AN ELECTRONICALLY CONTROLLED FUEL INJECTION SYSTEM FOR AN INTERNAL COMBUSTION ENGINE

by

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Signature of Author
Department of Electrical Engineering, May 25, 1962

Certified by _____
Thesis Supervisor

Accepted by _____
Chairman of Departmental Committee on Graduate Students

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ABSTRACT

The variables involved in a carburetion or fuel injection system for an internal combustion engine are air flow and fuel flow. If both of these can be measured by transducers with electrical outputs, and either one controlled by an electrical signal, then the ease, speed, and accuracy of manipulation of electrical quantities can be brought to bear.

A system of this type would probably be far too complicated for general commercial application, but might prove valuable in determining the performance that could be expected from a given engine under an accurately controlled and easily adjustable fuel-air ratio.

The experimental work on this thesis has been the development and preliminary testing to prove feasibility of a novel air flow rate meter. This work consisted of the selection of a pressure reference and the use of it to design and construct a closed loop servo system to measure air flow rate accurately, quickly, and over a wide range.

The other components required for the fuel injection system are available commercially, but the time involved has postponed testing of the entire system until after this thesis is submitted.

Thesis Supervisor: Leonard A. Gould
Title: Associate Professor of Electrical Engineering

ACKNOWLEDGMENT

The author acknowledges his indebtedness to the following:

Professor A. L. Winn, Chairman of the Department of Electrical Engineering of the University of New Hampshire for the technical assistance and encouragement in beginning this project and without whose help it would not have been possible.

Associate Professor Leonard A. Gould of the Department of Electrical Engineering of the Massachusetts Institute of Technology for supervising this thesis.

My wife, Roberta, for her help in preparing the photographs and in typing of this thesis.

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I INTRODUCTION

This thesis is a part of a larger project which began in 1960 as a special project under the supervision of Professor A. L. Winn, Chairman of the Department of Electrical Engineering at the University of New Hampshire. Hopefully it will end some time in the future, after appropriate laboratory tests, with the installation of the complete fuel injection system in either an automobile or boat.

Figure 1 shows a block diagram of a continuous flow, port injection system for a gasoline engine. The position of the throttle (at a given engine speed and air density) determines the amount of air entering the engine. The flow meters measure the amounts of air and fuel entering the engine. If the fuel-air ratio is not that for which the system is adjusted, a comparison of the outputs of these flow meters will yield an error signal. This error signal, after amplification, operates a valve in the fuel line. Thus the fuel-air ratio is always maintained very near the desired value.

This system is intended to be nearly ideal from a functional viewpoint, although complexity would make general commercial application unfeasible. The completed system should, however, be a valuable research tool. It would save time in taking data in the laboratory and

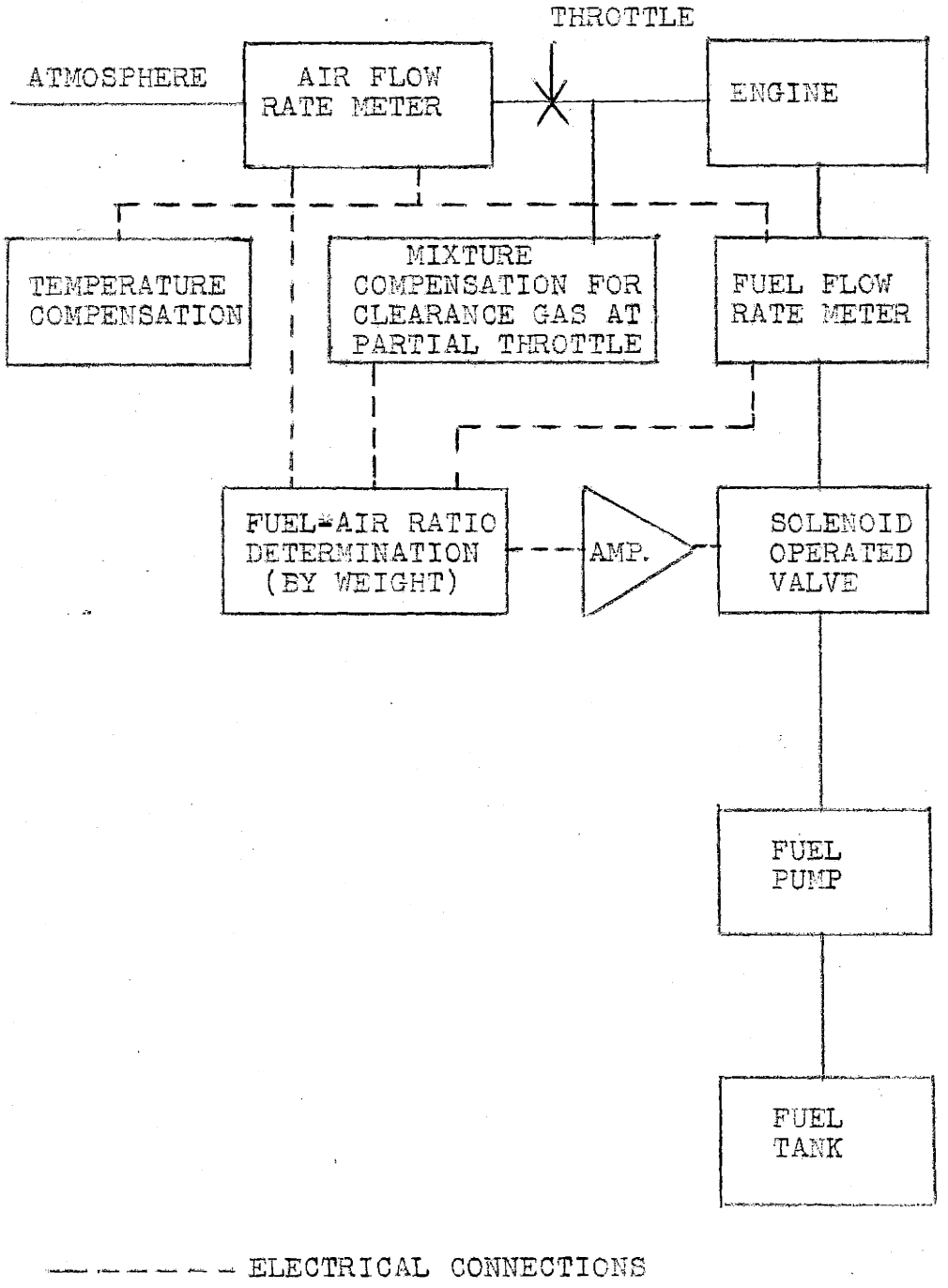

THROTTLE
ATMOSPHERE
AIR FLOW RATE METER
ENGINE
TEMPERATURE COMPENSATION
MIXTURE COMPENSATION FOR CLEARANCE GAS AT PARTIAL THROTTLE
FUEL FLOW RATE METER
FUEL-AIR RATIO DETERMINATION (BY WEIGHT)
AMP.
SOLENOID OPERATED VALVE
FUEL PUMP
FUEL TANK
ELECTRICAL CONNECTIONS

Figure 1

allow fuel-air ratio to be maintained under actual operating conditions to an accuracy that can be done now only in the laboratory. The air flow rate meter described herein should also have other applications.

Most of the components for this system are available commercially or easily constructed. The major exception is the air flow rate meter.

The experimental work of this thesis has been the selection of a suitable pressure reference and using it, the design, construction, and preliminary testing of a closed loop servo system to measure air flow accurately, quickly, and over a wide range.

The following is a list of characteristics that this meter should have:

1. Operating range of 100:1 flow variation.
2. Cut-off frequency greater than 5 cps.
3. Pressure drop less than 1% of an atmosphere.
4. Other specifications not effected by the acceleration and vibration of an automobile.
5. Accuracy greater than ±3% over entire operating range.
6. Compensation for the variation of air density with temperature and, if possible, pressure so that the output will represent lb./min. of air.
7. Temperature range from 0 to 200°F.
8. Volume less than 2 $ft.^3$

9. Power requirement less than 200 watts.

A meter satisfying even requirements (1) through (5) is not, to my knowledge, available commercially.

One method of constructing such a meter is shown in Figure 2. The servo system maintains a constant pressure drop (except for temperature compensation) across a variable orifice created by the butterfly valve. The position of this valve can then be calibrated in lb./min. of air flow. The approximate relationship will be $G = a + b \sin^2 (\theta \pm \phi)$. "G" is the flow rate of air (mass/time). "a" is a function of the clearance around the butterfly valve when the valve is closed. Note that "a" may vary with temperature if the coefficients of thermal expansion of the components of the butterfly valve are not all the same. "b" is a constant. "θ" is the angle the butterfly valve is open. "ϕ" is an error term that depends on the accuracy of the pressure reference and the servo system.

The pressure transducer is a combination of a pressure reference with an extremely sensitive pressure or flow transducer. The pressure reference is a centrifugal blower run at a known speed by a syncronous motor. The transducer is a hot wire anemometer.

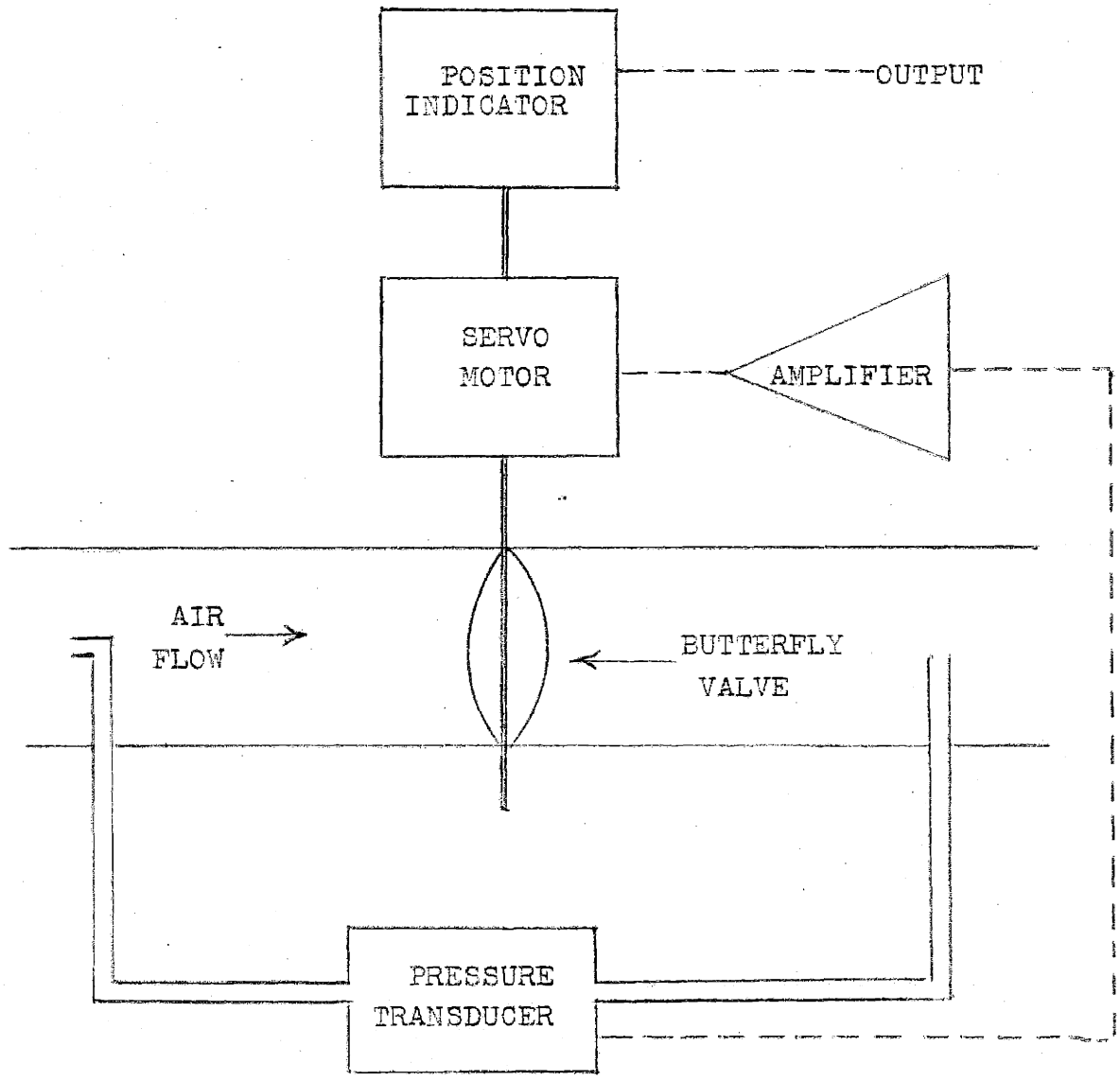

POSITION INDICATOR
OUTPUT
SERVO MOTOR
AMPLIFIER
AIR FLOW
BUTTERFLY VALVE
PRESSURE TRANSDUCER
ELECTRICAL CONNECTIONS

Figure 2

II PRELIMINARY CALCULATIONS

One of the first steps in proceeding from the block diagram to the mechanical design of the system was the determination of the maximum air flow rate. This was chosen as that of a 400 $in.^3$ 4-cycle engine @ 6,000 rpm with volumemetric efficiency approaching 100%. This would operate well on most of Detroit's current V-8 engines.

$$\frac{2 \times 10^2 \text{ in.}^3}{\text{rev.}} \times \frac{6 \times 10^3 \text{ rev.}}{\text{min.}} \times \frac{\text{min.}}{6 \times 10 \text{ sec,}} \times \frac{\text{ft.}^3}{1.44 \times 1.2 \times 10^3 \text{ in.}^3} =$$

11.55 $ft.^3/sec.$

If a total pressure tap is used on the upstream side of the butterfly valve and a static tap on the downstream side, the pressure drop, regardless of flow rate, between these two points will approximately equal the kinetic energy at maximum flow rate. This neglects head loss between the two taps when the butterfly is wide open and also errors introduced by the variation of velocity with position in the pipe. A pressure drop of .4% atmosphere was chosen as a reasonable compromise between butterfly valve size and pressure drop. Since the .4% chosen is approximate, the variation in velocity with position in the pipe will be neglected in this calculation.

$$\frac{v^2}{2g} = \frac{4 \times 10^{-3} \times 1.47 \times 10 \text{ lb.}}{\text{in.}^2} \times \frac{1.44 \times 10^2 \text{ in.}^2}{\text{ft.}^2} \times \frac{\text{ft.}^3}{7.52 \times 10^{-2} \text{ lb.}}$$

$$v^2 = \frac{2 \times 32.2 \times 4 \times 10^{-3} \times 1.47 \times 10 \times 1.44 \times 10^2}{7.52 \times 10^{-2}} \quad \frac{ft.^2}{sec.^2}$$

$v = 85.3$ ft./sec.

$$A = \frac{\pi d^2}{4} \qquad d^2 = \frac{4A}{\pi} \qquad d^2 = \sqrt{\frac{4A}{\pi}}$$

$$\frac{11.55 \text{ ft.}^3}{\text{sec.}} \quad \frac{\text{sec.}}{85.3 \text{ ft.}} = A = .1355 \text{ ft.}^2$$

$$d = \sqrt{\frac{4 \times .1355}{\pi}} = \sqrt{.1722} = .416 \text{ ft.} = 5 \text{ in.}$$

Using the method given by Vennard in Elementary Fluid Mechanics, 3rd edition, Chapter 9, and assuming $e/d = 2 \times 10^{-3}$ V/V_c approximately equals .85. Neglecting the pressure drop across the hot wire anemometer, the pressure reference must be $4 \times 10^{-3} \times 1.47 \times 10/.85$ lb. per sq. in. $= 6.95 \times 10^{-2}$ psi. This represents a velocity head of 85.3/.85 or about 100 ft./sec. To give this pressure the centrifugal blower must be $100/\sqrt{1 + .25} = 89.3$ ft./sec. This calculation assumes that the inlet radius of the blower is much less than the outlet radius, and that 25% of the kinetic energy of the air is converted to pressure.

4" was selected for the rotor diameter. The required speed is therefore approximately 5,100 rpm. This is approximately the middle of the range of efficient speeds for the type H31ES-2 Hysteresis Synchronous donated by Eastern Air Devices for this project.

The servo-motor, which was chosen mainly because of

availability, is an Eastern Air Devices, Size 15, 400 cycle unit with a stall torque of 1.45 oz. in. and a no load speed of 9,500 rpm. The gear ratio used was 16 to 1. This ratio was selected to match the inertia of the butterfly valve to that of the motor. Friction and holding torque are negligible.

III DESCRIPTION OF CONSTRUCTION

Plates 1 through 51 show the details of construction and assembly of the flow meter. The photographs are not to an exact scale, but Plates 1, 2, and 38- 41 are approximately .5 actual size. The remaining plates are approximately .8 actual size.

All of the parts, with the exception of the commercial components and the reference rotor (which was made by the Electronic Systems Laboratory's machine shop) were machined by me. Two reasons for this were: 1) This was not a sponsored project, so funds were not available for the machine shop work. 2) Detailed drawings were never made for most of the parts.

Gaskets were used between the parts shown in Plates 10 and 14; 14 and the connector in Plate 15; 46 and 49; and 49 and 51. An O ring was used as a seal between the parts shown in Plates 4 and 10. This O ring is in place in its groove in Plate 12 and is visible as a black line. Stainless steel washers used as spacers to form the static pressure pickoff are barely visible in Plate 9.

A few minutes thought using the Bernoulli principle should convince the reader that the position of the high pressure side of the reference blower is a very good approximation of that shown in Figure 2.

The chart below shows a few of the critical dimensions and characteristics:

Butterfly valve diameter	5.00 inches
Butterfly valve clearance when closed	.010 inches
Maximum pressure butterfly valve can withstand when closed	20 psi
Pressure reference rotor diameter	4.00 inches

The hot wire anemometer filament is from a #49 General Electric light bulb. It is .00035 in. in diameter. Figure 3 shows the voltage vs. current of this filament.

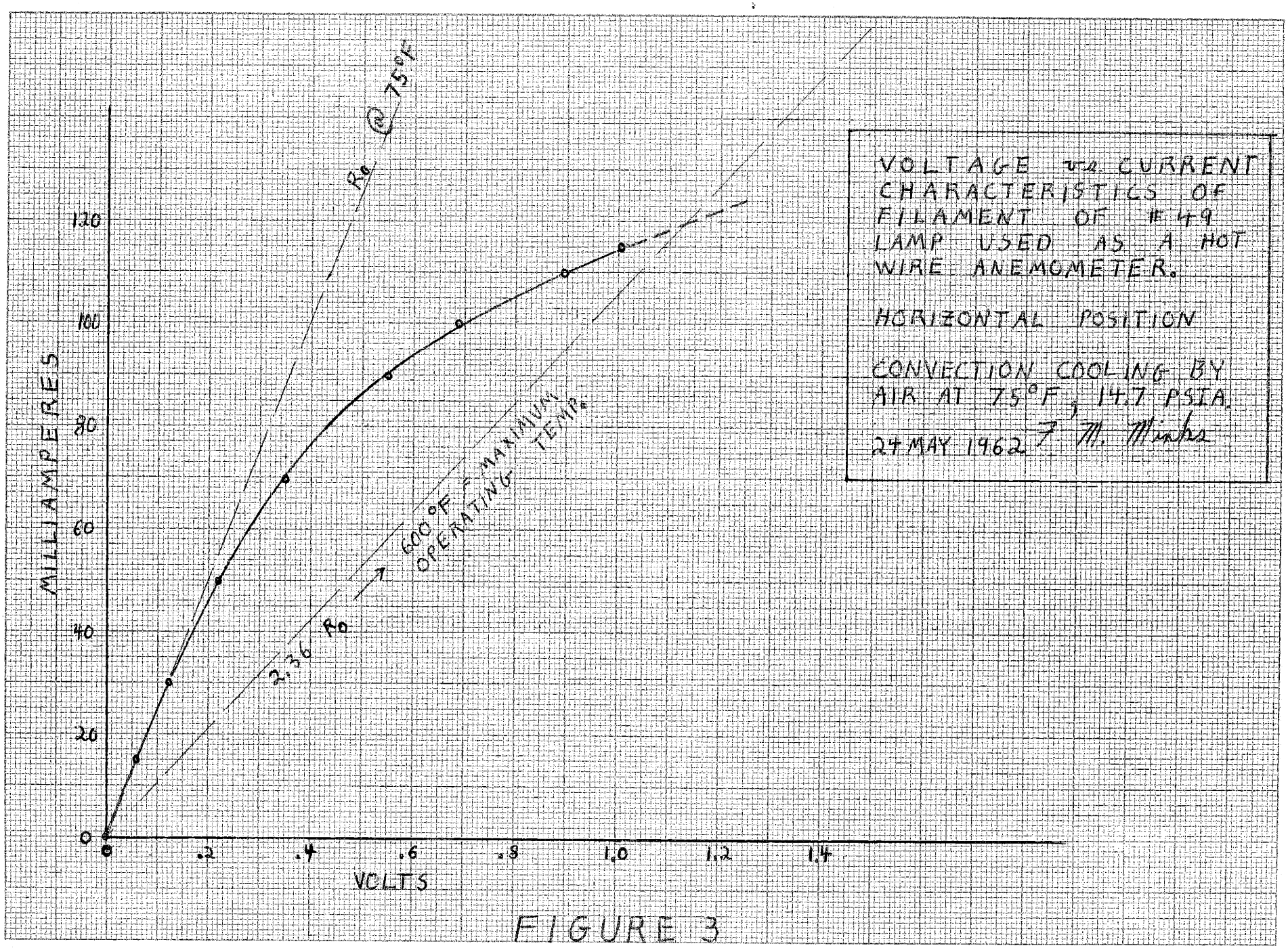

VOLTAGE vs CURRENT CHARACTERISTICS OF FILAMENT OF #49 LAMP USED AS A HOT WIRE ANEMOMETER.
HORIZONTAL POSITION
CONVECTION COOLING BY AIR AT 75°F, 14.7 PSIA.
24 MAY 1962 M. Winkler
MILLIAMPERES
VOLTS
0
20
40
60
80
100
120
.2
.4
.6
.8
1.0
1.2
1.4
Ro @ 75°F
2.36 Ro
600°F MAXIMUM OPERATING TEMP.

FIGURE 3

IV TEST RESULTS AND CONCLUSIONS

Preliminary tests were made to determine whether the air flow meter would operate. Figure 4 shows the pressure reference vs. rpm characteristic of the pressure reference. Most of the electrical circuitry used was conventional and therefore will not be described here. The only exception is the bridge circuit used to excite the hot wire anemometer and derive from it a signal that when amplified would drive the control phase of the servo motor. This circuit is given in Figure 5. Figure 6 shows the voltage and phase output of this bridge, the hot wire anemometer, and the pressure reference, vs. the pressure drop across the butterfly valve. The data for Figure 6 was computed from Figure 4 and data taken at very low pressure reference speed with the pressure drop across the butterfly valve zero.

As a qualitative operation test a ventilating blower was used to draw air through the air flow meter. The meter operated properly under steady state or slowly varying conditions. The system became unstable in the presence of high amplitude variations above the maximum frequency that the servo system can follow. Reference to Figure 6 will show the reason. The large error signal forces the operating point from its normal position at "a" to a point "b". The servo motor will therefore move the butterfly valve away

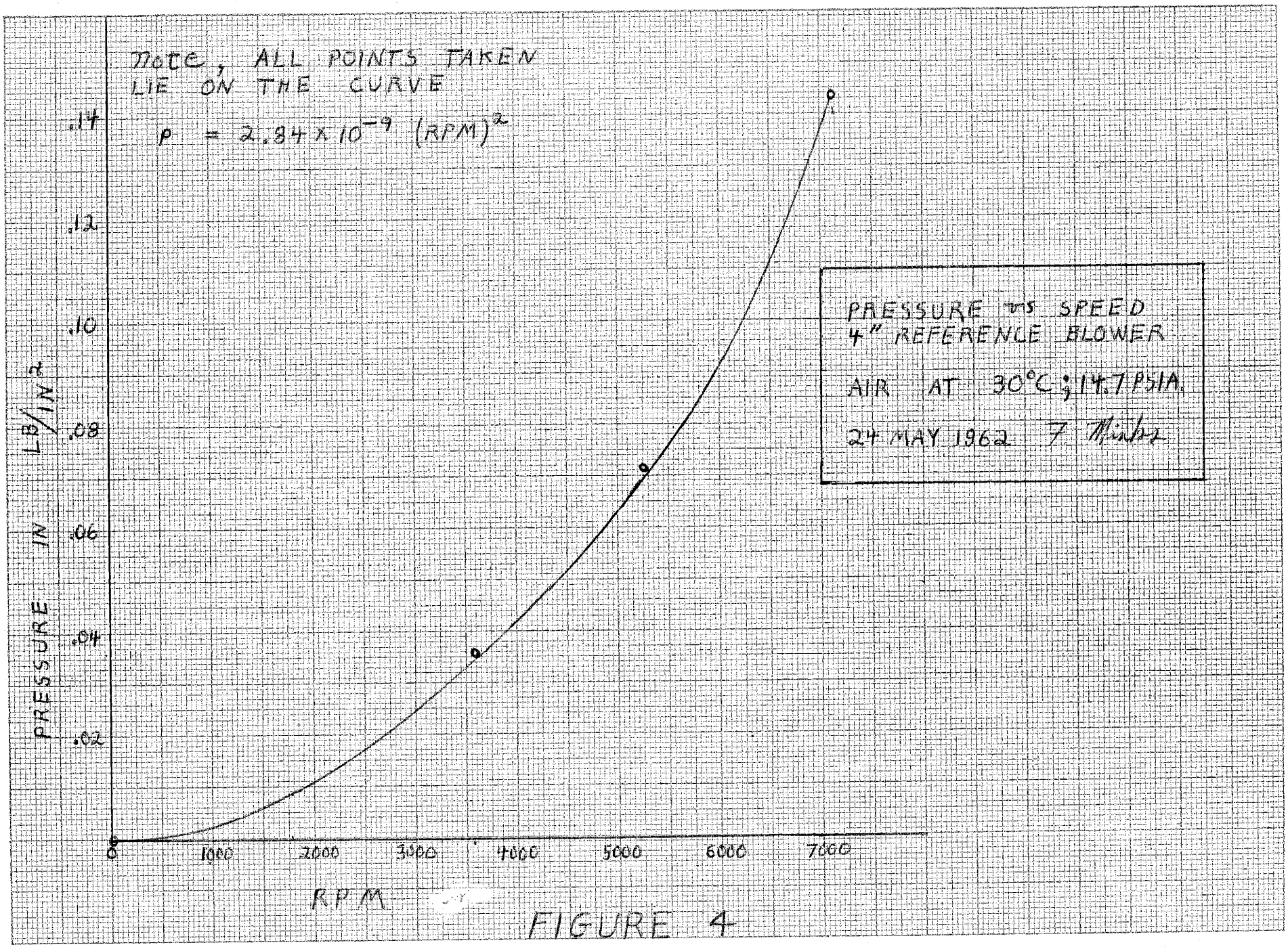

NOTE, ALL POINTS TAKEN LIE ON THE CURVE
$P = 2.84 \times 10^{-9} (RPM)^2$
PRESSURE VS SPEED
4" REFERENCE BLOWER
AIR AT 30°C; 14.7 PSIA.
24 MAY 1962 7 Nozzle
PRESSURE IN LB/IN²
.14
.12
.10
.08
.06
.04
.02
1000
2000
3000
4000
5000
6000
7000
RPM

FIGURE 4

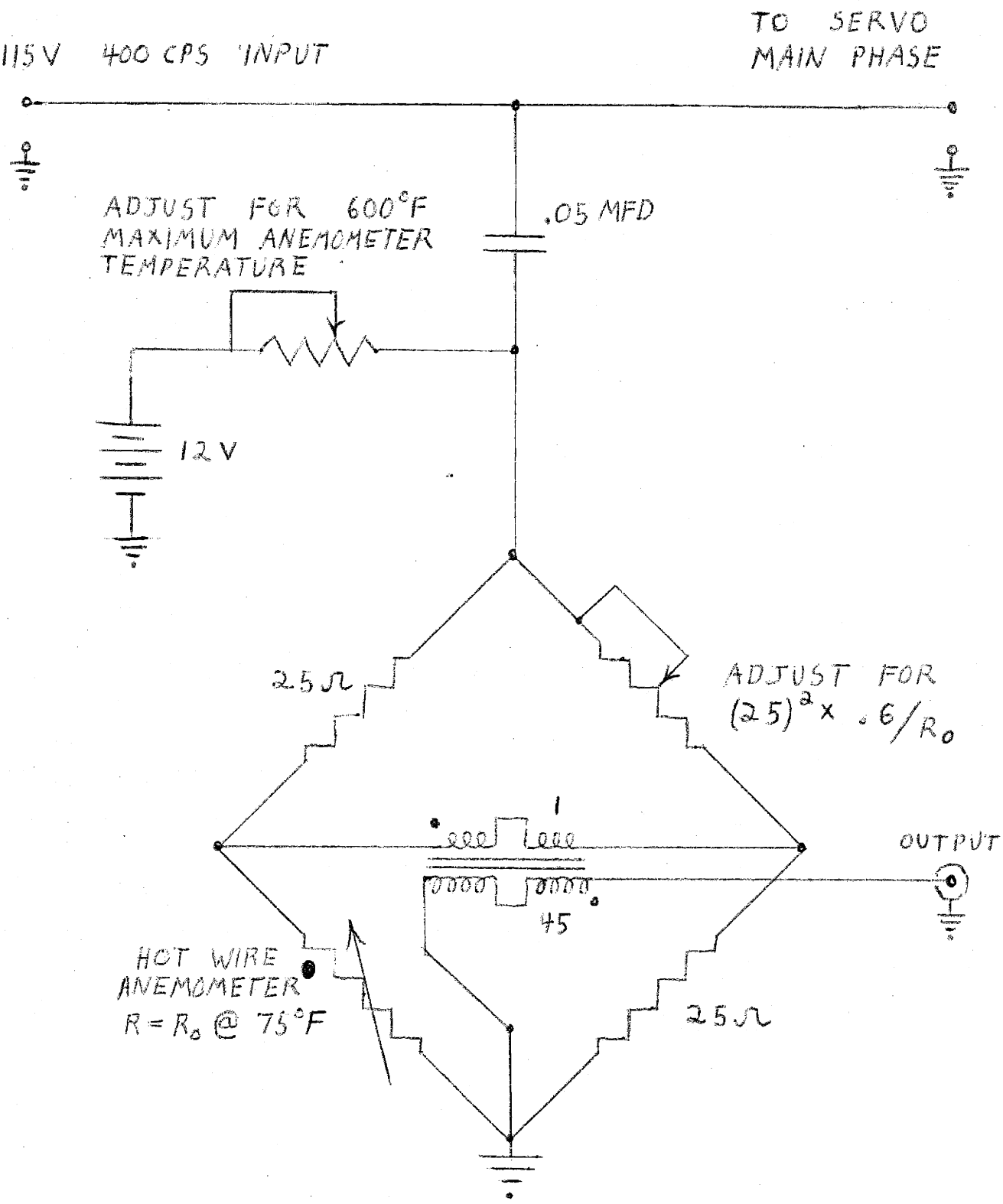

115 V 400 CPS INPUT
TO SERVO MAIN PHASE
ADJUST FOR 600°F MAXIMUM ANEMOMETER TEMPERATURE
.05 MFD
12 V
25 Ω
ADJUST FOR (25)² x .6/R₀
1
OUTPUT
45
HOT WIRE ANEMOMETER R = R₀ @ 75°F
25 Ω

