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A RADIOACTIVE-IONIZATION-GAGE PRESSURE-MEASUREMENT SYSTEM

N. W. Spencer
R. L. Boggess
L. R. Brace
M. A. El-Moslimany

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ABSTRACT

An air-pressure-measurement system employing a radioactive ionization gage has been developed for use in rockets for the determination of surface pressures which can be interpreted in terms of the ambient pressure, density, and temperature of the atmosphere. The system has proven useful for the measurement of pressures from atmospheric to at least 10^{-3} mb.

1.0 INTRODUCTION

The remote measurement of a quantity with a precision of approximately 1 part in 50, when the quantitative variation covers several decades, poses interesting and challenging problems. Such a quantity is the ambient air pressure of the earth's atmosphere, whose magnitude decreases from approximately 1000 millibars (mb) at sea level to 10^{-3} mb at an altitude of 50 miles.

This report is concerned with a description of a pressure-measurement system illustrated in Figs. 1.1 and 1.2 that has evolved through several years of upper-atmosphere investigations carried out by The University of Michigan as part of the upper-atmosphere sounding program of the Geophysics Research Directorate of the Air Force Cambridge Research Center.

Very crude measurements were first accomplished through the use of thermionic ionization gages (VG-1A) which were employed on several V-2 flights. The VG-1A, however, was not useful at pressures greater than approximately 10^{-2} mb, and thus alternative designs were sought.

Possible use of an ionization gage employing a radioactive ionizing source was brought to the writer's attention by Professor W. G. Dow of The University of Michigan's Electrical Engineering Department, who was at that time directing the research program, and by Dr. J. R. Downing, the Inventor of the Alphatron,* the name of the commercial version of the device.

Consideration of radioactive ionization gages in the light of known operating limitations imposed by the rigors of a rocket flight demonstrated that the device possesses considerable merit for rocket-borne service. Pertinent factors include:

a) undamaged by exposure to atmospheric density;
b) physically rugged;
c) nearly instantaneous electrical response;
d) manufacturing precision unnecessary; and
e) current vs. pressure range adequate for ground-to-50-mile measurements.

Certain drawbacks are likewise evident, such as:

a) very small output current magnitude;
b) radioactive ionizing source constitutes potential health hazard;

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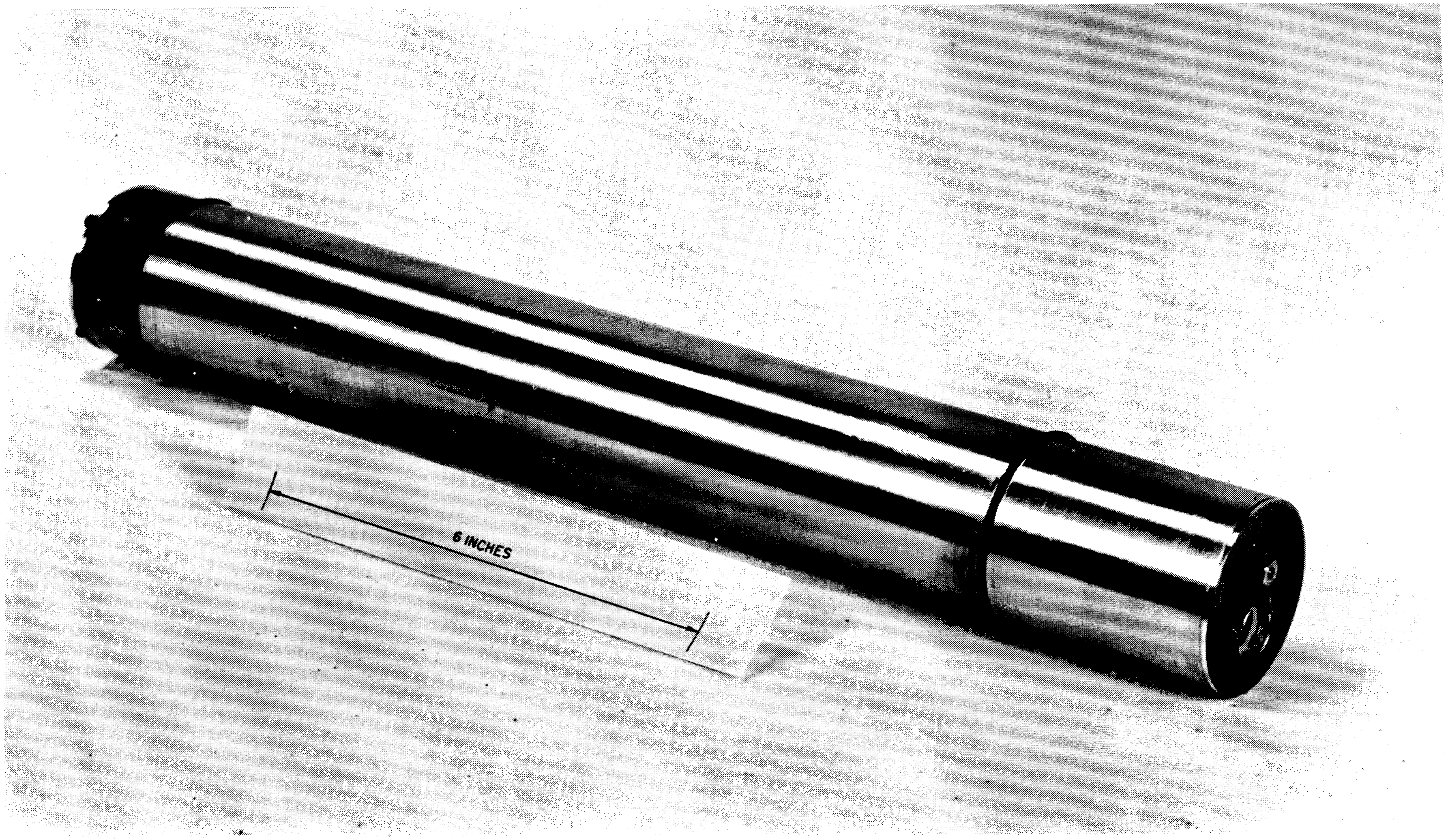

Fig. 1.1. Complete system in enclosing tubing.

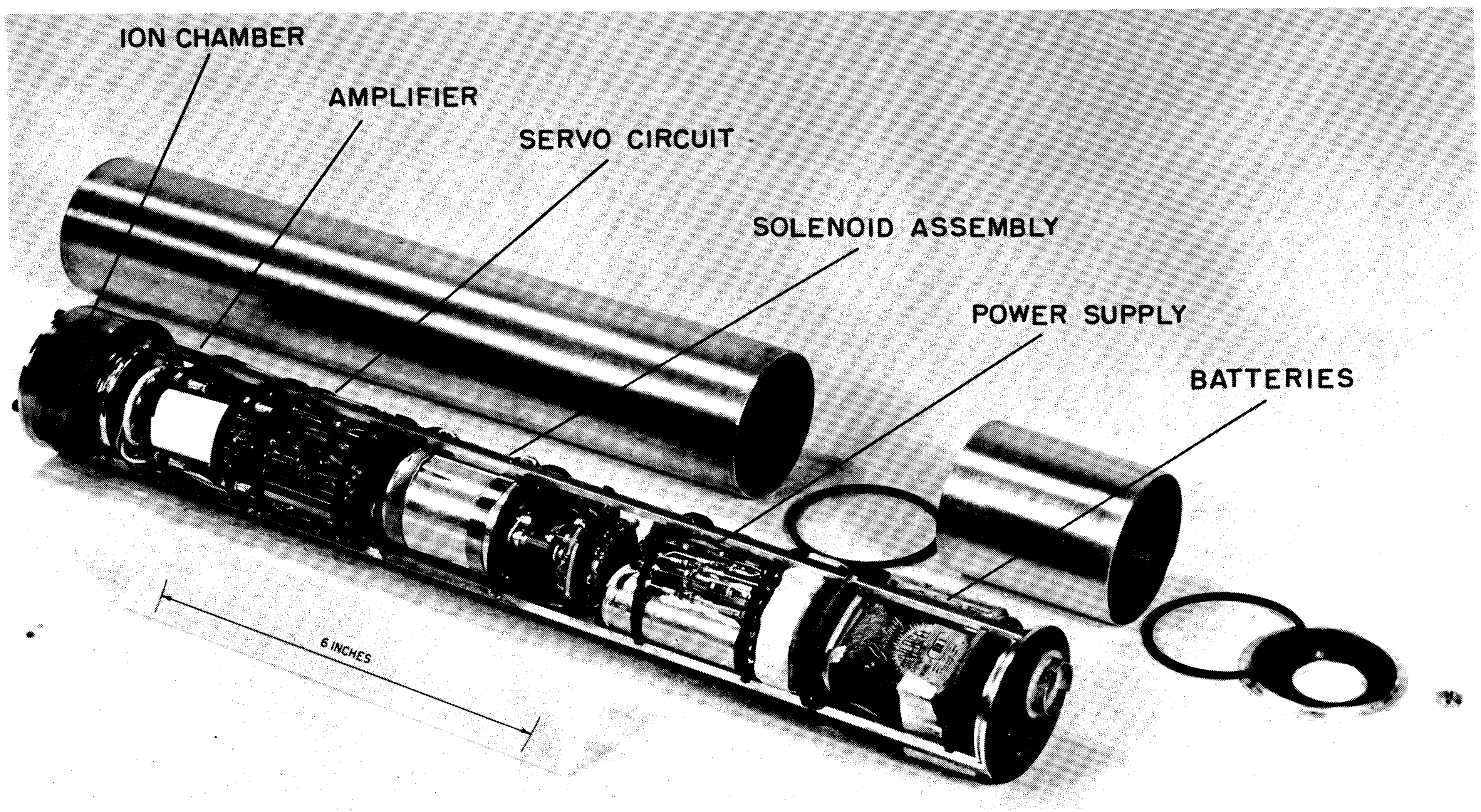

Fig. 1.2. Complete system out of enclosing tubing.

c) relatively large physical volume (at that time) of existing gages (cylinder 3-1/2-in. diam and 4-in. length); and
d) nonlinearity of current-pressure characteristic at both high and low pressures.

Consideration of these several factors led to the conclusion that the device could best be used by employing a d-c amplifier with unity negative feedback as a means of representing the small ionization current in terms of a voltage suitable for telemetering. Thus, following an original design by Dr. Downing (communicated personally), a completely battery-powered amplifier employing an electrometer input stage and a cathode-follower output stage was developed. Advantage was taken of the multi-decade useful range of the ionization chamber by incorporating a series of several hi-meg* input resistors which enabled the measurement of currents in the range 10^{-7} to 10^{-12} ampere, and subsequent interpretation in terms of pressure with adequate resolution considering the experimental technique employed.

Since the equipment had to operate unattended in a rocket, automatic insertion of the proper hi-meg resistor consistent with the chamber pressure during rocket ascent was essential. Thus a d-c servo circuit was devised which would accomplish the desired operation. Ionization chambers** obtained from the National Research Corporation were employed, and several units constructed and flown in Aerobee rockets, resulting in measurements of upper-atmosphere pressure, temperature and density.[1,2,3]

Experience with these units and the constructional techniques employed at that time made evident the desirability of redesigning the circuitry to (a) eliminate many of the several batteries employed, (b) consolidate the various circuit portions into a single unit, and (c) bring about a simplification in the then complicated constructional technique. At the same time it was desired to decrease the chamber volume, increase the ionization current, and if possible reduce the hazard associated with the use of a radioactive source.

Aside from these factors, the desirability of conducting relatively extensive pressure measurements during the IGY rocket program, which would involve nearly 50 pressure-measuring units, made it imperative to develop a unit embodying the improvements mentioned above, which could be easily hand-produced in quantities of 10 to 20 units.

Accordingly, the development was undertaken and carried out, resulting in a pressure-measurement unit which is the subject of this report. The work was initiated under two contracts/ and essentially concluded under a third// with

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*Victoreen RX-1.

**National Research Corporation, No. 510, patented.

/AF 19(604)-1511, AF 19(604)-545.

//AF 19(604)-1948.

additional substantial support from a U. S. National Committee—National Science Foundation IGY Project grant.

Initial studies which led to the design of an improved ionization chamber have been recorded in a report[4] prepared in partial fulfillment of the obligations under Contract AF 19(604)-1511.

2.0 GENERAL ASPECTS OF THE SYSTEM

The general instrumentation scheme underlying the pressure-measurement unit is essentially identical to that originally reported in the literature,[3] and can be illustrated by a block diagram, as in Fig. 2.1. (See also the complete schematic diagram, Fig. 2.4.) The ionization chamber supplies, as a function of the density, composition, polarizing voltage, and, in some cases, temperature of the gas contained within its walls, a current which is passed through an appropriately valued hi-meg resistor. The voltage drop across this resistor appears as a portion of the voltage in the feedback loop of a d-c amplifier for which β, the feedback factor, is unity. Thus a voltage change effected at the "output" of the amplifier is nearly equivalent in magnitude to a voltage change across the hi-meg resistor (the input signal) but opposite in sense. The degree of equivalence is determined by the magnitude of the system loop gain as indicated by the familiar expression

$$V.G. = \frac{A}{1 - A\beta} , \qquad (2.1)$$

where

V.G. is the voltage gain with feedback,
A is the loop gain, and
β is the fraction of output voltage returned to the input, unity in this case.

In this system the loop gain is the order of several thousand so the voltage gain is, for the purposes of this instrumentation, unity. Thus one can consider the amplifier system as an impedance matching device or as a current amplifier, whichever is most convenient.

The current produced by the ionization chamber lies in the approximate range of 10^{-12} to 10^{-8} amp as will be detailed in a later section of the report. Applicational aspects of the units require a resolution necessitating "division" of the total current range into 5 "sub-ranges." The necessity for maintaining the output signal in a nominal 0-5 volt range (determined by telemeter requirements) thus requires that 5 different ionization-chamber load resistances be employed. Since the voltage gain of the system is unity, it is apparent that these resistances must be of sufficient magnitude to produce the desired magnitude of output signal.

Equation (2.1) means that the voltage gain will be essentially unity with no phase shift for considerable variation of circuit parameters, tube character-

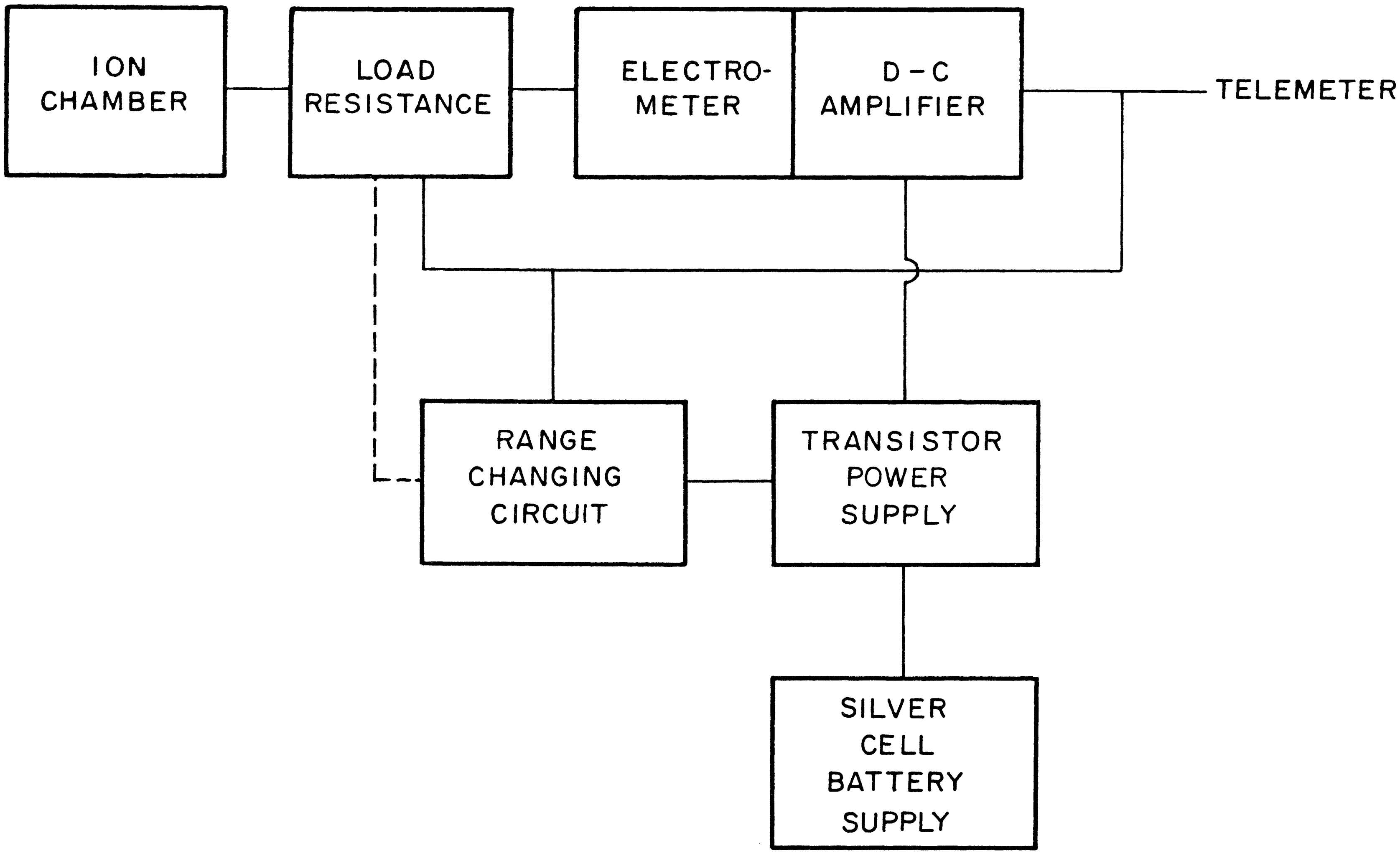

Fig. 2.1. Block diagram of radioactive pressure-measurement system.

istics, etc., provided the loop gain A remains sufficiently high. This concept is applicable when considering a change in the input signal and a corresponding change in the output signal, but does not require any particular d-c output level corresponding to a particular, constant d-c input level. Thus an arbitrary operating level may be chosen for reference.

Consider the situation for zero ionization-chamber current, consequently zero volts across the hi-meg resistor. The system is so arranged, that is, voltages, circuit constants, etc., are so chosen, that the output operating level will be 6.0 volts, herein referred to as the "zero pressure voltage," or "ZPV." Now, if the pressure in the ionization gage is increased from zero, the output voltage will correspondingly decrease from 6.0 volts. When the drop across the gage load resistor (hi-meg) reaches 6 volts, the output will be zero volts, and the point will have been reached (limit of telemeter) where the next desired hi-meg resistor in the series of 5 should be inserted. Its value is chosen so that the output voltage will be 5.0 volts when it is inserted. If the ionization-gage current is permitted to increase further, the output will again decrease, allowing, when 0 volt is reached, repetition of the above operational sequence. These considerations are illustrated in Fig. 2.2, which shows the output voltage corresponding to several decades of input current.

