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DEVELOPMENT OF COLD CATHODE IONIZATION GAUGES FOR SPACE VEHICLES

PART I

RESEARCH AND DEVELOPMENT

W. KREISMAN

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GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

NOVEMBER 1964

GEOPHYSICS CORPORATION OF AMERICA BEDFORD, MASSACHUSETTS

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W. Kreisman

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ABSTRACT

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A study was made of the characteristics of standard and experimental magnetron type cold cathode ionization gauges in order to better understand their operation and improve their performance. Among the characteristics studied were gauge sensitivity, stability, linearity, ion energy distribution, space charge distribution, and current flow distribution. Discharge instability within certain narrow ranges of anode voltage was observed. Hysteresis in the current-voltage characteristic was discovered that could explain multimode operation. One experimental gauge was constructed to be used as a low resolution mass spectrometer. The importance of the cathode surface in determining the nature of the discharge was demonstrated.

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DEVELOPMENT OF COLD CATHODE IONIZATION GAUGES FOR SPACE VEHICLES

Wallace S. Kreisman

INTRODUCTION

The general objective of this research program was to study, develop, and improve cold cathode ionization gauges. These gauges have a number of applications in the space program. They can be installed on rockets and satellites for the purpose of measuring total ambient densities in the Earth's atmosphere. They can be installed in space vehicles for measuring the low pressures expected at the Moon's surface or the total ambient pressures of other planetary atmospheres. Finally, they can be used in the laboratory to measure the low pressures achieved in ultra high vacuum space simulation chambers.

A cold cathode ionization gauge is a vacuum device consisting essentially of two electrodes, an anode and a cathode, with a potential of several kilovolts between them. The electrodes are positioned relative to an external magnetic field of the order of one kilogauss. The low pressure gas within the interelectrode region breaks down as a result of the strong electric and magnetic fields, and a relatively stable discharge results. It has been found that the discharge current is a direct measure of the gas pressure (actually a direct measure of the number density of gas molecules) within such a gauge.

The first cold cathode gauge was developed by Penning in 1937.[1] The original Penning type gauges utilized plane parallel circular plates for cathodes and a wire ring as an anode. These gauges would measure pressures only as low as 10^{-6} or 10^{-7} torr. In the late 1950's a number of improved cold cathode gauges were developed, notably the magnetron-type gauge of Redhead.[2] The essential elements of this new device were a spool-shaped cathode, a surrounding concentric, cylindrical anode, and an auxiliary cathode or shield ring interposed between the edges of the anode and cathode. The shield ring facilitates the initiation of the discharge and separates the discharge initiating current from the positive ion current to the ion collector. Recently, a Penning type discharge gauge has been constructed that is capable of measuring pressures as low as 10^{-14} torr.[3] A filament is used to start this gauge at low pressures. The design of this gauge is such that it may be operated with an electron multiplier to increase its sensitivity.

In spite of the many advances made in the design of new cold cathode gauges for low pressure operation, very little is known about the detailed manner in which they operate. The discharge in the gauge is believed to be a self-sustained Townsend discharge.

Although the theory of the discharge initiation has been developed by Beck and Brisbane,[4] Haefer,[5] and Redhead,[6] a detailed theory of the gauge's steady state operation has not been worked out.

In order to be able to better understand the operation of the magnetron type cold cathode gauge, an experimental program was initiated in which various characteristics of the gauge were studied: The instabilities of the discharge were determined as a function of anode voltage and magnetic field strength. Attempts were made to measure the electron and positive ion spatial distributions and the ion energy distribution in the gauge. The effects of various geometrical changes in the gauge electrodes were studied. Residual gases within the gauge were studied. Variations in the gauge sensitivity with anode voltage and magnetic field strength were determined. These and many other characteristics of magnetron type cold cathode gauge operation were investigated.

The objective of the research program was to gather new information pertaining to cold cathode gauge operation. It was hoped that the new data obtained would help us to design better gauges and also provide an experimental background on which a theory of gauge operation could be based.

EQUIPMENT

Most of the experiments concerning the characteristics of typical magnetron type cold cathode gauges were performed with the use of an all pyrex glass vacuum test system. The test system is shown in block diagram form in Figure 1. Figure 2 is a photograph of the complete apparatus.

The test system used on H. S. Martin Co. Model 40-1100 mercury diffusion pump, a three jet pump with a nominal pumping speed of about 50 liters/sec as the main pump. The Martin pump was backed up with a second glass diffusion pump, Eck and Krebs model 4000 pump having a speed of about 5 liters/sec. By decreasing the forepressure of the large Martin pump, lower pressures could be attained in the test chamber. The backing diffusion pump exhausted into a Welch model 1400 mechanical pump that had a speed of 21 liters/min. A single, demountable glass vacuum trap cooled with dry ice was located between the mechanical pump and the backing diffusion pump while a dual glass vacuum trap cooled with liquid nitrogen was located between the two diffusion pumps. A conventional Bayard Alpert type ionization gauge was connected between the two single sections of the dual trap. The ionization gauge indicated the forepressure of the Martin pump and was used to monitor the system pressure during bakeout.