FIGURE 5

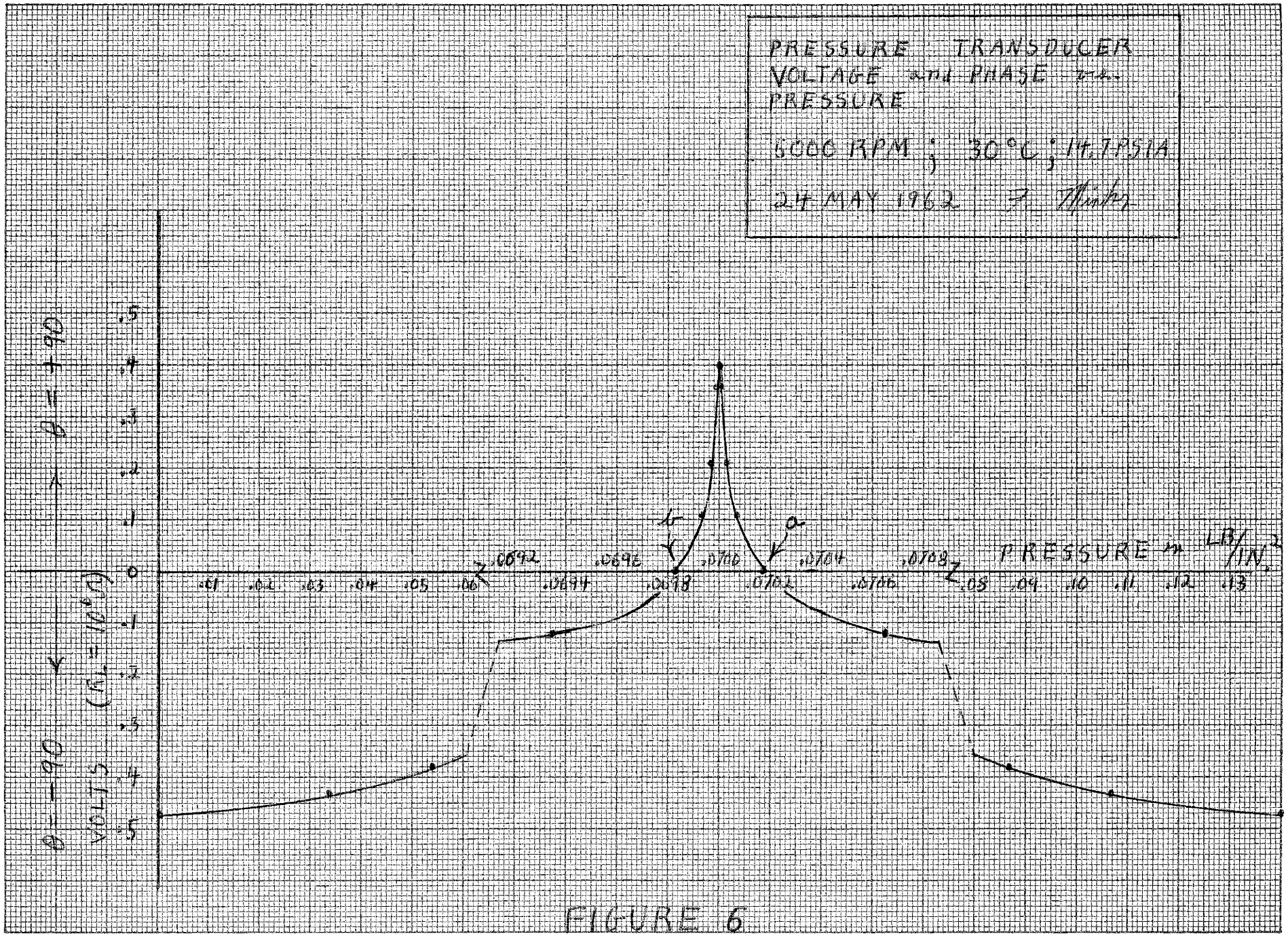

PRESSURE TRANSDUCER
VOLTAGE and PHASE vs.
PRESSURE
5000 RPM ; 30 °C ; 14.7 PSIA
24 MAY 1962
PRESSURE in LB/IN.²
VOLTAGE (E) in VOLTS
PHASE (φ) in DEGREES
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12
.13
.0692
.0694
.0698
.0702
.0704
.0706
.0708
a
b

FIGURE 6

rather than toward null. Stable operation may be regained the next time the butterfly approaches its null position. This will depend on the characteristics of the air flow at that time as well as the relationship between the kinetic energy of the rotating butterfly valve and the braking from the servo. Because of this characteristic it was decided to replace the hot wire anemometer with a type of flow transducer which can distinguish direction of flow. This would eliminate the necessity of the servo system being able to rotate 360° and would permit the "a" in the equation on page 4 to be reduced to a negligible factor. Such a flow transducer could be made from a thin sheet of aluminum foil (or other material) so mounted that air flowing over it would bend it. Either optical or capacitive position indication could be used.

The installation of such a transducer and subsequent calibration have been postponed until after the completion of this thesis. Nevertheless the feasibility of such an air flow meter has been proved.

V Plates 1 - 51

The following plates show contruction and assembly details of the air flow rate meter.

Plate 1

Plate 2

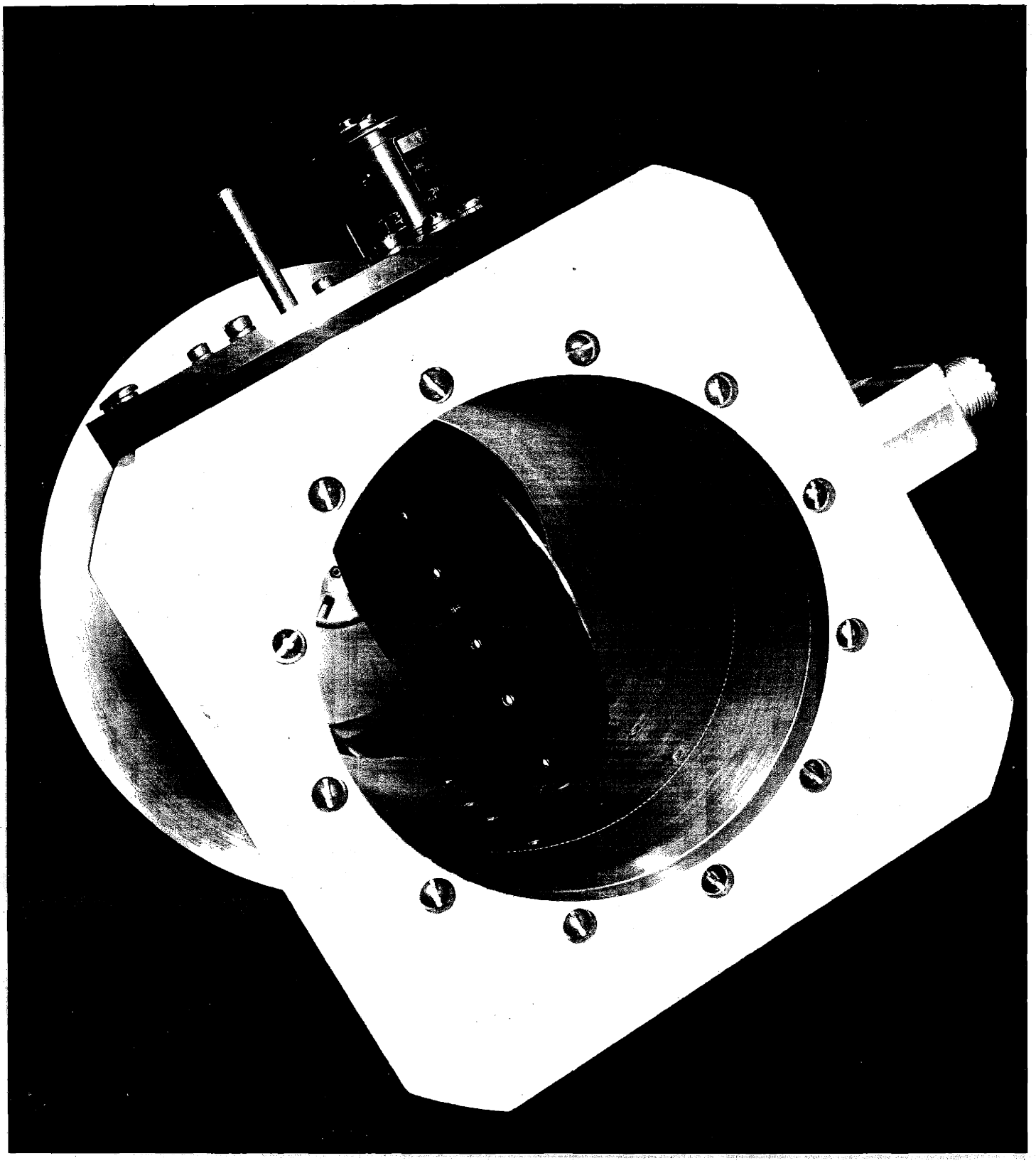


Plate 3

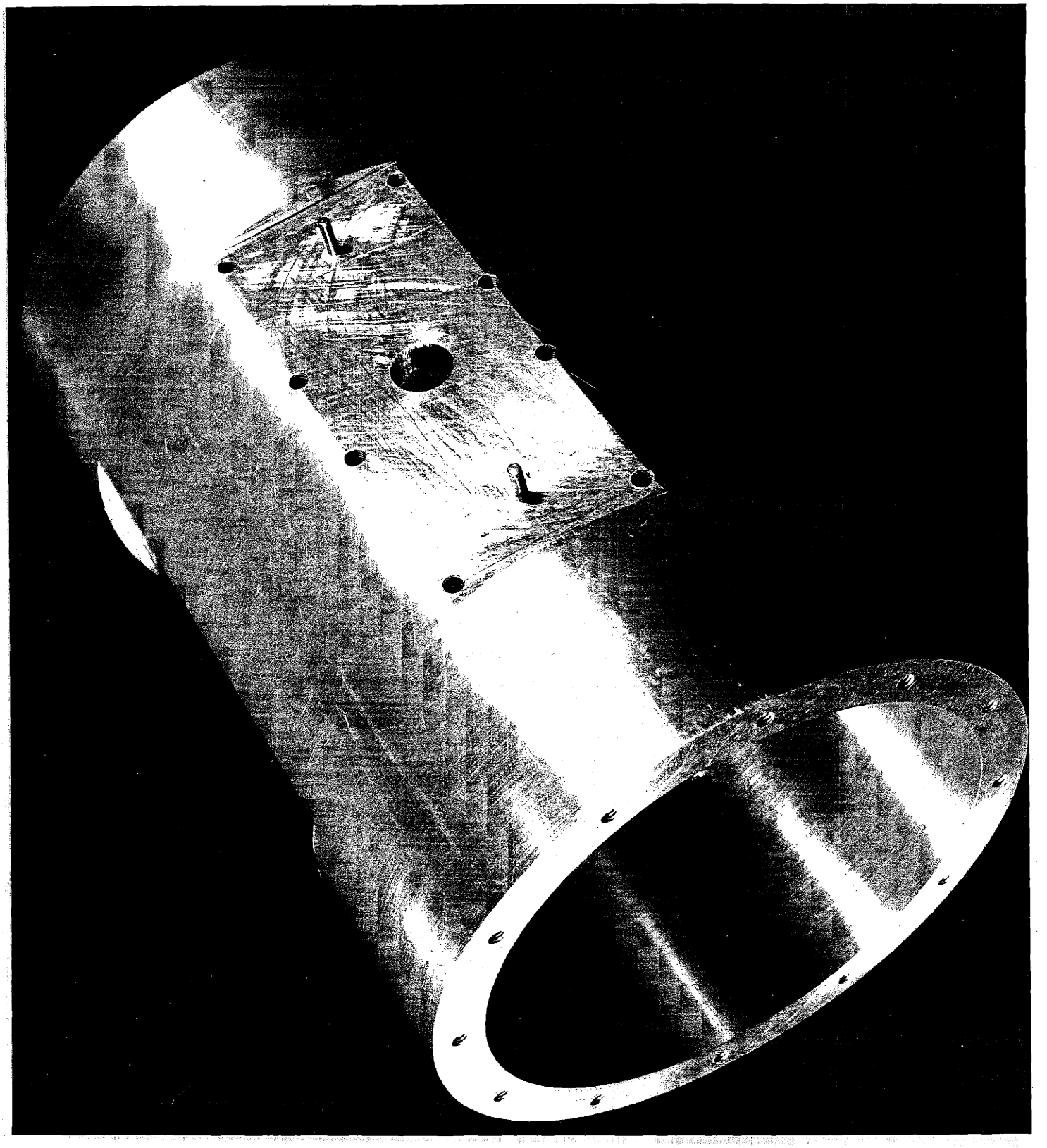
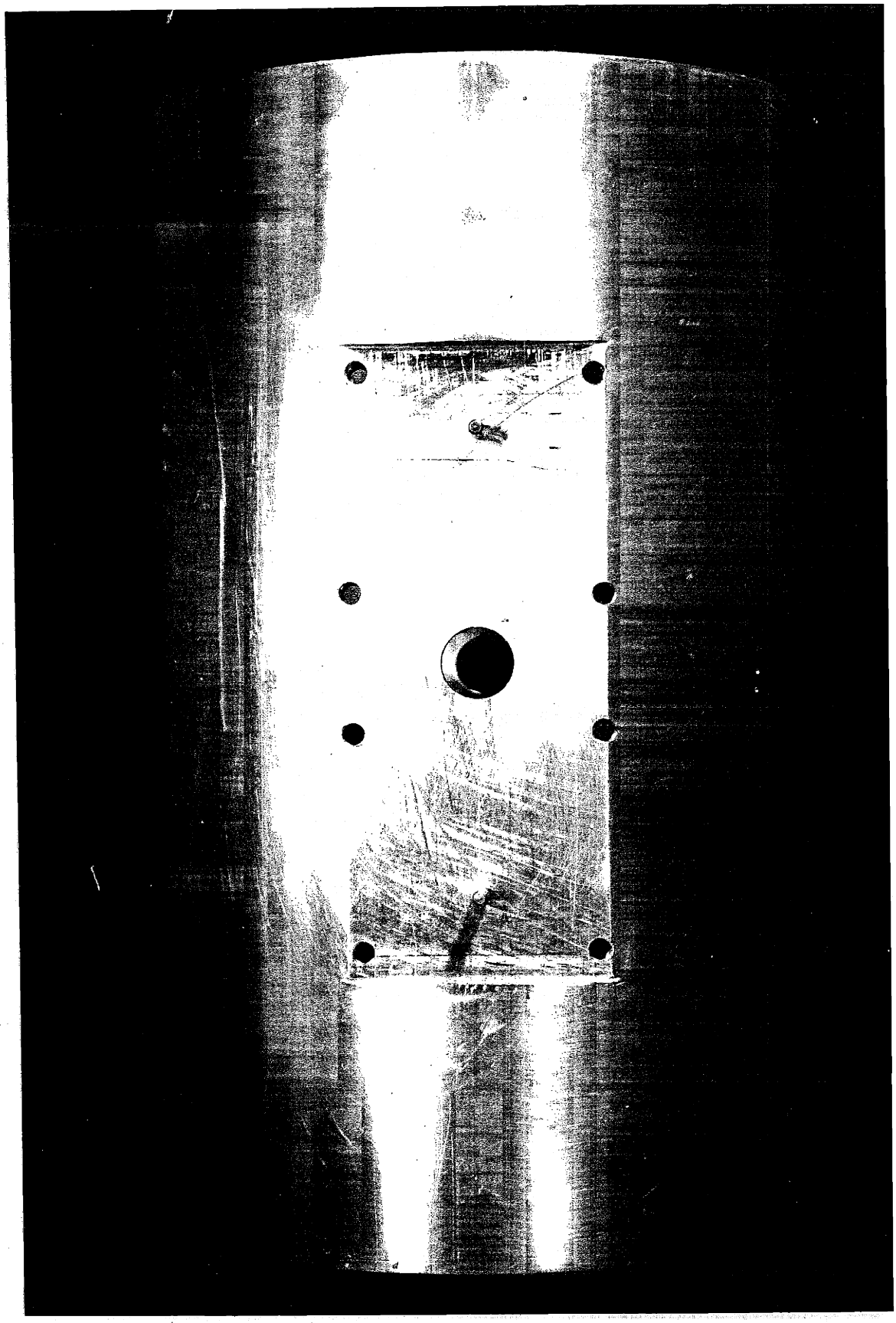


Plate 4



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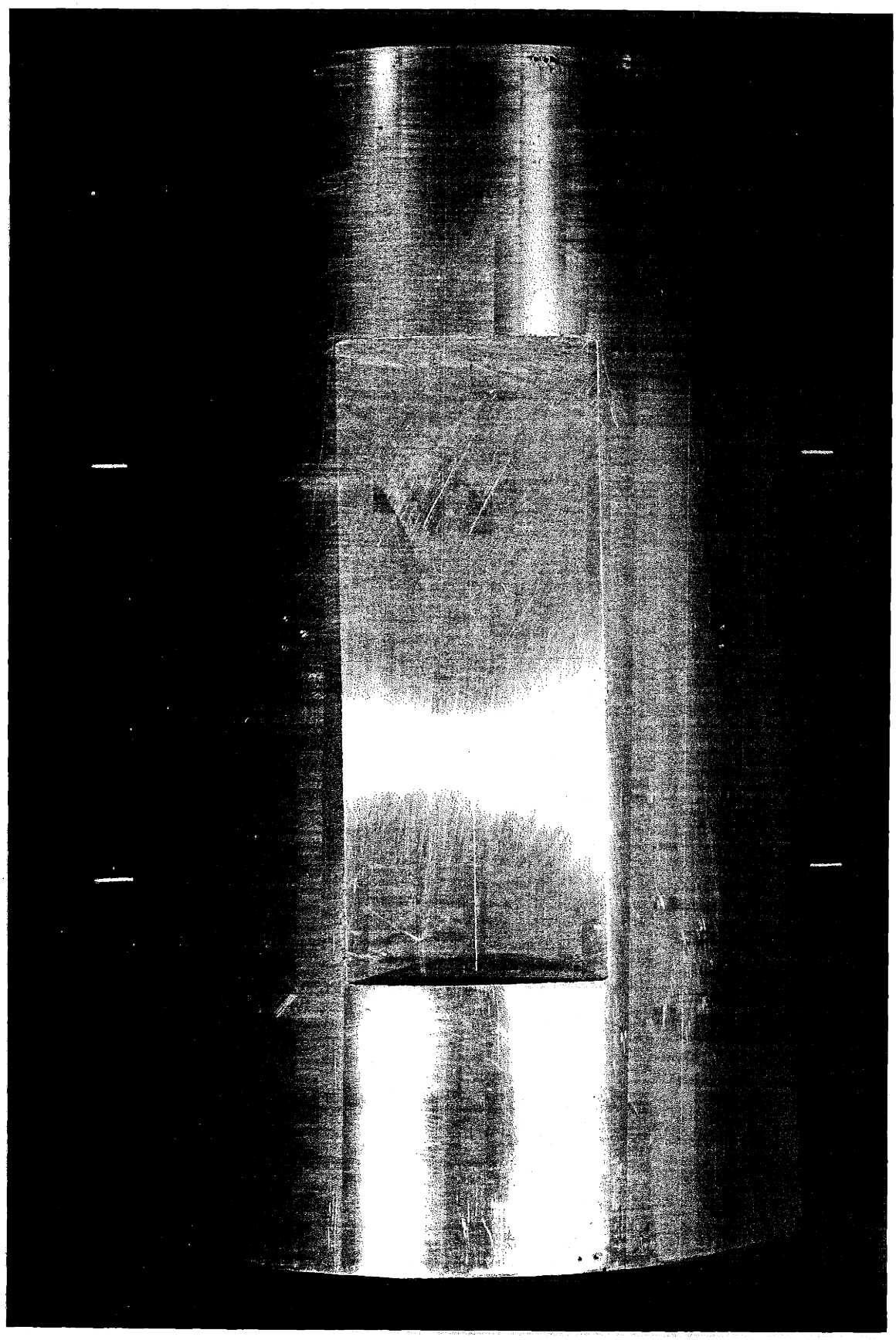


Plate 6

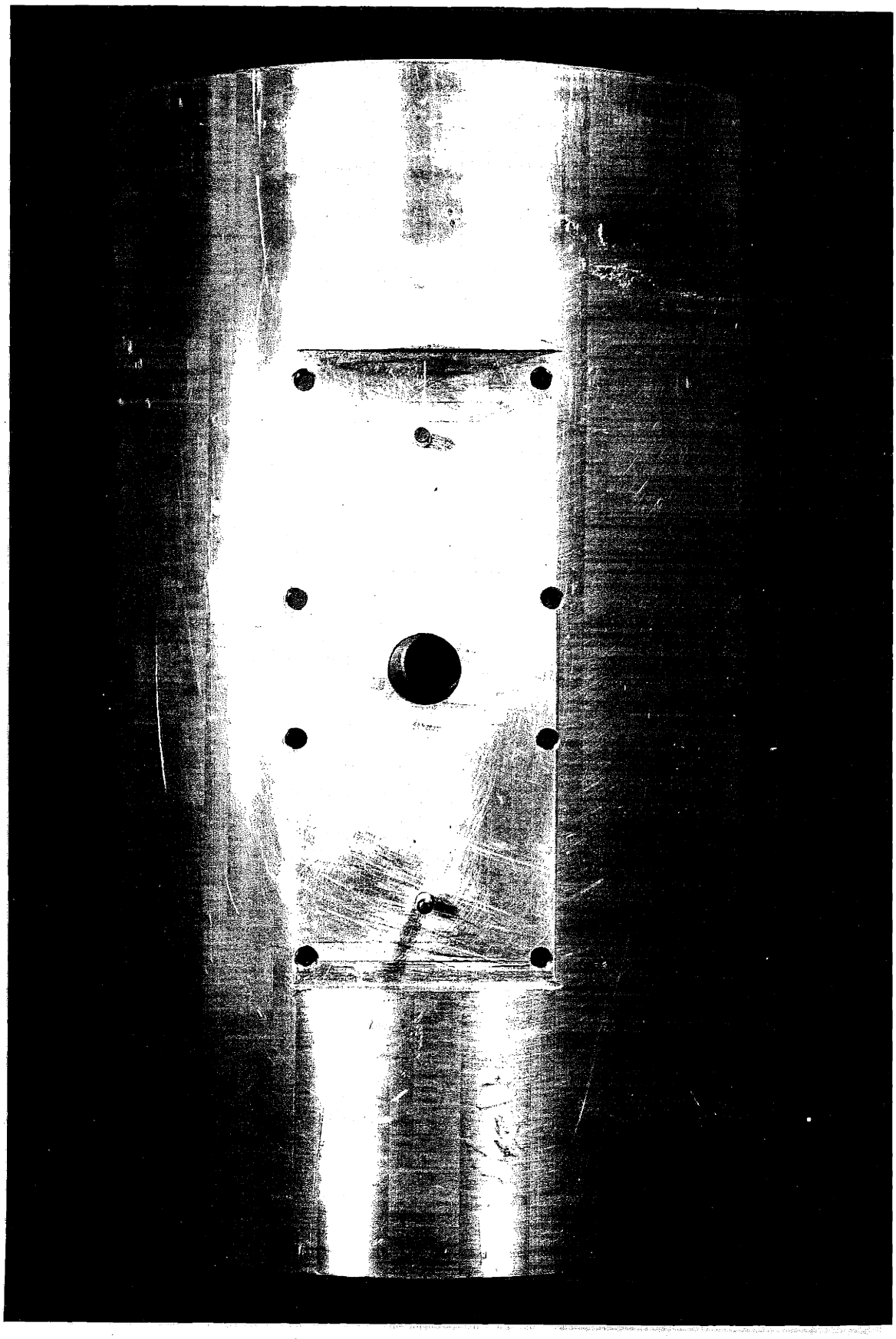
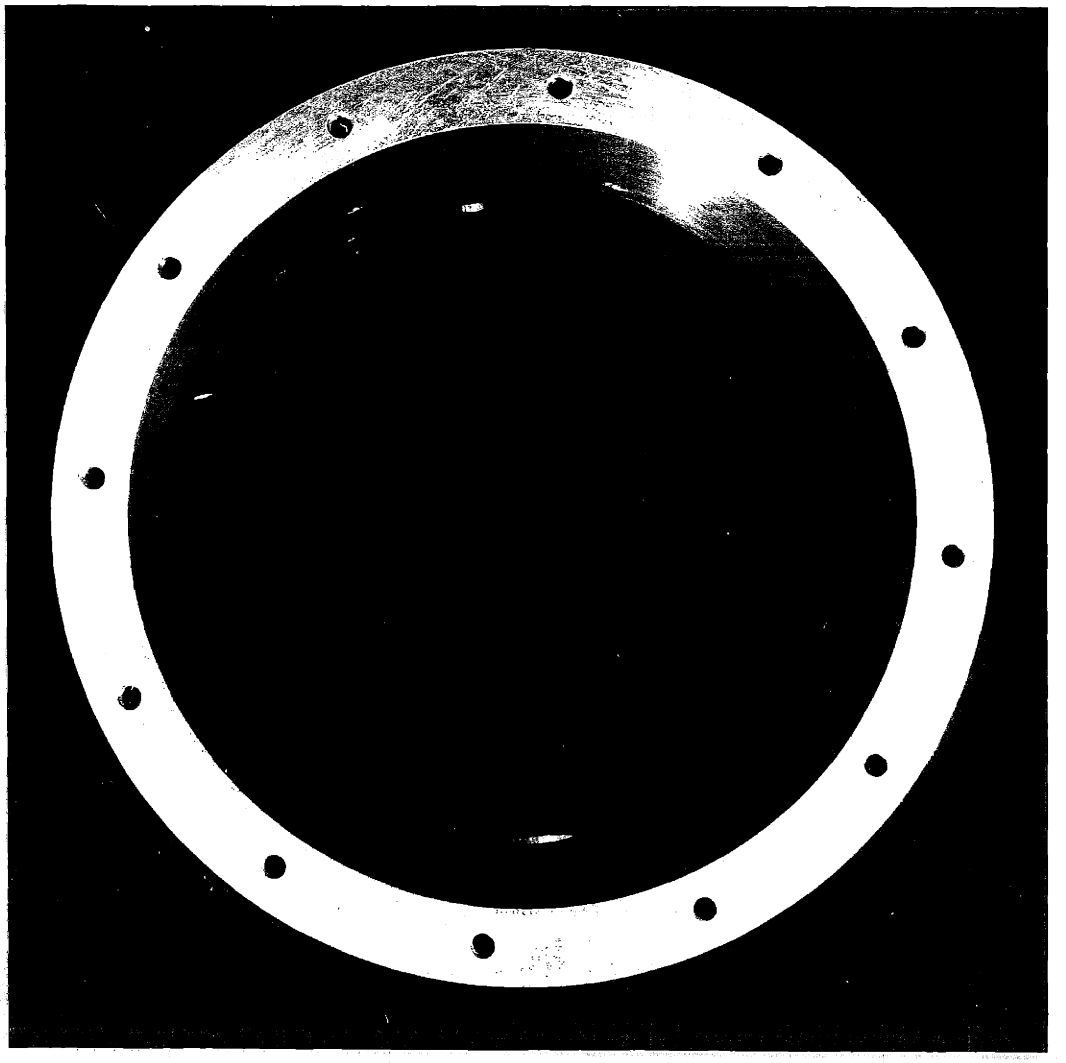