It is apparent that for proper operation the load resistance should be changed each time the output reaches 0 or 5 volts. To this end, the range-changing circuit uses the system output voltage as an "error signal" to control operation of a bi-directional rotary solenoid stepping switch. Self-induced switching is accomplished in either the increasing or decreasing current direction, hence either increasing or decreasing pressure direction, and thus the range-changing circuit acts to select the proper resistance for an on-scale output indication throughout the total acceptable pressure-measurement range of the instrument.

Figure 2.3 illustrates a typical current-pressure relationship for this equipment. The corresponding subdivision into "sub-ranges" by the ionization-chamber load resistances is shown by superposing a calibration voltage-resistance grid.

It is apparent from Fig. 2.3 that peak currents near 100-mb pressure, and low currents near 10^{-12} amp lie outside the grid, that is, no provision is made for determining these values. The corresponding outputs will lie below zero and above 5.0 volts, respectively. This situation is not detrimental to operational use of the instrument as these regions lie outside the useful range of the instrument. Although, normally, range-changing would occur, it will not under these two circumstances as the circuit is disabled to prevent switching below range 1 and above range 5.

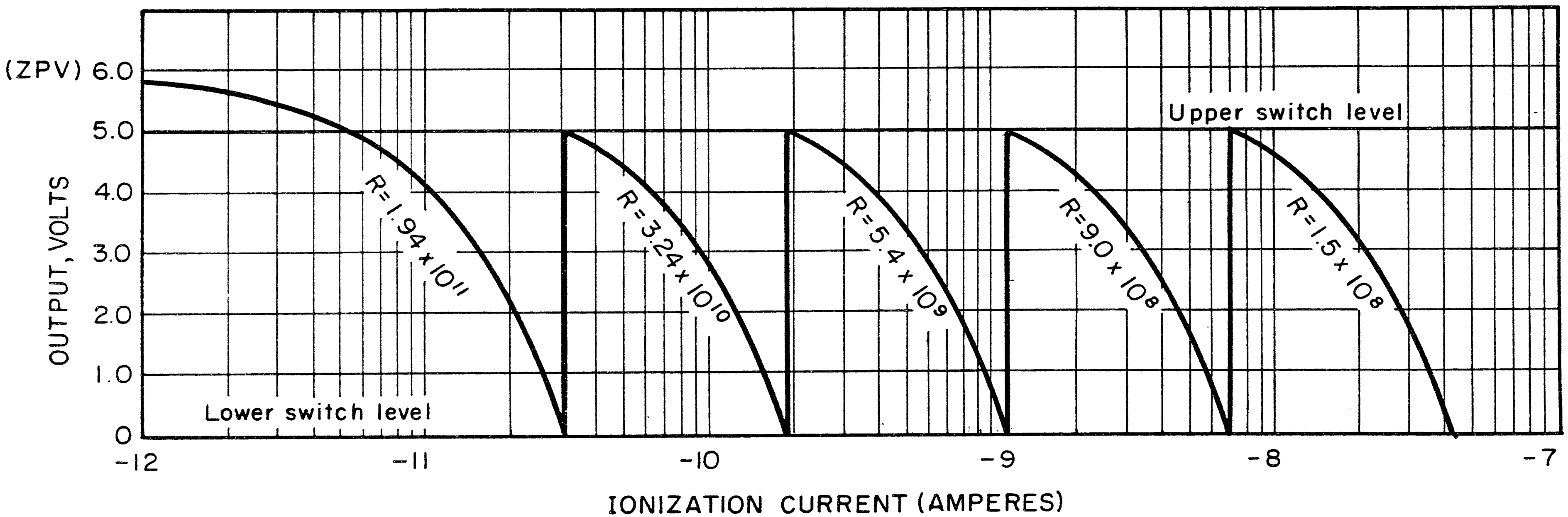

Fig. 2.2. Output voltage and hi-meg resistor relationships.

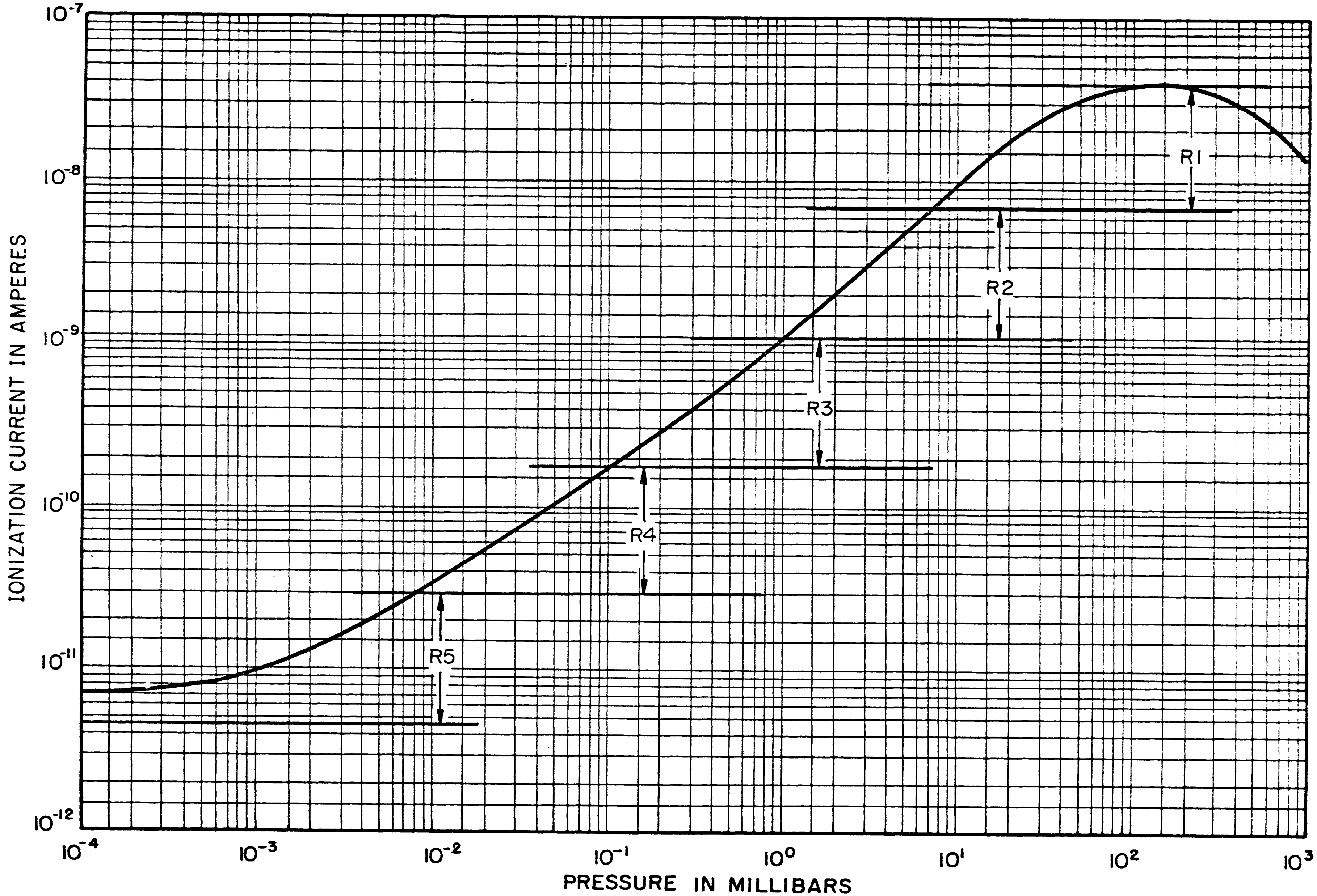

Fig. 2.3. Typical i-p curve for ionization chamber showing corresponding load resistances.

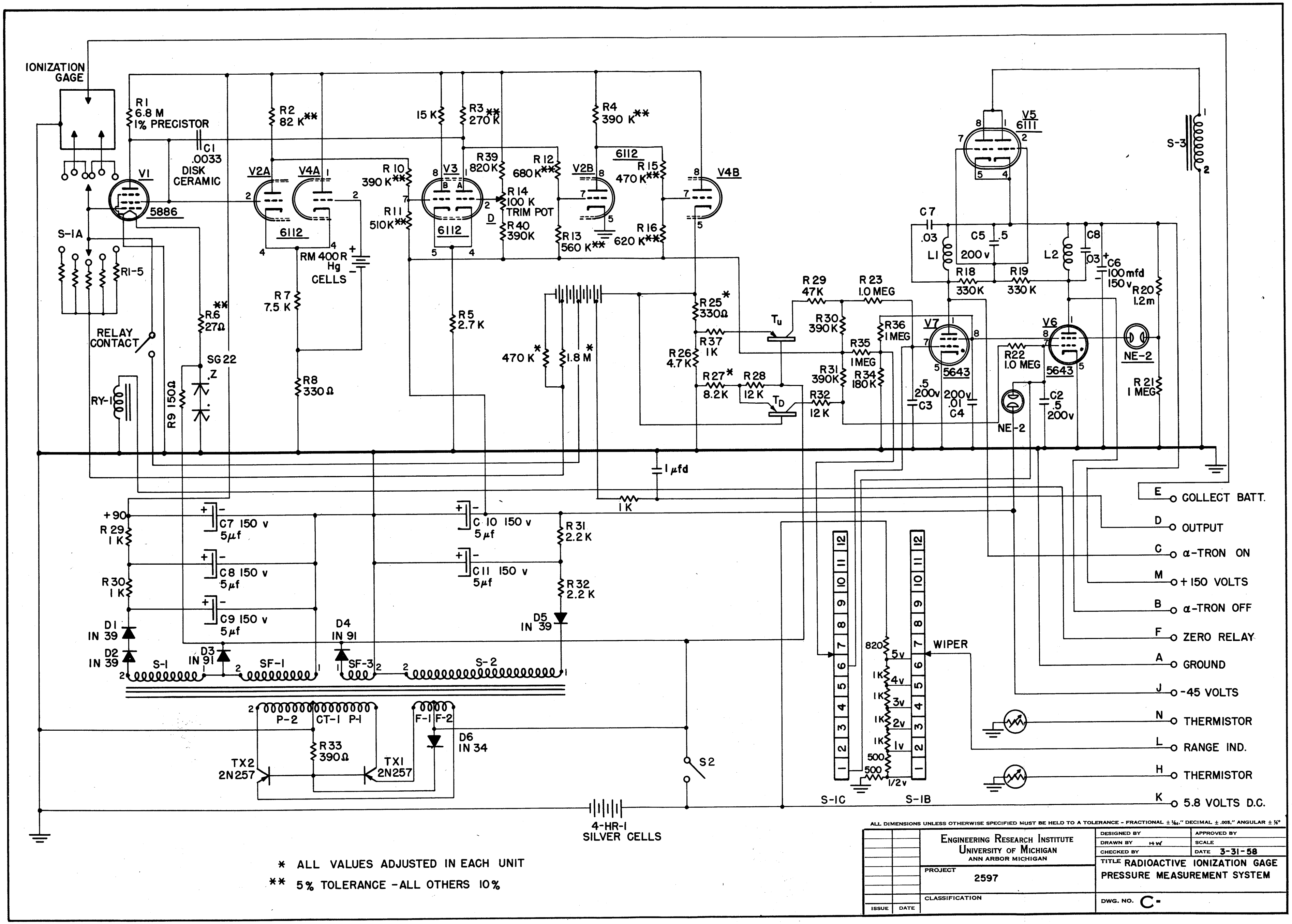

Fig. 2.4. System schematic diagram.

3.0 IONIZATION CHAMBER

A radioactive ionization gage produces a current that is proportional to the density of the gas within its walls, for a large range of densities. Several factors determine the magnitude of the current at a particular density, including:

a) volume of the chamber;
b) strength of the radioactive source;
c) composition of the gas; and
d) electrode potentials.

Although the i-p characteristic is essentially linear over a large portion of the chamber's useful range, it departs from linearity at low densities and ultimately at high densities. At the low-density end, the i-p curve approaches a particular low value of current, not gas-density-dependent, known as the dark current. As the density decreases and the ionization current correspondingly decreases, the dark current becomes a larger and larger fraction of the total current, finally masking the ionization current completely.

At the high-density end of the scale, recombination occurs for a larger and larger fraction of the ions as the density increases, thus limiting the number of particles available for collection. In addition, the useful path lengths of radioactive source particles become shortened by greater energy loss as the density, and hence the number of collisions, increase. These two major factors cause the i-p characteristic to depart from an extension of the linear portion.

One aspect of the i-p characteristic warrants further comment. Many chambers exhibit, in the operating region where recombination plays an important role in determining the output current, a hysteresis effect. That is, if the output current is observed for density change in one direction, for example, to lower densities, and then observed for increasing densities, it becomes apparent that the current is greater for a particular density when $d\rho/dt$ is negative. The magnitude of the difference is observed to vary with the geometry of the chamber, and is at present believed due primarily to adiabatic temperature changes and their effect upon the recombination and attachment coefficients for the gases in the chamber.

The particular ionization chamber employed as the basic sensing element in the pressure-measurement system described in this report has been designed on the basis of a laboratory investigation that considered various geometries,

*See Ref. 4 for further details of an investigation of this effect.

electrode configurations, electrode potentials, and radioactive sources. In general, the objectives of the investigation were to:

a) increase the magnitude of the output current for a given density as compared with an earlier model (see above);
b) reduce chamber volume;
c) discover the causes for and if possible decrease the dark current;
d) discover the causes for and if feasible eliminate the hysteresis effect;
e) eliminate hazard due to presence of radioactive ionizing source; and
f) determine a design that could be easily fabricated by relatively unskilled technicians.

To a substantial degree, all the above objectives are realized in the current design illustrated in Fig. 3.2, which shows a completed chamber with attached low-leakage ceramic wafer and associated hi-meg resistors.

The design changes leading to realization of these objectives are largely interdependent, and the single factor which makes the re-design possible is the radioactive source. Previous units employed a sealed (nickel overlay) stabilized radium source of activity up to 3 mC, which emitted, for useful ionization purposes, adequate 5 Mev alpha particles. The sources also emitted significant gamma radiation of an intensity sufficient to cause hazardous working conditions within 2 ft of the source. The gamma was of no value, producing a wholly insignificant contribution to the useful ionization current.

Consultation with the source supplier* led to consideration and subsequent adoption of tritium as a source material. Tritium is a high-activity beta source emitting 17 kev particles. Its known characteristics make it very suitable as an ionizing source for this application. It is characterized by a half-life of 12 years, adequate for calibration constancy for this application.

Under normal conditions it exists as a gas and is thus unsuitable directly. However, it readily combines with titanium to become titanium tritide. This form can be bonded to a stainless-steel foil which in turn can be secured to a convenient backing plate for applicational purposes. Figure 3.3 shows the titanium tritide—stainless-steel foil backed source secured** to an ionization-chamber end plate.

In preparation of the source, a thin layer of titanium ($\sim 1\ \mu$) is rolled on the stainless foil and then tritiated in a vacuum furnace. A thin layer is necessary to limit penetration of tritium and the consequent unnecessary loss of beta emission in the material, which, because of the low energy of the particles, is substantial in the 1-μ layer. Quantitative data on the relationship between effective and total activity are not obtainable utilizing existing

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*T. W. Taylor, U. S. Radium Corporation.

**Araldite Epoxy Resin No. 502, Catalyst HN951, CIBA, Inc.

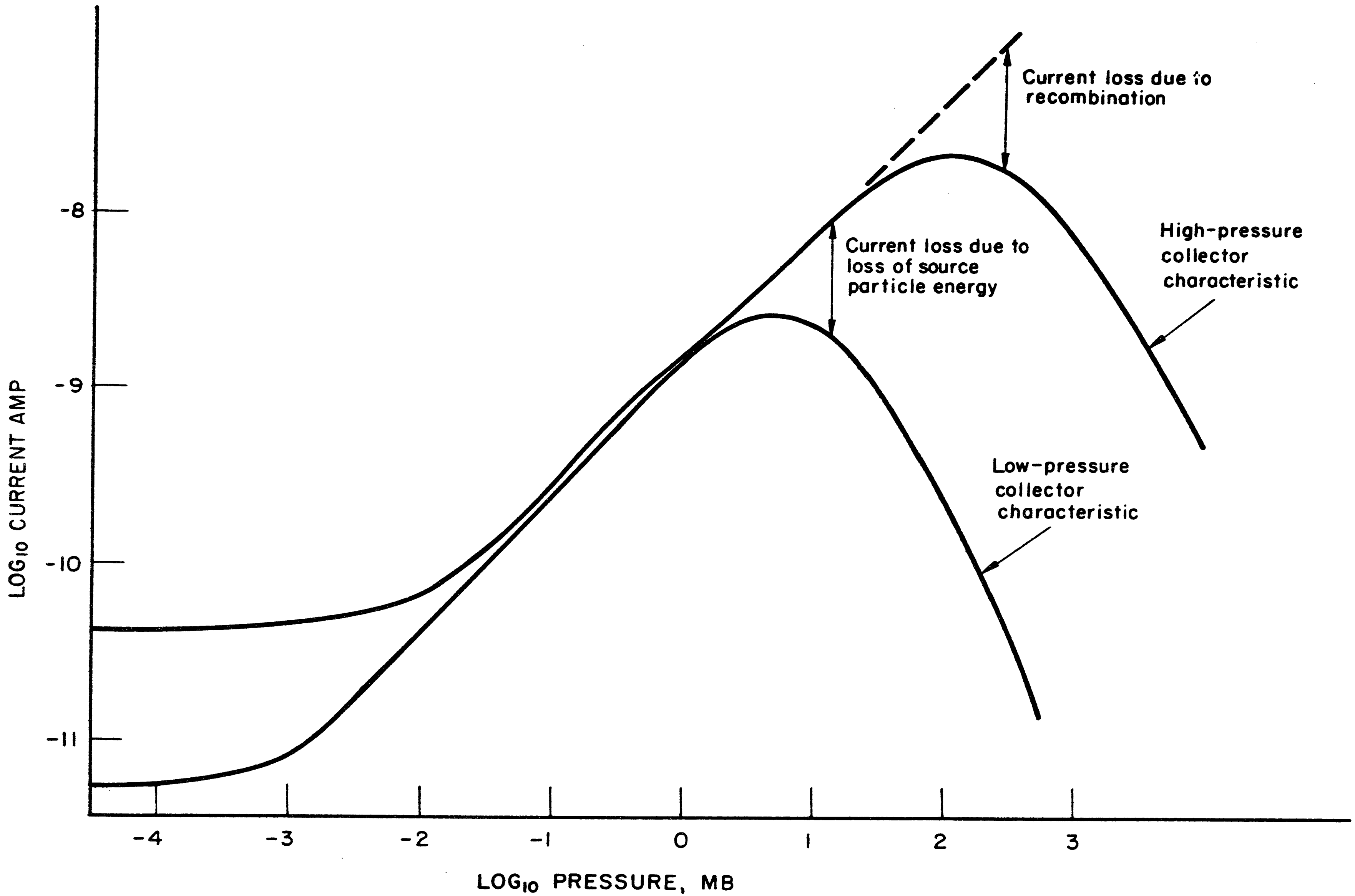

Fig. 3.1. i-p curve of typical ionization chamber showing low-pressure and high-pressure characteristics.

