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DPEX-R30

INS 439097

ENGINEERING

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LABORATORY

OCTOBER 1952

LOGARITHMIC ELECTROMETER

E. I. DU PONT DE NEMOURS & COMPANY, INC.
ENGINEERING DEPARTMENT
WILMINGTON, DELAWARE

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This document was prepared in conjunction with work accomplished under Contract No. AT(07-2)-1 with the U.S. Department of Energy.

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Serial No. DPEX-R30

Contract No.
Account No. 8980-ED-10-768

E. I. DU PONT DE NEMOURS & COMPANY

ENGINEERING DEPARTMENT

Development Engineering Division

Engineering Research Laboratory

WILMINGTON, DELAWARE

October 1952

LOGARITHMIC ELECTROMETER

By

J. M. Morris

ABSTRACT

This report describes the development and design details of an instrument that measures current in the range 10^{-6} to 10^{-13} a. and indicates or records this current on a single logarithmic scale.

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Serial No. DPEX-R30

LOGARITHMIC ELECTROMETER

ENGINEERING DEPARTMENT

DEVELOPMENT ENGINEERING DIVISION

ENGINEERING RESEARCH LABORATORY

I. SUMMARY

A. PROBLEM UNDER INVESTIGATION

It is frequently desirable to measure a wide range of low current values without range switching. Since no instrument with such characteristics is commercially available, this study was made to determine whether or not the Beckman Model "V" Micromicroammeter could be modified to provide a logarithmic response.

B. RESULTS

1. Simple modifications permit the Beckman Model V Micromicroammeter of the type that is employed at the Savannah River Plant, to be made logarithmic over as many as six decades in the current range of 10^{-13} to 10^{-6} a. Instabilities and drifts in the modified instrument are less than one per cent of full scale meter movement.

2. Beckman Instruments, Inc. has agreed to supply the modified instrument at a cost of $975. The standard linear Micromicroammeter costs $550.

3. A period meter that operates in conjunction with the logarithmic instrument was developed and will be described in another report.

C. RECOMMENDATIONS

The feasibility of operating this instrument over six decades of input current has been demonstrated. As many as seven decades can be accommodated if a slight non-linearity in the lowest decade is tolerable. This non-linearity is insignificant in most applications. Fewer decades with increased readability and precision can also be obtained.

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Since range changing is not necessary when using a logarithmic instrument, and no errors due to applying the incorrect range to the meter reading can occur, a logarithmic instrument provides a useful service in many applications. It is recommended that logarithmic Beckman micromicroammeters be used as follows:

1. A 6-decade instrument in reactor areas where wide range is required and period (easily obtained from a logarithmic instrument) is a useful measurement.

2. A 2 or 3-decade instrument in 200 Area operations where measurements over this range are common and frequent range changing may present serious problems.

Prepared by:

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Submitted by:

H. C. Vernon

H.C.Vernon, Asst. Dir. AE,ERL

[redacted]

II. DISCUSSION

REASONS FOR INVESTIGATION

Since many of the Savannah River Plant operations require the measurement of ion-chamber currents over a range that is too great to be measured on a single linear scale, it is necessary either to provide a large number of ranges on the measuring instrument or to compress the scale so that an indication proportional to some function of the current can be seen over the entire operating range. For highest accuracy of measurement a range changing switch is provided on the Beckman Model V Micromicroammeter, the standard ion-chamber current measuring instrument at the Savannah Plant. The output indication or recording does not reflect the range setting of the input of the instrument so that it is possible to make errors by noting the incorrect instrument range. Furthermore, when ranges are changed, transients are produced which can be objectionable if the output of the instrument operates safety circuits.

It therefore appeared desirable to accept a sacrifice in precision by eliminating range changing and by providing a compressed scale of the logarithmic type to avoid possible errors of range setting and to eliminate the transients that are produced by range changing. Furthermore, the output from a logarithmic meter can be differentiated electronically to obtain a period measurement which is very desirable for the control of the reactor.

Since a number of logarithmic instruments may be employed in both the reactor and separations buildings it was desirable to create a source of supply. The circuits and techniques described in this report were transmitted to the Beckman Instrument Company which is now in a position to supply these instruments.