Plate 7



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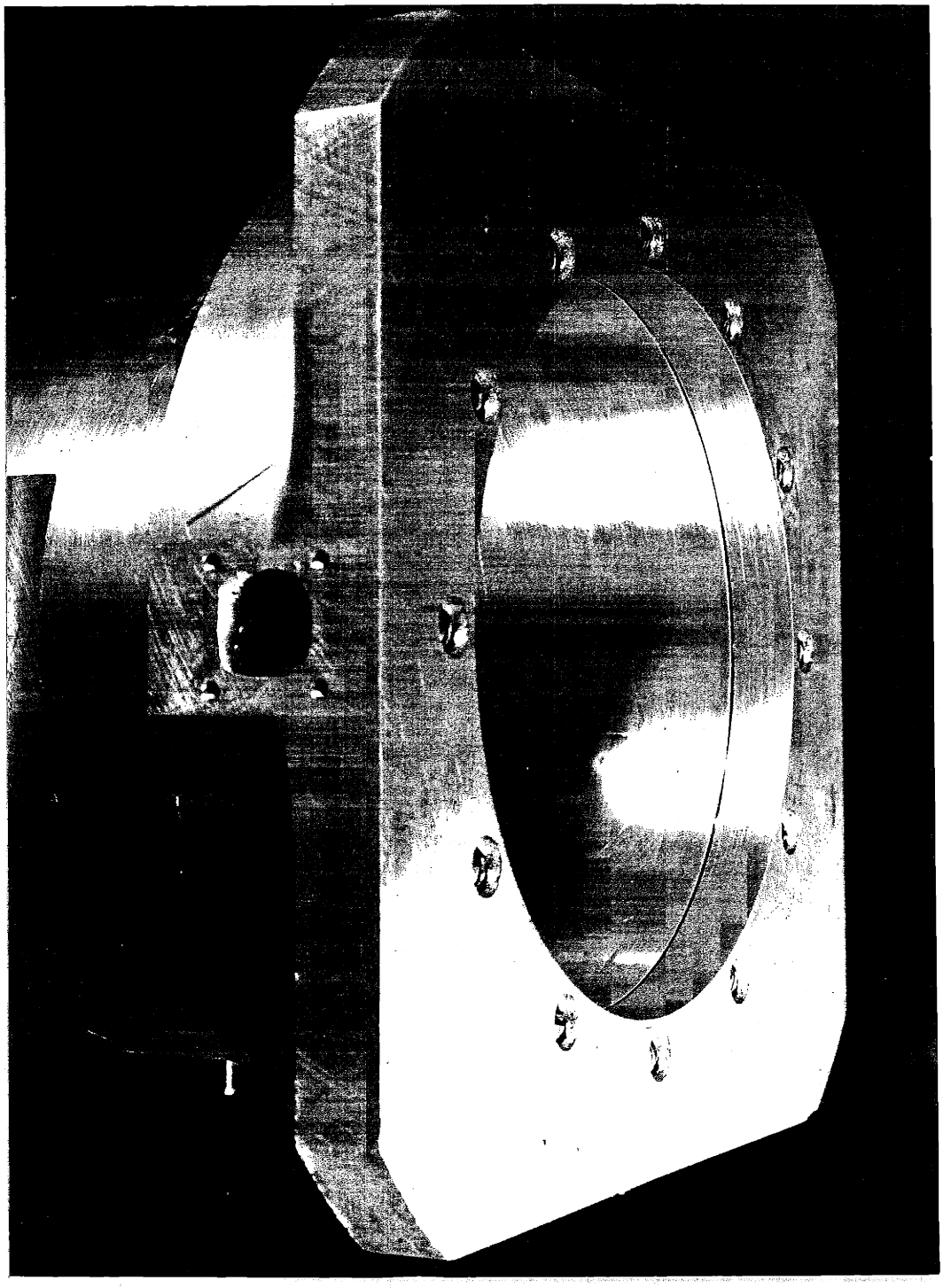


Plate 9

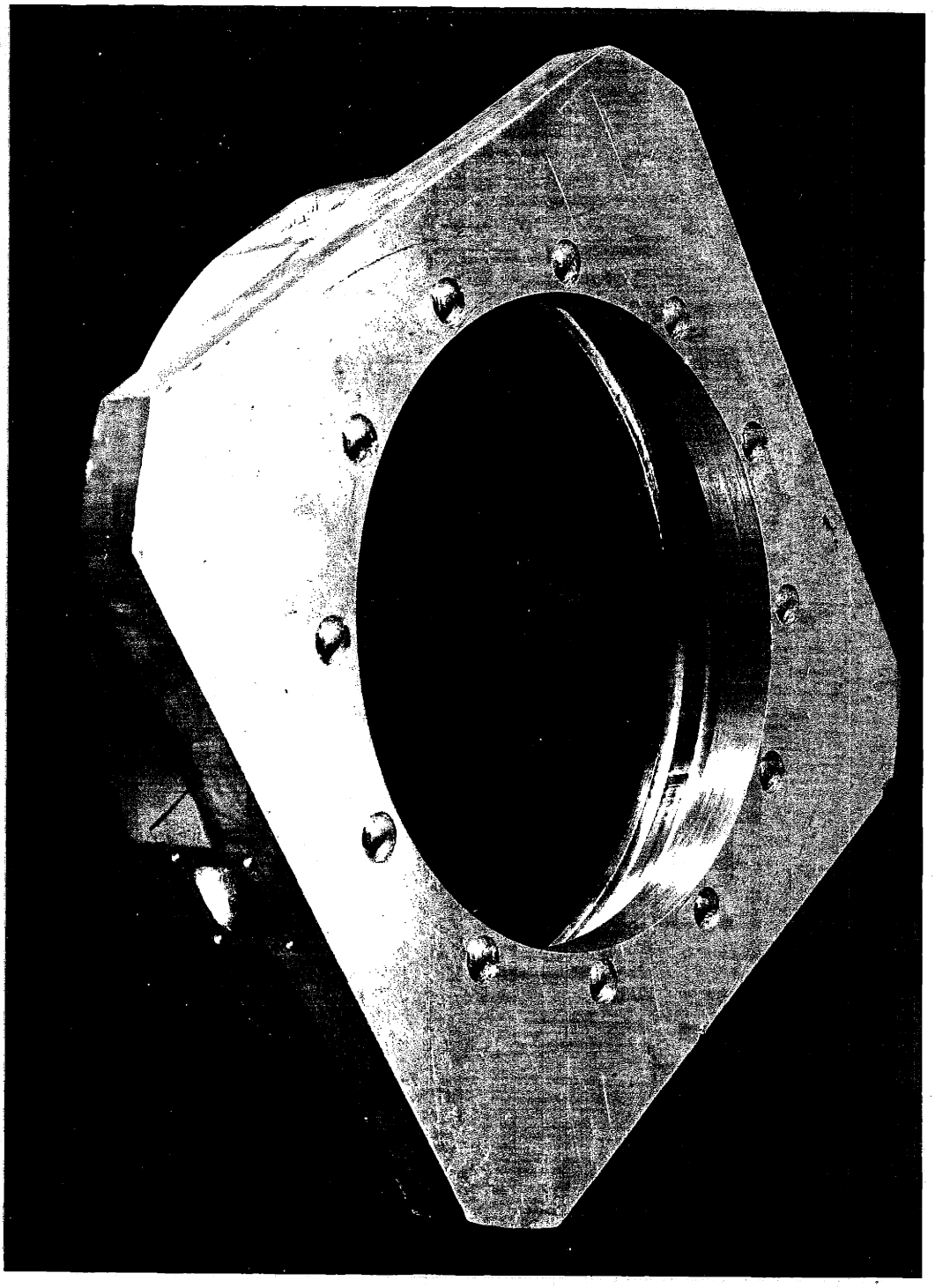
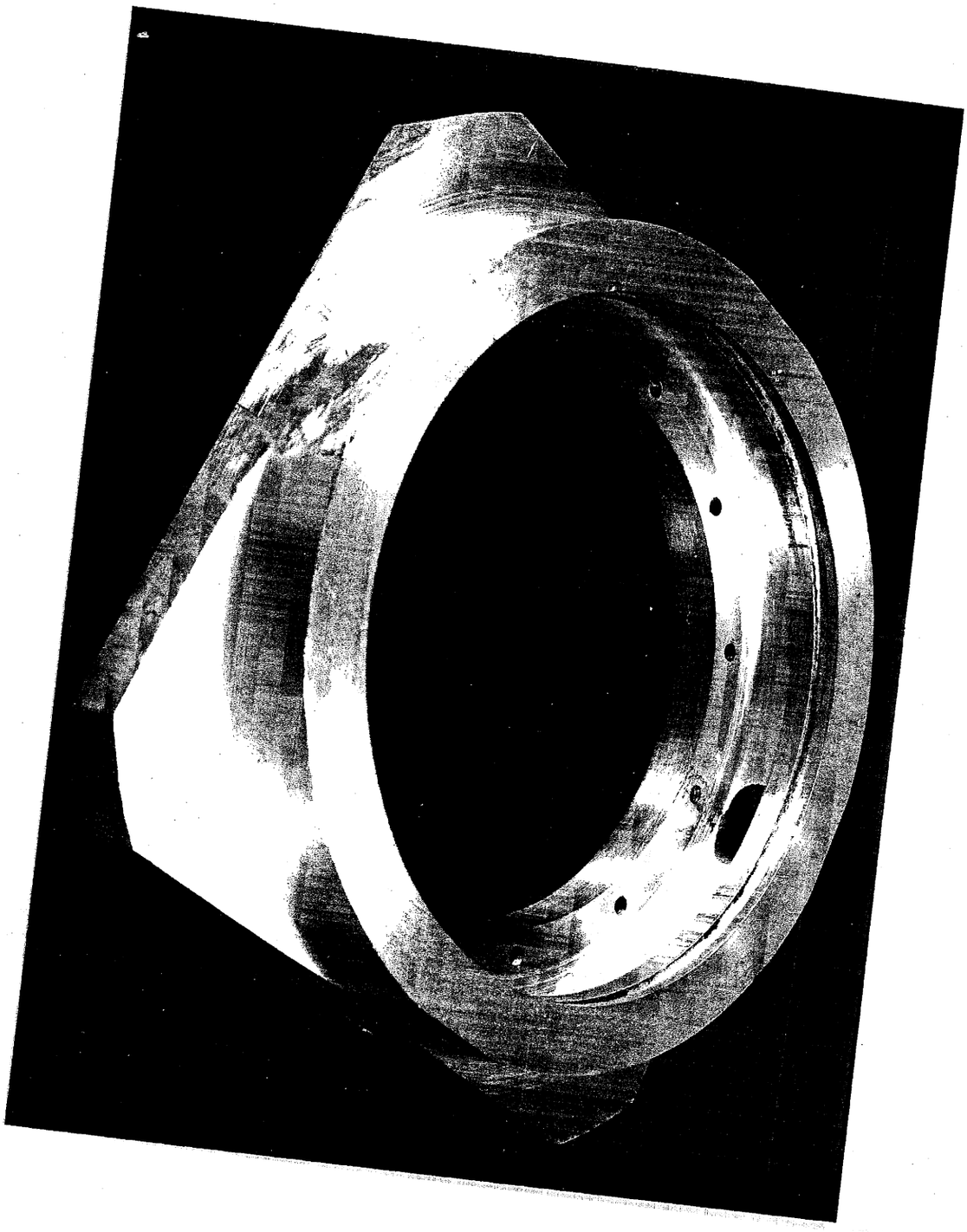


Plate 10



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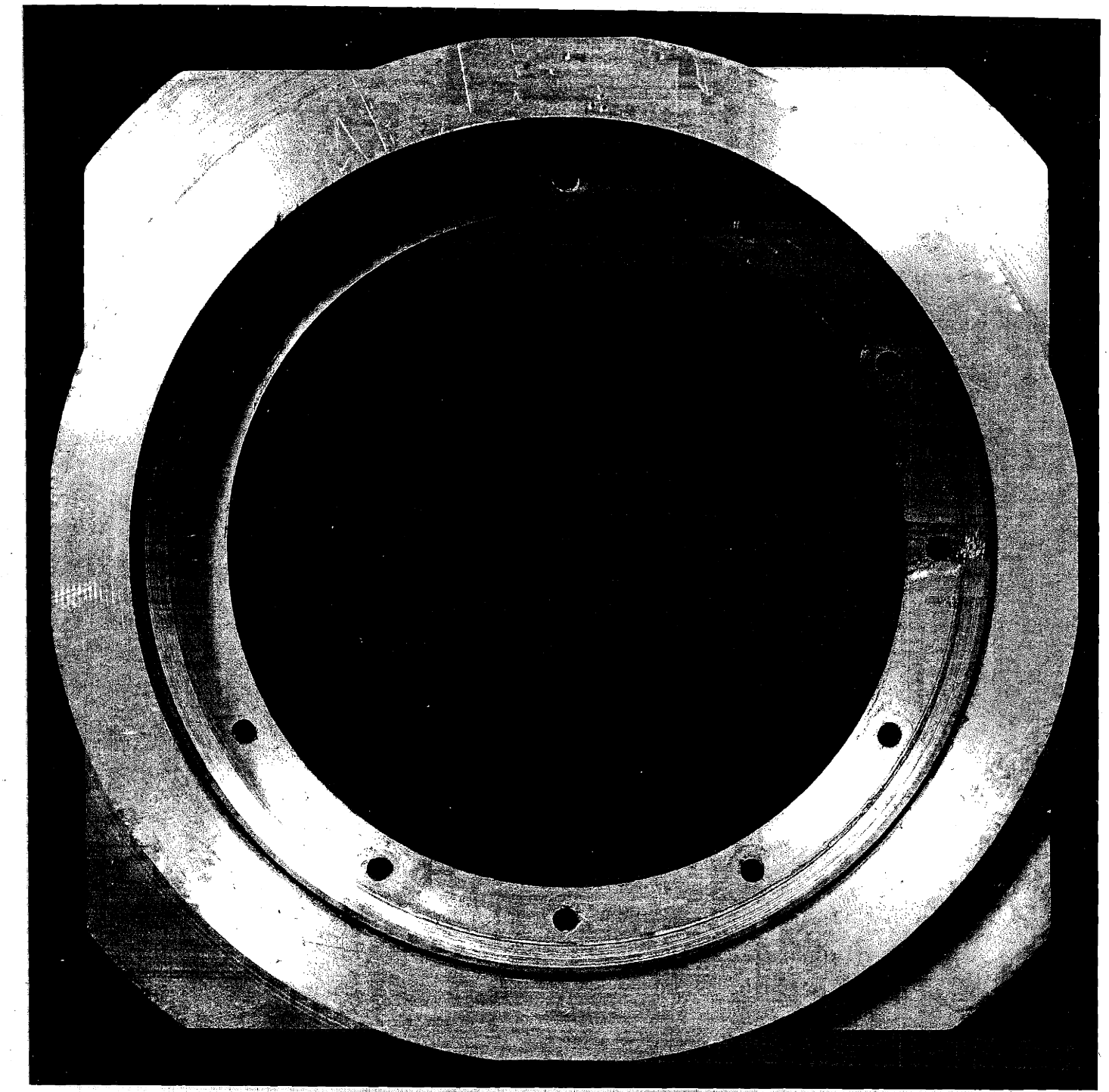

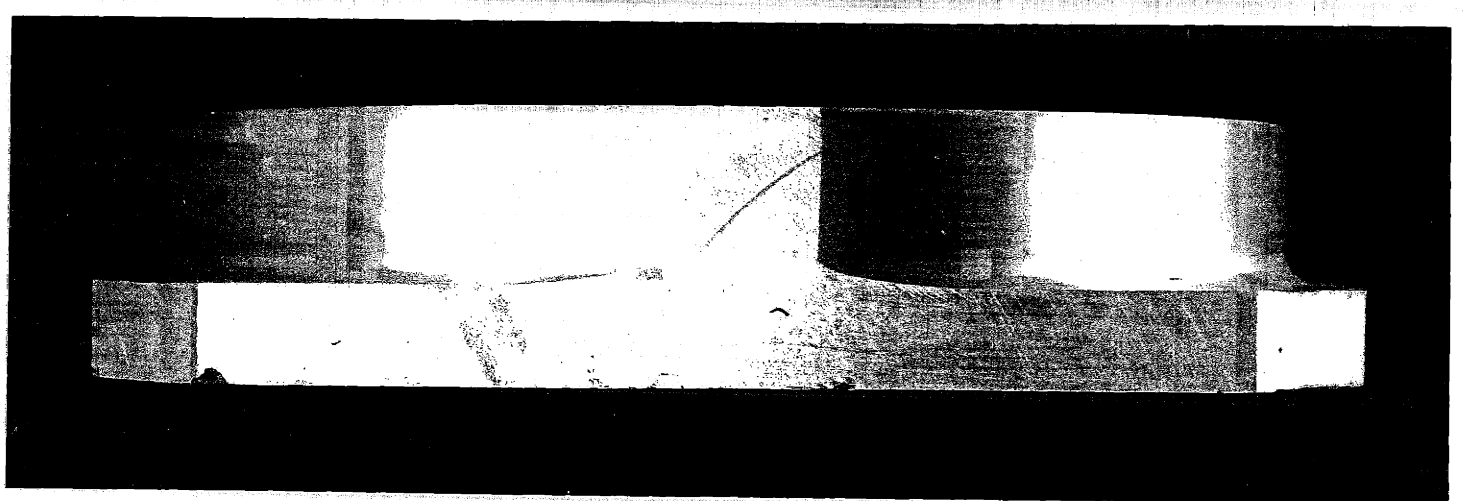

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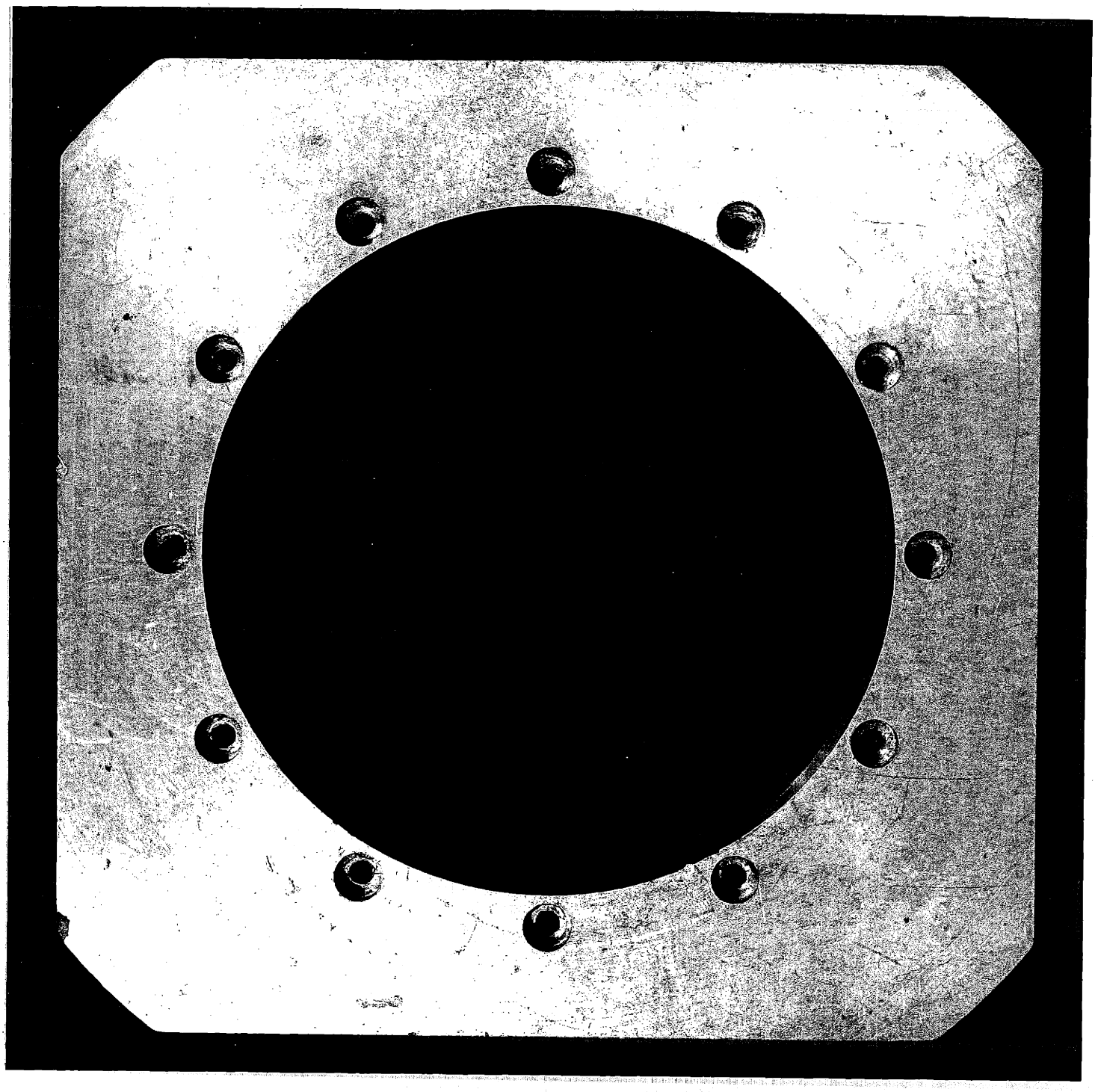


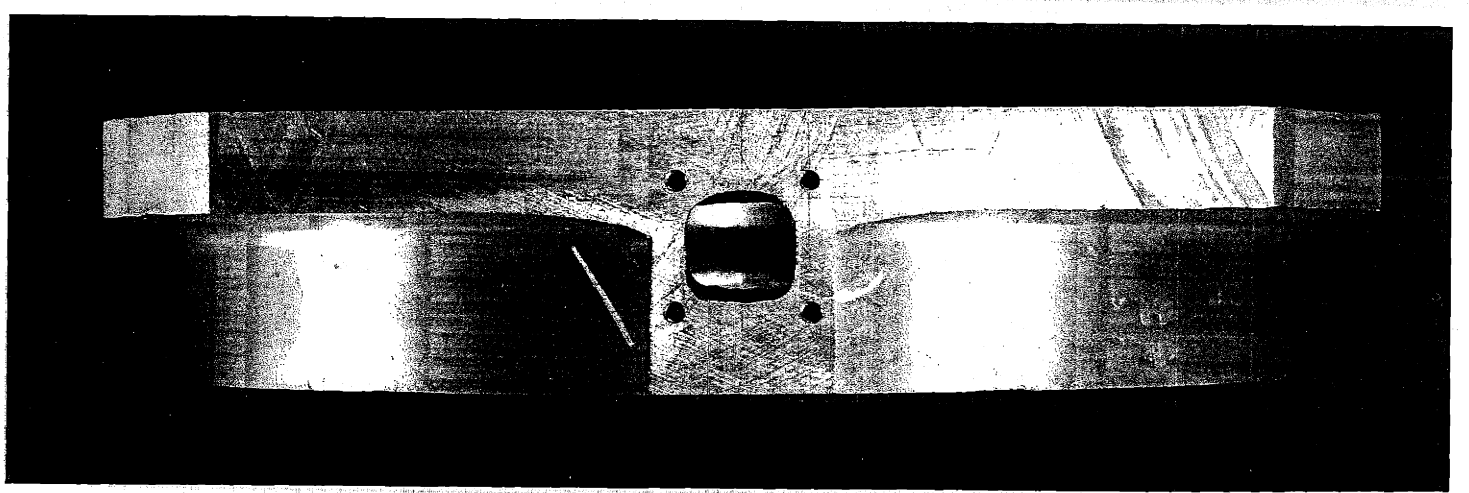
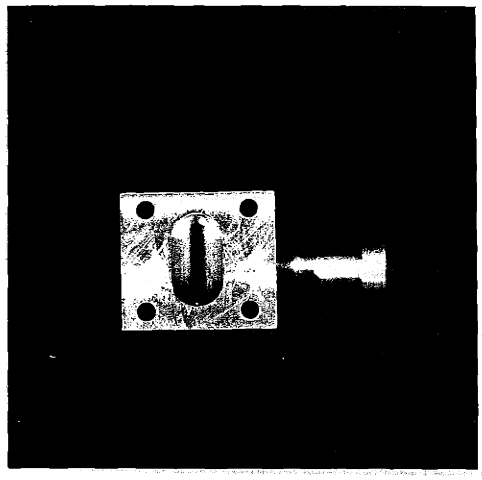
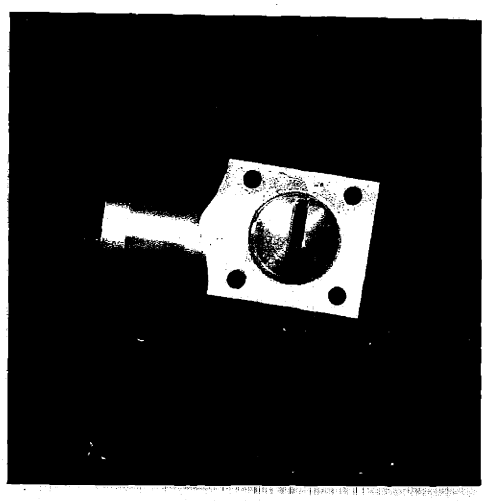


Plate 13





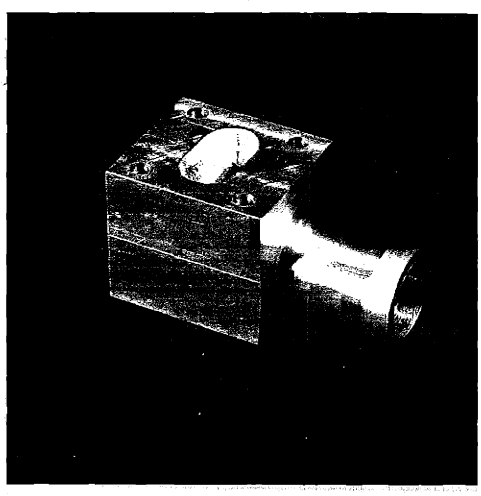
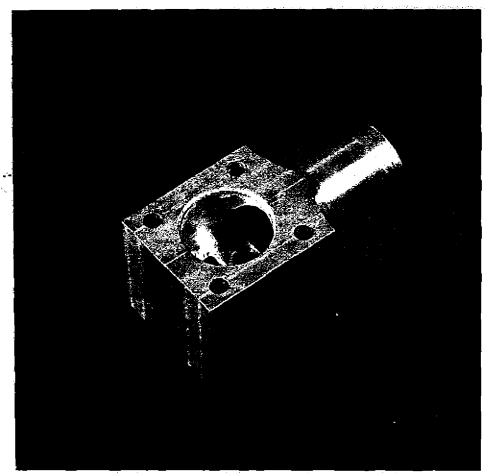
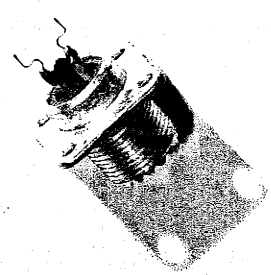


Plate 14





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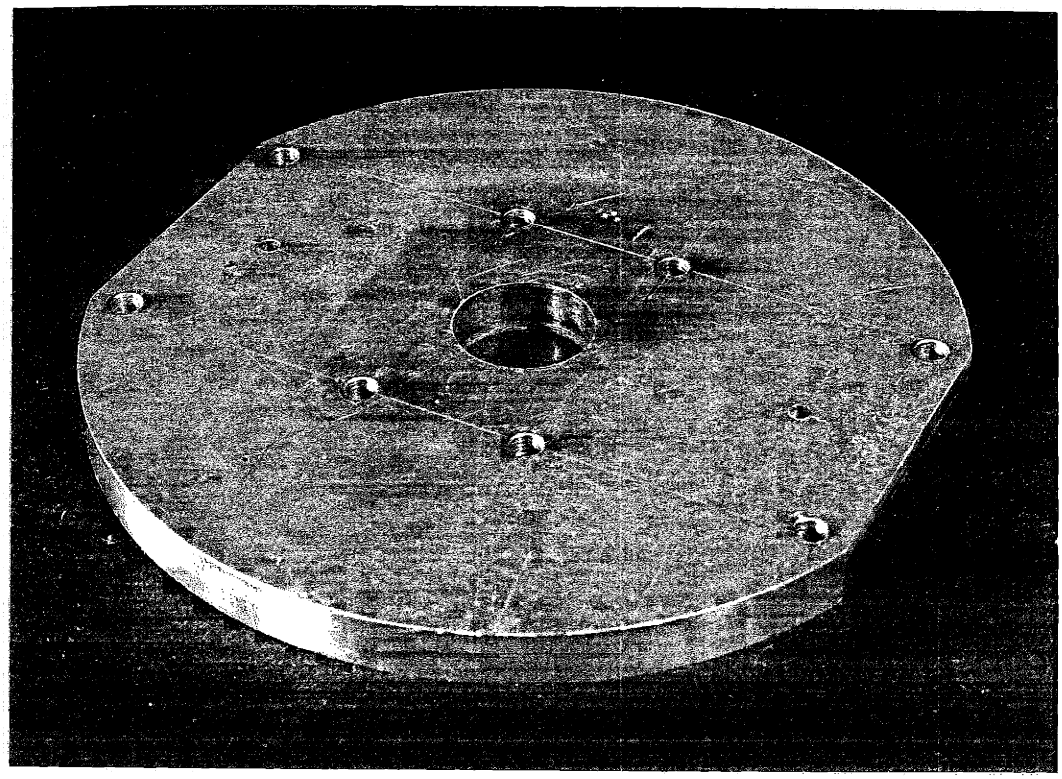