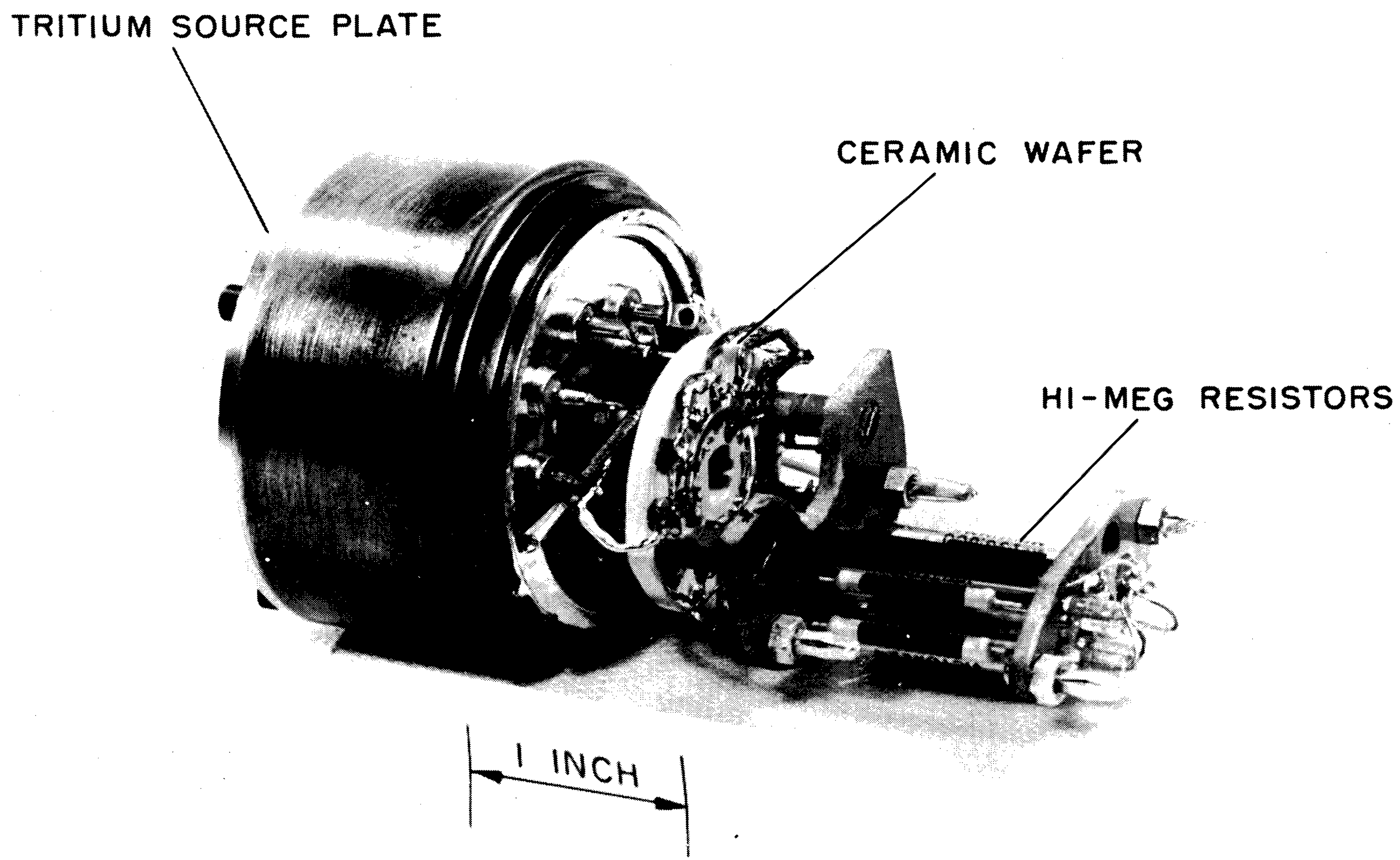

Fig. 3.2. Assembled ionization chamber with attached low-leakage wafer and hi-meg resistors.

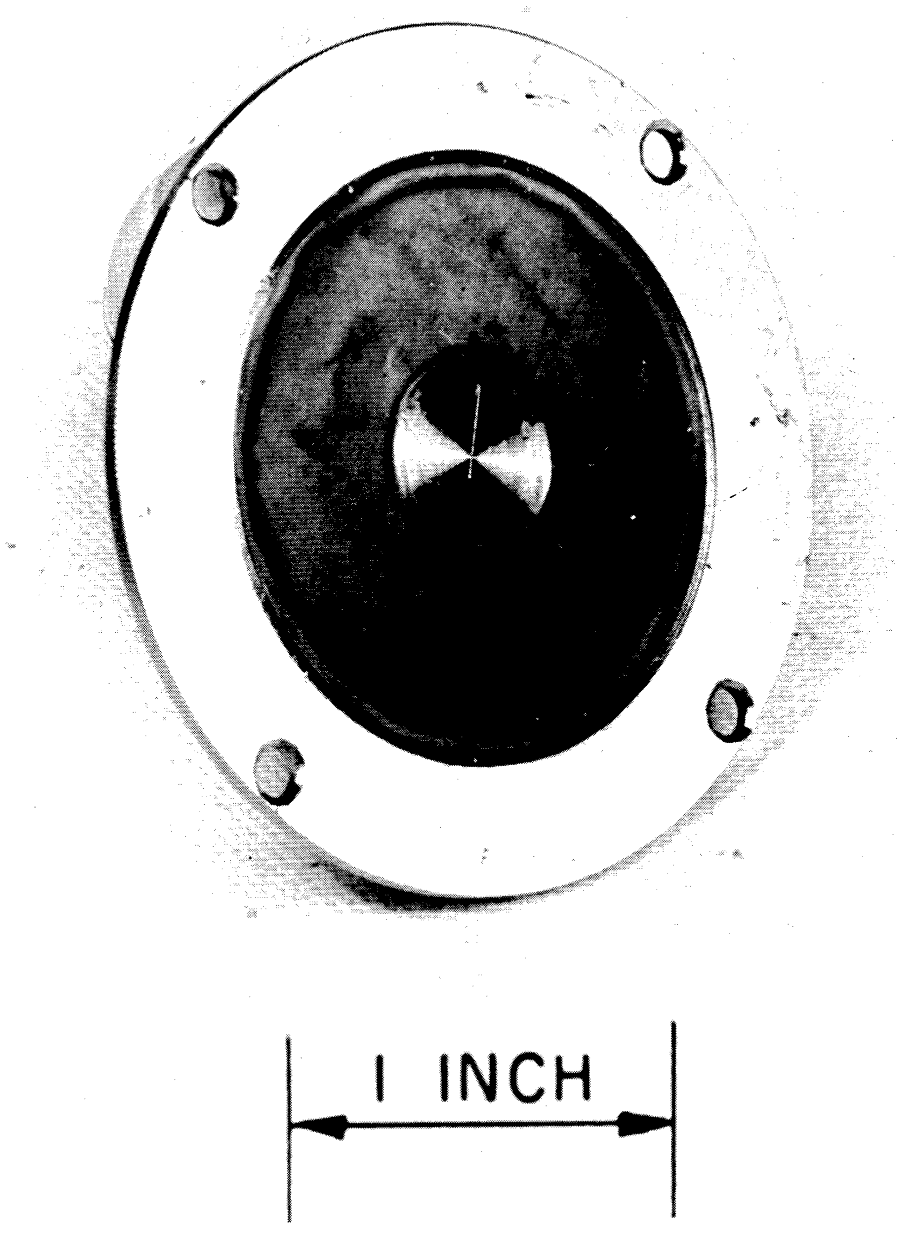

Fig. 3.3. End plate of ionization chamber showing titanium tritide source.

techniques. It is estimated from chamber measurements, however, that an effective activity of approximately 1 curie per square inch is attained. The source in Fig. 3.3 has an area of about 1.4 sq in.

Figures 3.2 through 3.7 illustrate the physical aspects of the ionization chamber. It is seen to consist of an outer stainless-steel wall, cylindrical in shape, closed at one end by the source-bearing end plate, and at the other by a disc carrying several glass-metal seals, to provide for external electrical connections, and element mounting. Internally, the gage consists of a cylindrical polarizing electrode (Fig. 3.6) and a collector assembly (Fig. 3.7) which supports 2 collectors, one for the high-density end of the range, the other for the low-density end.

It is to be noted that the source faces the open end of the polarizing electrode cylinder, directly adjacent to the high-pressure collector, the circularly formed wire shown in Fig. 3.5. This collector is supported on 2 glass-metal seals which are in turn supported by a bridge which spans the open end of the polarizing electrode.

The glass-metal seal visible in Fig. 3.5 in the center of the bridge supports the low-pressure collector which is shielded from direct source radiation by the bridge. The purpose of shielding the low-pressure collector is to minimize direct impact of the source electrons and the consequent secondary emission. The area of the collector is minimized to reduce electron emission that will occur due to x-ray radiation from the surface of the polarizing electrode under the influence, again, of the source electrons.

These precautions are essential to reduce the dark current, an important consideration, for the system cannot distinguish between collecting + ions and emitting electrons. Extensive tests have shown the dark current to be directly dependent upon the area of the collector (consistent with the x-ray concept as reported for thermionic ionization gages by Alpert[5]) and upon exposure to beta (or alpha) source emission.

The relatively low energy of the radiation means that the path length of the betas in air decreases sharply as the density increases. At higher densities, little ionization is produced in the vicinity of the low-pressure collector and an alternative collector near the source must be employed. Thus the chamber is provided with both a low- and high-pressure collector. They are proportioned so that in their linear region, near 1 mb, the currents are roughly equivalent, eliminating a step when changing from one to the other. Typical i-p characteristics of each are shown in Fig. 3.1, and a composite curve in Fig. 2.3.

The chamber elements are fashioned from stainless steel, spot welding being employed in the assembly of the structure. Two thermistors are usually employed during flight measurements, one in air, visible in Fig. 3.6, the other held in a small depression in the outside of the polarizing electrode end plate, the depression being visible in Fig. 3.6. These thermistors enable estimates of the

Fig. 3.4. Ionization-chamber elements.

Fig. 3.5. Ionization-chamber element assembly.

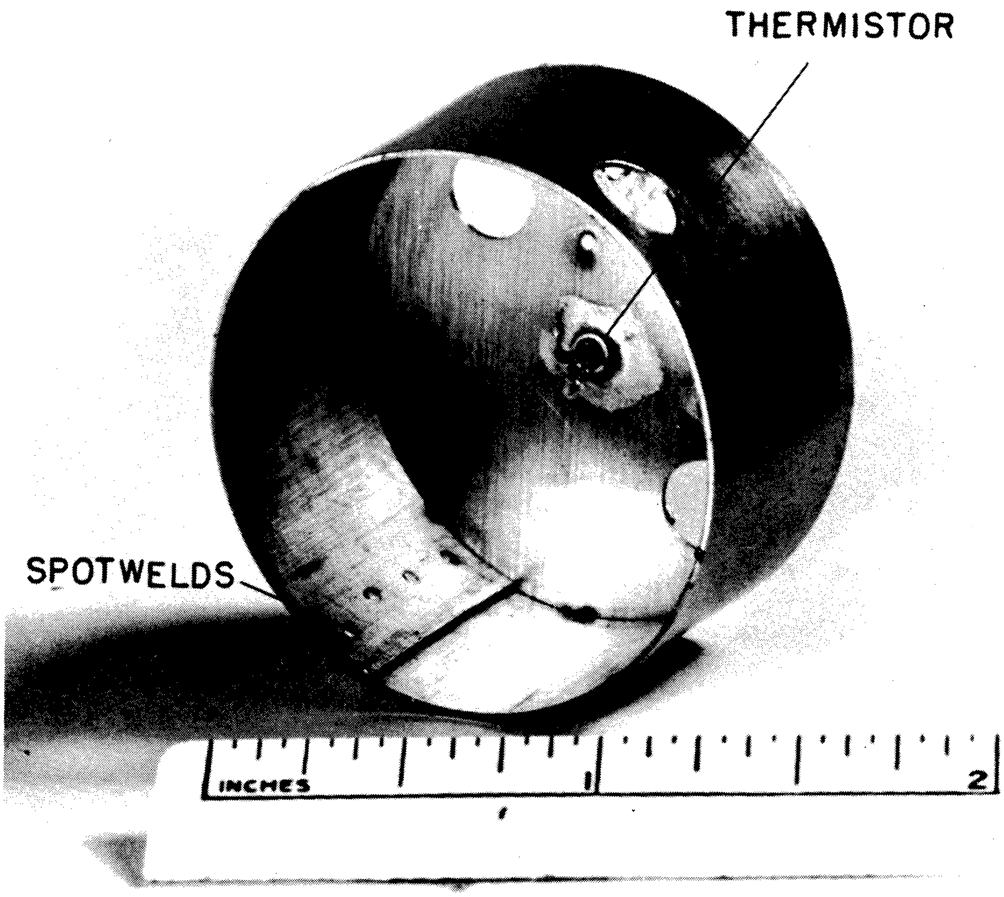

Fig. 3.6. Ionization-chamber polarizing electrode.

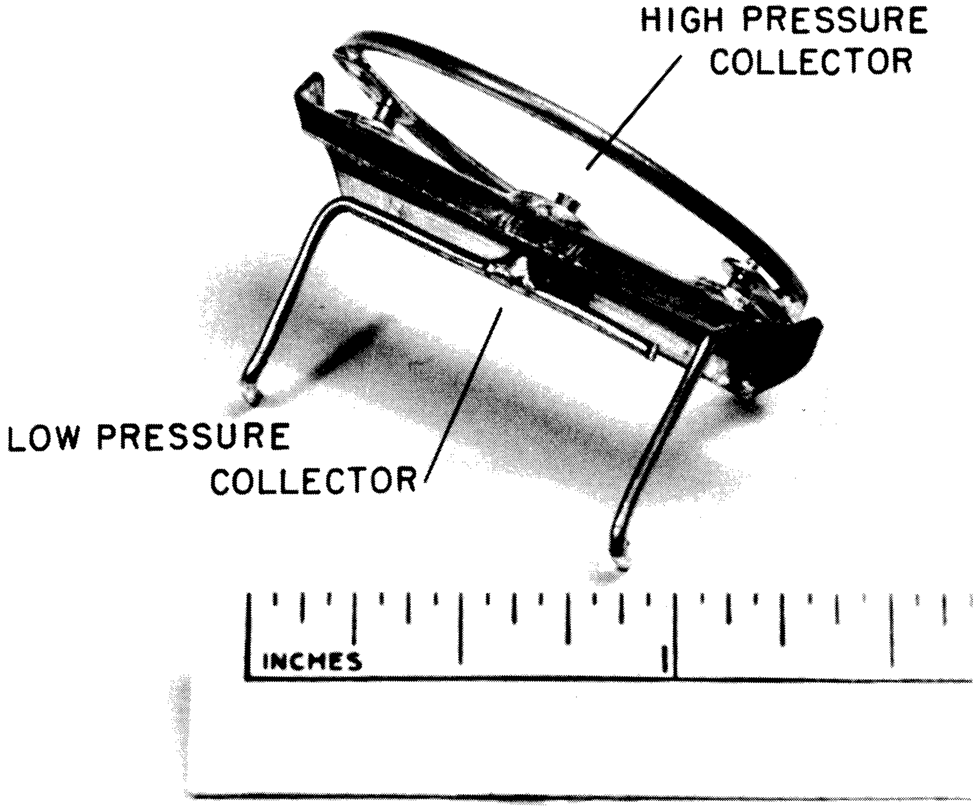

Fig. 3.7. Ionization-chamber collector assembly.

gas temperature in the chamber.

The collector potential +45 volts is established by an external battery. This arrangement is necessary to obtain a constant potential. It is expected that a Zener diode will ultimately be incorporated for this purpose, as constancy is required.

4.0 AMPLIFIER

The amplifier, Fig. 4.3, employed in this system has been developed to meet several requirements including (a) high input impedance to make negligible any loading effect on the highest value of chamber load resistance (1.9×10^{11} ohms), (b) low output impedance so that externally connected devices such as the telemeter, meters, etc., would not appreciably alter the magnitude of the output signal, (c) reasonable independence from supply-battery voltage changes, and (d) a loop gain of several thousand, so that the gain would not be a factor in the system calibration.

To meet these requirements, the circuit of Fig. 4.1 has been devised. Outwardly, it is a straightforward 5-stage direct-coupled amplifier with an electrometer input and a cathode follower output stage (see block diagram, Fig. 4.1). The electrometer input stage satisfies the first requirement for high input impedance, while the loop gain and cathode-follower output enables a low output impedance, which can be shown to be

$$Z_o = \frac{1}{g_m A} , \qquad (4.1)$$

where g_m is the transconductance of the cathode-follower tube and A is the loop gain, a real quantity for the usual operating range of the amplifier.

The five stages are centered about the electrometer (V1), a voltage amplifier (V2A), a differential stage (V3), another voltage amplifier (V2B), and the cathode follower (V4B). The individual stage gains taken singly are approximately, in the above order, 2, 20, 10, 10, and 0.8. The product of these gains is not, however, the loop gain, for the internal resistances of the power supply (both B+ and B-) have a profound effect upon operation of the amplifier. The effect of these impedances is to impose a complicated feedback situation, both positive and negative. For example, a change in current in the cathode follower reflects into the preceding stages a feedback voltage in the form of a B+ change. The polarity is effectively different for each stage, and the magnitude is sufficient to overwhelm the normal signal. Thus it is not possible to determine the loop gain by simply multiplying the individual stage gains. It may be obtained, however, by determining the ratio of the output voltage swing to the electrometer grid voltage swing for a representative change in voltage in the feedback line. Measurements of the gains of groups of stages indicates that the gain V2A is much greater than anticipated, indicating that it is probably operating as a starvation amplifier, very close to cut-off. In contrast, the gain of a representative system from the grid of V3 to the output is generally only about 10.

