measurement of radiation was appreciably greater at 2 volts. It is probable that when 60 volts were applied across the cell, most of the ions produced were being collected. Statistical fluctuations in the radiation were thus directly observable on the meter. When there were only two volts across the cell, only about half the ions were being collected and the other half were being lost by recombination. Since recombination is a function of the number of ions per unit volume of the gas, the recombination would increase as the quantity of radiation would randomly increase and would decrease as the quantity of radiation would randomly decrease.

Since the average developed voltage is a linear function of the flux density over a rather wide range, it is difficult to see how this mechanism alone could account for the remarkable integrating effect obtained at these low voltages. Perhaps there is a "rapidly" varying space-charge effect which controls the rate of collection of the ions. Whatever the mechanism, this smoothing or integrating effect is so pronounced that, with complete collection of the ions, the same degree of smoothing can be obtained only by use of a marked increase in the time constant of the measuring circuit.

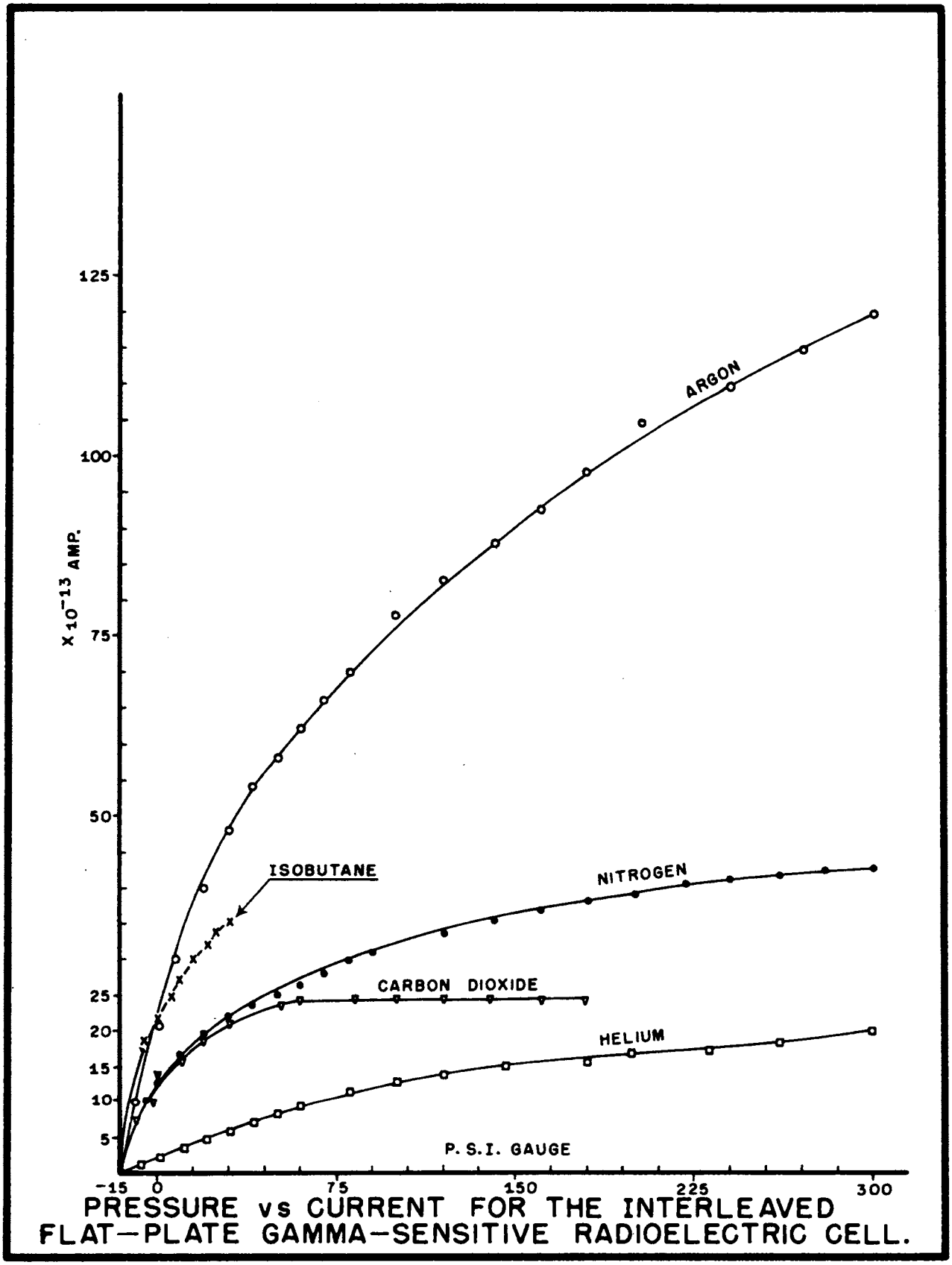
In order to check various gases readily over a wide pressure range and for ease of testing different electrode materials, the experimental cell shown with the negative-feedback d.c. amplifier[6] in Figure 5 and disassembled in Figure 6 was made. The negative electrode is brought out through a Teflon insulator so that checks may be made, if desired, with the negative electrode electrically insulated from the case. The electrode holders are constructed so that different electrodes are easily inserted and removed and the spacing between the electrodes can be readily changed. The cell may be operated up to pressures of several hundred pounds per square inch; it is referred to as the interleaved, flat-plate type.

The current-versus-gas-pressure curves for several gases are shown in Figure 10; the interleaved, flat-plate cell, gamma excited, was used for these measurements. It appears that xenon would be a good filling gas for the detection of gamma. Also of interest in Figure 10 is the leveling of the curve for the current at such a low pressure with carbon dioxide as the filling gas. The formation of negative ions is indicated with a subsequent decrease in the percentage of ions collected at the higher pressures.

The first actual instrument which was constructed around one of these cells was a gamma survey meter, which is shown in Figures 11 and 12, and was an approximate equivalent of the Cutie Pie. The positive electrode was made by plating gold on copper and coating the gold with lead dioxide. The negative electrode was made by plating the brass cell case with lead and evaporating aluminum on the lead. Argon at approximately three atmospheres was used as the filling gas.

