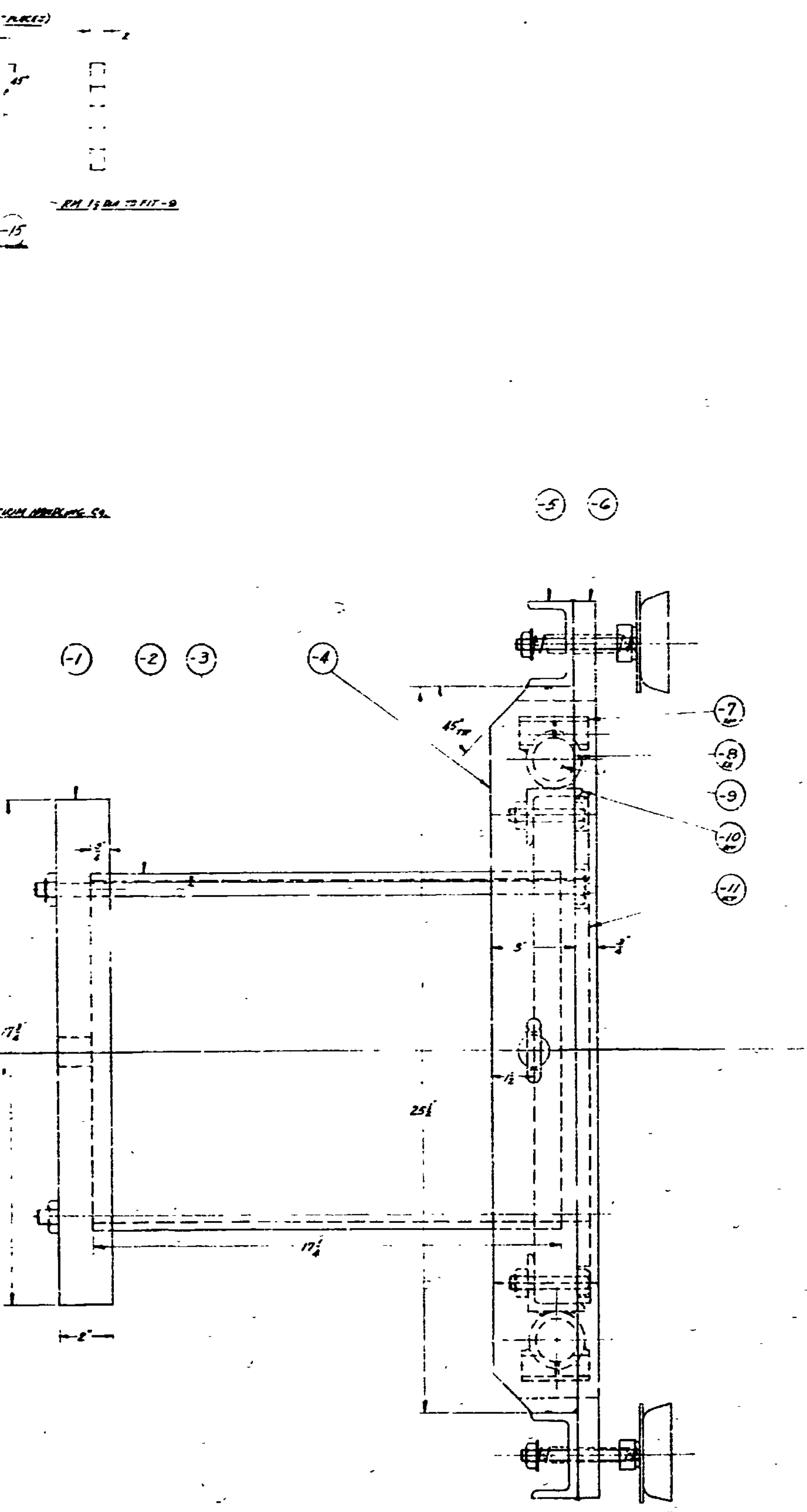


FIGURE 7



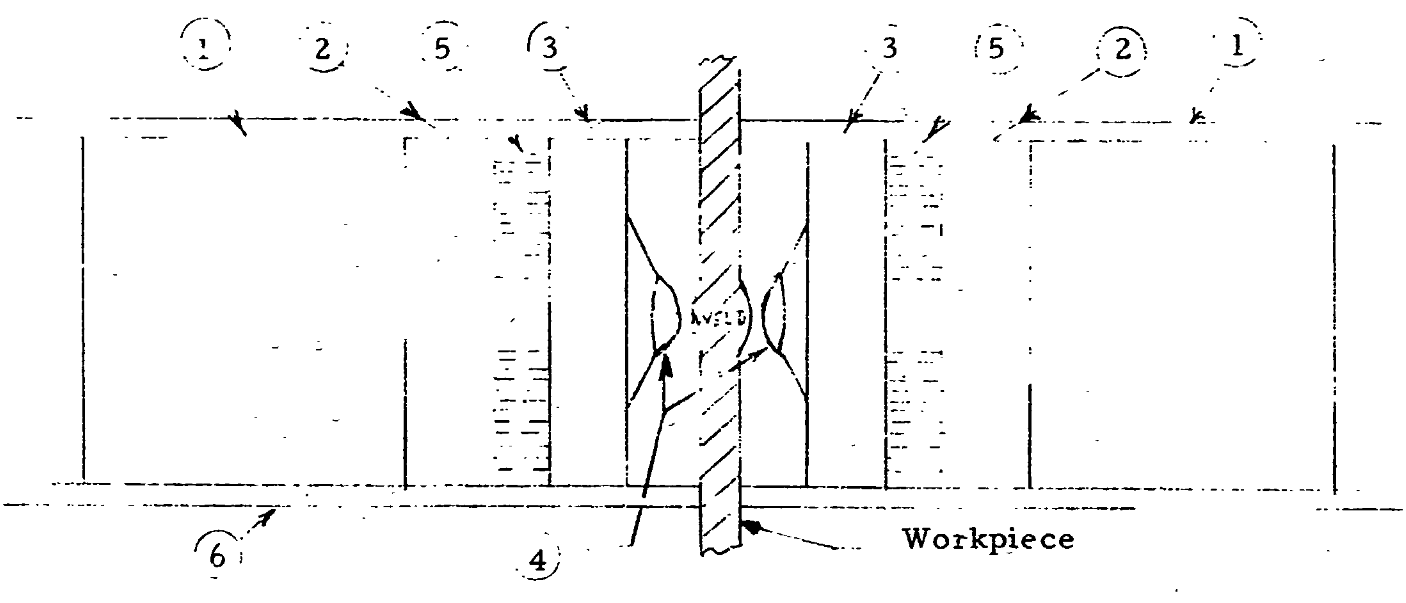
"IGURE 7

2. Magnetic Weld Peening Experiments

A series of tests were performed using 4 inch diameter coils to propel an aluminum driver (with a steel hammer point) directly against the weld surface with the intention of correcting distortion by means of successive adjacent impacts. The principle of operation as illustrated in sketch below was as follows:

A magnetic field of a short duration high current flow, through coils (5) induced opposing current and field in the conductive drivers (3) causing these components to move away from each other due to magnetic forces. Movement was perpendicular to guide (6) which positioned the drivers as the hammers (4) impacted upon the weld of the workpiece.

Based on the law of conservation of momentum, the ratio of the oppositely directed velocities is inversely proportional to the respective masses. Therefore, a 20 pound weight (1) was attached to the coil holder (2) and coil (5) so that the weight of this assembly was much heavier than the combined weight of the driver (3) and hammer (4). Consequently, little movement of the heavier assembly occurred during the current pulse, and most of the kinetic energy was imparted to the driver and hammer.



The coils and assemblies were used singly and in series to produce individual impressions in aluminum specimens, for efficiency determinations of the 240 uf and 960 uf capacitor banks at varying energy level discharges (up to 16,000 joules) with little difference noted in the work produced at equal discharge energy. Welded test strips 20 inches long in 1/2 inch aluminum plate were simultaneously peened at both weld surfaces with impacts spaced at 1/4 inch intervals at 4300 joule discharges. The peening action reduced a slight bow (.012" at panel center) to .003" as shown in illustration below, indicating that preferential working of one surface with regard to the other could be achieved by adjustment of the anvil area.

WELD PEENING OF 1/2" PLATE. IMPACTS 1/4" APART AT 4300 JOULES

Details of the magnetic peening experiments such as workpiece impressions at various discharge energy levels are given in Progress Report #3. The magnetic peening experiments were discontinued in favor of forming the panel directly with magnetic pressure in accordance with the original program objective.

3. Methods of Panel Contour Measurement

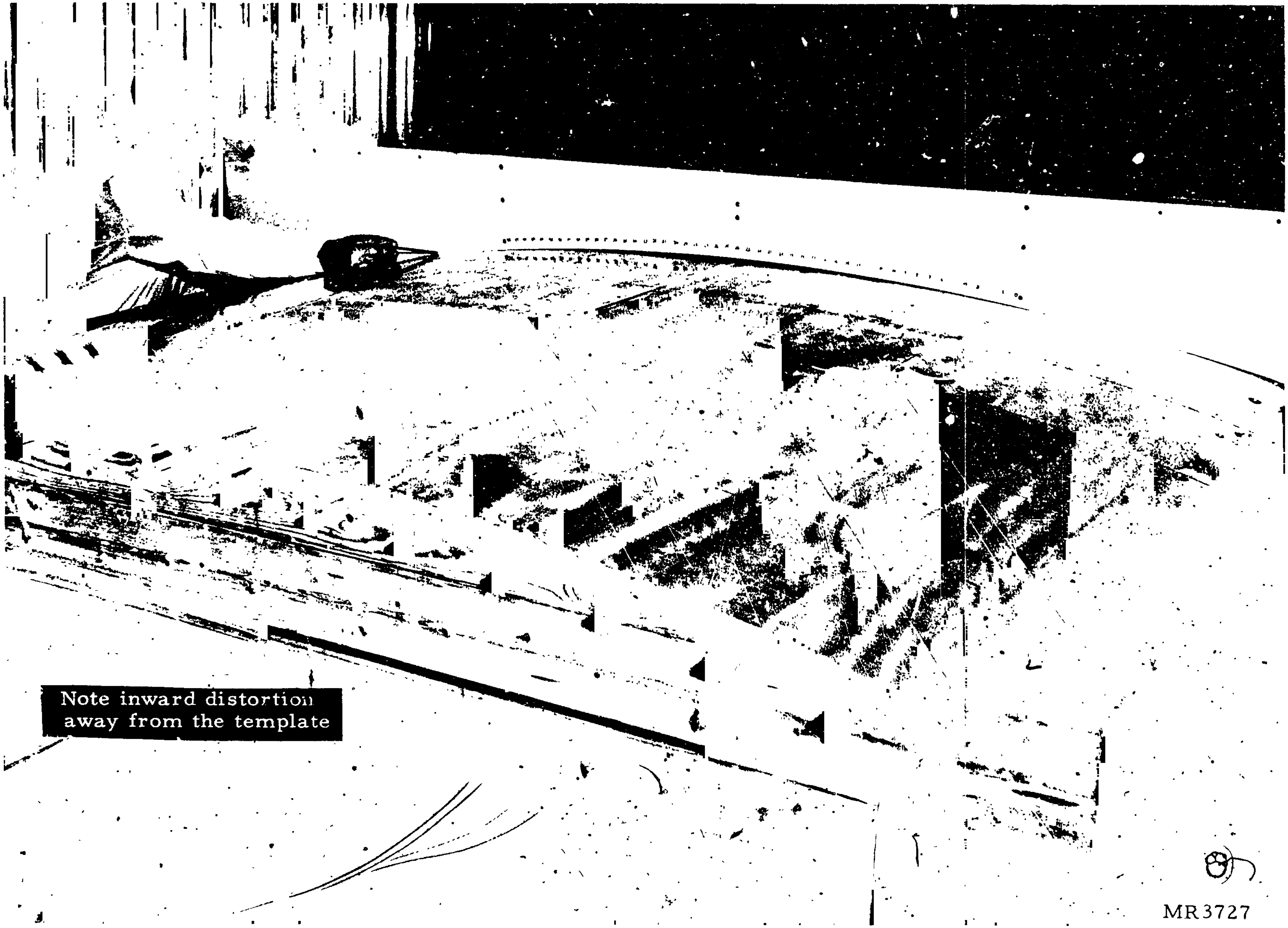
Before magnetic forming experiments could be performed upon the two MSFC furnished welded panels, it was necessary to establish contour dimensions in cylindrical and longitudinal directions.

