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ABSTRACT

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A Marshall Coil was fabricated by the LASL CMB-6 Materials Technology Group for use in an electrical testing program to evaluate the Marshall Coil concept. The coil is basically a hat-shaped epoxy insulator which was electroplated with copper on all surfaces, and a complex conductor pattern was machined out of the copper. The brim of the coil is approximately 84 cm diameter and the crown is 24 cm high. Other techniques for fabricating Marshall Coils were studied, the one selected being that which was felt to offer the best chance of success on a one-time basis. Alternate proposals involved (a) the potting of a freestanding copper insulator array in epoxy resin, and (b) inlaying stamped copper conductor sections in the slots of a machined epoxy insulator.

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## Summary

A Marshall Coil was fabricated by the Los Alamos Scientific Laboratory CMB-6 Materials Technology Group for use in an electrical testing program to evaluate the Marshall Coil concept. The coil is basically a hat-shaped epoxy insulator which was electroplated with copper on all surfaces, and a complex conductor pattern was machined out of the copper. The brim of the coil is approximately 84 cm diameter and the crown is 24 cm high. Other techniques for fabricating Marshall Coils were studied, the one selected being that which was felt to offer the best chance of success on a one-time basis. Alternate proposals involved (a) the potting of a freestanding copper insulator array in epoxy resin, and (b) inlaying stamped copper conductor sections in the slots of a machined epoxy insulator.

## Introduction

A program to fabricate a Marshall Coil was initiated in the Materials Technology Group at the Los Alamos Scientific Laboratory to provide one Marshall Coil for evaluation as a Theta Pinch Reactor Implosion Coil.[1]

The proposed coil can best be described as a "hat-shaped" epoxy insulator which is clad with a copper conductor pattern. It measured 84.1 cm on the OD of the "brim" with a 24.5-cm-high tubular "hat" section which was bored to 21.6-cm diameter. Ninety 1.5-mm-thick copper conductors were interconnected by the copper current feed rings on the top and the bottom perimeters of the coil brim. Each conductor may be imagined as beginning at the current feed ring on the tube side of the flange, passing radially inward and then straight up the outside of the tube, spiralling one-half turn to the opposite side as it passed downward through the tube bore, and continuing radially outward to the current ring on the underside of the flange, 180° opposite its imaginary starting point. The conductor width diminished as it radially approached the "hat" section on both the upper and lower brim surfaces, but remained constant on the outer and inner hat surfaces. The ratio of conductor/non-conductor spaces was essentially 1:1. Figure 1 illustrates the coil before it had been overpotted with epoxy and before final machining was completed.

## Proposed Fabrication Techniques

Several methods for fabricating the coil on a "one only" basis were proposed; two of the methods were selected for final consideration. They were:

### Aluminum Mandrel

(a) Form an aluminum mandrel, (b) electroplate the surface with copper, (c) machine the required conductor pattern into the copper, (d) dissolve out the aluminum mandrel, (e) and pot the resulting copper "basket" in epoxy.

### Epoxy Mandrel

(a) Cast an epoxy mandrel, (b) machine it to size, (c) electroplate the surfaces with copper, (d) machine the required conductor pattern into the copper, (e) and over-pot a portion of the conductor with epoxy.

Fig. 1. Marshall Coil Before Overpotting And Final Machining.

## Evaluation of Proposed Fabrication Techniques

The aluminum mandrel technique utilized conventional fabrication technology; the only real problem visualized was in the handling and positioning of the conductor "basket" in an epoxy casting mold. This was considered to be a potentially serious problem, however, as the stability of the copper "basket" once it was released from the aluminum mandrel was an unknown.

The success of the epoxy mandrel technique depended primarily upon the adhesion of the copper electroplating to the epoxy mandrel. Adhesion would have to be sufficient to permit machining of the conductor pattern into the copper without separation of the two. A test sample plate of copper-plated epoxy was fabricated and several 2.3-mm-wide slots were machined into it with 2.3-mm-wide copper conductor strips between each slot. Proper fixturing, cooling, and care was required during machining but it was found that slots could be cut without serious loss of adhesion. From this observation a decision was made to use the epoxy mandrel technique to fabricate the Marshall Coil.

## Mandrel Fabrication

A mandrel machine blank was cast from epoxy in an aluminum mold (Fig. 2). The epoxy formulation was:

Fig. 2. Cast Epoxy Insulator Machine Blank

| Material | Parts by Wt. |
|---|---|
| Epon 828[2] | 75 |
| Epon 871[3] | 25 |
| Diethanolamine | 10 |

The material was heat cured at 75°C for 16 hours. The blank was then machined to size in preparation for electroplating.

The coil design called for 3.9-mm thick x 152-mm wide circumferential slots in the epoxy insulator at the perimeter immediately adjacent to the copper conductors on both the top and bottom surfaces of the coil "brim". The purpose of these slots was to increase the electrical path length between the top and bottom conductors. When the coil was placed in service the cavities formed by the slots would be filled with polyethylene insulators. Formation of the slots was accomplished by adhesive bonding polystyrene rings of the same size as the slots to the epoxy mandrel prior to electroplating. They were to be dissolved out after all of the machining operations on the coil were finished. Figure 3 shows the polystyrene rings in place on the epoxy insulator.

## Electroplating

The machined epoxy mandrel with polystyrene rings adhesive bonded to both sides of the "brim" was sandblasted and delivered to the Group CMB-6 Electrochemistry/Coatings Section. There a 12.7-mm-wide copper strip was fastened around the circumference of the insulator to serve as a means of supporting it in the baths and to make electrical contact. The "Shipley Cuposit" process was used to form a plateable surface.

Fig. 3. Machined Epoxy Insulator With Polystyrene Rings Bonded to Surfaces.

A copper strike was then put on the insulator using a copper cyanide bath (23 gm/liter CuCN, 46 gm/liter KCN, 20 gm/liter $K_2CO_3$).