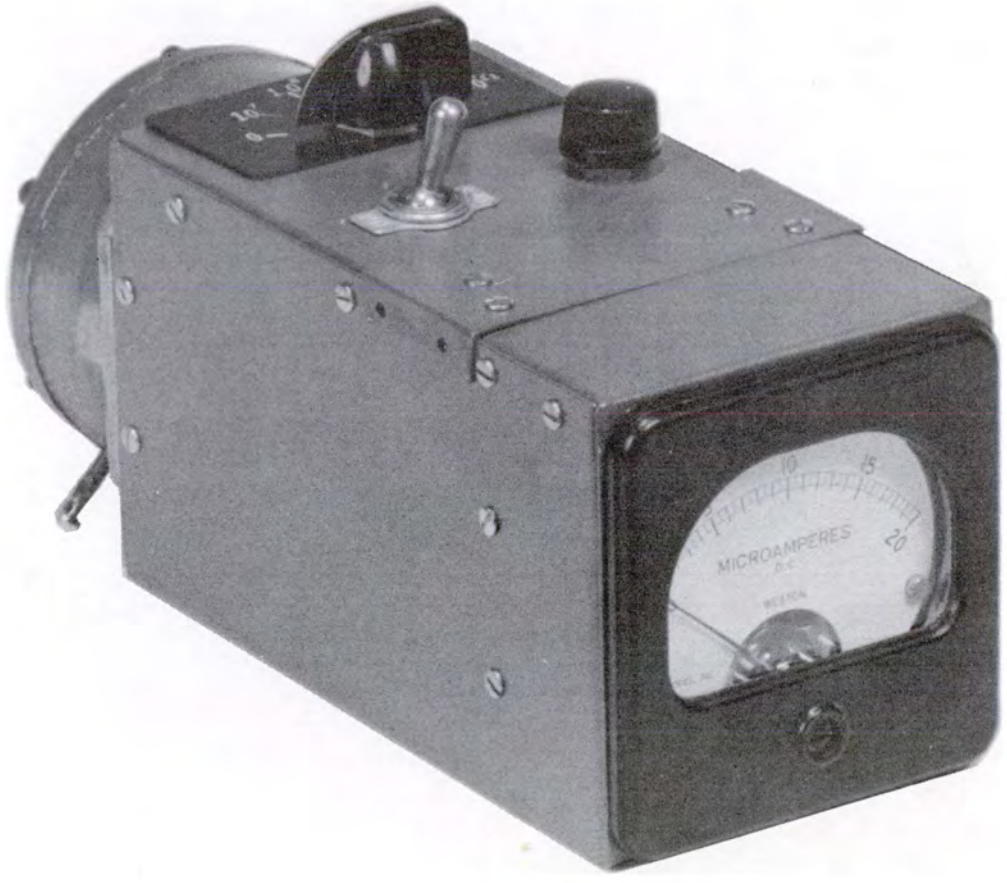
The circuit diagram of the survey meter is shown in Figure 13. It should be noted that the instrument is simpler than the Cutie Pie in that no high-voltage, ionization-chamber battery is required. Also, since the cell generates its own current in a radiation field and can, therefore, simply be connected between the grid of the vacuum tube and ground, there is no high-voltage insulation problem. The elimination of the high-voltage battery made it possible to simplify the battery-replacement problem by mounting the filament and plate-supply batteries in a drawer-type case for easy replacement.

The instrument is $3\frac{1}{8}$ by $3\frac{1}{8}$ by $7\frac{1}{4}$ inches over-all which is just slightly larger than the ionization chamber alone of the Cutie Pie. Even so, there is a large amount of waste space, particularly in the electrometer-circuit compartment, so the survey meter could



PRESSURE vs CURRENT FOR THE INTERLEAVED FLAT-PLATE GAMMA-SENSITIVE RADIOELECTRIC CELL.

5139



SIMPLIFIED GAMMA-SURVEY METER

FIGURE 11

MLM-629

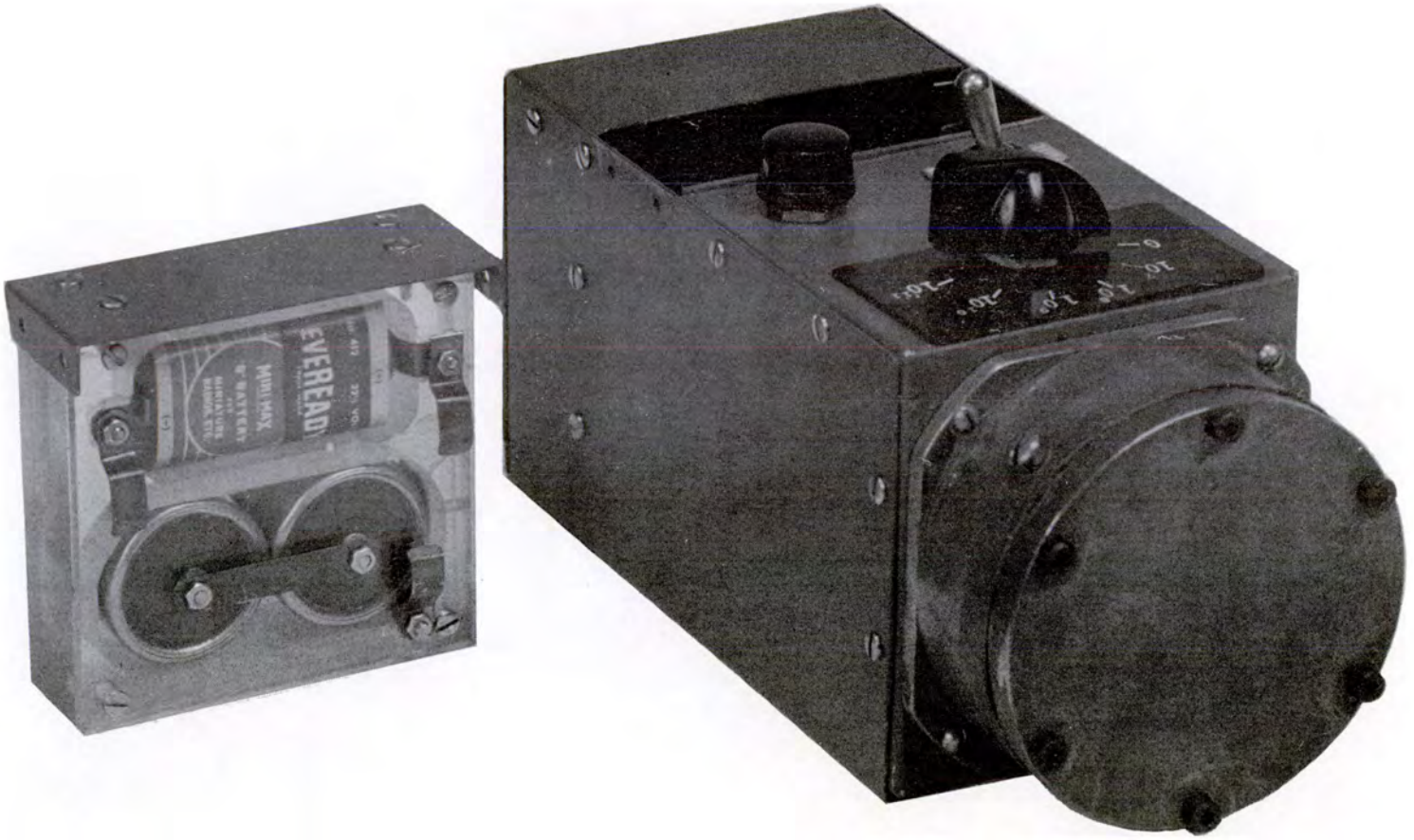
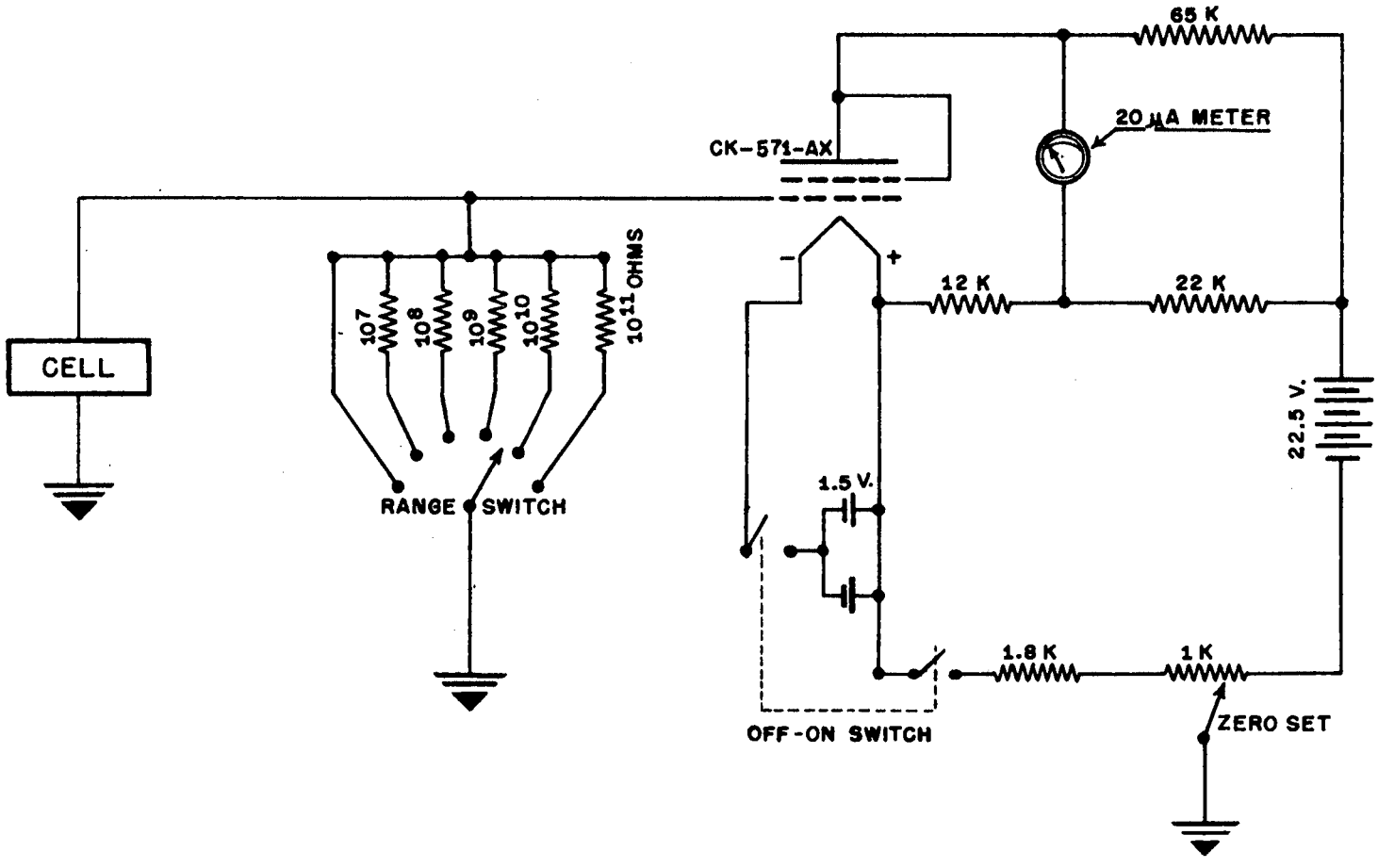


