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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Semiconductor Measurement Technology:

Suppression of Premature Dielectric Breakdown for High-Voltage Capacitance Measurements

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Semiconductor Measurement Technology:

Suppression of Premature Dielectric Breakdown for High-Voltage Capacitance Measurements

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PREFACE

This study was carried out at the RCA Laboratories as a part of the Semiconductor Technology Program in the Electronic Technology Division at the National Bureau of Standards. The Semiconductor Technology Program serves to focus NBS efforts to enhance the performance, interchangeability, and reliability of discrete semiconductor devices and integrated circuits through improvements in measurement technology for use in specifying materials and devices in national and international commerce and for use by industry in controlling device fabrication processes. The work was supported by the Defense Advanced Research Projects Agency* through the National Bureau of Standards' Semiconductor Technology Program, Contract 5-35912. The contract was monitored by R. L. Raybold as the Contracting Officer's Technical Representative (COTR) and R. Y. Koyama as Assistant COTR.

Larger scale drawings of the mechanical parts are available on request from the COTR, TECH-A-361, National Bureau of Standards, Washington, DC 20234.

DISCLAIMER

Certain commercial equipment, instruments, or materials are identified in this report in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

*Through ARPA Order 2397, Program Code 6D10.

SEMICONDUCTOR MEASUREMENT TECHNOLOGY: Suppression of Premature Dielectric Breakdown for High-Voltage Capacitance Measurements

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Abstract: Surface-initiated premature dielectric breakdown is encountered in extended-range MIS C(V)* measurements at applied-bias voltages above some sample-dependent threshold value, e.g., 3 to 5 kV across a 150-μm-thick wafer of sapphire. It is necessary to suppress this premature breakdown in order that a much larger applied-bias voltage may be used without damaging the sample. This may be accomplished by eliminating the air space adjacent to the sample surface at the junction of the dielectric and the electrode edge. A simple, easy-to-use apparatus (sample holder and probe assembly) which allows this to be done conveniently and quickly by using a silicone rubber washer to cover the edge of the electrode and the adjacent area is described. Construction details of the apparatus and a test chamber which have been tested to 30 kV are provided in an appendix.

Key Words: Capacitance-voltage measurements; dielectric breakdown suppression; discharge suppression; electronics; extended-range MIS C(V) measurements; high-voltage C(V) measurements; MIS capacitor; premature dielectric breakdown; semiconductor devices.

1. INTRODUCTION

1.1. Description of the Problem

A recently developed modification of the MIS C(V)* technique [1] has extended its useful range allowing it to be used for the measurement of samples with insulating layers more than two orders of magnitude greater in thickness than was previously possible. This use, however, requires the application of large bias voltage to the capacitor sample to be measured. When the bias voltage exceeds some threshold value (e.g., 3 to 5 kV across a 150-μm-thick wafer of sapphire [2]) there exists the danger of breakdown in the critical region along the insulator surface or in air at an electrode edge as shown schematically in figure 1(a).

The breakdown at the surface or in air usually leads to breakdown of the dielectric under test (sapphire in the present work). This problem is similar to the one of "premature breakdown" encountered in the measurement of "breakdown strength" in dielectric media [3]. The present problem is different, however, in three respects: for C(V) measurements (a) the high-field region should have a well-defined area; (b) the field within this region should be as uniform as possible; and (c) there is no need to raise the applied field to the breakdown level.

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*MIS C(V) is a commonly used abbreviation for metal-insulator-semiconductor capacitance as a function of voltage.

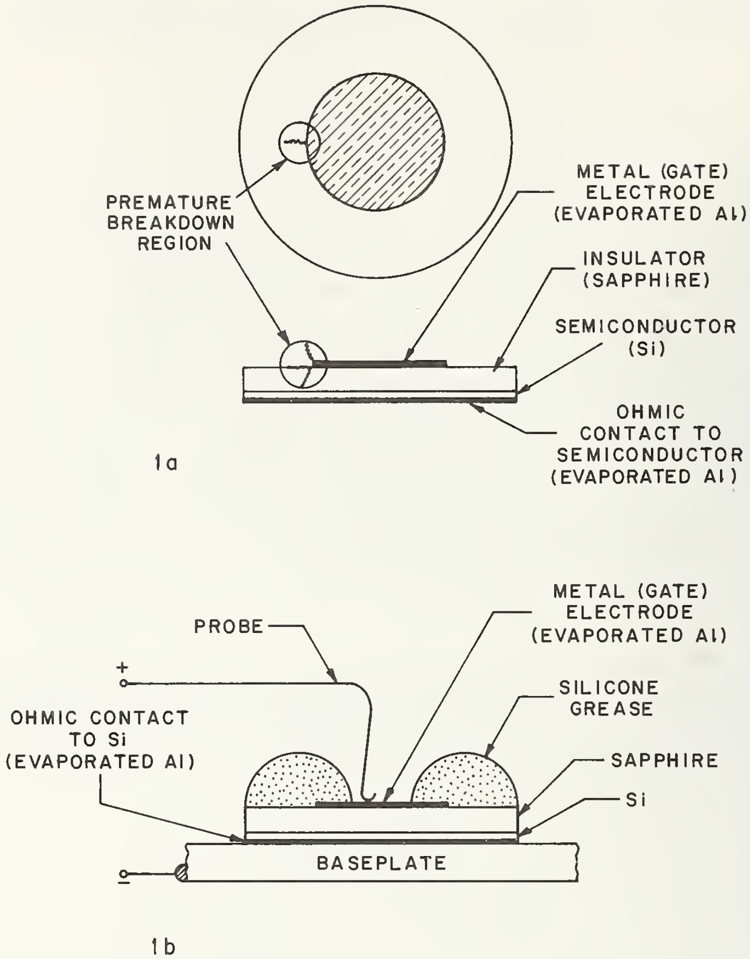

Figure 1. Sample configuration illustrating: (a) Critical region where premature breakdown occurs; and (b) Use of silicone grease to suppress premature breakdown.

1.2. Conventional Techniques for Suppression of Premature Breakdown

The known methods of preventing premature breakdown [3] can be roughly categorized as follows:

1. Immersion of the sample or its critical region in
   (a) suitable gas at high pressure (e.g., N_2 at 100 atmospheres)
   (b) liquid, either insulating (e.g., oil) or partially conducting (e.g., aniline)
   (c) solid (e.g., silicone grease or elastomer)
2. Shaping of sample geometry to reduce the electric field at the electrode edges (e.g., "recessed specimen" or "McKeown specimen" technique).

Each of these methods in its conventional embodiments is undesirable in the present application for one or more reasons: 1(a) would be difficult and time-consuming to implement; 1(b) and 1(c) are messy and inconvenient to use; and 2 is inconsistent with our requirement of a uniform field over a well-defined area. Method 1(c) was used [2] with partial success up to about 8 kV. The solid used to immerse the critical region was a silicone grease (Dow Corning "4-Compound").* This is shown in schematic cross section in figure 1(b). The application of the silicone grease to the sample and its removal after the measurement were difficult, messy, and time-consuming. In addition, the technique did not *consistently* prevent breakdown above about 6 kV.

In one set of experiments half of the samples were destroyed by dielectric breakdown when voltages up to 8 kV were applied across 150-μm sapphire wafers during measurements. These and other equally catastrophic results made it clear that a better method for breakdown prevention was needed to make the measurement technique a practical one for everyday use rather than a research laboratory curiosity.

The new breakdown suppression technique and the associated apparatus and test chamber described in the following sections of this report were developed as part of a measurement system, to be used for routinely carrying out high-voltage extended-range MIS C(V) measurements. The first part of that system (a capacitance meter bias-isolation unit) has been previously described [4].

2. A NEW TECHNIQUE

2.1. Basic Description

It has been found that if an insulating silicone rubber toroidal washer having appropriate properties is pressed over the sample surface including the electrode edge, premature breakdown can be effectively prevented. The surface of the rubber in contact with the sample must be smooth and the rubber itself must be very resilient. It is also important that the rubber contain no voids in the vicinity of the critical region and that it have both a very high resistivity and a low dissipation factor. The technique includes a means for pressing the washer uniformly and controllably over the surface of the sample. Washers molded from two silicone compounds have been used successfully; these are Dow Corning Sylgard #182 and #186.* It has been found that a thin coating of silicone grease on the surface of the washer in contact with the sample gives even more reliable protection against breakdown than using just the washer alone. Photographs of one version of the apparatus used for implementing the technique are shown in figures 2, 3, and 4.

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*See Disclaimer on p.iv.