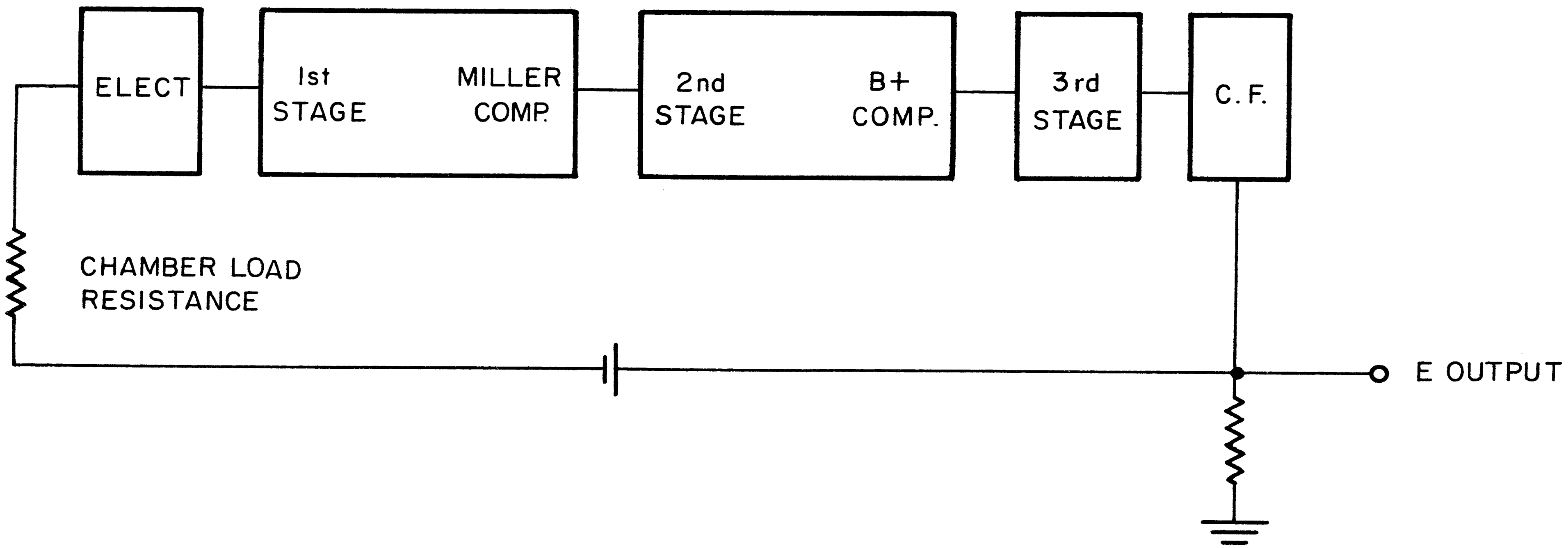

Fig. 4.1. Amplifier block diagram.

V4A provides compensation* for cathode temperature change and its effect upon the amplifier operating reference level. Apparently it does not play a decisive role in determining the system gain, although this possibility has not been investigated.

Several special points warrant comment:

a) V3A, although part of the differential amplifier stage necessary for proper phase relationships, acts also to compensate for the effect of B+ change upon the reference level of the amplifier. Adjustment of the grid's operating point, R14, permits quantitative variation of the compensation.

b) R6, R9, and Z comprise a regulator (Zener) for stability of the electrometer filament current. Two series connected diodes are employed to attain the desired voltage level.

c) Relay RY-1, when closed, forces a constant and known voltage in the feedback loop across the hi-meg resistor group and thus simulates a pressure-derived current. The corresponding output voltage becomes the reference level for the system, so that changes from an adopted value can indicate necessary corrections of output indications.

d) The ZPV is selected by adjusting the d-c battery voltage inserted in the feedback loop. This adjustment is accomplished by the voltage divider associated with battery BA2, Fig. 4.2.

e) Capacitor C1 prevents high-frequency oscillation within the loop.

f) The frequency response of the system is largely a function of the magnitude of the hi-meg resistor in use and the capacitance across the hi-meg resistor. This response is difficult to measure satisfactorily because of the low frequencies involved, and the necessity for inserting the test voltage (in lieu of a pressure change) in the feedback line. Measurements have shown, however, that the response is flat, for practical purposes, to at least 3 to 4 cps for the highest input resistance used. Generally, rates of change encountered during flight (for example, due to roll) do not require a response in excess of 1 cps.

g) Stability of the reference level of the amplifier is considered excellent. The reference output, generally 2.3 volts, is usually stable throughout a typical flight within 0.01 to 0.02 volt, the limit of most telemeters. From cold to operating temperature, the drift of the reference output generally does not exceed 0.03 volt.

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*Miller Compensator.

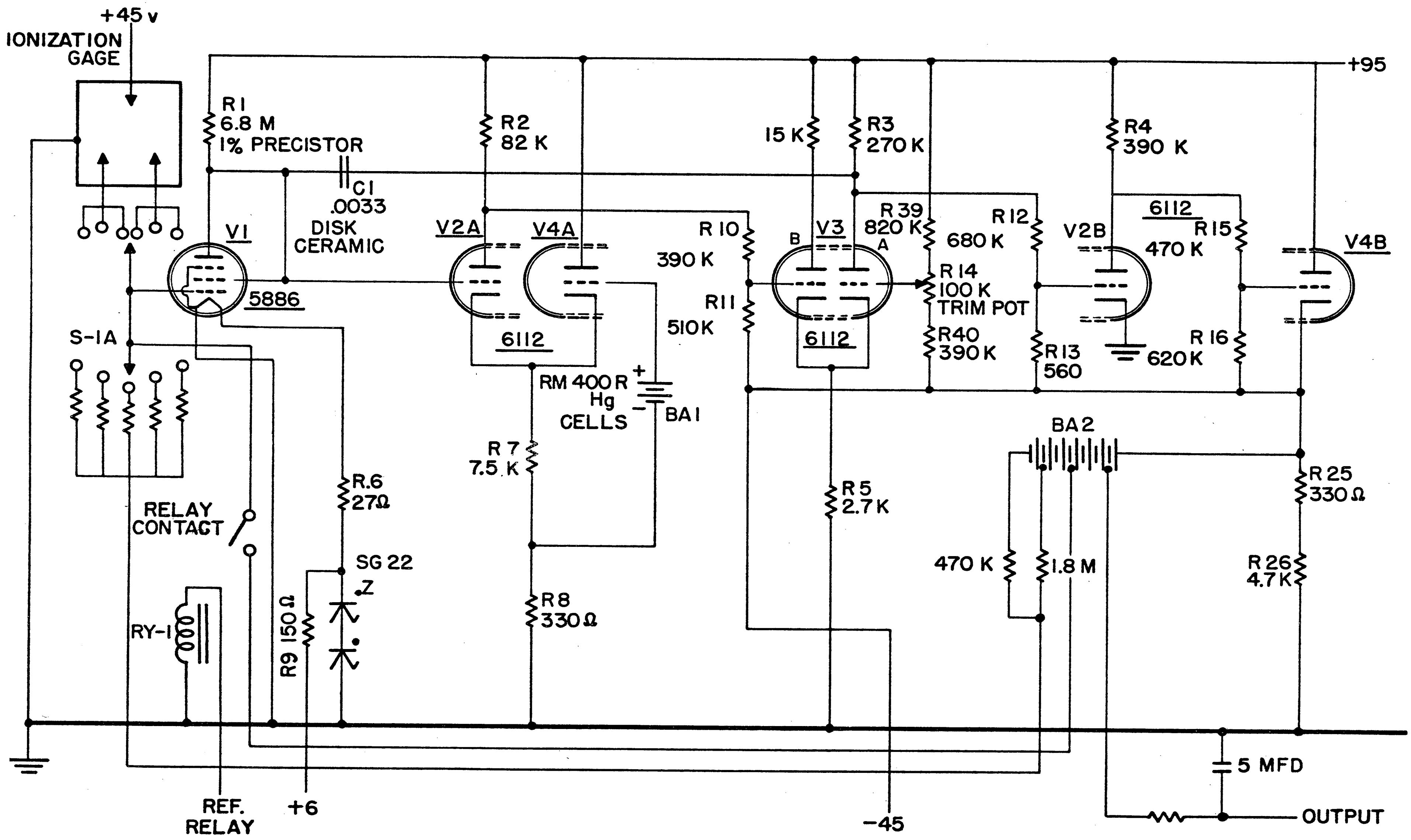

Fig. 4.2. Amplifier schematic diagram.

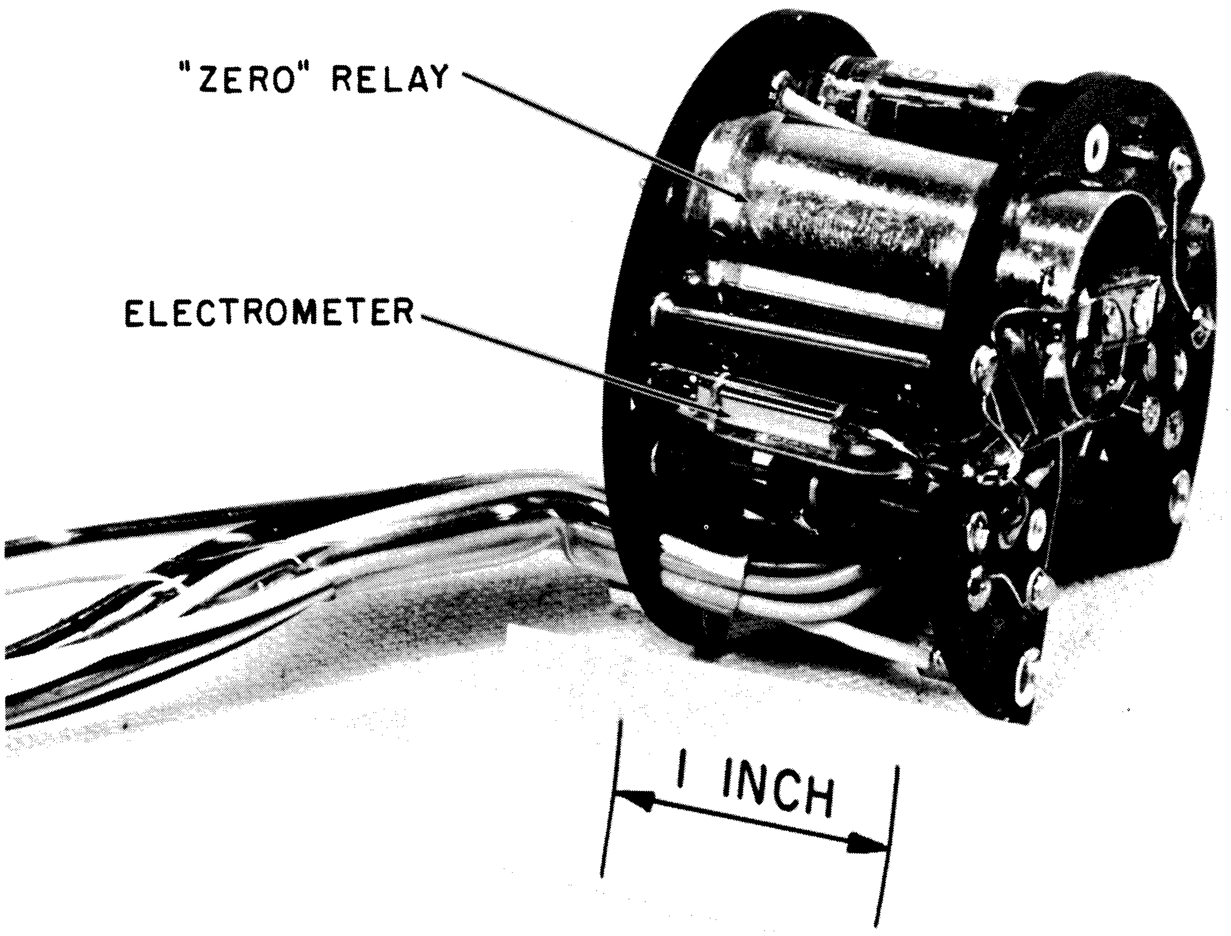

Fig. 4.3. Amplifier subassembly.

5.0 RANGE-CHANGING CIRCUIT

As noted in Section 2.0, the purpose of the range-changing circuit is to enable automatic insertion of any one of 5 possible ionization-chamber load resistances consistent with the current and fulfilling the requirement that there be maintained an on-scale output indication. Thus each time the output signal exceeds 5 or becomes less than zero volts a switching action is required. The output signal accordingly offers a natural means to initiate the switching action.

Physically, the resistor changes are brought about by bi-directional rotary solenoids actuating a ceramic wafer switch. See Figs. 5.1 and 3.2 for some mechanical details.

Typical rates of pressure change during rocket ascent do not indicate a need for range changes more frequently than every 10-15 sec. For this reason, the average energy requirements placed on the power supply for this mechanical function are relatively modest. However, the impulse required to activate a solenoid is substantial (typically 0.5 w sec) and so an energy storage system is indicated.

In this equipment (see Fig. 5.2), the energy is stored in a capacitor (C6, 100 mfd) and is expended in the solenoid (L1 for decreasing pressure or L2 for increasing pressure) through the thyratrons V7 and V6, respectively, causing one solenoid action and thus stepping the ceramic wafer one position.

Capacitor C6 is charged through V5 from winding S-3 of the main power transformer. The R-C networks R18 or R19 and C5 hold the charging tube V5 cut-off during discharge, preventing continued conduction through the thyratron once C6 has discharged. As soon as C5 has discharged, V5 will conduct, permitting the storage capacitor C6 to become charged again to its normal level, approximately 145 volts.

V7 conducts when the system output reaches 5.0 volts. A voltage related to the output level appears at the emitter of transistor T_u whose base is held at 5.8 v for reference. Roughly speaking, when the emitter exceeds the base potential, emitter-collector current flows. This current, flowing in R29, R30, and R35, swings the control grid potential of V7 positive, firing the tube.

A similar situation exists for V6 when the output signal goes negative. The emitter of transistor T_D is referenced to a fraction of the 5.8 volts by R27 and R28. When the output of the system passes through zero, base and hence collector current flows, swinging the grid of V6 positive, causing conduction. There are several additional aspects of the circuit which are necessary for proper operation:

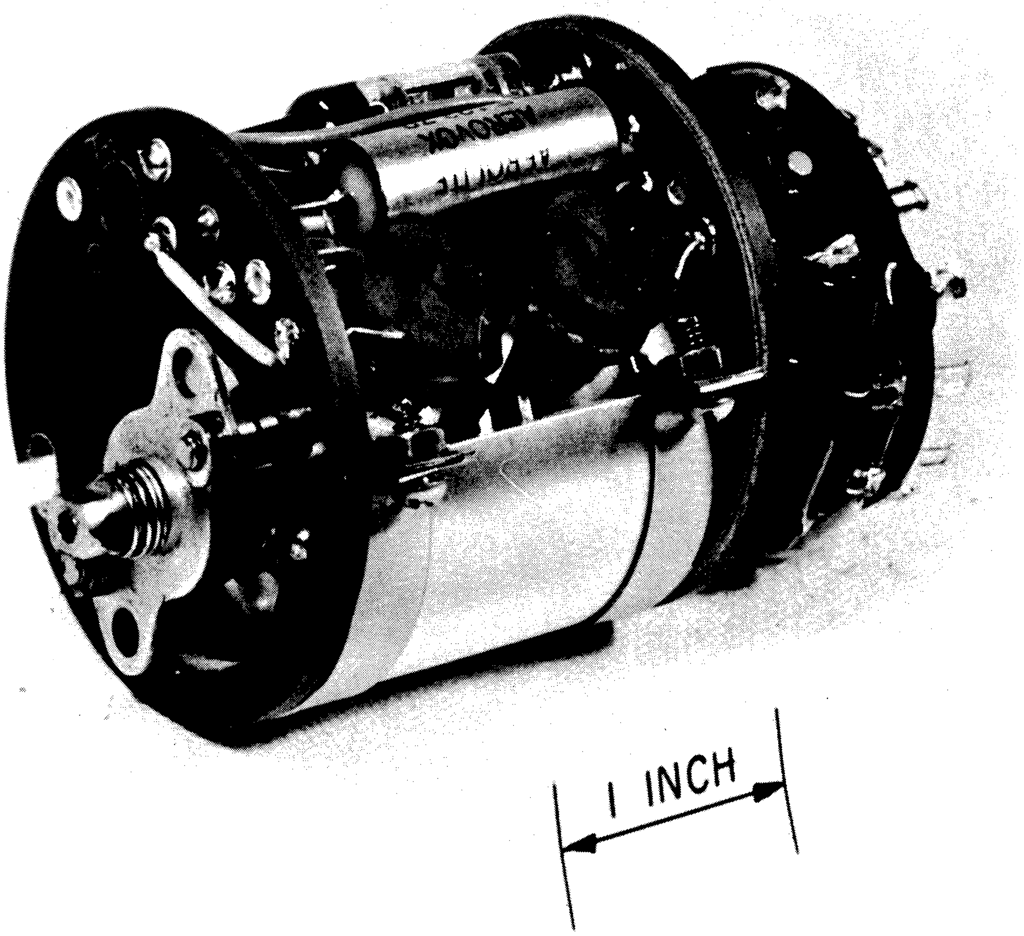

Fig. 5.1. Solenoid assembly.