FIGURE 12

MLM-629

SIMPLIFIED GAMMA METER WITH BATTERIES REMOVED



CIRCUIT OF SIMPLIFIED GAMMA SURVEY METER.

FIGURE 13

MLM-629

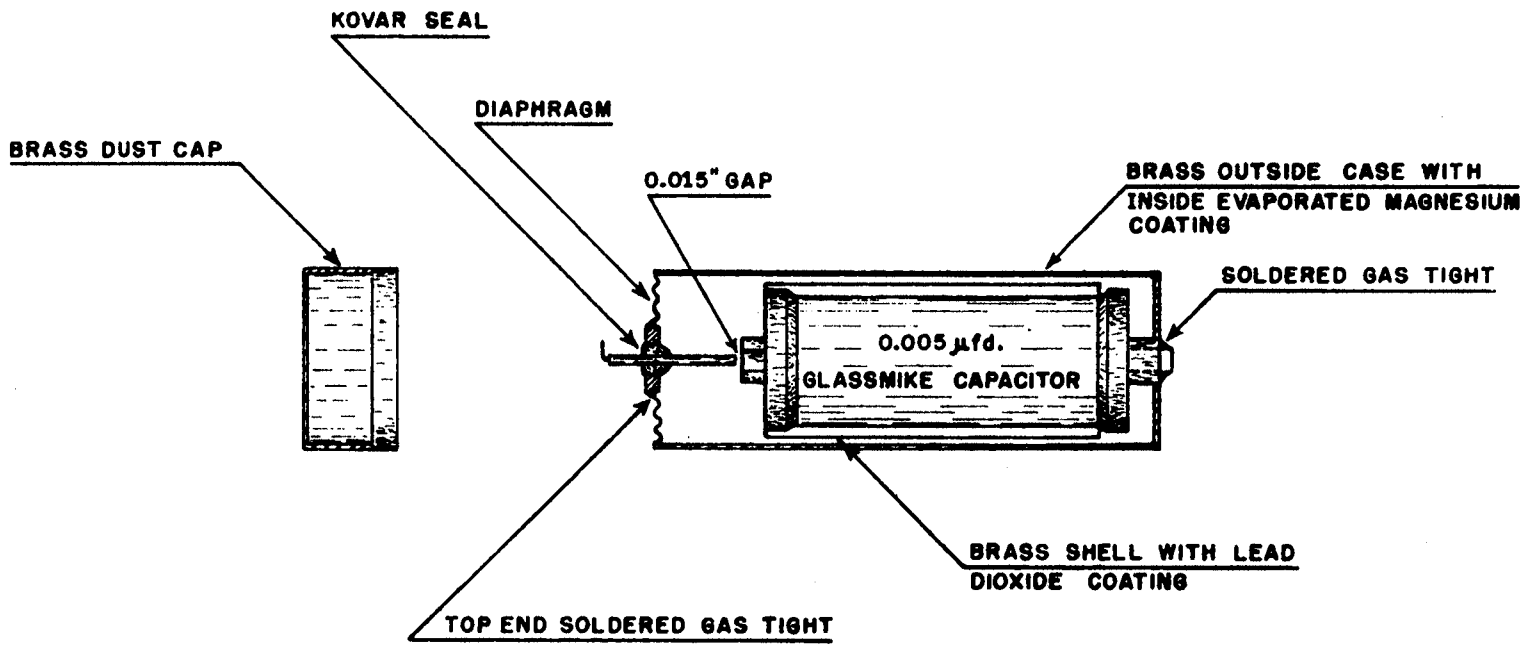
readily be made smaller. Preliminary tests indicate that it is over twice as sensitive as the Cutie Pie when used for measuring a uniform flux and, because of improved geometry, several times as sensitive for a point source of gamma radiation.