COURSE PURSUED DURING INVESTIGATION

A. LOGARITHMIC TRANSFORMATION TECHNIQUES: It has been shown (1) that for currents less than 200 μa., the current in a thermionic diode whose anode is negative with respect to its cathode is

$$I = I_0 e^{-\frac{V\epsilon}{kT}} \qquad (1)$$

where I_0 is the saturation current (in which T is the only variable), V is the anode potential, ϵ is the charge on an electron, k is Boltzmann's constant, and T is the

[redacted]

absolute cathode temperature. Eq. (1) may also be written,

$$I = I_o(T)e^{-\frac{V\epsilon}{kT}}.$$

Taking logarithms

$$\ln I = \ln I_o - \frac{\epsilon}{kT} V \qquad (2)$$

If the voltage proportional to $\ln I_o$ is bucked out, a voltmeter which measures anode voltage can be calibrated directly in terms of the logarithm of anode current. The above equation is not valid for currents greater than about 200 μa. because the effect of space charge becomes appreciable. At currents in the order of 3×10^{-14} a. internal leakage of the diode sets a practical lower limit to the logarithmic relationship.

In logarithmic circuits the 9004 acorn-type diode has been used successfully[2] in the past because of its low internal leakage. This is important because leakage contributes an error in measured voltage which is proportional to anode current. Figure 1 shows the current-voltage relationship in a 9004 at different filament potentials. The graph indicates that with varying cathode temperatures (filament voltages) the slope of the line varies only slightly, whereas the intercept varies appreciably. This indicates the importance of maintaining a well-regulated filament supply. From the graph it also can be seen that the impedance of the diode varies from 10^6 to 10^{13} ohms throughout the operating range. This impedance variation is insignificant when the current source is a phototube or an ionization chamber, both of which have high internal impedances. However, if the current source does not have an impedance at least as large as that of the diode, considerable error will result since part of the total current flow will be determined by the diode impedance. For a discussion of the effect of source impedance see Exhibit A in the Appendix.

B. DEVELOPMENT OF INSTRUMENT

1. Reasons for Selecting Model V Beckman Meter: A voltmeter which measures diode anode voltage can be calibrated directly in terms of the logarithm of anode current provided the internal leakage of the diode is low, the source impedance is high, and the impedance of the voltmeter is high. In Project 25606, "Electrometer Evaluation", undertaken by this laboratory to evaluate commercially available electrometers, the Beckman Model V Micromicroammeter, a vibrating-capacitor electrometer, was selected for use at the Savannah River plant because of its simplicity, low cost, and good performance. This instrument was therefore selected for the

[redacted]

logarithmic circuit so that field maintenance problems would not be unduly complicated by an additional type of instrument.

2. Operation of Beckman Model V Micromicroammeter: The circuit principles of the Beckman Model V Micromicroammeter[3] are shown in the block diagram of Figure 2. The current to be measured flows through the input resistor (whose value is 10^7 - 10^{13} ohms depending upon the current range) and produces a voltage drop across it. Since the feedback resistor is relatively small (500 - 10,000 ohms), the voltage developed across it by the signal current does not contribute a measurable error. The signal voltage across the input resistor is converted to a.c. by the vibrating capacitor, is then amplified and demodulated, resulting in a d.c. output current proportional to the input signal current. This current flows in such a direction that the voltage drop which it produces in the feedback resistor equals the signal voltage except for an error of about 1 mv. in 100 - 3000 mv. depending on the feedback resistor. This feedback current is indicated on the instrument meter which is calibrated in terms of input current and it also provides a signal for a 50 mv. recording potentiometer by means of a suitable voltage dropping resistor. Range on the instrument is changed by switching input resistors, and voltage sensitivity is changed by switching feedback resistors. The full scale current range of the instrument is determined by Ohm's law, $I = E/R$ where E is the voltage sensitivity of the instrument and R is the input resistor.