An upright fixture was constructed to contain the welded panel in a vertical position, and secure it in a 198 inch radius of curvature by means of fixed contour plates at the top and bottom edges. All contour deviations were measured relative to these two edges, as shown in Figure 8. A contour checking fixture was made to locate from fixed points on the upright fixture, straddle the outer surface of the panel, and represent a radius 198.50 inches, 1/2" outside the indicated contour of the upright fixture. All measurements made indicated the difference between the panel surface and the checking fixture.

The upright fixture was ideally suited for the first panel (No. 1) received from NASA, which measured 103" x 105", but the second panel (No. 2) received was 90" x 90", and was too small to be mounted within the fixture. Forming experiments were actually begun with the panel No. 2 for which a fixture was made of two wood contour boards 90" long cut to a 196" radius of curvature (allowing 2" for the height of the tee stiffeners upon which the panel rested.) See Figure 9. The panel was permitted to rest on the boards without any restraint. Measurements were made by resting a template including an arc of 198.50 inch radius on the external surface of the panel using 1/2" shims and making cylindrical readings for 24 inches on either side of the weld. Longitudinal readings were made using a straight template, offset 1/2" from the panel surface. These readings required correction since the template banking surfaces were the panel itself, rather than a fixed reference.

Progress Reports 5 and 6 contain more detail with regard to measurement of Panels 2 and 1, respectively.

PANEL #1 MOUNTED IN VERTICAL FIXTURE FOR CONTOUR MEASUREMENT
AND CORRECTIVE FORMING EXPERIMENTS
FIGURE 8

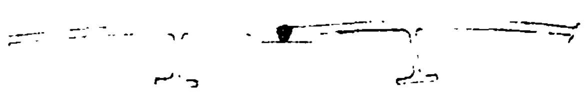


PANEL #2 BEFORE CORRECTIVE FORMING
FIGURE 9

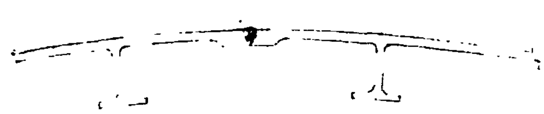
4. Corrective Forming of No. 2 Panel

Panel No. 2 included severe distortion along the weld line (see Figure 9) which produced reverse contour curvature at the weld joint, and extended to the tee stiffeners adjacent to the weld, causing an angular error of 2° 30', preventing them from making normal contact with the contour boards. (See Figure 10, upper and the sketch below.) The distortion extended toward the panel center with increasing magnitude to form a concave depression .230" deeper there than at the panel edges. The work performed was primarily corrective forming of the weld line, using the 4 inch diameter coil mounted between the tee stiffeners. Measurements were made after each discharge during the early phases of the test program to establish deformation versus energy level data, and is contained in Report #5 in detail.

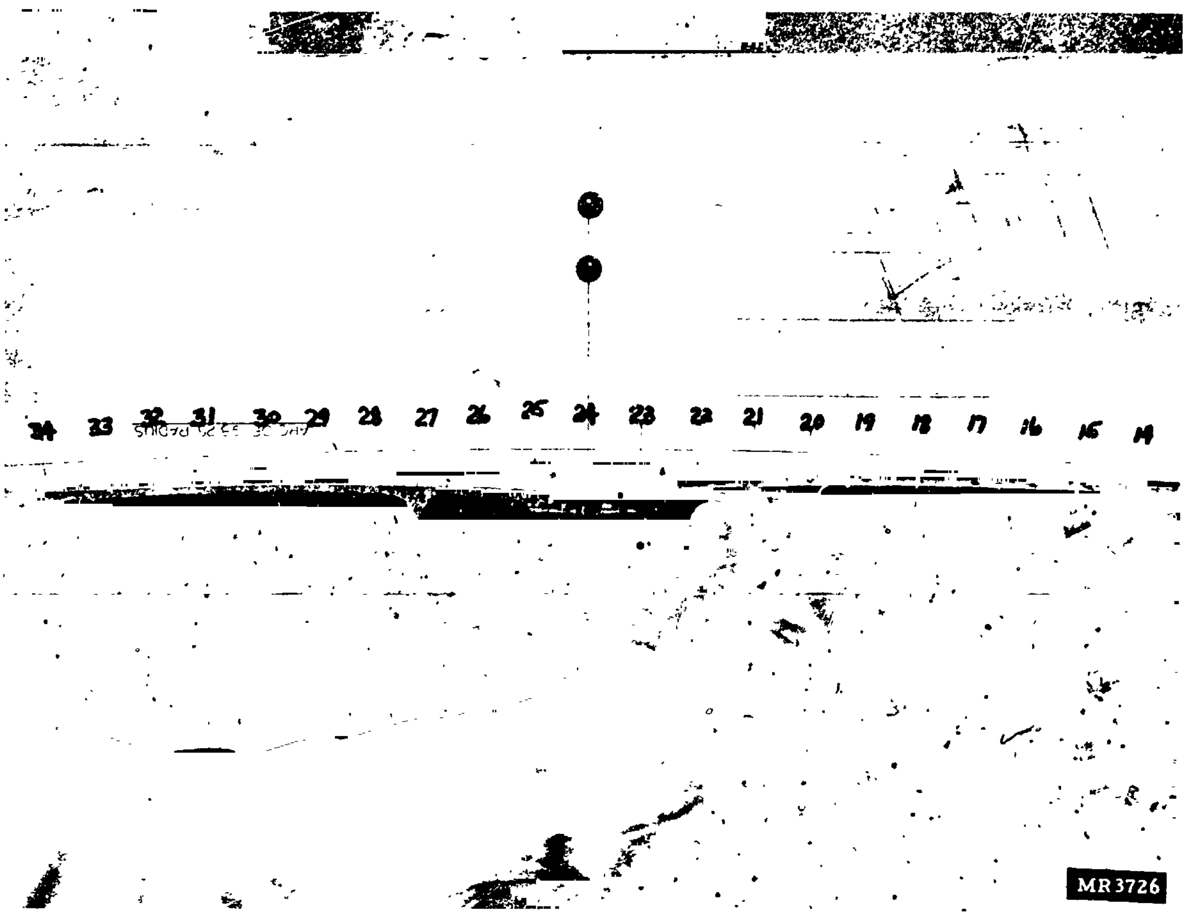
Fifty-seven magnetic discharges were made with the 4 inch diameter coil in this weld region containing the most severe distortion, along a line 45 inches long, at energy levels between 5000 and 12,000 joules. Material in the area of contact with the coil was relocated about .035" per discharge. The angular error of the tee stiffeners was corrected and they were moved into proper contour, as shown in the sketch below, and the concave depression of the weld line was reduced, producing a relatively straight element having a deviation of ± .015". Figures 10 lower and 11 show the panel after these discharges and Report #6 presents the corrective forming data in detail.