Since a radioelectric cell will deliver a current which is proportional to the radiation flux and since this current can be used to charge a capacitor, the total charge on the capacitor should be proportional to the total flux passing through the cell. Such a combination offers promise for use as a dosimeter. There would be some tendency for the capacitor to be discharged by the radiation; but if the capacitor were made with both electrodes of the same material and with a solid dielectric, this effect should be negligible. Two experimental systems have been constructed and tested. The tests indicate that practical pocket dosimeters based on the radioelectric cell design can be made. The second design is shown in Figure 14. It should be noted that the capacitor is supported by the case which is also the outer electrode of the cell and that the inner electrode is supported by the capacitor. Thus, the only insulation for the radioelectric cell is the capacitor itself, and hence the cell has no effect on the time constant of the capacitor. One end of the case is of flexible construction, and the Kovar seal in its center does not make contact with the capacitor unless it is pushed in mechanically to do so. A cap completes the mechanical and electrical shielding of the capacitor, protects the Kovar seal, and prevents accidental discharge of the capacitor. Since the capacitor is hermetically sealed in an inert gas, the capacitor should retain its electrical characteristics indefinitely. A dosimeter of this type should have a very long shelf life. Accumulation of dirt or moisture on the Kovar seal should have no effect on the dosimeter, since the seal could be cleaned before measuring the exposure. The exposure could be determined by measuring the voltage on the capacitor with a high-impedance electrometer or by measuring the total charge on the capacitor with a ballistic galvanometer.

The capacitor used in this dosimeter was a Condenser Products Company Type LSG Glassmike of 0.005-microfarad capacity. It was selected from stock and had a resistance of about 10^{13} ohms or a time constant of about 14 hours. Although this time constant is too short for a practical dosimeter, it was long enough for laboratory measurements. Several measurements were made of the charge collected by this instrument. A two-minute exposure to a one-milligram radium source at one inch gave a reading of 39 millivolts across 10^{11} ohms with the Beckman Ultrohmeter. A five-minute exposure to a 24.8-milligram radium source at one inch gave a deflection equivalent to 2×10^{-9} ampere on a galvanometer.

Since cells can be placed in parallel to increase current output, multiple, interleaved, coaxial electrodes were suggested for a cell design of greater efficiency than had previously been attained. A nine-electrode cell of this type was constructed and is shown in Figure 15. The positive electrodes (besides the outer case) were made of 0.003-inch brass shim stock plated with gold and then with lead dioxide. The negative electrodes were made of 0.003-inch brass shim stock plated with lead and then coated with magnesium by evaporation.

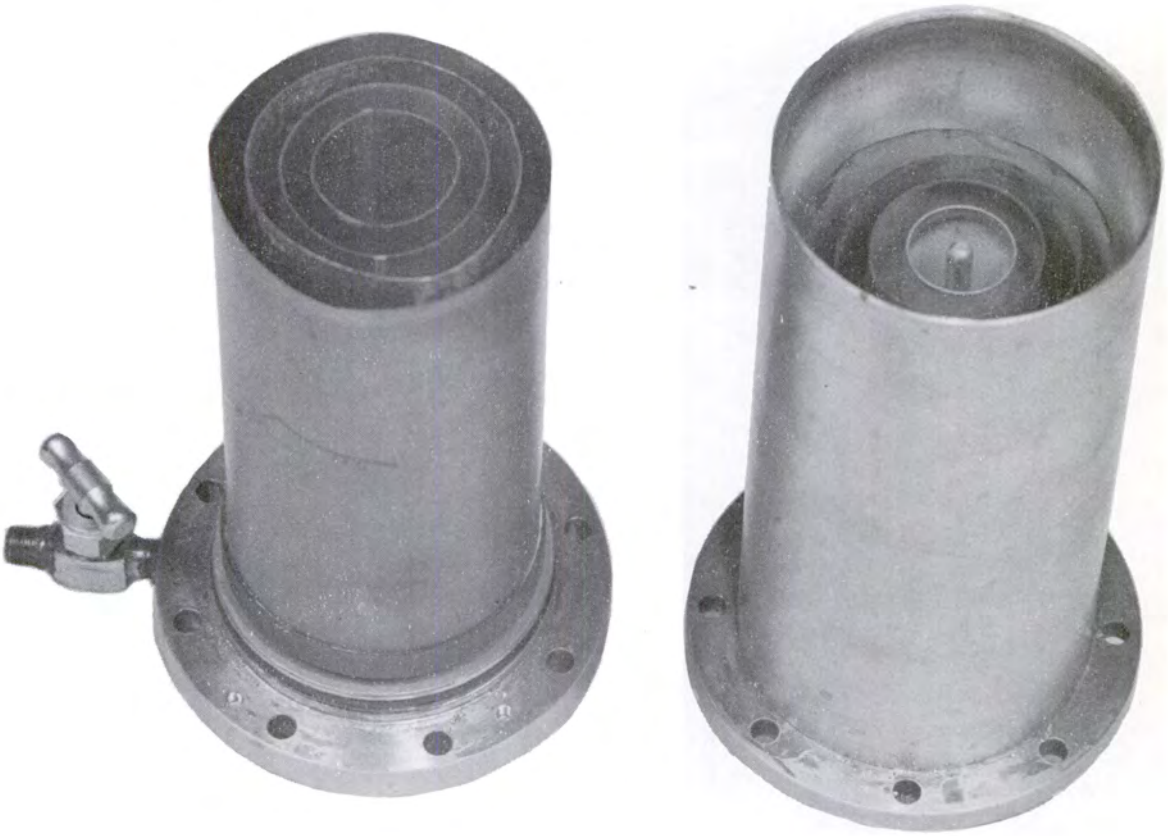
When filled with argon at 200 pounds per square inch gauge, this cell was far more efficient for the detection of gamma radiation than any previous cell tested. When the cell was connected to a Speedomax pH recorder with a 10^{9}-ohm load resistance, a deflection of 22 millivolts was obtained with the cell in a semiuniform gamma flux of approximately 12.5 milliroentgens per hour intensity. A reading was obtained with a Micromax pH recorder, and this cell should be useful with almost any type of glass-electrode pH meter. This cell was mounted on a box containing a simple electrometer circuit and was given to one of the analytical groups for testing. The complete instrument is shown in Figure 16; the electrometer