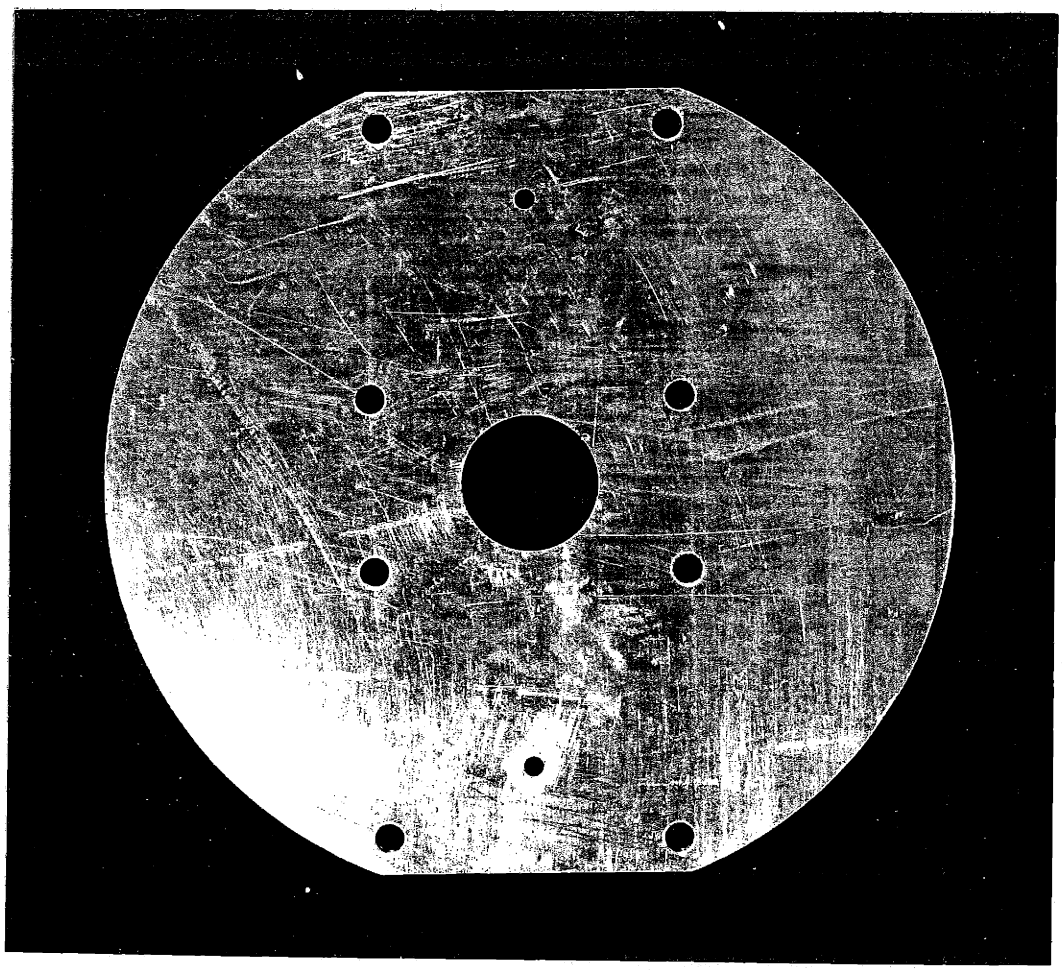
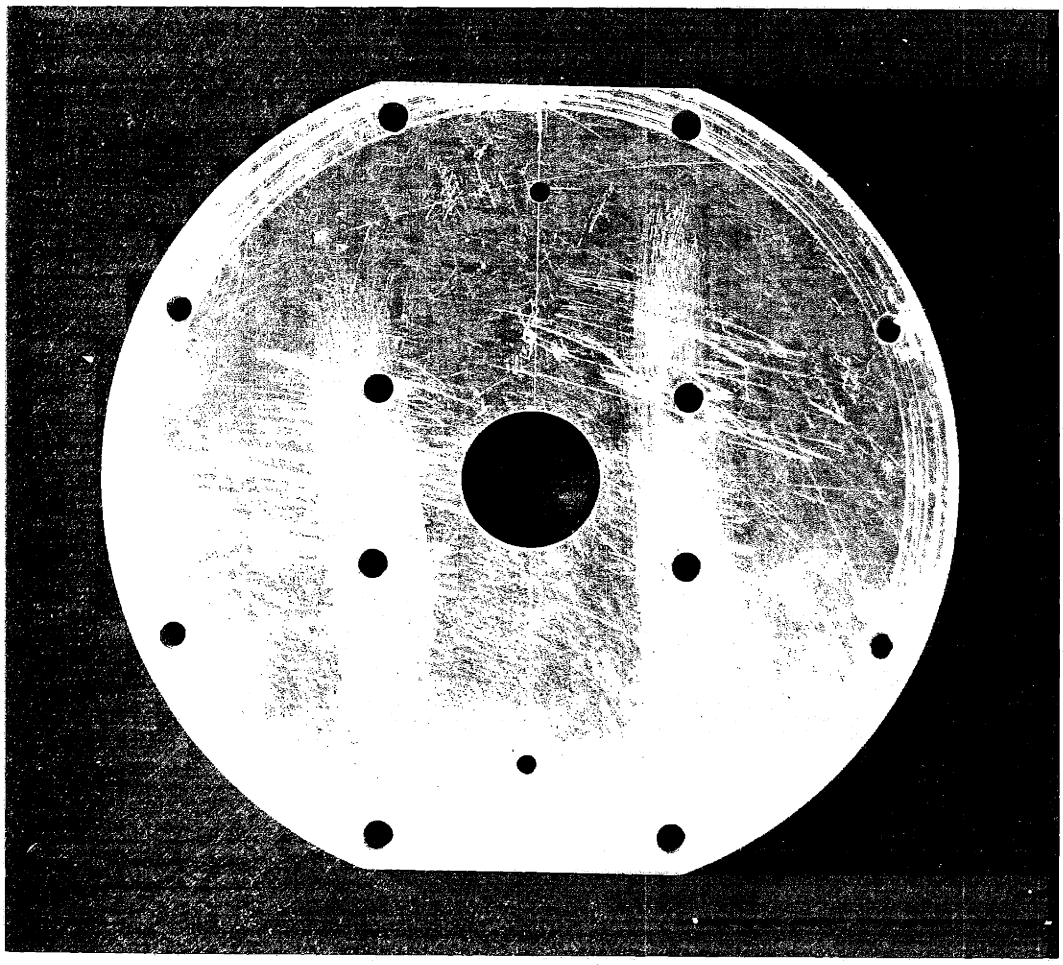


Plate 16



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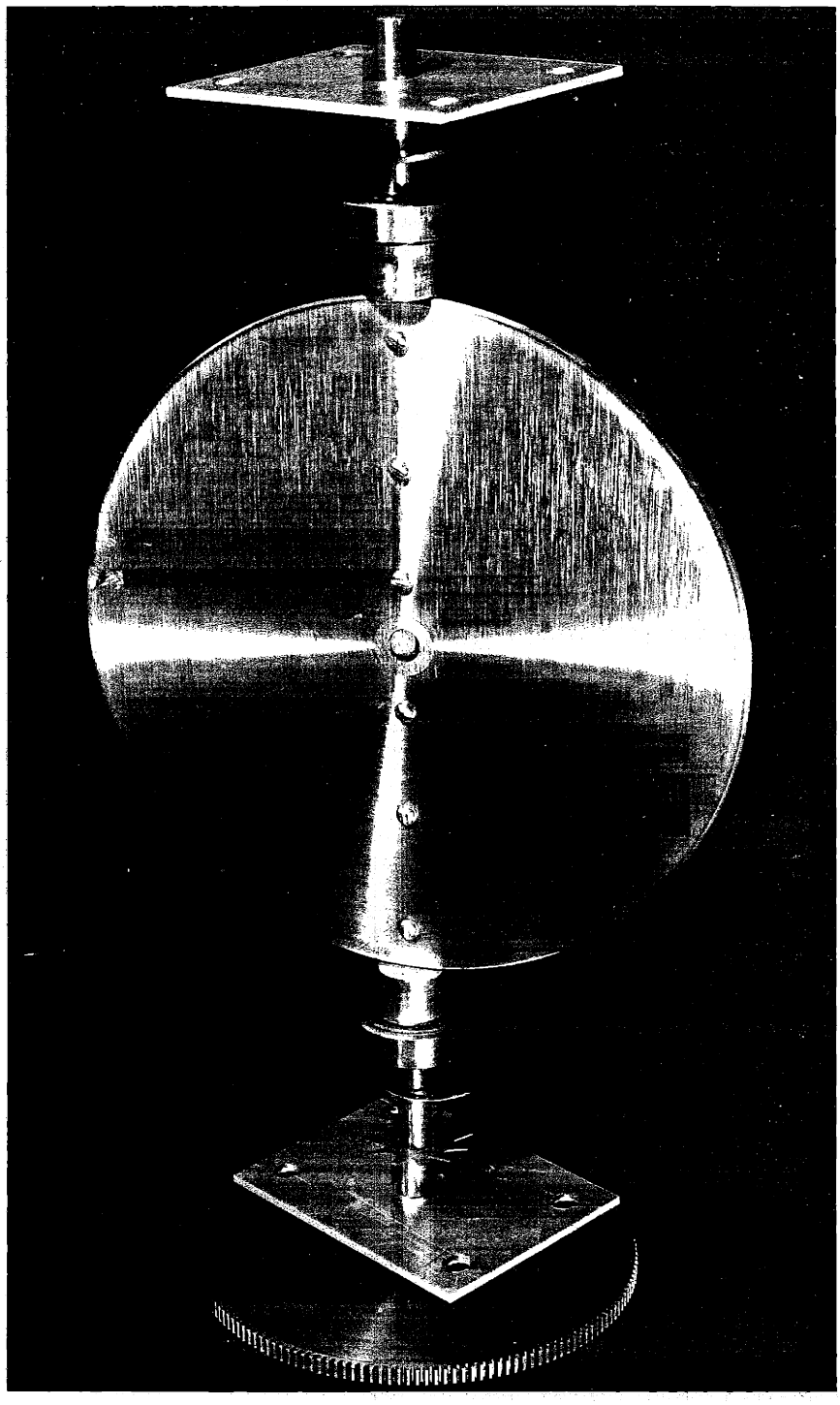
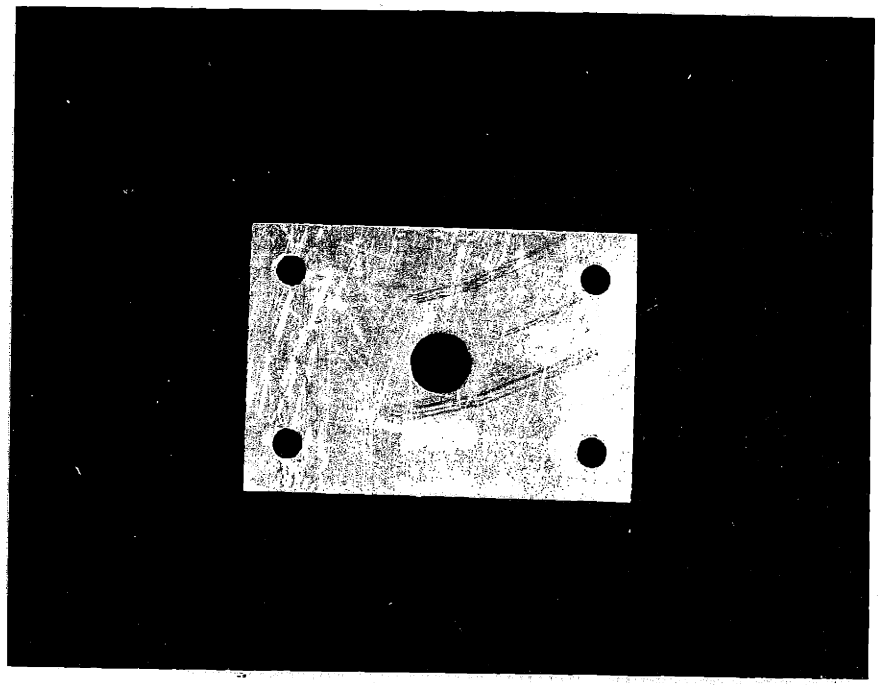


Plate 18



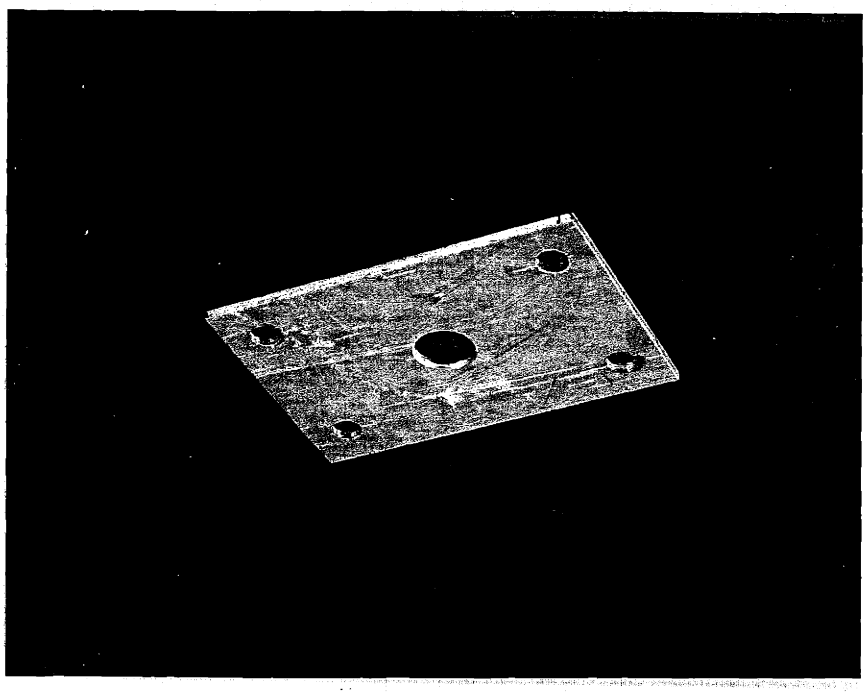
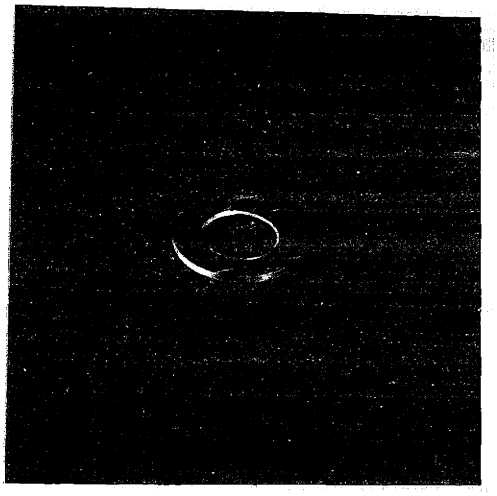
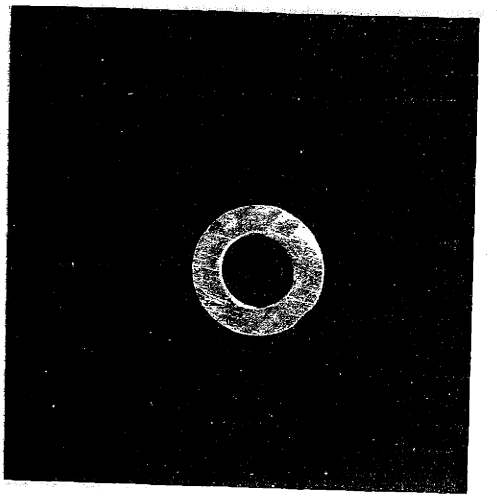


Plate 19





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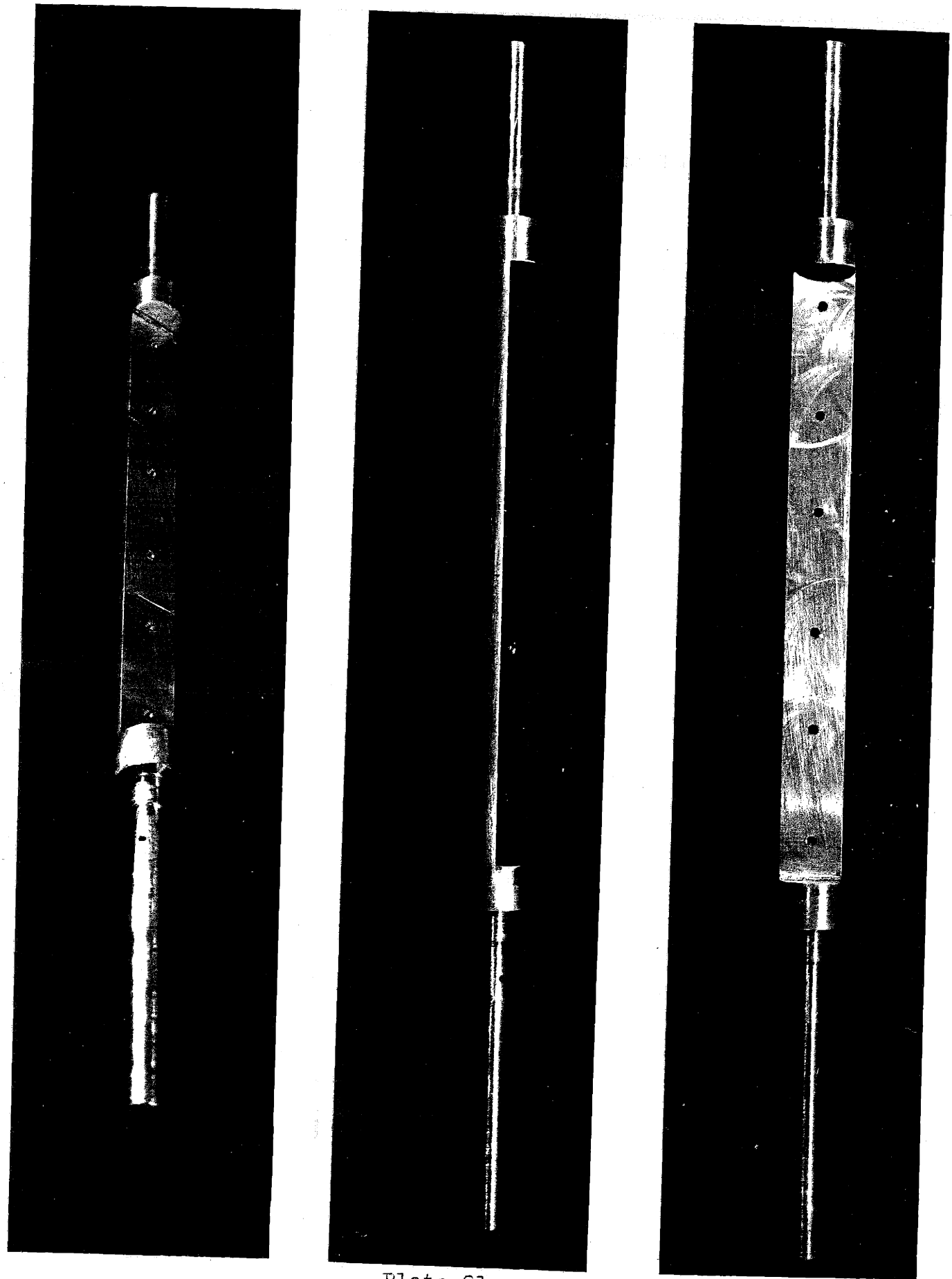

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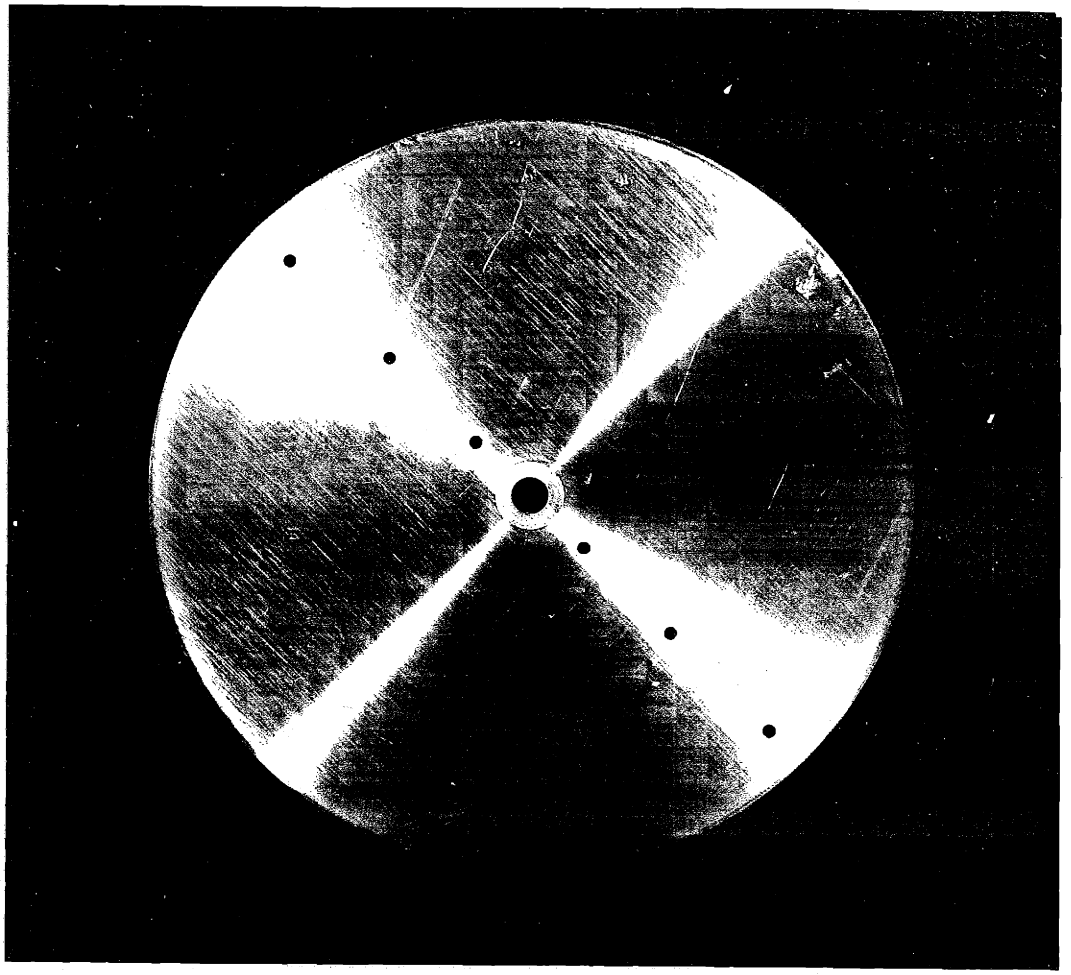

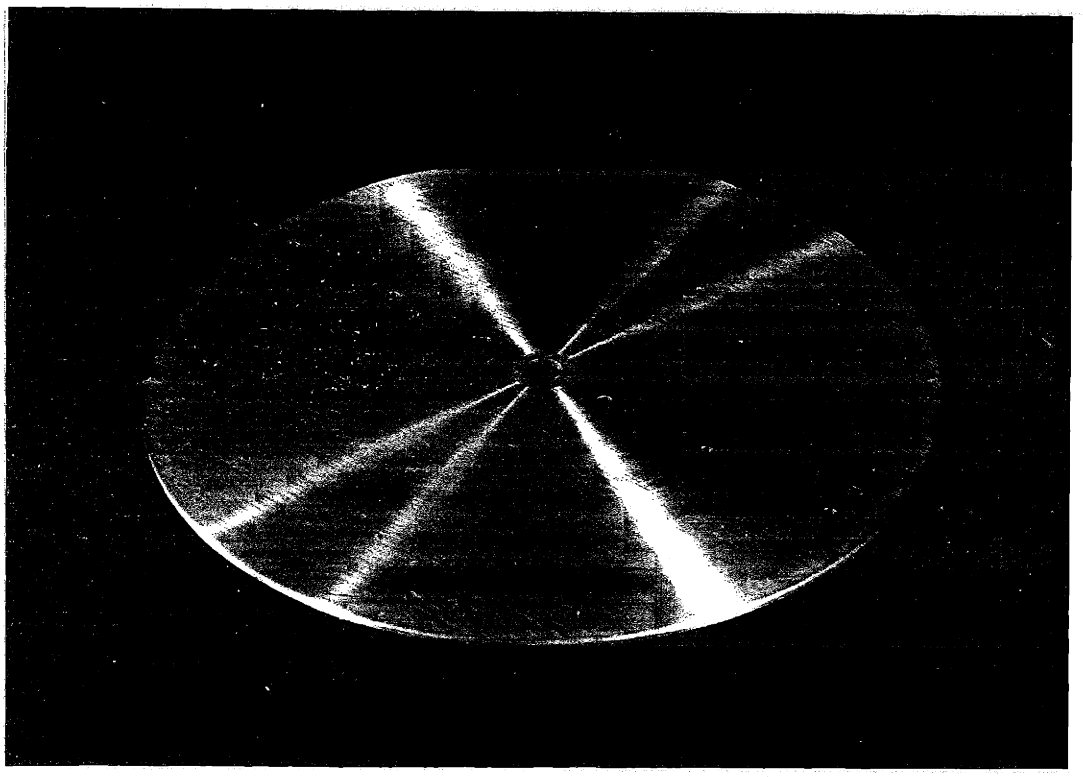

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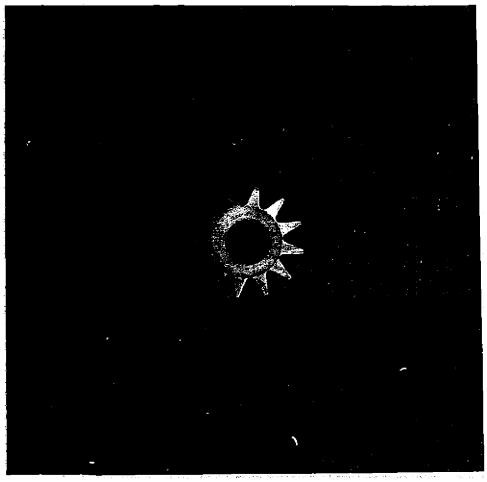

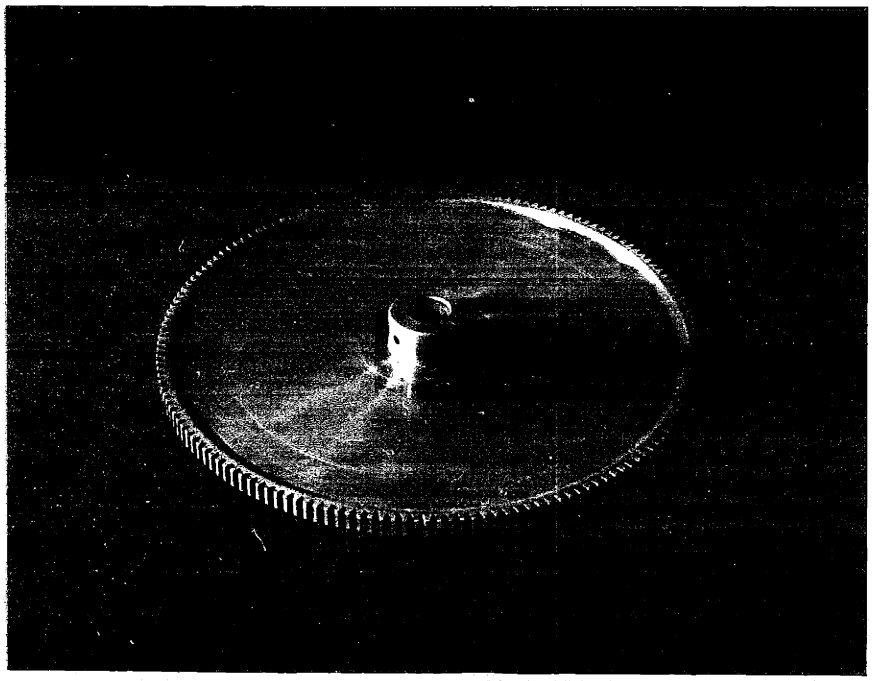

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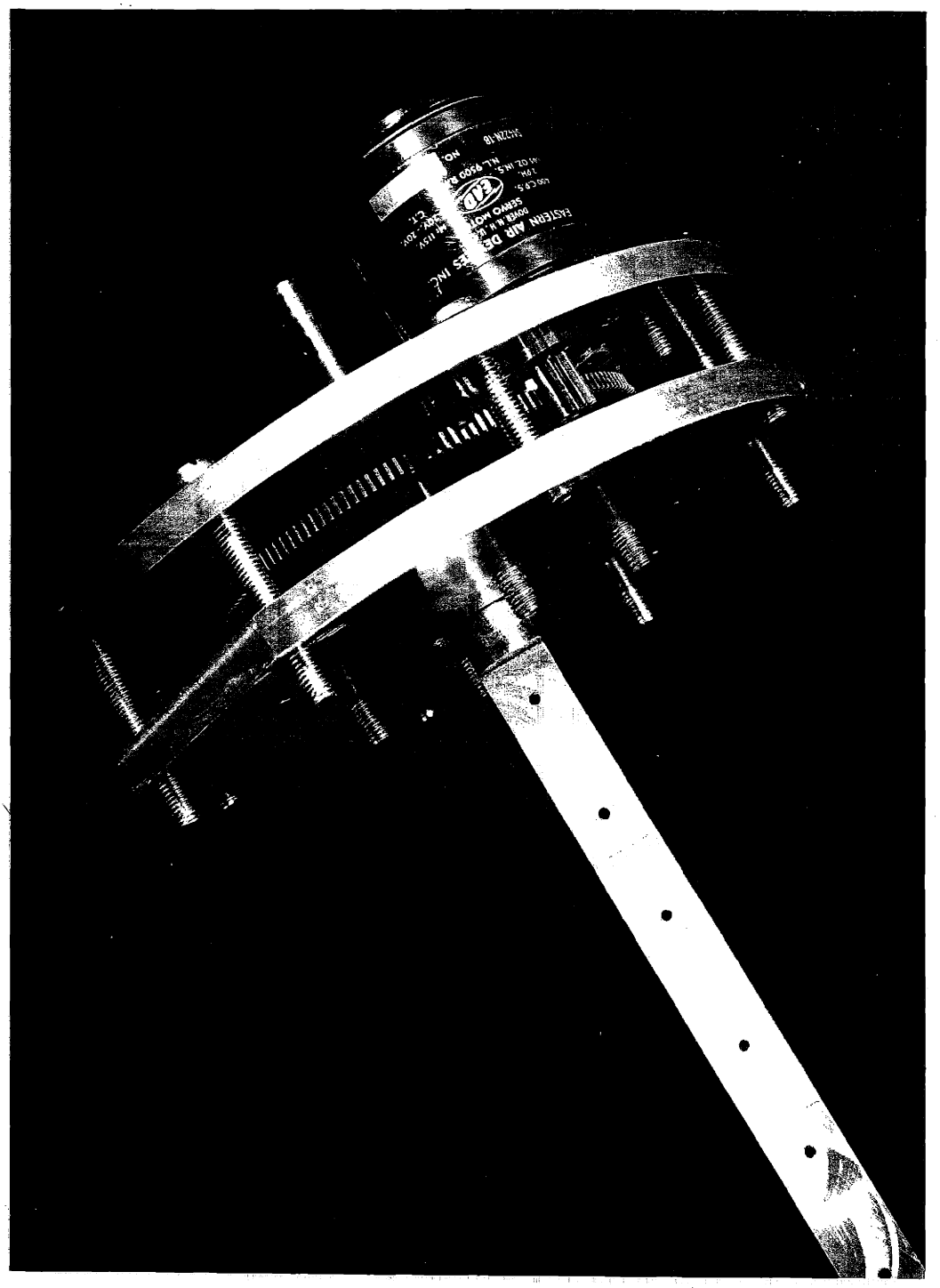