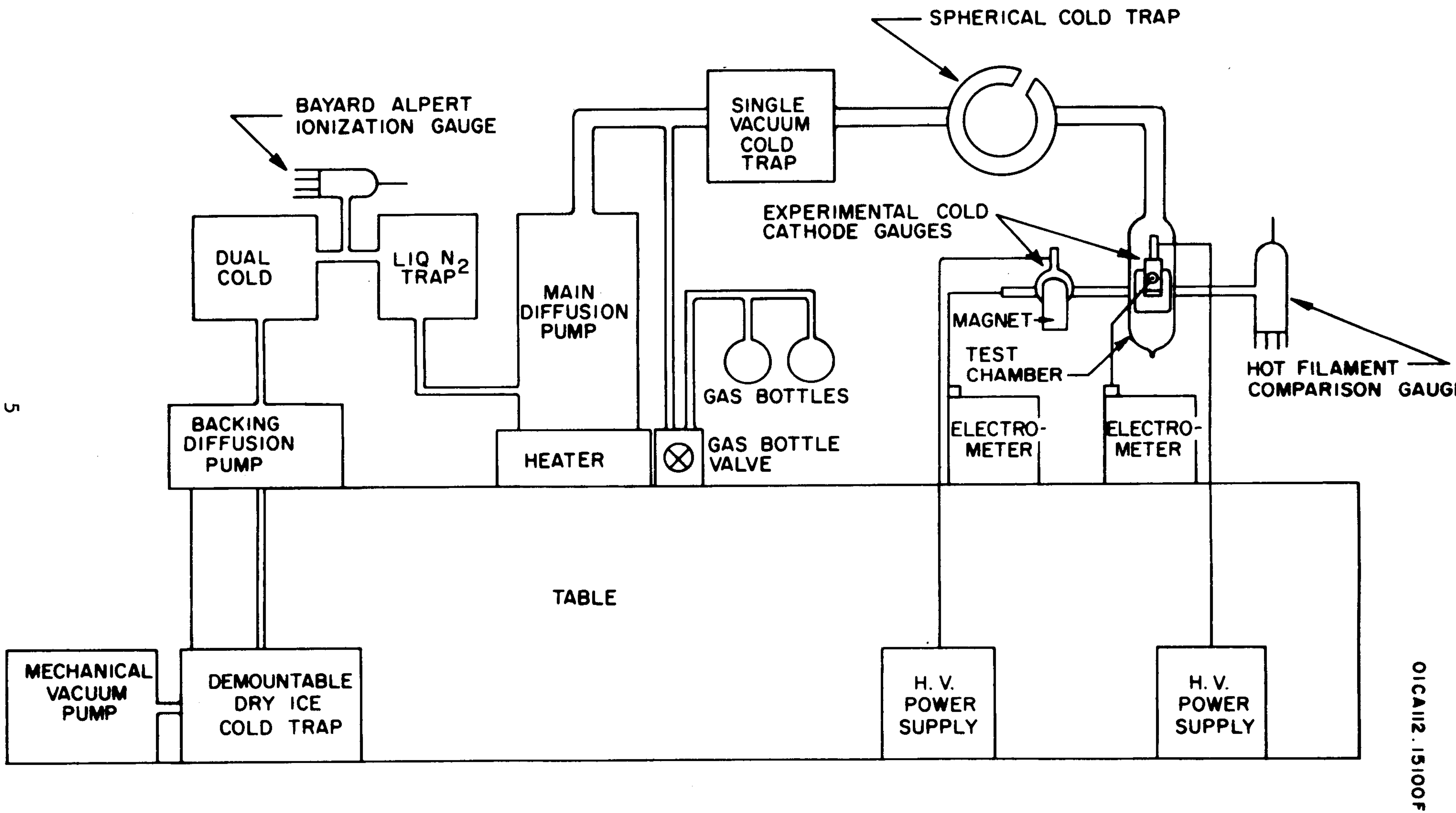

Figure 1. Block diagram of vacuum test system.

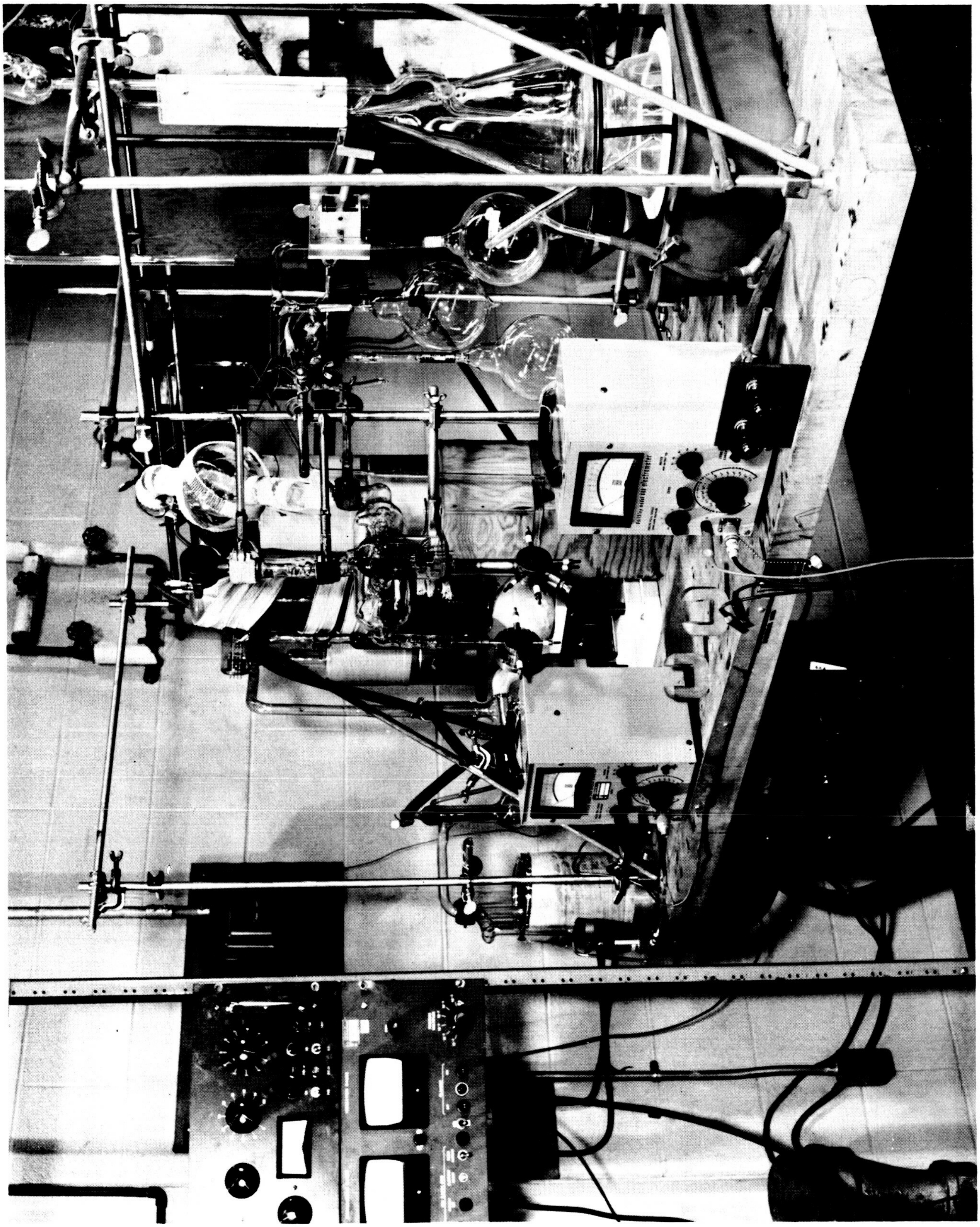

Figure 2. Photograph of vacuum test system.