3. Logarithmic Modifications: The conversion of the linear multirange instrument to one having an indication proportional to the logarithm of the input current was achieved by making the following changes:

a. The input resistor was replaced with a 9004 diode mounted on a Teflon support inside the isothermal housing in the instrument.

b. The diode was biased to buck out the constant term $\ln I_o$ in Equation (2).

c. The diode filament was operated with d.c. to prevent hum pickup in the high-impedance input circuit.

d. The diode filament was operated at a reduced voltage of 3.5 volts to reduce anode photoemission.

e. A feedback resistor was selected to give a six-decade current range.

Initially the 6.3 volt winding on the built-in constant voltage transformer was used with a full-wave bridge rectifier to provide regulated d.c. at 3.5 volts for the diode filament.

[redacted]

The proper size feedback resistor for a six-decade current range was found by trial and error to be 9500 ohms. This was done by observing the meter deflection with currents of 10^{-12} and 10^{-6} amp. for different values of feedback resistor.

At this stage of the development, the instrument oscillated in portions of its measuring range. In the standard Beckman instrument stability is achieved by inserting a phase-correcting network in the feedback loop to critically damp the high-gain loop to prevent oscillation. Different phase-correcting networks are used for the various current ranges. Since there is no range change in the logarithmic instrument, one network must suffice for the entire range. Phase correction with a time constant that varies with current level was achieved by shunting the diode with a 150 μμf. polystyrene capacitor, which in conjunction with the variable resistance of the diode, provided a varying time constant of the proper amount to prevent oscillation. To increase the damping further so as to provide a wider margin of stability, a 1500-ohm resistor (R_D in Figure 3) was inserted in the demodulator circuit to increase its time constant. This change increased the full-scale response time of the instrument from one second to about three seconds. Since six decades of current are covered, however, the response of the logarithmic instrument is still faster than that of the standard instrument.

The circuit should be adjusted by positioning the 50-ohm rheostat until 3.5 volts is applied to the diode filament. The 1000-ohm potentiometer is then adjusted until small (about 10°) changes in the 50-ohm rheostat setting cause no change in meter or recorder indication. Since appreciable time is required for the diode filament to reach a new temperature when its voltage is changed, it is necessary to delay the compensation correspondingly. The time constant of the 3000 μf. capacitor in conjunction with the source impedance of the compensating network is approximately that of the thermal inertia of the cathode so that compensation is supplied at the same rate that the zero tends to shift. The zeroing potential of 5 volts is obtained from point "C" on the regulated series filament string.

C. DYNAMIC CHARACTERISTICS OF INSTRUMENT: The response of the instrument to sudden step-changes in the input current is shown in Table I. It can be seen that, for positive changes, the instrument responds rapidly. However, for negative step-changes of 10^4 the response is slow. This is because the cable and input capacities charge negatively from the feedback circuit and the diode cuts off so that the only discharge path is through the leakage resistance of the diode. On positive step-changes of input current this effect does not appear because the diode conducts at all times. In plant

[redacted]