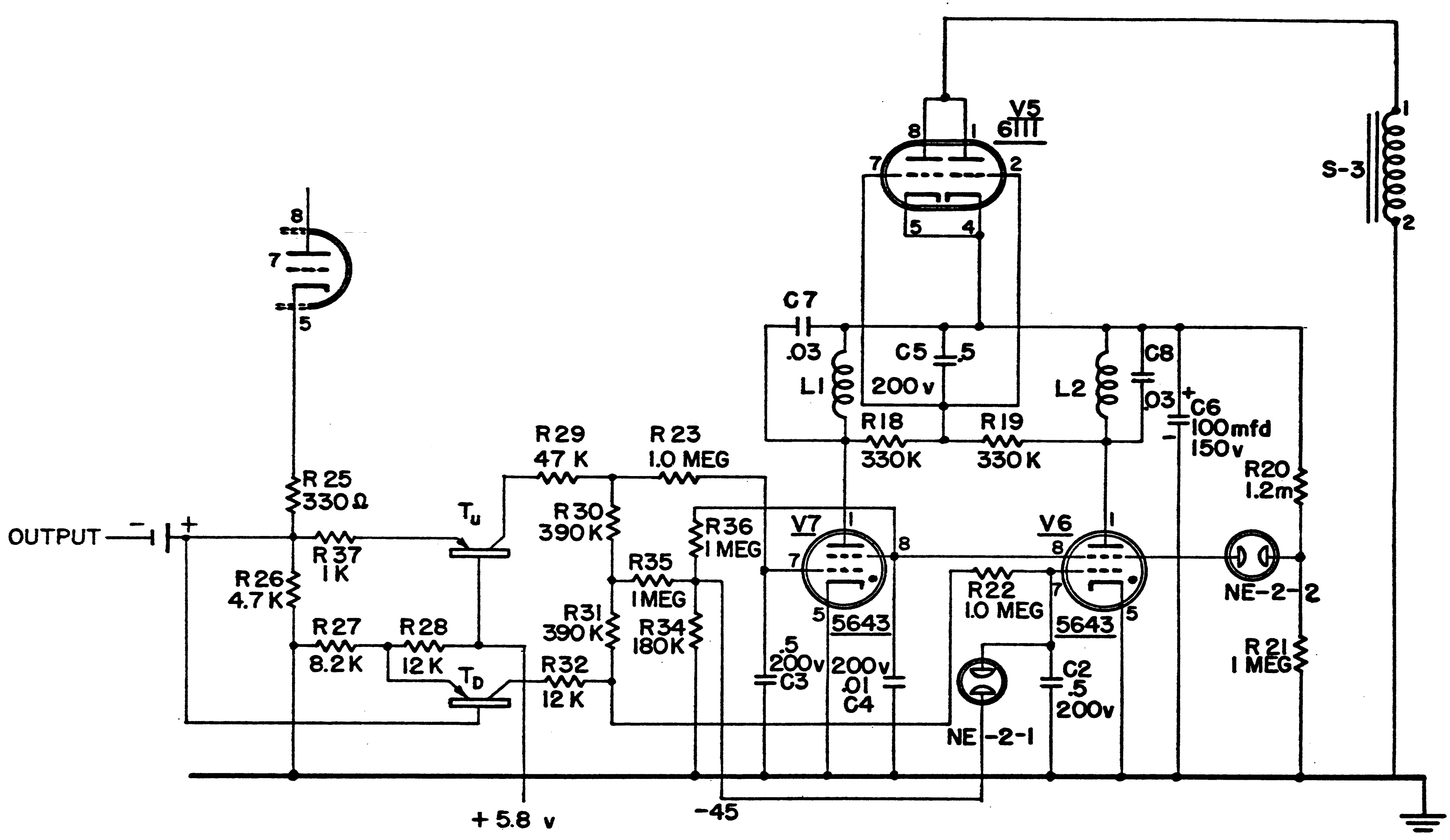

Fig. 5.2. Range-changing-circuit schematic diagram.

a) The system must continue to carry out the switching function under a circumstance which would maintain the control grid of either thyratron positive. Such a condition arises, for example, in performing a total head pressure measurement, where a sudden decrease in current is encountered due to a rapid increase in ram pressure during boost phase. The system may call for a 2- or 3-step range change which will hold the V7 control grid positive. The controlling function of the shield grid is utilized under these circumstances. It can be noted (Fig. 5.2) that the 2 shield grids are returned to -45 volts through R36 and to a fraction of the voltage of C6, determined by R20 and R21, through the neon tube NE-2-2. Thus, when conduction of a thyratron ceases, the shield is biased negative, and remains so, preventing re-ignition even though the control grid may be positive, until NE-2-2 conducts again. R20 and R21 are chosen so that the NE-2-2 will not re-ignite until there is sufficient charge in C6 to effect correct switching. Thus the shield grid controls the switching function in this circumstance, and permits repetitive switching when needed.

b) The RC combinations R23, C3 and R22, C2 are employed to impose a time delay in the thyratron ignition sequence. During rocket ascent when the angle of attack of the nose cone is less than 1-2 degrees, the cone wall pressure does not exhibit significant roll modulation. However, for larger angles of attack, which are not great enough to render the data useless, the output signal may momentarily exceed the switching limit. Under this circumstance, switching is not desired, for more data will be obtained by maintaining the mean value range in use. The RC delay is introduced to prevent a range change under these circumstances. The time constant is not great enough to delay "normal" functioning.

c) NE-2-1 is employed only during activation or deactivation of the system to prevent inopportune firing of V6 and does not function during normal operation.

d) Capacitors C7 and C8 in shunt with the solenoids assist in extinguishing the thyratrons when C6 becomes discharged.

6.0 TRANSISTOR POWER SUPPLY

The usefulness of any instrumentation power supply depends on its ability to supply the required load voltage with acceptable voltage regulation, noise, and efficiency, but in upper-atmosphere research instrumentation a vital first consideration is reliability. The amplifier and switching circuit described in this report were designed with this thought in mind. Accordingly the use of a negative voltage supply for grid return enabled the elimination of several bias batteries in the d-c amplifier and thus all interstage biasing could be accomplished through the use of a common supply, thereby minimizing the number of energy sources.

These considerations, and others relative to available space, and the necessity for physical ruggedness imposed by rocket use, indicated the desirability of employing a transistorized power supply.

Transistor-oscillator power supplies were in the early development stage at that time; considerable effort was applied to the problem at several laboratories. The authors are indebted to Mr. George C. Uchrin of the U. S. Army Signal Corps Engineering Laboratories, Fort Monmouth, New Jersey, for suggesting a fundamental circuit and for contributing his experience to the design of the power supply which is to be discussed. Mr. Uchrin had successfully built several supplies, including one which delivered 10 watts at 1000 volts.[6]

The basic circuit employed utilizes two transistors, a transformer having a center-tapped primary, and a center-tapped feedback winding in addition to the load secondary winding. These components correspond to T1, T2, P1, and P2, the two halves of the primary windings, and F1, F2 the feedback windings, as shown in Fig. 6.1.

To minimize switching transients, it is necessary that the leakage reactance of the transformer be as low as possible. The toroidal core which is used for this reason also provides a square hysteresis loop. A shorter switching time results, allowing a power supply to be designed for maximum efficiency. It is possible with such a transformer to switch a high current safely, causing the transistors to exhibit a greater-than-rated power dissipation during the short switching cycle. However, for the sake of reliability, the power supply to be described is not operated under these conditions, that is, at maximum power-transfer capability.

The operation of the circuit can be briefly explained as follows: while one transistor is conducting, the voltage induced in the feedback winding is $e = -N(d\phi/dt)$. The windings are connected so that the conducting transistor

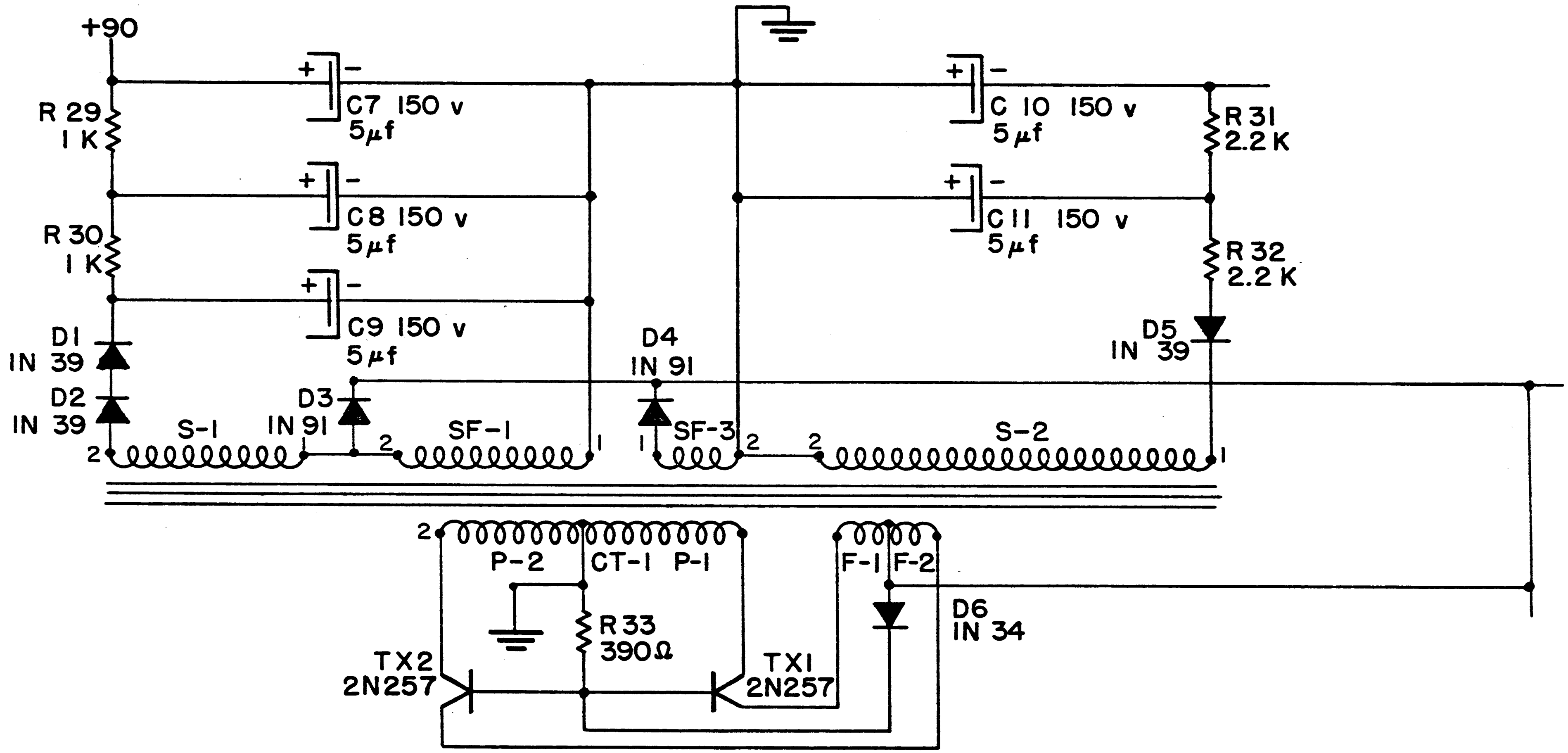

Fig. 6.1. Power-supply schematic diagram.

will be biased "on" and the nonconducting transistor will be biased "off." However, as the primary current reaches a limit, imposed by the circuit constants, or as the core becomes saturated, the emitter potential will drop to zero and the conducting transistor will cease to conduct. This will result in the collapse of the field and reversal of sign of the feedback voltage, causing the originally conducting transistor to be biased "off" and the nonconducting transistor to conduct. This cycle will repeat at a frequency primarily dependent on the magnetic characteristics of the transformer and the battery voltage, the transistors acting essentially as switches. The output of the power supply is a square wave which may carry relatively large switching transients, unless particular care is taken in the choice of circuit parameters.

Three basic configurations, common base, common emitter, or common collector, can be used. The operation of any of these is the same in principle; however, in the case of the common collector and common emitter circuit, the feedback windings must be independent.

One of our primary considerations is the ability of the power supply to start under load. The power supply is a loaded oscillator and thus overloads may stop oscillation, and further, any load may prevent reliable starting. It is possible, of course, to apply a starting pulse of some type or to energize with reduced load. The first solution involves control complications, while the latter is not dependable and could result in transistor damage. Instead, a simple starting circuit, such as that employing R33 and D6 as seen in Fig. 6.1, has proven very satisfactory. It can be seen from the circuit that the base-to-emitter voltage is that of the battery minus the drop in R33 and the feedback winding F1 and F2. Thus, when the unit is first turned on, both transistors will tend to conduct heavily. However, the normal unbalance of the circuit components will cause an unbalance of current in P1 and P2. This will introduce different voltages in F1 and F2 which will allow one of the transistors to gain control and cut the other off. The circuit will oscillate just as in the previously explained elementary circuit. Once oscillations start, the starting circuit has negligible effect, and since only the base current flows in R33, it is not necessary to remove the starting resistance. The diode protects the transistor by causing an IR drop in R33 so that full battery voltage is never applied to the transistor.

By choosing the number of feedback turns to supply just enough base current for the maximum load and making fine adjustments in R33, it is possible to prevent the transistors from experiencing even transient overloads in either power or current. Thus, this simple starting circuit enables dependable operation and also provides a convenient adjustment of circuit operation.

The simplicity of this starting circuit was a primary factor in the choice of the common base circuit, as starting circuits for other configurations were generally more complex. It can be seen by reference to Fig. 6.1 that the primary circuit has the configuration of the common base circuit with the addition of the starting components.

Two loads must be supplied by the power supply, one steady-state and the other transient and intermittent. The steady-state load requires a B+ of 95 volts at 4 mils and a B- of 45 volts at 0.4 mil. The transient load involves the intermittent recharging of a 100-mfd condensor to 150 volts.

Two separate power supplies could have been used but the desired results were obtained in a single supply by utilizing half-wave rectification and supplying each of the two loads on alternate power strokes. Transistor T1 supplies energy for the steady-state requirement and resetting the core following conduction of T2. T2 supplies the energy for the transient load and resets the core following conduction by T1. This is accomplished by arranging the polarity of the rectifying diodes appropriately. The steady-state load voltage is sufficiently independent of the transient loading.

The power supply (see Fig. 6.2) has proven to be a dependable unit. A total of 28 units have been flown and to date no field servicing has been necessary, and no known flight failures have occurred. Its efficiency varies from 20%, when the 100-mfd condenser is charged, to 65% at the start of the recharging cycle. Battery utilization is 85% at the lowest efficiency of the power supply since the amplifier and range-changing circuit's filament load places the largest demand on the battery.

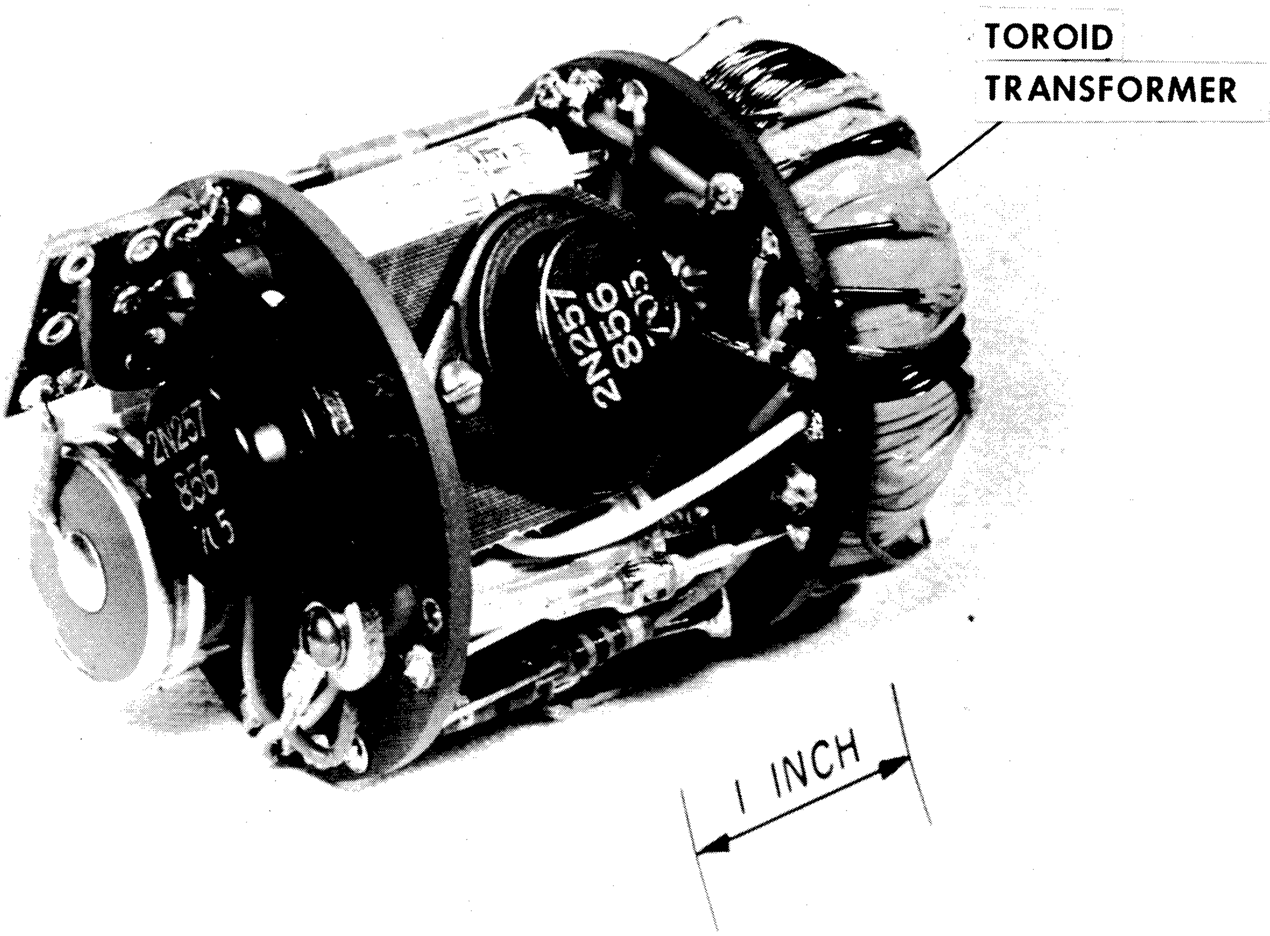

Fig. 6.2. Power-supply assembly.

7.0 MISCELLANEOUS

7.1 EXTERNAL CONTROL

External control of the system, including turning on, turning off, range changing, etc., is accomplished through the use of externally applied power and switching. The main power switch, connecting the internal 4-HR1 battery pack (or an external test source) is S2, Fig. 2.4, a cam-actuated microswitch. The bi-directional rotary solenoid (S1) employed for range changing (Section 5.0) carries this cam on its shaft. It can be noted that connections to the positive side of the storage capacitor C6 and the two thyratron plates are available externally, thus enabling external charging of C6 and subsequent discharge through the solenoids to step the rotary solenoid, by externally connecting the appropriate plate lead to ground.

In addition to the ceramic hi-meg wafer, the solenoid assembly carries 2 single-throw 12-position wafers, visible in Fig. 5.1 and shown schematically in Fig. 2.4 as S1B and S1C. S1B provides an external indication of the position of the shaft of the rotary solenoids, thus indicating the particular hi-meg resistor in use. Thus, using an external 0-5 voltmeter, 5 volts correspondsto range 5, 4 volts to range 4, etc., and 0.5 volt to the "off" position. S1C functions to bias the appropriate thyratron grid when the system is in position 1 or 5, preventing possible self-induced switching to the "off" position or past range 5 as discussed at the end of Section 2.0. It is also to be noted that a connection to the -45 volt bus is available. This is employed externally to disable the system during warm-up or turn-off, by applying a sufficiently high negative voltage (approximately -90) to bias every accessible tube grid beyond cut-off. This function is obviously particularly necessary for the thyratrons, and the electrometer which becomes cut off when the cathode potential of V4B goes to zero.

Figure 7.1 illustrates the external control circuit. It provides the necessary external power sources either by battery or rectifier supply, and in addition enables monitoring of the pertinent voltages. The terminal indications correspond to those of the system plug.

This control system plus the circuit arrangement noted indicate the following procedure for activating the system, assuming the correct setup has been established.