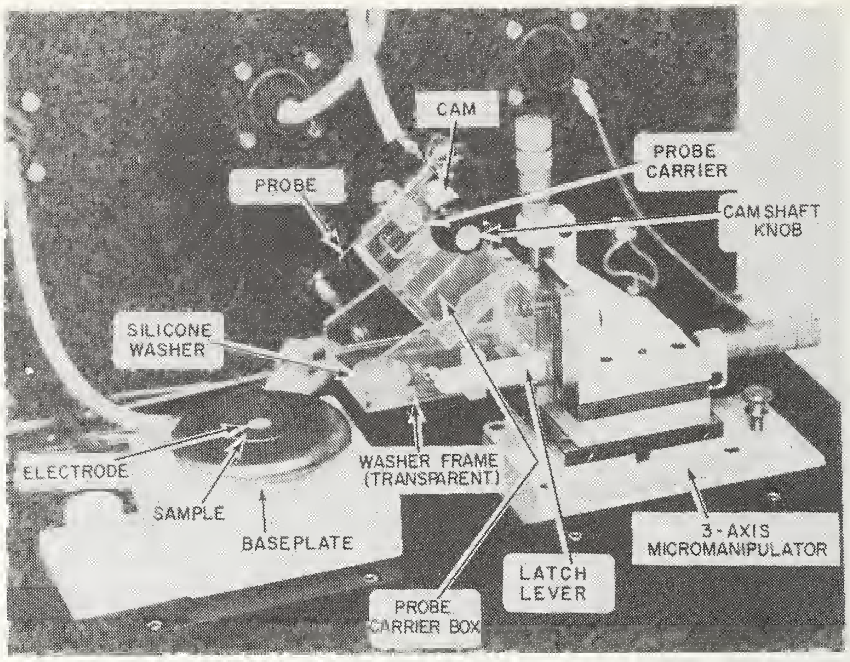


Figure 2. Oblique view of apparatus. The washer frame is raised, the baseplate is moved to the side, and the probe-carrier box is partially raised on its hinge for visual clarity.

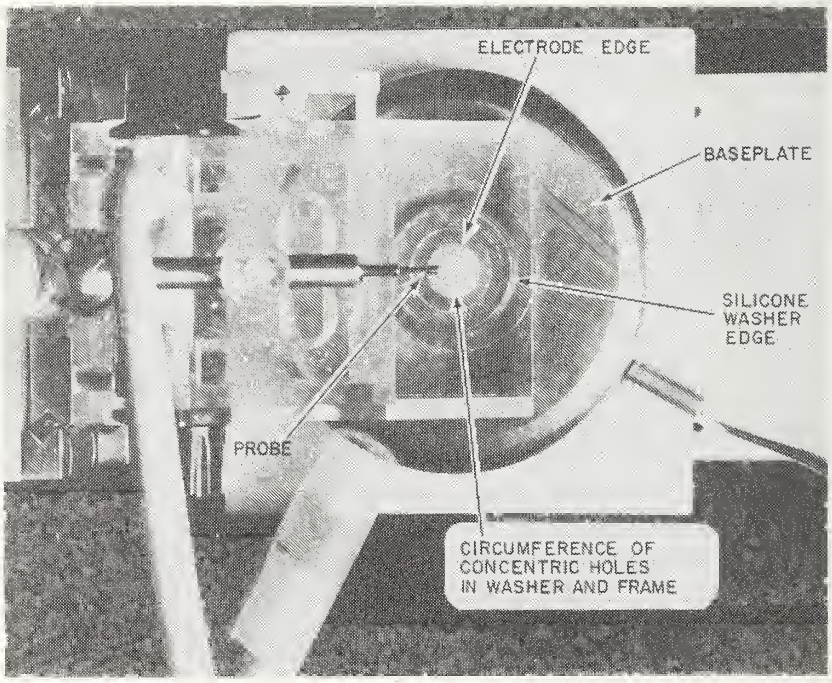


Figure 3. Overhead view of apparatus with sample in place and probe-carrier box in extreme upward position.

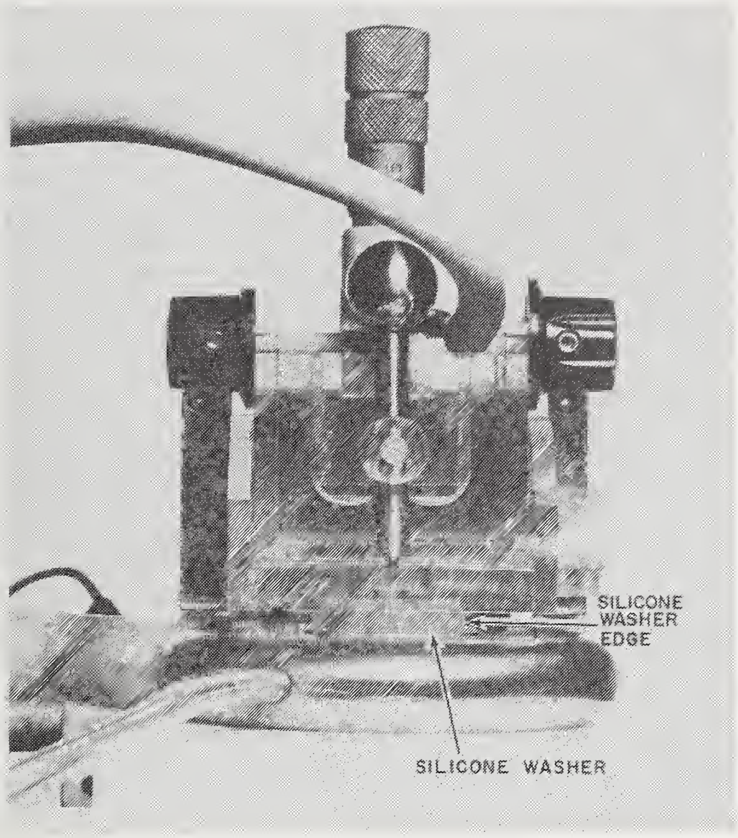


Figure 4. Side view of apparatus with silicone washer pressed firmly against sample and probe lowered to contact sample electrode.

In figure 2 an oblique view of the apparatus is shown. The washer frame has been raised and the baseplate has been moved to the side for visual clarity. The silicone washer is held in a recessed hole which has been counter-bored in the bottom of the washer frame. The probe carrier box is shown unlatched and partially raised on its hinge. In figures 3 and 4, the sample is shown in place with the washer frame lowered and the washer pressed firmly against the sample.

2.2. Operation

In operation, the baseplate with the sample mounted on it is slid under the washer frame and the two horizontal-axis micromanipulators are adjusted to make the washer concentric with the edge of the electrode on the sample. Both the washer and washer frame are transparent allowing this adjustment to be made quickly and easily. During this adjustment, the probe carrier box is swung up as far as it can go to allow the operator maximum visibility; this is illustrated in figure 3. The vertical-axis micromanipulator is then used to move the washer frame down, pressing the washer against the sample.

It is important that the washer be pressed against the sample hard enough to fill any air spaces or voids at the sample surface. This pressure extrudes the washer slightly as can be seen in figures 3 and 4.

The probe carrier box is then swung down and latched in place. The probe can then be lowered through the concentric holes in the washer and frame to make contact with the electrode. This is accomplished by turning either of the two cam-shaft knobs, thereby rotating the cam against the probe carrier and forcing it down. The probe has a spring-loaded retractable tip to provide a reliable contact to the evaporated electrode on the sample without damaging it.

3. EXPERIMENTAL RESULTS

The use of the technique described in the preceding section has virtually eliminated dielectric breakdown during MIS C(V) measurements at applied-bias voltages up to 12 kV across 150-μm-thick sapphire wafers. In addition, further tests were carried out at higher voltages. A 125-μm-thick sapphire wafer was tested to breakdown at 16 kV. One 350-μm-thick sapphire wafer was tested without breakdown up to 30 kV which was the approximate limit of our test capability.

In summary, a new, simple, easy-to-use technique for suppressing premature dielectric breakdown during high voltage C(V) measurements has been described. The technique allows the use of a much larger applied-bias voltage than was previously possible.

ACKNOWLEDGMENT

I am indebted to J. D. Morgan for his contribution to the design and construction of some of the essential hardware, to N. Capone, Jr. for the drafting in the appendix of this report, and to J. M. Breece for his help with the sample preparation and measurements.

REFERENCES

1. Goodman, A. M., A Useful Modification of the Technique for Measuring Capacitance as a Function of Voltage, *IEEE Trans. Electron Devices* ED-21, 753-757 (1974).

2. Goodman, A. M., An Investigation of the Silicon-Sapphire Interface Using the MIS Capacitance Method, *IEEE Trans. Electron Devices* ED-22, 63-65 (1975).

3. Garton, C. G., Intrinsic and Related Forms of Breakdown in Solids, *High Voltage Technology*, L. L. Alston, Ed., pp. 144-157 (Oxford University Press, London, 1968).

4. Goodman, A. M., *Semiconductor Measurement Technology:* Safe Operation of Capacitance Meters Using High Applied-Bias Voltage, NBS Special Publication 400-34 (December 1976).

