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

Semiconductor Measurement Technology:

Safe Operation Of Capacitance Meters Using High Applied-Bias Voltage

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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.

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.

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

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SEMICONDUCTOR MEASUREMENT TECHNOLOGY: Safe Operation of Capacitance Meters Using High Applied-Bias Voltage

by

Alvin M. Goodman

Abstract: The use of capacitance meters (C-meters) to determine small-signal (differential) capacitance at 1 MHz as a function of applied-bias voltage is widespread. The maximum value of the bias voltage which may be applied to a sample under test with any commercially available C-meter is 600 V or less. A larger bias-voltage capability is required for certain applications.

This report describes a technique for using a commercial C-meter with a Bias-Isolation Unit (BIU) for capacitance measurements at bias-voltage magnitudes up to 10 kV without damage to the measurement equipment. The basic principles of operation and the details of the electrical design of a BIU are discussed.

The use of the BIU imposes certain limitations on the range of sample capacitance which may be measured without introducing excessive error. The theory of these limitations is presented and compared with experimental results obtained from the use of the BIU with each of three commercially available C-meters. The measurement capability demonstrated by these results appears to be adequate for all current and future applications. For less than $\pm 1\%$ error in the indicated (measured) capacitance, the measurable range of the sample capacitance is found to be from 0 to at least 400 pF. In some applications, it is important to be able to accurately measure small changes in the sample capacitance; for less than $\pm 1\%$ error in the indicated (measured) value of a small change in the sample capacitance, the measurable range of the sample capacitance is found to be from 0 to at least 130 pF.

Construction details of the BIU are appended.

Key Words: Bias-Isolation Unit; capacitance measurements at high applied-bias voltage; capacitance-meter; extended-range capacitance measurement; high-voltage C(V) measurements; modified MIS C(V) measurements.

1. INTRODUCTION

The use of capacitance meters (hereinafter abbreviated as C-meters) to determine small-signal (differential) capacitance as a function of applied-bias voltage is commonplace today in many research, development, and manufacturing applications. Many, if not most, of these applications are connected with the semiconductor industry. A variety of commercial instruments* is available to meet most existing measurement requirements.

Typically, an instrument of this type uses a crystal-controlled 1-MHz test signal whose amplitude is ∿15 mV. The test signal is applied to the unknown capacitance; the resulting current is amplified, and its quadrature component (with respect to the applied voltage) is determined using some form of phase-locked synchronous detector. The quadrature component of the current is directly proportional to the measured capacitance, and the C-meter is usually calibrated to read directly in picofarads. In addition, an analog output voltage is generally made available to enable the plotting of capacitance on a recorder. Means are usually provided for applying a quasi-dc bias voltage to the unknown capacitance through the C-meter. This allows the capacitance to be recorded as a function of the applied-bias voltage using the arrangement shown in figure 1. The magnitude of the bias voltage that may be applied in this way is limited. Although the limit differs for different instruments, it is in no case greater than 600 V.

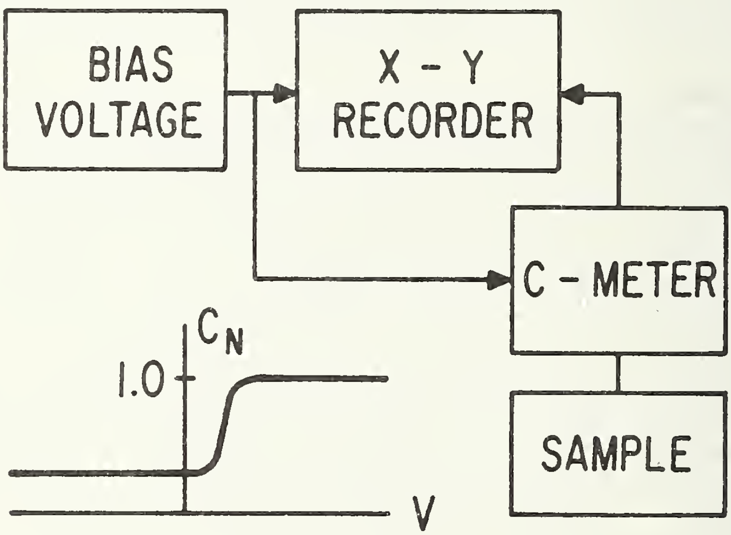
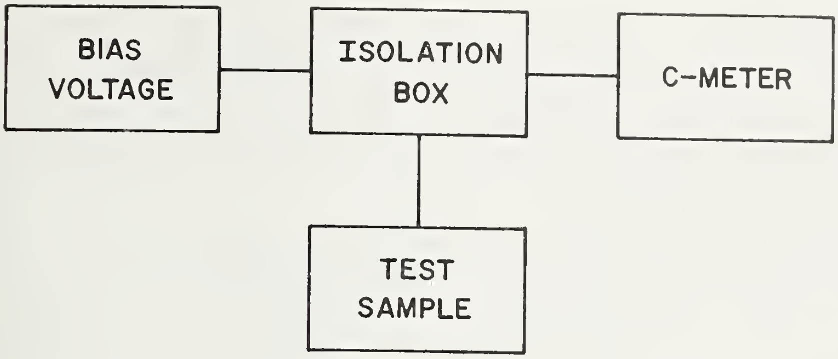


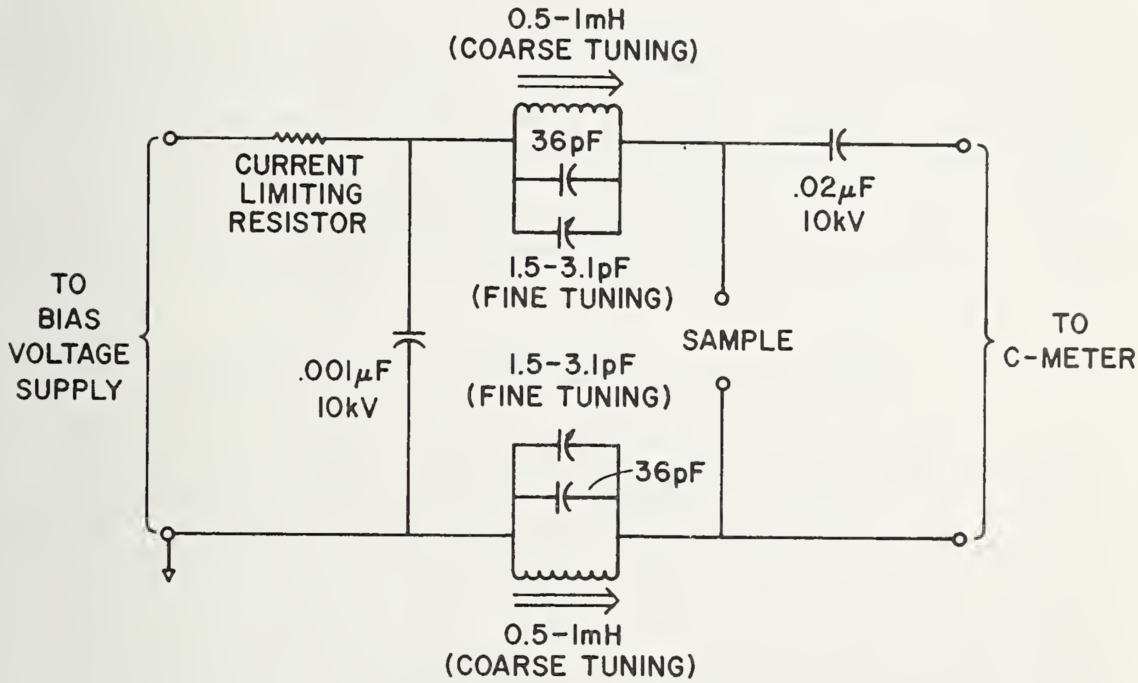
Figure 1. Conventional high-frequency C(V) measurement. The inset is a schematic illustration of a typical plot of normalized capacitance C_N versus voltage.

It is sometimes necessary to apply a bias voltage larger than 600 V to a capacitor sample [1,2]. This can be accomplished by using an arrangement which applies the bias directly to the sample but not to the C-meter. An example (based on a circuit described in reference 3) is shown in figure 2. The isolation box allows the bias voltage to be

*Some examples of commercial C-meters (or instruments containing C-meters) are as follows: BEC (Boonton Electronics Corporation) Models 71A, 71AR, 72A, 72AD, 72B, 72BD; and PAR (Princeton Applied Research Corporation) Model 410.



(a) BLOCK DIAGRAM



(b) ISOLATION BOX CIRCUIT

Figure 2. Isolation box arrangement for measuring C(V) with an applied bias voltage larger than the C-meter limit: (a) block diagram, and (b) isolation box circuit.

applied to the sample while keeping it out of the C-meter; at the same time, it isolates the bias-voltage supply from the high-frequency test signal. It is assumed that there is a dc path through the C-meter to allow the high-voltage-blocking capacitor to charge and discharge as the bias voltage is (slowly) varied. The parallel resonant circuits are tuned to the test frequency (1 MHz in this case) to provide the necessary ac isolation. This isolation can also be obtained by using sufficiently high-value resistors instead of the tuned circuits. The blocking capacitor between the sample and the C-meter must be sufficiently large that it does not introduce unacceptable error into the measurement. For the value shown (0.02 μF), the maximum error for samples with C $\gtrsim$ 100 pF would be $\lesssim$ 0.5%. The voltage rating of the blocking capacitor must, of course, be at least as large as the greatest anticipated bias voltage.

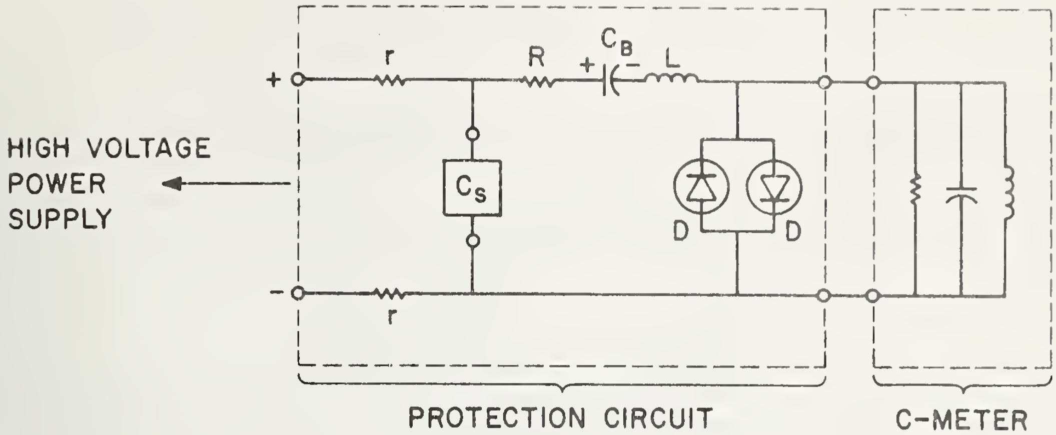
The arrangement shown in figure 2 does not, however, provide complete protection for the C-meter in the case of sample failure. If the sample develops a short-circuit while a large bias voltage is applied to it, the blocking capacitor (which is also charged up to the bias voltage) must discharge through the C-meter. If the voltage across the blocking capacitor just before the sample "shorts" is sufficiently large, the C-meter will be damaged.

In order to prevent this type of damage to the C-meter, a "bias-protection circuit" has been developed. The basic principles of this circuit and some of the design considerations are discussed in section 2. The actual circuit and operation of a C-meter "Bias-Isolation Unit" (BIU), which allows safe capacitance measurements at bias voltage up to $\pm$ 10 kV, are described in section 3. In section 4, some of the experimental results obtained using the BIU with commercial C-meters are presented. Finally, in section 5, present and possible future applications of capacitance measurements at high applied-bias voltage are discussed.

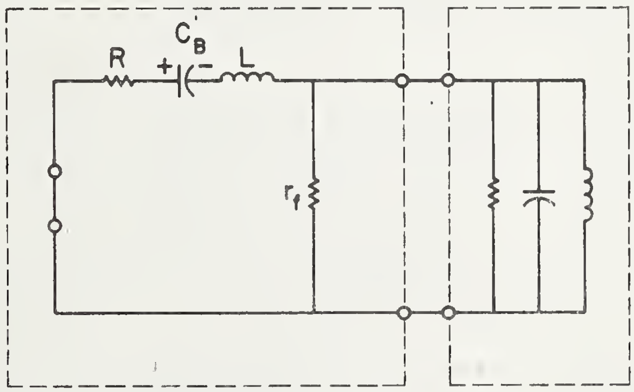
2. SIMPLIFIED CIRCUIT AND PRINCIPLES OF OPERATION

The operation of the C-meter bias-protection circuit can best be described by considering a simplified version: first, in the normal operating mode, as shown in figure 3(a), and second, the equivalent circuit after a sample "breaks down" with a large bias voltage applied to it, as shown in figure 3(b). The sample capacitance being measured is represented by C_S. The series combination of L and C_B is tuned to resonance (at the measurement frequency of the C-meter) so that there is no reactance in series with C_S. The diodes D exhibit very small capacitance and conductance at the measurement signal level ($\sim$ millivolts) and thus do not interfere with the measurement of C_S. The shunt capacitance and conductance of the diodes can be reduced still further by applying a small reverse bias to each of the diodes. The value of R is much less than X_{C_S}, and in a first approximation its effect on the measurement of C_S may be ignored. A detailed consideration of its effect will be presented later. The bias voltage is supplied to C_S through high-value resistances ($r \gg X_{C_S}$); they serve two functions: (i) to effectively isolate the bias supply from the measurement circuit, and (ii) to limit the current in case of a sample breakdown (short circuit).

The C-meter is represented by a parallel RLC circuit at the measurement frequency. There is a low-resistance dc path between the terminals of the C-meter. This allows the dc voltage at the C-meter terminal to remain effectively zero during slow variations of the applied-bias voltage.



(a)



(b)

Figure 3. Simplified version of C-meter bias-protection circuits: (a) normal operating mode, and (b) after a capacitor sample breaks down with a large bias voltage applied to it.

During large rapid variations of the sample bias-voltage, the voltage at the C-meter terminals would start to become significantly different from zero; one or the other of the diodes would then start to conduct heavily when biased in the forward direction. One rather important example of rapid variation of sample bias-voltage is the case in which the sample develops a short-circuit during application of a large bias voltage; the voltage across the sample drops (almost) instantaneously to zero and C_B must discharge through R, L, and the parallel combination of the diodes and the C-meter. This is illustrated schematically in figure 3(b). The forward resistance of the conducting diode r_f must be sufficiently low that the voltage at the input terminals of the C-meter never exceeds the maximum allowable value; i.e., it remains "clamped" within some allowable range.

3. ACTUAL CIRCUIT

3.1. Circuit and Functional Description

The schematic circuit diagram of the C-meter bias-isolation unit (hereinafter abbreviated as BIU) is shown in figure 4 and the individual circuit elements are described in table 1. The circuit performs not only the bias-protection function but a number of others as well; these will now be described.

a. Bias-Protection Circuit

The high and low terminals of the output to the C-meter are individually clamped by diodes (D1 and D2 on the high side, D3 and D4 on the low side) to remain within some allowable range with respect to ground. The diodes D1 through D4 are PIN diodes with a low forward resistance, high reverse resistance, and fast turn-on. To reduce their loading effect on the C-meter, they are normally maintained at a reverse bias of 6.8 V. The bias voltages (+6.8 and -6.8 V) are provided with a very low source impedance by the Zener diodes, VR1 and VR2.

The high-voltage blocking capacitors C3 and C4 are at (or nearly at) series resonance at 1 MHz with L1 + L6 and L2 + L7, respectively. Adjustment of L6 and L7 can be used to compensate for series inductance of the connecting leads both inside and outside the BIU.

The voltage dividers formed by R1 and R8 on the HIGH side and R2 and R9 on the LOW side serve to attenuate the bias input by a factor of 1000:1 so that it may be fed directly to the X-axis of an X-Y recorder.

High-frequency noise from the bias supply is attenuated by the low-pass filter formed by R5, R6, and C1. The resistors R3 and R4 and the capacitor C1 form a filter isolating the bias supply from the 1-MHz measurement signal.

A bias voltage equal to that at the high side of the sample is available at J5 for application to a guard ring electrode. The 1-MHz series resonant circuit formed by L3 and C2 assures that the guard ring is effectively grounded at the measurement signal frequency.

b. Zero Adjustment and Zero Suppression

In order to facilitate the nulling ("canceling out") of capacitance between the high side and low side test terminals, a circuit (labeled ZERO SUPPRESSION in figure 4) has been provided to allow a wide range of zero adjustment. This is useful not only for the usual nulling of stray capacitance due to sample holder and/or connecting leads but also for operation of the C-meter in a suppressed-zero mode as is required for "modified MIS C(V) measurements" [1,2].

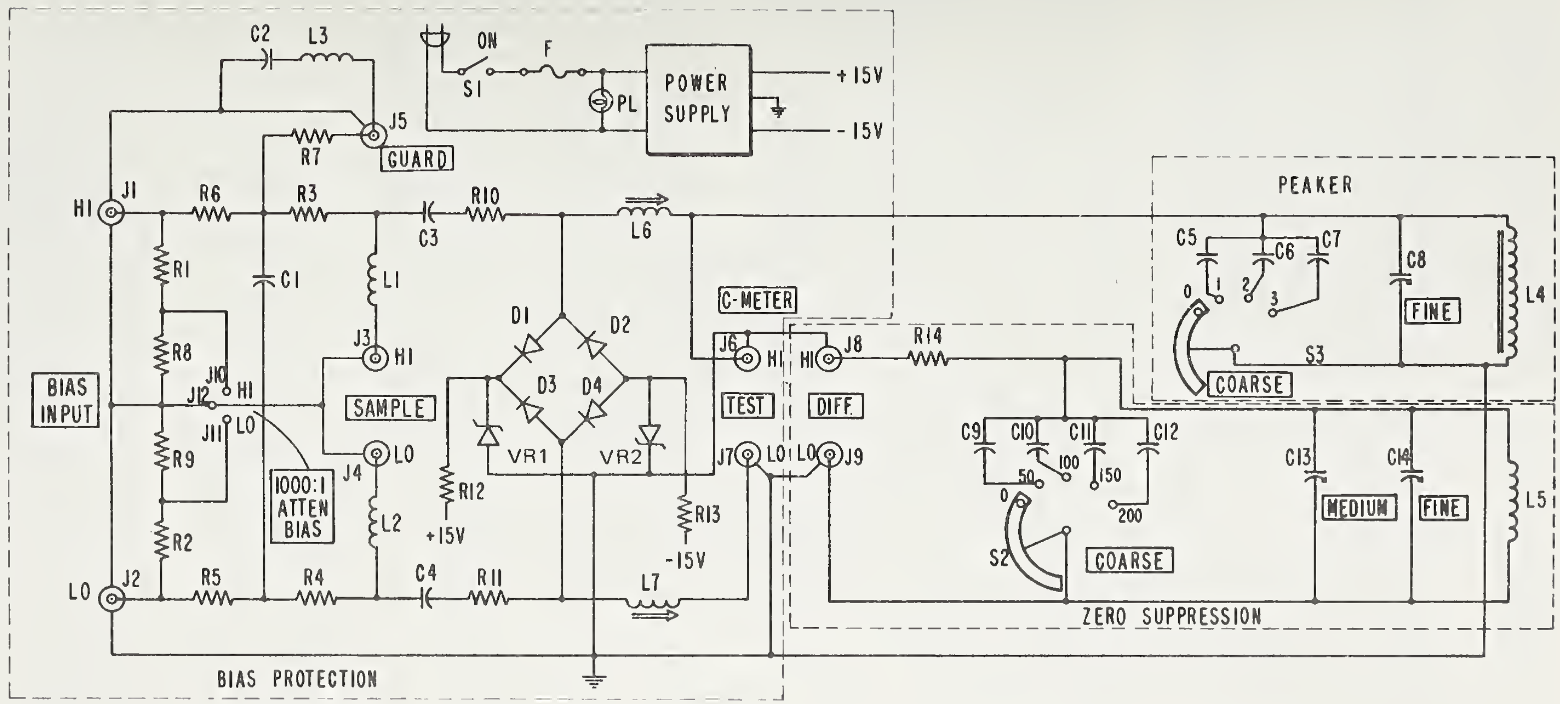


Figure 4. Schematic circuit diagram of C-meter bias-isolation unit.