1) Check:
   - a) range position 0.5 volt (M3)
   - b) reference relay off (S6)
   - c) battery at 5.8 (or more unloaded) (M2)
   - d) overbias on (S7)
   - e) output negative (M1)

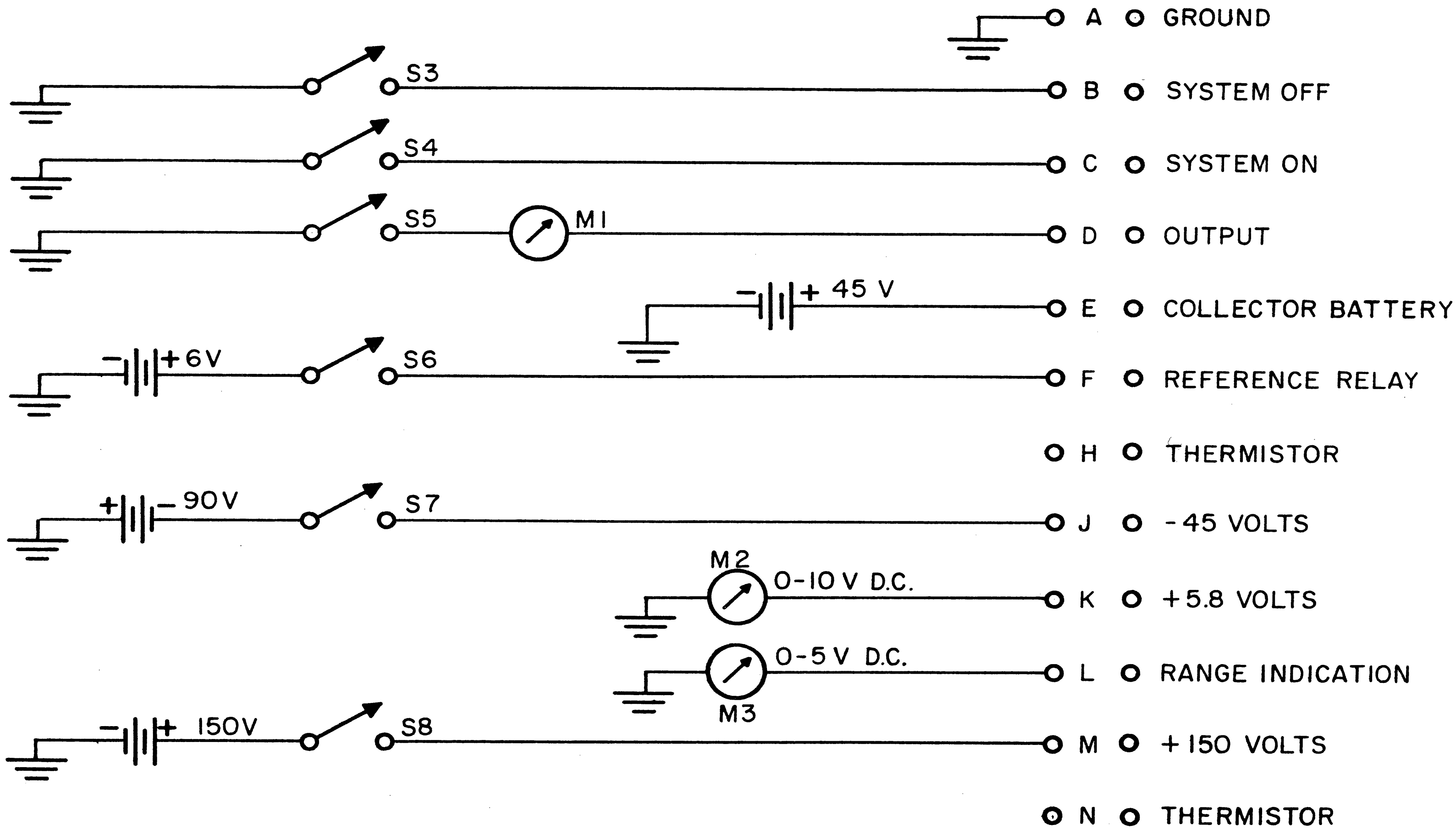

Fig. 7.1. Schematic diagram of external control circuit.

2) Close S8 for a few seconds to charge "+150" (capacitor C6)

3) Close S4 for a few seconds, stepping the solenoid, and permit warm-up for 60 seconds. Range should indicate 1 volt.

4) Remove overbias (S7). Output should indicate an on-scale value for atmospheric chamber pressure.

5) Check reference level by closing S6, thus energizing RY-1. Output should indicate approximately 2.3 volts.

6) Switching action may be checked by forcing (momentary closure of S4) to range 2 (output goes negative) and observing self-induced return to range 1.

7) To 'turn-off,' reapply overbias and then step rotary solenoid to off position by closing S3 momentarily.

8) Open S5 to prevent meter (M1) drain on internal feedback line battery.

7.2 BATTERY PACK

As noted from Fig. 2.4, the power for normal functioning of the system is obtained from 4 HR1 silver cells. This pack (Fig. 7.2) has sufficient capacity to operate the system for approximately 1 hr after having been fully charged at 0.1 amp to a terminal voltage of 2.0 volts per cell. Nonmilitary grade cells are employed and generally provide 0.1 to 0.2 volt higher terminal voltage than military procurement. The higher voltage is particularly desirable for the thyratron heaters.

A fully charged set of batteries is normally operated for at least 15 min prior to flight to enable the terminal voltage to drop to its long-term value. For this application, which requires approximately 1.75 amp, the initial voltage is generally about 6.5 volts and the final value very nearly 5.8 volts. Experience indicates excellent constancy at this value for 30-40 min.

7.3 CALIBRATION

Units prepared in this laboratory are calibrated over the range 10^{-3} mb to atmospheric pressure using the laboratory vacuum system. The setup utilized is illustrated in Figs. 7.3 and 7.4.

For pressures from 10^{-3} mb to approximately 5 mb, McLoed gages are employed. For pressures greater than 1 mg, Wallace and Tiernan aneroid gages are used. The vacuum system employs mechanical fore pumps and an oil diffusion pump and is capable of pressures as low as 10^{-7} mb.

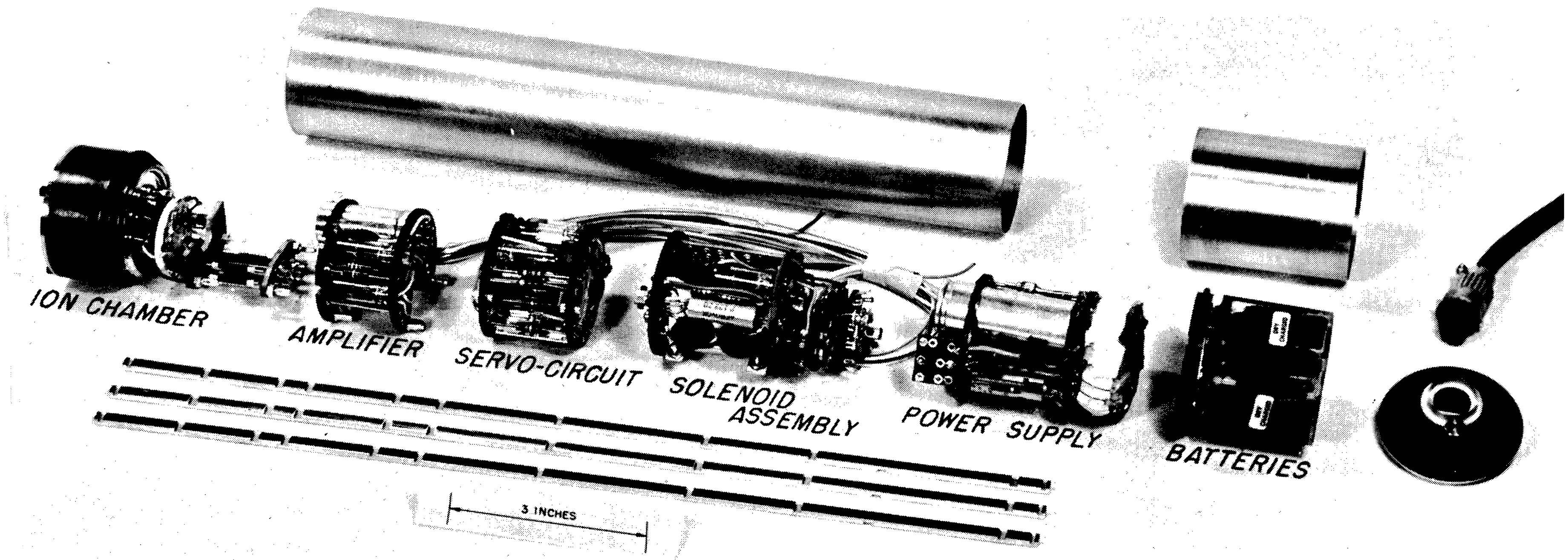

Fig. 7.2. Exploded view of unit subassemblies.

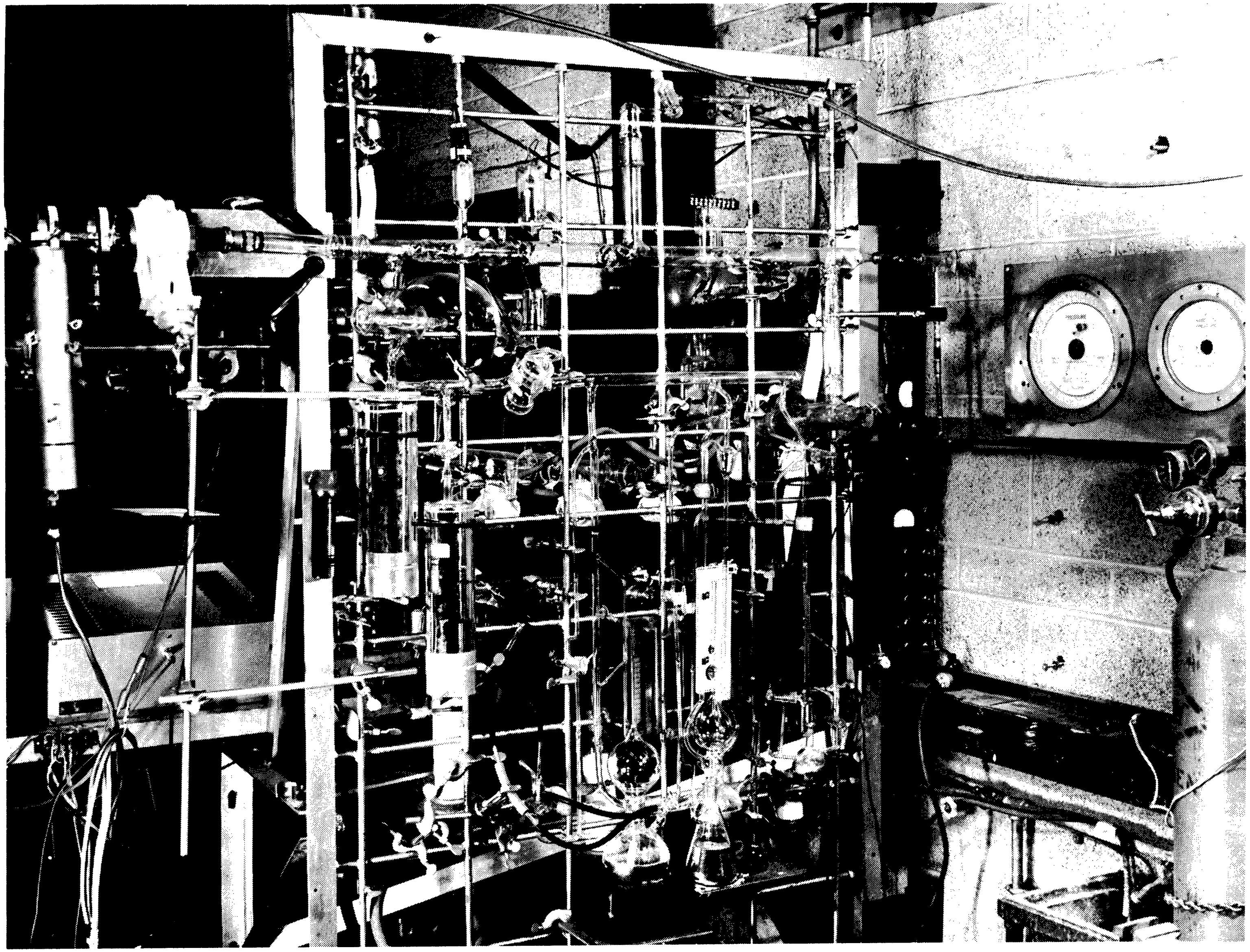

Fig. 7.3. Vacuum system used for calibrating pressure-measurement system.

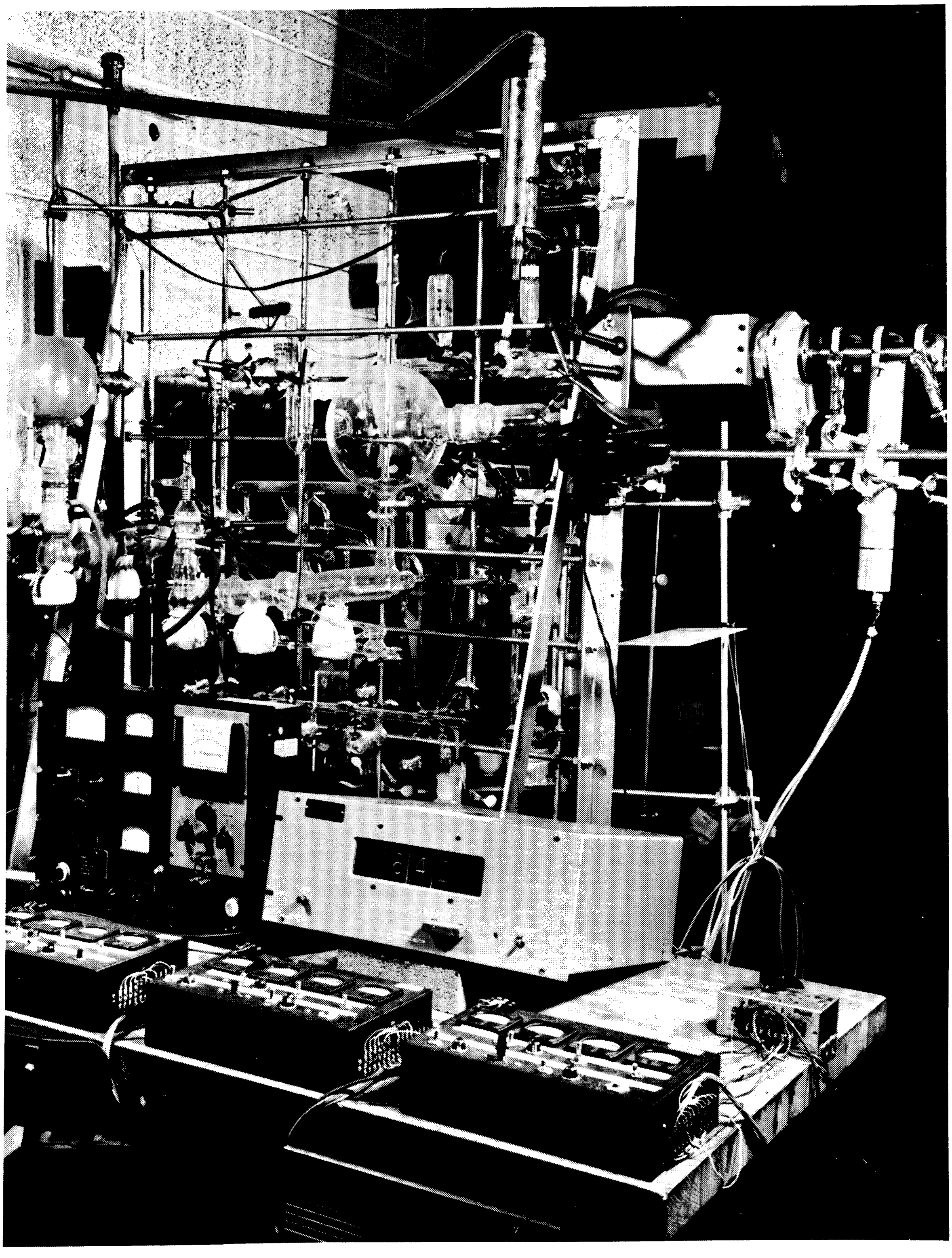

Fig 7.4. Calibration setup at vacuum system.

The system is equipped with typical accessories for rough pressure indication, protection in the event of glass breakage, air dryer inlets, liquid nitrogen traps to prevent contamination by mercury, and an arrangement visible in Fig. 7.3 to permit ready connection of 1 to 3 ionization-chamber systems.

The calibration procedure involves a preliminary pump down of the chambers to effect adequate outgassing. Generally, the units are pumped for 1-2 days prior to calibration although a clean chamber will reach about 10^{-5} mb in less than 2 hr.

A point-by-point calibration is carried out, starting at pressures somewhat less than 10^{-3} mb, gradually admitting dry air to the system. Five to ten points are taken for each range and plotted point by point as taken so that possible errors can be detected during the process.

The systems are operated from a regulated power supply which provides the 5.8 volts. The output is measured to the nearest hundredth of a volt with a digital voltmeter. The values obtained, the reference value, and thermistor resistances are recorded. A complete set of calibration curves of a typical system is shown in Figs. 7.5 through 7.10.

7.4 CHOICE OF HI-MEG RESISTANCE VALUES

Proper values of the hi-meg resistances are determined by (a) the desired pressure resolution, (b) the range of currents to be measured, (c) the ZPV, and (d) the switching limits. The relationships between these factors can readily be shown to be:

$$\frac{ZPV - E_{LL}}{ZPV - E_{UL}} = \frac{R_n}{R_{n-1}} = k \qquad (7.41)$$

$$\frac{i_{max}}{i_{min}} = k^n \qquad (7.42)$$

$$ZPV = \frac{kE_{UL} - E_{LL}}{k - 1} \qquad (7.43)$$

where

i_{max} = maximum current to be recorded (e_o = 0 v),
i_{min} = minimum current to be recorded (e_o = 5 v),
n = number of resistors (determined by required resolution),
E_{UL} = upper switching limit,
E_{LL} = lower switching limit, and
R_n = n th resistance.

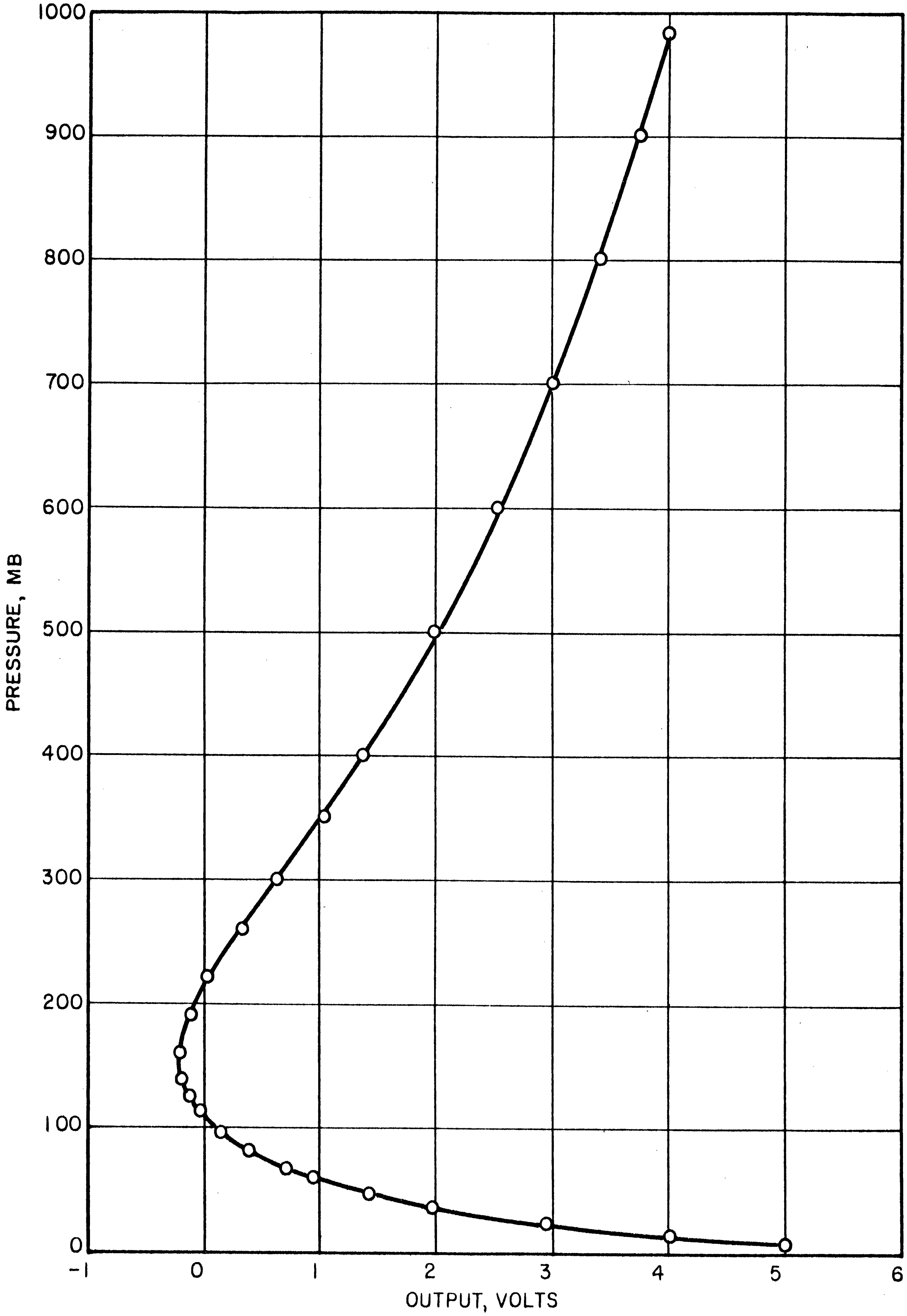

Fig. 7.5. Calibration curve, range 1.