Four conforming copper electrodes were cast and two thicknesses of polypropylene cloth were sewn around them to prevent contamination of the bath by insoluble inclusions from the copper anodes. The outer regions of the epoxy "brim" which were not to be plated were masked, the four copper anodes were assembled on the insulator, and it was plated in an acid copper bath (200 gm/liter $CuSO_4$ to 78.75 gm/liter $H_2SO_4$) at room temperature and 29 amps/cm$^2$. Figure 4 shows the coil ready for plating.

Solution flow patterns developed during plating because of the large size of the part in relation to the plating tank size. The part was plated to a thickness of 2.0 mm and then machined smooth and replated. This process was repeated several times until the necessary thickness of copper was achieved.

## Machining

Machining of the electroplated copper cladding to proper thickness and subsequent slotting to form the 90 conductor strips required proper fixturing, some special tools, and constant care. However, all of the work involved standard machining technology.

Fig. 4. Epoxy Insulator With Plating Anodes.
(with polypropylene cloth removed to expose anodes)

All of the electroplated copper surfaces were first machined to proper thickness using a tracer on a 1.4 m swing lathe. Some problems were encountered. Adhesion of the copper to the epoxy was marginal and it was difficult to maintain firm clamping on some areas as they were machined. As a result, about two thirds of the copper on the "brim" area opposite the tubular "hat" section released from the epoxy insulator. The "brim" was again clamped down snugly and the surface machining operations were completed.

The exterior slots on both sides of the "brim" and on the "hat" were machined into the copper with an end mill on a horizontal boring mill. Multiple cuts were required to form the 90 slots between conductors on both sides of the coil "brim". No serious loss of adhesion was experienced but care was taken to clamp the copper area as it was being machined.

The slots between conductors on the inside of the bore were also cut with an end mill, this time on a 90° arm on a standard milling machine. A low lead was used to obtain the spiral down the bore. Some of the conductor strips released from the epoxy insulator during this operation but no serious problems resulted. Figure 5 shows the Marshall Coil during some of the machining operations.

Fig. 5. Marshall Coil During Machining.
(Top) Slotting The Inside Bore
(Bottom) Set-up for Slotting Exterior Surfaces.

## Overpotting

After the machining operations were completed the coil was scrubbed with warm water and detergent. A "Jet-X" car wash sprayer was also utilized to dislodge dirt and grease particles, particularly beneath the copper that had come loose during machining. After thorough drying, the loose copper on the underside of the "brim" was rebonded to the epoxy insulator with an epoxy adhesive. The copper surfaces were cleaned with Brillo pads and steel wool to remove oxide accumulations. Figure 6 is a close-up view of the machined conductors and grooves.

Fig. 6. Close-up Views of Machined Grooves on Marshall Coil "Brim" and Inside the Bore.

In preparation for overpotting the interior and exterior of the "hat" section and all of the "brim" area extending radially inward from the polystyrene rings, all of the radial slots on both sides of the coil rim were filled with polyurethane sealant from the point at which epoxy overpotting was to end. This was to prevent epoxy resin from running over the polystyrene rings which lay directly beneath that portion of the slots. If these slots had filled with epoxy during overpotting, the polystyrene rings would no longer have been exposed and considerable difficulty would have been experienced in subsequently dissolving out the polystyrene rings. In addition, a bead of polyurethane sealant was run circumferentially around each side of the coil in the areas where the mold was to shut off the epoxy flow. This was also to insure that epoxy would not leak out over the slot areas covering the polystyrene rings.

The same casting mold which was used for casting the epoxy insulator machine blank was also used for overpotting the coil. Some modifications were required, including the addition of a lid and o-ring seals so vacuum assist could be used in filling the mold. A room temperature cure epoxy resin system was selected solely because there was concern that the application of heat to the coil might cause separation of the copper conductor strips from the epoxy insulator by differential expansion. There were disadvantages to the room temperature cure system also. Its higher viscosity would extend the mold filling time while the pot life was relatively short. It would also be more apt to entrap air.

The system selected was Epon 815 resin (70 parts by weight) cured with Versamid 140 (30 parts by weight). This offered a fair compromise relative to viscosity and pot life. Vacuum assist was used to speed the mold filling and a vibrator was utilized to minimize air entrapment. Complete mold filling was accomplished, but there were several small air voids entrapped in the casting. They were later repaired by drilling them out and refilling the voids from a hypodermic syringe.

## Completion of Coil

Two operations remained to complete the Marshall Coil: (1) dissolution of the polystyrene rings and (2) machining of the epoxy insulator perimeter to final size.

To dissolve out the polystyrene rings, the coil "brim" was immersed in xylene solvent in a suitable metal tank. Agitation was provided by two stirrer paddles driven by air motors. Several days were required for complete dissolution of the rings and the solvent was replaced with fresh material as needed. There was no visible damage to the epoxy insulator or the copper/epoxy bond. Figure 7 shows the coil in the dissolution tank. Three views of the completed coil are shown in Fig. 8.

Fig. 7. Dissolution of Polystyrene Rings

Fig. 8. Completed Marshall Coil

## Other Fabrication Techniques

The techniques used for fabrication of this Marshall Coil, though quite successful, are not well suited to the production of several coils. A proposal for fabricating coils on a production basis is outlined below:

(1) Injection mold or compression mold plastic insulator mandrels with the conductor pattern grooved in.

(2) Stamp out copper conductor ribbon to fit the grooves in the insulator.

(3) Adhesive bond the conductor ribbon into the insulator grooves, and the current rings to the insulator surface.

(4) Join the conductor ribbons to the current rings by laser welding or crimping.

(5) Overpot or coat with epoxy.


## Acknowledgements

The authors wish to gratefully acknowledge the assistance of the following people in fabricating the Marshall Coil: Claude Blatti and Robert Ginder, SD-5 Machine Shop; Alfred Zerwas, Robert Larson, Ed Roemer, and Paul Harris, SD-1 Machine Shop.