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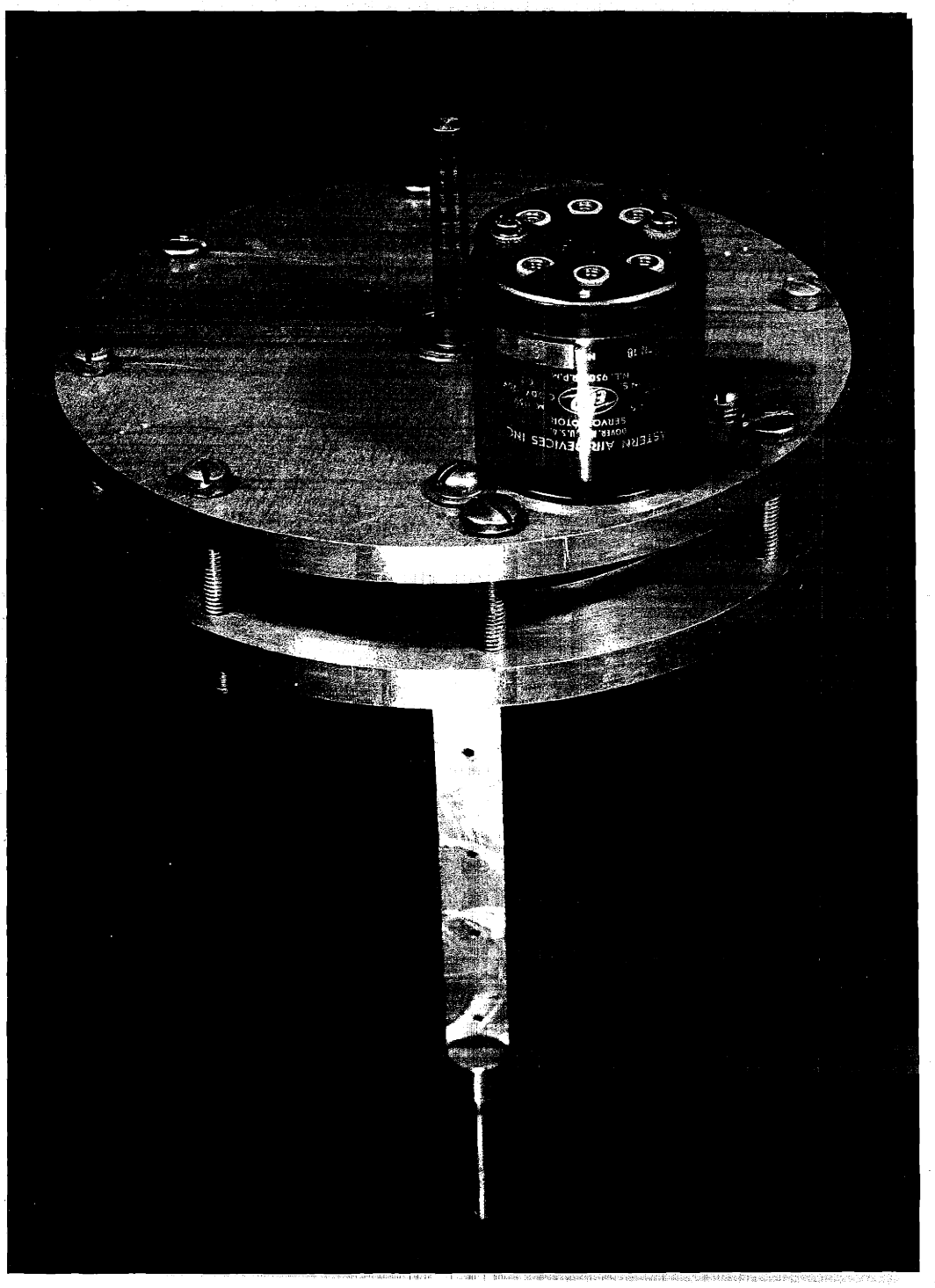

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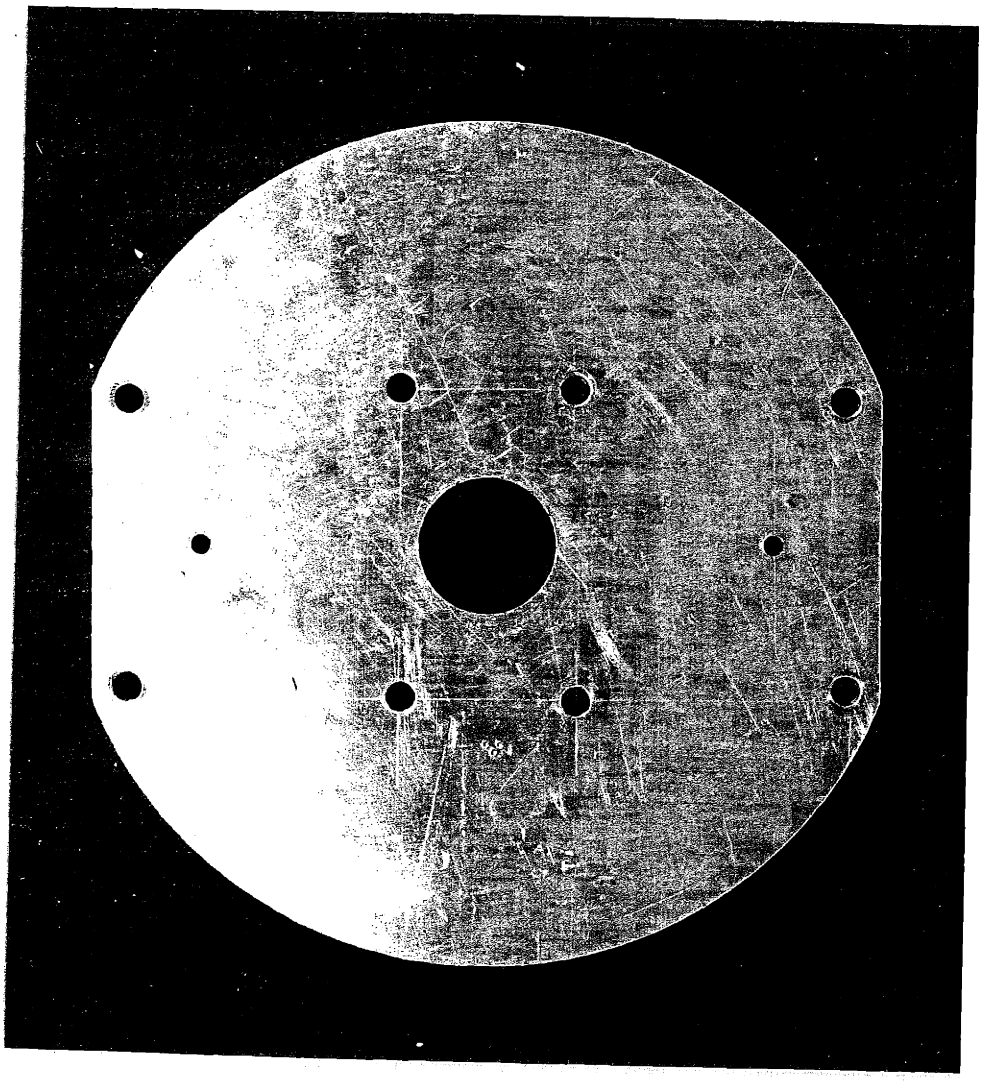

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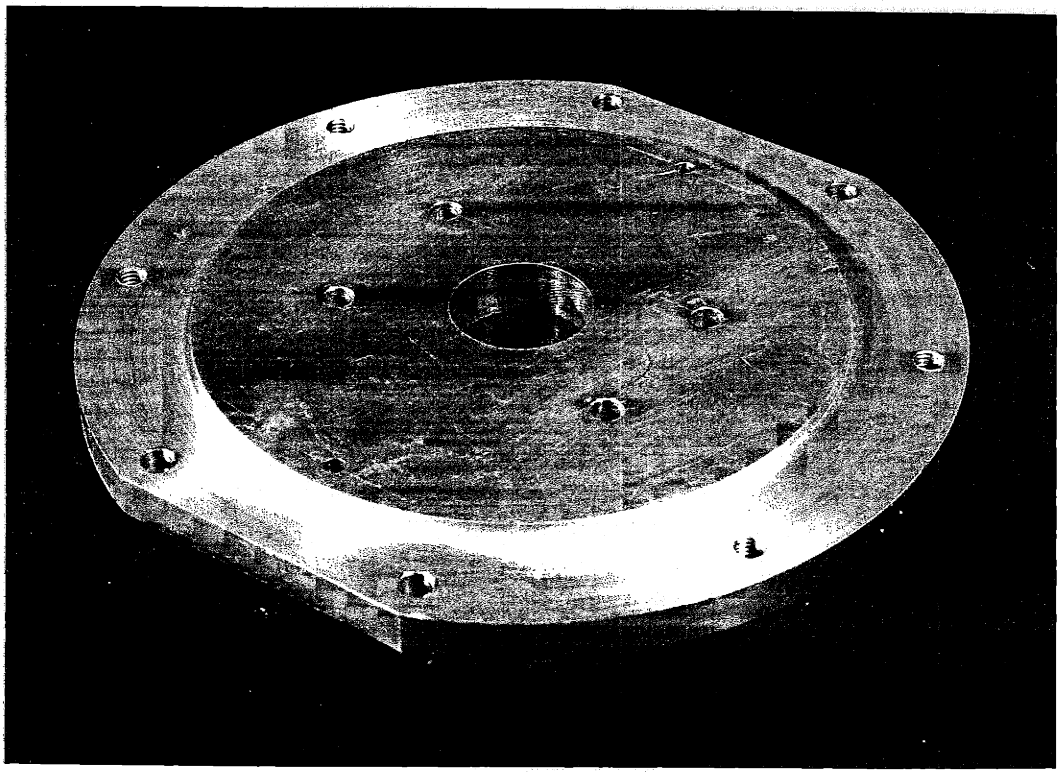

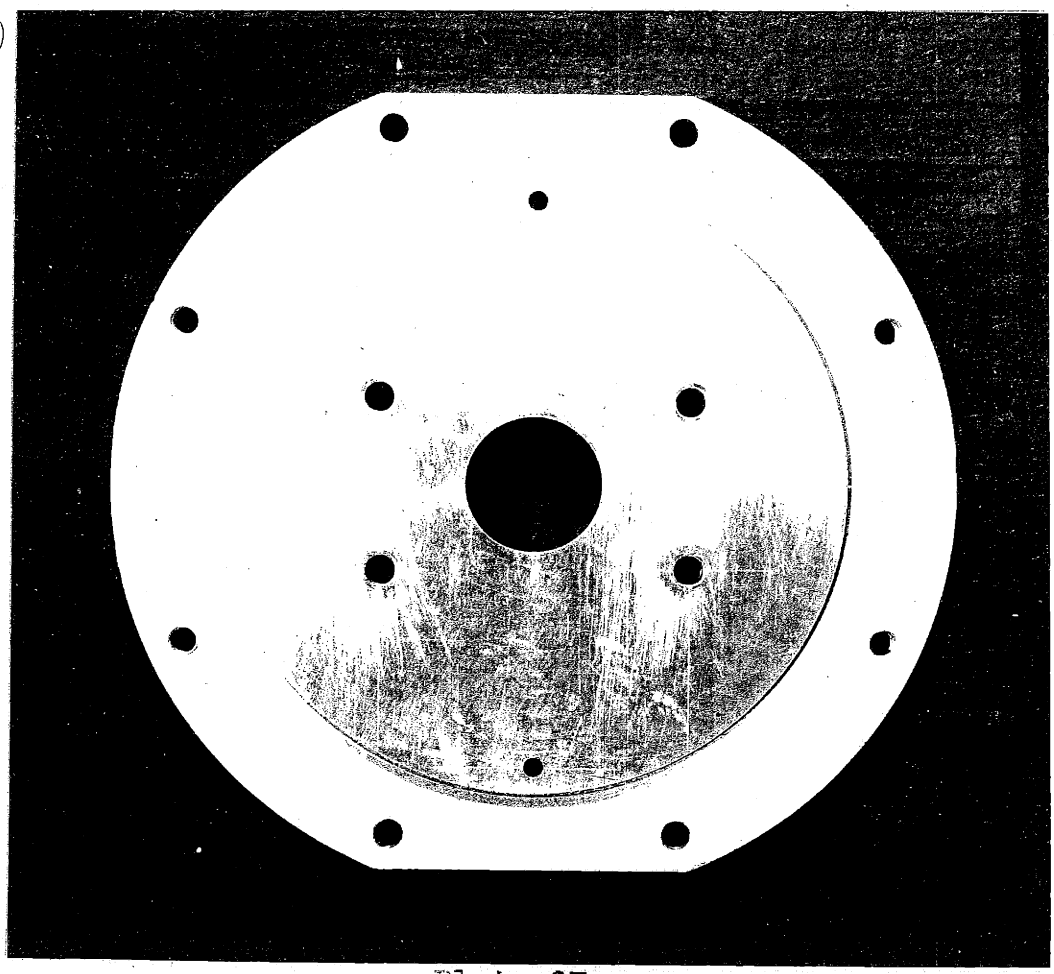

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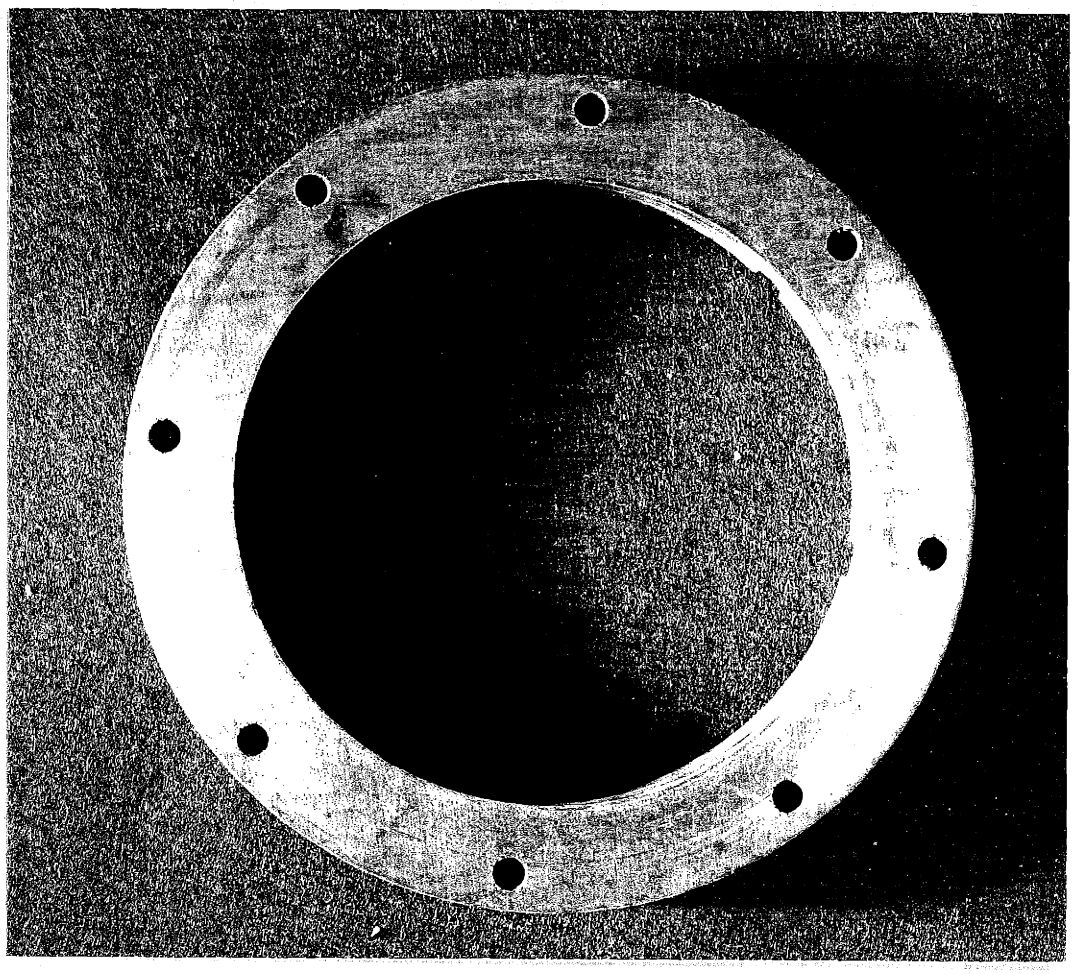

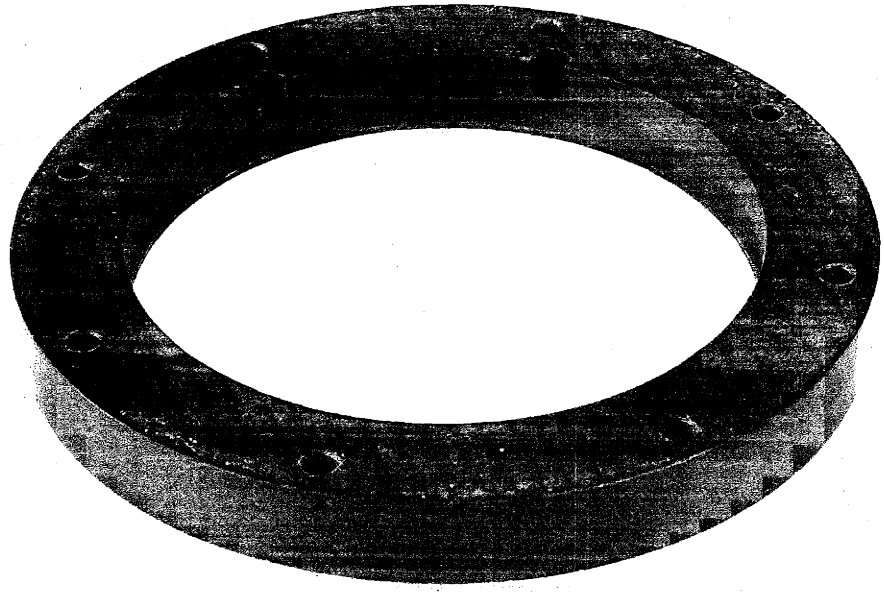

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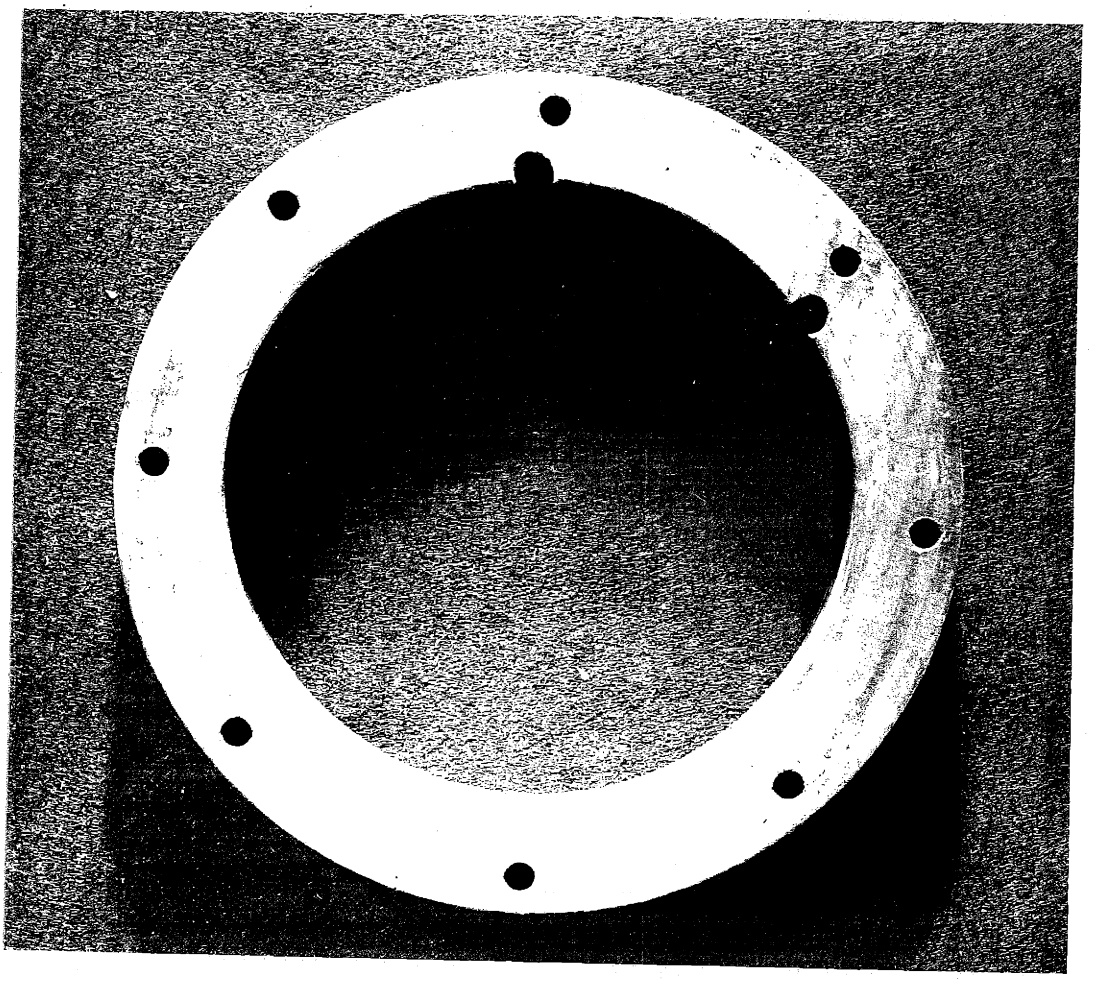

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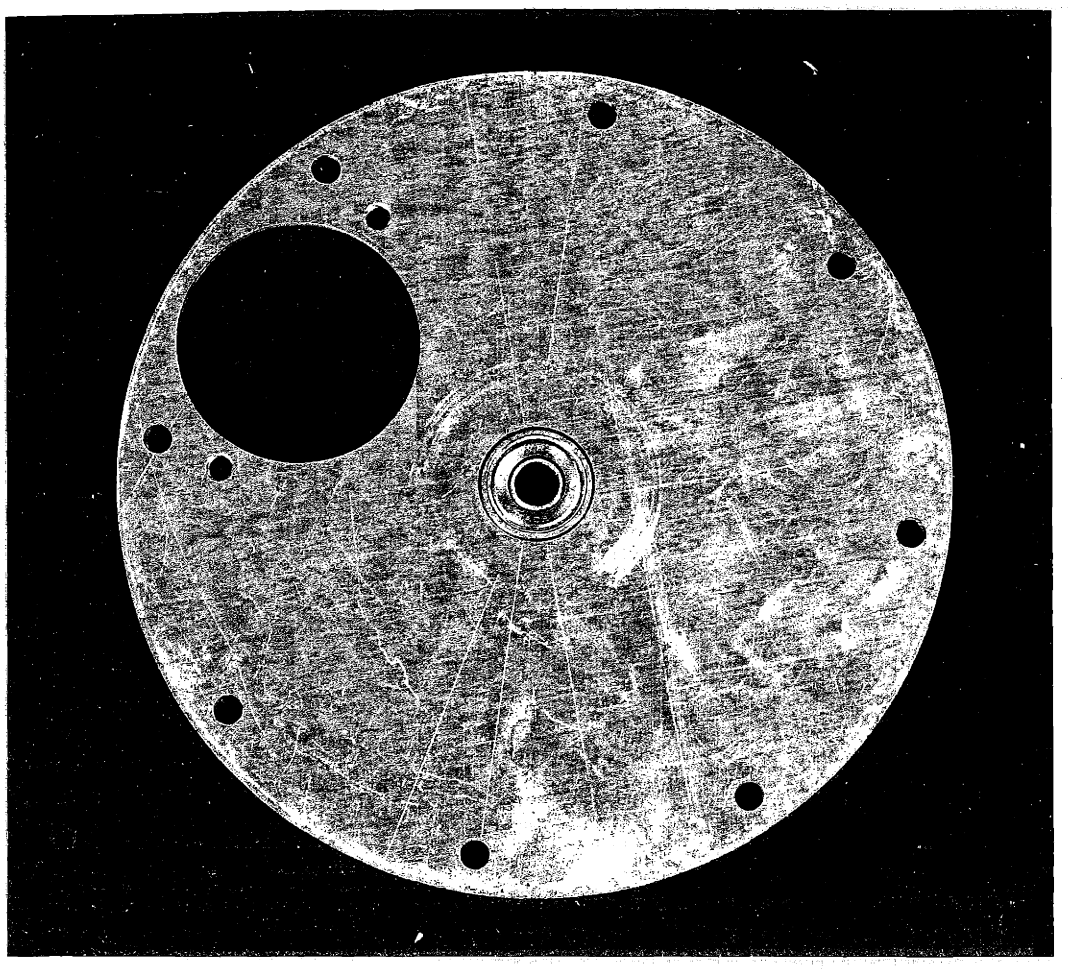