Two additional liquid nitrogen cooled vacuum traps separated the Martin diffusion pump from the test chamber. The first of these was a conventional single trap 30 cm long and 5 cm in outer diameter with a 3 cm diameter inner tube. The second trap was of the spherical variety, designed to have a high vacuum conductance. The inner bulb, which held the liquid nitrogen, had a capacity of 500 ml. The outer bulb was constructed from a 1 liter spherical flask. The tubulations joining the two cold traps and the test chamber was 3.5 cm in diameter.

The test chamber was fashioned from a length of 7.5 cm O.D. pyrex tubing. Essentially, it was a cylinder about 25 cm long, closed at one end and tubulated with 3.5 cm diameter tubing at the other end that connected to the spherical cold trap. At the center of the cylinder, there were four 2.5 cm diameter tubulations spaced 90 degrees apart to which various experimental gauges could be attached.

Pure gases were introduced into the test system from a glass manifold to which three 1 liter flasks of reagent grade gases were attached. The manifold was separated from the system by a Hoke No. 411 all-metal diaphragm valve. This valve could be adjusted so as to establish very small flows of gas. The pure gases entered the test system near the top of the Martin diffusion pump.

It was found possible to obtain low pressures in this system of the order of 10^{-9} torr and even 10^{-10} torr by baking all of the high vacuum components at temperatures ranging between 250 and 350^{o}C. Bakeout was accomplished by using heating tapes on practically all of the components, and using a heat gun to heat some parts of experimental gauges that could not be conveniently heated with tapes.

In addition to the test system just described, several experiments were performed with the use of all glass Venema type calibration systems. These systems are illustrated schematically in the block diagram of Figure 3. A photograph of three of these systems is presented in Figure 4.

As can be seen with the aid of the block diagram, the Venema type calibration system made use of two mercury diffusion pumps in series with three cold traps and the test chamber to which experimental gauges or gauges to be calibrated were connected. A mechanical fore pump was used to create a forevacuum of about a few microns of mercury pressure. A dry ice cold trap, a vacuum valve, and a forevacuum reservoir separated the mechanical forepump and the backing diffusion pump. The function of the dry ice cold trap was to keep pump oil out of the mercury diffusion pump and mercury out of the mechanical pump. The presence of the valve and forevacuum reservoir permitted the mechanical pump to be turned off (to reduce vibration, for example) and still permit the diffusion pumps to operate and exhaust into a low pressure reservoir.