Table 1. Electrical Parts List for Capacitance-Meter Bias-Isolation Unit

Schematic Reference	Description (Commercial designation,* if appropriate, shown in parentheses)
R1, R2	48.8 x 10^6-Ω nominal value, "high-voltage stable"; series string of 17 resistors: 2.87 x 10^6 Ω, 1%, T2.
R3, R4	5 x 10^6 Ω, 1%, 12.5 W, "high-voltage stable."
R5, R6	4.7 x 10^5 Ω, 10%, 2 W.
R7	4.7 x 10^6 Ω, 10%, 2 W.
R8, R9	51,350-Ω nominal value. Actual values are obtained by selecting resistor combinations that will result in 1000:1 bias voltage attenuation at J10 and J11 when those terminals are shunted by the input impedance of the recorder (10^6 Ω).
R10, R11	25-Ω, "high-voltage stable"; series string of 25 resistors: 1-Ω, 3-W noninductive.
R12, R13	820 Ω, 10%, 2 W.
R14	51 Ω, 1%, 1/2 W, noninductive.
C1	0.01 μF, 14 kVDCW (Plastic Capacitors, Type HG 140-103).
C2, C3, C4	0.002 μF, 14 kVDCW (Plastic Capacitors, Type HG 140-202).
C5, C6, C7	36 pF silvered mica capacitor.
C8, C13	5.2 - 75 pF variable capacitor (E. F. Johnson, Type "L", No. 167-0004-001).
C9, C10, C11, C12	51 pF silvered mica capacitor.
C14	2.2 - 10 pF variable capacitor with speed-reducing planetary drive. (E. F. Johnson Type "L", No. 167-0001-001) (Jackson Brothers, Type 4511/DAF planetary ball drive with 6:1 ratio).
D1, D2, D3, D4	PIN diodes (Unitrode, Type 7201D diodes).
L1, L2	Special choke, 33 turns wound on 1 in. dia. x 4 in. length plastic form.
L3	Special choke, ~50 turns wound on 1 in. dia. x 4 in. length plastic form to resonate with C2 at 1 MHz.
L4	145 μH, high Q choke (Boonton Electronics Corp., Type 400124).
L5	1000 μH.
L6, L7	1.2 to 2.5 μH (North Hills, Type 120A with 3 turns removed leaving 12 turns remaining).
J1, J2, J3, J4, J5	High voltage coaxial chassis connector (Amphenol, Type 97-3102A-18-420S).
J6, J7, J8, J9	Insulated BNC coaxial chassis connector (Amphenol, Type 31-010).
J10, J11, J12	Insulated banana jack.
S1	SPST toggle switch.
S2, S3	Ceramic insulated continuous shorting type switch.
VR1	Type 1N3305B Zener diode.
VR2	Type 1N3305RB Zener diode.
Fuse	Type 3AG-1A.
Power Supply	Regulated with + and − 15 V outputs (Semiconductor Circuits, Type 2.15.100).

*The commercial designations listed above are for components whose dimensions are consistent with those of the mechanical parts described in the appendix. The use of other components may require modification of the mechanical parts on which they are mounted. This commercial identification of components does not imply recommendation or endorsement by the National Bureau of Standards nor does it imply that these components are necessarily the best available for the purpose.

The circuit consists of a variable amount of capacitive susceptance that is applied between the high side test terminal and a source of voltage* which is approximately equal to the test signal in magnitude but is 180 deg out of phase with it. A range of greater than 250 pF of zero suppression is available. In order that this range include "zero" (i.e., no zero suppression) the minimum value of C13 + C14 plus the stray capacitance of the wiring must be "canceled out" by a small inductive susceptance (L5). The resistor R14 is approximately equal to the sum of R10 + R11 to minimize the phase imbalance between the signals applied to the high-side input terminal of the C-meter during operation in a suppressed-zero mode.

c. Peaker Circuit

A C-meter with a high-impedance input is sensitive to loading due to stray capacitance from the (high side) input terminal to ground. There is in the BEC Models 71A/71AR an adjustable tuned circuit that provides inductive susceptance from the high side input terminal to ground; this circuit may be used to null (or compensate) up to about 100 pF of stray capacitance. The BIU, sample holder, and connecting cables may provide more stray capacitance than can be nulled by this circuit. Therefore, an additional circuit providing inductive susceptance has been built into the BIU for use if needed; it is capable of nulling up to an additional 150 pF. This portion of the circuit is labeled PEAKER in figure 4. In operation the PEAKER is adjusted as follows:

(i) With the cables and sample connected, the C-meter is set to its highest sensitivity (highest input impedance).
(ii) The ZERO SUPPRESSION control is set to produce a reading in the upper half of the scale.
(iii) The PEAKER is then adjusted to obtain a maximum reading. If the meter goes off-scale, repeat steps (ii) and (iii).

The peaker circuit adjustment is important only when the C-meter used has a high input impedance. If the C-meter has a low-impedance input like the PAR Model 410, its performance will be completely indifferent to adjustment of the peaker circuit.

The capacitor to be measured is connected to the terminals marked SAMPLE and the bias-voltage power supply is connected to the terminals marked BIAS INPUT. If a guard-ring electrode system is to be used on the sample, the guard ring is connected to the terminal marked GUARD and the guarded electrode must be connected to the HIGH side; the unguarded electrode is connected to the LOW side.

If the BIU is used with a BEC C-meter, the TEST and DIFF terminals of the C-meter are connected to the correspondingly marked terminals of of the BIU. The external bias terminals of the C-meter should be connected together (short-circuited).

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*This voltage is available at the LO side of the terminals marked DIFF on BEC Models and at the terminal marked NULL on the PAR Model 410.

If the BIU is used with a PAR Model 410 C-meter, the HI side of the TEST and DIFF terminals of the BIU should be connected together and to the C-meter terminal marked INPUT. The LO side of the TEST and DIFF terminals of the BIU should be connected, respectively, to the C-meter terminals marked DRIVE and NULL.

3.2. Measurement Accuracy

a. Basic Considerations

The use of the BIU places certain constraints upon the range of test capacitance values which can be measured and the accuracy with which these measurements can be made. In what follows we shall first consider a simple equivalent circuit for the combination of the test capacitance and the BIU, and second, derive expressions describing the deviation of the apparent or "measured" capacitance from the actual value as a function of the equivalent circuit parameters.

b. Equivalent Circuit

The C-meter measures the capacitive susceptance of a test capacitance C_S connected between its terminals and displays this value on a suitably calibrated linear scale reading directly in units of capacitance (usually picofarads). Let us define this value of susceptance as:

$$B_o\,(C_S) \equiv \omega\, C_S \tag{1}$$

When the C-meter is used with the BIU to measure the same test capacitance, the equivalent circuit is one in which the test capacitance appears to be in series with a resistance R and (possibly) a reactance X. The resistance is due principally to the sum of R10 + R11 in figure 4. There may also be a small contribution due to the resistance in the windings of L1, L2, L6, and L7 and in the blocking capacitors C3 and C4. The reactance X is equal to the difference between the inductive reactance of the sum of the circuit inductances (L1 + L2 + L6 + L7 + lead inductance) and the capacitive reactance of the series combination of C3 and C4. We shall see shortly that there is no advantage to X being capacitive (negative); in practice, we would like it to be either zero or slightly inductive. We shall therefore treat it as if it were due to an "excess" inductance L_X.

The susceptance $B(C_S)$ of the series combination of C_S, R, and L_X measured by the C-meter is

$$B(C_S) = \frac{\omega C_S[1-\omega^2 L_X C_S]}{\omega^2 R^2 C_S{}^2 + [1-\omega^2 L_X C_S]^2} \tag{2}$$

We may now define a relative sensitivity factor, $S(C_S)$.

$$S(C_S) \equiv \frac{B(C_S)}{B_o(C_S)} = \frac{[1-\omega^2 L_X C_S]}{\omega^2 R^2 C_S^2 + [1-\omega^2 L_X C_S]^2} \tag{3}$$

This gives the ratio of the apparent value of the C_S that would be indicated by the C-meter when used with the BIU to the actual value of C_S that would be indicated by the C-meter alone. In some measurement applications [1,2] it is necessary to determine small changes in a test capacitance. It is, therefore, of interest to derive an expression for the relative *incremental* sensitivity factor which we shall call $S'(C_S)$.

$$S'(C_S) \equiv \frac{dB(C_S)}{dC_S} \bigg/ \frac{dB_o(C_S)}{dC_S} \tag{4a}$$

$$S'(C_S) = \frac{[1-\omega^2 L_X C_S]^2 - \omega^2 R^2 C_S^2}{[(1-\omega^2 L_X C_S)^2 + \omega^2 R^2 C_S^2]^2} \tag{4b}$$

This gives the ratio of the apparent value of a small change in C_S that would be indicated by the C-meter when used with the BIU to the actual value of the small change in C_S that would be indicated by the C-meter alone. Ideally, of course, both S and S' should be equal to 1.0 for all values of C_S, but this could be true only for both L_X and R equal to zero; i.e., without the protection circuit to which R is essential.

It is helpful to consider two separate regimes (a) $L_X = 0$ and (b) $L_X \neq 0$.

(1) $L_X = 0$

In this regime, eqs (3) and (4b) reduce to

$$S(C_S) = \frac{1}{1 + \omega^2 R^2 C_S^2} \tag{5}$$

and

$$S'(C_S) = \frac{1-\omega^2 R^2 C_S^2}{[1 + \omega^2 R^2 C_S^2]^2} \tag{6}$$

In figure 5, S and S' are plotted as a function of C_S with R as a parameter. For the value R = 50, it can be seen that the added error in measurement due to the BIU should be less than 1% in S for $C_S \lesssim 300$ pF and less than 1% in S' for $C_S \lesssim 180$ pF. These ranges of C_S measurable with low added error far exceed any application requirements encountered to date.

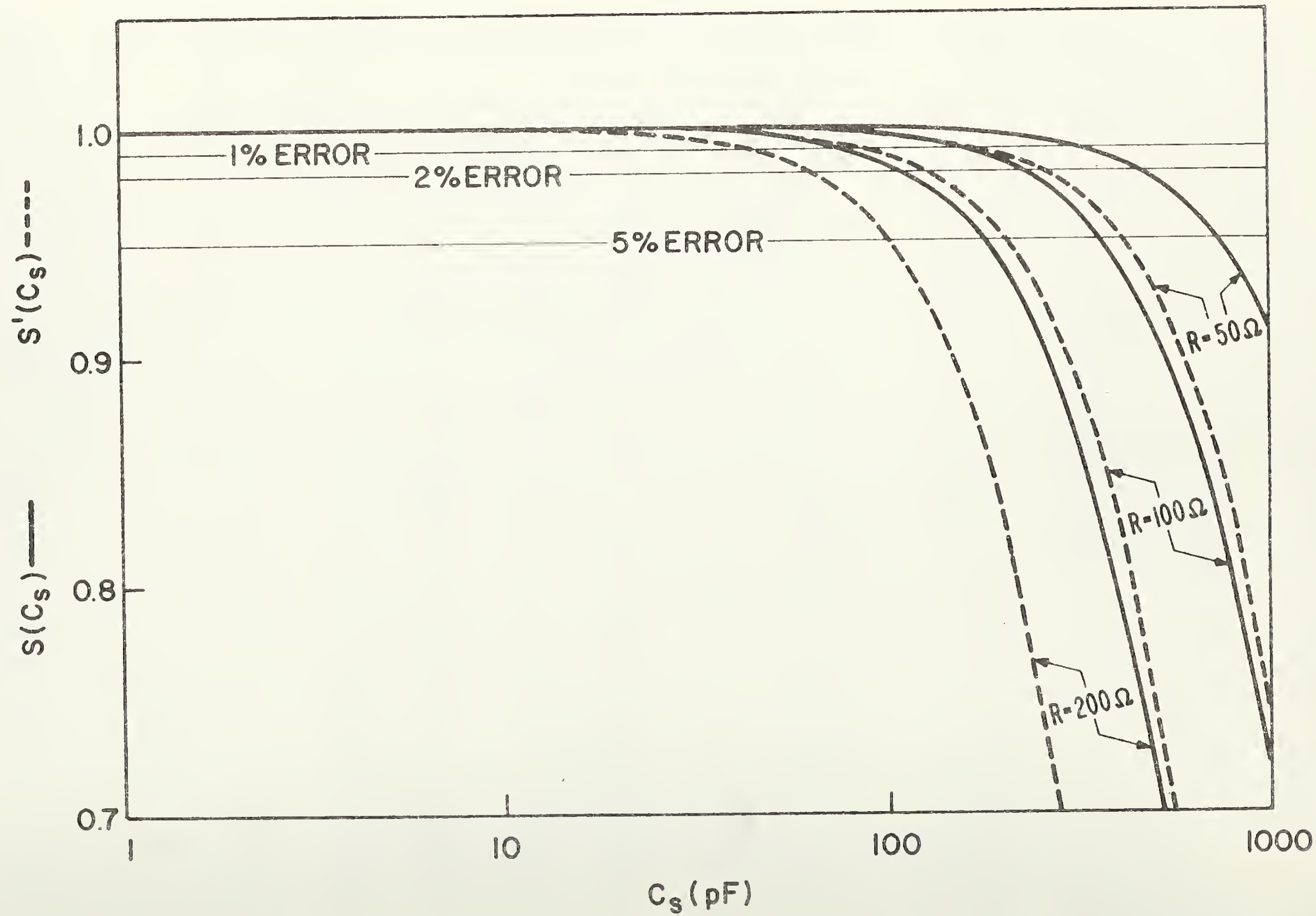

Figure 5. Plots of relative sensitivity factor $S(C_S)$ and relative incremental sensitivity factor $S'(C_S)$ versus C_S with series resistance R as a parameter.

(2) $L_X \neq 0$

It is helpful to write eqs (3) and (4b) in the form

$$S(C_S) = \frac{1-\alpha C_S}{(1-\alpha C_S)^2 + \beta C_S{}^2} \tag{5a}$$

and

$$S'(C_S) = \frac{[1-\alpha C_S]^2 - \beta C_S{}^2}{[(1-\alpha C_S)^2 + \beta C_S{}^2]^2} \tag{5b}$$

where $\alpha = \omega^2 L_X$ and $\beta = \omega^2 R^2$.

We are particularly interested in the region in which $S(C_S)$ and $S'(C_S)$ are close to 1; i.e., the region in which $\alpha C_S \ll 1$ and $\beta C_S{}^2 \ll 1$. Equations (5a) and (5b) may be simplified by carrying out the indicated operations and retaining only first-order terms in αC_S and $\beta C_S{}^2$. This gives

$$S(C_S) \doteq 1 + \alpha C_S - \beta C_S{}^2 \tag{7a}$$

and

$$S'(C_S) \doteq 1 + 2\alpha C_S - 3\beta C_S{}^2 \tag{7b}$$

For non-zero α, both $S(C_S)$ and $S'(C_S)$ are increasing functions of C_S at low values of C_S, go through maxima and become decreasing functions of C_S. These maxima may be found by differentiating eqs (7a) and (7b) and setting them equal to zero. This gives

$$S(C_S)_{max} = 1 + \beta C_S{}^2 \tag{8a}$$

$$\text{at } C_S = \alpha/2\beta \tag{8b}$$

and

$$S'(C_S)_{max} = 1 + 3\beta C_S{}^2 \tag{8c}$$

$$\text{at } C_S = \alpha/3\beta \tag{8d}$$

It was previously stated that there is no advantage to the reactance X being capacitive (negative); that this is true can be seen from the following argument. If the reactance were negative, the terms in eqs (7a) and (7b) which are linear in C_S would become negative and the departure of $S(C_S)$ and $S'(C_S)$ from their ideal values of 1.00 would occur more rapidly with increasing C_S. This is clearly undesirable.

It is easily demonstrated that for a given allowable error *magnitude* in either $S(C_S)$ or $S'(C_S)$, a wider range of measurable C_S can be obtained by using an "appropriate" value of $\alpha(L_X)$ than would be possible for $\alpha = 0$.

Let us consider two examples. *First*, we consider the case in which the maximum allowable error in $S(C_S)$ is $\pm\ \varepsilon$. At its maximum value, $S(C_S)_{max} = 1 + \varepsilon$. It follows from eqs (8a) and (8b) that the appropriate value of α is

$$\alpha(\varepsilon) = 2\sqrt{\beta\varepsilon} \tag{9}$$

The maximum value and, therefore, the maximum range of C_S which can be measured without exceeding the allowable error ε, is found from eqs (7a) and (9) to be

$$\Delta C_S(\alpha,\varepsilon) = [1 + \sqrt{2}]\ [\varepsilon/\beta]^{1/2} \tag{10}$$

This may be compared with the maximum range of C_S which can be measured without exceeding the allowable error in $S(C_S)$ when $\alpha = 0$, i.e., when there is no excess inductance; in this case the range is

$$\Delta C_S(0,\varepsilon) = [\varepsilon/\beta]^{1/2} \tag{11}$$

Thus, the appropriate value of α can provide an increase in measurable range of C_S by a factor of

$$\frac{\Delta C_S(\alpha,\varepsilon)}{\Delta C_S(0,\varepsilon)} = 1 + \sqrt{2} \tag{12}$$

As a *second* example, we consider the case in which the maximum allowable error in $S'(C_S)$ is $\pm\ \varepsilon'$. At its maximum value, then, $S'(C_S) = 1 + \varepsilon'$. It follows from eqs (8c) and (8d) that the appropriate value of α for this case is

$$\alpha(\varepsilon') = \sqrt{3\beta\varepsilon'} \tag{13}$$

The maximum value and, therefore, the maximum range of C_S which can be measured without exceeding the allowable error ε' is found from eqs (7b) and (13) to be

$$\Delta C_S(\alpha,\varepsilon') = [1 + \sqrt{2}\ ]\ [\varepsilon/3\beta]^{1/2} \tag{14}$$

This may be compared with the maximum range of C_S which can be measured without exceeding the allowable error in $S'(C_S)$ when $\alpha = 0$, i.e., when there is no excess inductance; in this case the value is

$$\Delta C_S(0,\varepsilon') = [\varepsilon/3\beta]^{1/2} \tag{15}$$

Here again, there is an increase in the measurable range of C_S by a factor of

$$\frac{\Delta C_S(\alpha,\varepsilon')}{\Delta C_S(0,\varepsilon')} = 1 + \sqrt{2} \tag{16}$$

Note, however, that the "appropriate" values of α are not the same for equal error magnitudes ε and ε'.

In summary then, excess inductance L_X can be used to increase the measurable range of C_S without exceeding a set of preassigned error limits on either $S(C_S)$ or $S'(C_S)$.

4. EXPERIMENTAL RESULTS

4.1. General

The BIU described in section 3 was tested to ensure that it would properly perform the desired bias-protection (transient-suppression) function and that the accuracy of measurements made with it would not be excessively degraded. These tests and their results will now be described.

4.2. Transient Suppression

The experimental arrangement for testing the transient-suppression capability of the BIU is shown in figure 6. A test capacitor periodically short-circuiting under high bias (10 kV) is simulated by a motor-driven spark gap. The resulting transient voltage at the C-meter terminals is picked up with a probe and displayed on a fast oscilloscope. The voltage from *each* C-meter terminal to ground was checked individually for each polarity of applied bias and found to have a peak value less than ± 200 V. A typical example is shown in figure 6(b).

In addition, repeated sample breakdowns were simulated under actual test conditions; i.e., with a C-meter connected. These tests were conducted with three different types of commercially available C-meters: (i) a BEC Model 71A, (ii) a BEC Model 72AD, and (iii) a PAR Model 410. The C-meters were tested before and after the simulated breakdowns; no damage or change in calibration was found.

Furthermore, many actual sample breakdowns have occurred during C(V) measurements using the BIU at high voltage levels (approaching 10 kV). In none of these breakdowns was a C-meter damaged.