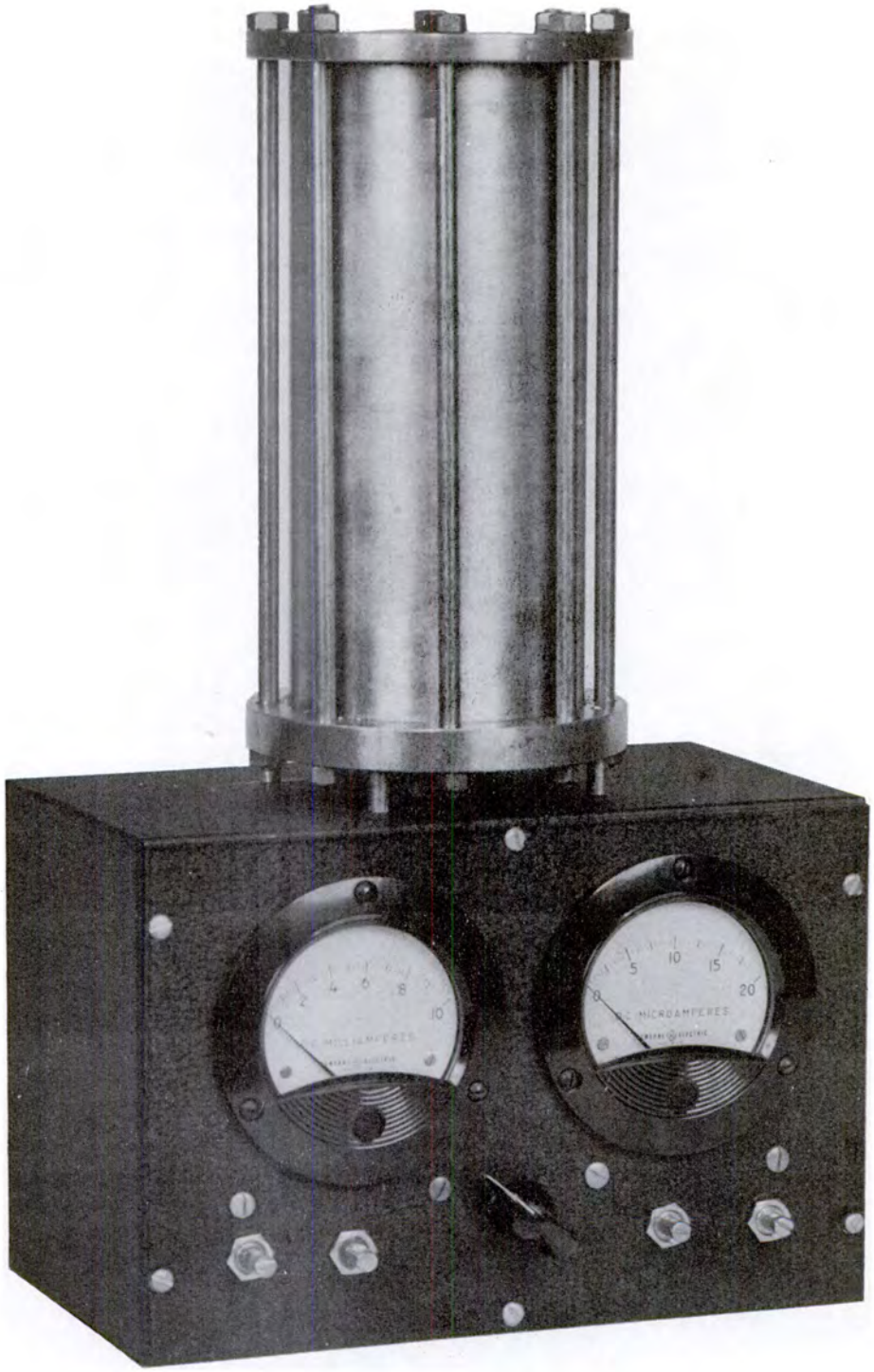
GAMMA POCKET CHAMBER.

FIGURE 14

MLM-629



MULTIPLE-ELECTRODE COAXIAL CELL, DISASSEMBLED



510081

GAMMA COAXIAL CELL AND ELECTROMETER CIRCUIT

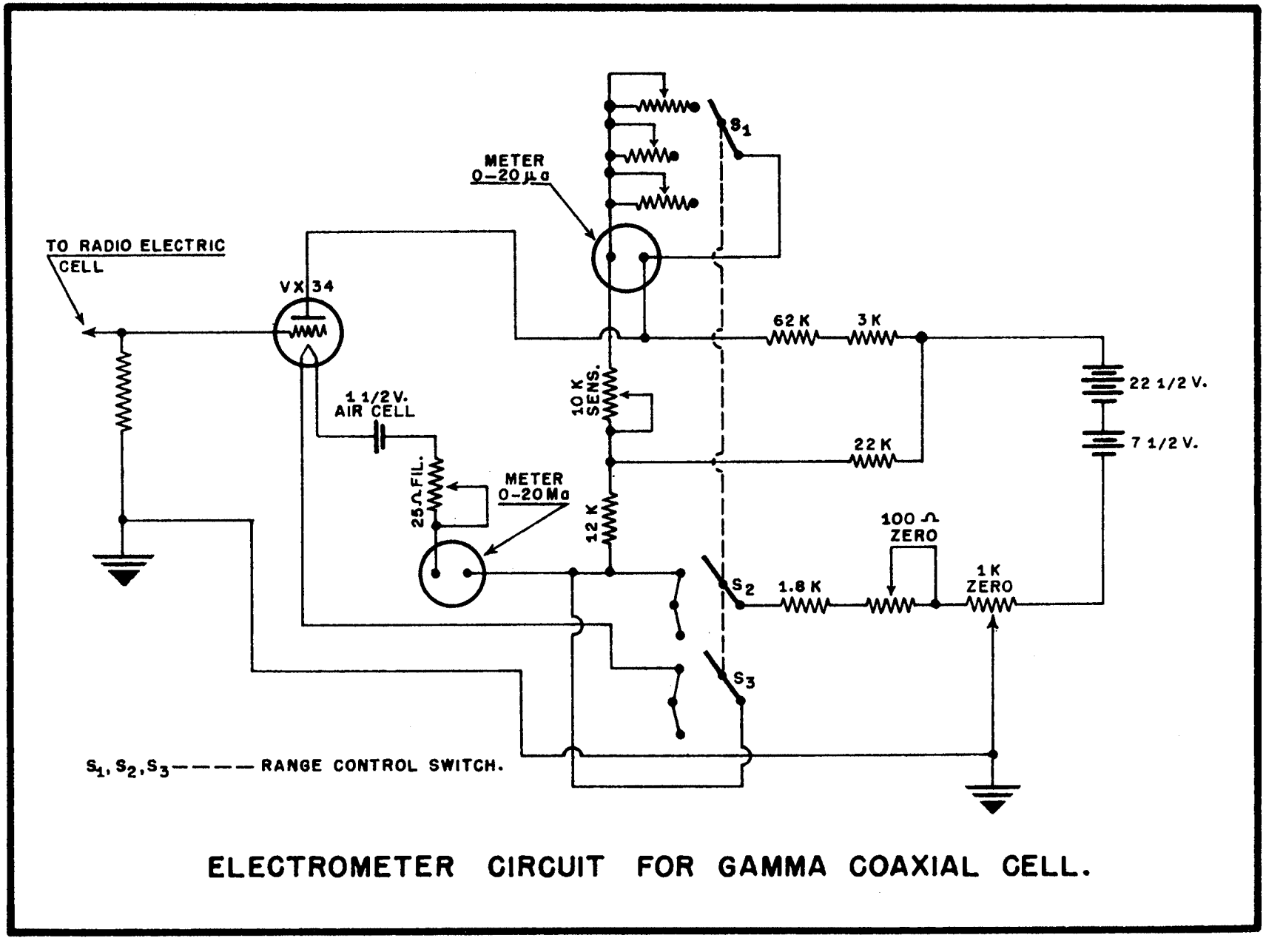
schematic is shown in Figure 17. A test was made on the gamma assay of samples which have a very unsymmetrical flux distribution. The instrument which is normally used rotates the sample and uses a hand-figured lead lens between the sample and the Geiger-Mueller tube.[8] This elaborate and expensive array has been found to give satisfactory gamma assay of such unsymmetrical sources, but long counting times are necessary because of the low geometry. A run of 165 measurements was made on both instruments.[9] The radioelectric instrument gave a precision of 1.5 per cent, while the rotating gamma counter gave a precision of 1.8 per cent. Thus, although the radioelectric instrument required only a fraction of the time to make a measurement compared to the rotating gamma counter, it was at least equally precise. The precision obtained with the radioelectric instrument was essentially the precision of reading the 3-inch meter. Hence, the precision could probably be improved by use of a large, mirror-scale meter. More stable electrometer circuits are also available.