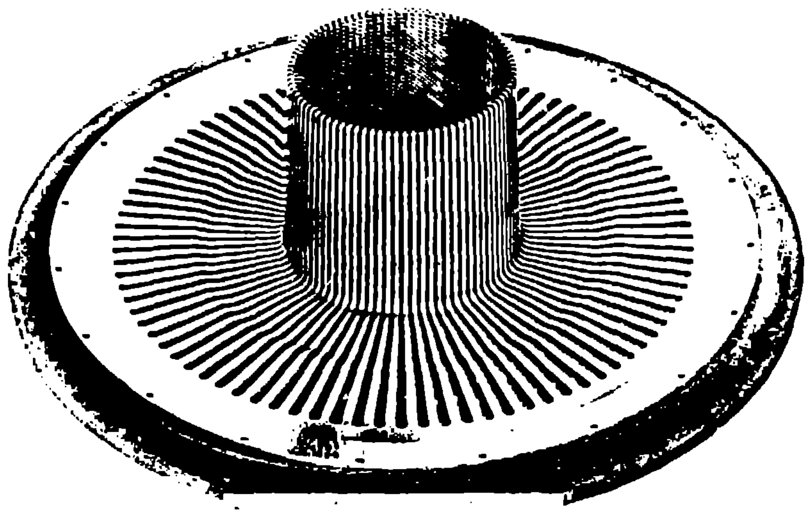

## References

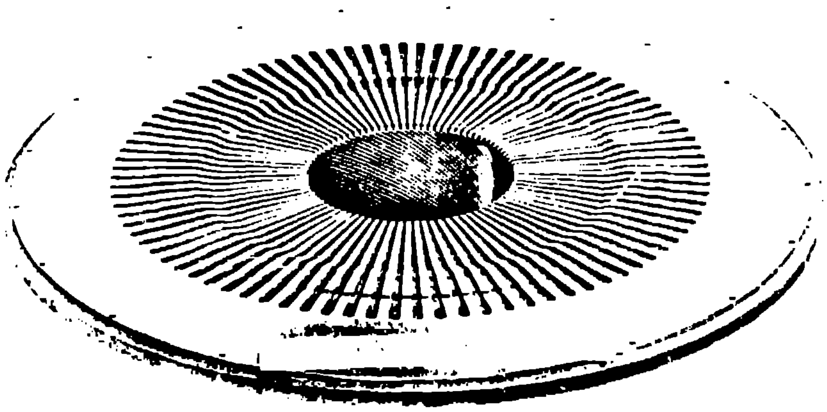

1. For a discussion of design parameters for the Marshall Coil refer to "Design and Fabrication of a Radially-fed Implosion Heating Coil" by L. D. Hansborough, J. M. Dickinson, J. G. Melton, and W. C. Nunnally, Seventh Symposium on Engineering Problems of Fusion Research, Knoxville, TN., October, 1977.