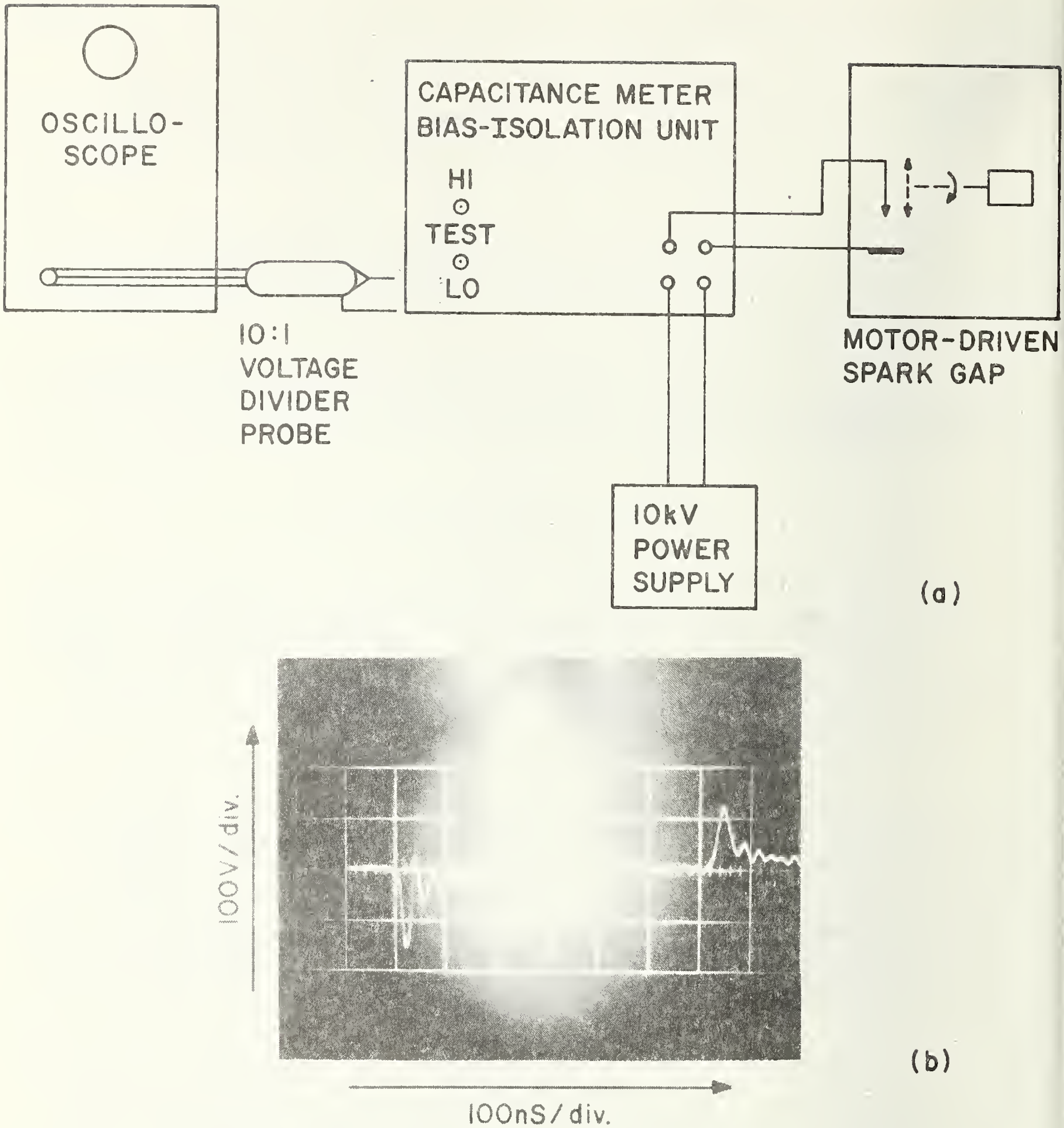

Figure 6. (a) Schematic representation of the experimental arrangement for testing the transient suppression capability of the BIU. (b) Photograph of a typical observed transient (HI terminal to ground).

4.3. Effect of the BIU on Measurement Accuracy

In section 3.2 the effect of the BIU on the accuracy of C-meter measurement was considered from a theoretical point of view. The actual effect was determined experimentally by measuring $S(C_S)$ and $S'(C_S)$ for each of the three C-meters used in the transient suppression tests (section 4.2). Prior to these measurements L6 and L7 were adjusted to produce minimum reactance at 1 MHz between the terminals J3 and J6 and between J4 and J7 of figure 4. That is, there was no intentional use of excess inductance to "stretch" the measurable range of C_S. Some slight additional inductance was, of course, present due to the leads connecting the BIU to the C-meter and the test capacitor to the BIU.

In order to measure $S(C_S)$ and $S'(C_S)$, a precision decade capacitor was used as a standard. This 3-terminal capacitance standard has an accuracy of 0.25% for each of its component capacitors. In each case, the output of the C-meter was read on the 10-inch scale of an X-Y recorder with an accuracy of 0.2% of full scale. Each C-meter was calibrated on the appropriate scale(s) by connecting the standard capacitor *directly* to the C-meter (i.e., with BIU out of the circuit), and following the manufacturer's calibration instructions.

After the completion of the calibration procedure, the standard capacitor was connected to the C-meter through the BIU, and the apparent capacitance (as measured through the BIU) was determined as a function of the standard capacitance.
From section 3.2 $S(C_S)$ = apparent value of C_S/standard value of C_S.

It was not possible to obtain $S'(C_S)$ directly. Therefore, the following approximation was used: $S'(C_S) \doteq$ (measured increase in the apparent value of C_S due to an actual increase of $\delta C_S)/\delta C_S$. For all of the measurements discussed in this report, $\delta C_S = 1$ pF. The actual measurement procedure was as follows: (i) a value of C_S was set on the standard capacitor, (ii) the output was reduced to zero using the ZERO SUPPRESSION controls, (iii) the sensitivity of the recorder was increased by a factor such that an additional 1 pF should cause full-scale deflection on the recorder, (iv) the output was again adjusted to zero, (v) the standard capacitor was increased by 1 pF, and (vi) the value of $S'(C_S)$ was read directly from the recorder with full scale corresponding to $S' = 1.00$; if the deflection exceeded full scale by more than 1% (the available recorder over-range) the sensitivity was reduced by a factor of 1/2, in which case half-scale deflection corresponded to $S' = 1.00$.

Measurements of apparent capacitance versus standard capacitance were carried out using each C-meter, and the value of $S(C_S)$ was computed for each data point. The results are shown in figures 7, 8, and 9. For comparison, the theoretical expression, eq (5) for $S(C_S)$ based on the simplified equivalent circuit with $L_X = 0$, is also shown in each figure. Qualitatively, the results are similar for the three C-meters, viz., the falloff of $S(C_S)$ with increasing C_S is smaller than would be expected from eq (5) over most of the measured range of C_S. This occurs undoubtedly because the connecting leads provide a small excess inductance

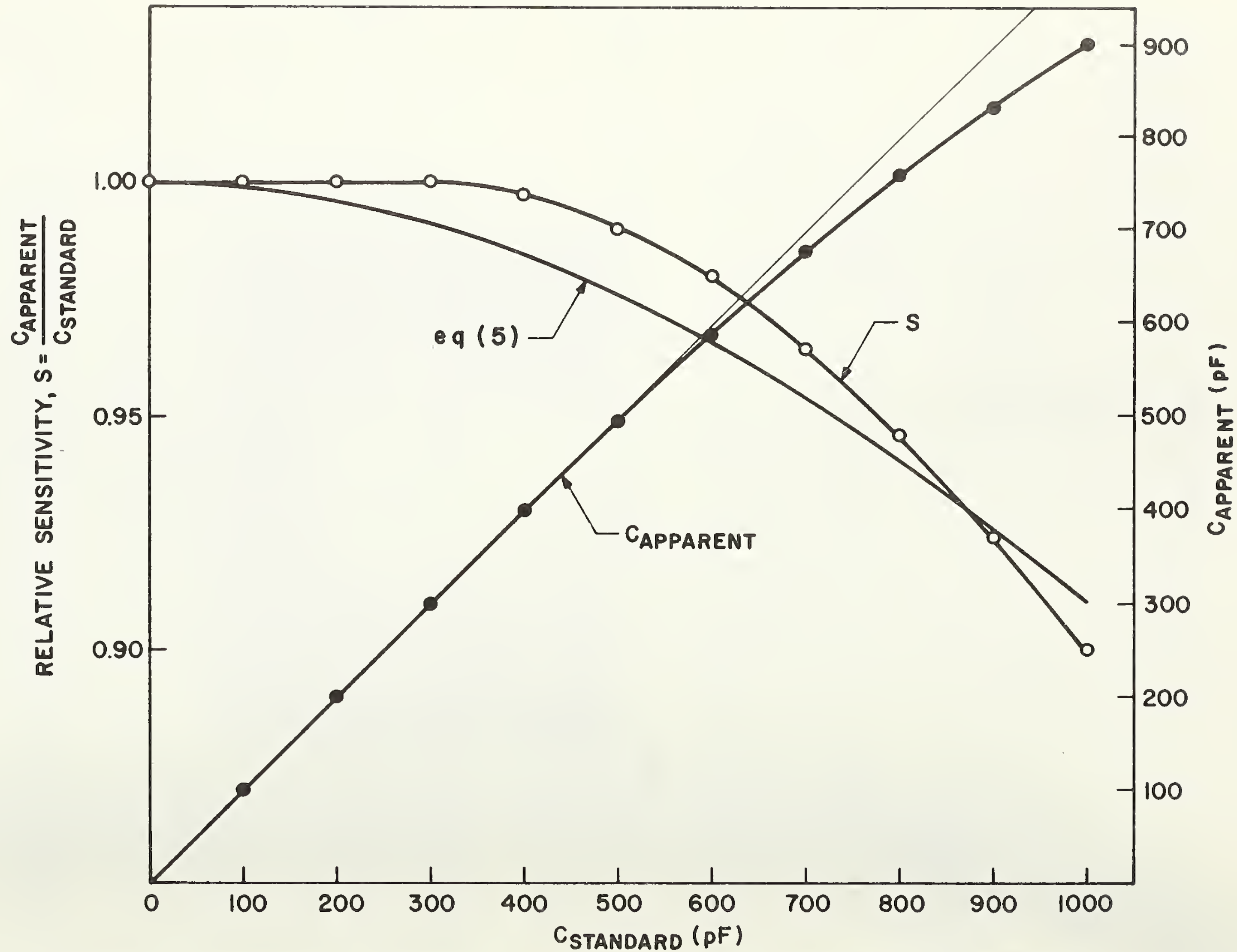

Figure 7. Calibration curves for BIU operating with BEC Model 71A C-meter.

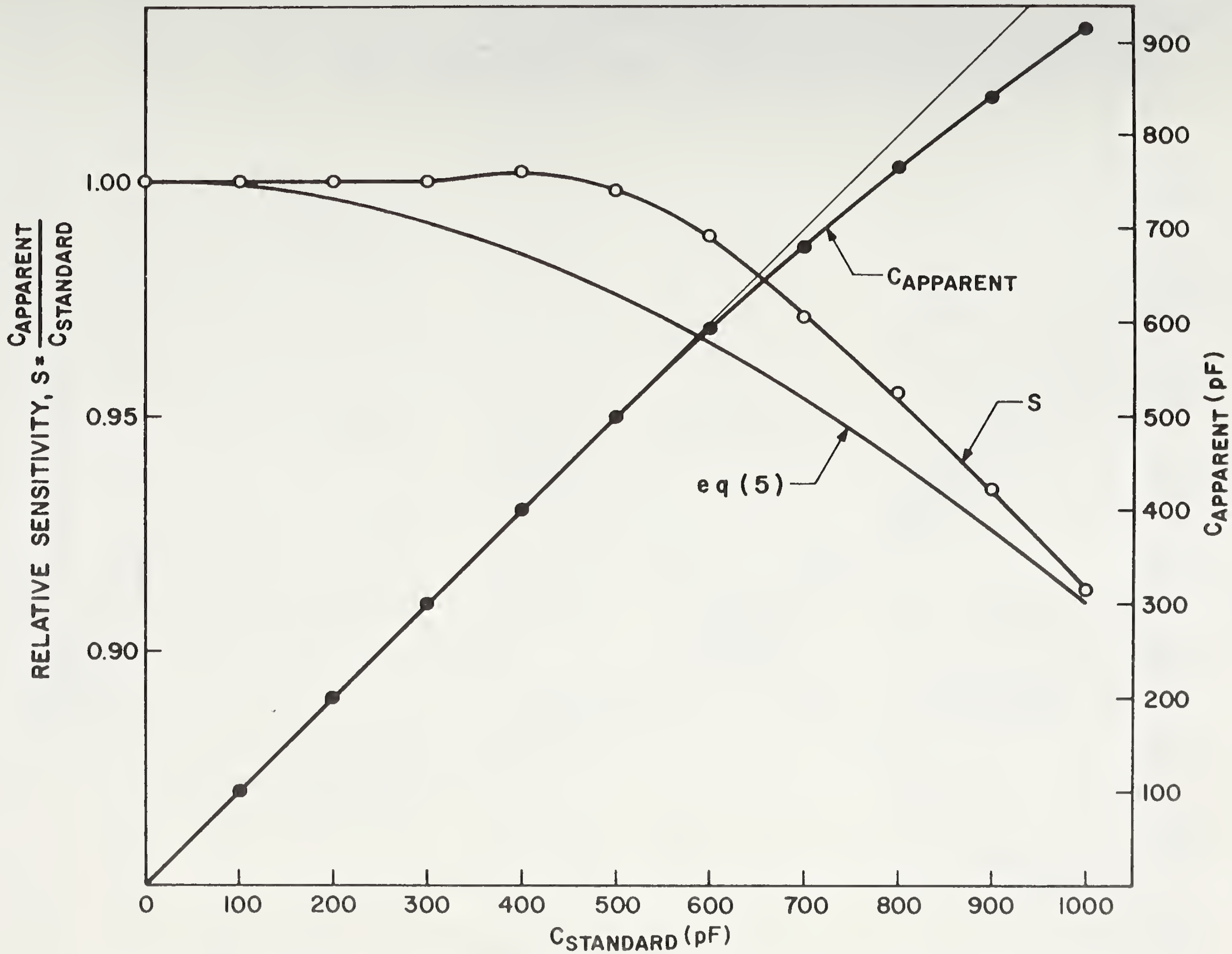

Figure 8. Calibration curves for BIU operating with BEC Model 72AD C-meter.

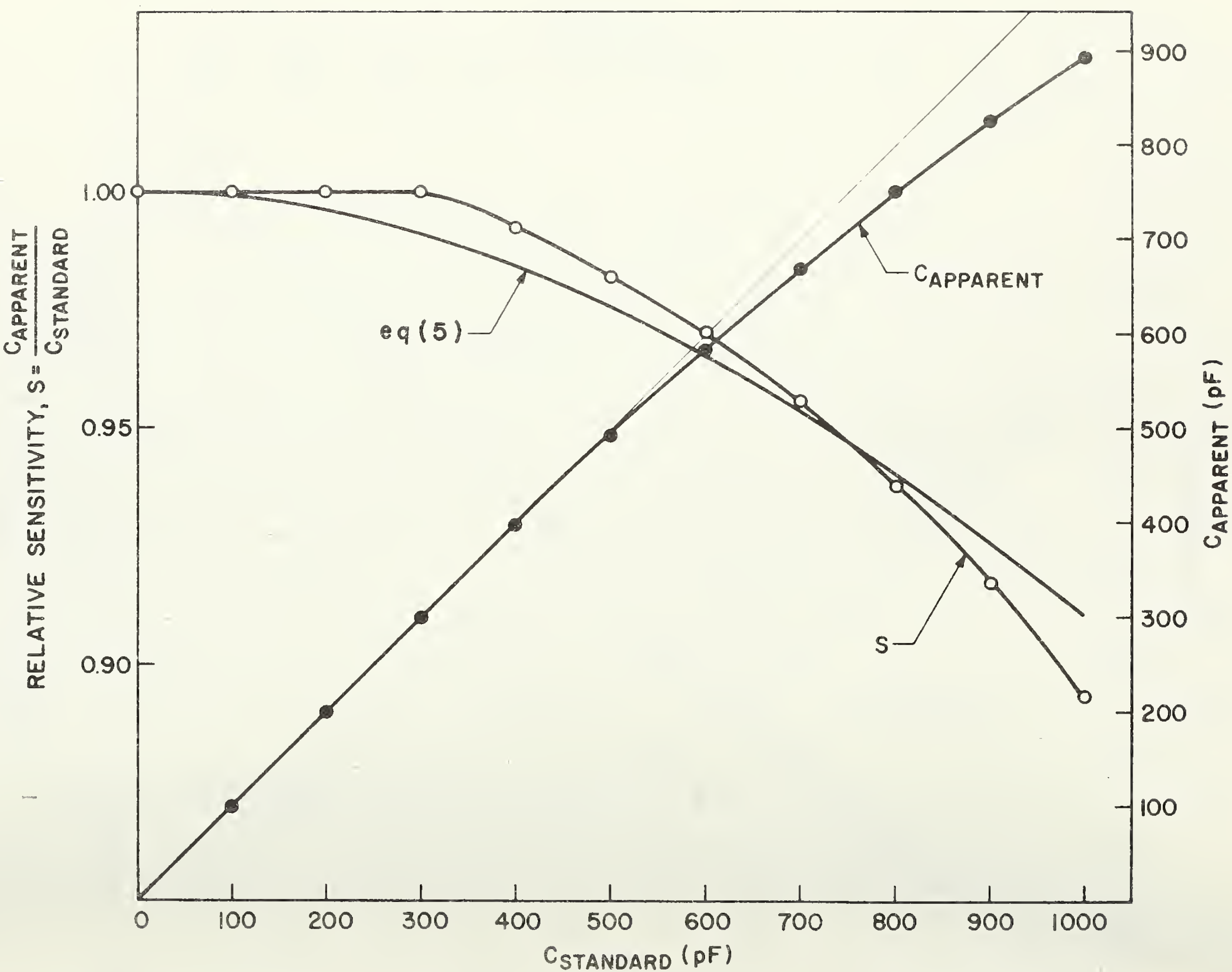

Figure 9. Calibration curves for BIU operating with PAR Model 410 C-meter.

L_X, having the effect discussed in section 3.2. This is most evident in the data for the Boonton Model 72AD C-meter (see fig. 8), where there is a detectable peak in $S(C_S)$.

There is one other deviation from $S(C_S) = 1.00$ using the BEC Model 71A. This occurs on the lower capacitance ranges where the input resistance is high. On the 1, 3, and 10 pF scales, $S(C_S)$ was 0.892, 0.968, and 0.995, respectively, independent of C_S. This falloff in sensitivity is due to the loading of the input circuit by the BIU. The effect is not detectable on the 30 pF and higher capacitance ranges. The effect is not a serious one in any case since it is independent of C_S and may easily be compensated by an appropriate internal adjustment of the C-meter sensitivity on the lower scales (if the C-meter is dedicated to operation with the BIU) or, alternatively, by appropriately adjusting the recorder sensitivity. The input impedance of each of the other two C-meters tested is sufficiently low that they are not loaded by the BIU on any scale.

The value of $S'(C_S)$ was then determined for each of the C-meters. The results are plotted as open circles in figures 10, 11, and 12. The other data in figures 11 and 12 will be discussed shortly. For comparison, each figure also shows the theoretical expression, eq (6), for $S'(C_S)$ based on the simplified equivalent circuit with $L_X = 0$. The results for the three C-meters are distinctly different in this case.

For the BEC Model 71A C-meter (see fig. 10) the experimentally determined values of $S'(C_S)$ rise above 1.0 at low C_S and fall below 1.0 at higher C_S. The initial rise is thought to be due to the excess inductance provided by the connecting leads. Above $C_S \approx 120$ pF, the experimental values of $S'(C_S)$ fall off more rapidly with increasing C_S than would be expected from eq (6). There are probably two reasons for this:

(i) The measurements were made using the 100 pF scale corresponding to an input resistance of approximately 60 Ω; as C_S and the zero-suppression capacitance are increased, the effective capacitance from the HI terminals to ground increases, shunting the 60-Ω input resistance and lowering the apparent sensitivity of the C-meter.