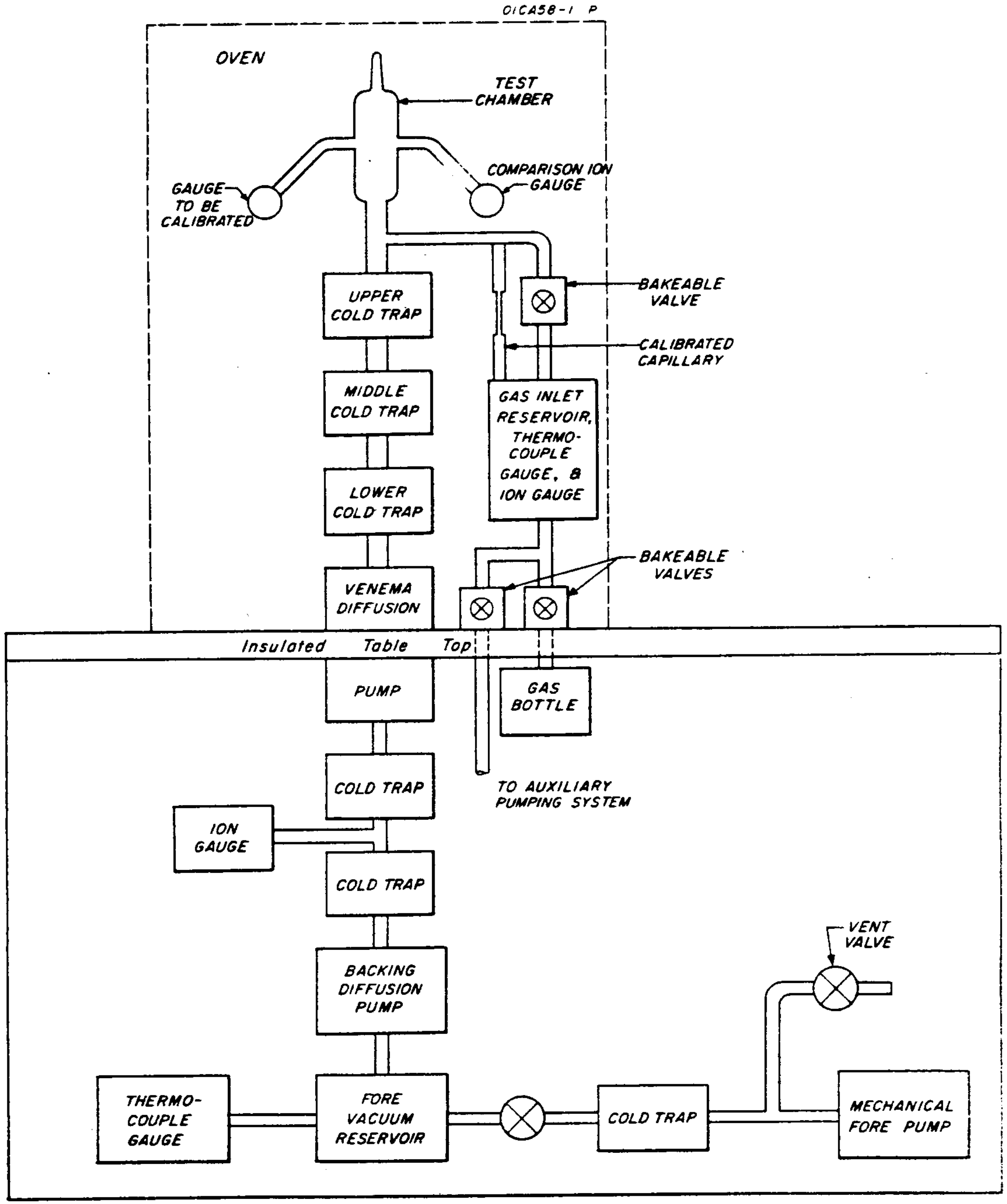

Figure 3. Block diagram of Venema type calibration system

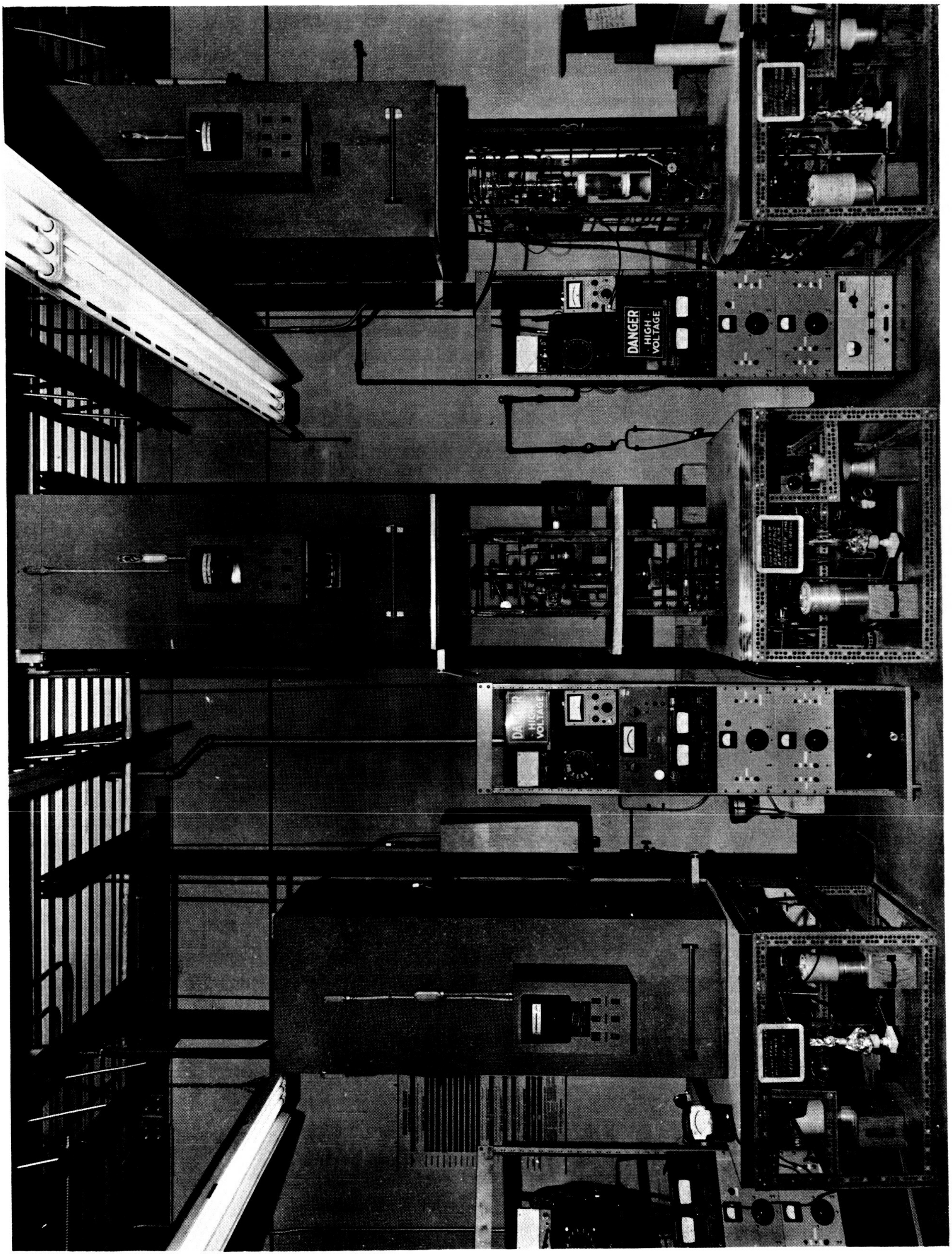

Figure 4. Photograph of Venema type calibration system.

The backing diffusion pump was a two-stage,water cooled, glass pump having a nominal pumping speed of about 10 liters/sec. The bakeable main mercury diffusion pump, the so-called Venema pump, was patterned after one designed by Dr. Venema. This pump was of two-stage design with a nominal pumping speed of about 70 liters/sec. It was located partly above an insulated table top so that its upper portion could be baked out at high temperatures together with the test chamber and the associated components shown in Figure 3. Notice the installation of a cold-trap-protected ion gauge of the Bayard Alpert variety between the Venema pump and the backing diffusion pump. This ion gauge was used to monitor the system pressure during the bakeout period, and was also used to continuously indicate the forepressure at the Venema pump.

The three cold traps located between the Venema diffusion pump and the test chamber were the re-entrant design described by Venema.[7] The traps consisted essentially of an inner sphere and an outer cylindrical jacket that both contained liquid nitrogen. The flow path in the cold traps for the gas being evacuated was basically an annular shaped region between the cold surfaces. Three cold traps were used to insure trapping of all of the mercury vapor that originated in the Venema pump and would otherwise migrate into the test chamber.