Two cells and electrometer circuits similar to the one described above were constructed to be used by another group. The first cell had two magnesium (oxide)-evaporated-on-brass electrodes and one lead dioxide-on-gold-plated-brass electrode. The characteristic potential was 1.44 volts. The second cell had three aluminum-foil electrodes and two lead dioxide-on-gold-plated-brass electrodes. The characteristic potential was 1.34 volts. These radioelectric cells were placed beneath "dry boxes" with a thin-walled stainless steel well extending from the bottom of the "dry box" to the center of the radioelectric cell. The electrometer tube and its load resistor were mounted on the radioelectric cell, while the meter, associated controls, and power source were remotely located. With this setup, it was possible to make gamma assays on material at various steps in an experiment in a few minutes without removing the material from the "dry box". Previously it was necessary to spend two hours or more to make a gamma assay. These units have been in daily use for many months, and have proved to be highly satisfactory. Additional units of improved design are being constructed.

A simple cell was designed and constructed to explore the feasibility of a radioelectric device as a fast-neutron detector. This cell (Figure 18) was made of a length of copper tubing lined with Aquadag-coated polystyrene to act as a source of recoil protons as well as the positive electrode. The negative electrode consisted of a length of magnesium ribbon supported by Kovar seals at each end of the copper tube. Hydrogen was used as the filling gas. This cell was sensitive to neutrons, but its efficiency was quite low. The response to the gamma radiation from a polonium source approximately equivalent to the polonium in the polonium-beryllium neutron source used in these tests was about 1.5 per cent of the response to the neutron source itself.

These preliminary results indicated that a further investigation of neutron-sensitive radioelectric cells was warranted. Hence, a multiple-electrode coaxial cell of the same general design previously described (Figure 15) was constructed. Various electrode combinations were checked with various filling gases over a range of pressures. The results with electrodes with polyethylene cores are presented graphically in Figures 19, 20, and 21. For each filling gas, a control set of electrodes, aluminum (oxide), and carbon on aluminum, was also tested so that an approximate determination could be made of the contribution of the hydrogenous core material. The gases were chosen to give a variable hydrogen content at fixed pressure.

In all cases (except at pressures above the crossover point for methane) the addition of the hydrogenous core increased the efficiency of the cell, and apparently also increased the neutron-to-gamma discrimination. The reason for the crossover point with methane gas is not clearly understood. It would seem that at the lower gas pressures the chief source of the recoil protons would be the hydrogenous core, while as the pressure was increased the



ELECTROMETER CIRCUIT FOR GAMMA COAXIAL CELL.