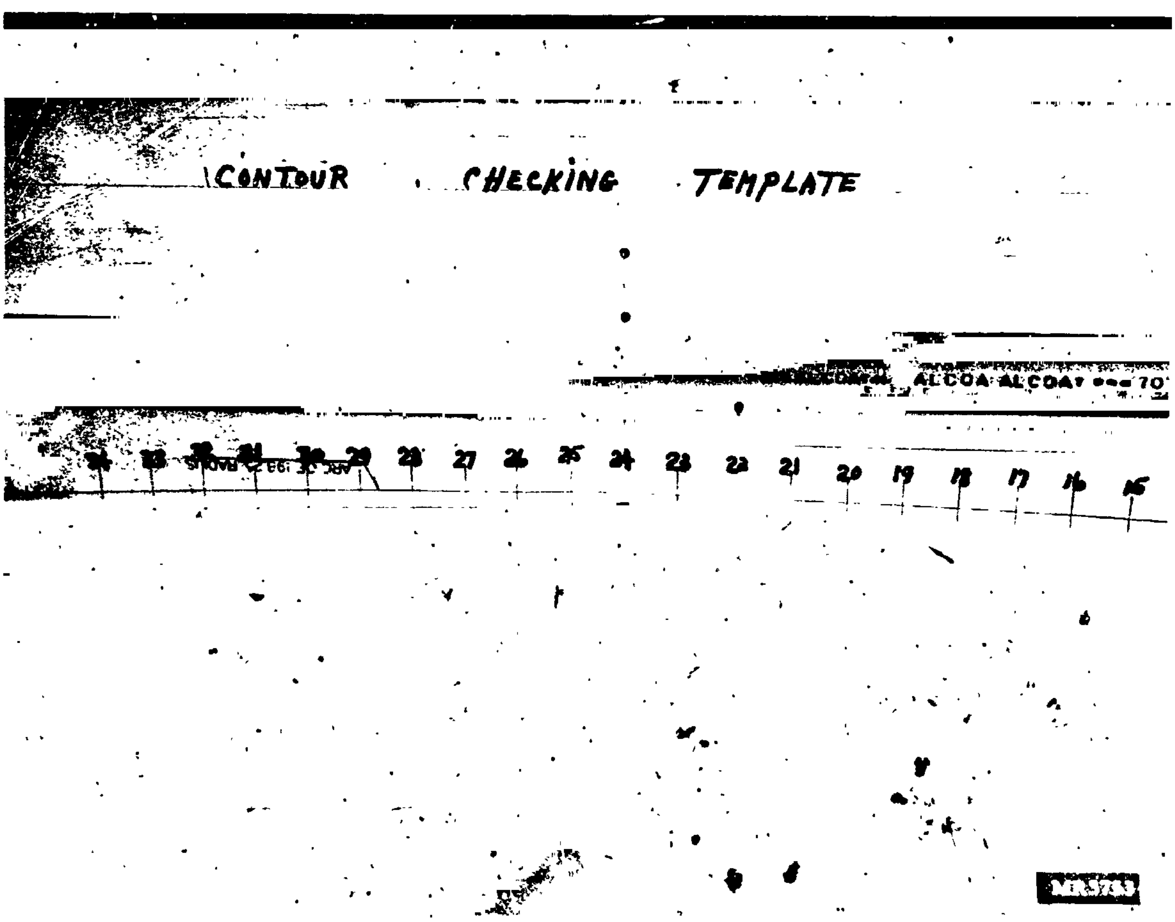


BEFORE DISCHARGE

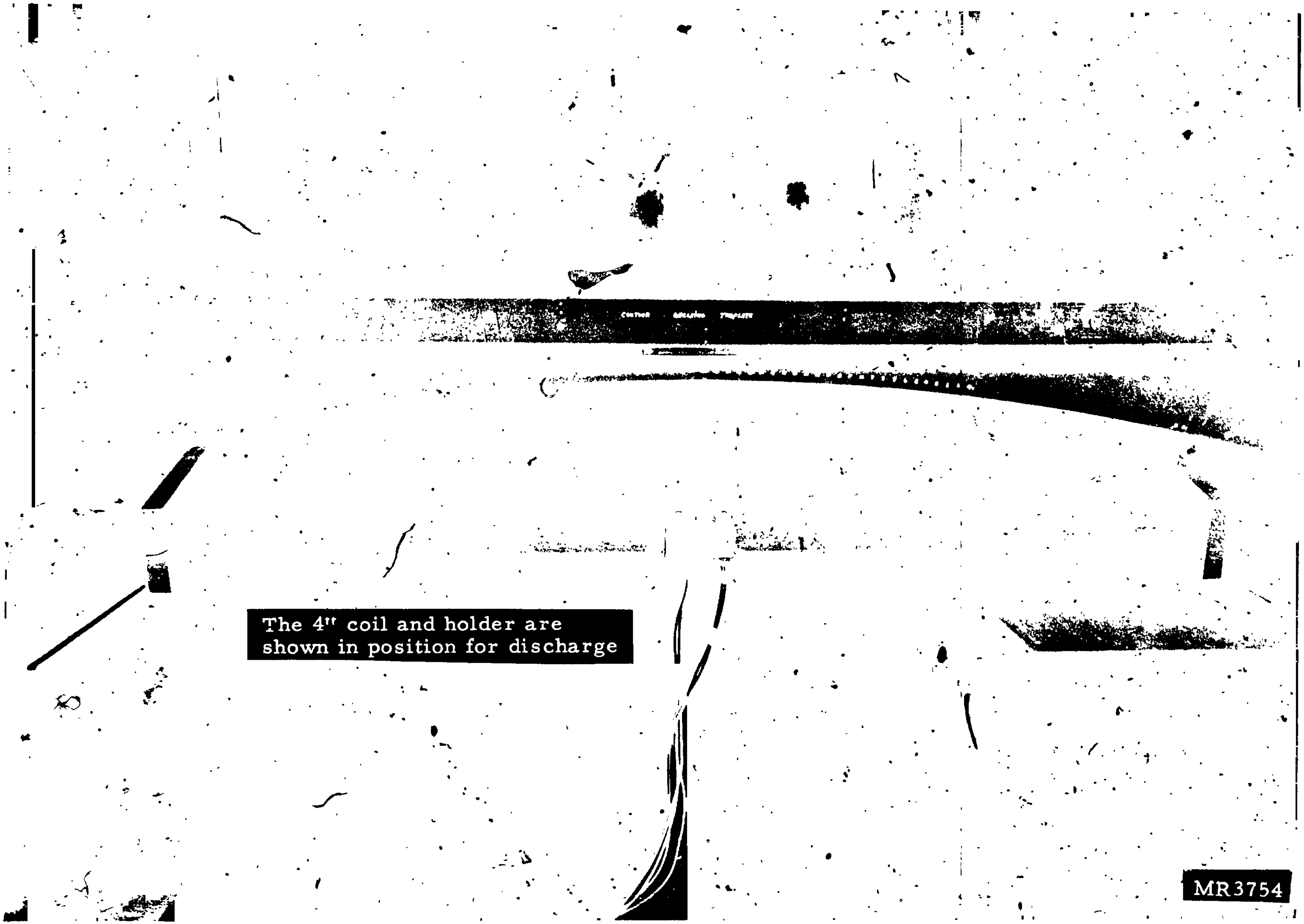


AFTER DISCHARGE





PANEL #2 BEFORE AND AFTER CORRECTIVE FORMING
FIGURE 10



CONTOUR TEMPLATE SHOWS CONFORMANCE OF PANELS AFTER CORRECTIVE FORMING
FIGURE 11

5. Corrective Forming of No. 1 Panel

Panel No. 1, mounted vertically in the upright fixture contained two types of contour error, shown by the dimensional contour check in Figures 12 and illustrated by Figure 1. The first was a concave depression formed in the panel center approximately at the mid point of the weld line, which reached a maximum depth of .145" (inside the 198" radius of curvature established by the upright fixture). This concave condition continued for approximately 12 inches on either side of the weld zone, where there was transition to a convex bowing, extending outward to the panel outboard edges. About two feet on either side of the weld line, at a point approximately in the middle of the panel, the bulges reached their maximum height (outside the 198" radius of curvature established by the upright fixture), to .192" beyond the radius line on the left side of the panel (Station 24) and to .286" on the right side of the panel (Station 80).

Weld line distortion was corrected by using the 4 inch diameter coil, mounted between the tee stiffeners, and discharging magnetically against the welded joint and the two machined bays six inches on either side of the weld line. See Figure 13. A series of 91 discharges, at energy levels between 4300 and 7700 joules, were made on the weld and adjacent bays, at 2-3 inch intervals between discharges, reducing the weld line deviation to .058" from the center to panel ends. Table I below tabulates the dimensional changes resulting from these discharges, with the contour dimensions derived with a 198" radius template offset .500" from fixed locating points outside skin ends.

Longitudinal Dimension - Inches	Contour Dimensions Before Corrective Action			Contour Dimensions After 91 Discharges, Using 4" Diameter Coil		
	STATIONS			STATIONS		
	46	52	58	46	52	58
95.0	578	558	554	565	550	553
76.0	630	617	604	570	544	557
66.5	640	633	630	578*	558	567
57.0	635	645*	621	563	556	557
47.5	610	620	591	547	552	540
38.0	568	582	557	533	547	527
28.5	528	544	528	468	503	490
9.5	490	544	515	475	532	510

TABLE I

The (*) numbers signify the points of greatest contour error, before and after forming, with (500) representing a point on the 198" radius contour line. Since the weld line deviation was reduced to within $\pm$ .030", this phase of work using the 4 inch diameter coil was concluded.

Because of the relatively large area of convex contour requiring correction, the 12 inch diameter coil, vacuum mounted to the smooth surface of the panel, was used at Stations 24 and 80. Six discharges were made along Station 24, at six inch intervals, for a linear distance of thirty inches. These discharges were highest at the point of greatest error, and diminished in energy level as the distortion decreased. Table II indicates the position and level of each discharge, with the dimension changes resulting from them.

TABLE II

Longitudinal Dimension - Inches	Contour Dimension At Station 24 Before Correction	Discharge Sequence and Energy Level	Contour Dimension At Station 24 After Correction
95.0	447		452
76	344		364
70	332	1st - 6000 Joules	355
64	322	2nd - 6400 "	353
58	311	3rd - 6550 "	352
52	303	4th - 6850 "	355
46	305	5th - 6750 "	358
40	317	6th - 6000 "	359
28.5	347		372
9.5	455		457

As can be seen by the data, the net distortion over the 30 inch worked zone is .007", and represents a maximum contour improvement of .053".

Sixteen discharges were made along station 80. Because of the extreme amount of distortion, forming energy levels were kept low to avoid depressing the skin areas adjacent to the tee stiffener which straddled station 80, and the discharges were not made in direct linear sequence as occurred at station 24, but were made at the high points of distortion, as they developed along the station line. Two discharges, made at 3000 and 4320 joules, produced no appreciable correction. The remaining fourteen discharges were made between 5500 and 6500 joules, which produced from .035" to .065" material movement per discharge. Table III tabulates the dimensional changes resulting from these discharges.

TABLE III

Longitudinal Dimensions - Inches	Contour Dimensions at Station 80 Before Correction	After Correction	Amount Gained (In Inches)
95.0	431	448	.017
76.0	312	325	.013
66.5	292	320	.032
57.0	214	323	.109
47.5	266	325	.059
38.0	282	339	.057
28.5	326	345	.019
9.5	467	480	.013

It can be seen from Table III that the total deviation between 28.5 and 76.0 has been reduced from .112" to .025", and the total contour gain at 57.0 is .109".

The corrective action on the outer surface of the panel at stations 24 and 80, using the 12 inch diameter coil discharging inward, produced metal movement in the opposite direction (outward) at the weld zone where the deformation was concave in shape, and resulted in a net contour gain at those regions. Table IV tabulates the contour dimensions at and around the weld before and after the twenty-two discharges made at stations 24 and 80.

TABLE IV

Longitudinal Dimensions - Inches	Before Correction At Stations 24 and 80			After Correction At Stations 24 and 80		
	46	52	58	46	52	58
95.0	565	550	553	564	552	554
76.0	570	544	557	554	534	540
66.5	578	558	567	565	551	560
57.0	563	556	557	555	546	540
47.5	547	552	540	525	527	510
38.0	533	547	527	512	525	506
28.5	468	503	490	498	507	495
9.5	475	532	510	481	507	502

From the above data, it may be seen that the total contour deviation of six inches on either side of the weld has been reduced from .110" to

.084" without performing any direct work upon the area. Combining the data available in Tables I and IV, the total correction in this area, resulting from all work done to Panel No. 1 has been .071", reducing the maximum distortion of .155" to .084".

This series of forming tests preceeds those described in the period of February 1 to March 31, 1964, included subsequently in this report.