The diffusion pumps, cold traps, and test chamber were made of pyrex glass. The test chamber was identical with that used in the vacuum test system described above. Provision was made to flow pure gases into the system and test chamber through either a calibrated capillary tube or an adjustable bakeable valve. A one-liter bottle of pure gas was used to establish a relatively low pressure of a particular gas in the gas inlet reservoir as shown. Gas pressures in the gas inlet reservoir were measured with either a Bayard Alpert type ionization gauge or a bakeable, glass thermocouple gauge. Practically all of the gas introduction system was baked at high temperatures together with the test chamber and ultra high vacuum part of the pumping system.

All of the system components that were located above the insulated table top were mounted within a non-magnetic stainless steel framework. Counterbalanced ovens mounted on a vertical I-beam structure were designed so that they could be easily lowered to the insulated table top and uniformly heat everything within the stainless steel framework. The ovens supplied 12 Kw of heat and were temperature controlled within about $1^{\circ}C$. Temperatures as high as $500^{\circ}C$ could be attained within the oven. A demountable oven base made of marinite was provided so that various components in the upper part of the stainless steel framework could be heated while components in the lower part of the framework remain at room temperature.

The controls for the system diffusion pumps, mechanical pump and various gauges were housed in an auxiliary electronics rack.

Ultimate pressures in the 10^{-13} torr region could be attained in the Venema type calibration systems after overnight bakeout at $450^{o}C$. Pure gas pressures as high as 10^{-5} torr could be established in the test chamber. Tests requiring the lowest pressures were performed with the aid of these systems.

In addition to the vacuum systems just described, various commercially available electronic equipment was used to provide power to the experimental gauges and measure the positive ion and electron currents produced in these gauges. Highly regulated high voltages were obtained from a John Fluke, Inc. model 408A power supply. Occasionally, voltages were furnished by an unregulated low ripple high voltage power supply when voltage regulation was judged to be unimportant. Small dc currents were usually measured with battery operated Keithley model 600 electrometers. Occasionally, microammeters were used to measure larger dc currents within their range.

Magnetic fields were measured with a Rawson type 501 rotating coil gaussmeter. Two or three different types of permanent magnet were used to provide magnetic fields for the experimental gauges.

An electromagnet was specially constructed for use in this program. It consisted of a U-shaped Armco iron core, removable Armco iron pole pieces, and a magnet coil containing about 2800 turns of #17 wire. This electromagnet and its swivel type stand are shown in the photograph of Figure 5. Magnetic fields ranging between 500 and 1400 gauss at the center of a 1-1/2 inch diameter by 1-9/32 inch long air gap could be readily obtained with this electromagnet. Coil currents ranging between 0.5 and 1.5 amperes were required to achieve these fields as indicated in the calibration curve of Figure 6.

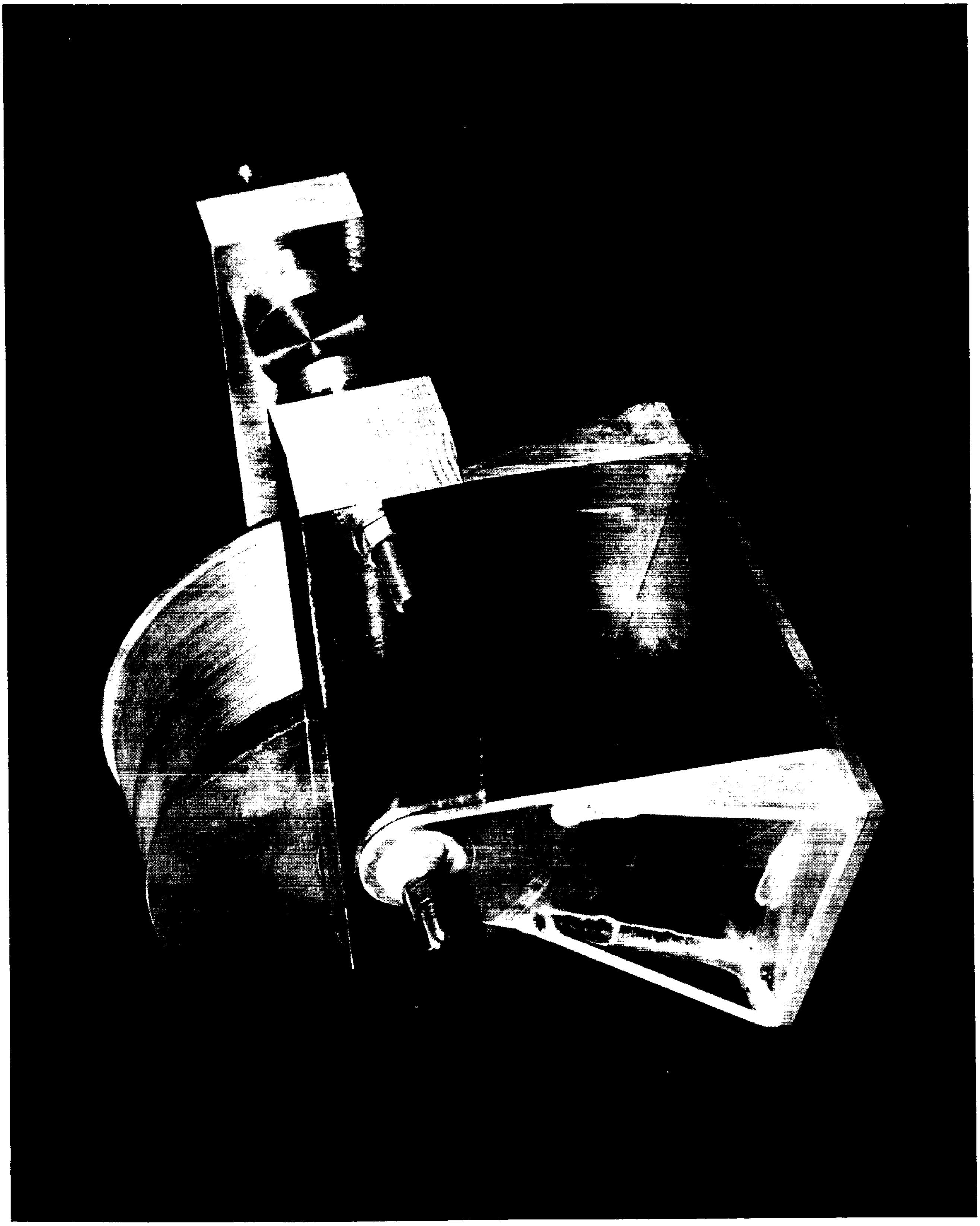

Figure 5. Photograph of electromagnet.