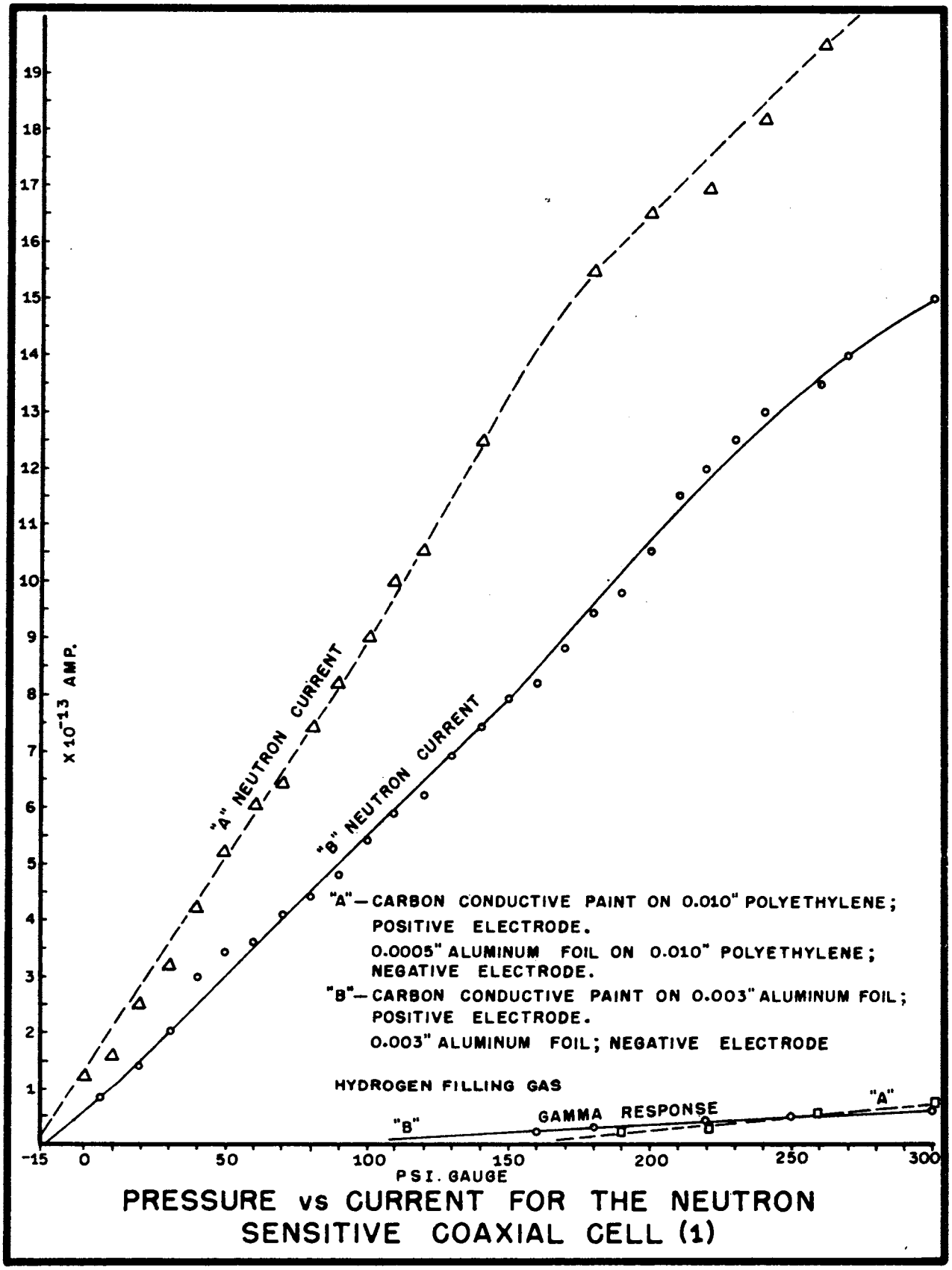
FIGURE 17

MLM-629

SIMPLE NEUTRON-SENSITIVE CELL

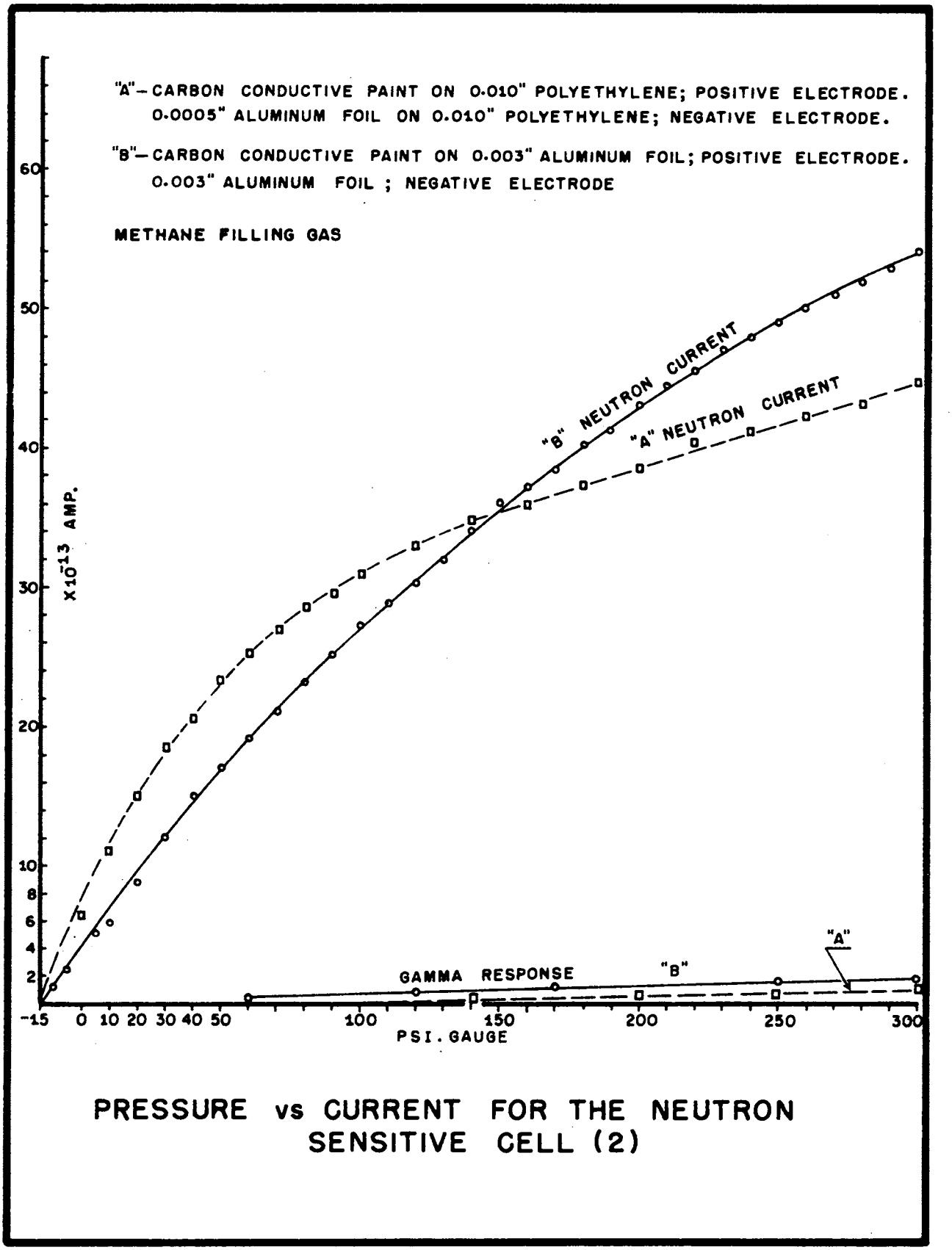
FIGURE 18

MLM-629



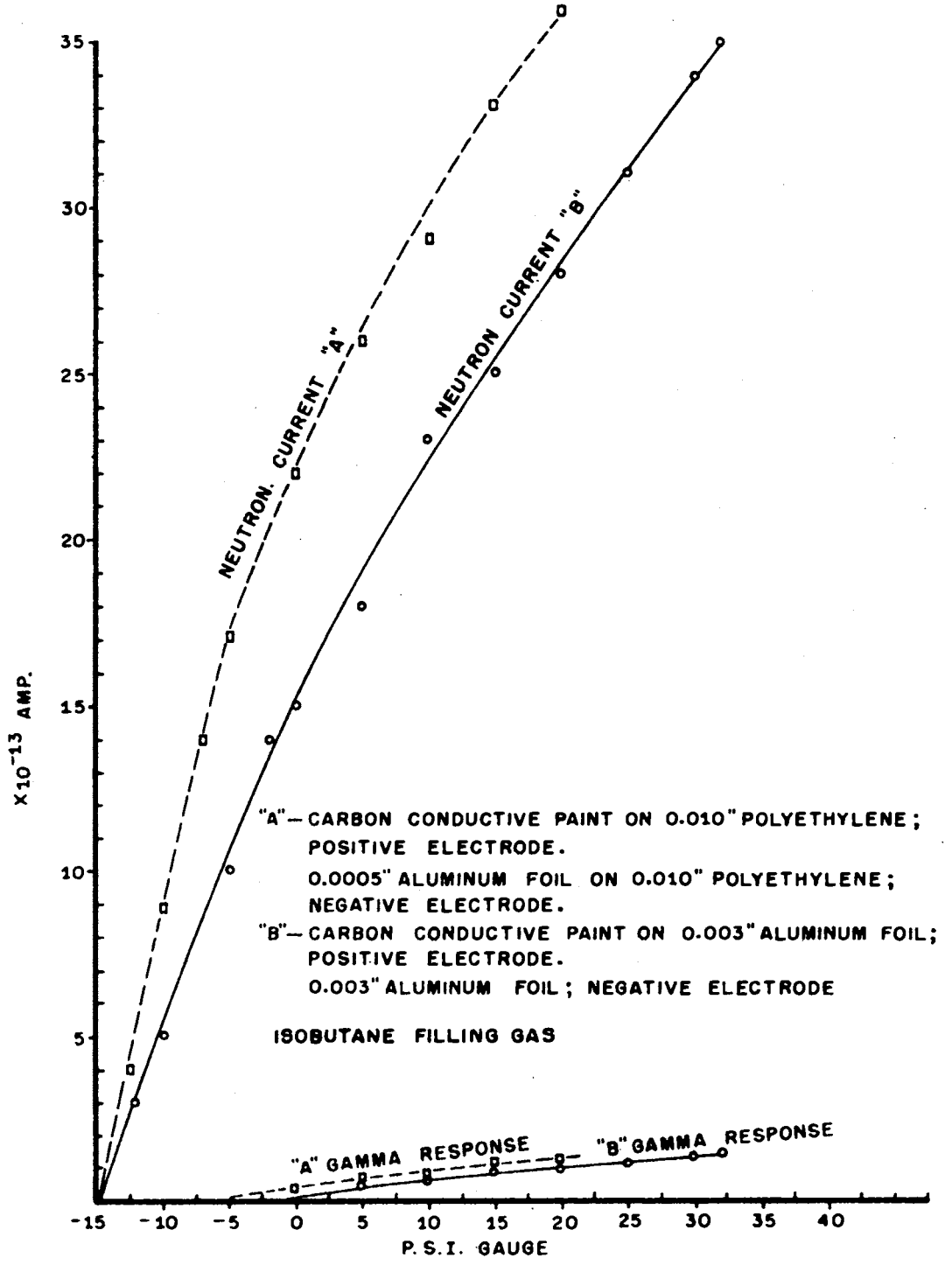
PRESSURE vs CURRENT FOR THE NEUTRON SENSITIVE COAXIAL CELL (1)