(ii) The effective series resistance of the BIU may be larger than 50 Ω due to the series resistance contribution of the coils and blocking capacitors.

Nevertheless, there is a measurement range of 140 pF in C_S in which S' does not deviate from its ideal value of 1.0 by more than 1%.

For the BEC Model 72AD C-meter (see fig. 11), the initial experimental results (unfilled circles) were rather bizarre. Similar results were obtained from the initial experimental measurements (unfilled circles in fig. 12) of $S'(C_S)$ using the PAR Model 410 C-meter. The undulation of $S'(C_S)$ suggested the possibility of resonances occurring at frequencies other than the 1-MHz test signal. An analysis of the equivalent circuit at harmonics of 1 MHz, taking into account the value of C_S at

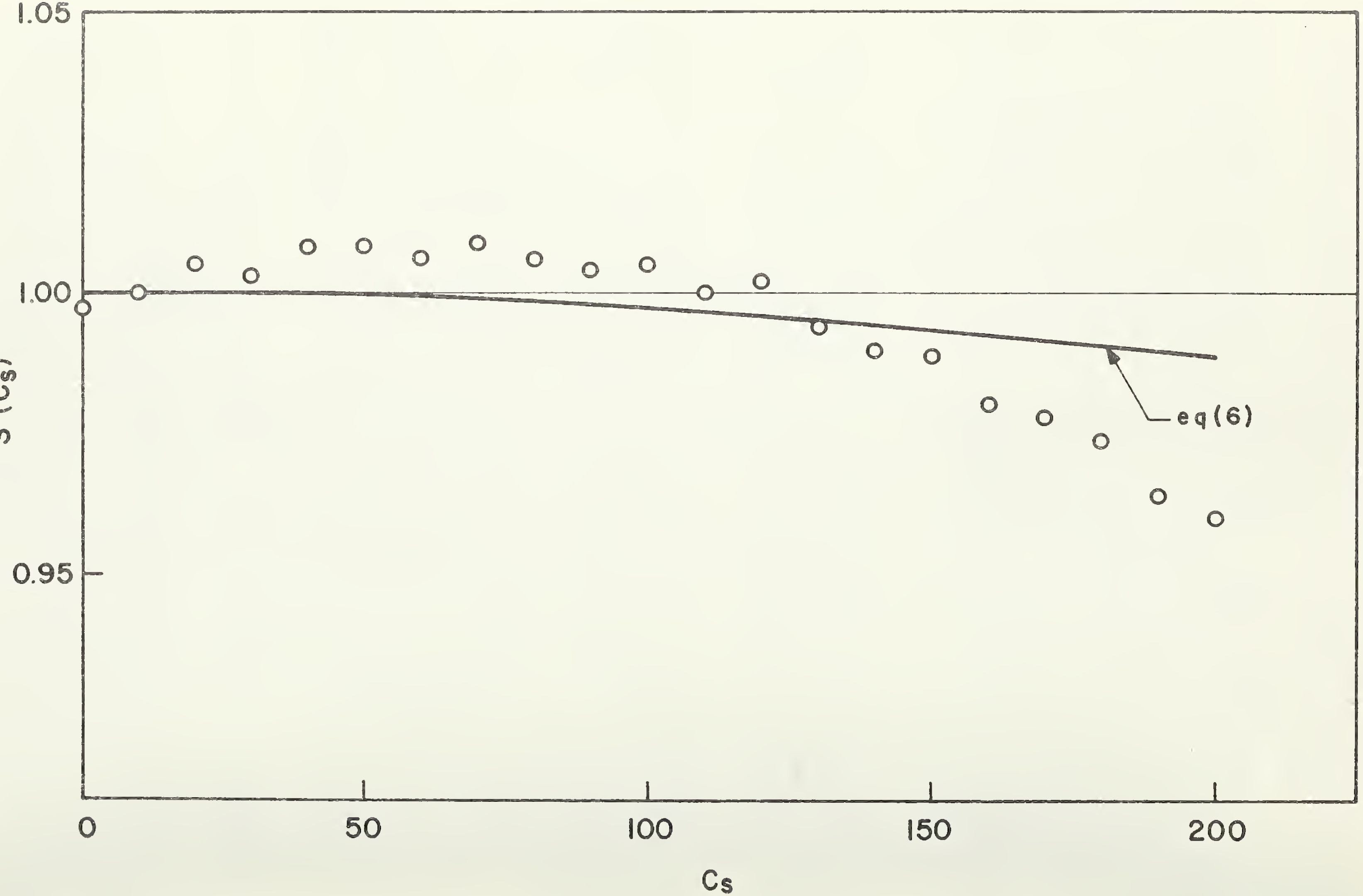

Figure 10. Relative incremental sensitivity $S'(C_S)$ for BIU operating with BEC Model 71A C-meter.

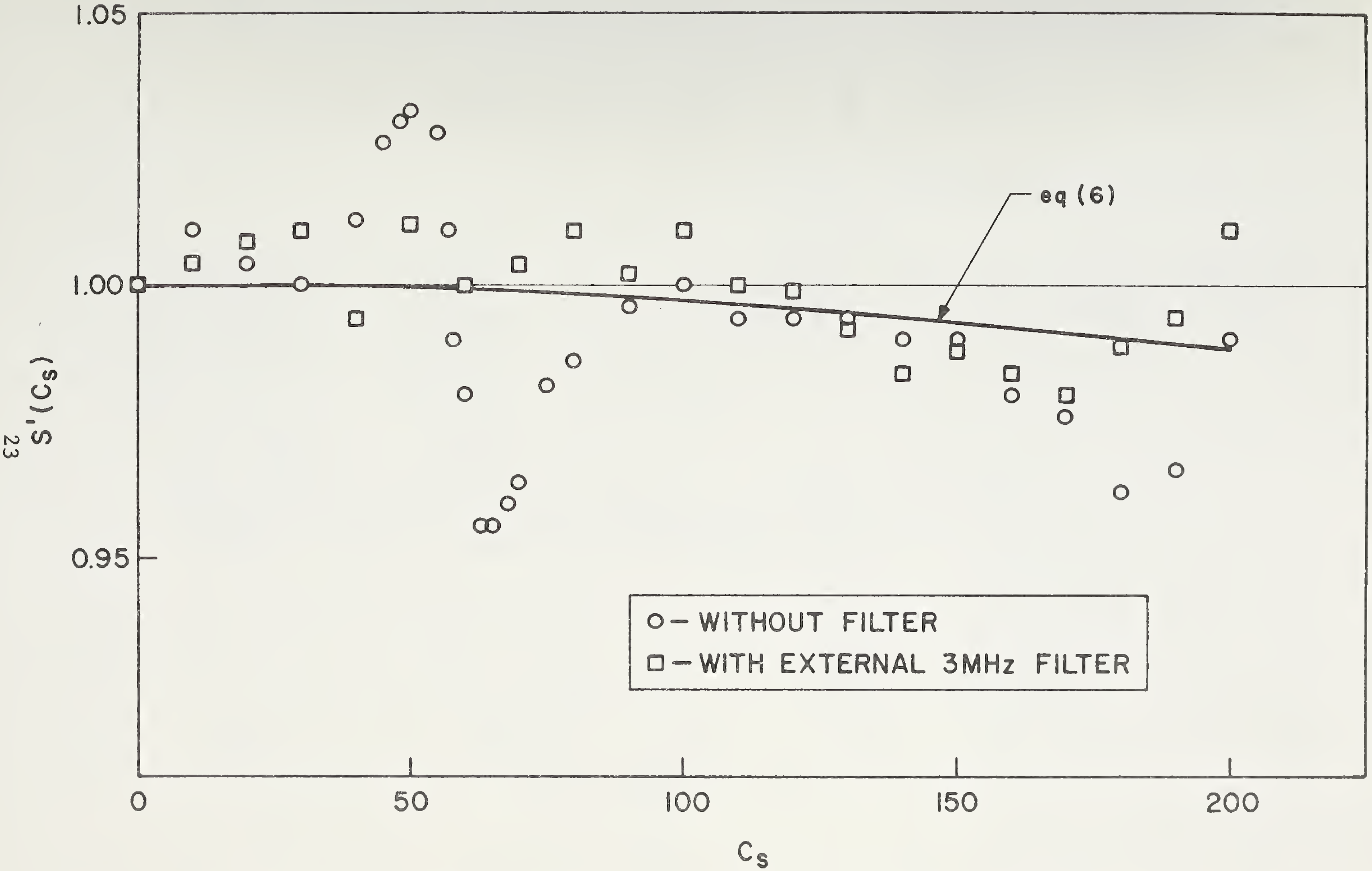

Figure 11. Relative incremental sensitivity $S'(C_S)$ for BIU operating with BEC Model 72AD C-meter.

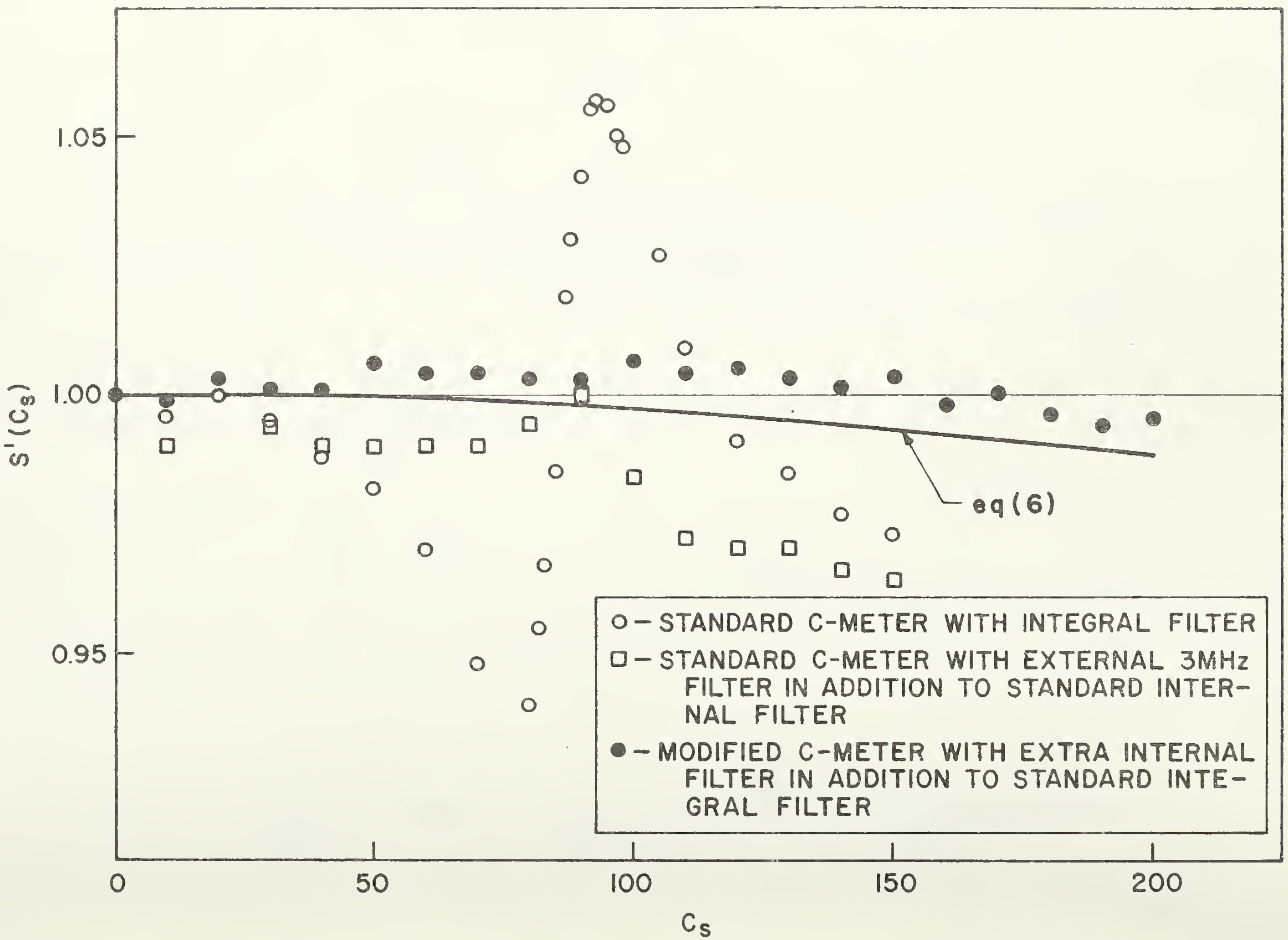

Figure 12. Relative incremental sensitivity $S'(C_S)$ for BIU operating with PAR Model 410 C-meter.

which the largest undulation takes place, indicated that the major culprit was probably a third-harmonic component in the test signal. To test this hypothesis, a crude filter was assembled for use between the BIU and the C-meter (fig. 13). The purpose of the filter was to attenuate the third-harmonic component of the current flowing from the test capacitor C_S into the C-meter HI terminal. The measurements of S' (C_S) were repeated for the BEC Model 72AD and PAR Model 410 C-meters using the filter. The results are shown as the squares in figures 11 and 12. It was clear that the filter provided a substantial improvement in the 0 to 100 pF range of C_S; it was equally clear that further improvement was desirable. For this reason, a spectral analysis of the test signal of each of the three C-meters was carried out. The results (shown in table 2) indicate that the BEC Model 71A has the "cleanest" test signal, while the test signals of the other two are relatively rich in harmonics. These results confirmed that the unexpected behavior of S'(C_S) was indeed due to the presence of undesirable harmonics in the test signal.

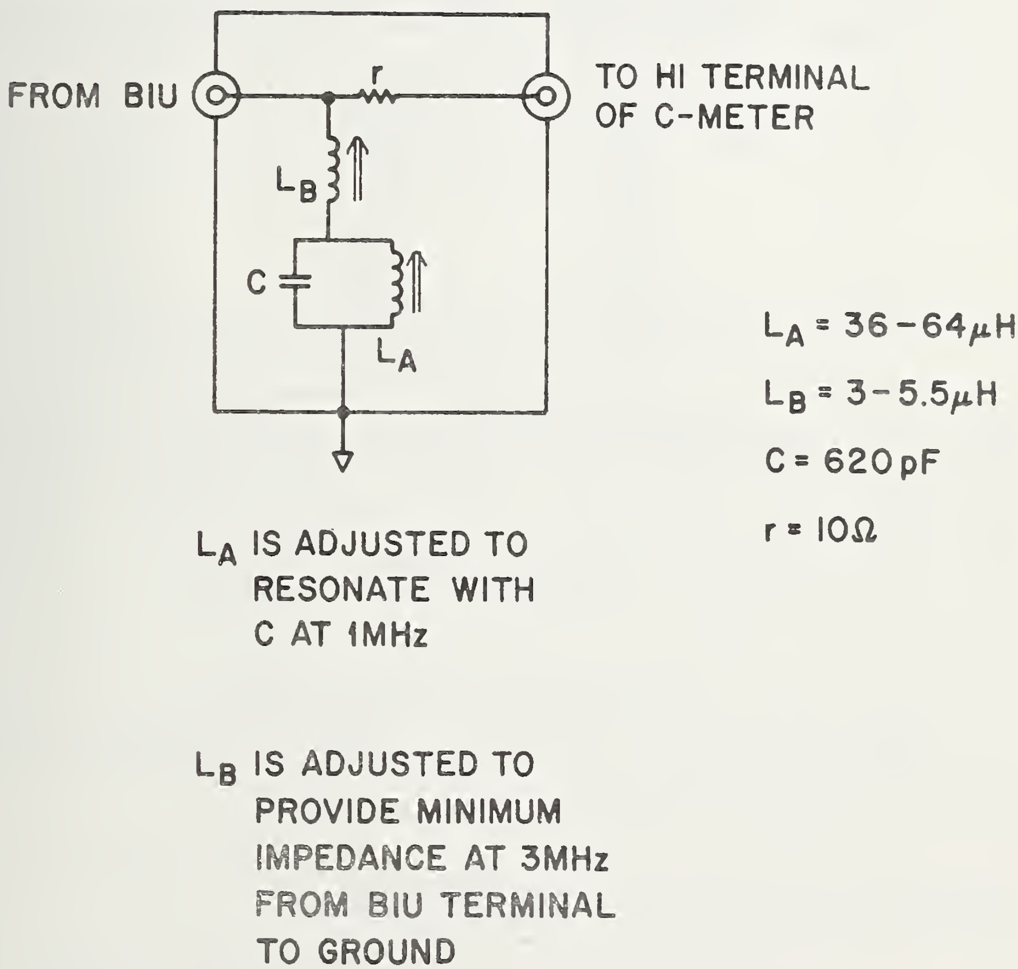

Figure 13. Schematic circuit diagram of 3-MHz filter.

It was felt that the best place to eliminate the harmonics was in the C-meter, either in the test signal generator or in the amplifier chain preceding the phase-sensitive detector. Accordingly, arrangements were made with the PAR Corp. to obtain a modified version of the PAR Model 410 C-meter with extra filtering to eliminate the unwanted harmonics. The results of a measurement of $S'(C_S)$ using the BIU with this C-meter are shown as the filled circles in figure 12. The deviation of $S'(C_S)$ from 1.0 is less than 1% over the range 0 to 200 pF. The experimental points do not fall below 1.0 as rapidly with increasing C_S as would be expected from eq (6); this is consistent with the behavior expected from a small excess inductance provided by the connecting leads. It is reasonable to expect that similar results could be obtained using the BIU with a BEC Model 72AD C-meter suitably modified to filter out the test signal harmonics.

Table 2. Test-Signal Spectral Analysis for Three C-Meters

	Test Signal Component (mV_{rms})		
F (MHz)	BEC Mod. 71A	BEC Mod. 72AD	PAR Mod. 410
1	13.0	12.7	10
2	0.112	0.590	0.35
3	0.050	0.063	0.400
4	0.010	0.044	0.100
5	<0.007	0.050	0.112
6	<0.007	0.014	0.050
7	<0.007	0.009	0.045
8	<0.007	0.009	0.040
9	<0.007	0.009	0.032
10	<0.007	0.010	0.028

These results may be summarized as follows: It has been demonstrated that the BIU can be used with any of three commercially available C-meters at applied voltages up to 10 kV. For less than $\pm$ 1% error in relative sensitivity $S(C_S)$, the measurable range of C_S is from 0 to greater than 400 pF; for less than $\pm$ 1% error in relative incremental sensitivity $S'(C_S)$, the measurable range of C_S is from 0 to greater than 130 pF.

5. DISCUSSION AND CONCLUSIONS

It is useful to consider the results which have been achieved thus far with the BIU and to place them in the broader perspective of the requirements of present and possible future applications.

The two applications of high-voltage capacitance measurements which have already been investigated in some detail are:

(i) measurements of C(V) of metal-glass-silicon capacitors for the purpose of characterizing the interface between silicon and a passivating glass layer ($t_{glass} \approx$ 10 to 100 μm), and

(ii) measurements of C(V) of metal-sapphire-silicon capacitors for the purpose of characterizing SOS and the silicon-sapphire interface ($t_{sapphire} \approx$ 100 to 150 μm).

In these applications the range of values of C_S encountered was 5 to 55 pF. Clearly, the equipment described herein is entirely adequate for these measurements. It is anticipated, however, that future measurement applications (using thicker sapphire wafers) will require bias-voltage capability up to about $\pm$ 25 kV, and current efforts are directed toward the development of equipment that will be capable of operating at these higher voltage levels.

Two other applications have been investigated only in sufficient detail to show that the measurement technique is a useful one. These applications are: (i) characterization of the interface between heavily doped silicon and a thick (> 1 μm) overlying insulator, (ii) measurement of the base-collector capacitance of a very high voltage transistor (max $V_C \gtrsim$ 1500 V) in order to nondestructively characterize the doping profile of its base-collector region. Other possible future applications include the characterization of new passivating and encapsulating layers for semiconductor devices (e.g., plastics, resins, and epoxies), studies of the electric field dependence of dielectric polarization under high fields, and studies of dielectric-electrolyte interfaces. In each of these applications, the equipment described appears to be adequate for all current and future applications.