2. Bisphenol A epoxy resin from Shell Chemical Co.

3. Flexibilizing epoxy resin from Shell Chemical Co.

~~Figure 2~~





~~Figure 4~~

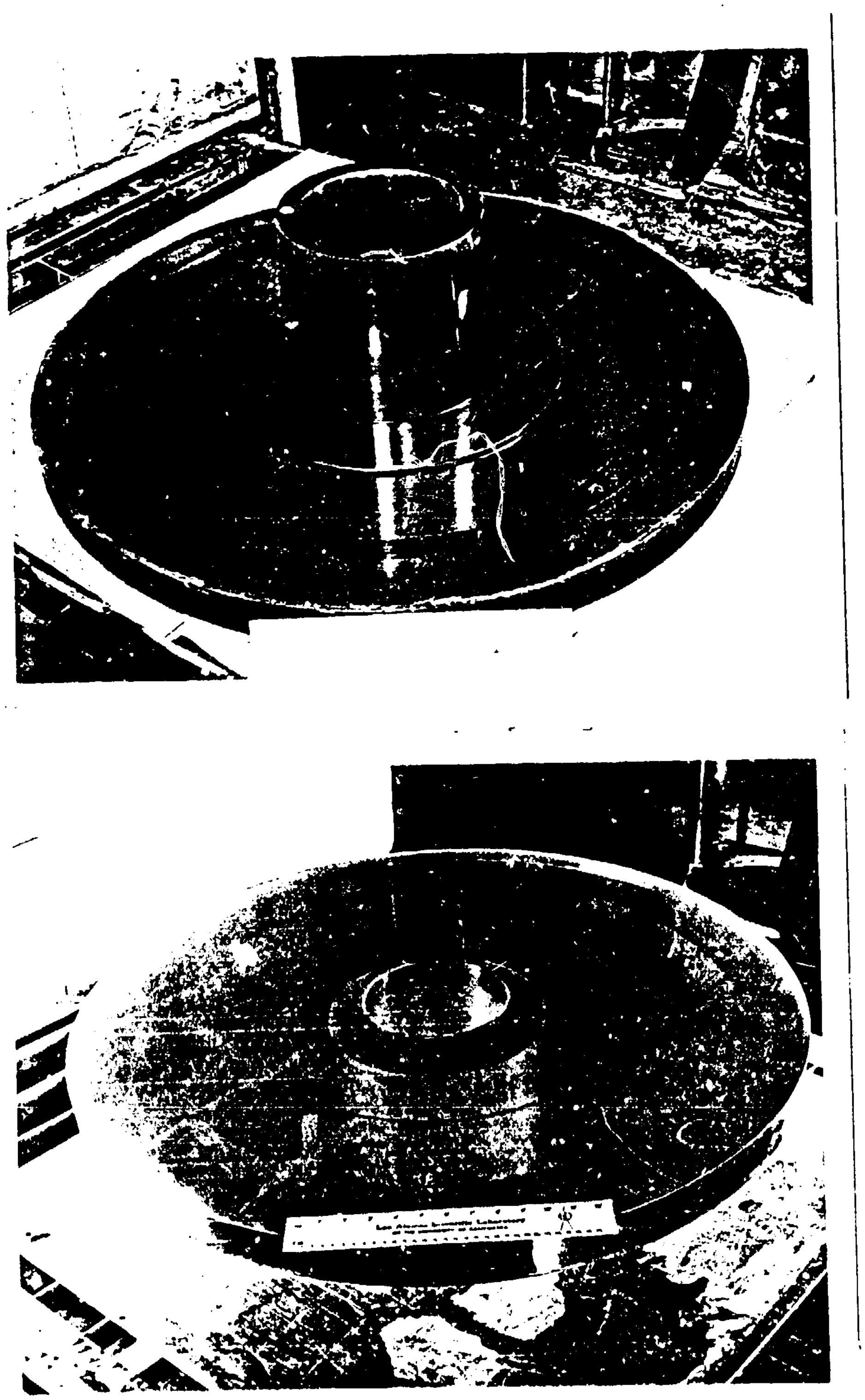
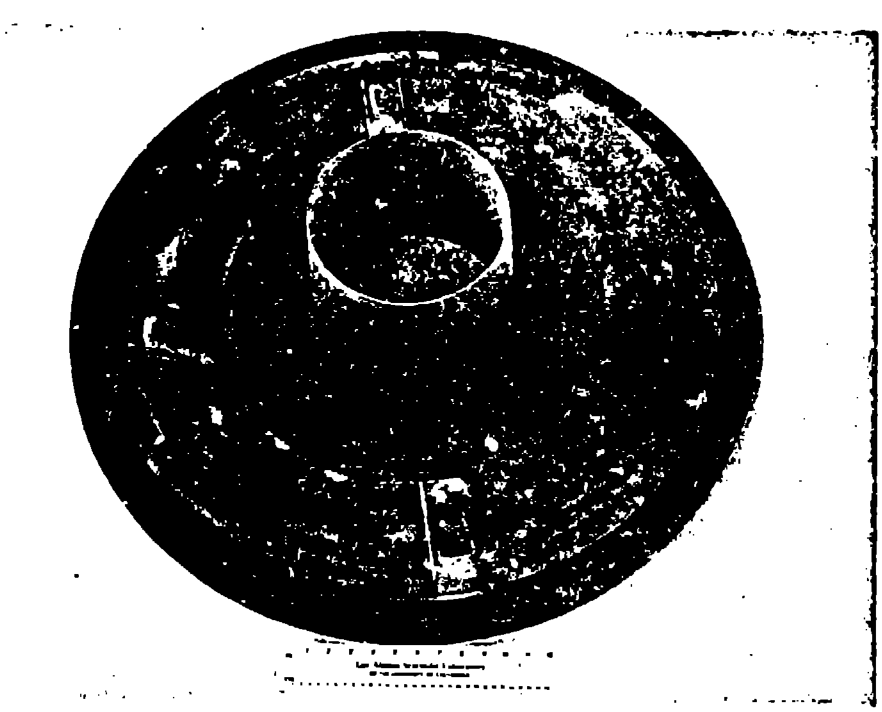


Figure 2 – Cast Epoxy Insulator Machine Blank

~~Figure 2~~



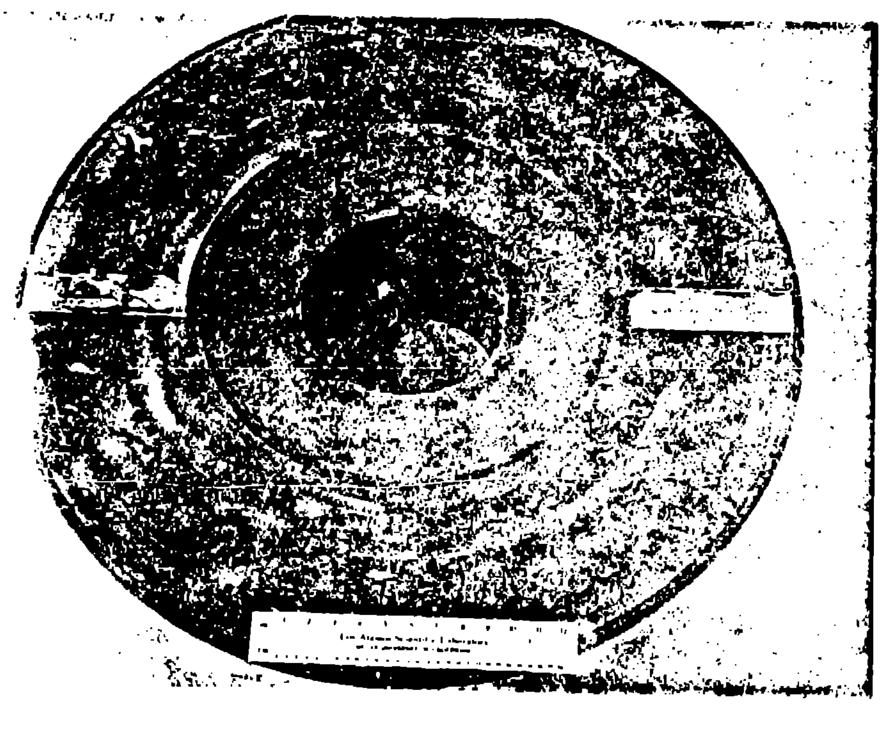


Figure 3 – [illegible] Epoxy Insulator with Polystyrene Rings
[illegible] to Surface