APPENDIX

A.1.0. General Description

The apparatus described in the body of this report has been designed for use inside a closed test chamber. This is necessary for electrical and optical shielding of the sample as well as for human safety. This appendix describes a safety-interlock arrangement used in conjunction with the test chamber and provides assembly and construction detail drawings of both the apparatus and the test chamber.

A.1.1. Safety Interlock

To prevent high (and potentially lethal) voltages from being applied to the sample while the test chamber is open, a pair of microswitches is provided as part of a safety-interlock system. Their location is shown in the Test Chamber Assembly drawing D-1686997 (See section A.1.3 below). The switches, which are closed only when the test chamber cover is fully closed, are wired in series and connected to an insulated BNC connector. A cable from this connector to the high-voltage power supply allows a relay-control circuit in the power supply to sense whether the switch circuit is open or closed. If the switch circuit is closed, voltage may be applied to the sample. If the switch circuit is open, a pair of high-voltage relays inside the power supply is de-energized; this opens the output lines and grounds the output terminals.

A.1.2. Probe and Breakdown-Suppression Washer Apparatus

The assembly and construction details for this apparatus are shown in drawings C-1687340, C-1687338, C-1687339, C-1687347, C-1687337; a list of the major mechanical parts and drawing reference numbers is given in table 1.

A.1.3. Test Chamber

The assembly and construction details of the test chamber are shown in drawings C-1687330, C-1687331, C-1687332, C-1687333, C-1687343, D-1686997; a list of the major mechanical parts and drawing reference numbers is given in table 2.

Two further explanatory notes:

1. Three high-voltage coaxial chassis connectors are provided in the back of the test chamber. Normally, only two of these are used. The third is provided for possible use with a sample having a guard-ring structure.

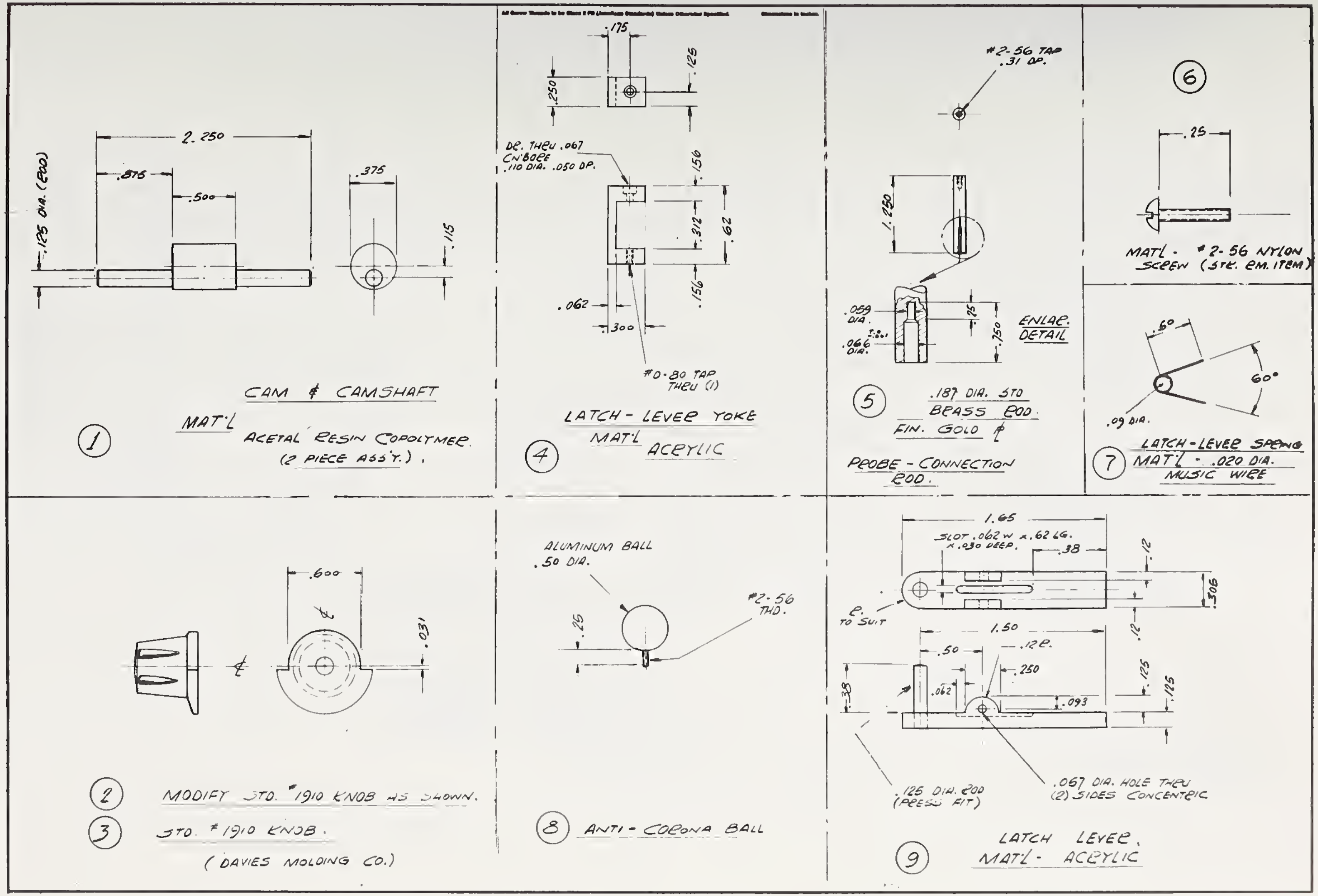
2. The poppet valve mounted in the back of the test chamber is connected to the line providing vacuum to the sample base. When the cover is closed, this line is opened to atmospheric pressure relieving the vacuum in the line to the base. This prevents an electrical discharge which might otherwise occur when high voltage is applied to the sample under test. The vacuum hold-down is of course not needed when the sample is held in place by the breakdown-suppression washer.

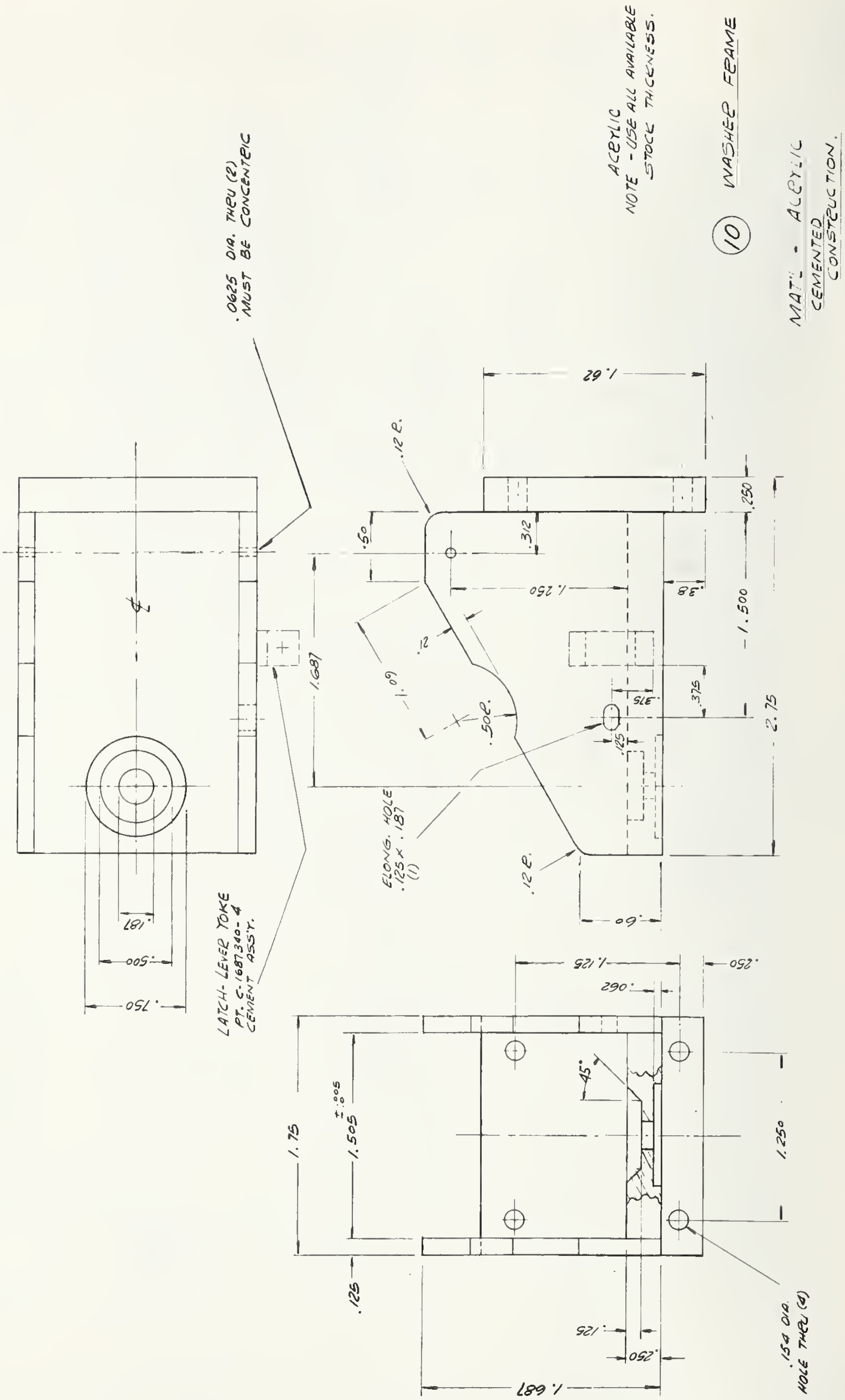
Table 1. List of Major Mechanical Parts Used in Probe and Breakdown Suppression Washer Apparatus