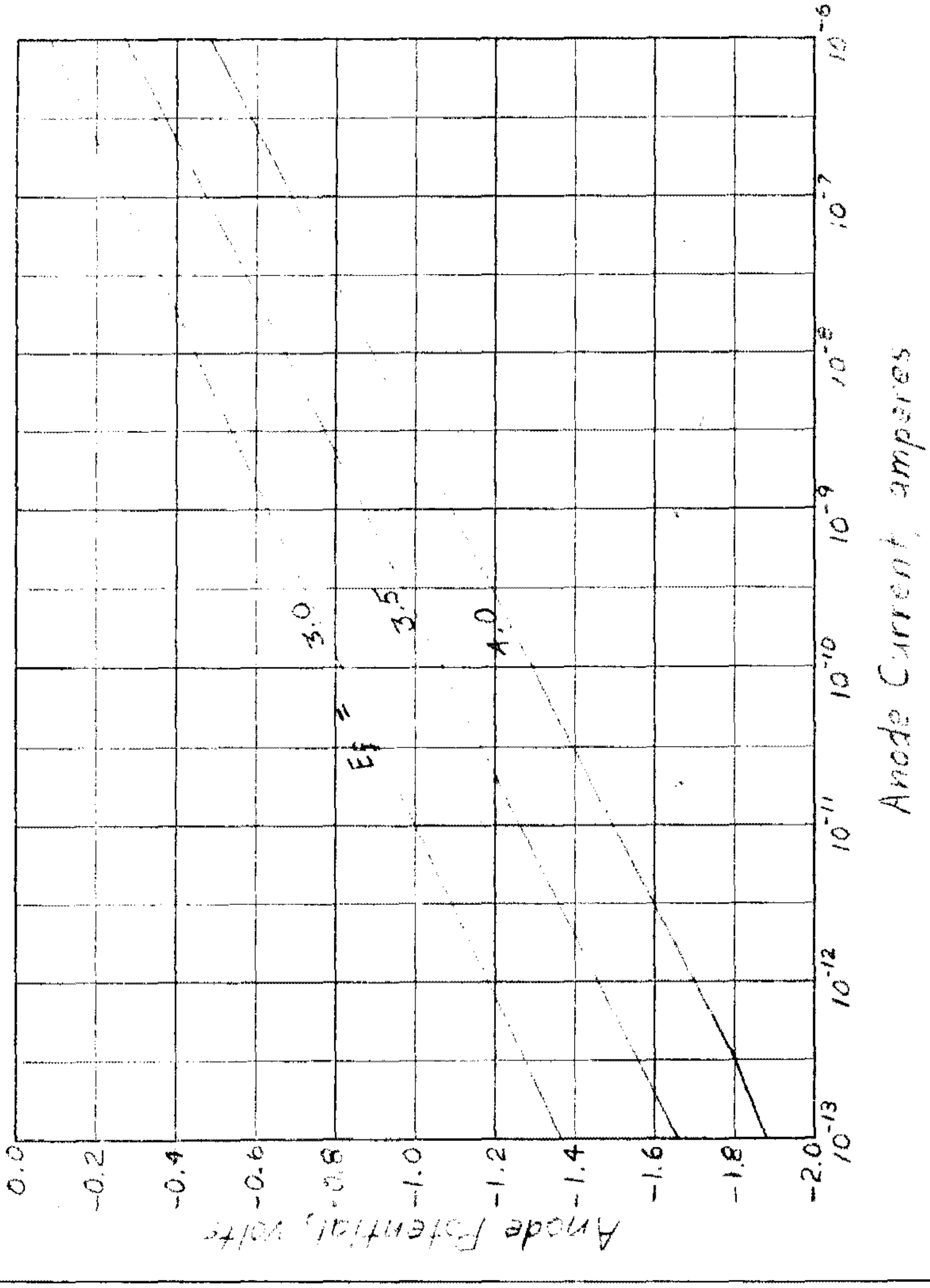
use the slow response to large negative changes will never be encountered since the current can never decrease by a factor of more than 100 over the period of one second.

D. AVAILABILITY OF INSTRUMENT: The Beckman Instrument Company will furnish these instruments according to the specifications supplied by this laboratory. As supplied, the instrument will include calibration check points which introduce standard current values in the input circuit. The meter face is calibrated logarithmically and the instrument can be supplied with ranges of from one to six decades. Figure 4 is a diagram of a six-decade instrument supplied by Beckman.

E. ACCESSORY EQUIPMENT: A period meter and alarm circuit was developed in conjunction with the logarithmic micromicroammeter and will be described in another report. A logarithmic count-rate meter was also developed and will be described separately.

[redacted]