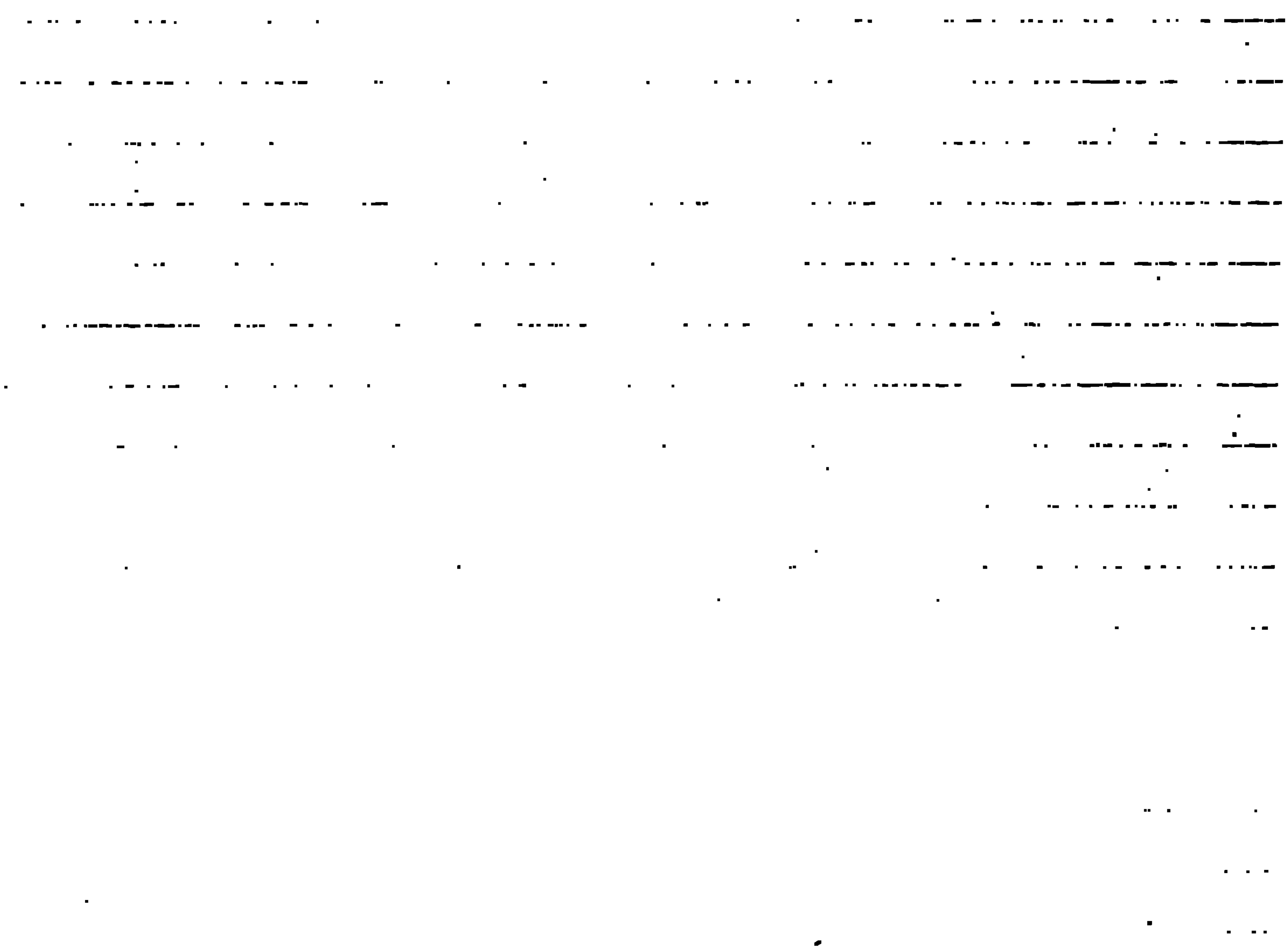
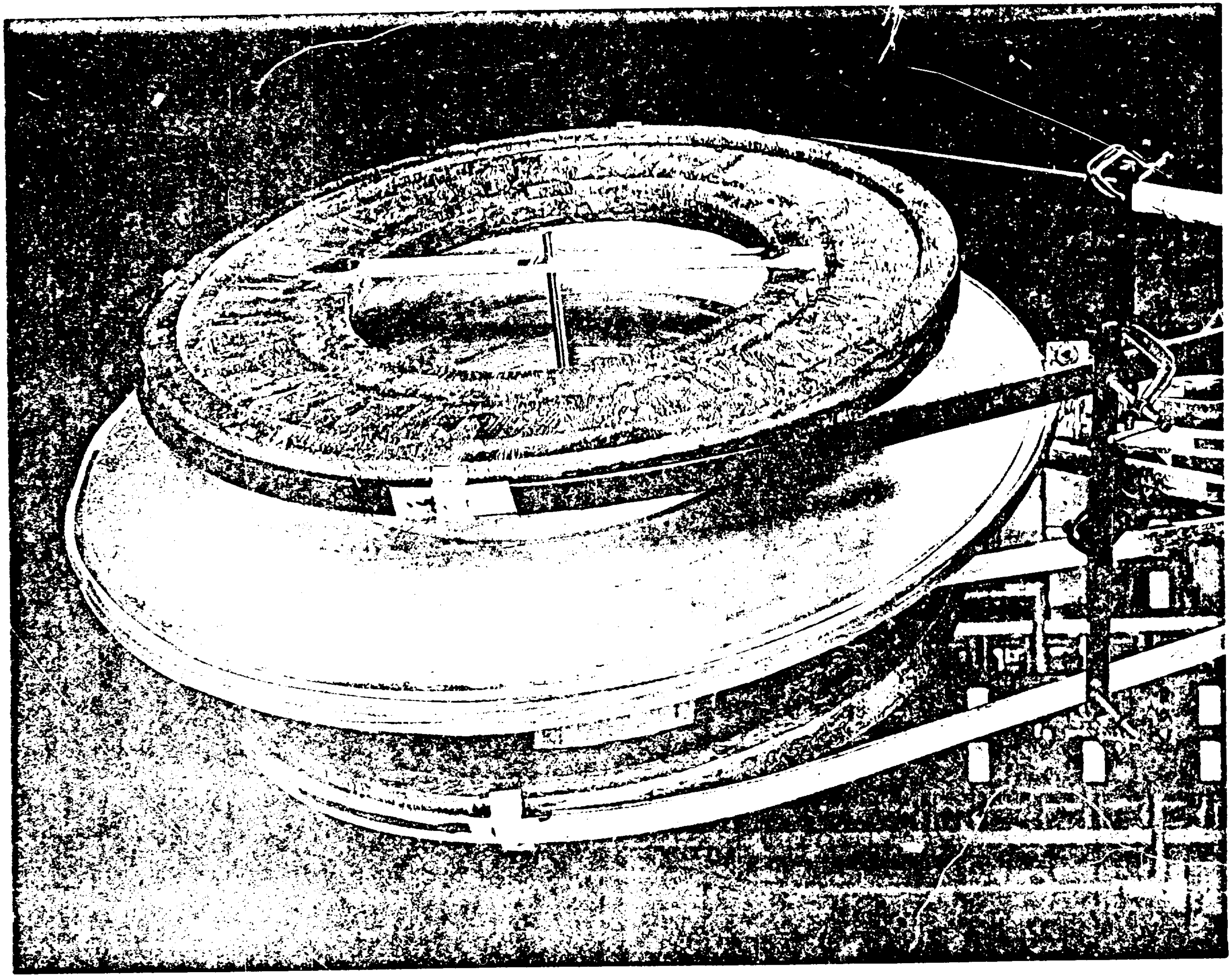