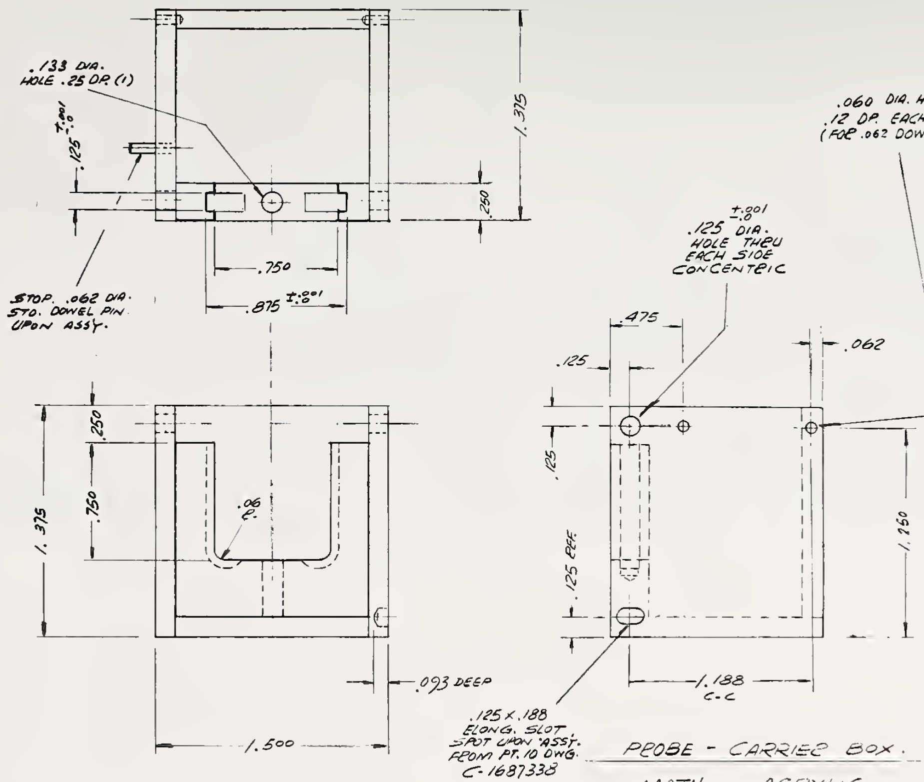
Part No.	Part Description	Drawing No.
1.	Cam and camshaft	C-1687340
2.	Modified knob	C-1687340
3.	Standard #1910 knob	C-1687340
4.	Latch-lever yoke	C-1687340
5.	Probe-connection rod	C-1687340
6.	Nylon screw	C-1687340
7.	Latch-lever spring	C-1687340
8.	Anti-corona ball	C-1687340
9.	Latch lever	C-1687340
10.	Washer frame	C-1687338
11.	Probe-carrier box	C-1687339
12.	Probe carrier	C-1687339
13.	Washer mold	C-1687347
14.	Probe-carrier spring	C-1687347
15.	Silicone washer	C-1687347
16.	Probe (sleeve jacket and spring-loaded plunger)	C-1687347
17.	Micromanipulator	C-1687337

Table 2. List of Major Mechanical Parts Used in Test Chamber

Part No.	Part Description	Drawing No.
1.	Test chamber base	C-1687330
2.	Test chamber back	C-1687331
3.	Test chamber cover	C-1687332
4.	Retaining ways	C-1687333
5.	Thumb screw	C-1687333
6.	Hold-down washer	C-1687333
7.	Vacuum feedthrough	C-1687333
8.	Slide block	C-1687333
9.	Baseplate	C-1687333
10.	Baseplate insulator	C-1687333
11.	Switch bracket	C-1687343
12.	Actuating-arm extension	C-1687343
13.	Thumb-screw cap	C-1687343


All Screw Threads to be Class 2 Fit (American Standard) Unless Otherwise Specified.
Dimensions in Inches.
1 CAM & CAMSHAFT
MAT'L ACETAL RESIN COPOLYMER (2 PIECE ASS'Y.)
.125 DIA. (ROD)
2.250
.875
.500
.375
.115
4 LATCH-LEVER YOKE
MAT'L ACRYLIC
DR. THRU .067 C'BORE .110 DIA. .050 DP.
#0-80 TAP THRU (1)
.175
.125
.250
.156
.312
.62
.062
.300
5 .187 DIA. STD BRASS ROD.
FIN. GOLD
PROBE-CONNECTION ROD.
#2-56 TAP .31 DP.
1.250
.059 DIA.
.066 DIA.
.25
.750
ENLAR. DETAIL
6 MAT'L - #2-56 NYLON SCREW (STK. RM. ITEM)
.25
7 LATCH-LEVER SPRING
MAT'L - .020 DIA. MUSIC WIRE
.60
60°
.09 DIA.
2 MODIFY STD. #1910 KNOB AS SHOWN.
3 STD. #1910 KNOB.
(DAVIES MOLDING CO.)
.600
.031
8 ANTI-CORONA BALL
ALUMINUM BALL .50 DIA.
#2-56 THD.
.25
9 LATCH LEVER.
MAT'L - ACRYLIC
1.65
SLOT .062 W x .62 LG. x .030 DEEP.
.38
.12
.306
R. TO SUIT
1.50
.50
.12R.
.250
.062
.093
.125
.38
.125 DIA. ROD (PRESS FIT)
.067 DIA. HOLE THRU (2) SIDES CONCENTRIC


ACRYLIC
NOTE - USE ALL AVAILABLE STOCK THICKNESS.
10 WASHER FRAME
MAT'L - ACRYLIC
CEMENTED CONSTRUCTION.
.0625 DIA. THRU (2) MUST BE CONCENTRIC
LATCH-LEVER YOKE PT. C-1687340-4 CEMENT ASS'Y.
ELONG. HOLE .125 x .187 (1)
.154 DIA. HOLE THRU (4)
.12 R.
.50 R.
45°
1.62
.250
.312
.50
1.250
.38
1.500
2.75
.375
.125
1.09
.12
1.687
.60
.187
.500
.750
1.125
.062
1.75
1.505 ±.005 .000
.125
.250
1.250
1.687

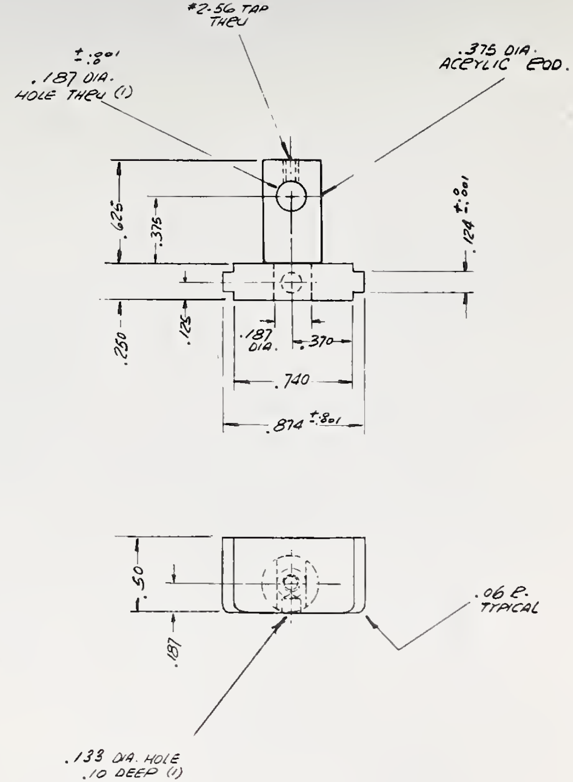


PROBE - CARRIER BOX.

MAT'L - ACRYLIC
CEMENTED
CONSTRUCTION.