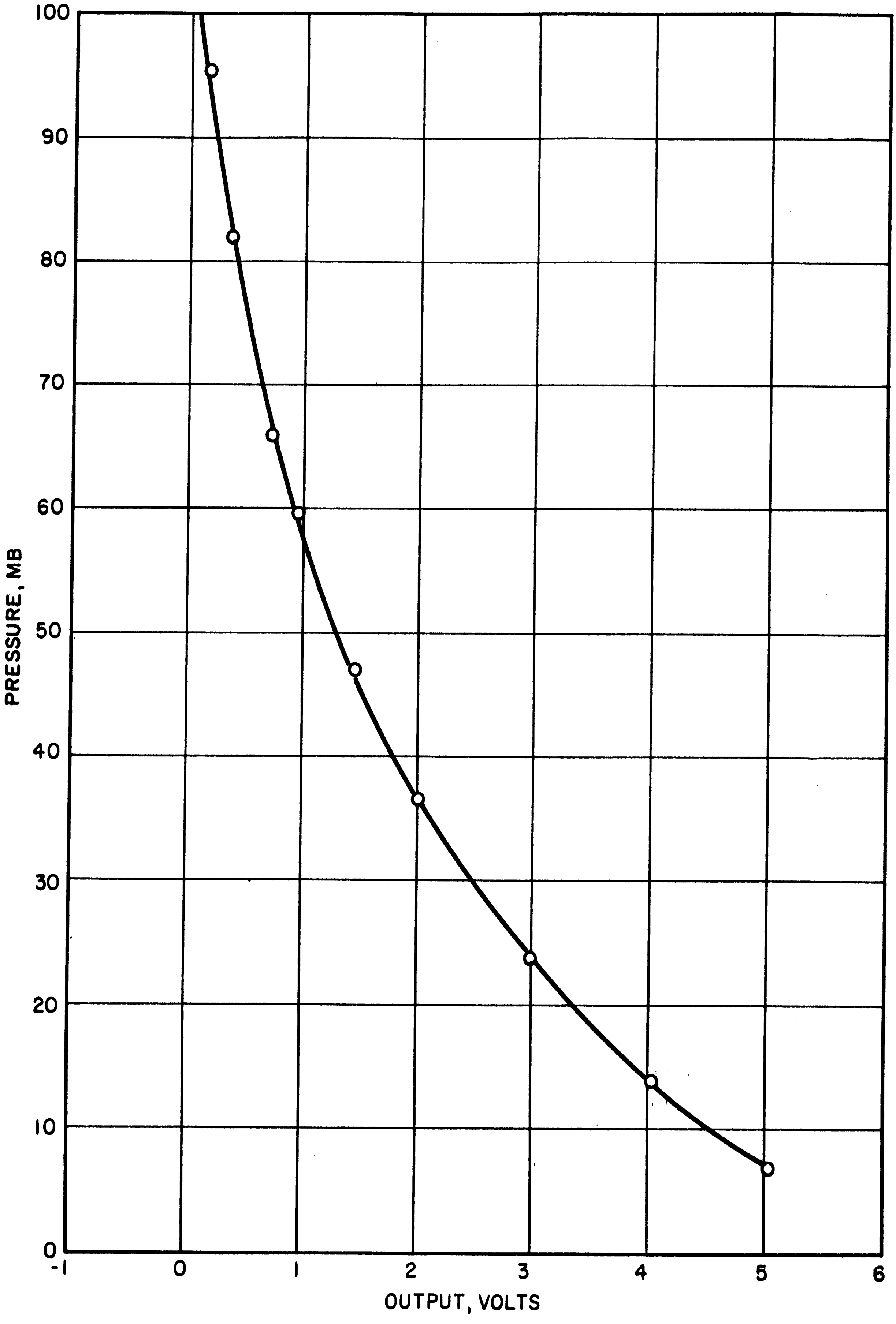

Fig. 7.6. Calibration curve, range 1.

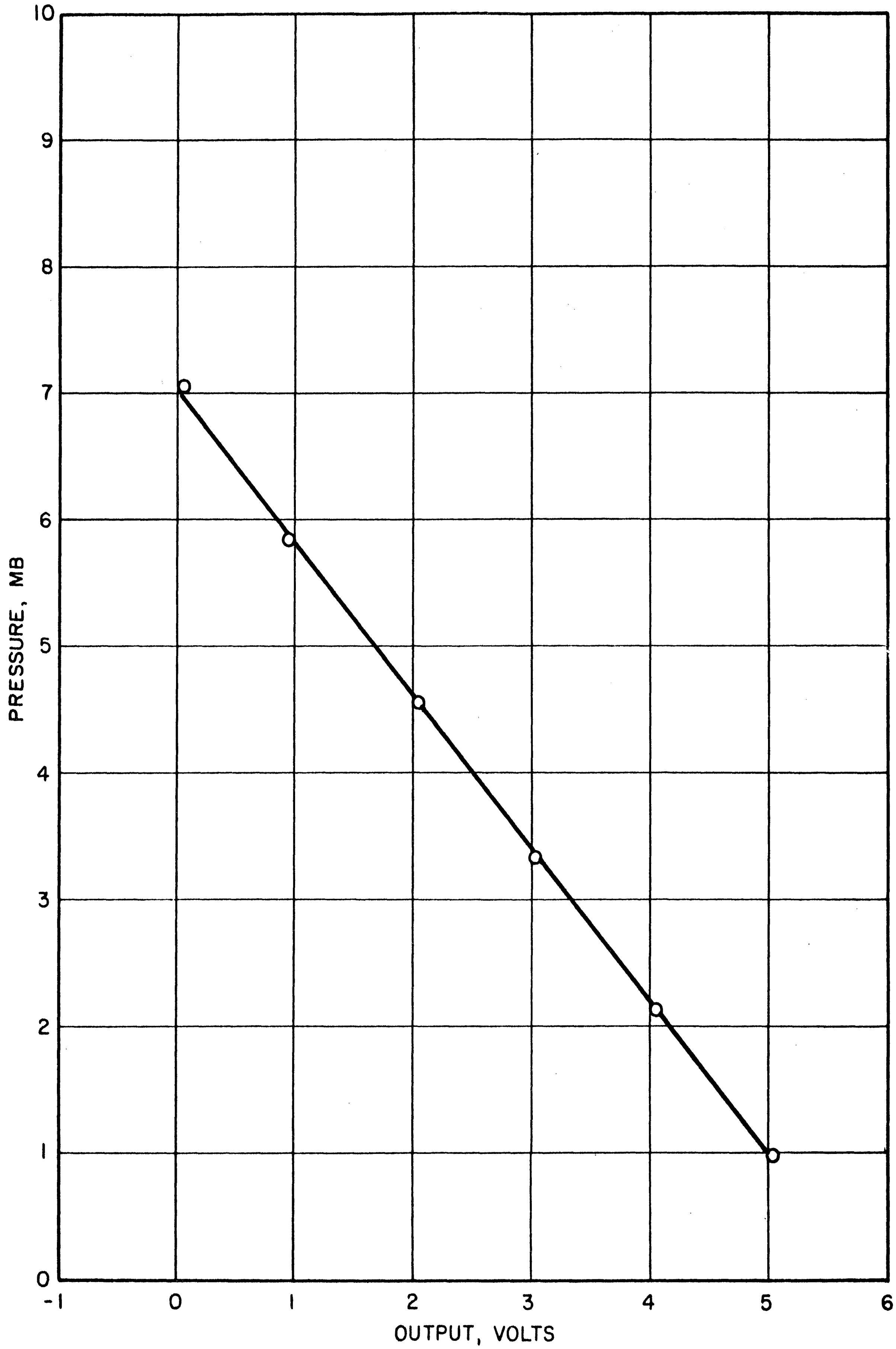

Fig. 7.7. Calibration curve, range 2.

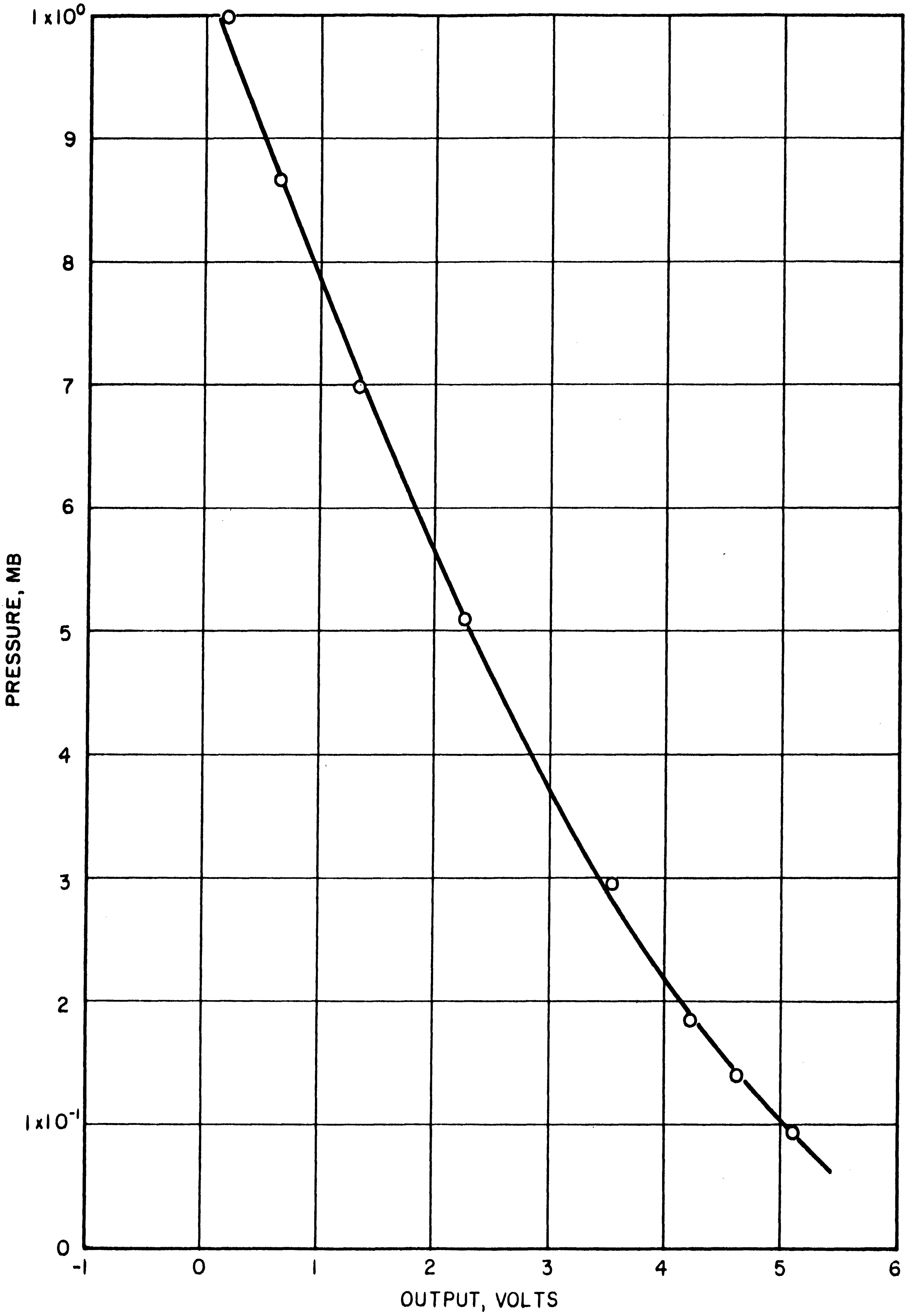

Fig. 7.8. Calibration curve, range 3.

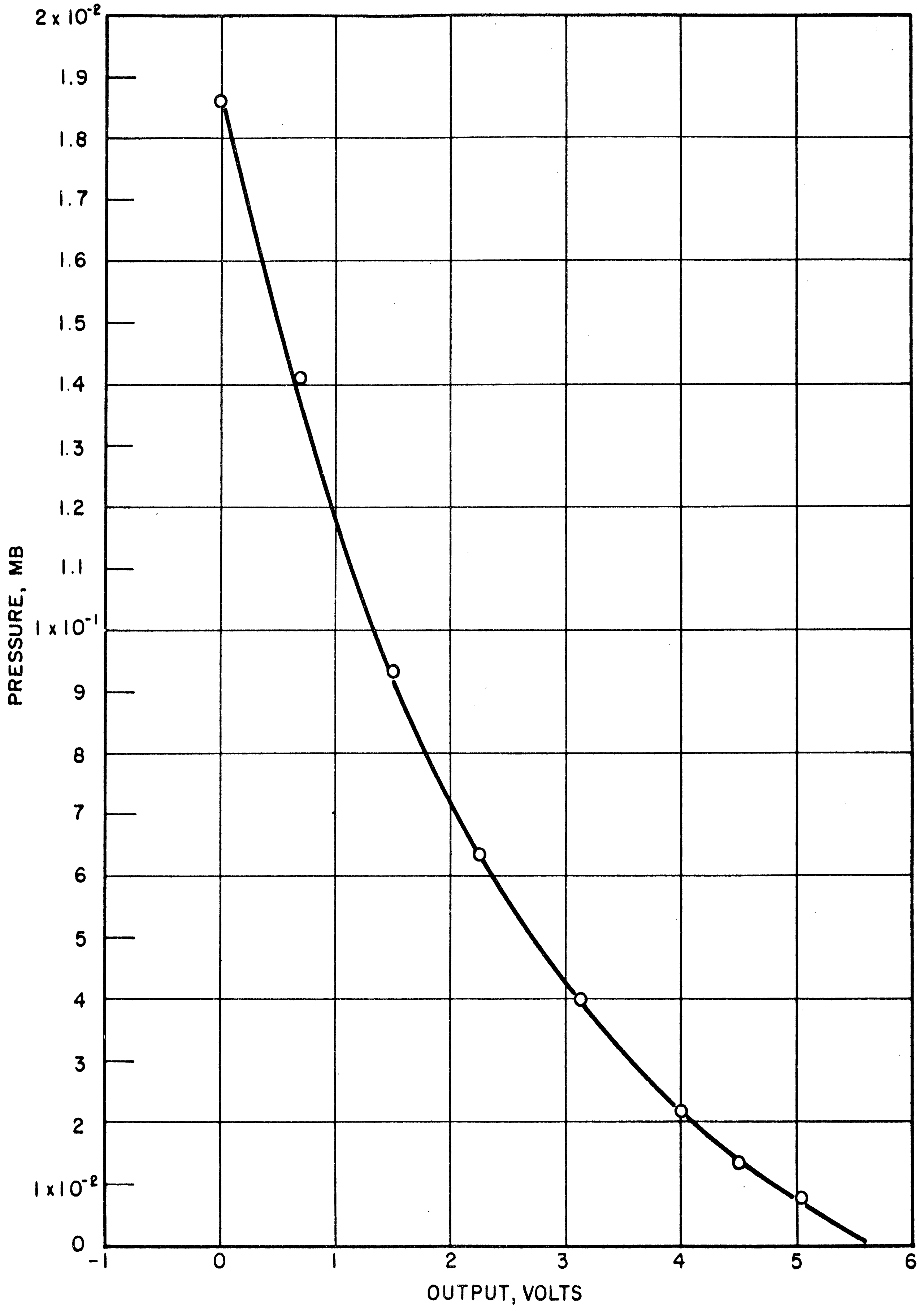

Fig. 7.9. Calibration curve, range 5.