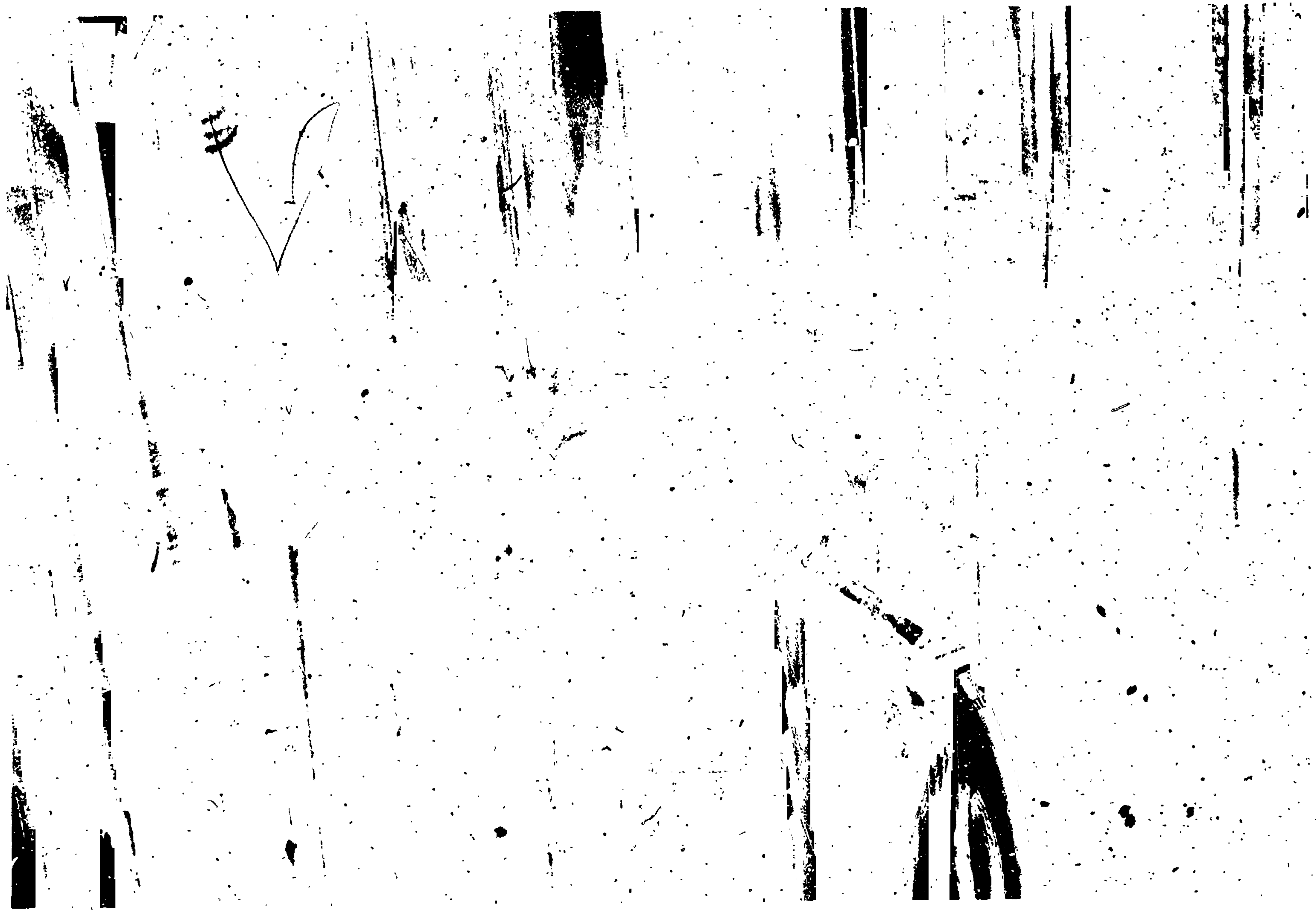
Longitudinal Dimensions - In Inches

Cylindrical Dimensions - In Inches

	95.0	76.0	66.5	57.0	47.5	38.0	28.5	9.5
92	539	532	532	518	507	493	498	513
80	431	312	292	214	266	282	326	467
68	483	452	455	443	424	414	419	488
62	545	575	593	584	557	527	505	507
56	561	632	660	657	625	588	551	522
55	556	627	655	659	627	589	551	525
54	549	622	647	646	625	583	550	523
53	549	615	641	638	625	584	550	523
Weld 52	553	615	632	636	627	585	551	544
Line 52	562	619	635	645	613	580	537	543
51	556	625	640	638	614	577	542	527
50	562	630	648	645	617	577	540	512
49	570	637	657	654	623	583	543	504
48	575	642	656	656	625	582	538	492
42	582	617	628	621	590	551	517	488
36	527	520	521	511	488	467	457	479
24	447	344	316	312	308	316	347	455
12	508	475	453	451	451	450	457	486

Contour readings in thousands of an inch with panel mounted in upright fixture. Contour dimensions obtained with 198" radius template offset .500" from fixed locating points outside skin ends.

DIMENSIONS OF PANEL # 1 BEFORE FORMING
FIGURE 12



MR3651

4" COIL MOUNTED ON TEE STIFFENERS FOR CORRECTIVE FORMING
OF WELD AREA
FIGURE 13

6. Characteristic Deformation versus Energy Curves

A series of tests were undertaken to compile data for the plotting of characteristic curves for each of the coils used in the magnetic forming experiments, at 3 or more different energy levels. All tests were performed on Panel No. 2, with coils mounted in their proper holders.

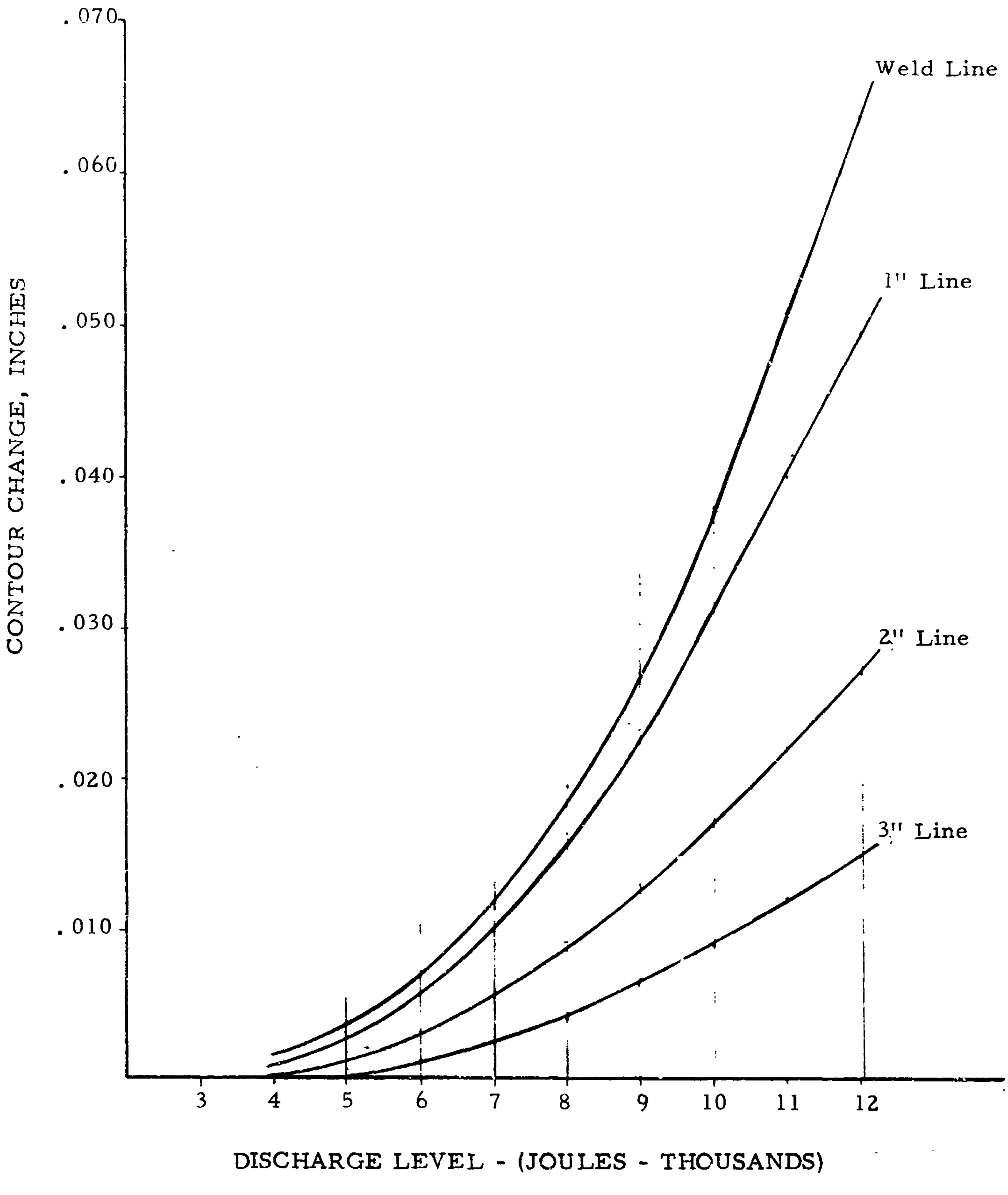
The 4 inch diameter coil was mounted between the tee stiffeners and discharged against the weld at a point approximately 40 inches from the leading edge of the panel at increasing increments of 1000 joules, between 3000 and 12,000 joules. Deformation measurements were taken of the weld at the coil center, and at one inch increments for three inches along the weld on each side of the coil center. Figure 14 contains the curves for this test sequence.

The 4 inch diameter coil was tested in the same manner as above, with discharges being made against the .200" thick machined skin, at a point 12 inches from the weld, 39 inches from the leading edge of the part. Discharges were made in increasing increments of 1000 joules, between 3000 and 7000 joules, and measurements were made as described above Figure 15 includes the curves for this test.

Two 4 inch diameter coils, connected in series and mounted in the tandem coil holder, were mounted between tee stiffeners spanning two machined bays, and discharged simultaneously against the .200" thick skin at points 12 and 18 inches from the weld and 30 inches from the panel leading edge. Contour changes were measured for both coils in the manner described for the single 4" diameter coil tests following discharges increasing in 1000 joule increments, from 4000 to 9000 joules. Figure 16 contains the plot for the left and right coils. Comparison with the deformation curves for a single coil shows that, as expected, deformation begins at lower energy levels with a single coil due to the greater energy per surface area.

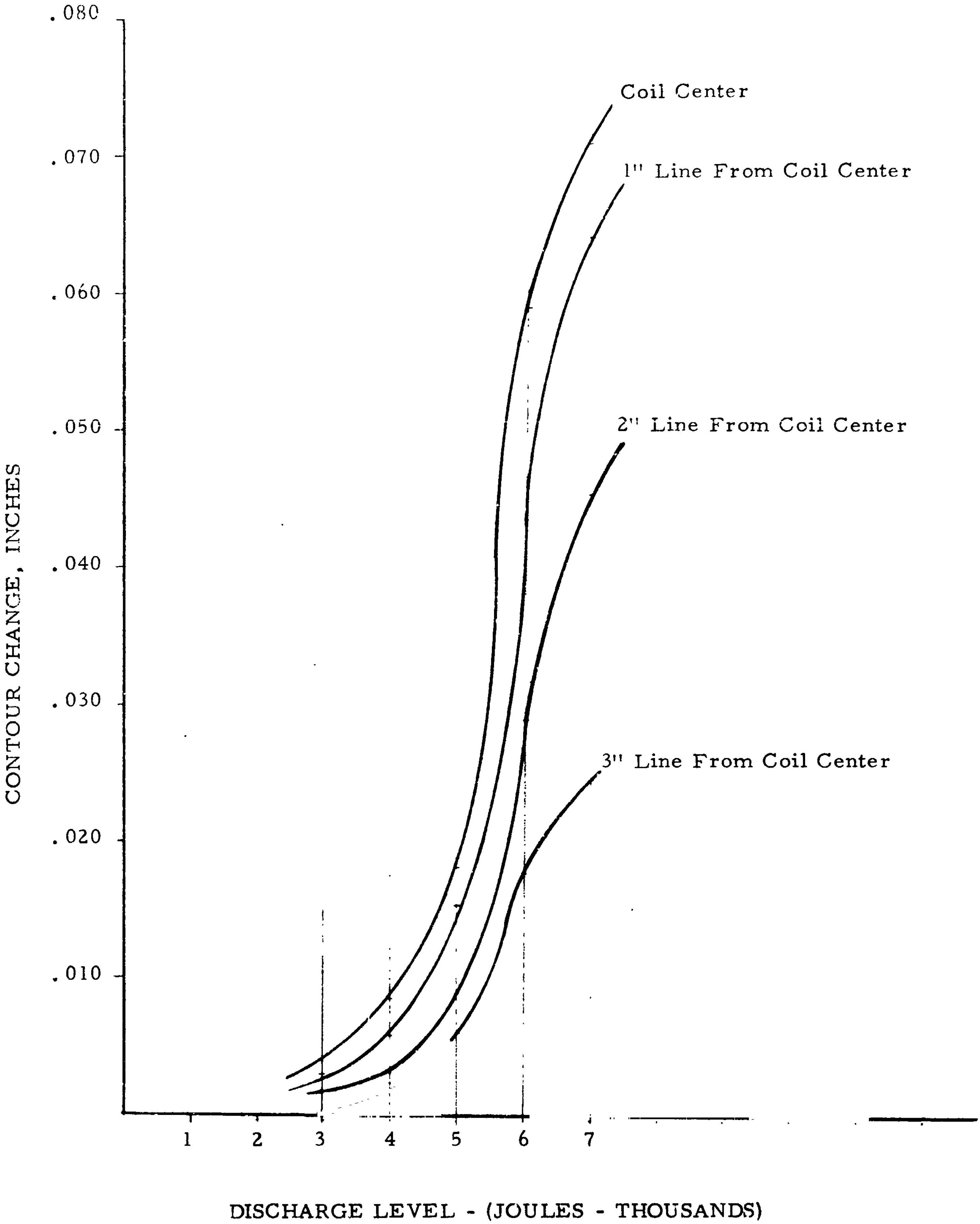
Comparison of the double and single coils on an equal energy per coil basis shows that the double coils produce more metal movement. This can not necessarily be construed as work since a different curvature is produced by the two systems. Also, as is observed in forming with a single 4" coil in adjacent positions along a line, succeeding discharges add to the deformation at earlier positions.