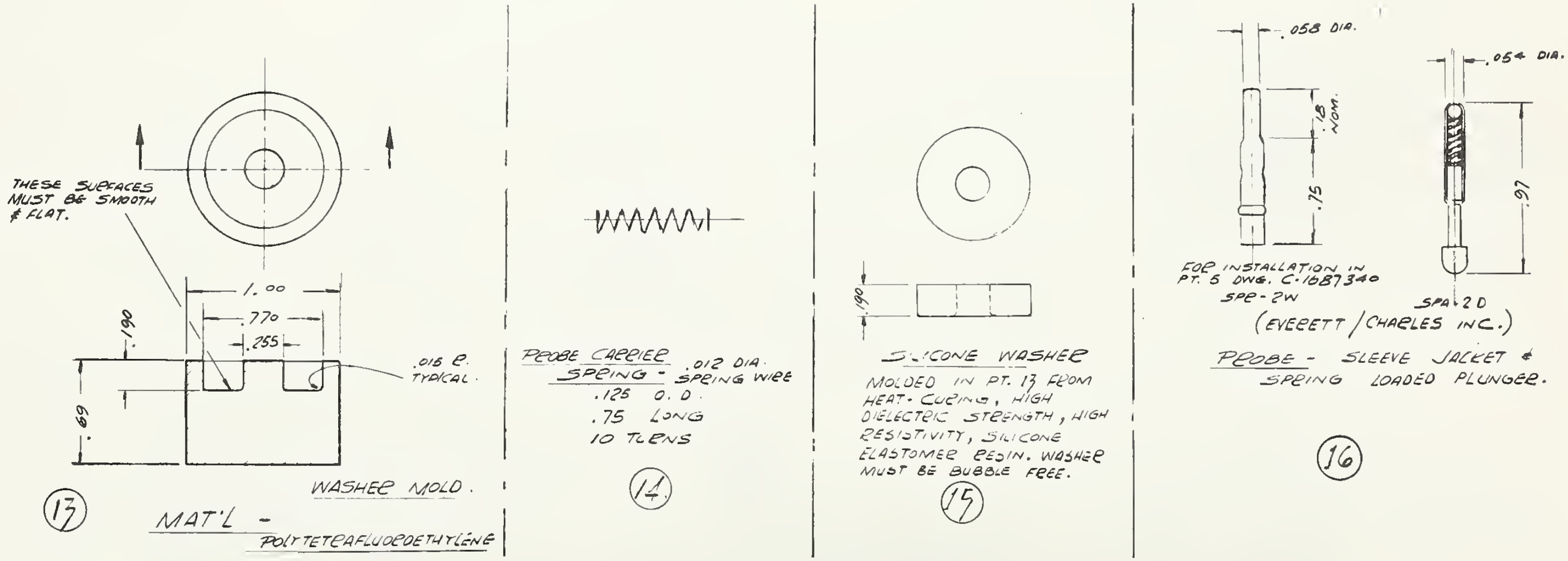
NOTE - USE ALL AVAILABLE
STOCK THICKNESS.
.12 THICKNESS UNLESS
OTHERWISE SPECIFIED.

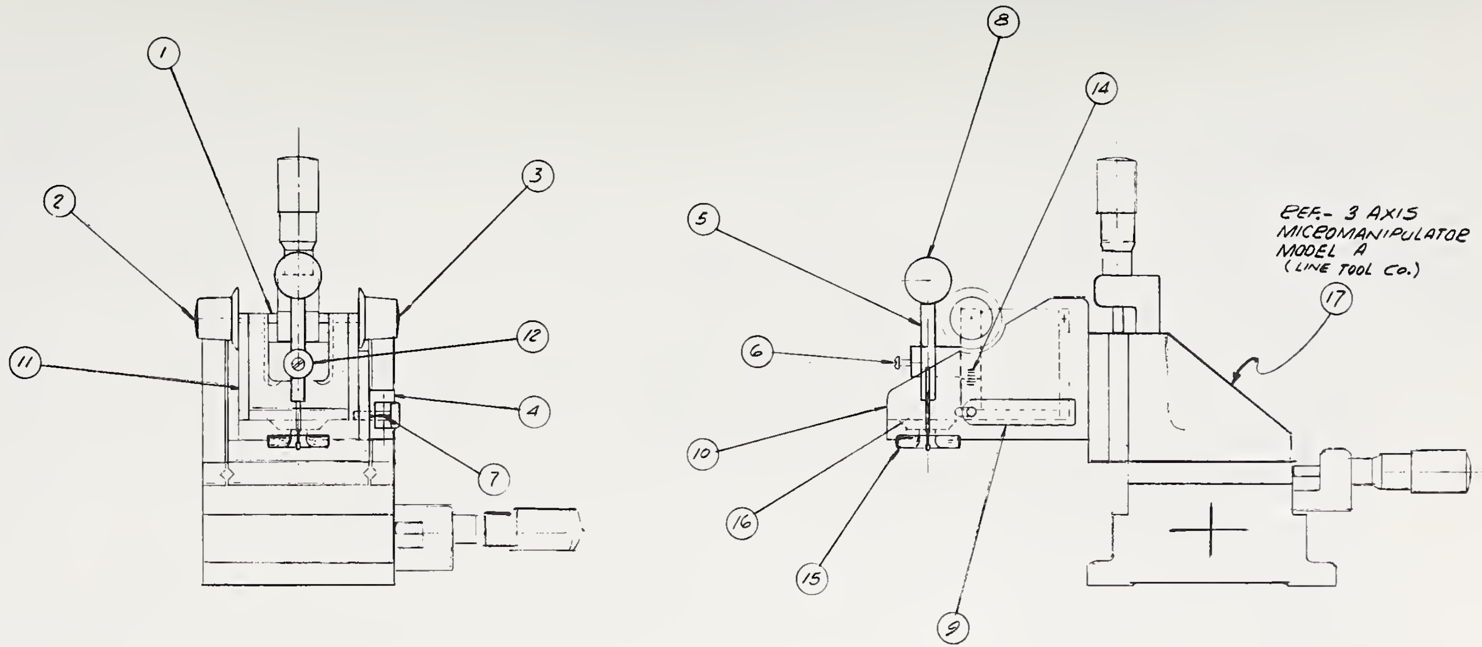
(11)



PROBE CARRIER.
MAT'L - ACRYLIC

(12)


THESE SURFACES MUST BE SMOOTH & FLAT.
1.00
.770
.255
.190
.69
.016 R. TYPICAL.
WASHER MOLD.
13
MAT'L - POLYTETRAFLUOROETHYLENE
PROBE CARRIER SPRING - .012 DIA. SPRING WIRE
.125 O.D.
.75 LONG
10 TURNS
14
.190
SILICONE WASHER
MOLDED IN PT. 13 FROM HEAT-CURING, HIGH DIELECTRIC STRENGTH, HIGH RESISTIVITY, SILICONE ELASTOMER RESIN. WASHER MUST BE BUBBLE FREE.
15
.058 DIA.
.18 NOM.
.75
FOR INSTALLATION IN PT. 5 DWG. C-1687340
SPR-2W
.054 DIA.
.97
SPA-2D
(EVERETT / CHARLES INC.)
PROBE - SLEEVE JACKET & SPRING LOADED PLUNGER.
16