In conclusion:

(1) A technique has been described which allows the safe operation of commercially available C-meters for capacitance measurements with applied-bias voltage up to $\pm$ 10 kV.
(2) The technique requires a bias-isolation unit for which the circuit, theory, and practical results have been presented.
(3) Details of construction of the bias-isolation unit are provided in the appendix.

ACKNOWLEDGMENT

I am indebted to Chester J. Halgas for the mechanical design and the construction of the bias-isolation unit described in this report, to Paul Kuczer for construction of an earlier developmental version, and to James M. Breece for assistance with some of the measurements.

APPENDIX

This appendix contains information which is intended for use by anyone who wants to duplicate the BIU described in the body of the report. It consists of:

(i) A list of the mechanical parts which are not commercially available,
(ii) detailed drawings of those parts, and
(iii) a drawing and photographs showing the placement of all parts (the circled numbers refer to the mechanical parts and electrical components identified in tables 1 and 3).

Table 3. List of Mechanical Parts (not commercially available)

Part No.	Part Description	Drawing No.
1.	Front panel	M1
2.	Left side panel	M2
3.	Right side panel	M2
4.	Rear panel	M3
5.	Top cover	M4
6.	Bottom cover	M4
7.	Clear acrylic base	M5
8.	Peaker/zero-suppression shield	M6
9.	Shield cover	M7
10.	Shield cover bracket	M7
11.	Mounting bracket for L6, L7	M7
12.	Acrylic bias-divider mounting plate	M9
13.	Acrylic front	M9
14.	Acrylic rear	M9
15.	Acrylic left side	M9
16.	Acrylic right side	M9
17.	Peaker/zero-suppression acrylic mounting bracket	M10
18.	Zero-suppression fine-capacitor acrylic mounting bracket	M11
19.	Support	M12
20.	Rectifier mounting plate	M13
21.	Zener diode heat sink	M14
22.	Peaker/Zero-suppression shield rear insulator	M15
23.	Acrylic cover insulator	M16
24.	PIN diode heat sink	M7

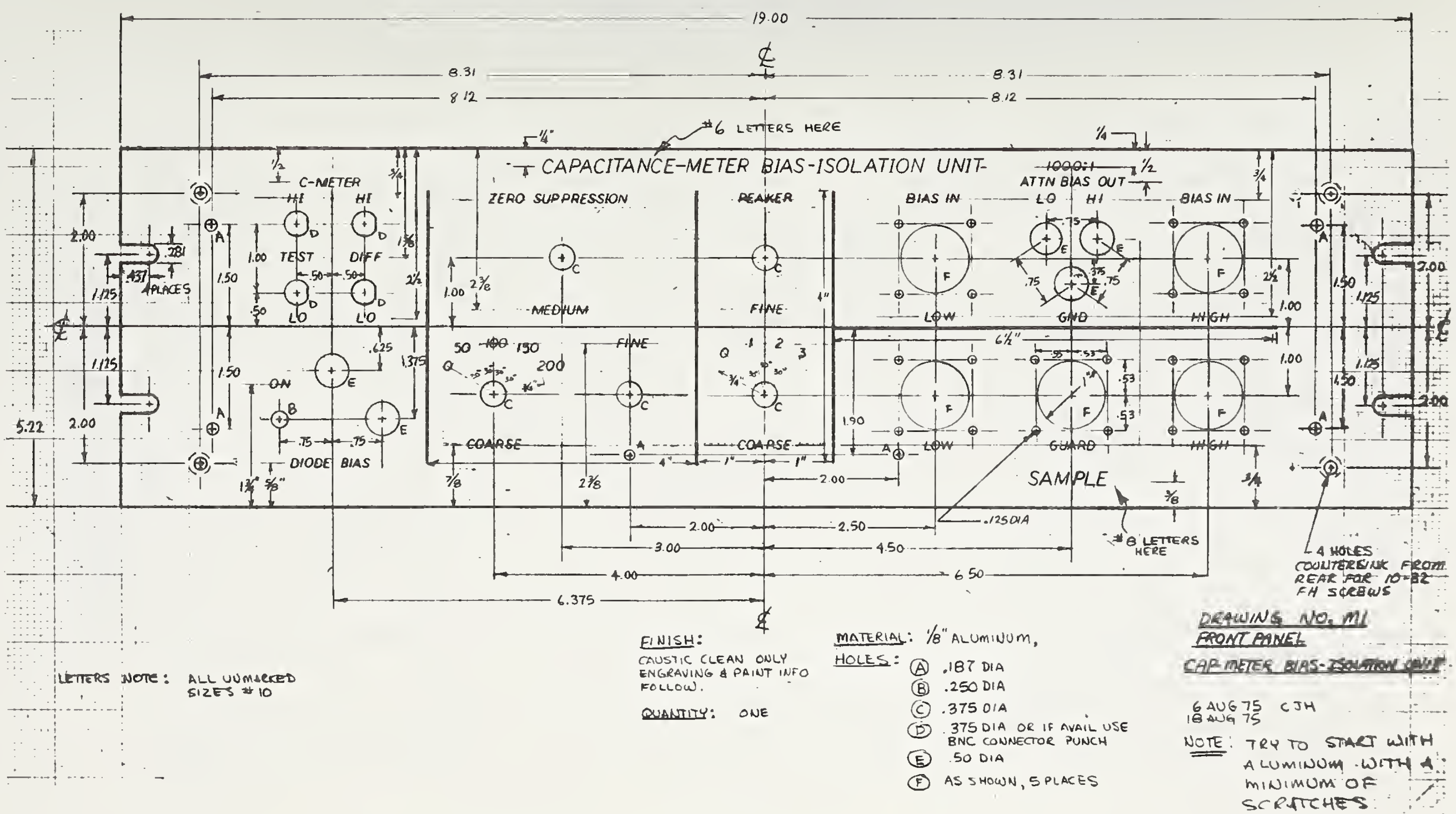

Figure M1 Front panel Capacitance-Meter Bias-Isolation Unit.

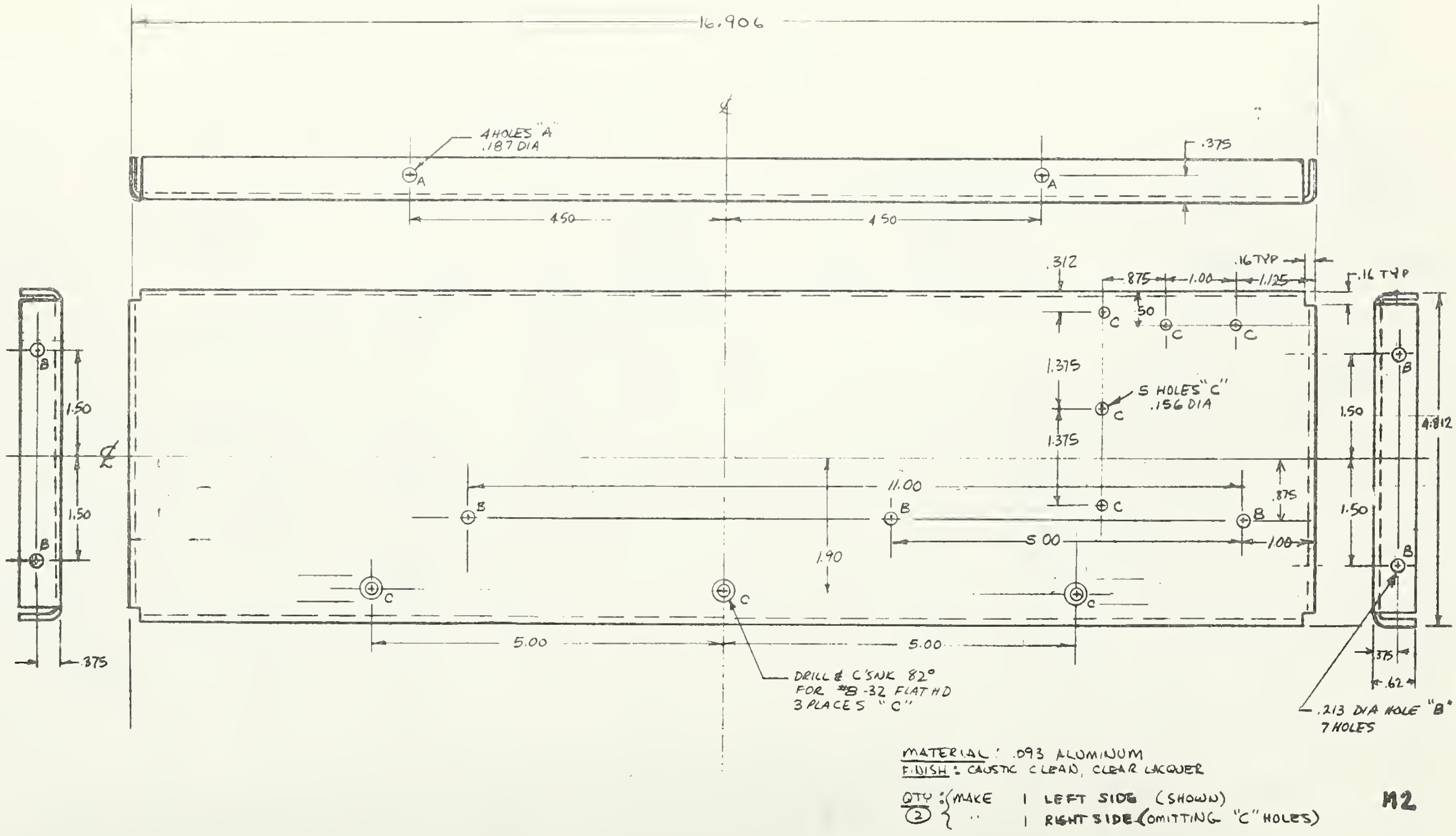

Figure M2 Side panels.

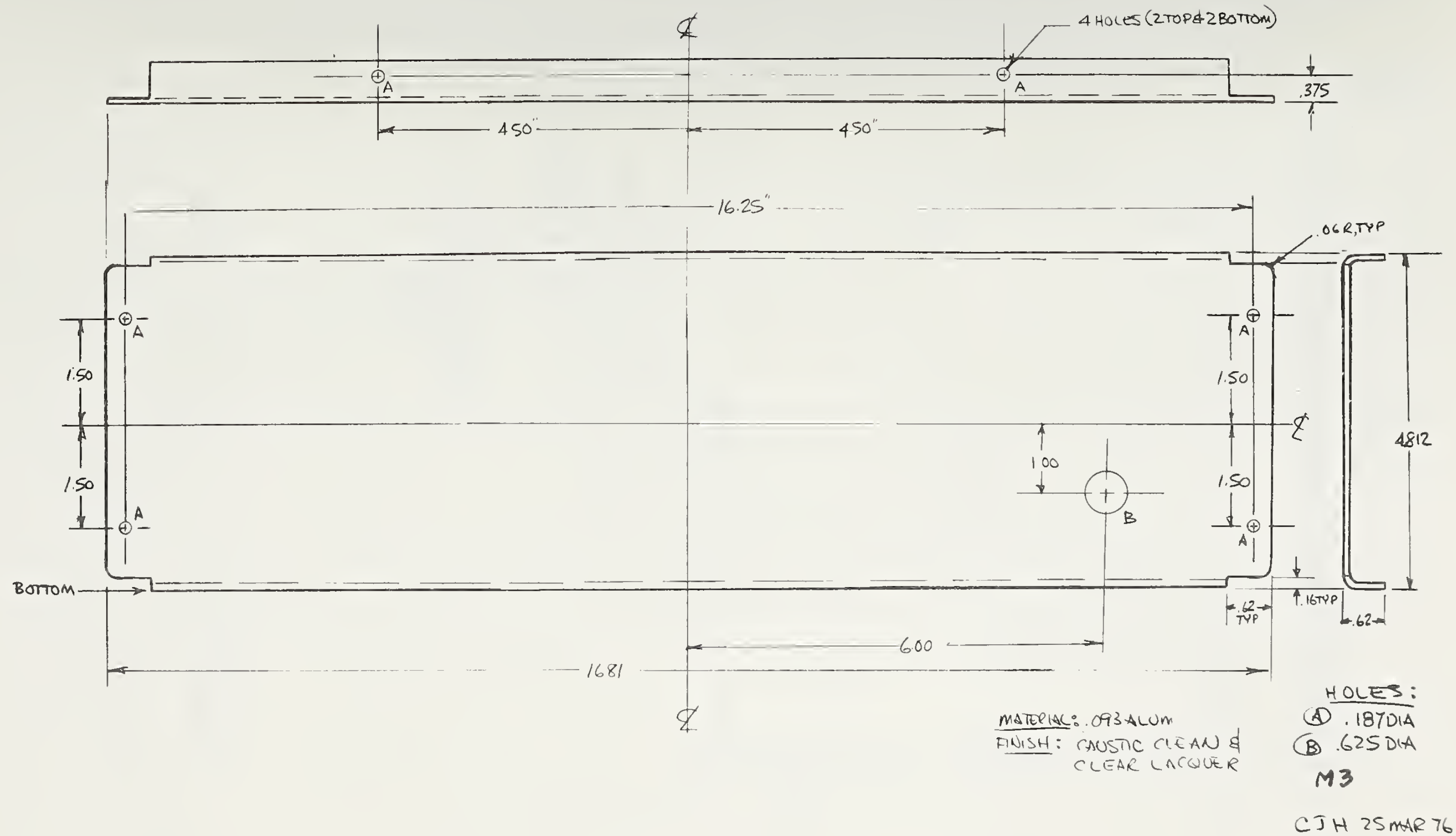

Figure M3 Rear panel.

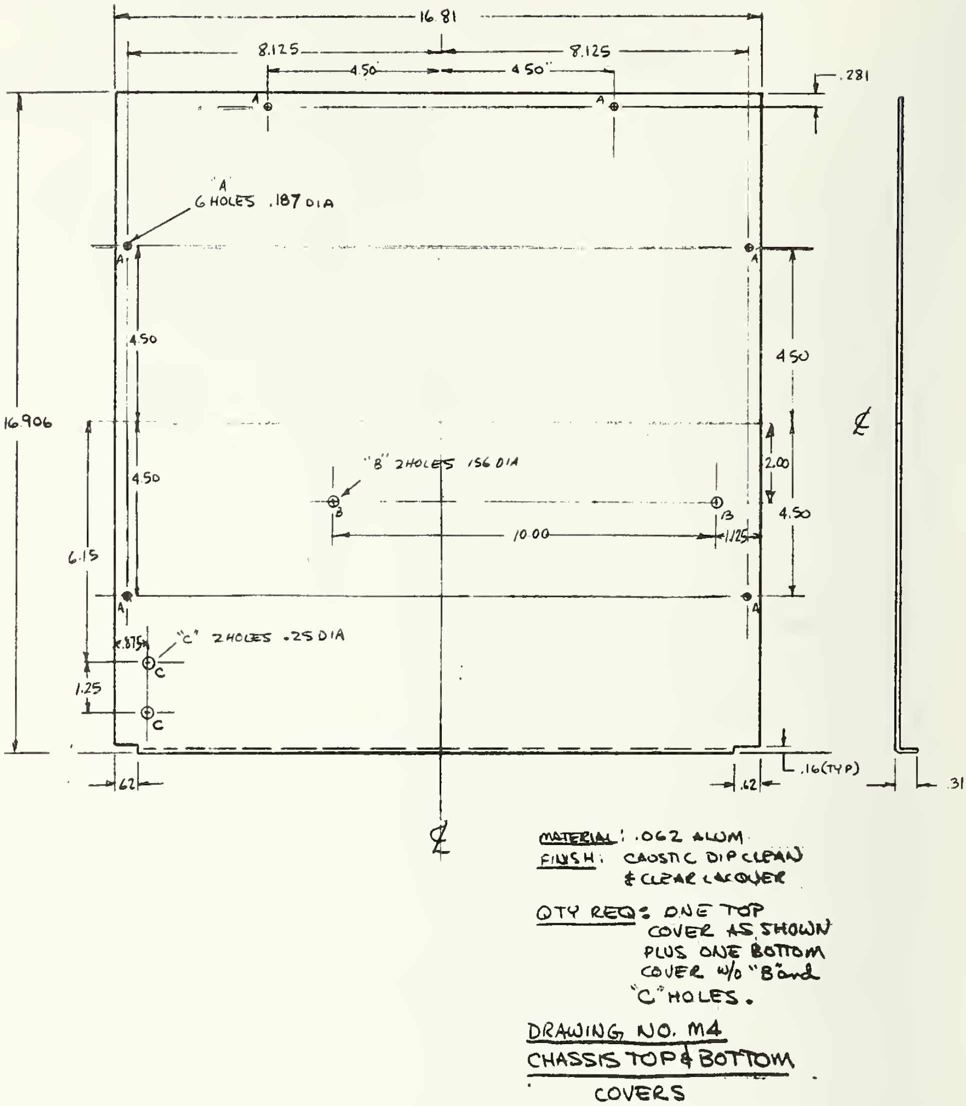

Figure M4 Chassis top and bottom covers.

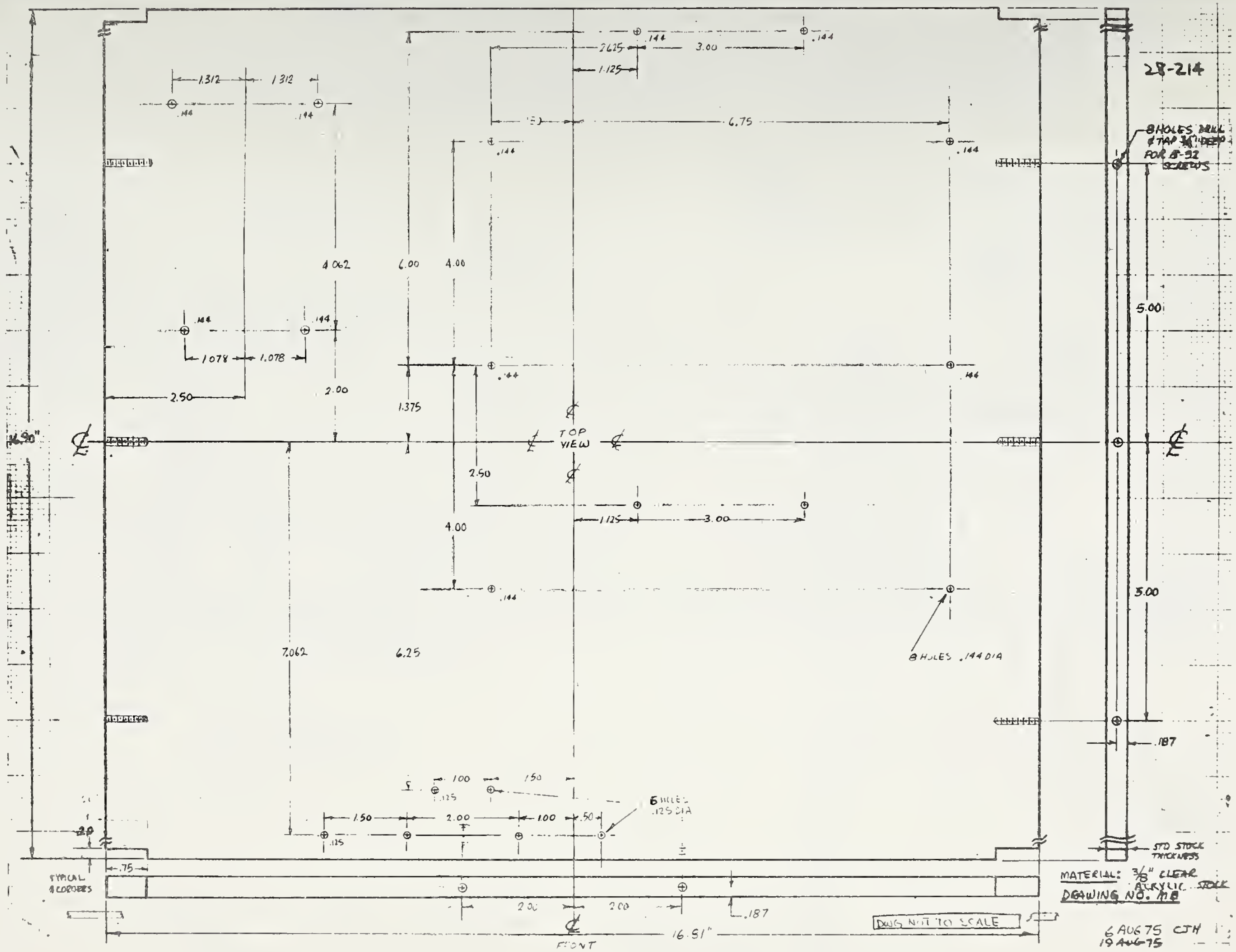

Figure M5 Clear acrylic (polymerized methyl methacrylate) base.