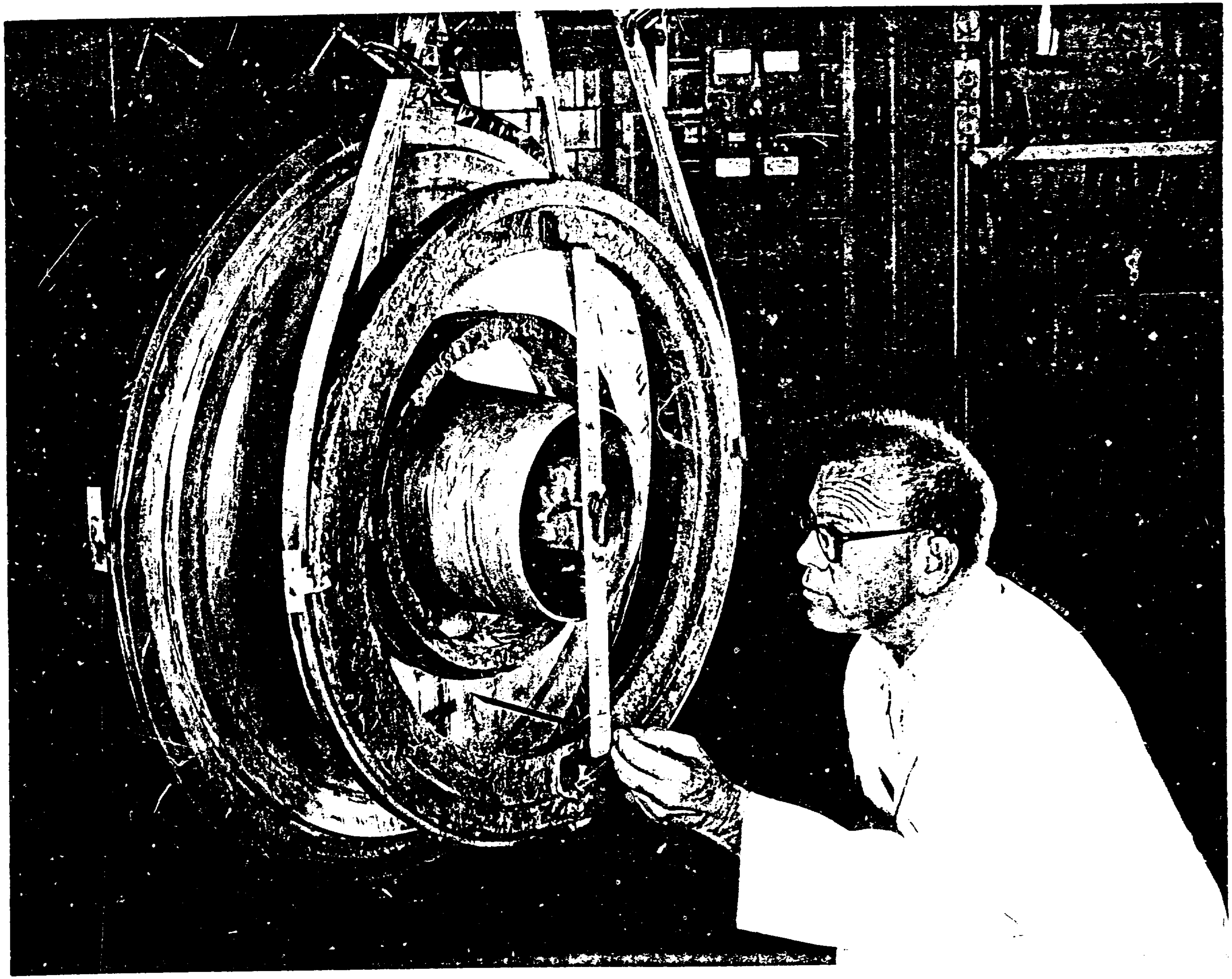
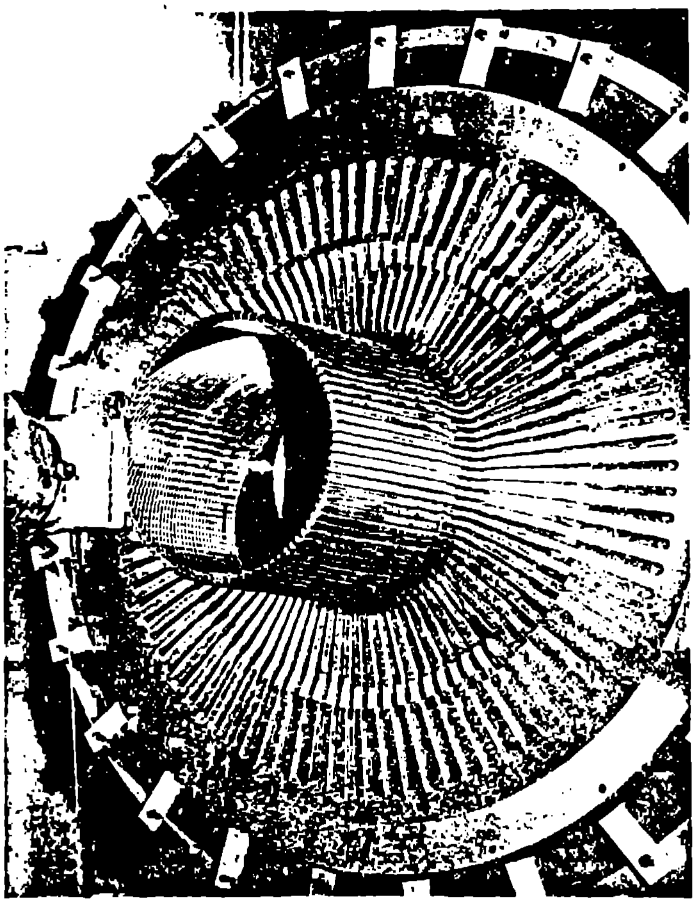