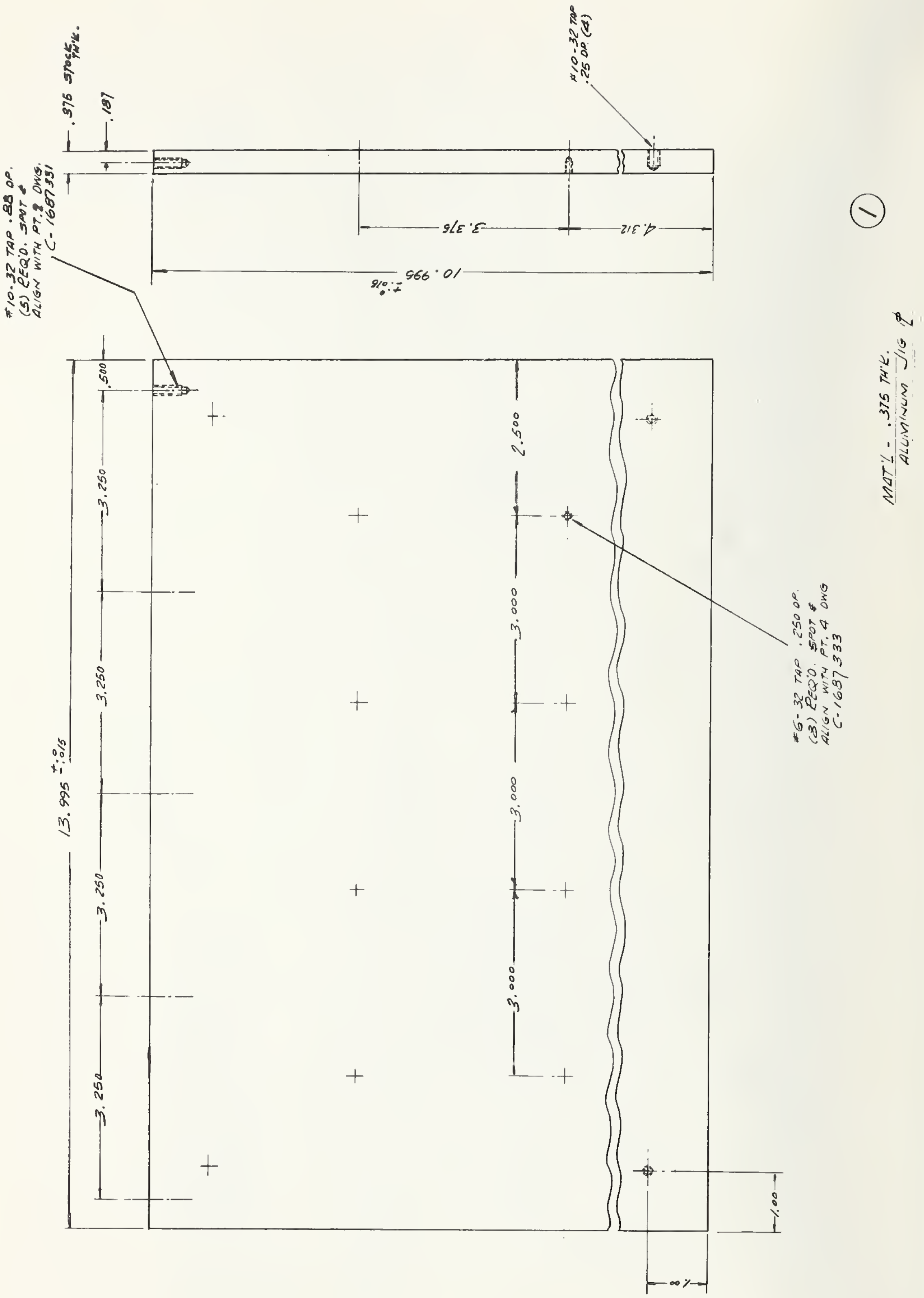


NOTE 1: PT. 13 IS A WASHER MOLD USED ONLY TO FABRICATE PT. 15; IT IS NOT AN ACTUAL PART OF THE APPARATUS.

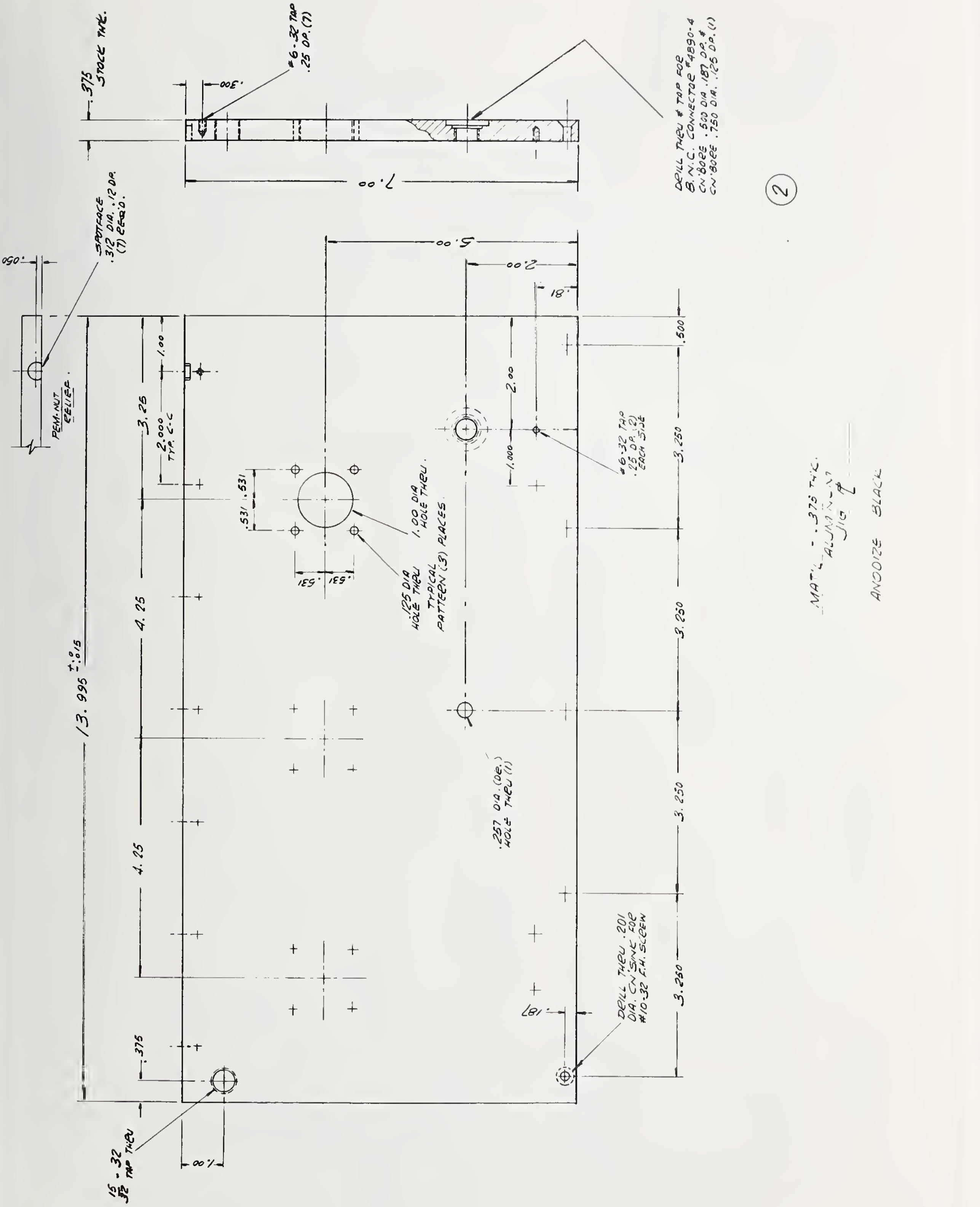
NOTE 2: ASSEMBLY DETAIL OF PTS. 4 & 10 IS SHOWN IN C-1687338

DWG. LIST

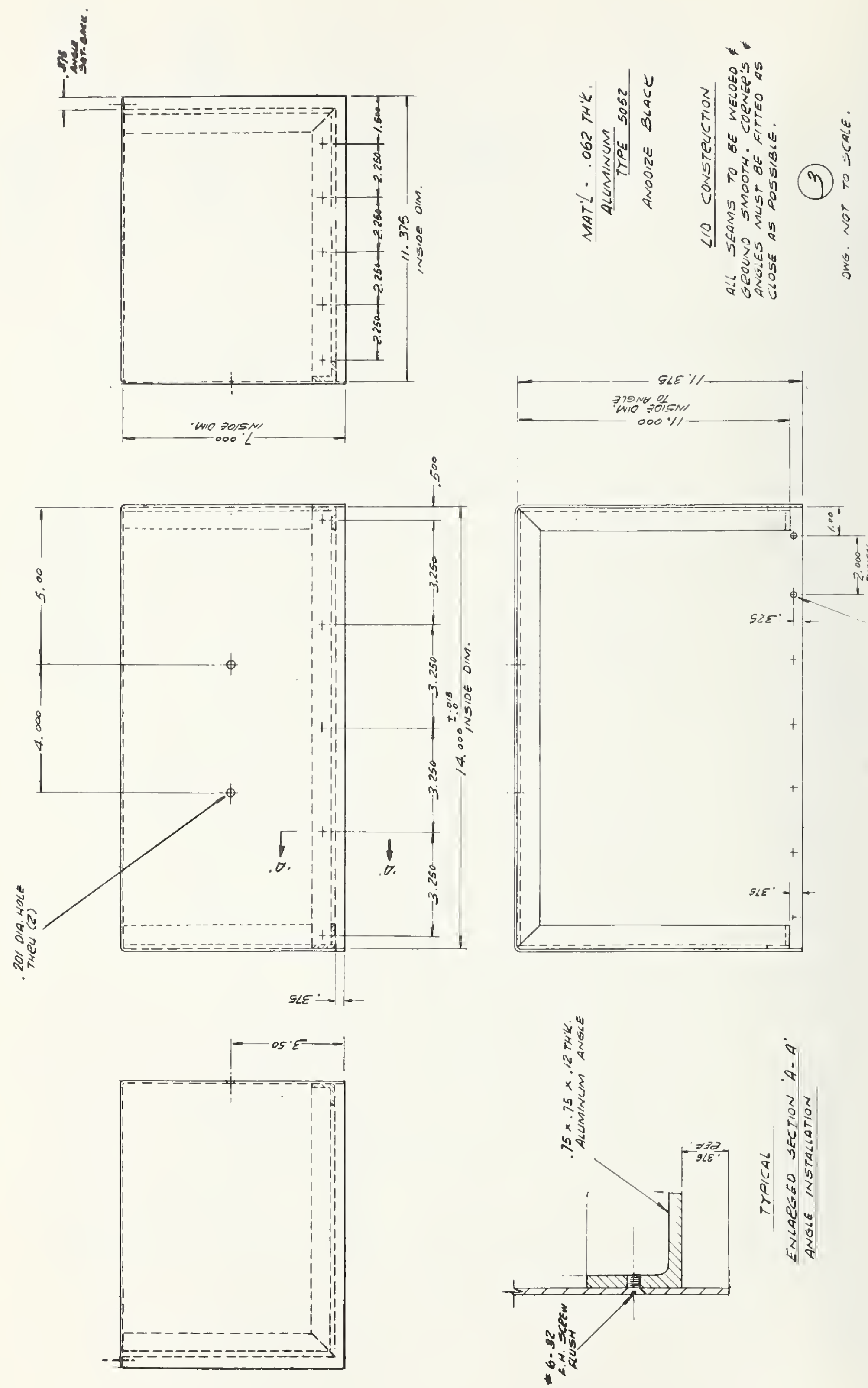
PT.	1-9	C-1687340
PT.	10	C-1687338
PT.	11-12	C-1687339
PT.	13-16	C-1687347