FIGURE 1



E. I. DU PONT DE NEMOURS & CO (INC.) ENGINEERING RESEARCH LABORATORY

TITLE: PLATE CURRENT 9004 DIODE

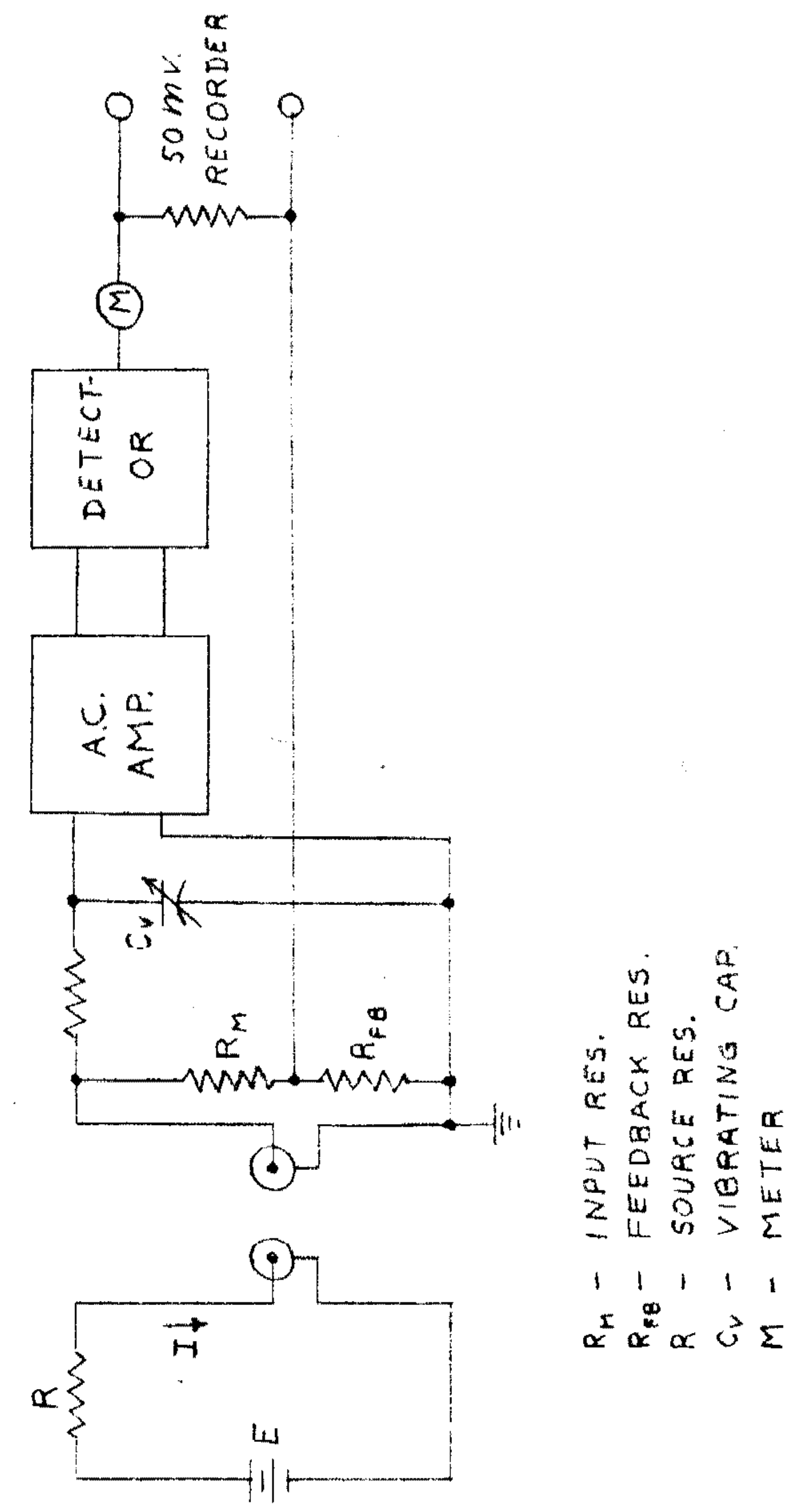
PROJ. NO. 8986-71-14-780

DRAWN BY J. M. M DATE 10-20-52 SHEET NO

THE OGILVIE PRESS, BROOKLYN 17, N. Y. BONDTEX NO. 150 [redacted] EN-3165 — NOV. 1, 1950 — 1000

[redacted]