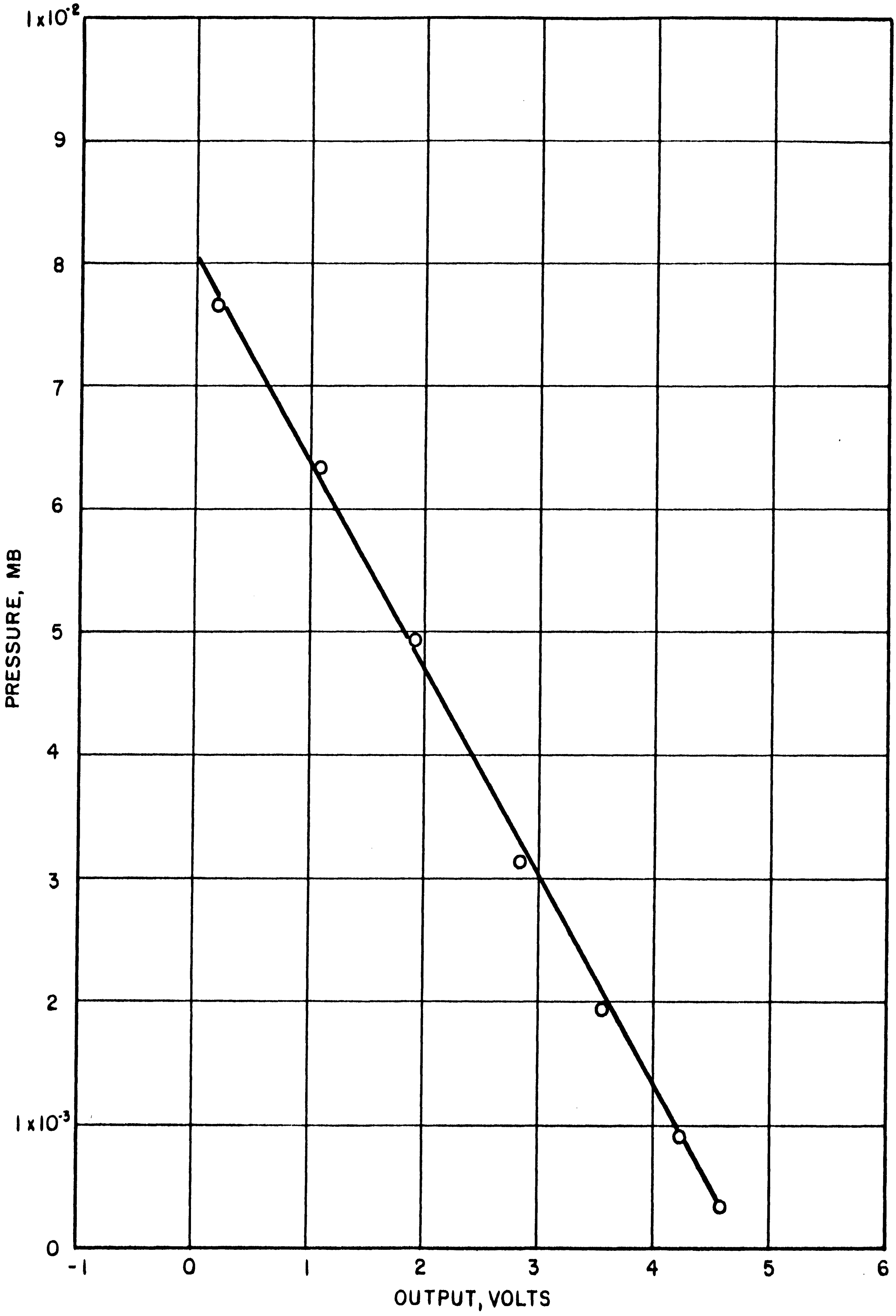

Fig. 7.10. Calibration curve, range 5.

As an example, the resistances employed in units at present are determined as follows:

Let

$$E_{UL} = 5.0 \text{ v} ,$$

$$E_{LL} = 0.0 \text{ v} ,$$

$$n = 5 ,$$

$$i_{max} = 4 \times 10^{-8} \text{ amp} , \text{ and}$$

$$i_{min} = 5 \times 10^{-12} \text{ amp} ;$$

thus from Eq. (7.42)

$$\frac{i_{max}}{i_{min}} = 0.8 \times 10^{4} = k^{5}$$

$$k = 6.03 \cong 6 ,$$

and from Eq. (7.43),

$$ZPV = \frac{5 \times 6}{5} \cong 6.0 \text{ v} .$$

To determine the lowest resistance value R_1,

$$i_{max} R_1 = ZPV - E_{LL} \tag{7.44}$$

$$R_1 = \frac{6}{4 \times 10^{-8}} = 1.5 \times 10^{8} \text{ ohms.}$$

Further use of Eq. (7.41) enables evaluation of all values; thus

$$R_1 = 1.5 \times 10^{8} ,$$

$$R_2 = 9.0 \times 10^{8} ,$$

$$R_3 = 5.4 \times 10^{9} ,$$

$$R_4 = 3.24 \times 10^{10} ,$$

$$R_5 = 1.944 \times 10 \text{ ohms.}$$

7.5 CONSTRUCTIONAL ASPECTS

The general constructional technique employed is illustrated in Figs. 1.2 and 7.2. "Lamacoid" decks with appropriately located eyelets support and are in turn spaced by the various components.

The subassemblies are joined by an interconnecting cable and supported by 3 struts, slotted to receive the lamacoid disks, which are secured with a bonding agent* at final assembly.

The ionization chamber at one end, and an aluminum plate at the other, are similarly secured to the struts. An aluminum can in 2 pieces axially covers the entire assembly, and through the use of O-rings forms an air-tight cover and shield. Foam** is employed at various points for mechanical support, insulation, etc.

The aluminum tubing is "keyed" to the ionization-gage body to prevent rotational movement between these components. The presence of the can also prevents torsional distortion of the main assembly which is necessary to maintain proper clearances for, and orientation of, the shaft linking the solenoid assembly and the ceramic wafer.

Electrically, two particular precautions have been taken: (a) to separate the transistor-oscillator power supply and the amplifier, the solenoid assembly and range-changing circuit have been interposed, and (b) the plate resistor and plate lead of the cathode-follower output tube have been placed reasonably far from the electrometer grid region, to minimize capacitive coupling and the resultant "motor-boating" which might otherwise occur when the input load resistance exceeds approximately 10^{11} ohms.

Several minor points warrant mention.

a) The main battery pack has been located at one end of the assembly and provided with plug-in terminals to facilitate replacement. This arrangement permits battery-pack replacement when a unit is installed in a nose cone.

b) Vacuum-tight connection between the ionization-chamber outer wall and rocket nose cone is accomplished through use of a right- and left-hand threaded brass coupling and soft copper sealing ring, illustrated in Fig. 7.11. A hexagonal passage (1/4 in.) through the threaded coupling permits adequate gas flow and enables assembly by use of an "Allen" wrench from outside the nose cone.

c) The units are 16 in. in length, 2-1/4 in. in diameter, and weigh 3-1/4 lb.

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*Carl H. Biggs Co., Bonding Agent R313, Los Angeles, Calif.

**E-P-Fome, Hardener H270, Electronic Plastics Corp., Jamaica, N. Y.

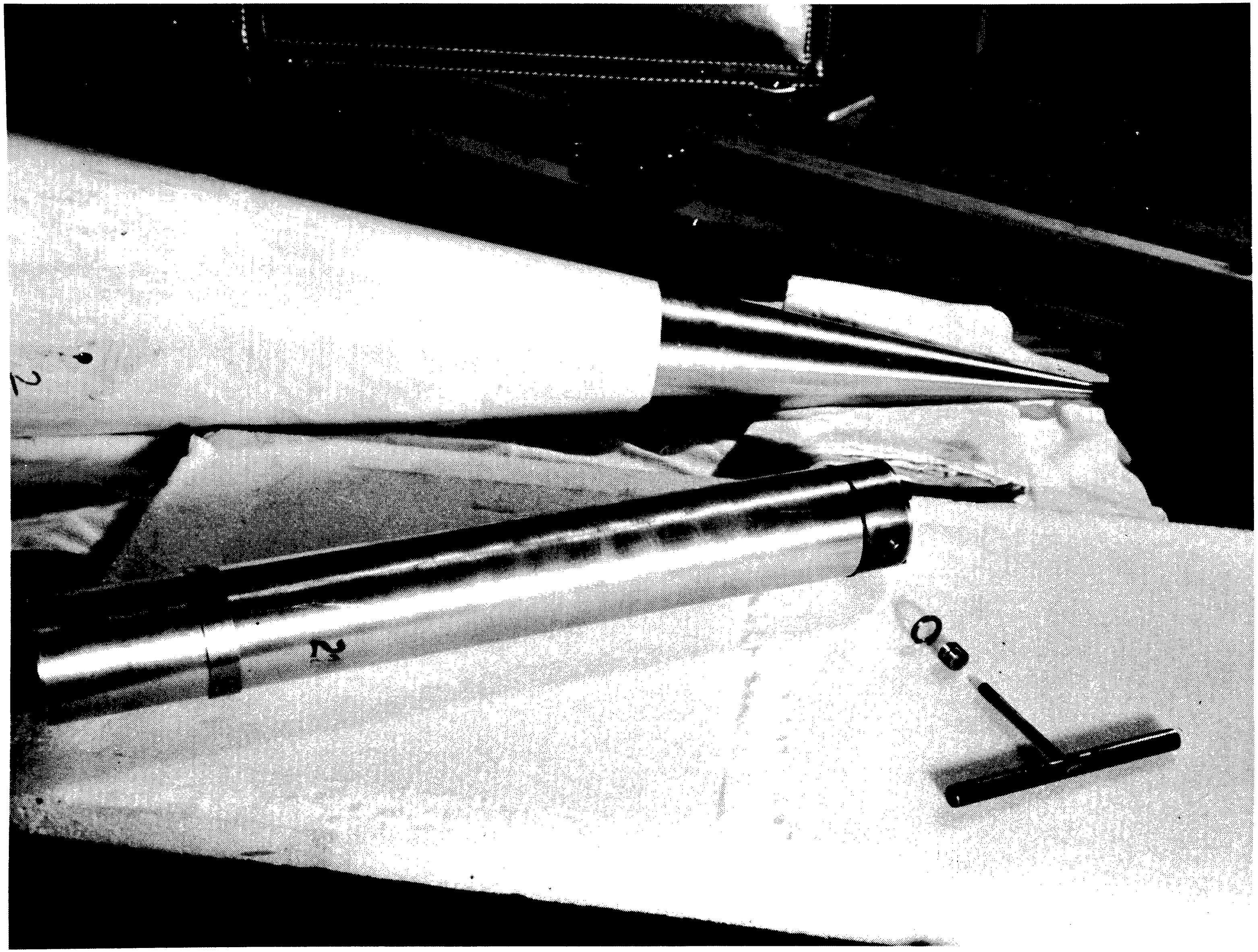

Fig. 7.11. Vacuum-fitting arrangement for connection of unit to nose-cone wall.

7.6 PERFORMANCE HISTORY

At the time of writing this report, 33 units, both prototype and operational, have been constructed. Of these, 28 have been expended in 9 Nike-Cajun and Aerobee rocket flights. Data from several of these flights are being reduced at present and indicate generally satisfactory performance. Final judgment must of course await completely reduced data.

The major difficulty encountered in securing proper operation has been associated with the range-changing circuit and in particular with making certain that the thyratrons would be extinguished following each switching function. This problem has been solved, however, and no further difficulty has been encountered. Figure 7.12 illustrates normal range-changing operation as experienced during the flight of Nike-Cajun AM 6.38.

Other difficulties, relatively minor, have been corrected. For example, the transistors T_u and T_D (Fig. 2.4) which switch the thyratrons have enabled adequate stability of switching points, and the "stabistors" which fix the electrometer filament voltage have eliminated a battery which was at least in 1 case responsible for a failure (serial 6-11).

Table 7.61 summarizes the disposition and operational results for the 33 units.

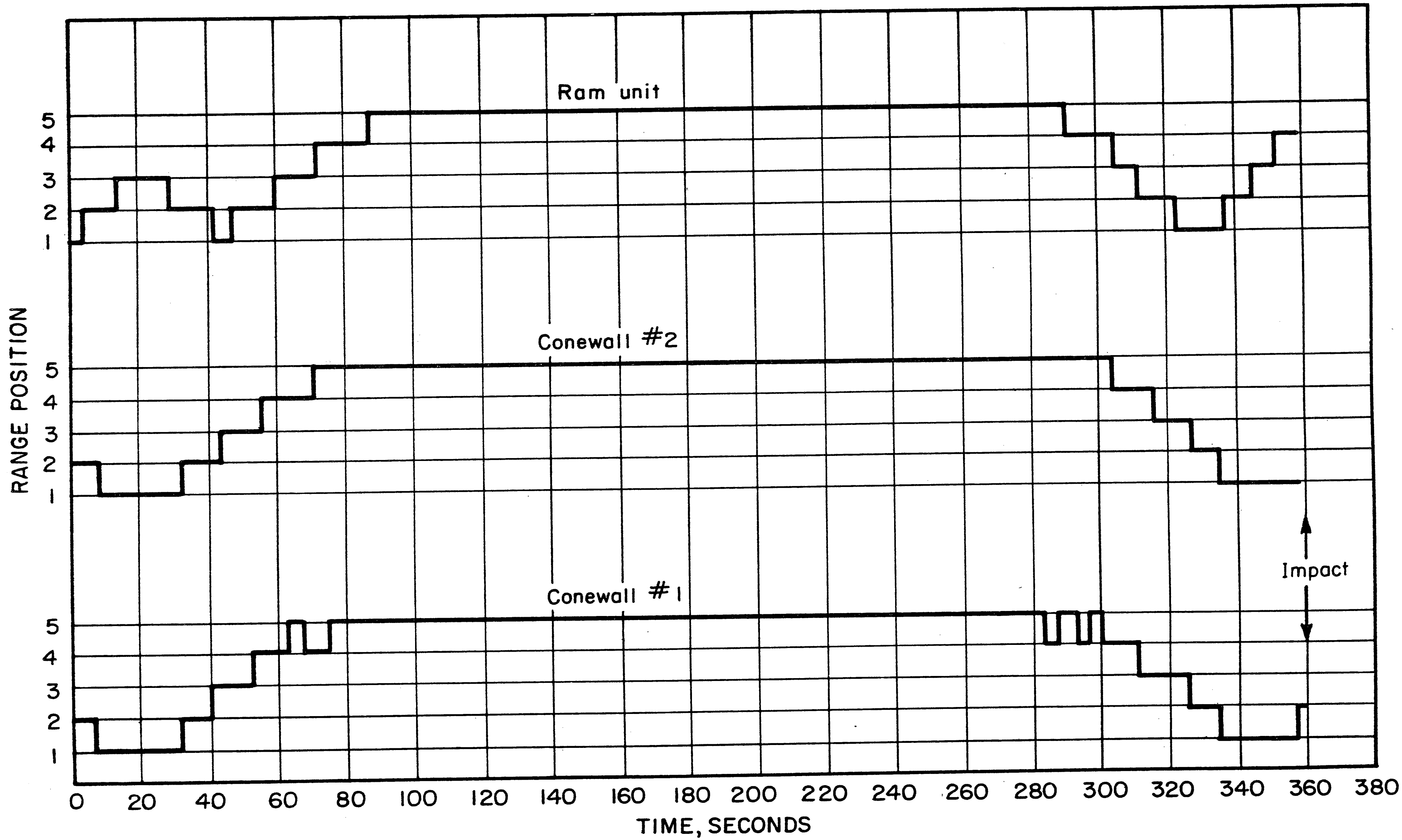

Fig. 7.12. Range position vs. time for 3 units on Nike-Cajun AM 6.38.

TABLE 7.61. DISPOSITION OF PRESSURE-MEASUREMENT SYSTEMS

Disposition	Serial No.*	Remarks
On hand	1	Prototype unit, used on sled test.
Expended in prototype test flight at W.S.P.G. August, 1956. IGY rocket AM 6.30	2	Amplifier and range-changing circuit failure during boost phase.
	3	Improper output. Range-changing apparently operated satisfactorily.
	4	Operation appears satisfactory to 50-km altitude when amplifier apparently failed. Range-changing circuit continued to function (output above 5 volts) and ultimately switched unit off.
Expended in first Ft. Churchill rocket, Nike-Cajun AM 6.31	5-5	Satisfactory operation.
	9-4	Satisfactory operation.
	10	Satisfactory operation.
Expended in first Ft. Churchill Aerobee, AM 2.21 October, 1956	6-11	Electrometer filament battery failure at launch. Unit turned itself off during flight.
	7-10	Satisfactory operation.
	8-9	Satisfactory operation.
	11-6	Satisfactory operation.
	12-12	Satisfactory operation.

*Second of double number indicates radioactive source serial number.

TABLE 7.61 (Continued)

Disposition	Serial No.*	Remarks
On hand	13	These two units were constructed like serial numbers 2-12 but were reworked as prototypes to incorporate many changes, including battery pack relocation, plug-in gage and hi-megs, elimination of zero adjust motor, addition of trimpots for switching limit adjustment, physical rearrangement of some components, replacement of chamber with new H^3 source chamber, modified range-changing circuit, etc
On hand	14	
Expended in AM 6.32 July, 1957	17	Satisfactory operation of all units for duration of limited flight. Second stage ignition did not occur. No significant data.
	19	
	20	
Expended in Aerobee AM 4.01 September, 1957	16-211	Satisfactory operation of No. 16-211 only. Range-changing circuits of other four units failed during flight. Common difficulty was continued firing of thyratrons after first or second range change. Reason not established but believed due to excessive heat or physical distortion of units due to nose cone expansion.
	18-214	
	21-210	
	22	
	23-212	
Flown in AM 6.34 December, 1957	15-203	Rocket broke up near end of boost. All units were recovered at impact in moderately undamaged condition. Operation satisfactory for brief flight. Repaired and reflown in AM 6.37.
	24-215	
	25-207	

*Second of double number indicates radioactive source serial number.

TABLE 7.61. (Concluded)

Disposition	Serial No.*	Remarks
Expended in Nike-Cajun AM 6.36 January, 1958	27	Satisfactory operation.
	28	Satisfactory operation.
	29	Satisfactory operation.
Expended in Nike-Cajun AM 6.37 February, 1958	15	Satisfactory operation of all three units. (These units recovered from impact of AM 6.34 for re-use.)
	24-207R	
	25-215	
Expended in Nike-Cajun AM 6.38 March, 1958	26-13483	Satisfactory operation.
	32-13481	Satisfactory operation.
	33-13479	Nearly satisfactory operation. Upper switching point moved to higher value causing loss of data between 0-2 volts only. Reason unknown.
On hand. To be flown.	30-13482	
On hand. To be flown.	31	

*Second of double number indicates radioactive source serial number.

8.0 CONCLUSIONS

This report describes an instrument which in the opinion of the authors offers a desirable and reliable means of measuring rocket-surface pressures. Many units have been successfully employed in several rocket flights. Use has, however, suggested the possible desirability of additional modifications which would simplify construction and check-out to some degree, and which would at the same time contribute to the reliability.

It would be desirable, for example, to simplify the complex feedback environment under which the amplifier operates at present, however satisfactory. To this end, regulation of the power supply (using transistors) would likely be helpful and might make possible a net saving in the number of components and volume the unit occupies, by eliminating at least part of the present need for filtering. Secondly, the addition of another winding of a few turns, with rectifier and Zener diode regulator, might make possible the elimination of the batteries in the feedback loop. Thirdly, it is now felt that the constancy of battery-pack voltage and hence heater voltage make the Miller compensator unnecessary. This change combined with the first might make the elimination of at least 1 tube of the amplifier possible without sacrifice of loop gain and hence stability.

Further use will certainly make evident the desirability of additional modifications. However, the system in its present form is more than adequate for the measurements like those performed by this research group.

9.0 ACKNOWLEDGMENT

The development of this system has taken place gradually with use over a period of many years, as noted in the introduction to this report. Naturally, many individuals have contributed to the effort, in varying degrees. Although the present equipment bears only a modest resemblance to the model first employed in a rocket by this research group (1949), the general outline of the system remains unchanged.

H. F. Schulte carried out much of the early development following adaptation of J. R. Downing's system, and contributed substantially to the early flight successes of the original equipments. H. S. Sicinski first noted and carried out some exploratory measurements of the ionization-chamber hysteresis effect. Several others, primarily student technicians, assisted in development of the early models.

Realization of the present configuration has likewise involved several individuals. Major contributors to circuit development, physical layout, etc., have been W. G. Kartlick, G. Burdette, J. A. Cornell, T. M. Muller, and J. Horvath.

The authors expressly acknowledge the contributions of these individuals. It is obvious but should be stated that the system reported represents the ideas and efforts of all.

10.0 REFERENCES

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