The 12 inch diameter coil, vacuum mounted to the horizontally resting panel, was discharged over a stiffening tee 24 inches from the weld and 40 inches from the leading edge. Four discharges were made at 4320, 5000, 7000 and 8500 joules, and measurements were made of metal movement (of the tee stiffener) at 3 inches, 6 inches and 9 inches from the coil center. The results of this test are plotted in Figure 17



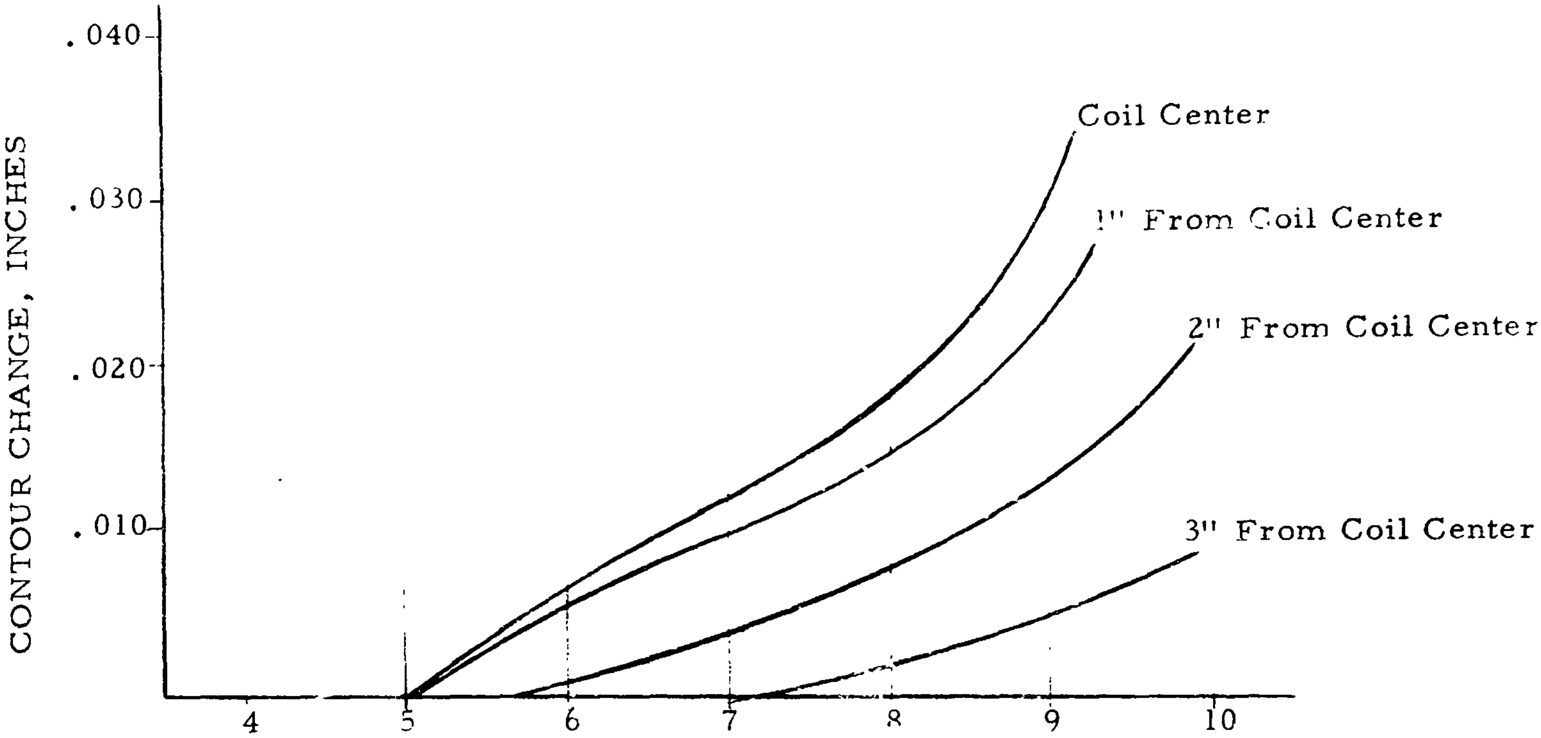
EFFECT OF VARYING DISCHARGE LEVELS
ON METAL MOVEMENT OF WELL BEAD
AND .400" THICK MACHINED SKIN
SECTION FOR 4" DIAMETER COIL

FIGURE 14

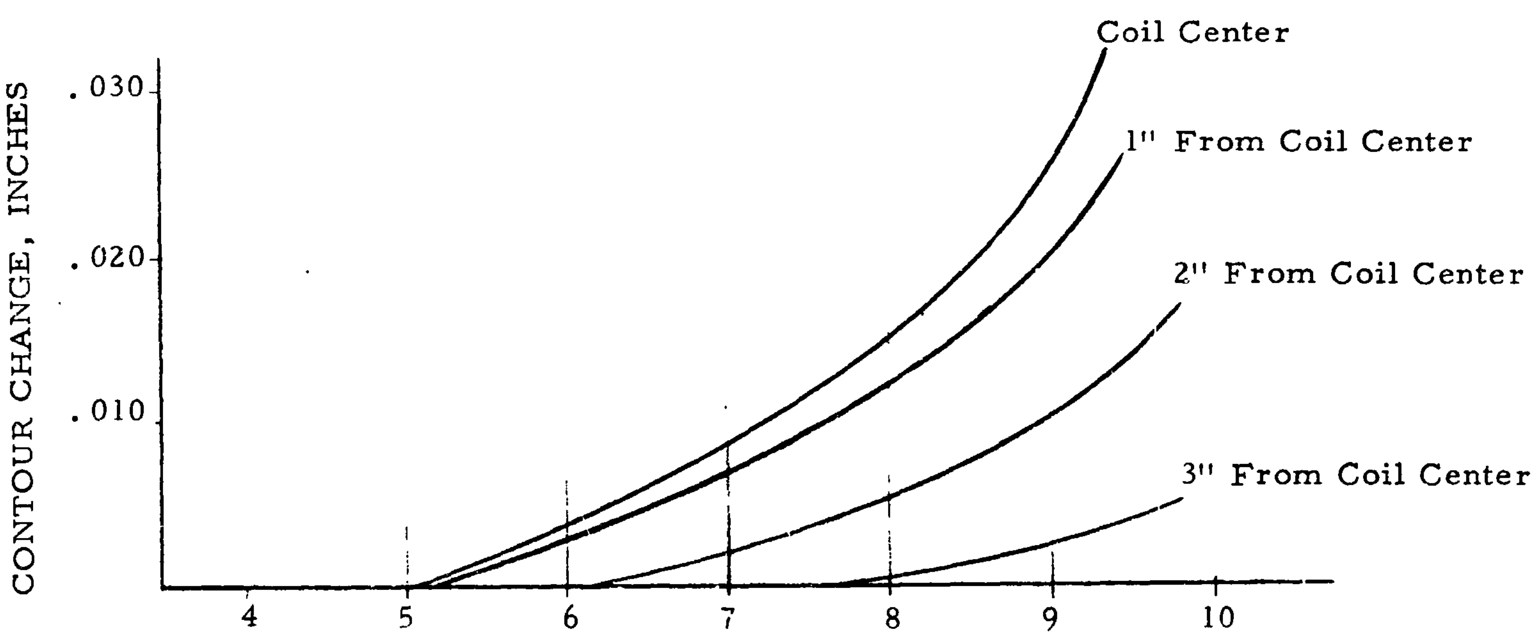


EFFECT OF VARYING DISCHARGE LEVELS ON METAL MOVEMENT OF .200" THICK MACHINED SKIN SECTION FOR 4" DIA. COIL

FIGURE 15



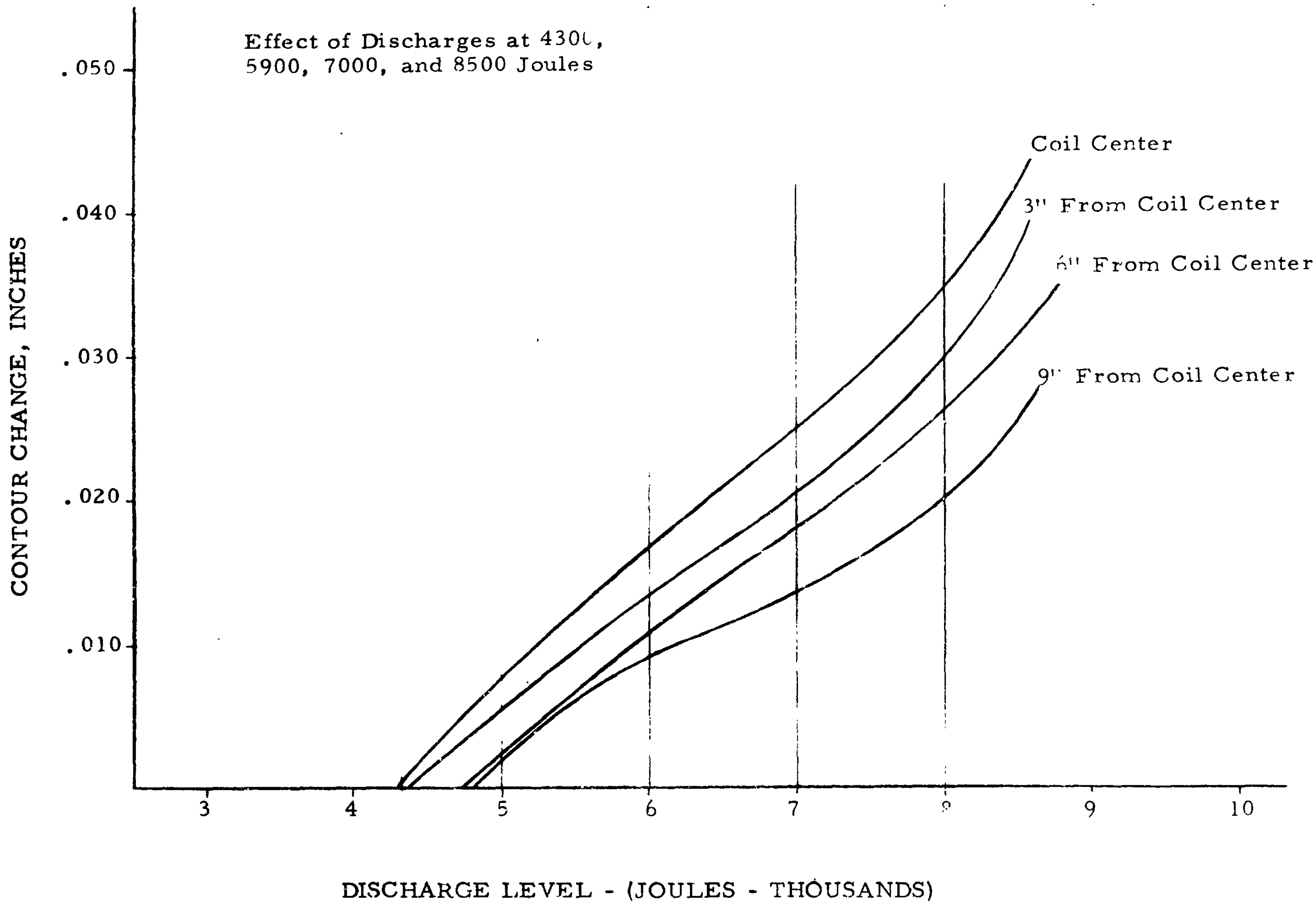
DISCHARGE LEVEL - (JOULES - THOUSANDS)
LEFT HAND (INBOARD) COIL



DISCHARGE LEVEL - (JOULES - THOUSANDS)
RIGHT HAND (OUTBOARD) COIL

EFFECT OF VARYING DISCHARGE LEVELS ON
METAL MOVEMENT OF .200" THICK MACHINED
SKIN SECTION FOR TANDEM 4" DIAMETER COILS

FIGURE 16



EFFECT OF VARYING DISCHARGE LEVELS ON METAL MOVEMENT FOR 12" DIAMETER COIL
(AGAINST STIFFENING RIB)