FIGURE 2

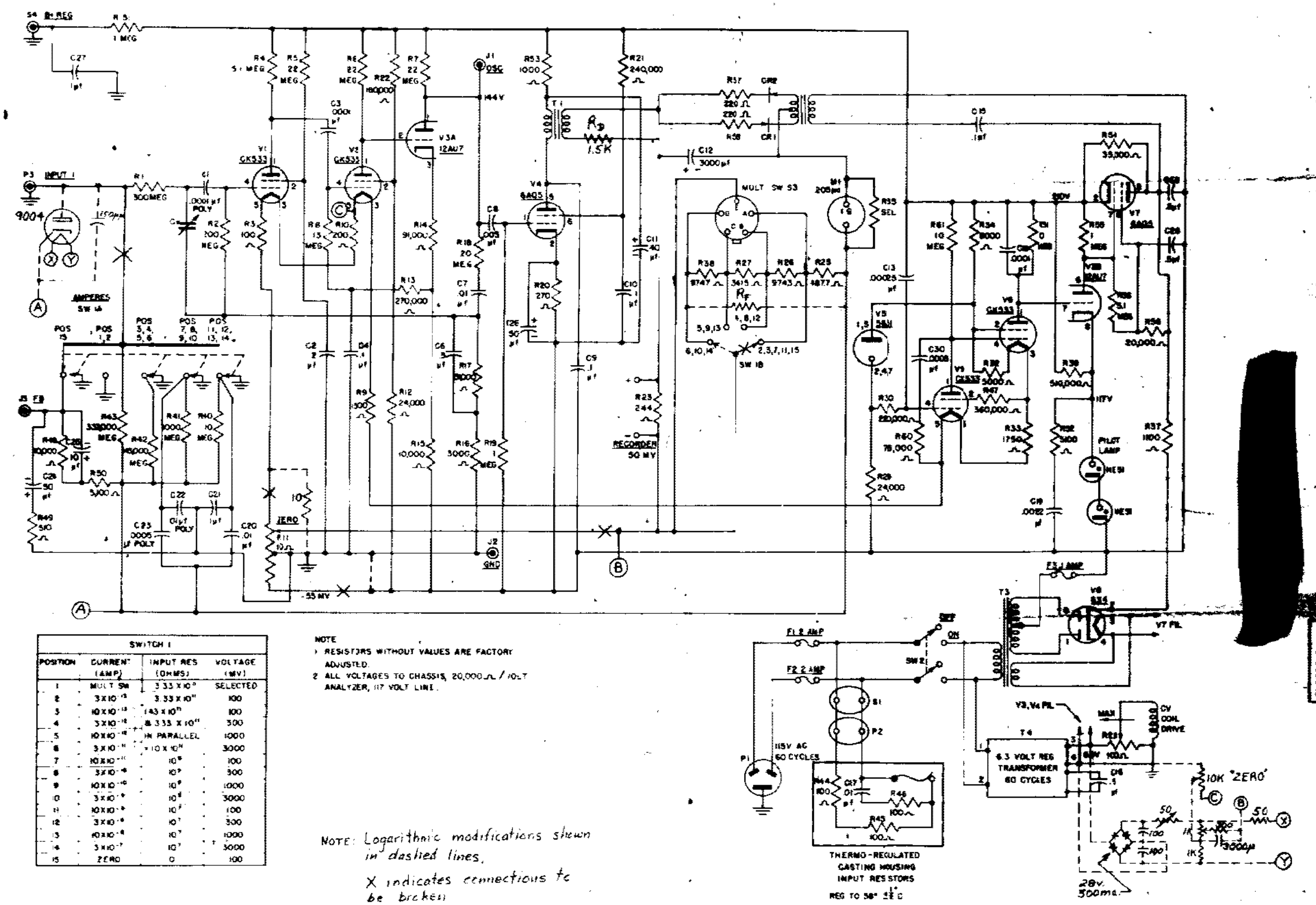


E. I. DU PONT DE NEMOURS & CO. (INC.)	ENGINEERING RESEARCH LABORATORY
TITLE: SIMPLIFIED DIAGRAM BECKMAN MODEL V	
	PROJ. NO. 8980-71-14-780
DRAWN BY J.M.M. SCALE	DATE 2-24-53 SKETCH NO.