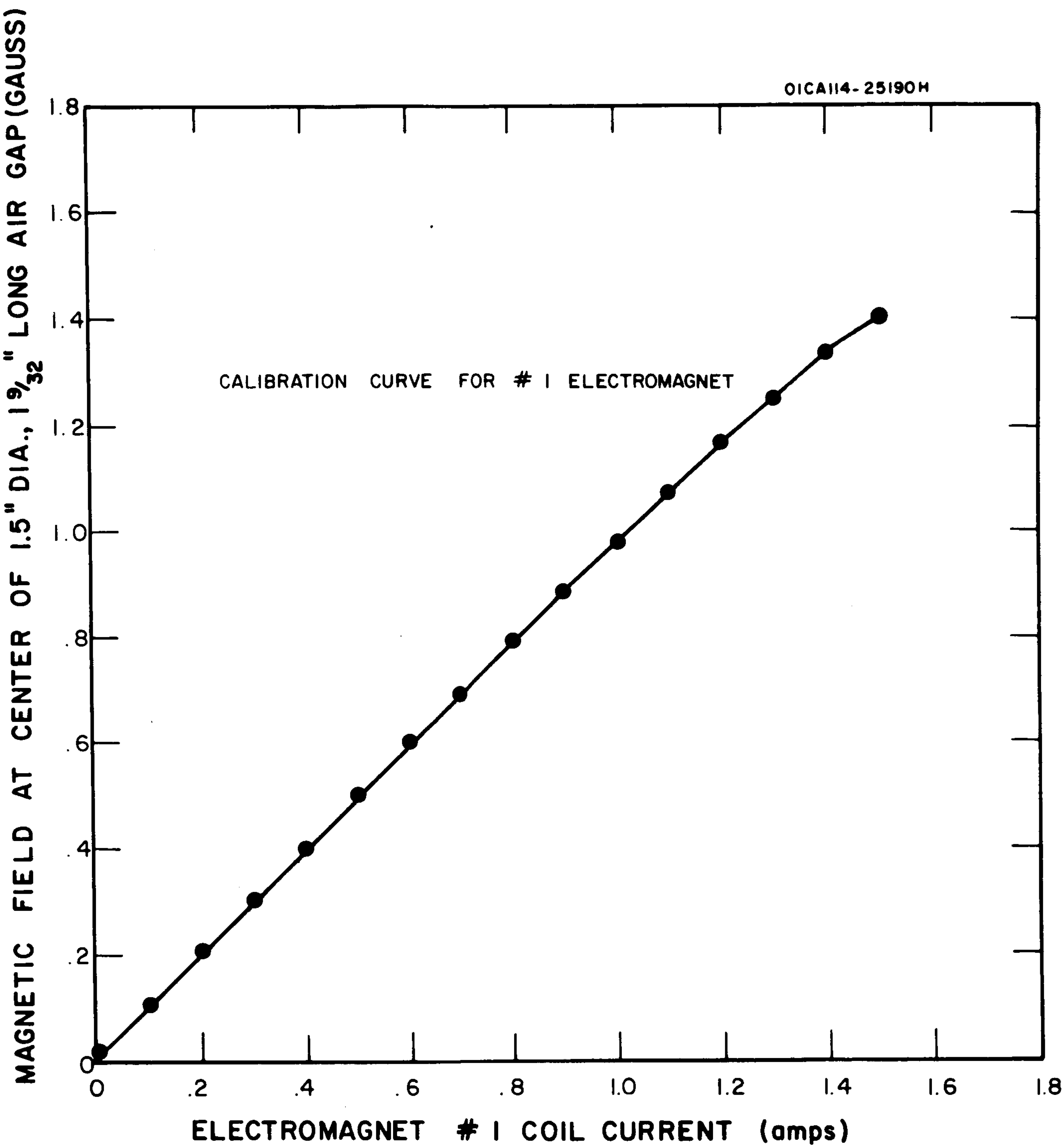

Figure 6. Calibration curve of electromagnet.

EXPERIMENTS

In order to implement the program of studying and developing magnetron type cold cathode gauges and gathering new information pertaining to gauge operation, a series of eight different experimental gauges were constructed. Six gauges in the series X-1 through X-6 were constructed, together with a so-called "Model A" gauge and a demountable gauge. The constructional features of each of these gauges, the objective of the gauge design, and the experiments performed with them are discussed below.

The experimental gauges in the series X-1 through X-6 were constructed by making use of the standard components of the Vacuum Industries (a subsidiary of the Geophysics Corporation of America) Model 1410 cold cathode gauge. Various components were modified for the different gauges. By using this technique, it was possible to build these gauges quickly and economically. Some experiments were performed with standard model 1410 gauges and closely allied flight model gauges to gain a standard of comparison and to determine certain characteristics of the standard gauges.