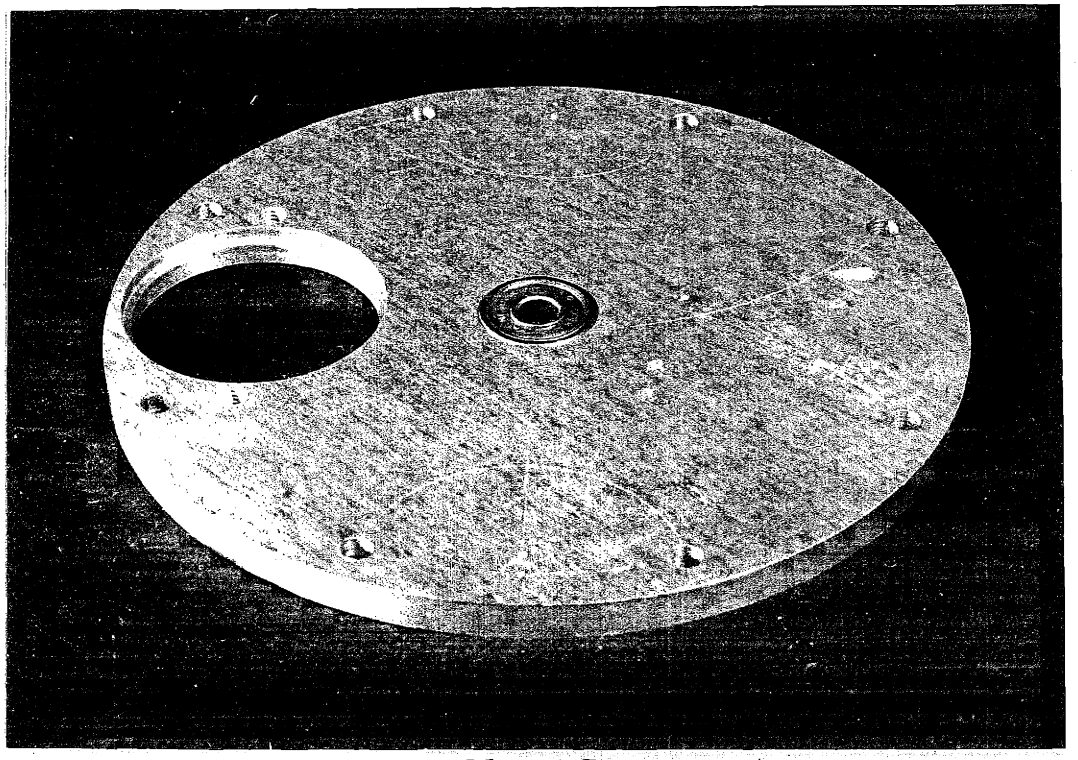

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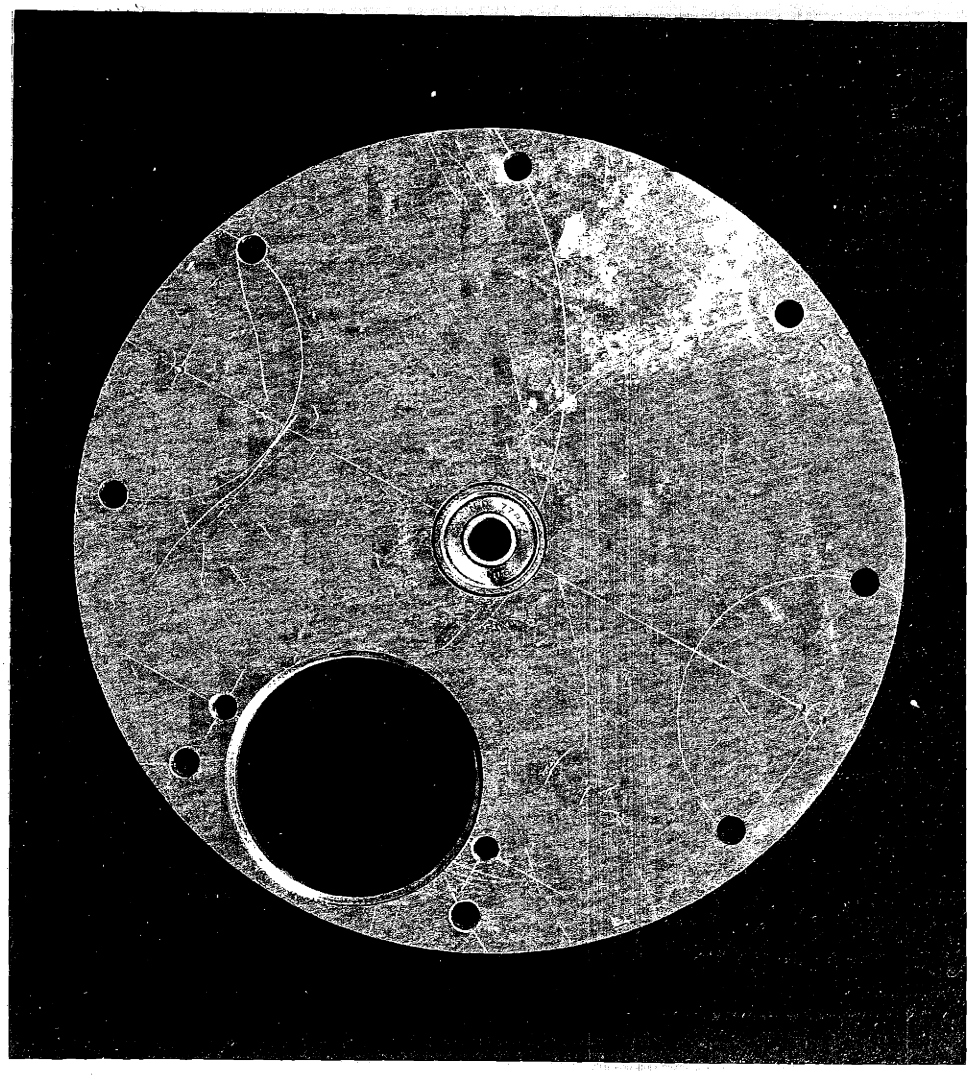

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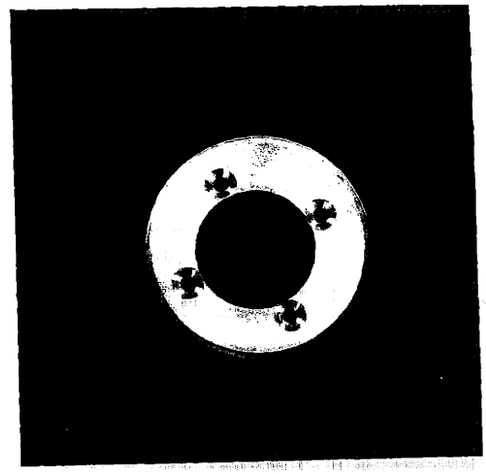

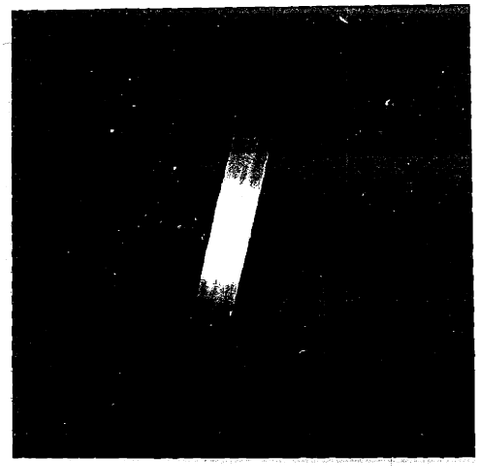

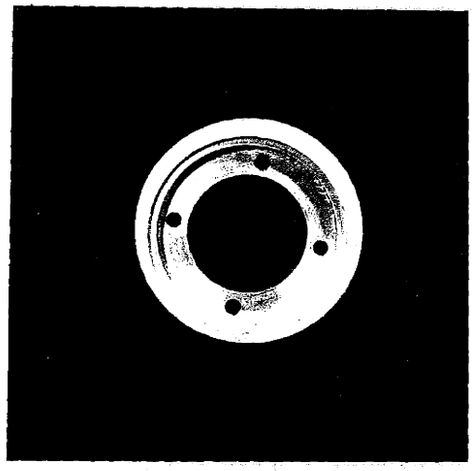

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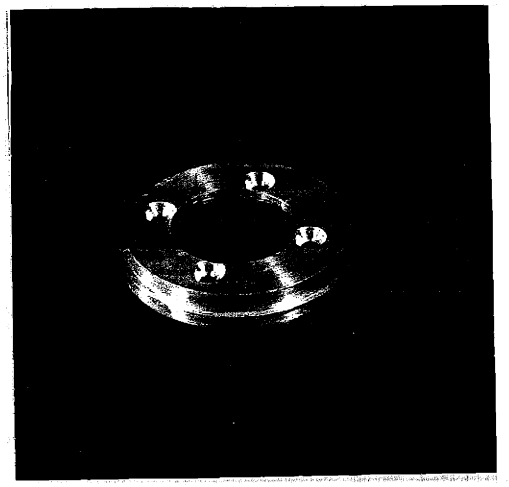

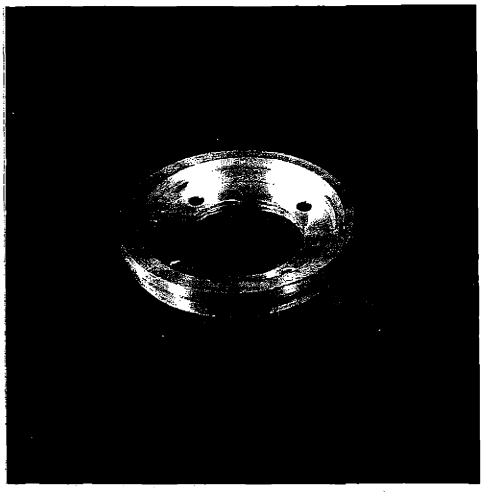

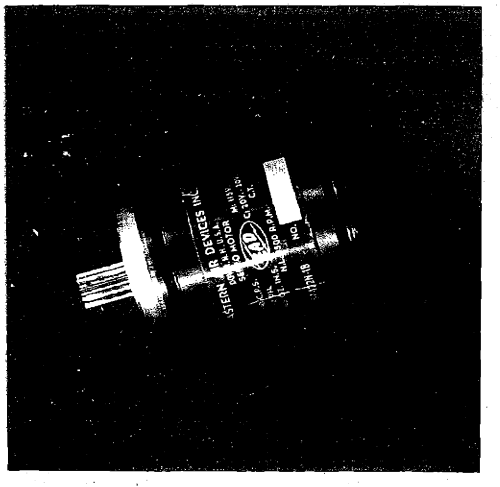

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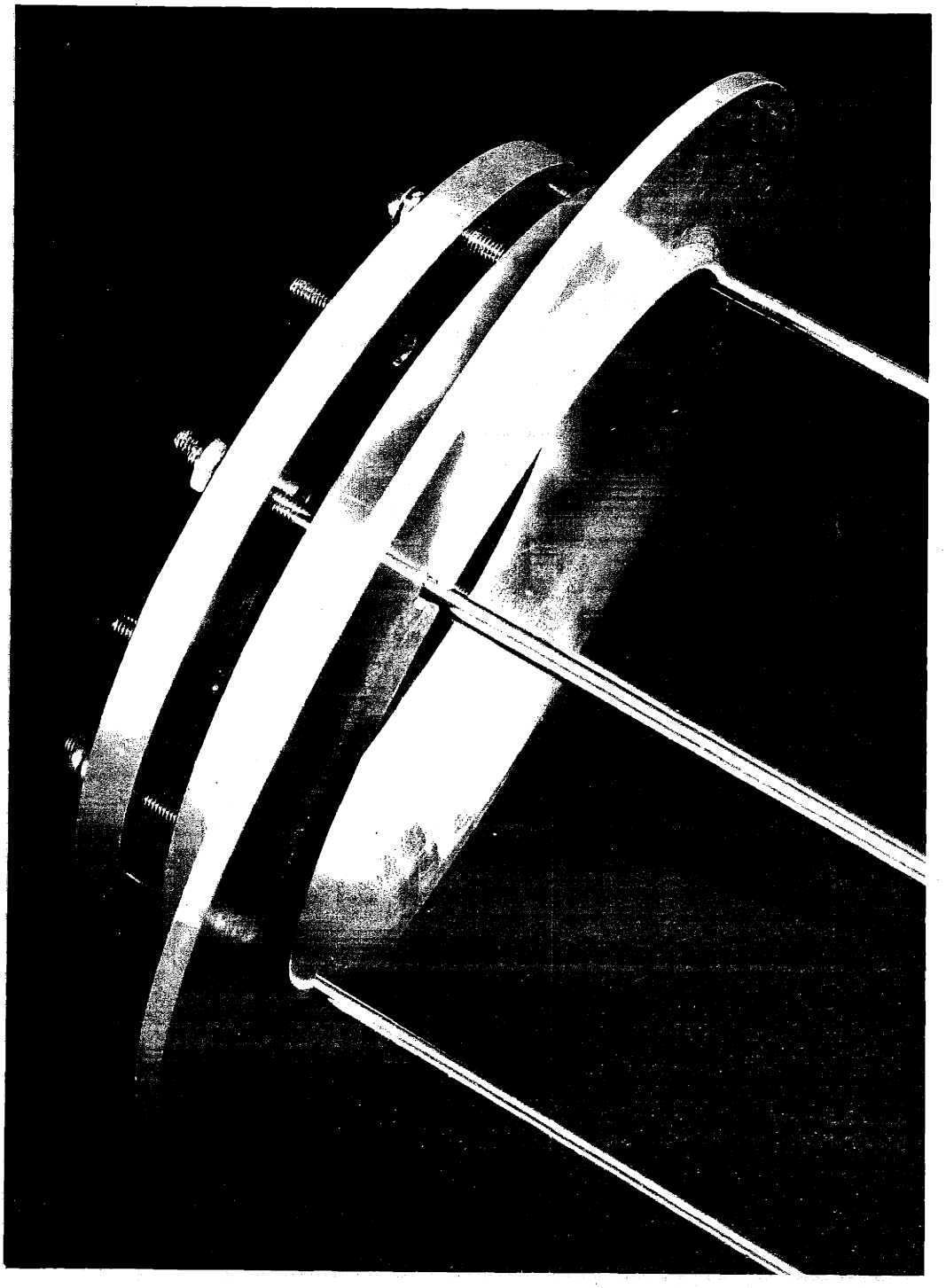

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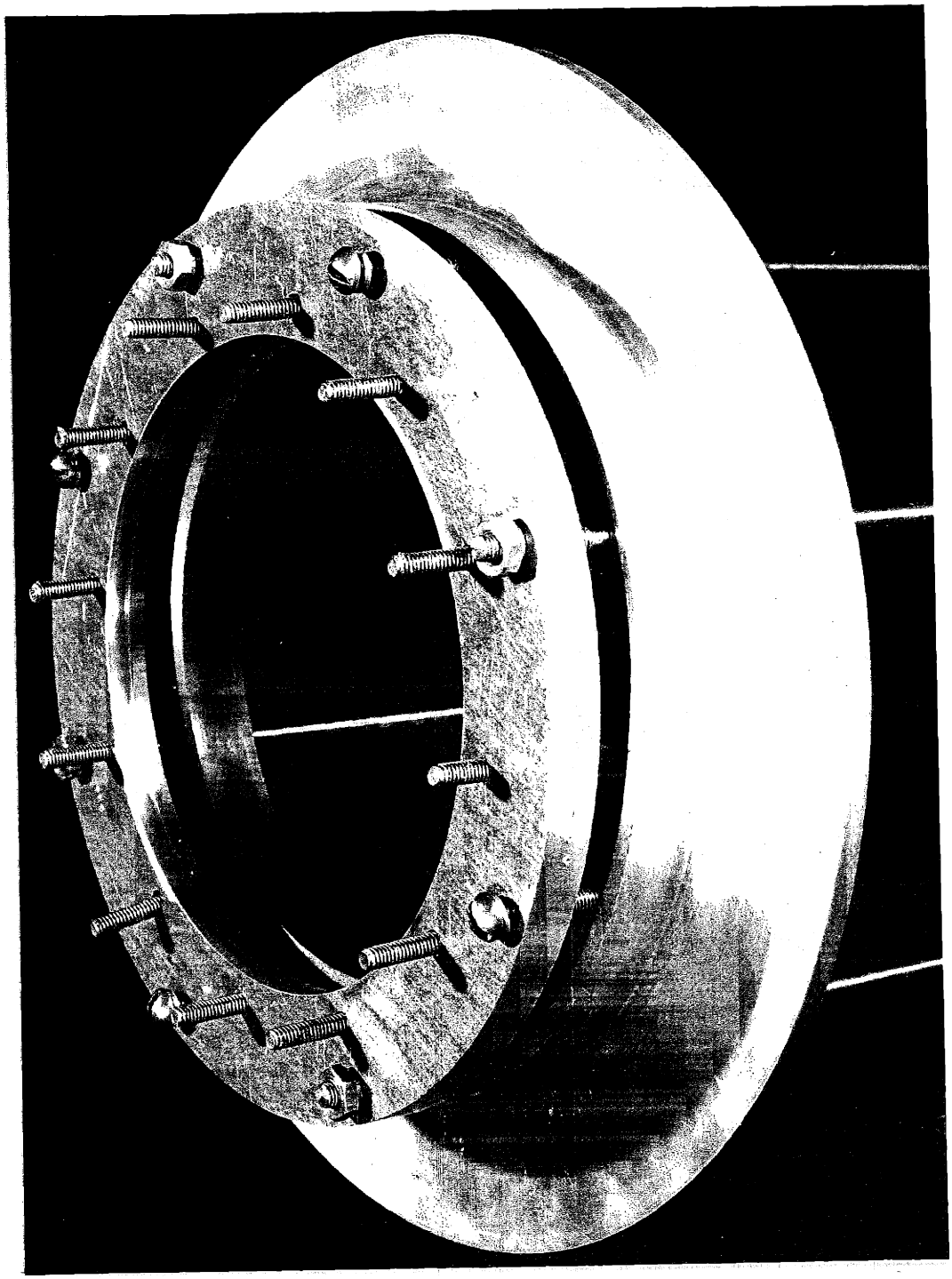

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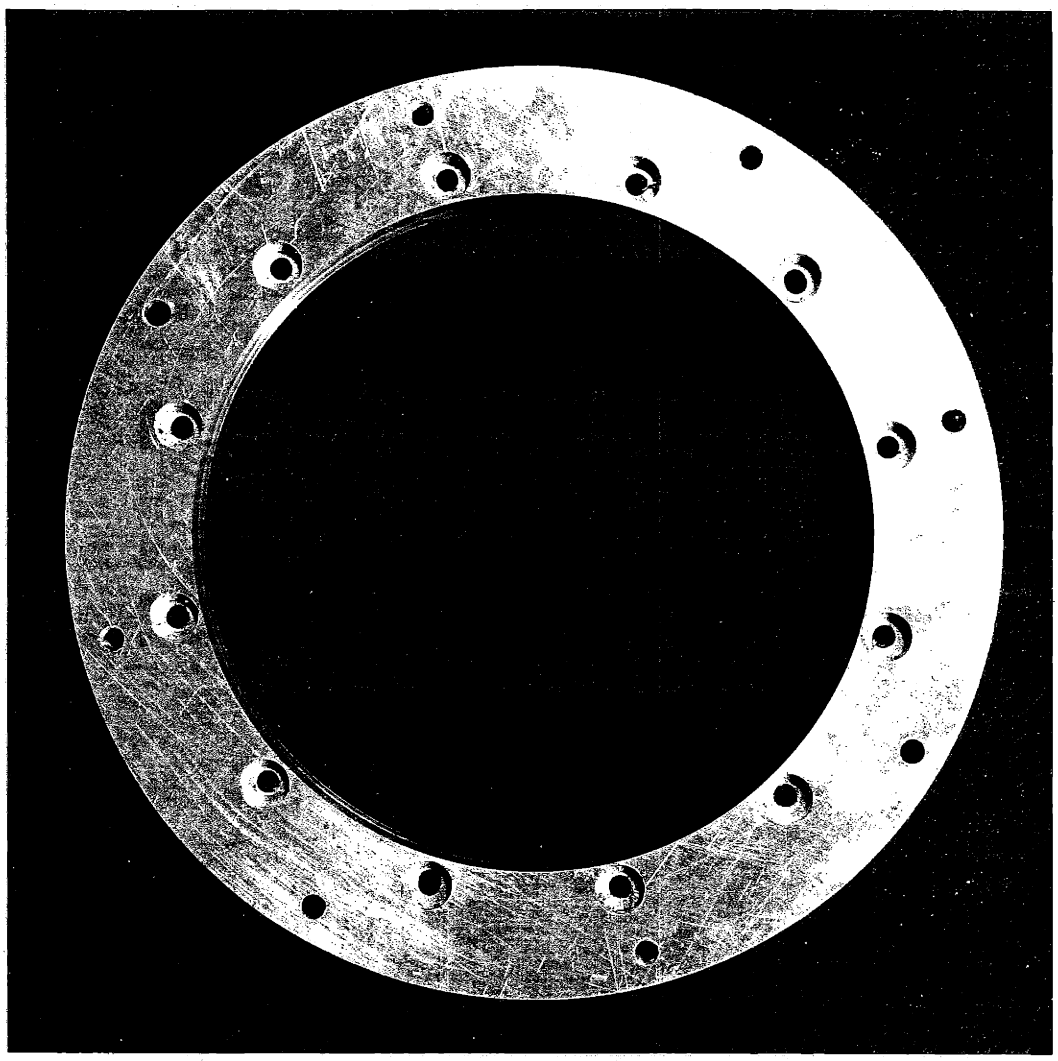

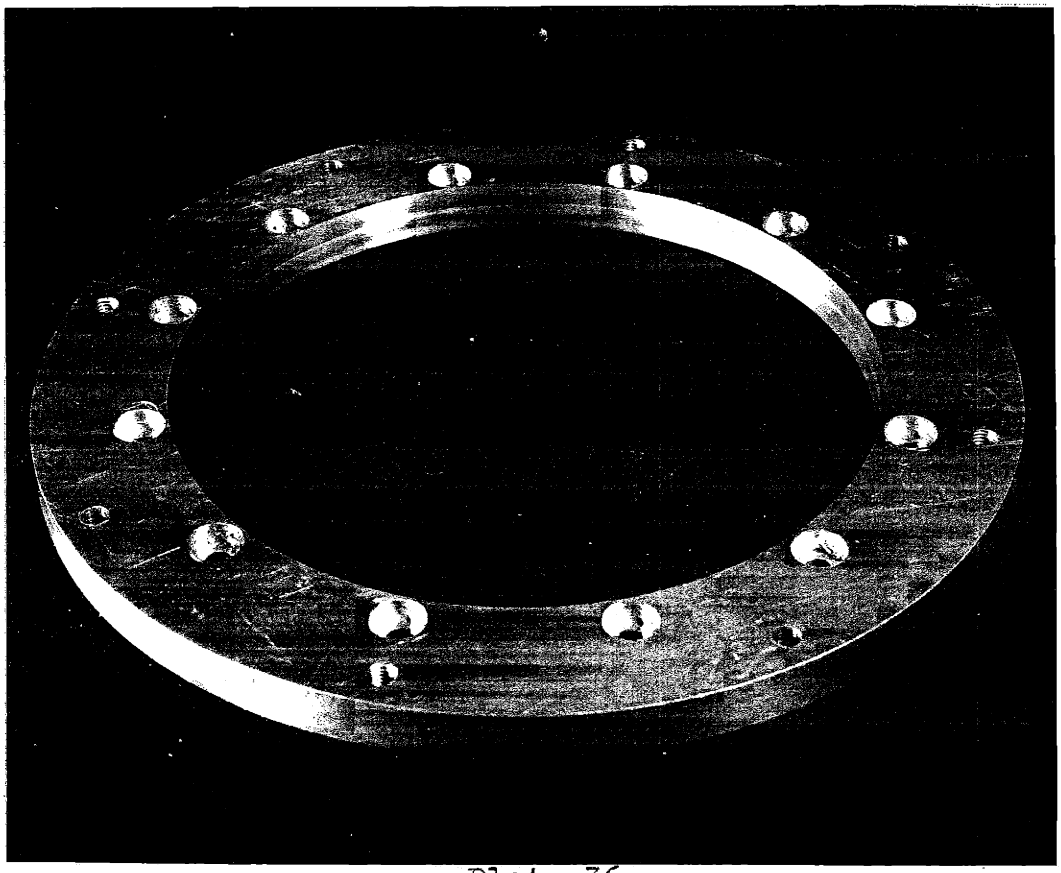

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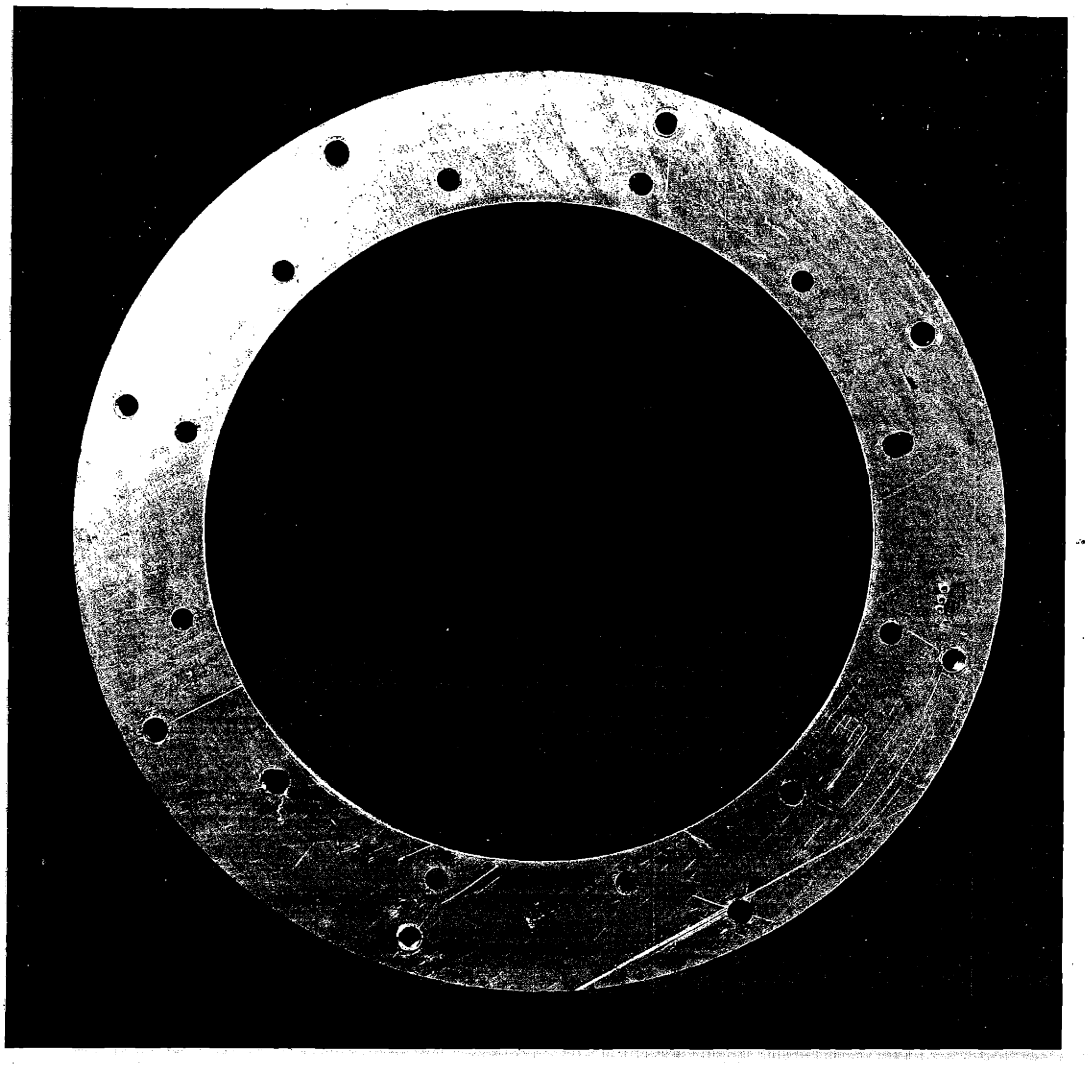

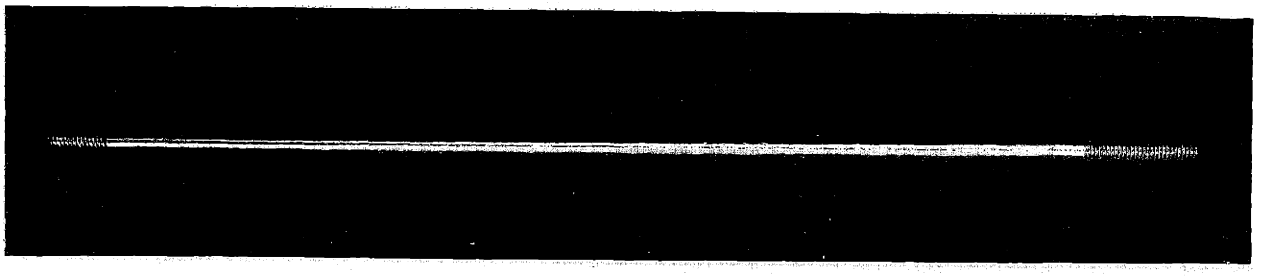

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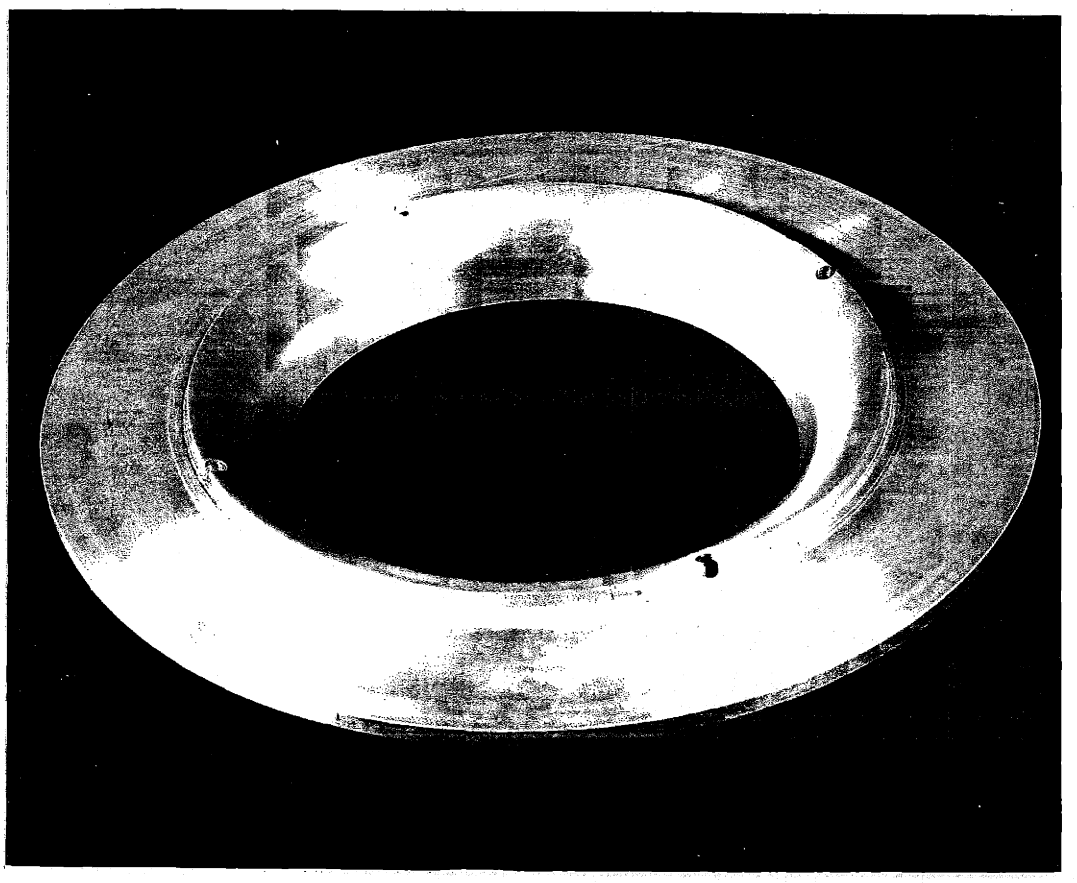