FIGURE 17

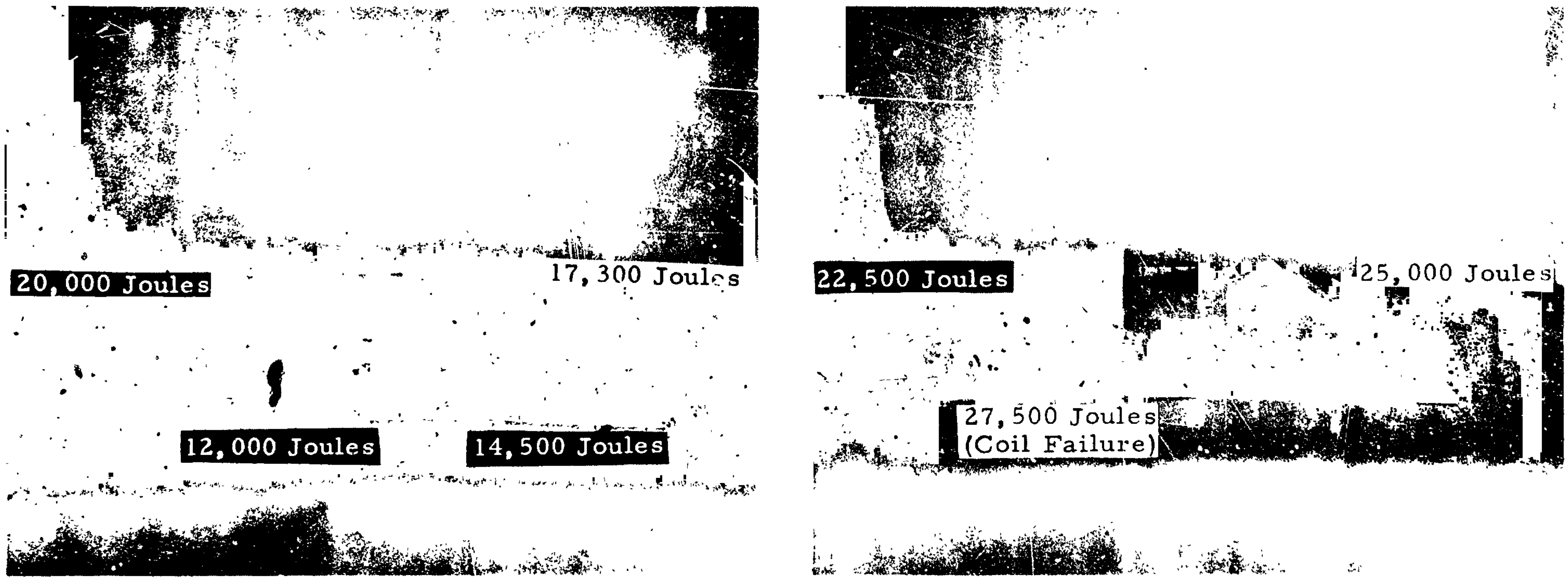
7. Coil Destruction Tests

Tests were performed upon the 4 inch and 12 inch diameter coils to determine the maximum energy discharges which the coils could sustain.

The 4 inch diameter coil used for this test had been employed for all previous single coil corrective forming operations made upon the two panel sections and for deformation versus energy level tests, being subjected to approximately 500 discharges at levels to 12,000 joules. The destruction tests were made using the 240 uf capacitor bank, with discharges commencing at 12,000 joules (10 KV) and increasing in 2500 joule increments. The coil was housed in its coil holder and coupled to .125" thick aluminum alloy workpieces. The results are summarized below and illustrated by Figure 18

Discharge	Voltage-Energy		Remarks
1	10 KV	12,000 Joules	No damage
2	11 "	14,500 "	No damage
3	12 "	17,300 "	Plastic facing on coil spalling
4	12.9 KV	20,000 "	Coil separating from plastic body
5 & 6	13.65 KV	22,500 "	No further damage
7	14.45 KV	25,000 "	Glass cloth insulation separating from coil face
8	15.15 KV	27,500 "	Coil failure - leads break away from coil proper

A previously unused 12 inch diameter coil, mounted in the vacuum holding fixture and coupled to a 1/2" thick 4' x 8' aluminum plate was used for this test series. Discharges were made at 20,000 and 23,500 joules, using the 240 uf bank (12.9 and 14 KV) and at 29,000 and 48,000 joules, using the 960 uf bank (7.75 and 10 KV). There was no damage inflicted upon the coil or coil supporting plastic by these tests, although the final discharge, at 48,000 joules, raised the vacuum held fixture and coil from the workpiece to an approximate three foot height. There was concern that higher energy discharges would damage the coil holding fixture without affecting the coil itself and further tests were suspended.



DEFORMATION OF .125" 7075-0 ALUMINUM ALLOY RESULTING FROM PROGRESSIVELY INCREASED MAGNETIC DISCHARGES USING 4" DIAMETER COIL TO DESTRUCTION

FIGURE 18

8. Discharge Current Traces

Current traces which were obtained during corrective forming (or with coils coupled to aluminum plates), are presented for a single 4" coil, double 4" coils and the 12" coil with 240 and 960 uf capacitor banks in Figures 19, 20, 21 and 22. The 240 uf bank was connected with two 85' lengths and the 960 uf was connected with one 70' length of MR1475 cable. The inductances of these cables are small with respect to the coils.

It has generally been observed in magnetic forming that frequency decreases to a fairly constant value after the first 1/4 current cycle so that it appears that the workpiece acceleration is principally accomplished during this time. These current traces also have this character although at lower energy levels several of the 960 uf traces have only a half cv le since the voltage after that time is insufficient to reionize the vacuum switch.

In all of the traces the current and 1/4 cycle time are indicated. It is observed by comparing the 240 uf and 960 u. . es for which discharge energy is equal that the impulse or product of cu. ent squared and time at 1/4 cycle is approximately equal. This is a reasonable result since the deformation work with the 240 uf and 960 uf equipment did not differ greatly.

The dashed lines in Figure 19 lower right, have been added to extend the current decay back to the origin (0 cycle). This approximation was performed for each trace and the current value was divided by the discharge voltage to obtain the initial amps/volt ratio. (I_o/E_o).

This ratio can be used to obtain an approximate value of inductance from the expression

$$I_o = \frac{E_o C^{\frac{1}{2}}}{L^{\frac{1}{2}}} \qquad \text{since} \quad \frac{1}{LC} \gg \left(\frac{R}{2L}\right)^2$$

or

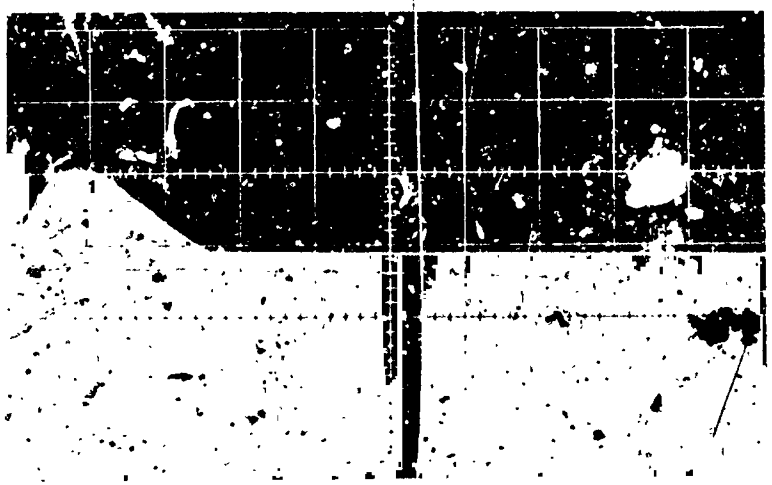
$$L = C\left(\frac{I_o}{E_o}\right)^{-2}$$

The values of inductance obtained from this expression and the current traces are:

	Single 4"	Double 4"	12"
240 uf	4.3 uh	9.6 uh	55 uh
960 uf	7.9 uh		125 uh

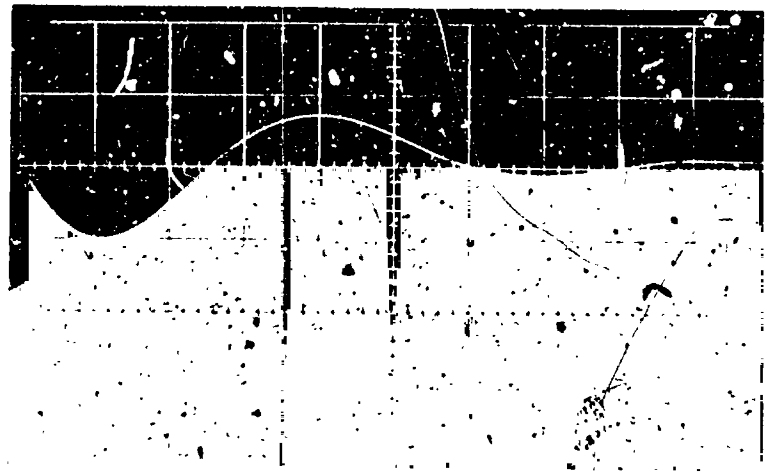
The inductances in the table appear creditable in that two 4" coils have a value twice as great as one coil and that the inductance of the 12" coil is much higher than that of the 4" coil. However, calculations for the 240 uf bank are considerably lower than for the 960 uf bank for both coils. Further comparison with MSFC bank traces and the 4" coil, where 1/4 cycle is 50 u sec and current is about twice as high, would indicate an even lower inductance. It therefore appears that the $\frac{1}{LC} \gg \left(\frac{R}{2L}\right)^2$ condition which can be reasonably used after the 1/4 cycle does not apply before that time since considerable change in inductance occurs during this period. It is of interest, however, to consider whether the artificial inductances which were calculated can be considered as a measure of merit for a discharge system.