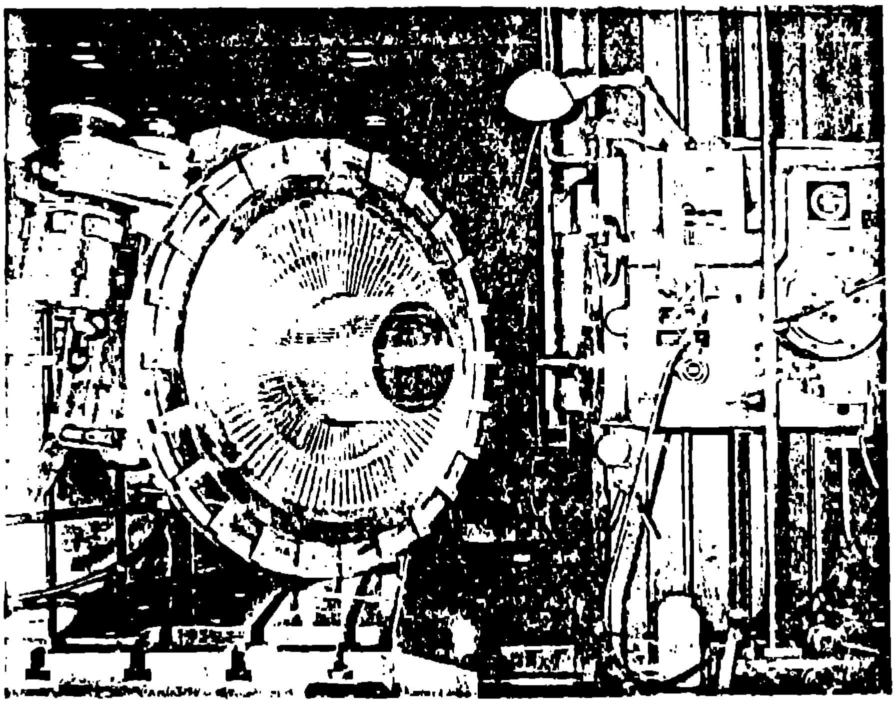
Fig. 4 – Epoxy Insulator with Plating Anodes.
(with polypropylene cloth removed to expose anodes)