[redacted]

FIGURE 3

[redacted]



SWITCH 1			
POSITION	CURRENT (AMP)	INPUT RES (OHMS)	VOLTAGE (MV)
1	MULT SW	3.33×10^{9}	SELECTED
2	3×10^{-13}	3.33×10^{11}	100
3	10×10^{-13}	1.43×10^{11}	100
4	3×10^{-12}	& 3.33×10^{11}	300
5	10×10^{-12}	IN PARALLEL	1000
6	3×10^{-11}	10×10^{11}	3000
7	10×10^{-11}	10^{9}	100
8	3×10^{-10}	10^{9}	300
9	10×10^{-10}	10^{9}	1000
10	3×10^{-9}	10^{9}	3000
11	10×10^{-9}	10^{7}	100
12	3×10^{-8}	10^{7}	300
13	10×10^{-8}	10^{7}	1000
14	3×10^{-7}	10^{7}	3000
15	ZERO	0	100

NOTE
1 RESISTORS WITHOUT VALUES ARE FACTORY ADJUSTED.
2 ALL VOLTAGES TO CHASSIS, 20,000 Ω / VOLT ANALYZER, 117 VOLT LINE.

NOTE: Logarithmic modifications shown in dashed lines.

X indicates connections to be broken.

(A) Points with like letters to be connected.

THIS DIAGRAM APPLIES TO SERIAL NO. 69440 THRU

LOGARITHMIC MODIFICATIONS TO STANDARD MICROMICROAMMETER

BECKMAN INSTRUMENTS, INC.

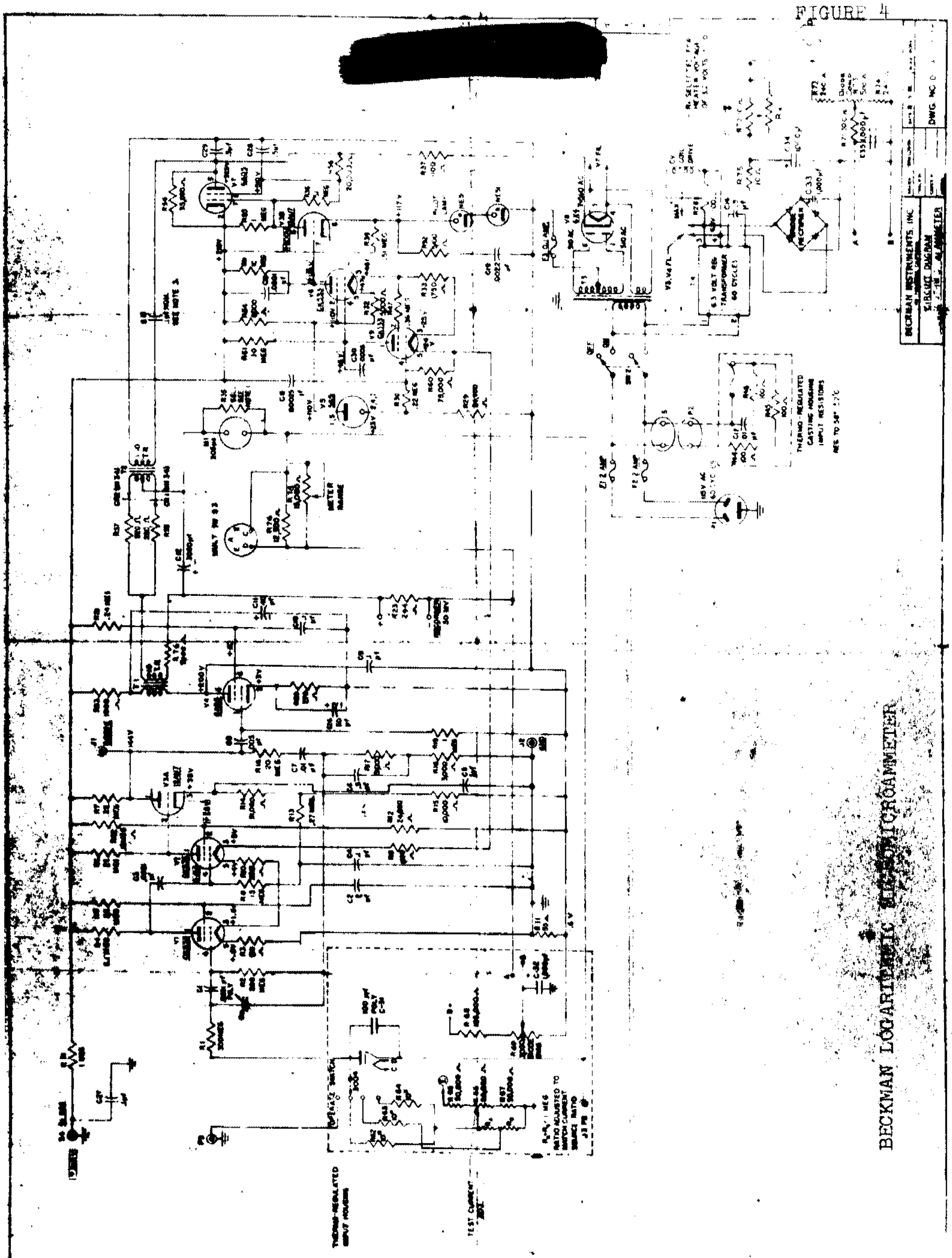
CIRCUIT DIAGRAM
VIBRATING REED µµ AMMETER