Scale 25,000 amps/div 100 usec/div



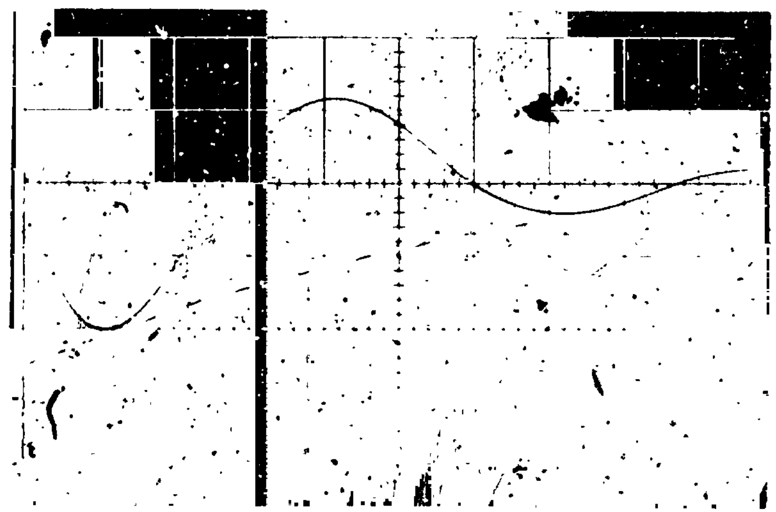
2.5 KV, 960 uf (3,000 joules)
1/4 cycle: 80 usec and 25,000 amps
Amps/volt: 0 cycle - 12.8 1/4 cycle 10.0

Scale 26,000 amps/div 50 usec/div



5 KV, 240 uf (3,000 joules)
1/4 cycle: 55 usec and 29,000 amps
Amps/volt: 0 cycle - 7.8 1/4 cycle 5.8

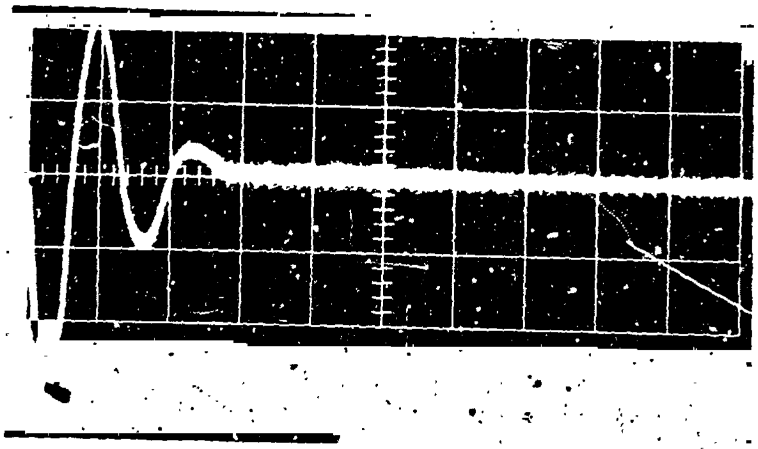
5 KV, 960 uf (12,000 joules)
1/4 cycle: 100 usec and 40,000 amps
Amps/volt: 0 cycle - 10.2 1/4 cycle 8.0