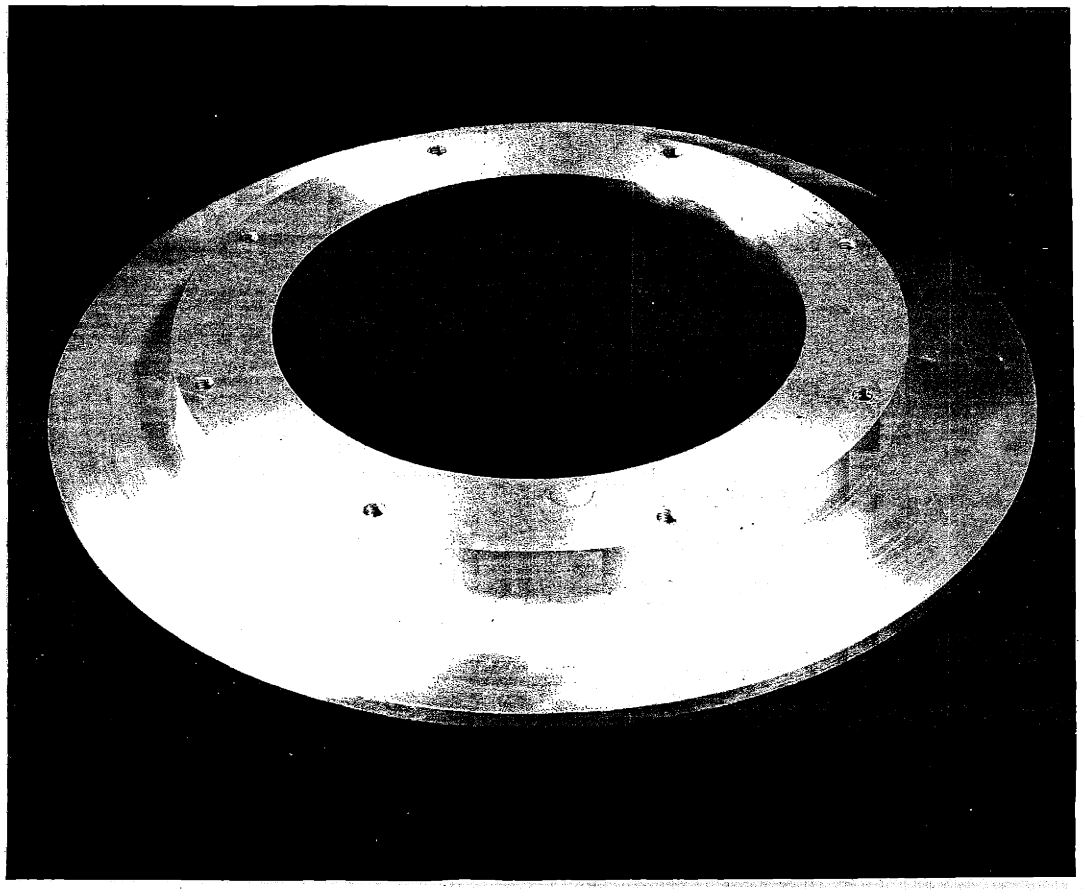

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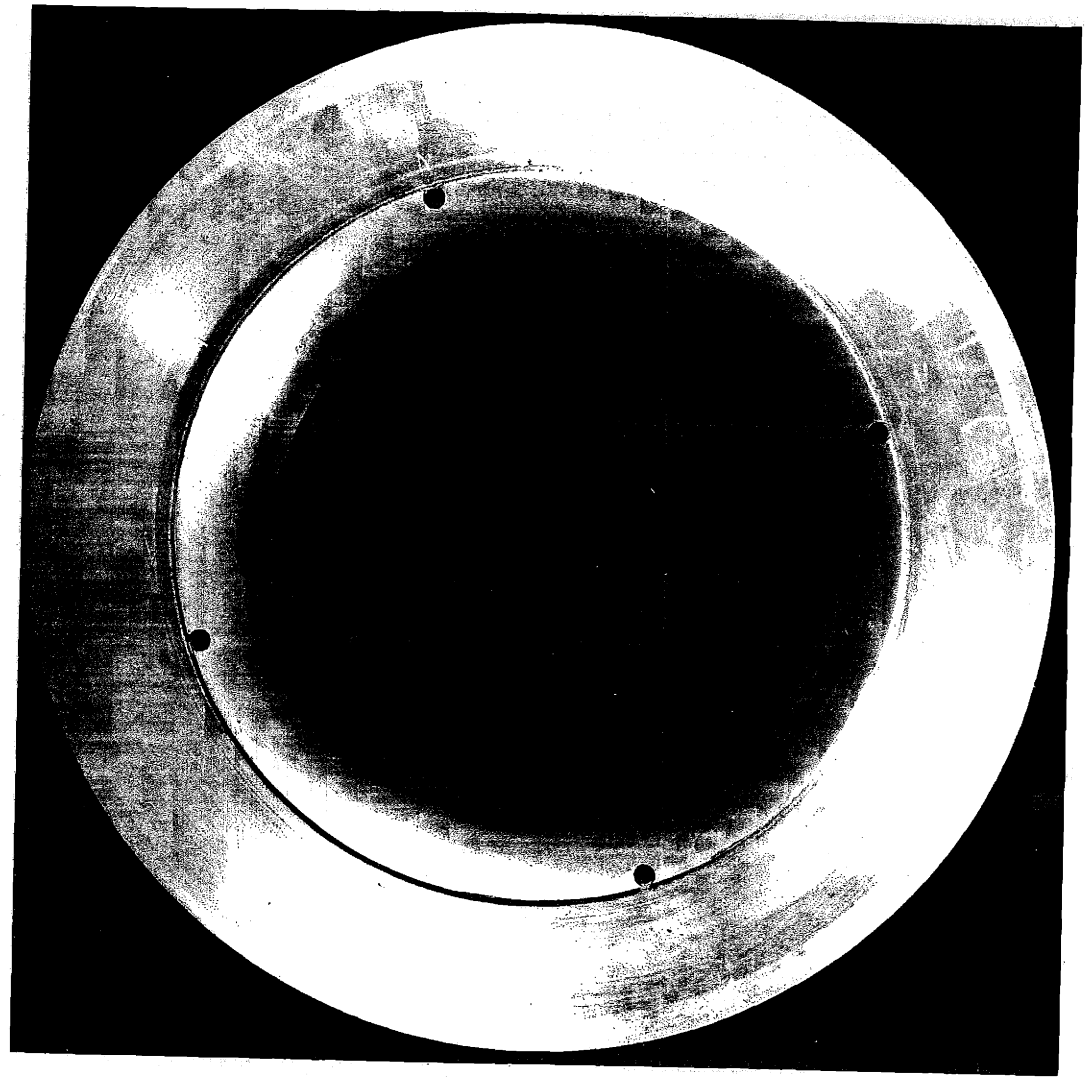

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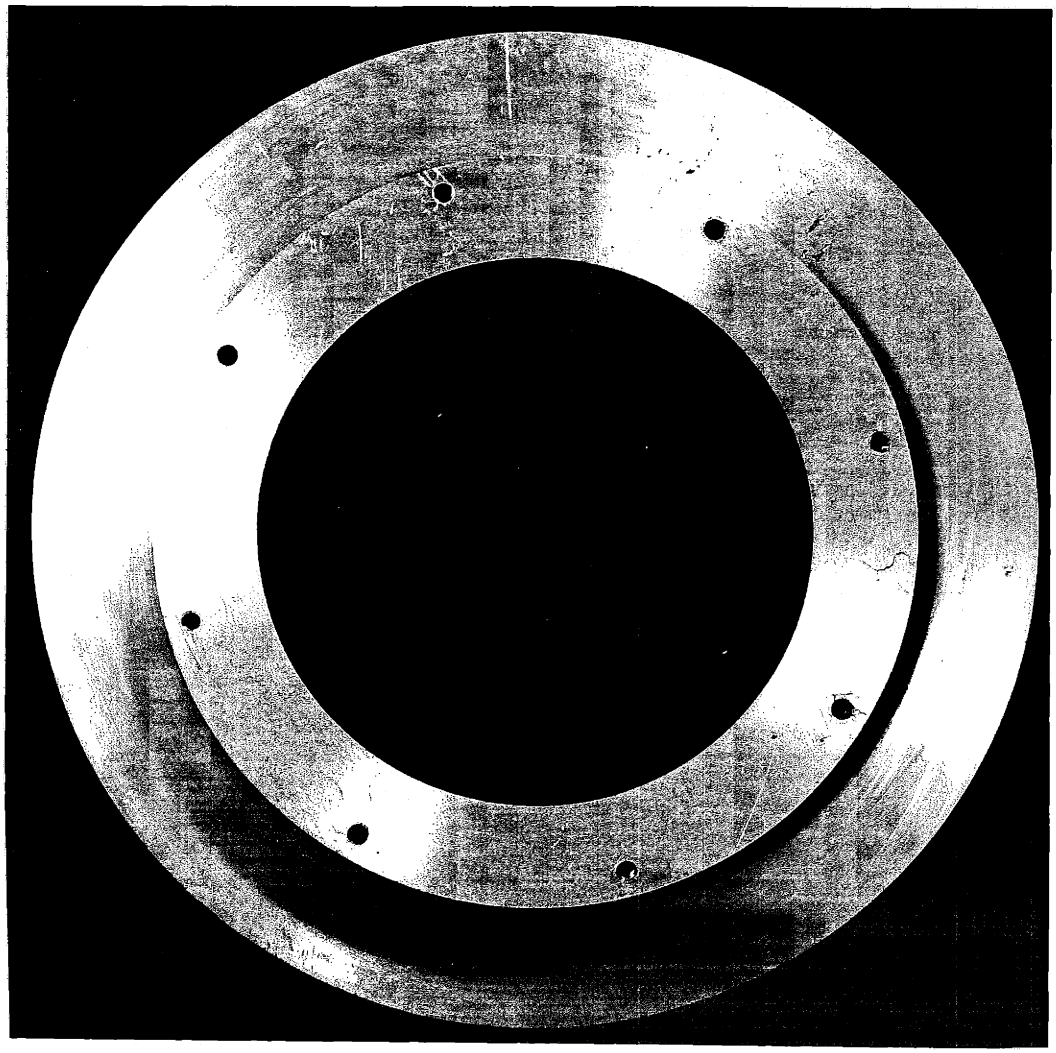

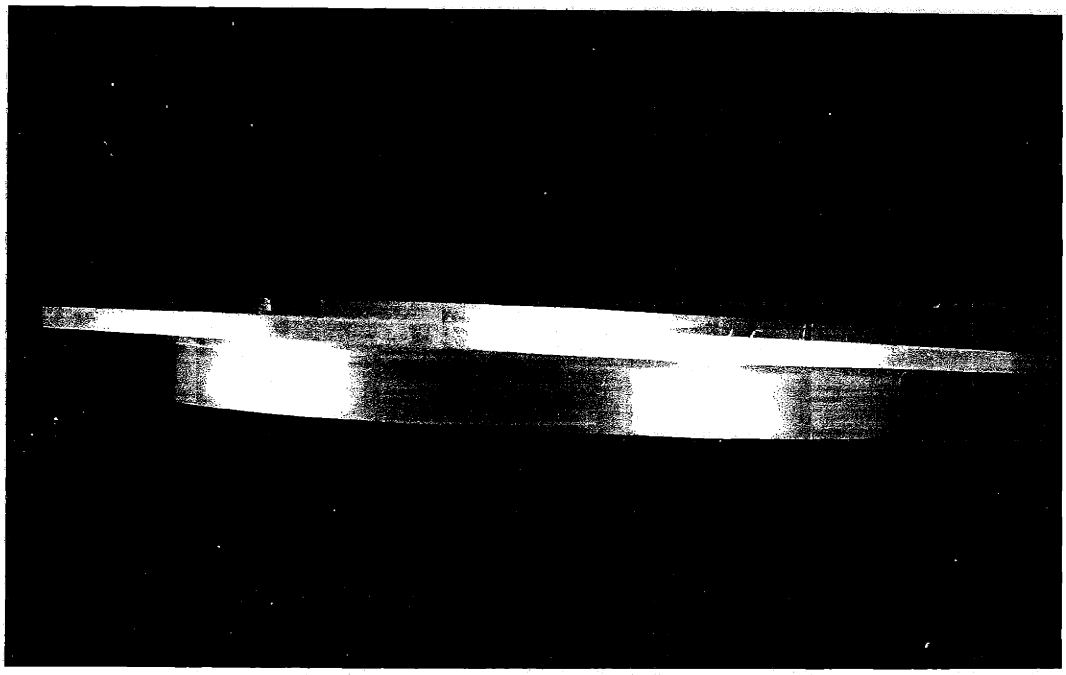

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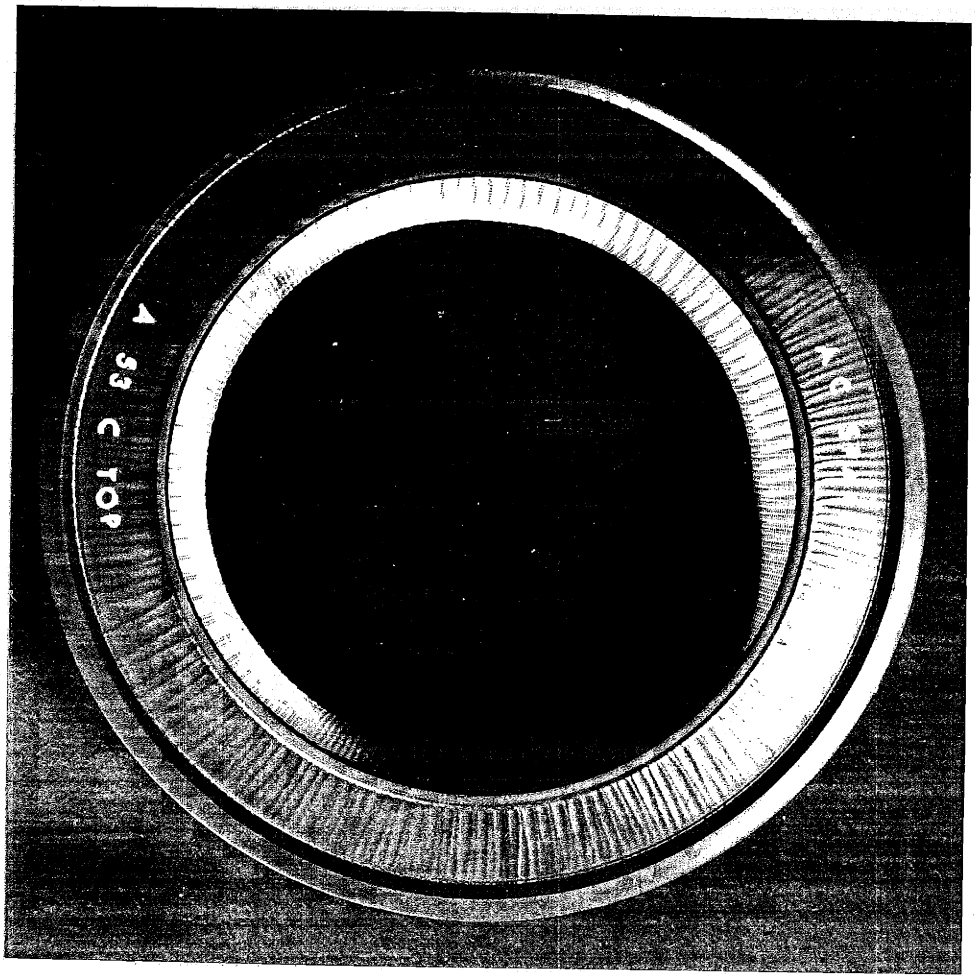

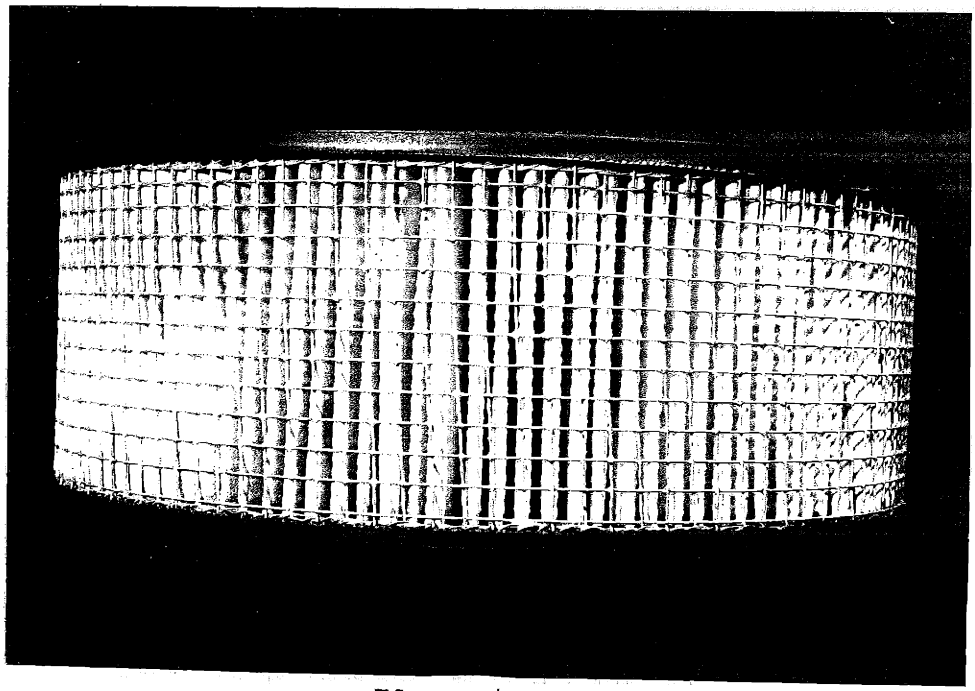

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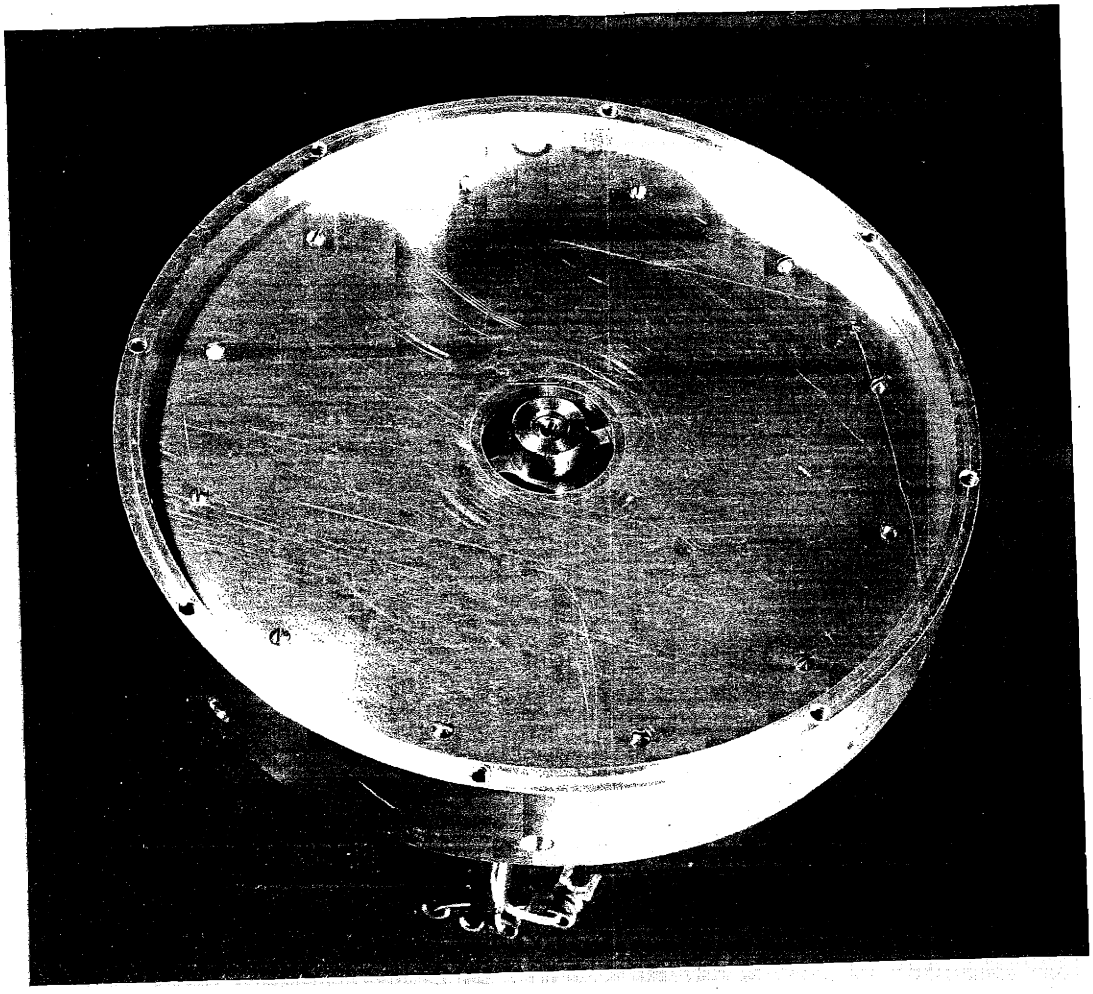
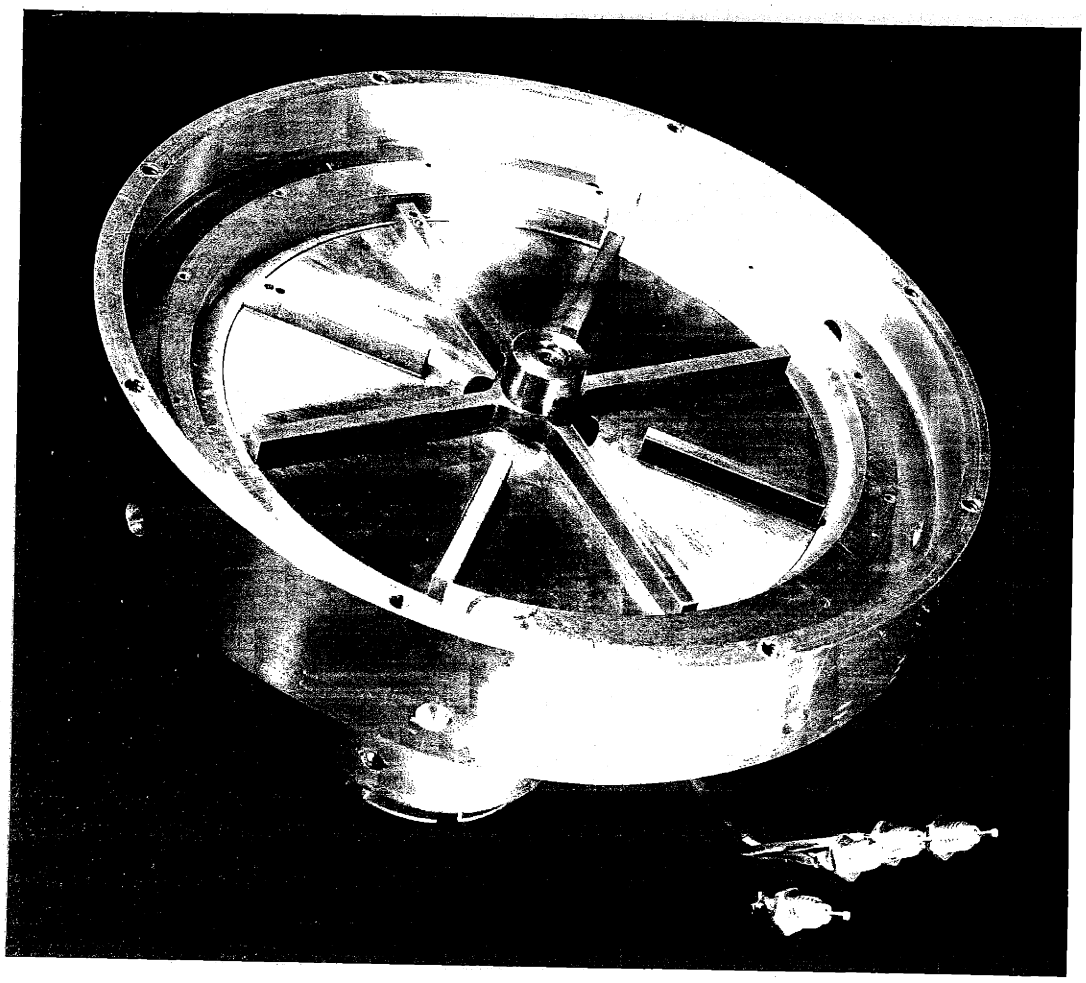


Plate 42



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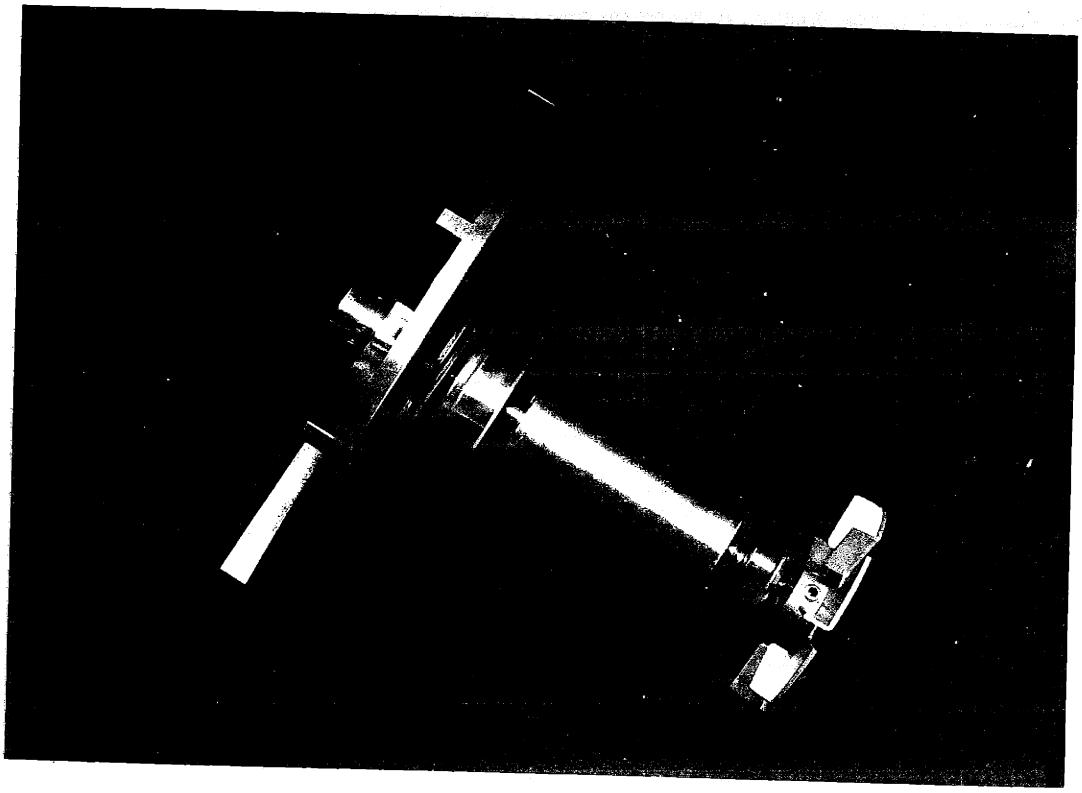
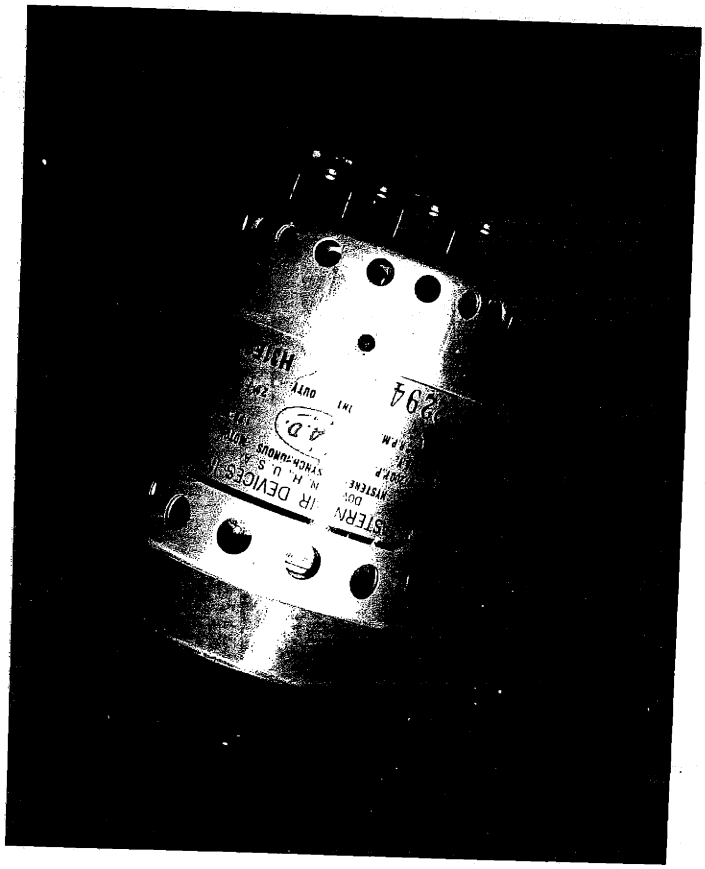