Experiments With Standard Model 1410 Gauges And Equivalent Flight Model Cold Cathode Gauges

A sketch of the standard Model 1410 gauge is shown in Figure 7. The gauge cathode, a spool-shaped electrode, was held in position by ceramic spheres placed under compression. The cylindrical anode was

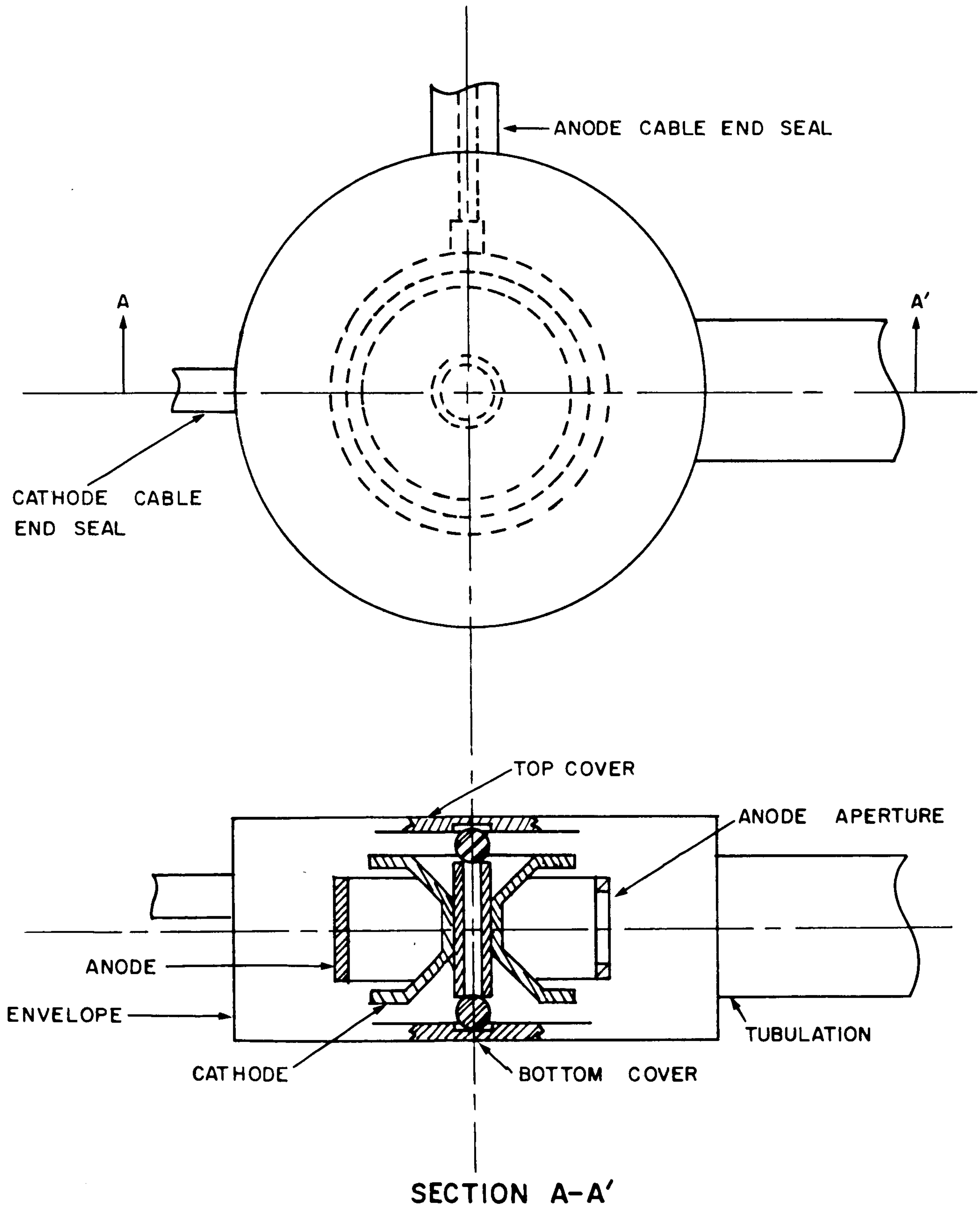

Figure 7. Standard Model 1410 cold cathode gauge.

positioned to be concentric with the cathode. The anode contained a single large aperture facing the gauge tubulation. The tubulation was about 3/4-inch in diameter with length that varied between about 3 and 6 inches depending upon the type of connection to be made to the test system. Electrical connections to the anode and cathode were made via ceramic-metal cable end seals. A small permanent magnet furnishing a field of about 1100 gauss was used with these gauges. The magnetic field direction was coincident with the axis of the gauge cathode and anode.

Comparison Readings of Two Standard Model 1410 Gauges for Nitrogen Gas. As mentioned earlier, the gauge comparison test was performed partly to establish a basis for comparing results obtained with the various experimental cold cathode gauges. In addition, this test provided an opportunity to look for differences between two supposedly identical gauges.

System Preparation and Tests Performed

The Model number 1410 gauges used in this experiment carried the serial numbers T-119 and T-127. The readings of these gauges were compared with the readings of an uncalibrated Veeco RG-75 Bayard-Alpert type gauge (serial no. 230S91) operated at 10 mA emission. Standard 1410 gauge permanent magnets were used. These magnets have a magnetic field strength of about 1050 oersteds at the center of the air gap. GCA laboratory type unregulated, but highly filtered, power supplies were used to furnish 4.0 kV to the cold cathode gauge anodes. Keithley model 600 electrometers were used to measure the positive ion current flow to the gauge cathodes.

The vacuum test system had been baked out a few days prior to the start of the experiment at temperatures ranging from about $200^{\circ}C$ to $300^{\circ}C$ for about 10 hours. Both heating tape and a hot air gun were used for this bakeout. Just before the test was performed, the system background pressure without the spherical cold trap being filled was 1.05×10^{-8} torr as measured with the Veeco gauge. The background pressure after the spherical cold trap had been filled was 1.0×10^{-9} torr.

The experiment was started by opening the nitrogen gas bottle valve slightly and then taking gauge readings every five minutes. An equilibrium pressure was established in the system about one hour after opening the valve. At this time, comparison readings of the cold cathode gauges and the Veeco gauge were taken. The nitrogen gas bottle valve was then opened a bit more to allow more gas to flow into the system, and the procedure outlined above was repeated. The cold traps in the test system were filled to the top about every twenty minutes to keep the liquid nitrogen level fairly constant. The nitrogen pressure range covered in the test extended from about 3×10^{-9} torr to about 3×10^{-6} torr. The grid of the Veeco gauge had sagged prior to the test, and a later comparison test with a new (but also uncalibrated) Veeco gauge showed that the readings were lower than those of the new gauge by 30 to 40 percent.