10 KV, 240 uf (12,000 joules)
1/4 cycle: 55 usec and 53,000 amps
Amps/volt: 0 cycle - 7.15, 1/4 cycle 5.3

SINGLE 4" COIL
DISCHARGE CURRENT TRACES

Scale 5,200 amps/div 200 usec/div

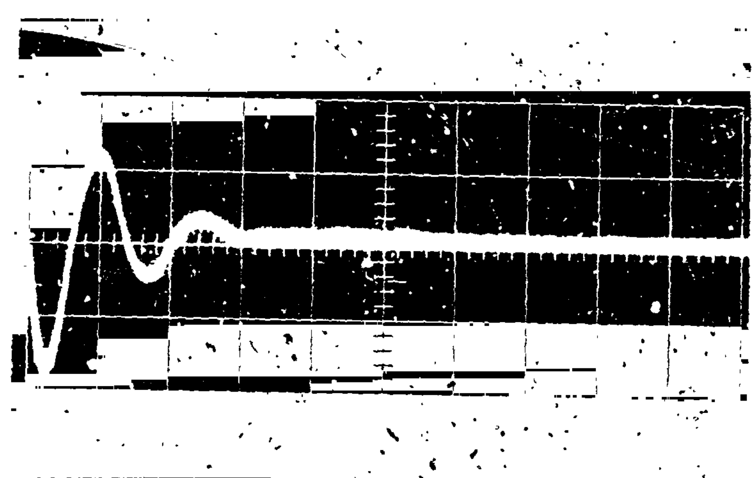


3.9 KV, 240 uf (1,820 joules)

1/4 cycle: 70 usec
16,000 amps

Amps/volt:
0 cycle - 4.5
1/4 cycle - 4.1

Scale 13,000 amps/div 200 usec/div

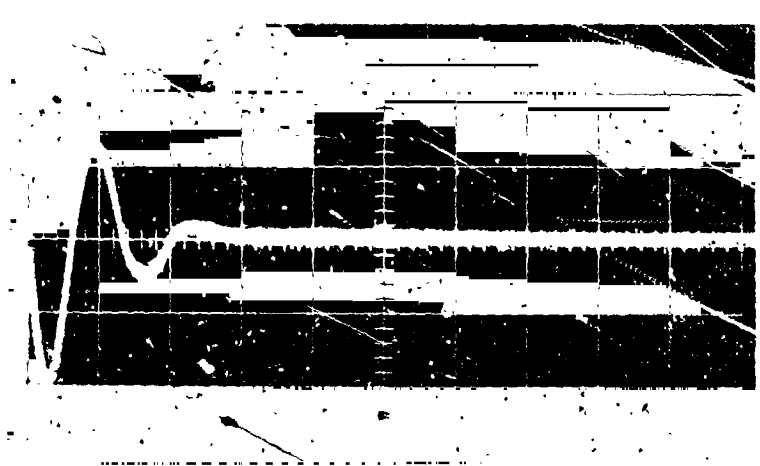


5.8 KV, 240 uf (4,050 joules)

1/4 cycle: 60 usec
24,000 amps

Amps/volt:
0 cycle - 4.5
1/4 cycle - 4.15

Scale 26,000 amps/div 200 usec/div



11.2 KV, 240 uf (15,000 joules)

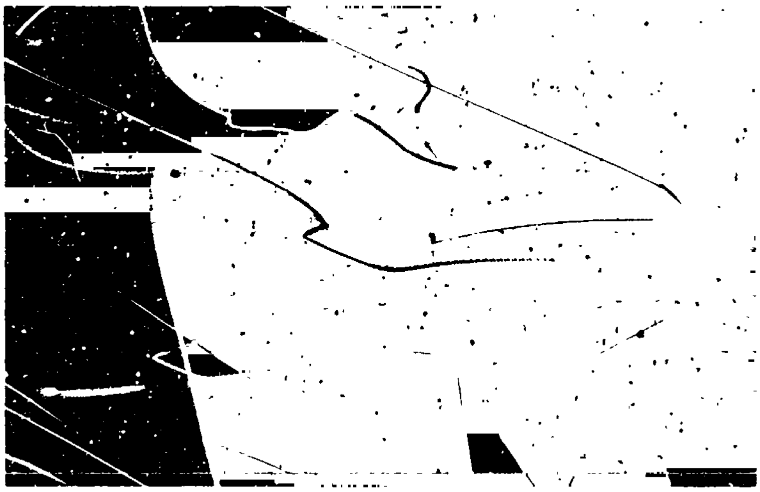
1/4 cycle: 60 usec
44,000 amps

Amps/volt:
0 cycle - 5.3
1/4 cycle - 3.9

DOUBLE 4" COILS (IN SERIES)
DISCHARGE CURRENT TRACES

FIGURE 20

Scale 13,000 amps/div   200 usec/div

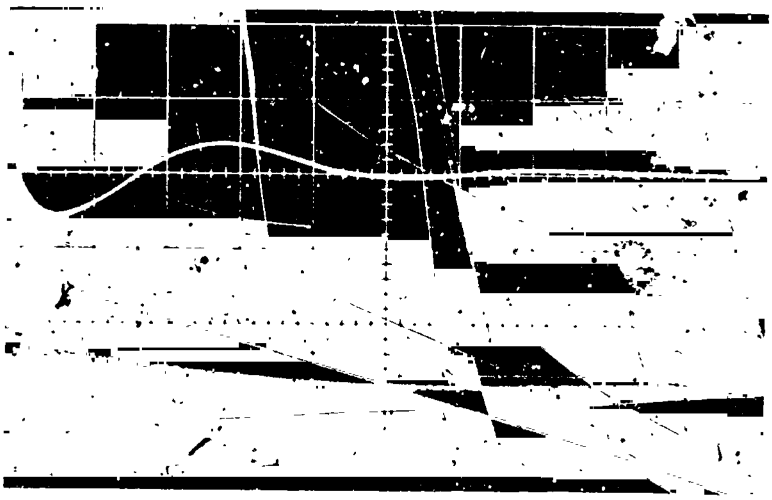


8.4 KV, 240 uf (8,500 joules)

1/4 cycle: 180 usec
14,000 amps

Amps/volt:
0 cycle - 1.9
1/4 cycle - 1.67

Scale 26,000 amps/div   200 usec/div, upper
20 usec/div, lower

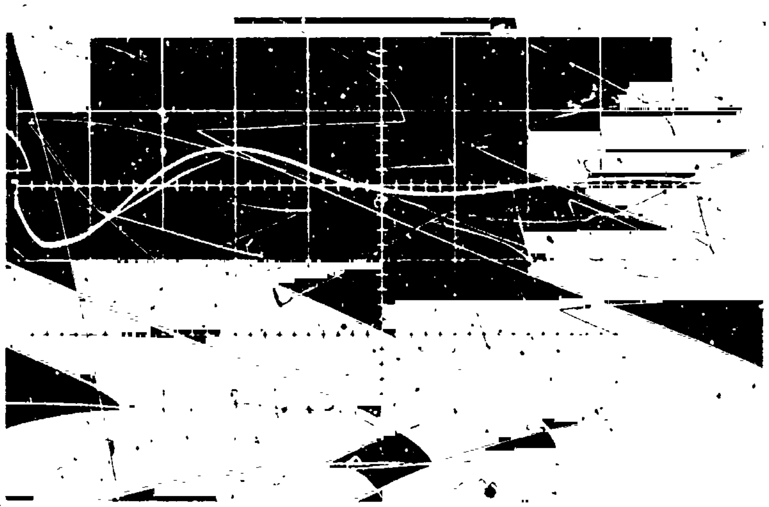


9 KV, 240 uf (9,720) joules

1/4 cycle: 120 usec
17,500 amps

Amps/volt:
0 cycle - 2.02
1/4 cycle - 1.95

Scale 26,000 amps/div   200 usec/div, upper
20 usec/div, lower



12 KV, 240 uf (17,280 joules)

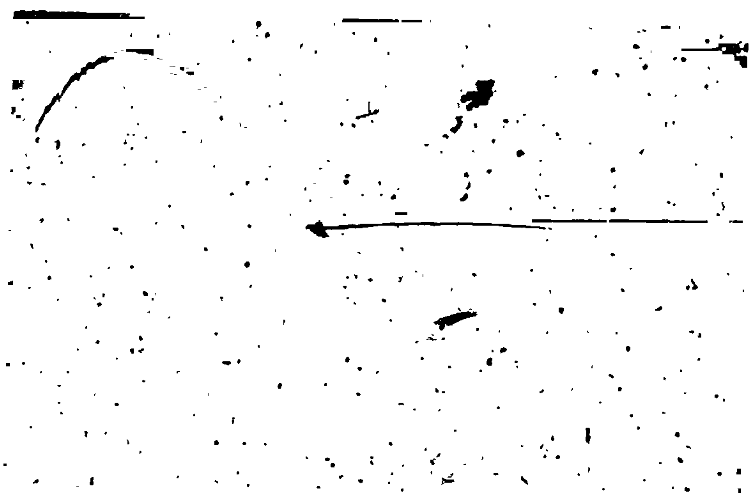
1/4 cycle: 110 usec
22,500 amps

Amps/volt:
0 cycle - 2.17
1/4 cycle - 1.88

12" COIL, 240 uf
DISCHARGE CURRENT TRACES

FIGURE 21

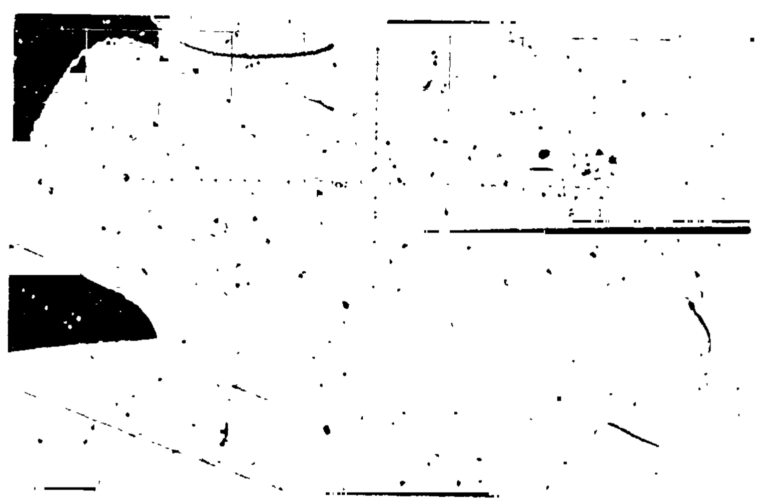
Scale 5,000 amps/div   200 usec/div



3.0 KV, 960 uf (4,320 joules)
1/4 cycle: 300 usec
8,000 amps

Amps/volt:
0 cycle - 2.83 est.
1/4 cycle - 2.67

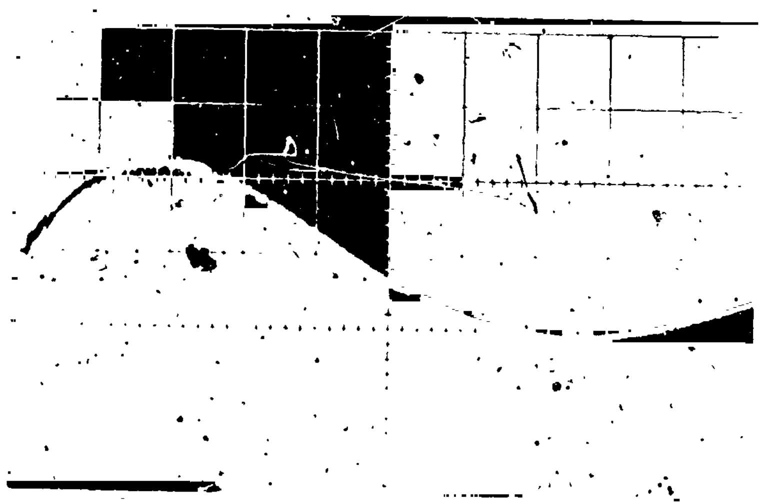
Scale 5,000 amps/div   200 usec/div



3.5 KV, 960 uf (5,900 joules)
1/4 cycle: 300 usec
9,100 amps

Amps/volt:
0 cycle - 2.8 est.
1/4 cycle - 2.6

Scale 12,500 amps/div   200 usec/div



6 KV, 960 uf (17,280 joules)
1/4 cycle: 360 usec
15,000 amps

Amps/volt:
0 cycle - 2.7
1/4 cycle - 2.5

12" COIL, 960 uf
DISCHARGE CURRENT TRACES

FIGURE 22

WORK COMPLETED BETWEEN 1 FEBRUARY AND 31 MARCH 1964

1. Forming operations were continued on integrally stiffened Panel #1, as mounted in the upright fixture, in order to reduce contour deviation to 198 inches (radial) $\pm$ .030" for 12 inches on either side of the weld joint. (See Figure 23 for contour dimensions prior to this test.) Corrective forming commenced by discharging the vacuum mounted 12 inch diameter coil twenty-two times along station 80, which included the greatest deviation, at levels between 5000 and 8500 joules (6.45 KV to 8.4 KV at 240 uf), reducing the deviation to a maximum of .105". The contour dimensions following these discharges are presented in Figure 24 and plotted in Fig. 28.

This test sequence was terminated when cracks were found in the webs of the tee stiffeners at the panel ends at stations 74 and 86, adjacent to the tee stiffener being magnetically impinged at station 80. Likewise the tee stiffeners at stations 18 and 30, adjacent to the tee stiffener at station 24 which had been worked on an earlier test, were found cracked, although less severely than the others. Figures 25 and 26 illustrate the damaged tee stiffeners. An investigation was begun to determine the causes of the failure, and the means to prevent reoccurrence of such damage.

2. Failure was apparently caused by the rapid deceleration of the tee stiffeners at the panel ends producing stresses beyond the ultimate strength of the alloy. Such deceleration may be due to lateral movement (radial direction) of the tees, or due to oscillatory motion of the tee about its root.

Since the panel had withstood approximately 91 discharges (average 6,000 joules) during the outward forming with the 4" coil and failed after relatively few (22) discharges during forming with the 12" coil, it seems reasonable to attribute the failure to the difference in overall panel motion imparted by both coils. The 4" coil produces intense pressure and deformation in the local area directly under the coil. Overall deflection outside the coil area falls off markedly. The 12" coil produces a much lower pressure although over a larger area. Consequently, a lower proportion of discharge energy is absorbed in deformation work and a larger proportion produces elastic strain and movement of the panel as a whole. The failure, which is believed to indirectly result from the overall panel movement, therefore indicates either that such movement be restricted or that the oscillation of the tees be limited.

3. In view of the above, an experiment was conducted to investigate the effectiveness of limiting tee oscillation to avoid failure. A contoured aluminum plate strap was screwed to wedge supports between the tee stiffeners of the panel. Figure 27 shows this clamping arrangement. The attachments prevented movement between tees and also added mass to the top and bottom edges of the panel.

Thirty-eight discharges were made at station 24 at levels from 7000 to 9700 joules (averaging 7270 joules per discharge). (Twenty-two discharges of 5000 to 8500 joules had caused the failure). Penetrant inspection of the stiffening tees disclosed no further damage.

4. Experiments at George C. Marshall Space Flight Center with the 4" coil showed that, at equal discharge energy, the coil produced several times as much metal deformation with the portable MSFC bank than with either the 240 uf or 960 uf Republic Aviation banks. The MSFC discharges attained higher current with greater frequency for about 10 half cycles, whereas the Republic Aviation discharges damp in 3 half cycles or are critically damped. Figure 19-22 illustrates current traces. With the higher currents and longer overall discharge time in the MSFC experiments it was observed that after one or two discharges a temperature rise noticeable to the hand would reach the coil face. Since this timperature rise had never been observed in Republic Aviation experiments, two sets of coil heatup tests were conducted.

Test #1

A 4 inch diameter coil made with the original room setting* epoxy plastic used on the coils furnished to Huntsville was discharged twenty-five times at 12,000 joules (10KV at 240 uf) against an aluminum plate at a rate of one discharge per minute without any heat buildup (as measurable by the hand), or plastic softening.

Test #2

The same coil, again coupled to an aluminum plate, was discharged five times per minute at 7,500 joules for 50 discharges. At this time the coil face temperature had increased to approximately 150°F and the plastic had begun to soften and distort around the coil.

* The formulation of the two plastics tested is as follows:

C-100 Room Setting	Heat Setting Epoxy
51% Epirez 5091	55.5% Epirez 5091
43.8% LP3	33.3% LP3
5.2% Diethylenetriamine	11.2% Curing Agent "Z" Shell Chemical Corporation

5. The room temperature curing epoxy plastic, which was satisfactory in being a relatively soft plastic which would not crack under the discharge impact, was unsatisfactory at MSFC since several minutes between discharges had to be allowed to avoid the coil bulging and distortion which would make it inoperable. Consequently, this composition was removed from another 4" coil (and from the 12" coils) at Republic Aviation and the coils were encapsulated in a heat setting epoxy* capable of withstanding 350°F continuous heat without deformation

This coil was tested by discharge against the aluminum plate at a rate of five discharges perminute, at 7500 to 9500 joules (7.9 KV to 8.9 KV at 240 uf) per discharge, for 75 discharges. Although the temperature of the coil face exceeded 150°F, the plastic remained firm and undistorted. (The energy level ranged from 7.9 to 8.9 KV since the discharge switch was permitted to self fire which produces this range in discharge energy level).

Longitudinal Dimensions - In Inches

Cylindrical Dimensions In Inches

Cylindrical \ Longitudinal	95.0	76.0	66.5	57.0	47.5	38.0	28.5	9.5
92	553	537	530	520	514	516	500	535
80	448	325	320	323	325	339	345	480
63	503	434	428	407	387	393	405	486
62	552	525	534	515	490	482	475	497
56	557	555	575	566	530	531	510	507
55	552	554	572	564	541	531	511	506
54	544	544	563	555	537	527	509	500
53	544	537	553	546	536	525	511	496
52	548	532	550	545	533	527	512	507
52 (Weld Line)	555	537	553	548	522	523	503	506
51	548	541	555	552	526	520	502	492
50	552	548	562	552	530	520	502	487
49	558	556	572	561	535	523	505	487
48	559	551	565	560	533	523	503	482
42	569	557	566	550	516	500	492	480
36	533	497	497	481	447	442	453	475
24	452	364	370	377	367	355	387	457
12	505	491	488	490	463	457	493	490

Contour readings in thousands of an inch mounted in upright fixture. Contour dimensions derived with 198" radius template offset .500" from fixed locating points outside skin ends.

DIMENSIONS OF PANEL # 1 AFTER 91 4" COIL DISCHARGES IN WELD REGION: 6 12" COIL DISCHARGES AT STATION 24; 16 12" COIL DISCHARGES AT STATION 80

FIGURE 23

Longitudinal Dimensions - In Inches

Cylindrical Dimensions In Inches

	95.0	76.0	66.5	57.0	47.5	38.0	28.5	9.5
92	571	543	553	520	517	501	509	531
80	476	427	425	363	372	378	432	482
68	502	423	432	392	382	369	380	472
64	527	473	485	442	432	412	413	479
62	542	500	513	475	462	439	436	485
56	544	529	553	523	512	492	475	496
54	532	522	543	516	512	490	476	487
53	532	524	537	507	512	490	476	485
52 (Weld Line)	540	526	532	509	507	491	474	496
51	537	529	537	507	503	489	471	481
50	542	531	547	517	509	489	470	477
48	548	532	556	527	516	496	472	473
42	563	546	559	525	504	481	462	473
40	557	533	542	507	487	465	448	472
36	533	492	492	462	447	427	426	470
24	451	368	371	362	370	356	361	457
12	512	490	474	472	457	465	469	495

Contour readings in thousands of an inch with panel mounted in upright fixture. Contour dimensions obtained with 198" radius template offset .500" from fixed locating points outside skin ends.

DIMENSIONS OF PANEL #1 AFTER 91 4" COIL DISCHARGES IN WELD REGION, 6 12" COIL DISCHARGES AT STATION 24, 38 12" COIL DISCHARGES AT STATION 80

FIGURE 24

CRACKED TEE STIFFENERS AT BOTTOM EDGE OF PANEL #1 AT STATIONS 74 AND 86, AFTER 38 DISCHARGES MADE AGAINST STATION 80, USING 12" DIAMETER COIL

FIGURE 25

CRACKED TEE STIFFENERS AT TOP EDGE OF PANEL #1, AT STATIONS 74, 86, AFTER 38 DISCHARGES MADE AGAINST STATION 80, USING 12" DIAMETER COIL

FIGURE 2

REINFORCEMENT ADDED TO TOP AND BOTTOM OF PANEL #1
FIGURE 27

PANEL 1 MOUNTED IN VERTICAL FIXTURE AFTER ALL CORRECTIVE FORMING
FIGURE 28

MR3790

INDEX OF SUBJECTS DISCUSSED IN PROGRESS AND FINAL REPORTS

LIST OF ITEMS SHIPPED TO MSFC

Item Number	Description
1	30 ft. of 4 conductor coaxial cable with block terminations on one end only. The specifications of each coaxial conductor are: Polyethylene jute core to .845" O. D. Inner conductor - 30 gauge bare copper braid Insulation - polyethylene to 1" O. D. Outer conductor - 30 gauge bare copper braid Jacket - PVC to 1.135" O. D. Characteristic impedance Inductance - .006 microhenry's per coax foot D.C. resistance - 53 microhms per coax foot
2	30 ft. of 16 conductor 1/0 welding cable with block terminations on one end only
3.	(2) 12" diameter 40 turn coils per MRP 2589
4.	(1) Vacuum held fixture for 12" diameter forming coil per MRP 2581
5.	(1) Dual 4" diameter coil holder per MRP 2586
6.	(4) 4" diameter 10 turn coils per MRP 2589
7.	(1) Single 4" diameter coil holder per MRP 2586