DWG. NO. 01-5600-A

[redacted]

FIGURE 4

[redacted]



BECKMAN LOGARITHMIC MICROMICROAMMETER

[redacted]

[redacted]

TABLE I

DYNAMIC RESPONSE OF LOGARITHMIC MICROMICROAMMETER

INPUT CURRENT CHANGE

	10^{-8} — 10^{-10}		10^{-10} — 10^{-12}		10^{-8} — 10^{-12}	
Capacity	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.
0 μμf.	4 sec.	3 sec.	4 sec.	15 sec.	8	43 sec.*
250 μμf.	4 sec.*	4 sec.*	5 sec.*	15 sec.	8	56 sec.*
2000 μμf.	5 sec.	15 sec.*	7 sec.*	16 sec.	8	8 min.*

* Overshoot in form of underdamping

[redacted]

Exhibit A-1

ANALYSIS OF MICROMICROAMMETER
(Refer to Figure 2)

Assume $R_{FB} \ll R_M$

$$G = \frac{E_{FB}}{E - IR}$$

$$I = \frac{E + E_{FB}}{R + R_M} \qquad (1)$$

$$E_{FB} = G\left[\left(\frac{E + E_{FB}}{R + R_M}\right)R_M - E_{FB}\right] \qquad (2)$$

$$E_{FB}(R + R_M) = GR_M(E + E_{FB}) - GE_{FB}(R + R_M)$$

$$E_{FB}\left[(R + R_M) + G(R + R_M) - GR_M\right] = GR_M E$$

$$E_{FB} = E\,\frac{GR_M}{R + R_M + GR} \qquad (3)$$

$$\frac{E}{E_{FB}} = \frac{R + R_M + GR}{GR_M} \qquad (4)$$

$$R_{input} = \frac{E_{input}}{I} = \frac{IR_M - E_{FB}}{I} = R_M - \frac{E_{FB}}{E + E_{FB}}(R + R_M)$$

$$= R_M - \frac{R + R_M}{\frac{E}{E_{FB}} + 1} \qquad (5)$$

from (4) and (5)

$$R_{input} = R_M - \frac{R + R_M}{\frac{R+R_M+GR}{GR_M} + 1} = R_M - \frac{(R+R_M)GR_M}{R+R_M+GR+GR_M}$$

$$= R_M\left(\frac{1}{1+G}\right) \qquad (6)$$

[redacted]

$$\text{but Error} = \frac{\frac{E}{R} - \frac{E}{R+R_{in}}}{\frac{E}{R}} = 1 - \frac{R}{R+R_{in}} = \frac{R_{in}}{R+R_{in}} \qquad (7)$$

from (6) and (7)

$$\text{Error} = \frac{R_M\left(\frac{1}{1+G}\right)}{R + R_M\left(\frac{1}{1+G}\right)} = \frac{R_M}{R(1+G)+R_M} = \frac{1}{\frac{R}{R_M}(1+G)+1} \qquad (8)$$

But G varies from about 2000 to about 70 depending upon the feedback resistor used. If the tolerable error is 1% and the gain is 70

$$\frac{R}{R_M} > \frac{1}{0.01(71)+1} = \frac{1}{1.71}$$

$$\text{or} \quad \frac{R}{R_M} > 0.59$$

[redacted]

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2. James, W. G., "Logarithms in Instrumentation," ORNL-413, 1950

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