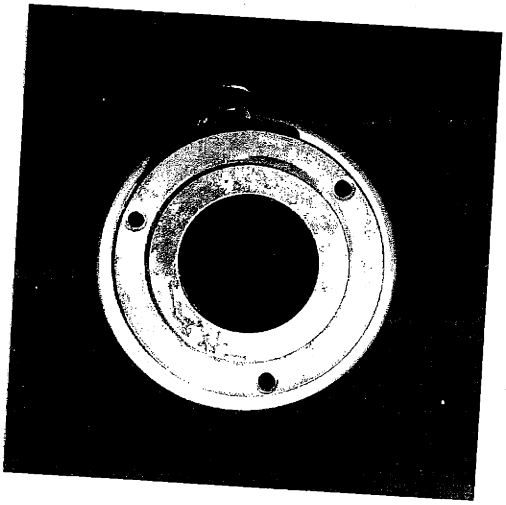
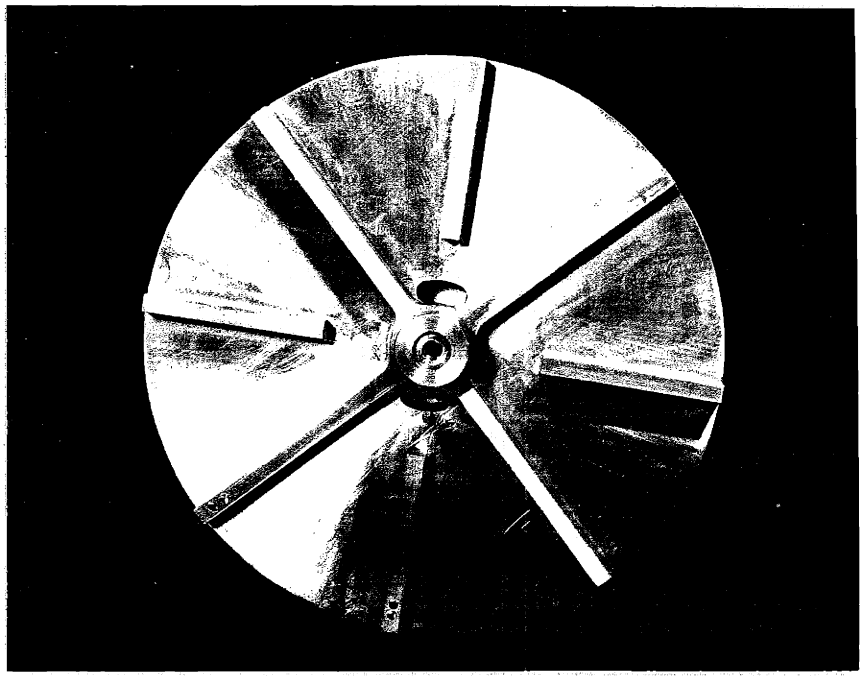


Plate 44



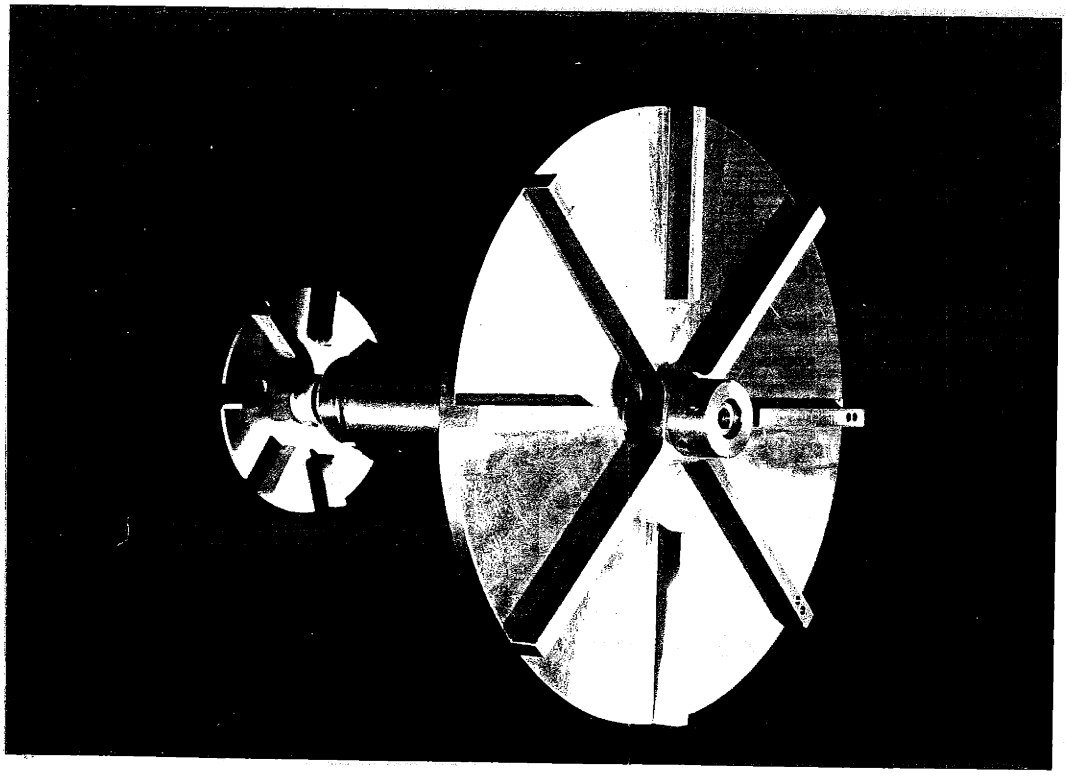
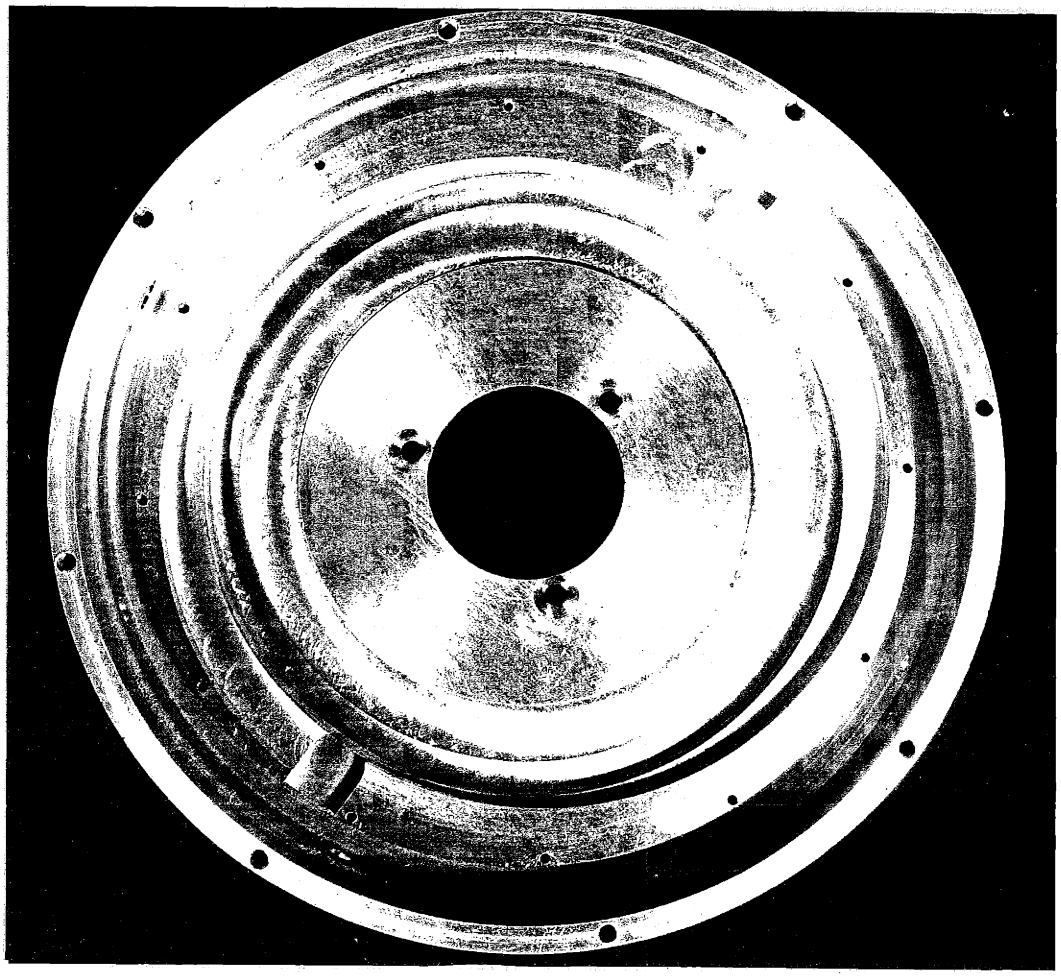


Plate 45



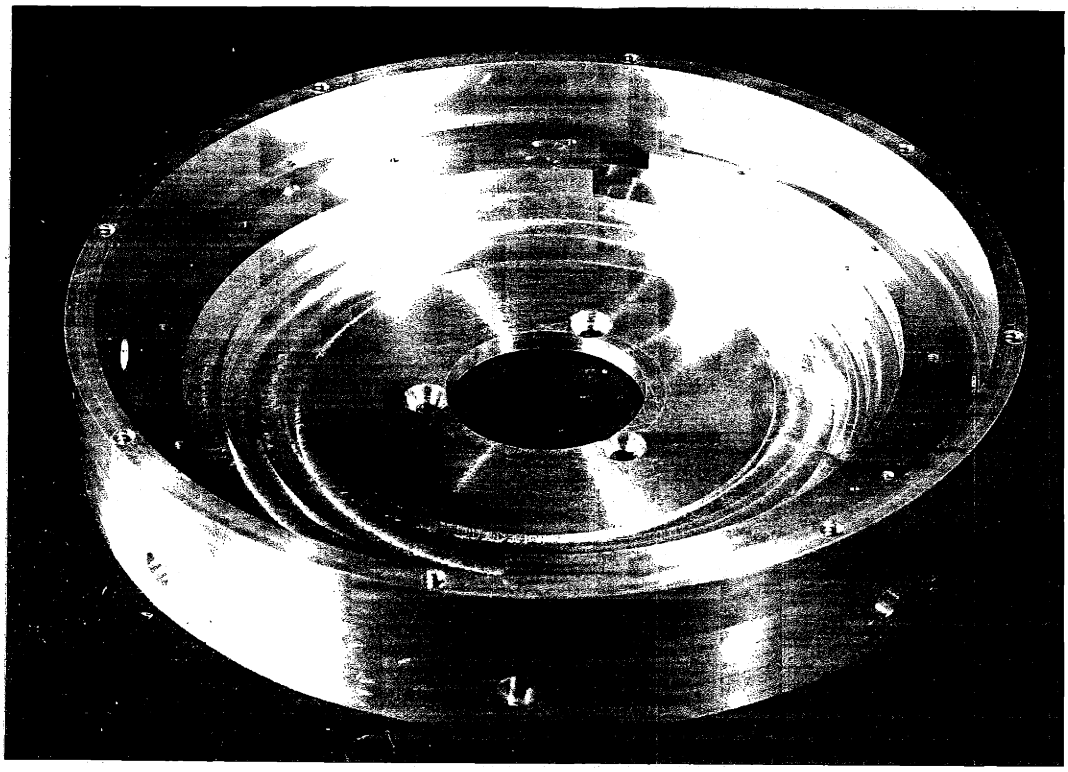
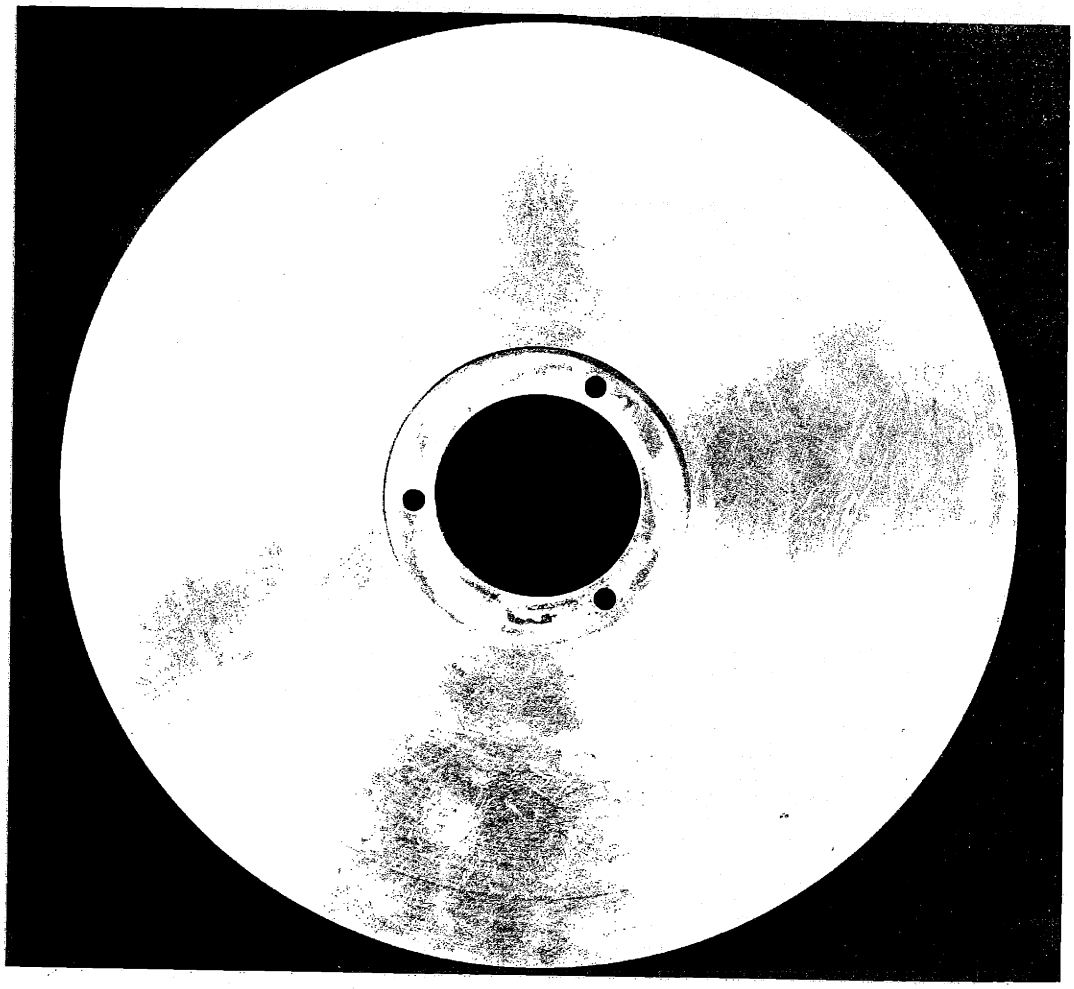


Plate 46



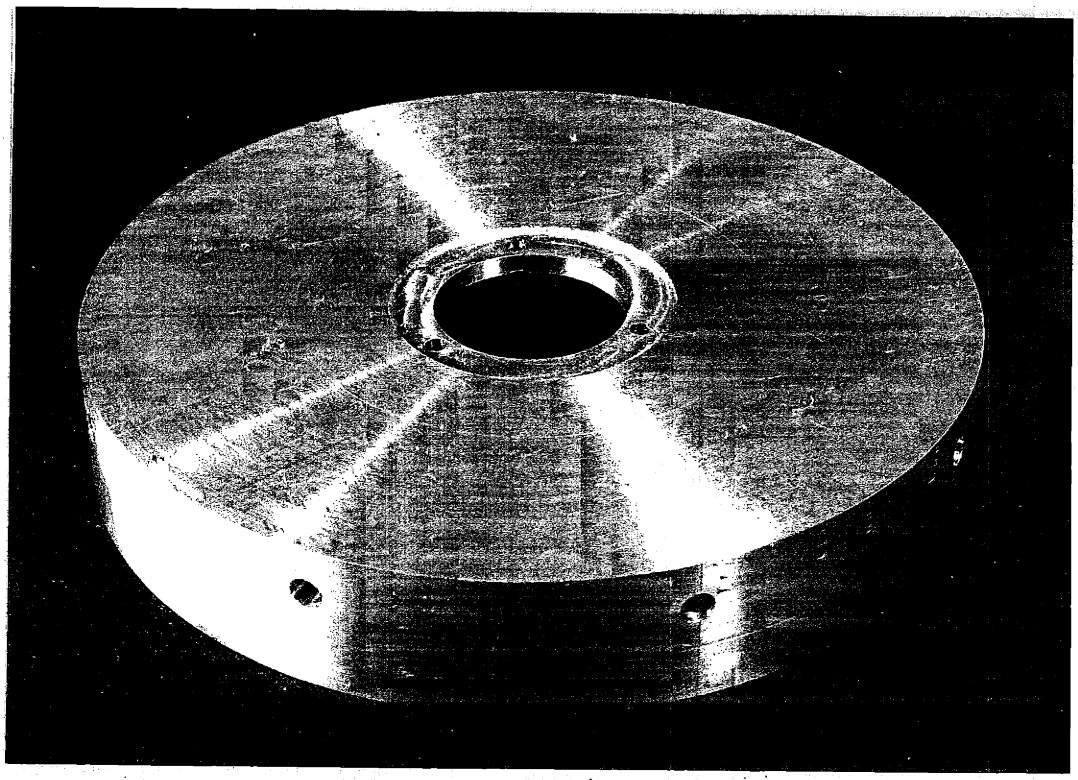
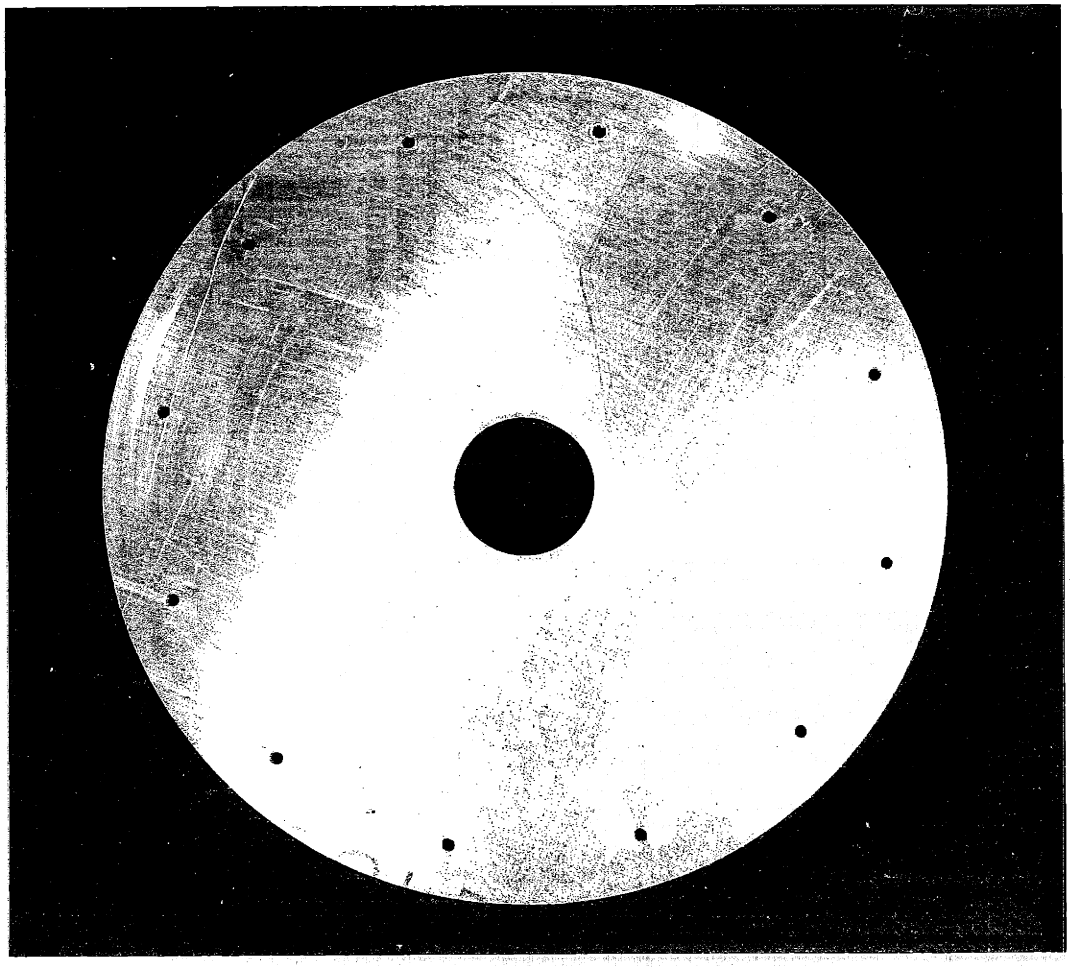


Plate 47



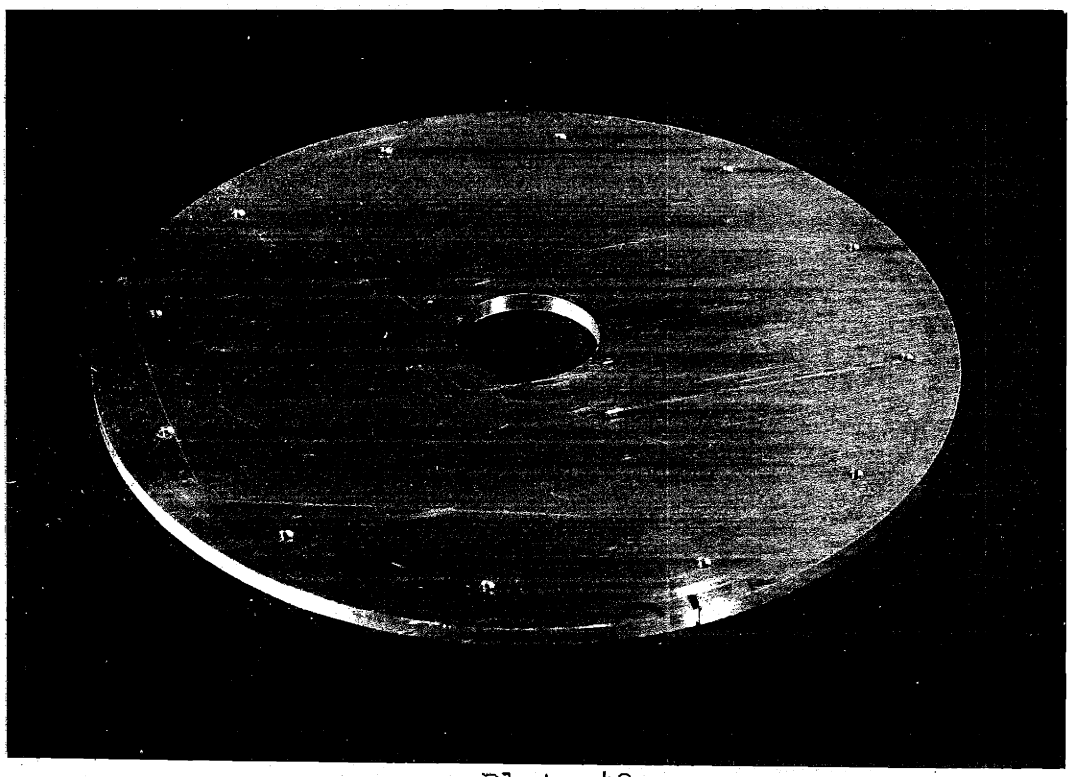


Plate 48

Plate 49

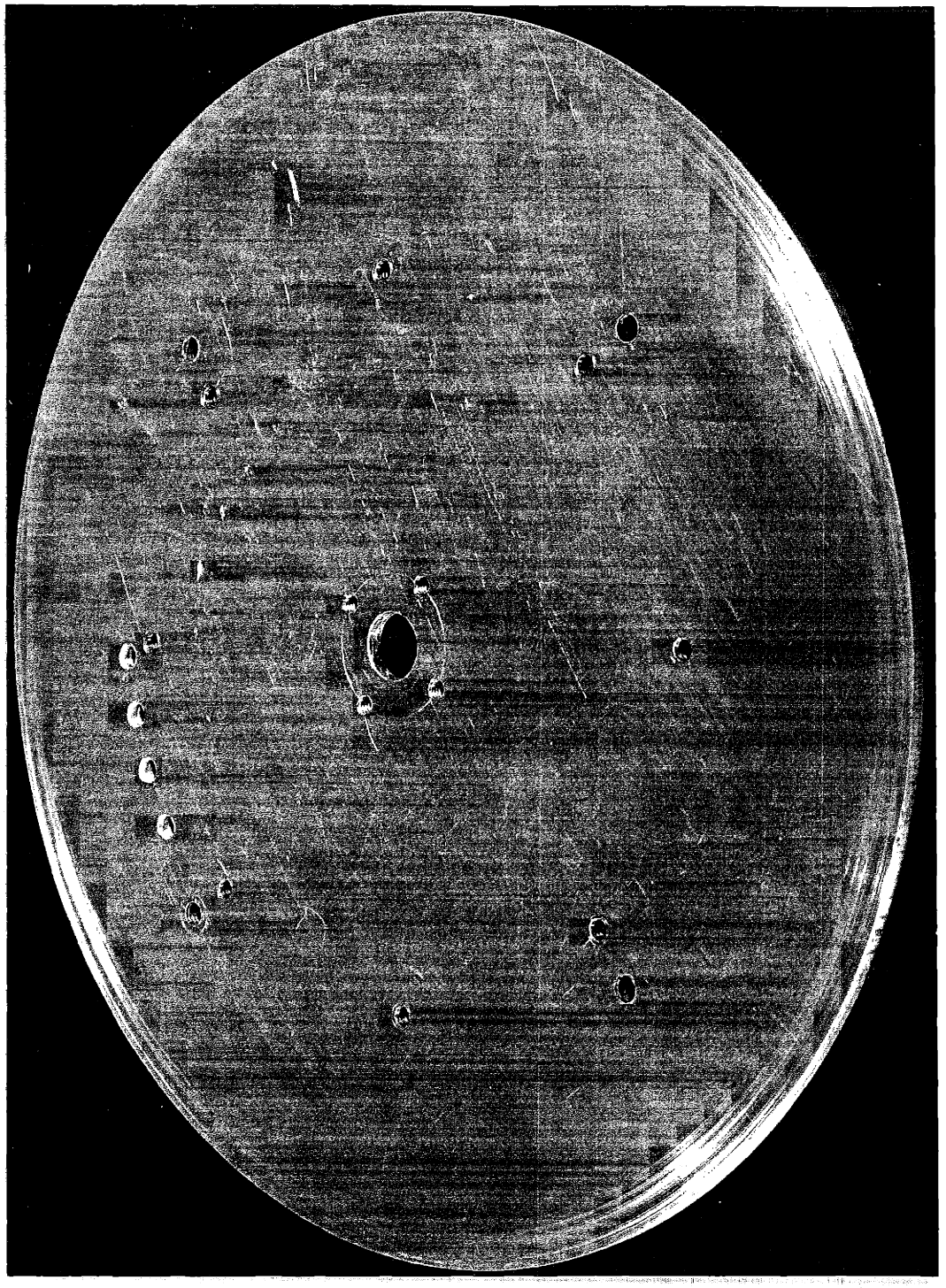


Plate 50

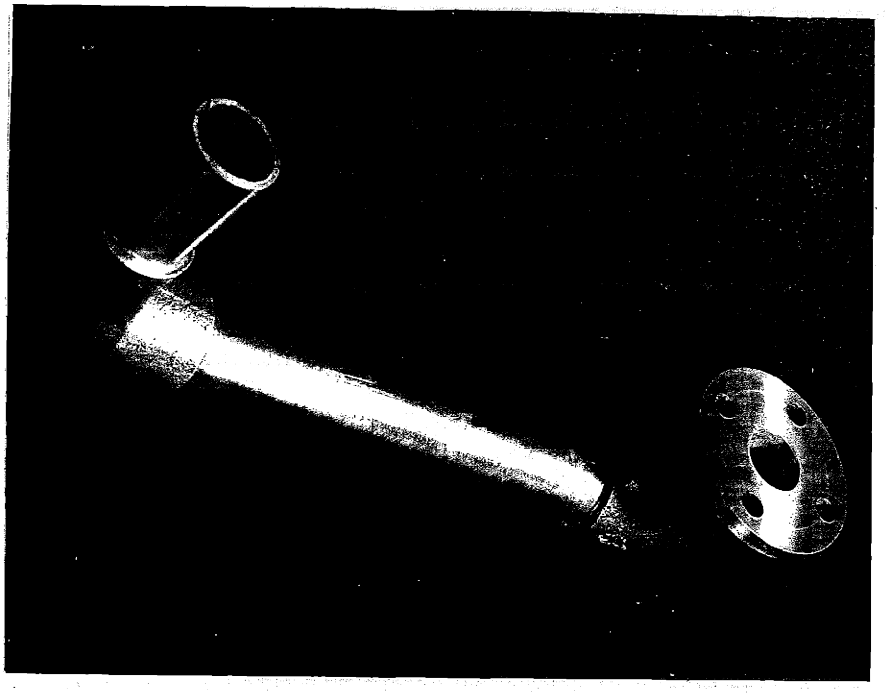


Plate 51