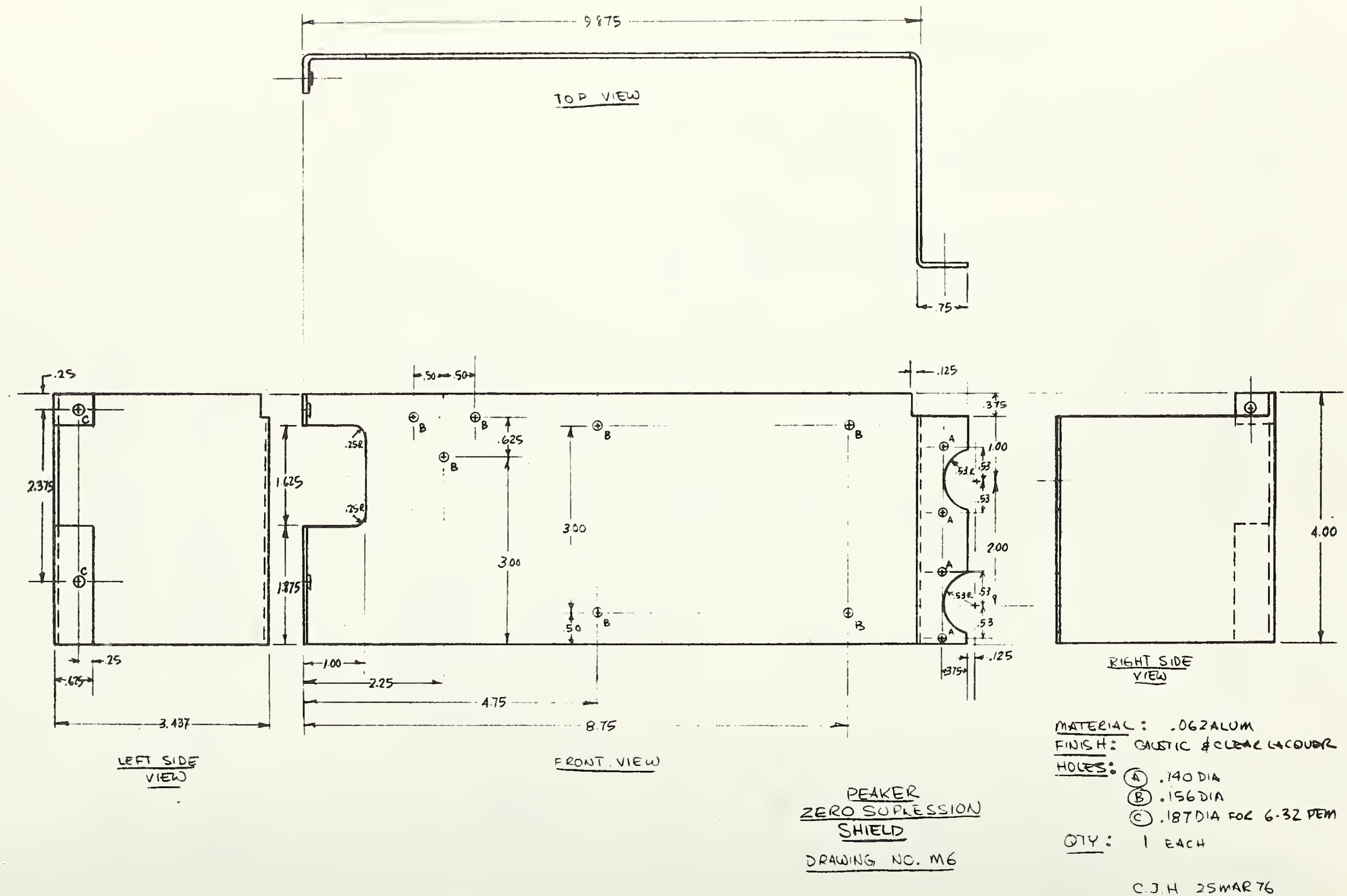

Figure M6 Peaker/zero suppression shield.

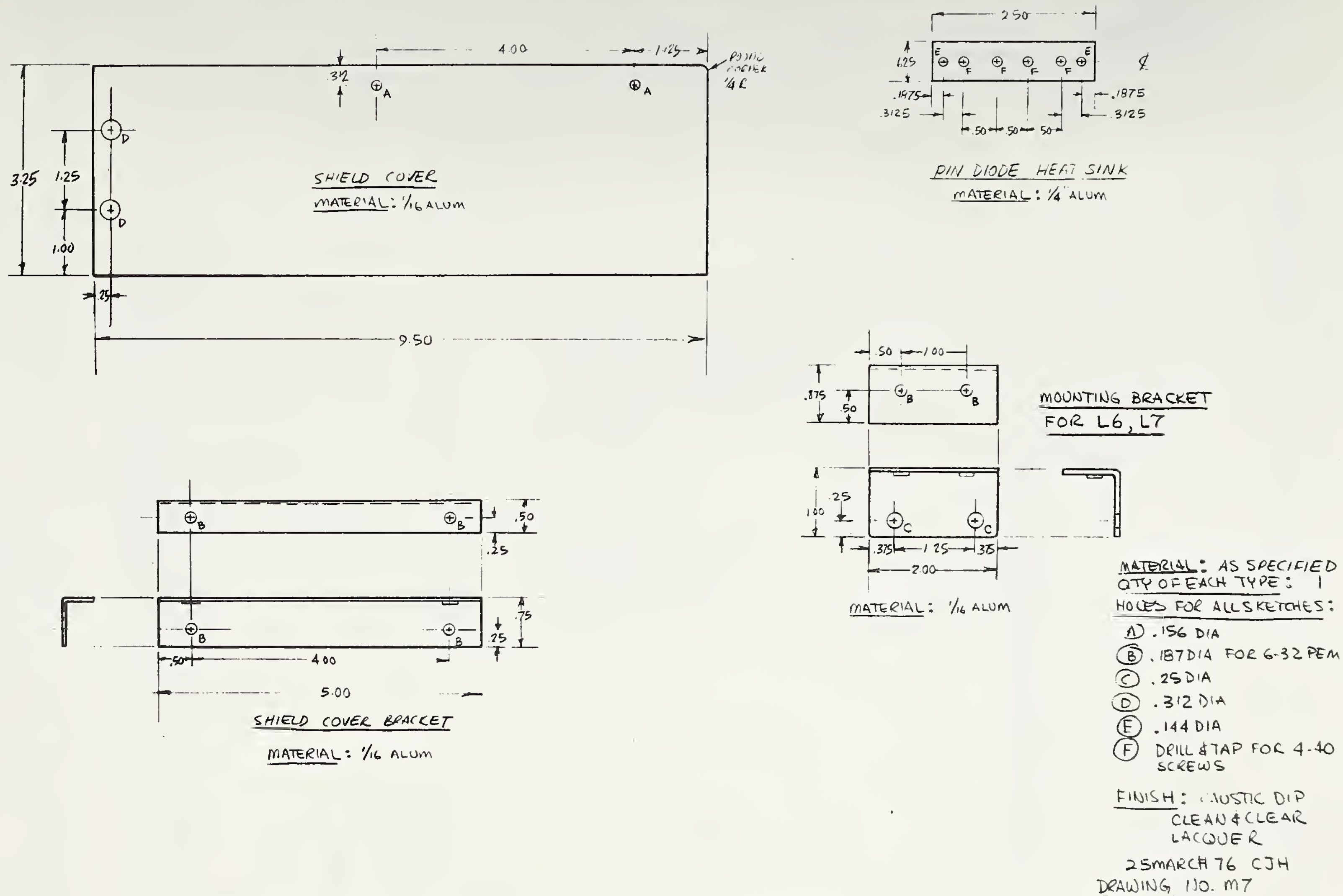

Figure M7 Drawing containing:

A. Shield cover
B. Shield cover bracket
C. Mounting bracket for L6, L7
D. PIN diode heat sink

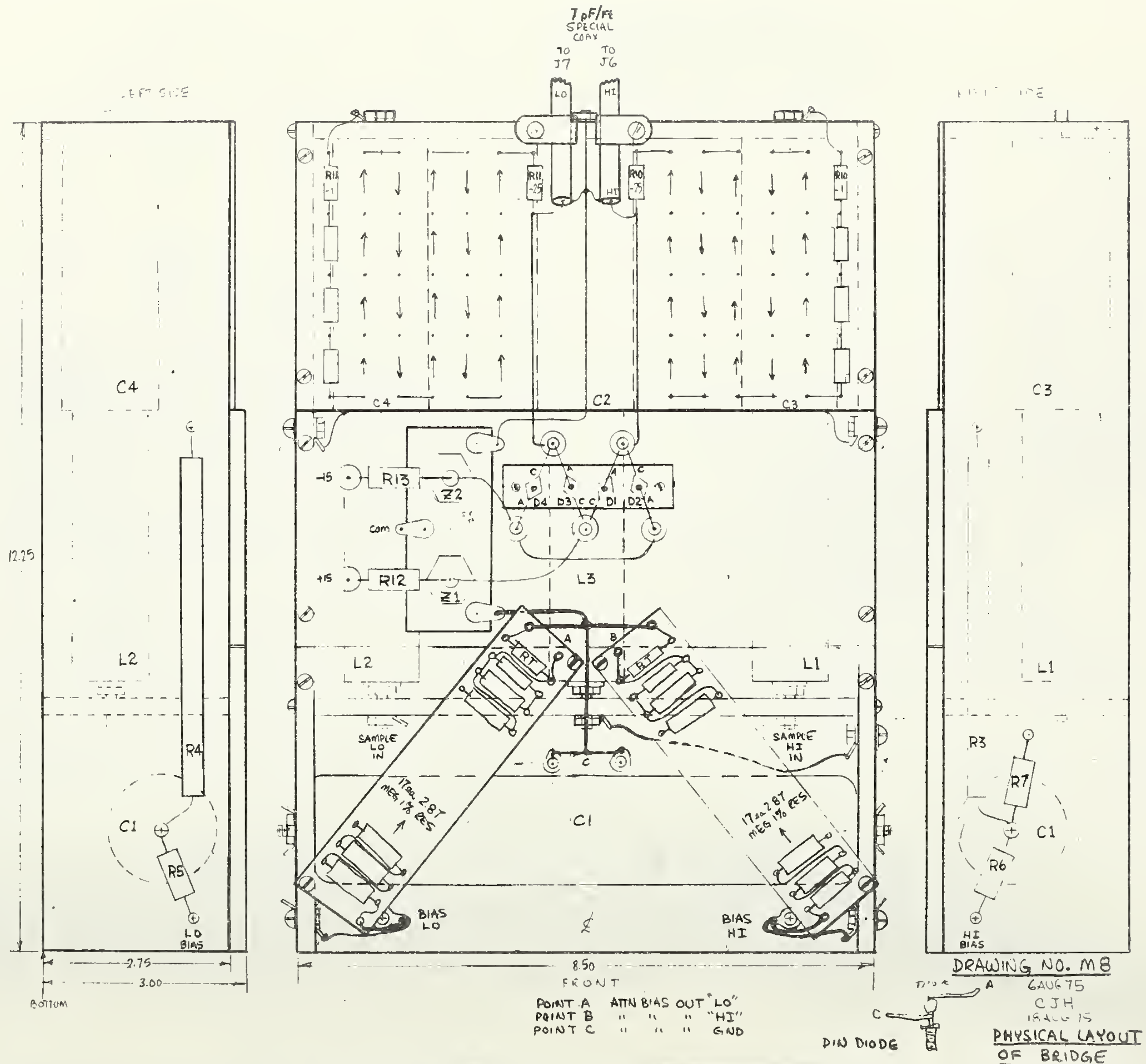

Figure M8 Physical layout of bridge.

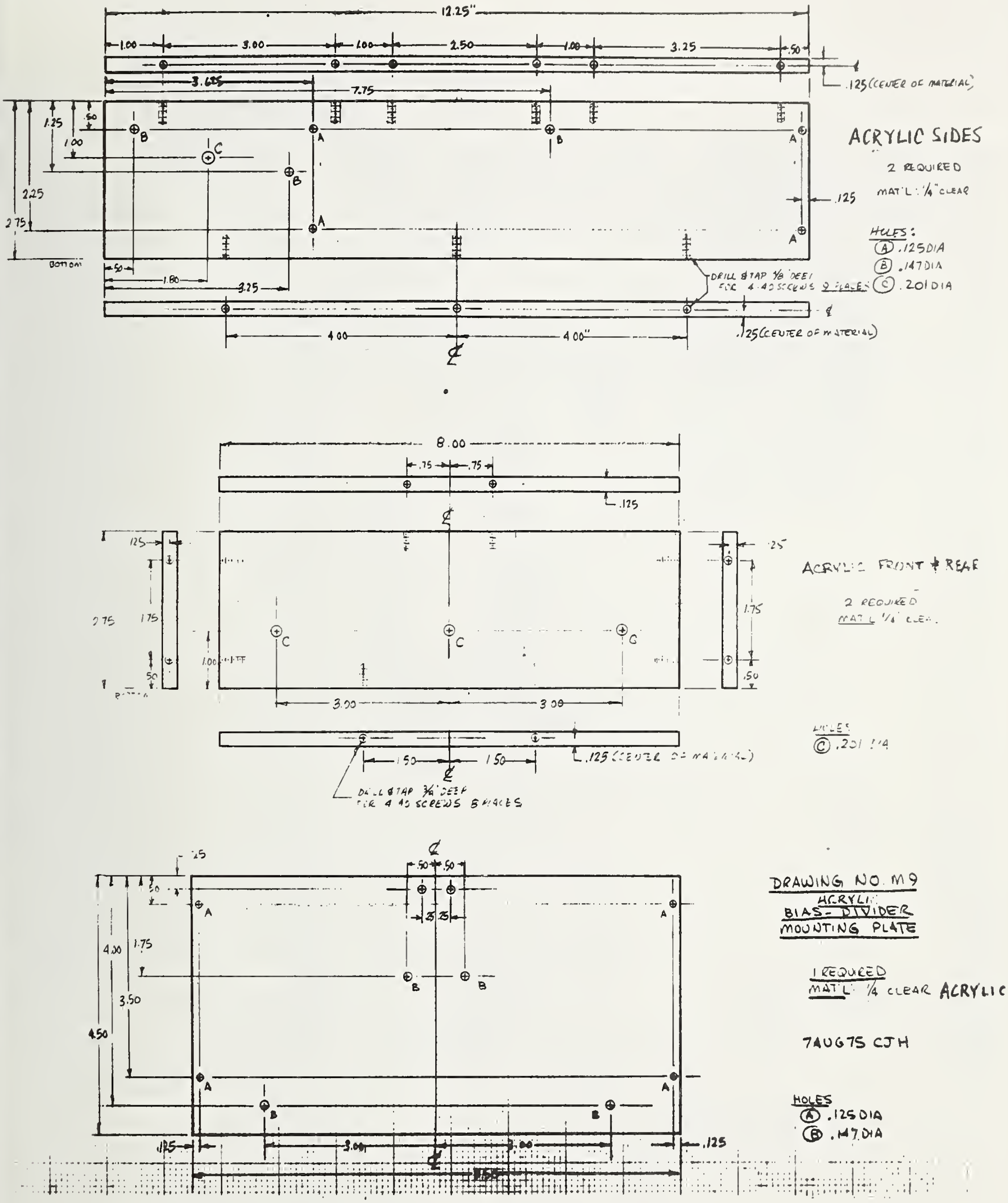

Figure M9 Drawing containing: A. Acrylic bias-divider mounting plate
B. Acrylic front and rear
C. Acrylic sides.

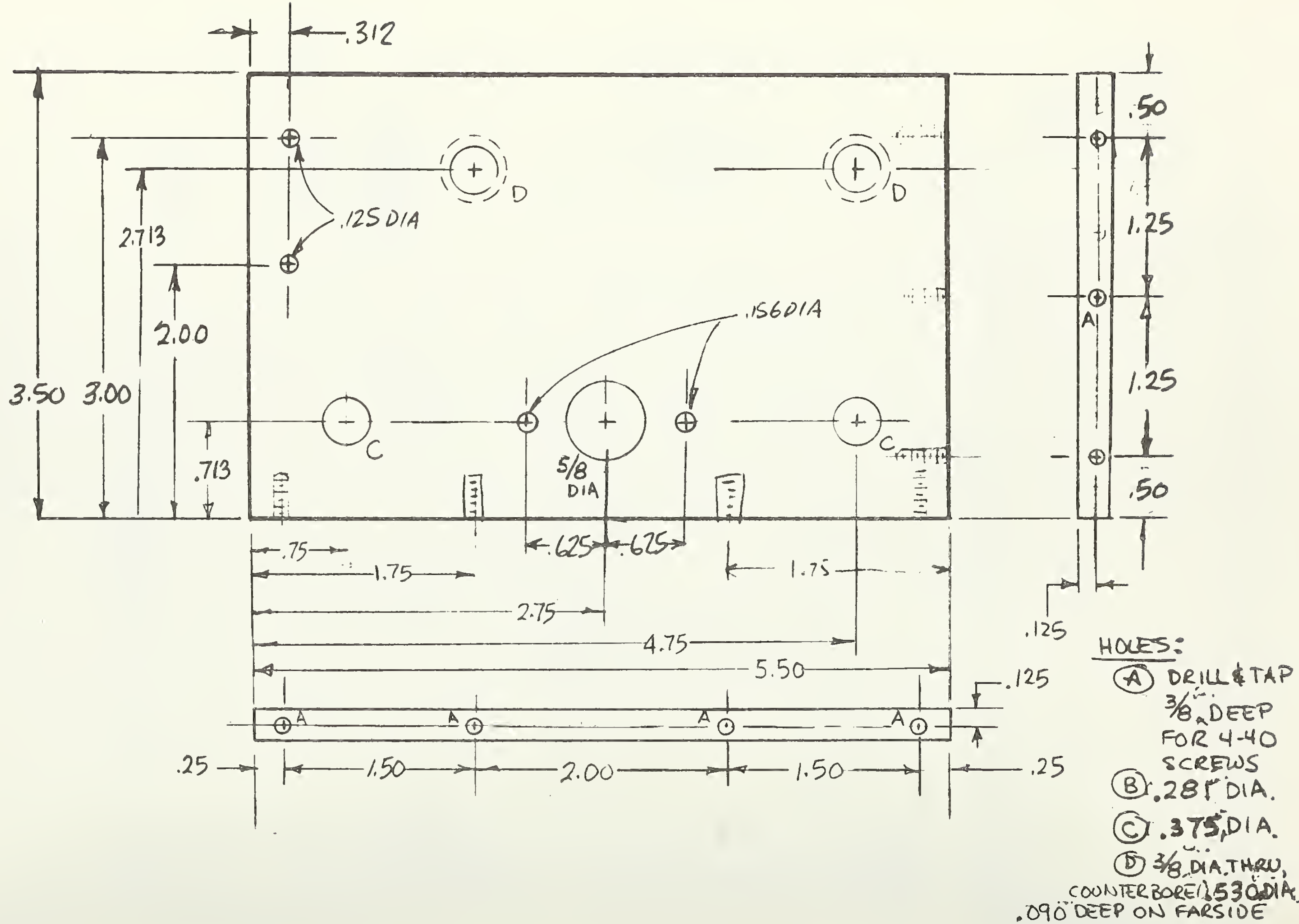

Figure M10 Peaker/zero-suppression acrylic mounting bracket.