5136



PRESSURE vs CURRENT FOR THE NEUTRON SENSITIVE CELL (2)

5135



PRESSURE vs CURRENT FOR THE NEUTRON SENSITIVE COAXIAL CELL.(3)

5140

filling gas would contribute an increasing percentage of the recoil protons formed. Increasing the pressure, of course, should result in the two curves converging asymptotically at higher pressures rather than a crossing of the curves. Most of the graphs do show signs of the two curves breaking toward each other at the higher pressures. It is also probable that this crossover point, as well as the efficiency of all cells with hydrogenous electrode cores, is a function of the thickness of both the hydrogenous core and the electrodes themselves. We were quite limited in our range of thickness (particularly of the hydrogenous cores) and had to use what was on hand. We are attempting to obtain some additional thicknesses and want to make further measurements when these become available.

With some combinations of electrodes, the current from an amount of polonium approximately equivalent to that in the neutron source used was only 0.05 per cent of the current obtained with the neutron source itself. Since there is evidence that a polonium-beryllium neutron source may give off appreciable gammas (of lower energy than the 4.5-million-electron-volt conversion gamma) in excess of the 0.8-million-electron-volt gamma from the polonium^{10} and since it is not known if this gamma flux is proportional to the neutron flux, the actual neutron-to-gamma-discrimination ratios of these cells is still uncertain.

Although practical cells might be developed for the assay of neutron sources with low gamma backgrounds, much further work is indicated. The relatively high efficiency for fast neutrons, the high geometry factor that can be obtained, and the simplicity and rapid response of such an instrument make it of definite interest.

SUMMARY

From theoretical considerations substantiated by experimental results, it appears that radioactive energy can be converted to electrical energy through the following mechanism. If two electrodes having different work functions for their surfaces are connected only through a load impedance, an electrostatic field will exist between them but no steady current will flow in the external circuit. If the gas between the electrodes is forcibly ionized by radiation, the positive ions will drift in this field toward the electrode of higher work function and be collected by it, while the electrons (and negative ions) will drift in this field towards the electrode having the lower work function and will be collected by it. The positive ions will be neutralized by electrons pulled out of the electrode of higher work function (field emission) as they are collected, and electrons will flow in the external circuit from the electrode of lower work function to the electrode of higher work function to replace those electrons lost in neutralizing the positive ions. Thus a portion of the radioactive energy lost by the production of ionizing events is recovered as electrical energy in the external circuit.

The radioelectric cell can be considered as a battery in which the driving force is the difference in the work functions of the two electrode surfaces and the source of energy is the ionizing radiation. Since the formation of a positive ion is a loss of electrons and hence an oxidation, and since the neutralization of a positive ion is the gain of electrons and hence a reduction, the current from a radioelectric cell can be considered as coming from an oxidation-reduction reaction. However, this oxidation-reduction involves the filling gas and does not imply any permanent valence change of the electrodes themselves. Also, the energy to produce this oxidation, and hence reduction, comes from outside the cell itself.

The radioelectric effect and instruments utilizing this phenomenon appear to have a definite place in the field of radiation detection, supplementing the types of devices currently in use. It has been effectively demonstrated that certain gamma detecting devices

are not only quite practical, but for specific uses offer marked advantages over conventional detectors. The small physical size, circuit simplicity, and portability should have much merit in application for survey and for civil defense work. Because no high voltage supply is needed, the cell is readily adaptable to construction shapes for many specific and difficult measurements. Although little has been done in the way of beta measurements, there is no fundamental reason why practical cells similar to those for gammas cannot be designed and built. We have done sufficient work with neutron-sensitive cells to be encouraged in this direction. As is well known, precise detection of neutrons is a highly complex problem, and we have by no means developed practical operating devices. On the other hand we do have sufficient data on neutron-sensitive cells to indicate that such a device might be achieved in time. We have not directed any serious effort toward practical alpha-measuring cells. One problem here from the standpoint of a practical device is that, because of the low penetrating power of alphas, the sample should be inserted into the cell. It is also true that present instruments satisfactorily measure alpha emitters; and except for a few specific cases, such as survey instruments, the radioelectric cells do not appear to have any particular advantage for this type of radiation.

It is possible to detect alpha, beta, gamma, and neutron radiation, and gamma radiation can be measured with high precision. The difference between the work functions of two surfaces can be simply and accurately determined. We have indicated that the radioelectric effect might be used to measure pressure, for gas analysis (variance in average nuclear charge), the rate of growth of surface films or their stability, and similar variables. However, except in certain special cases, it would probably be more practical to use more conventional methods for these measurements.

REFERENCES

1. Kelvin, Lord, Mathematical and Physical Papers VI, Cambridge, 1911.
2. Chalmers, J. A., Phil. Mag., *33*, 399-430 (1942).
3. Ohmart, P. E., A Method of Producing an Electric Current from Radioactivity, MLM-495 rev., September 11, 1950; Ohmart, P. E., J. App. Phys., *22*, 1504-05 (1951); Waldo, W. H., Ibid, *23*, 290 (1952); Ohmart, P. E., Investigation of a Method of Producing an Electric Current from Radioactivity, MLM-521, December 1, 1950.
4. Kramer, J. B., The Electrician, *93*, 497 (1924).
5. The unclassified data summarized in this report are taken from the following classified quarterly reports: Ohmart, P. E., MLM-481, pp. 52-75, August 28, 1950; Ohmart, P. E., MLM-507, pp. 8-26, November 20, 1950; Hutchinson, J. H., Stanton, J. S., Daggett, E., and Ohmart, P. E., MLM-531, pp. 28-38, February 12, 1951; Hutchinson, J. H. and Stanton, J. S., MLM-563, pp. 5-17, June 4, 1951; Hutchinson, J. H., MLM-623, pp. 61-70, November 19, 1951; Stanton, J. S., MLM-623, p. 71, November 19, 1951.
6. Rogers, A. J., Rpt. Gen. Res., MLM-561, pp. 28-30, May 21, 1951 (Secret).
7. Michaelson, H. B., J. App. Phys., *21*, 536, (1950).
8. Eyles, T. E., Quart. Rpt. Gen. Res., MLM-368-3, pp. 643-651, July 1, 1949, (Secret).
9. Shon, F. J., Private Communication, May 3, 1951.
10. Pringle, R. W., Roulston, K. I., and Standil, S., Phys. Rev., *78*, 627 (1950).