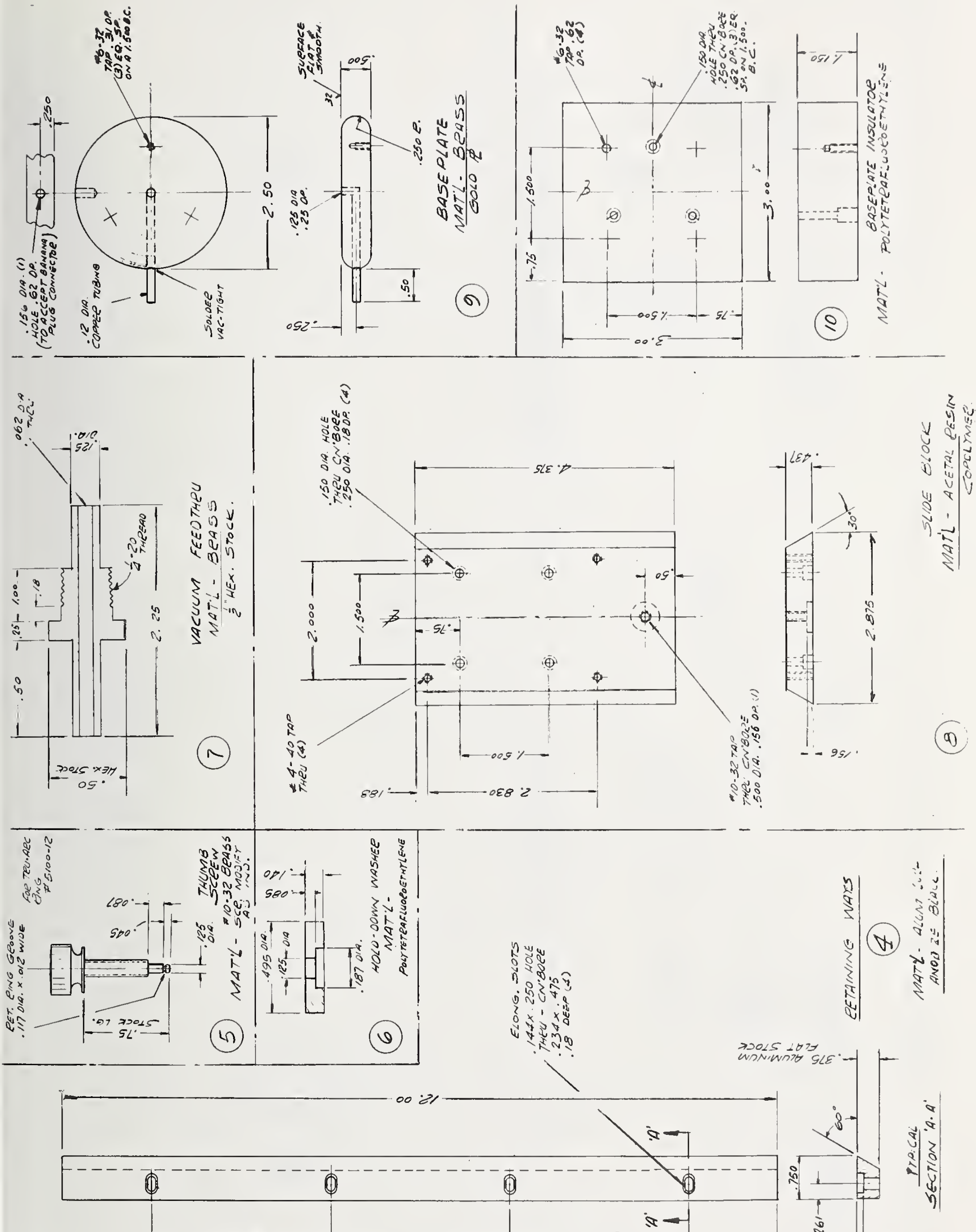


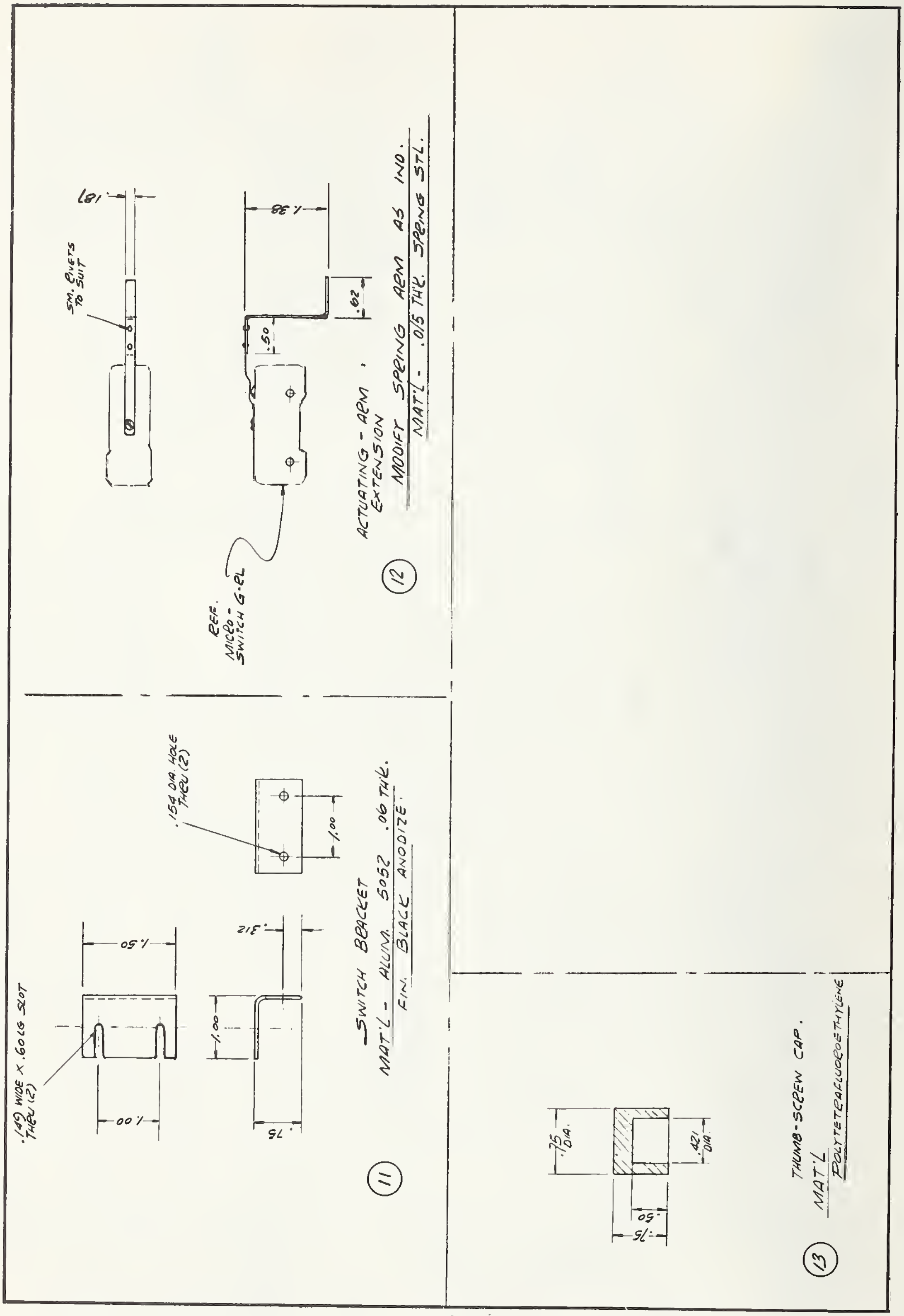
.375 STOCK TH'K.
.187
#10-32 TAP .25 DP. (4)
3.376
4.312
10.995
.500
3.250
3.250
3.250
3.250
13.995
2.500
3.000
3.000
3.000
1.00
MAT'L - .375 TH'K. ALUMINUM JIG PL
ANODIZE BLACK
1