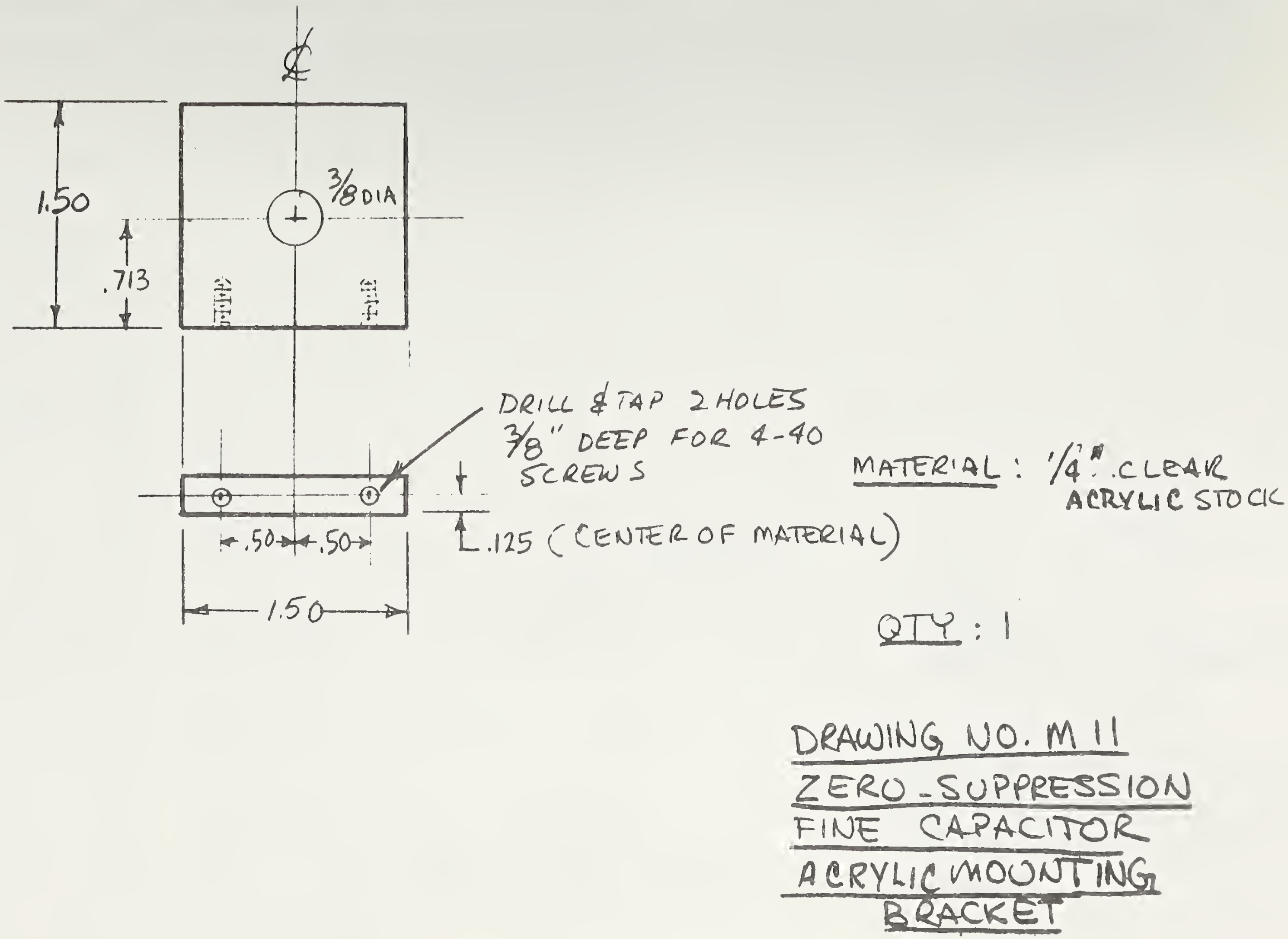

Figure M11 Zero-suppression fine capacitor acrylic mounting bracket.

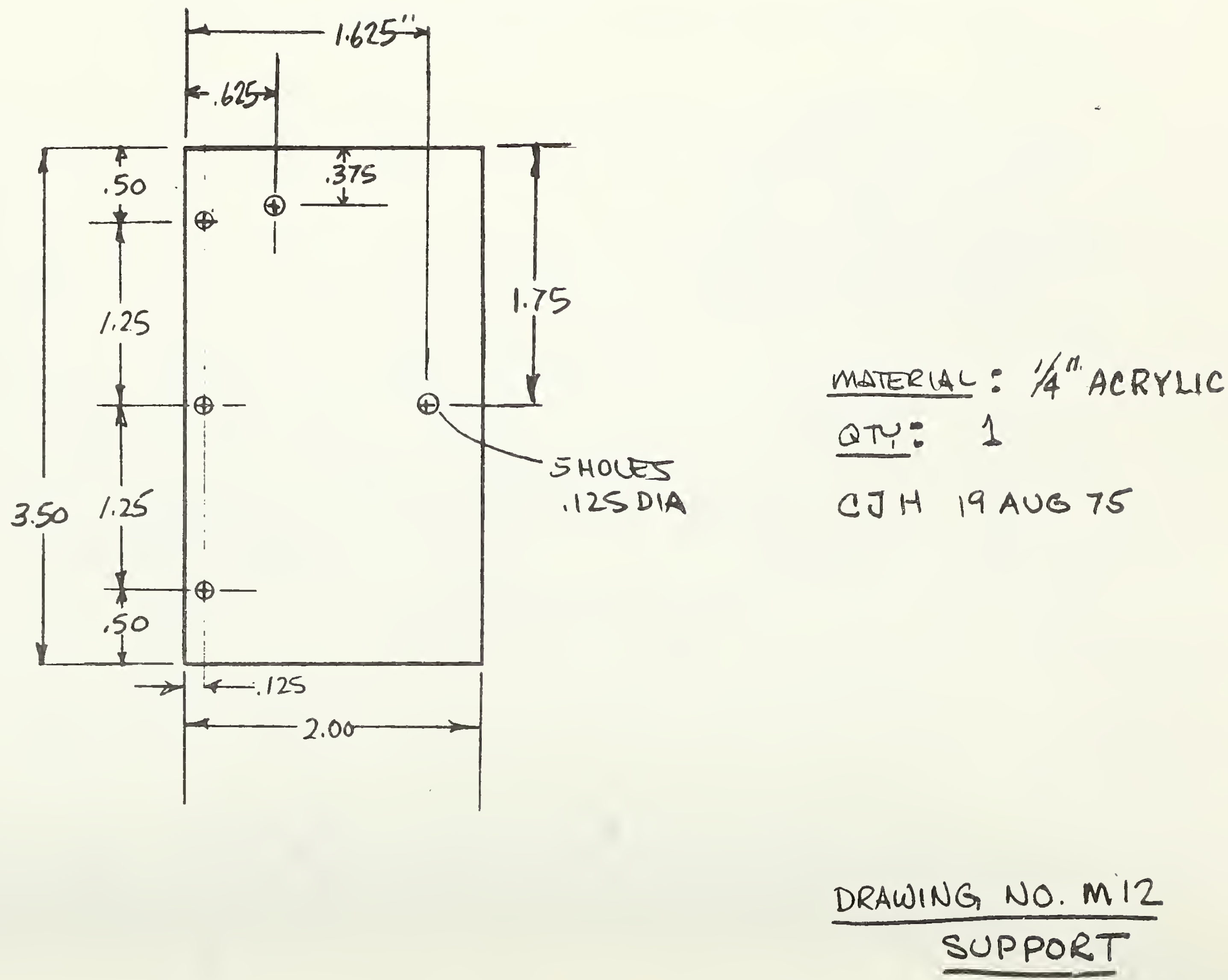

Figure M12 Support.

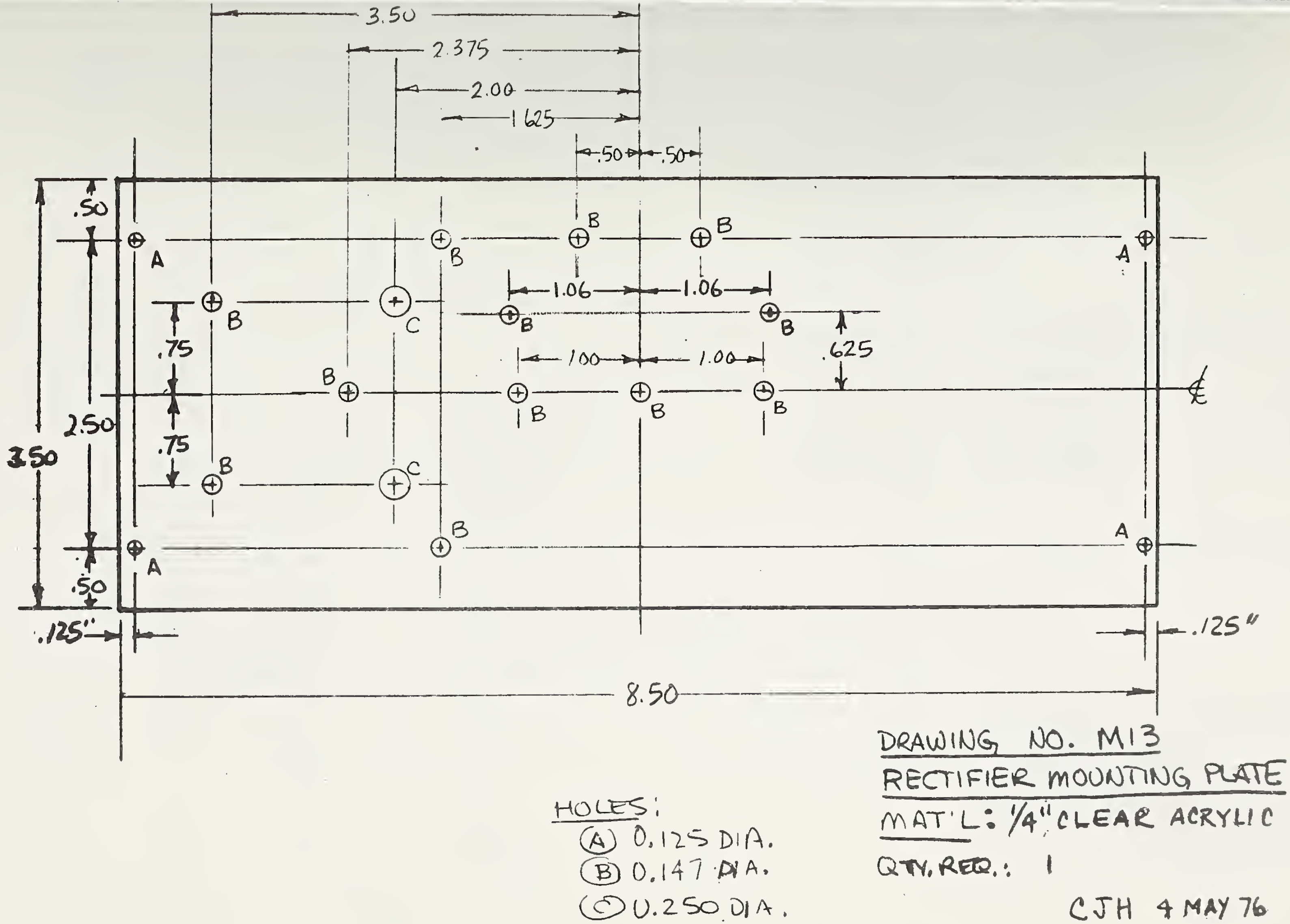

Figure M13 Rectifier mounting plate.

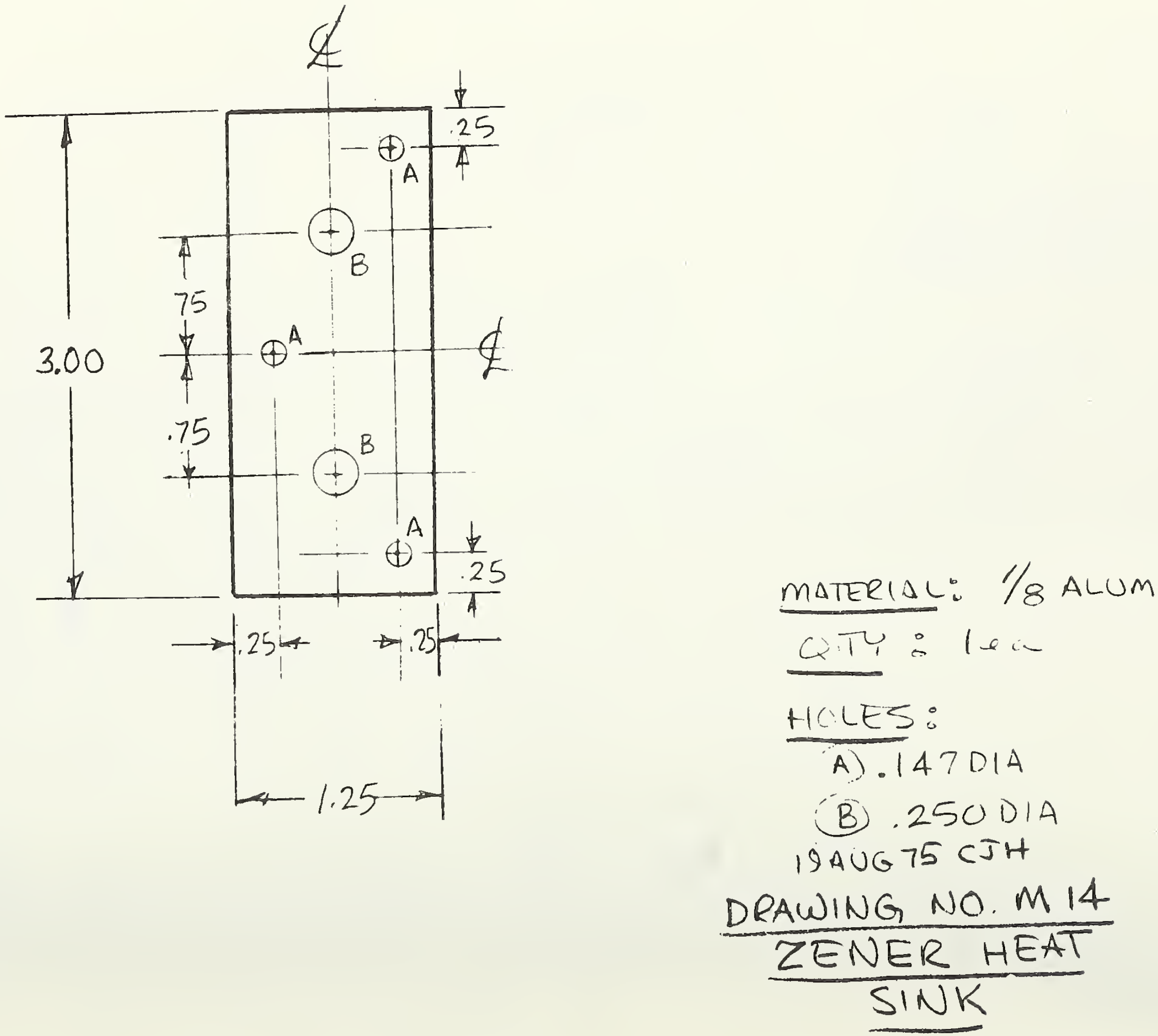

Figure M14 Zener heat sink.

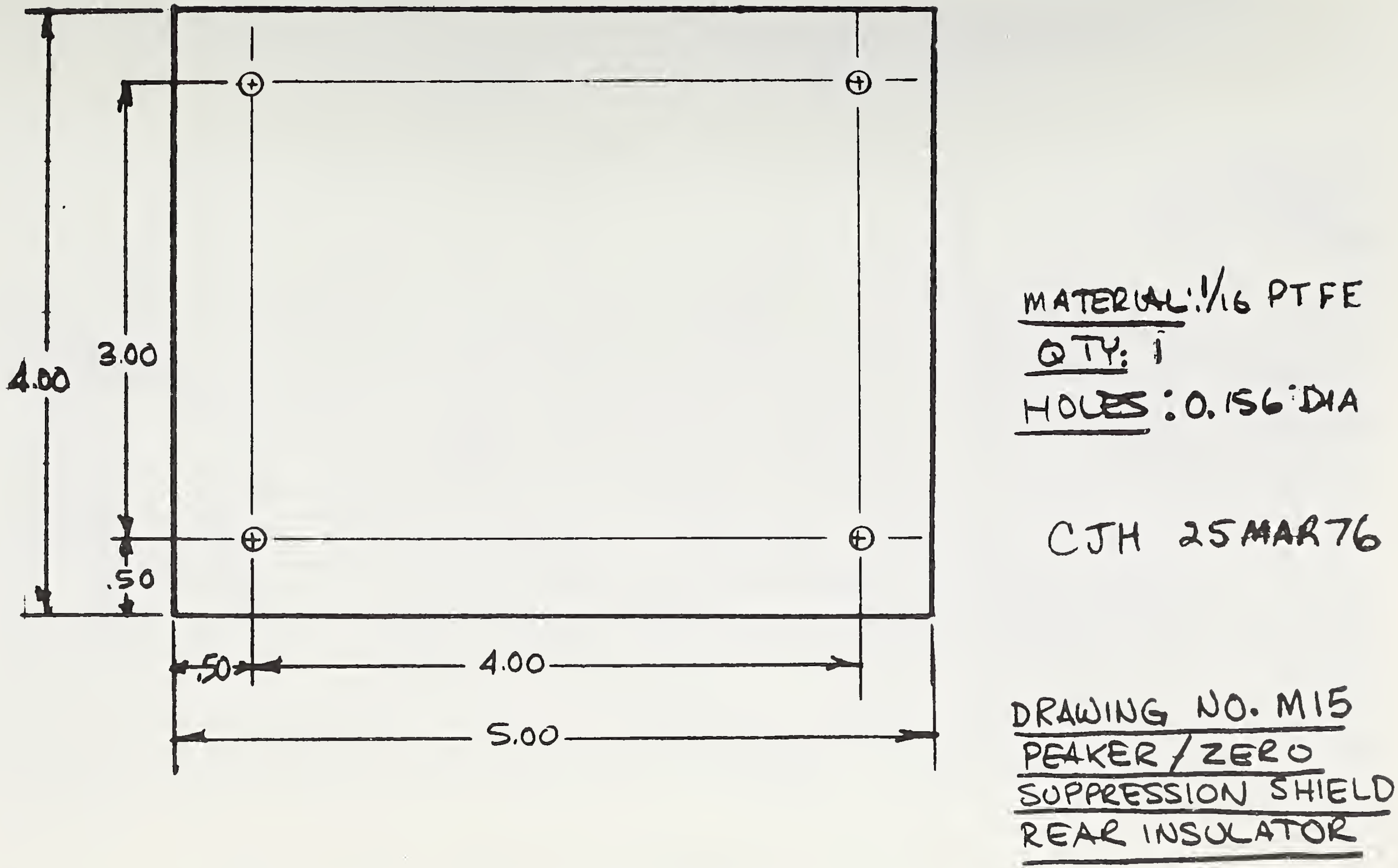

Figure M15 Peaker zero-suppression shield rear insulator.