~~Figure 5~~





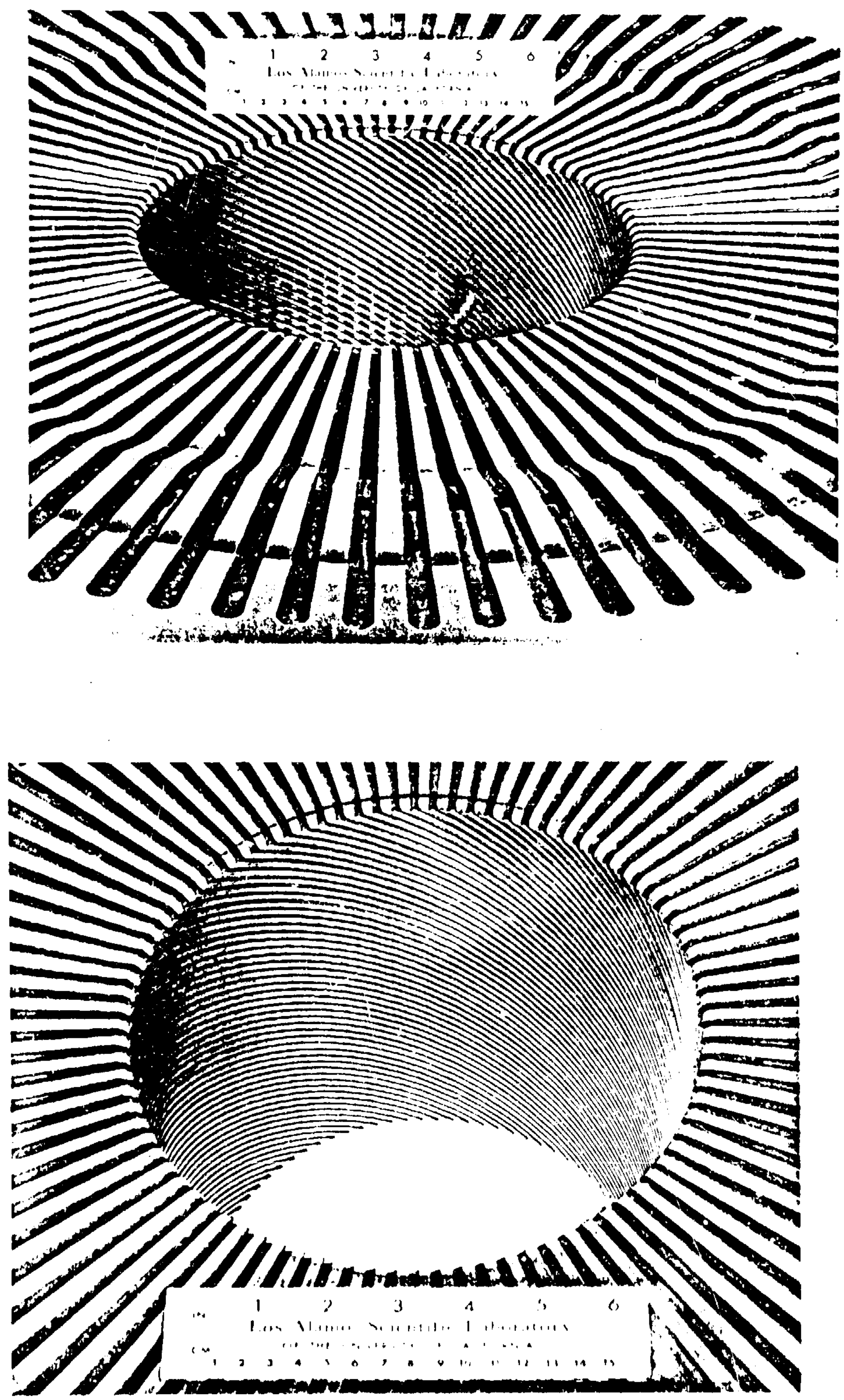



Figure 6. Close up View of Machined [illegible]
[illegible]

~~Figure 3~~

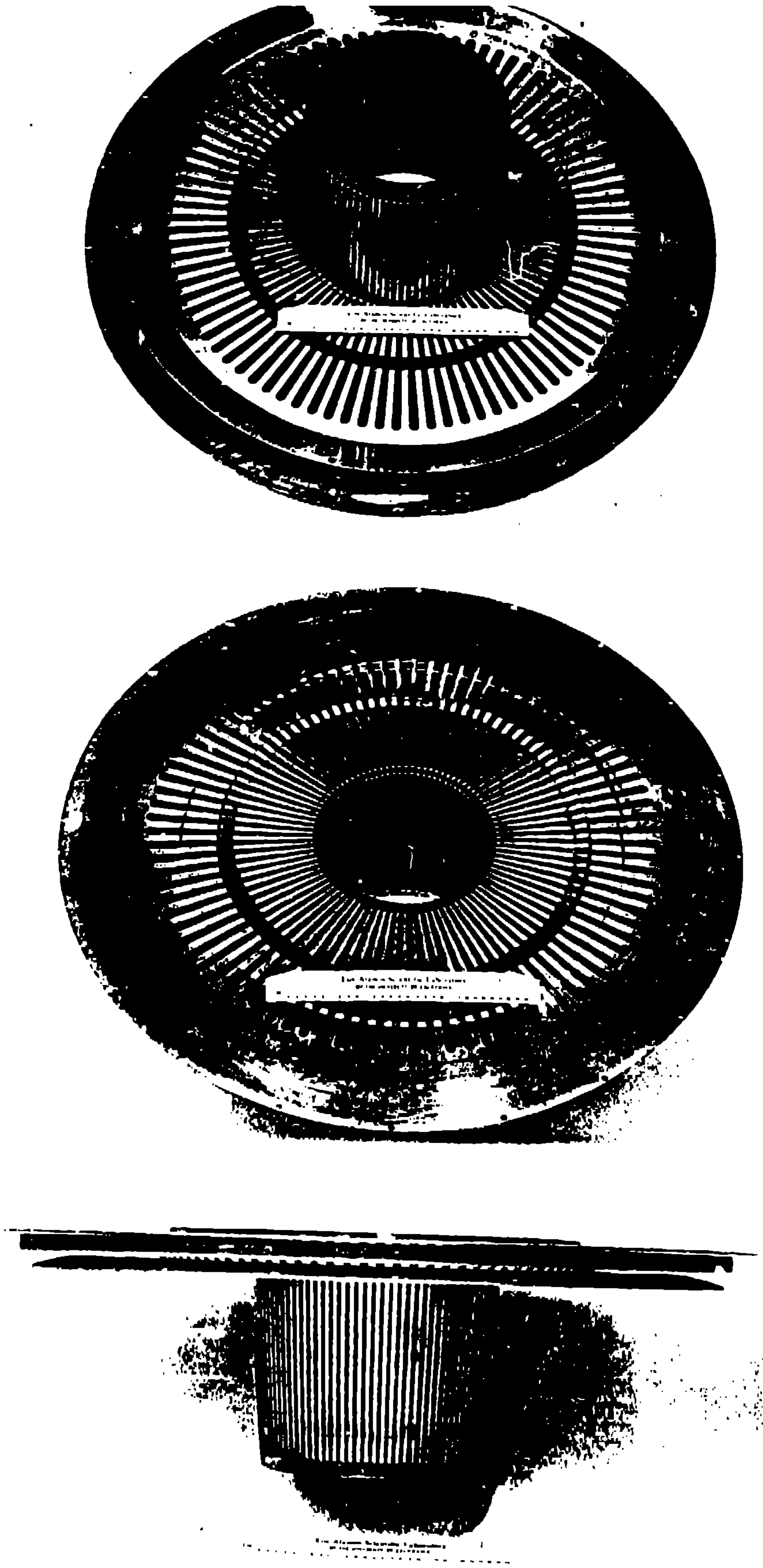


Figure 7 [illegible]