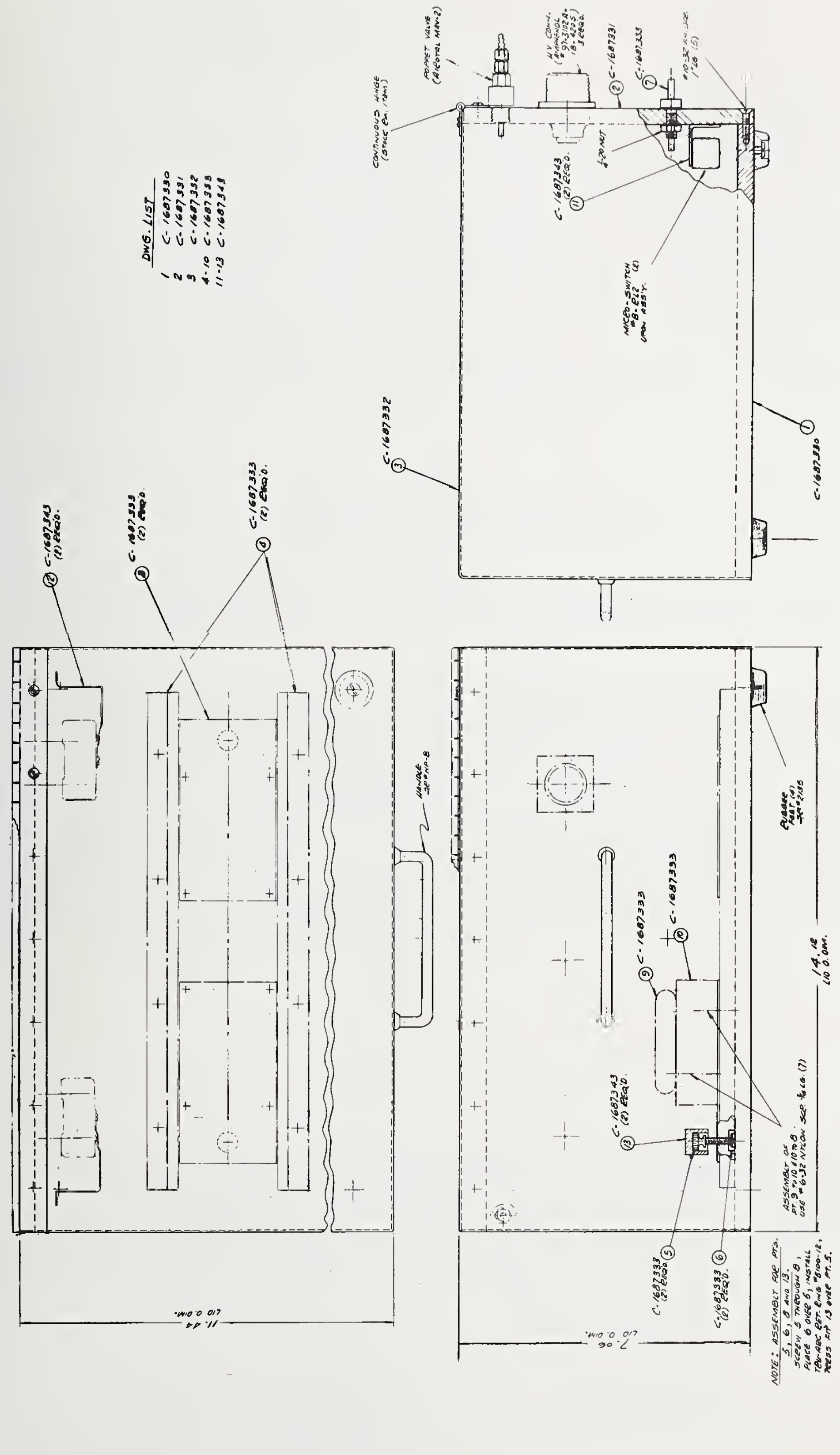


.375 STOCK THK.
#6-32 TAP .25 DP. (7)
.300
7.00
DRILL THRU # TAP FOR B.N.C. CONNECTOR #4890-4 CN'BORE .500 DIA .187 DP. # CN'BORE .750 DIA. .125 DP. (1)
2
SPOTFACE .312 DIA. .12 DP. (7) REQ'D.
.050
PEM-NUT RELIEF
5.00
2.00
.18
.500
1.00
3.25
2.000 TYP. C-C
2.00
1.000
#6-32 TAP .25 DP. (2) EACH SIDE
.531
1.00 DIA HOLE THRU
.125 DIA HOLE THRU TYPICAL PATTERN (3) PLACES
3.250
4.25
13.995
.257 DIA. (DR.) HOLE THRU (1)
DRILL THRU .201 DIA. CN'SINK FOR #10-32 F.H. SCREW
.187
.375
1.00
15/32 - 32 TAP THRU
ANODIZE BLACK


MAT'L - .062 TH'K.
ALUMINUM
TYPE 5052
ANODIZE BLACK
LID CONSTRUCTION
ALL SEAMS TO BE WELDED & GROUND SMOOTH. CORNERS & ANGLES MUST BE FITTED AS CLOSE AS POSSIBLE.
3
DWG. NOT TO SCALE.
11.375
INSIDE DIM.
7.000
INSIDE DIM.
11.375
11.000
INSIDE DIM.
TO ANGLE
.187 DIA. HOLE (PUNCH) (7)
TO ACCEPT #6 PEM-NUT
(HINGE ASS'Y.)
BOTTOM VIEW
.201 DIA. HOLE
THRU (2)
14.000 INSIDE DIM.
.75 x .75 x .12 TH'K.
ALUMINUM ANGLE
#6-32
F.H. SCREW
FLUSH
TYPICAL
ENLARGED SECTION 'A-A'
ANGLE INSTALLATION


BASE PLATE
MAT'L - BRASS
GOLD
9
BASEPLATE INSULATOR
MAT'L - POLYTETRAFLUOROETHYLENE
10
VACUUM FEEDTHRU
MAT'L - BRASS
1/2" HEX. STOCK
7
SLIDE BLOCK
MAT'L - ACETAL RESIN
COPOLYMER
8
THUMB SCREW
MAT'L - #10-32 BRASS
5
HOLD-DOWN WASHER
MAT'L - POLYTETRAFLUOROETHYLENE
6
RETAINING WAYS
4
TYPICAL
SECTION 'A-A'
.375 ALUMINUM FLAT STOCK


SM. RIVETS TO SUIT
.187
1.38
.50
.62
REF. MICRO-SWITCH G-PL
ACTUATING - ARM EXTENSION
MODIFY SPRING ARM AS IND.
MAT'L - .015 TH'K. SPRING STL.
12
.149 WIDE X .60 LG SLOT THRU (2)
1.50
1.00
1.00
.75
.312
.154 DIA. HOLE THRU (2)
1.00
SWITCH BRACKET
MAT'L - ALUM. 5052 .06 TH'K.
FIN: BLACK ANODIZE
11
.75 DIA.
.421 DIA
.50
.75
THUMB-SCREW CAP.
MAT'L POLYTETRAFLUOROETHYLENE
13



DWG. LIST
1 C-1687330
2 C-1687331
3 C-1687332
4-10 C-1687333
11-13 C-1687343
POPPET VALVE
CONTINUOUS HINGE
C-1687331
C-1687333
C-1687343 (2) REQ'D.
C-1687332
C-1687330
C-1687343 (2) REQ'D.
C-1687333 (2) REQ'D.
C-1687333
C-1687333 (2) REQ'D.
C-1687333 (2) REQ'D.
C-1687333 REQ'D.
14.12 (10 O.DIM.)
11.44 (10 O.DIM.)
7.06 (10 O.DIM.)
NOTE: ASSEMBLY FOR PTS. 5, 6, 8 AND 13.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Surface-initiated premature dielectric breakdown is encountered in extended-range MIS C(V) measurements at applied-bias voltages above some sample-dependent threshold value, e.g., 3 to 5 kV across a 150-μm-thick wafer of sapphire. It is necessary to suppress this premature breakdown in order that a much larger applied-bias voltage may be used without damaging the sample. This may be accomplished by eliminating the air space adjacent to the sample surface at the junction of the dielectric and the electrode edge. A simple, easy-to-use apparatus (sample holder and probe assembly) which allows this to be done conveniently and quickly by using a silicone rubber washer to cover the edge of the electrode and the adjacent area is described. Construction details of the apparatus and a test chamber which have been tested to 30 kV are provided in an appendix.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Capacitance-voltage measurements; dielectric breakdown suppression; discharge suppression; electronics; extended-range MIS C (V) measurements; high-voltage C (V) measurements; MIS capacitor; premature dielectric breakdown; semiconductor devices.

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