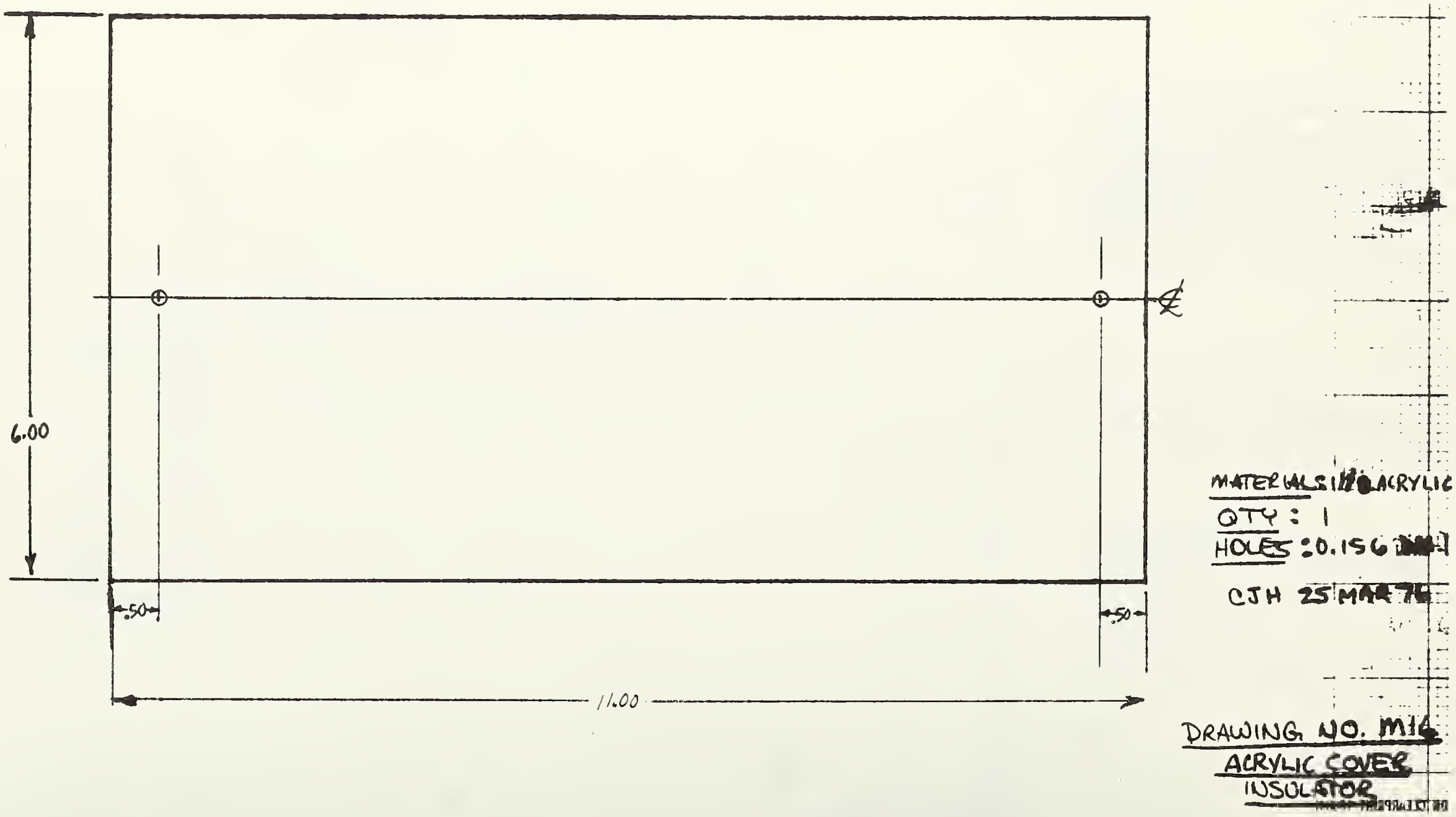

Figure M16 Acrylic cover insulator.

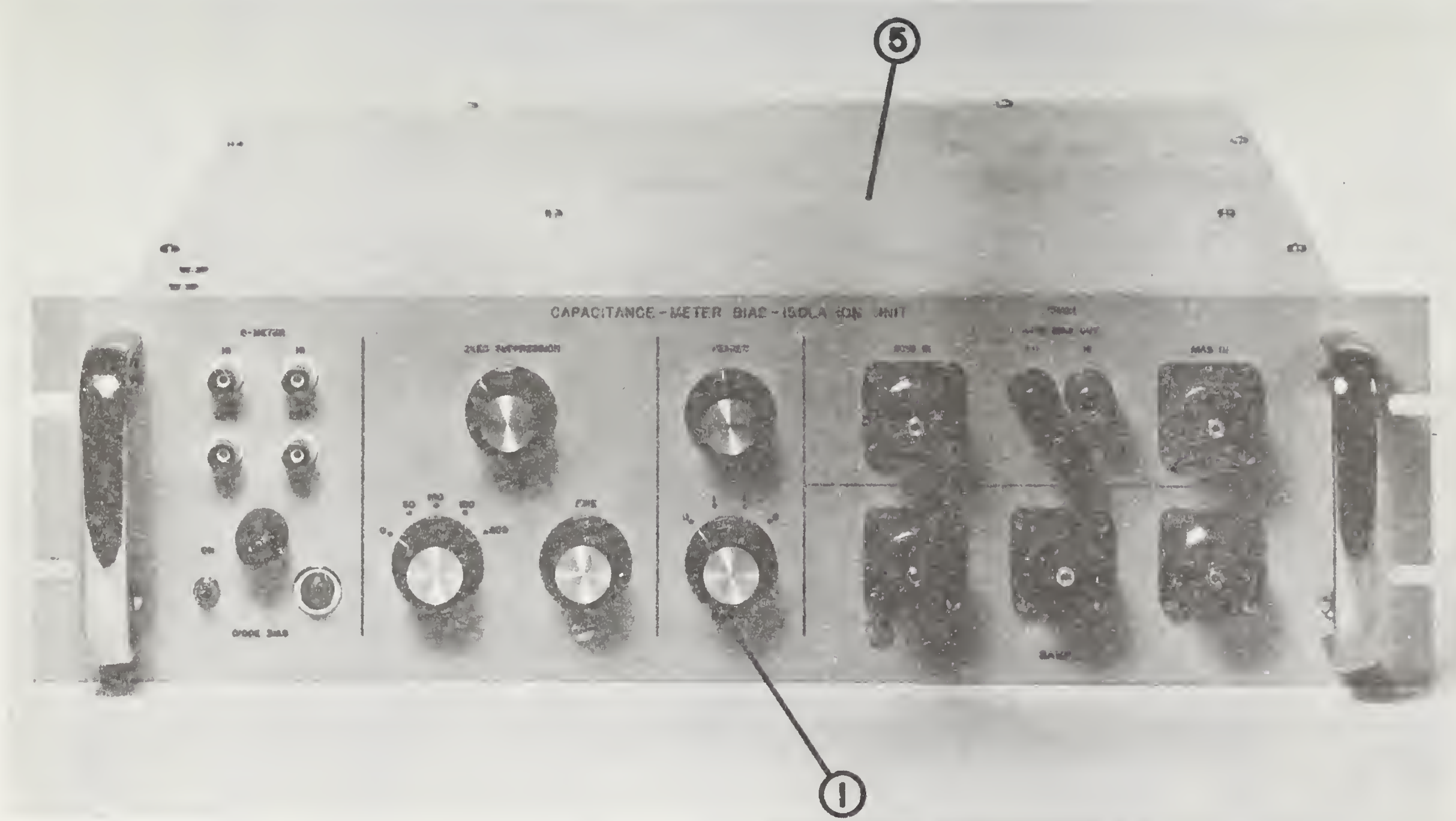

Figure A1 Front view of Capacitance-Meter Bias-Isolation Unit.

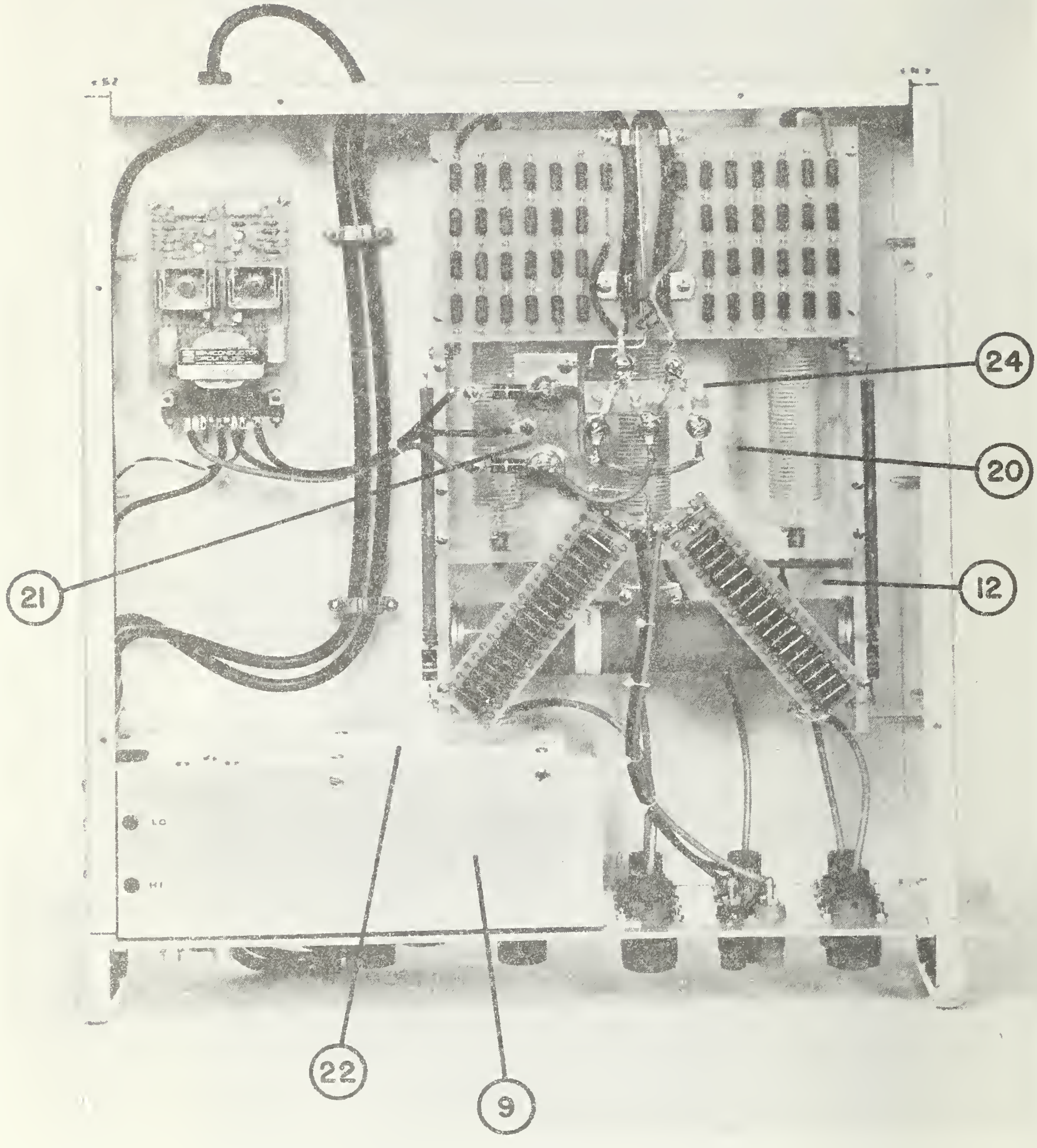

Figure A2 Top view with top cover removed.

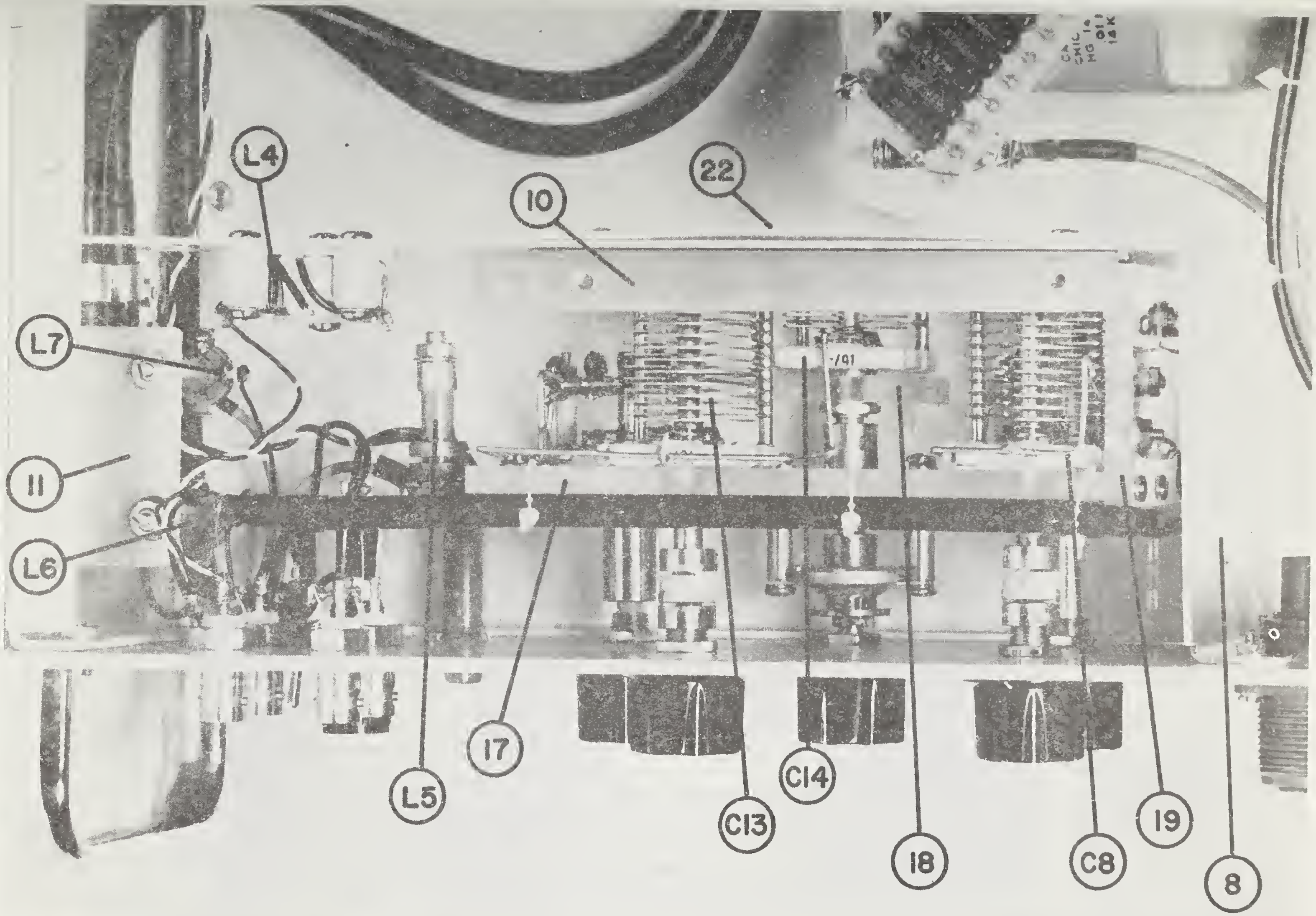

Figure A3 Top view of Peaker/Zero Suppression circuit with top cover and shield cover removed.

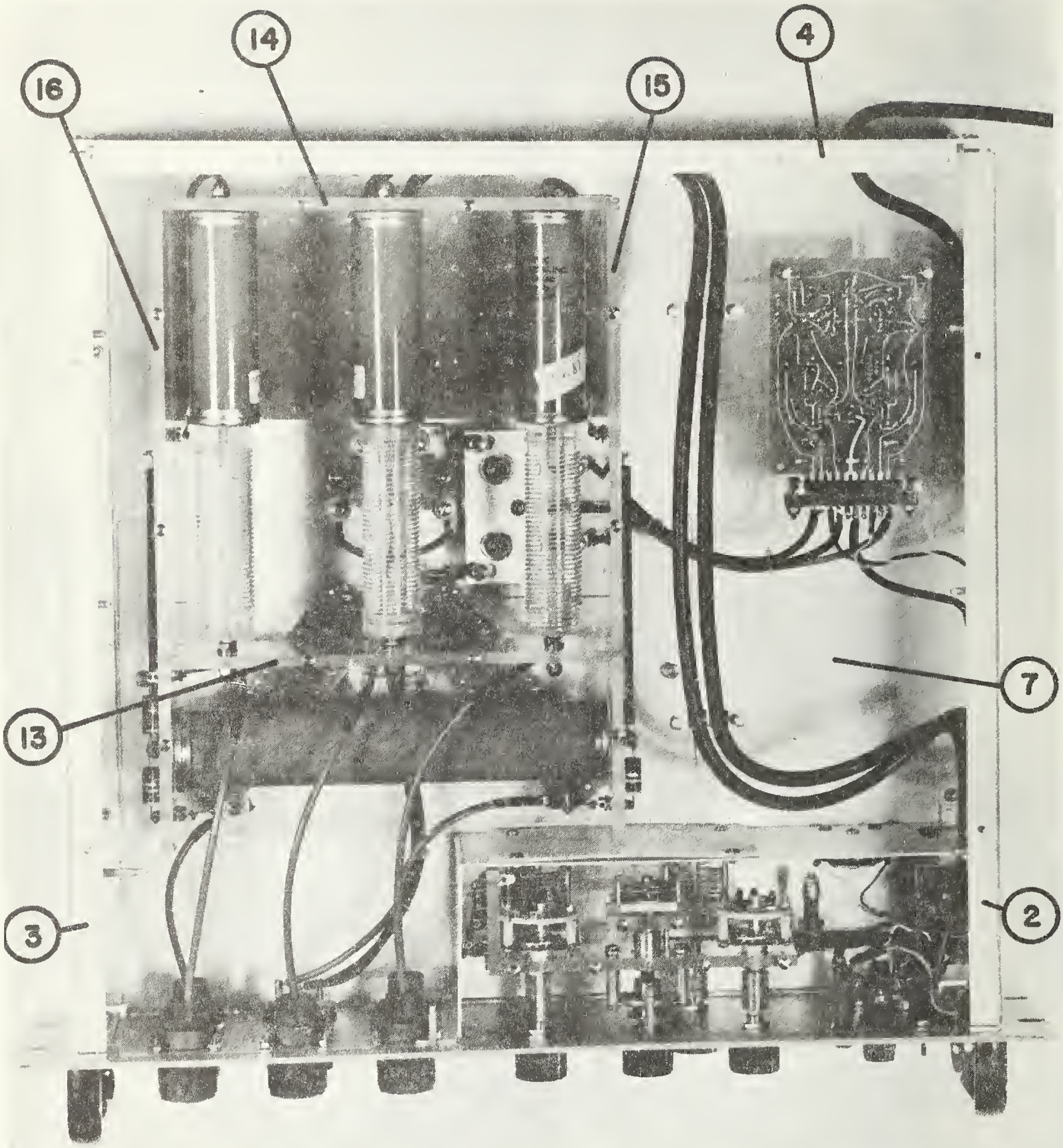

Figure A4 Bottom view with bottom cover removed.

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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.)*

The use of capacitance meters (C-meters) to determine small-signal (differential) capacitance at 1 MHz as a function of applied-bias voltage is widespread. The maximum value of the bias voltage which may be applied to a sample under test with any commercially available C-meter is 600 V or less. A larger bias-voltage capability is required for certain applications.

This report describes a technique for using a commercial C-meter with a Bias-Isolation Unit (BIU) for capacitance measurements at bias-voltage magnitudes up to 10 kV without damage to the measurement equipment. The basic principles of operation and the details of the electrical design of a BIU are discussed.

The use of the BIU imposes certain limitations on the range of sample capacitance which may be measured without introducing excessive error. The theory of these limitations is presented and compared with experimental results obtained from the use of the BIU with each of three commercially available C-meters. The measurement capability demonstrated by these results appears to be adequate for all current and future applications. For less than $\pm$ 1% error in the indicated (measured) capacitance, the measurable range of the sample capacitance is found to be from 0 to at least 400 pF. In some applications, it is important to be able to accurately measure small changes in the sample capacitance; for less than $\pm$ 1% error in the indicated (measured) value of a small change in the sample capacitance, the measurable range of the sample capacitance is found to be from 0 to at least 130 pF.

Construction details of the BIU are appended.

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)* Bias-Isolation Unit; capacitance measurements at high applied-bias voltage; capacitance-meter; extended-range capacitance measurement; high-voltage C(V) measurements; modified MIS C(V) measurements.

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