Results

The data obtained show a decided difference in the current-pressure characteristics of the two gauges over the pressure range covered. The T-127 gauge exhibited a linear response from 5×10^{-8} torr to 5×10^{-7} torr while the response of the T-119 gauge was decidedly non-linear in the region from 5×10^{-9} torr to about 1×10^{-6} torr. The responses of the two gauges are given in Figure 8. A mode change for the T-127 gauge appeared in the 10^{-9} torr region with the gauge alternating between readings of 3.9 and 3.2×10^{-9} amperes. Again in the 10^{-8} torr region, the T-127 gauge exhibited two modes when the current reading alternated between 2.0 and 1.4×10^{-8} amperes. The T-119 gauge current alternated from 1.3 to 1.6×10^{-8} amperes at one point. The readings of the two gauges were comparable at a pressure of 1×10^{-6} torr equivalent nitrogen reading of the test chamber Veeco RG-75 gauge. On this basis, the sensitivity of the two gauges was about 2.3 ampere/torr, a figure quite close to that obtained in calibrations of the same class of gauges. The Veeco gauge used in this experiment was uncalibrated. A later test showed that the readings of this Veeco gauge were about 40 percent lower than those of a new

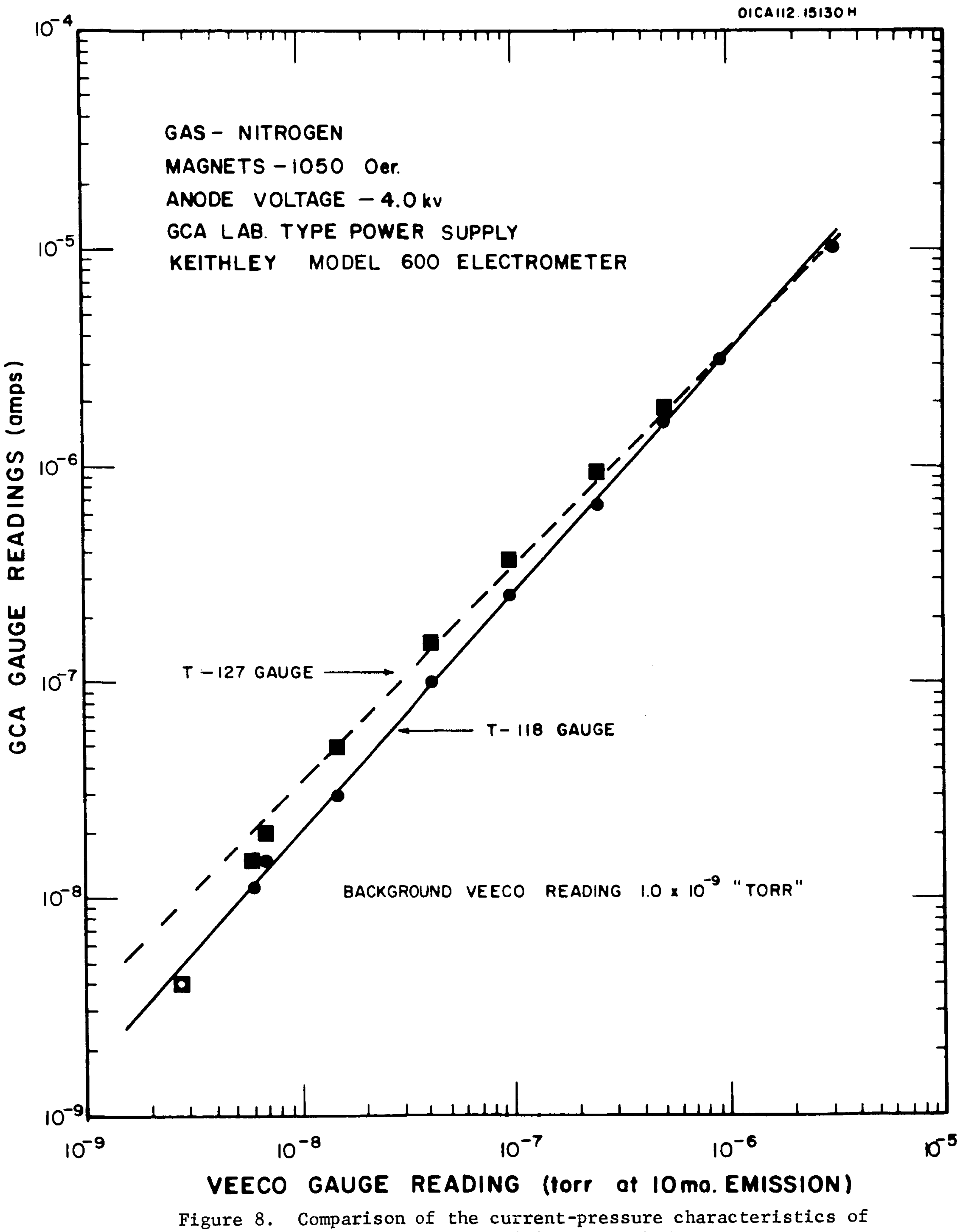

Figure 8. Comparison of the current-pressure characteristics of two standard Model 1410 cold cathode gauges.

Veeco gauge. Since neither gauge was calibrated against a standard, the absolute values of pressure remain in doubt.

Discussion

The spread in gauge characteristics could be due to either geometrical misalignment or differences in the cathode surfaces. Notice that there was a two-mode operation in the 10^{-8} - 10^{-9} ampere region. Linear operation, such as that exhibited by the T-127 gauge, is normally observed with the Model 1410 gauges. Instabilities, such as the two mode operation, is usually associated with specific current regions.

Current-Voltage Characteristics of Two Model 1410 Gauges for Various Pressures of Nitrogen Gas. This test was made to establish a basis for comparing current-voltage characteristics of the experimental gauges.

System Preparation and Tests Performed

This experiment used the same cold cathode gauges and hot filament gauge used in the previous test. The GCA Laboratory type unregulated power supplies furnished the anode voltage for the cold cathode gauges. Readings of gauge currents were taken for anode voltages ranging from 2500 volts to 6,000 volts at 500 volt intervals in the first test performed. The system background pressure was about 1.0×10^{-9} torr (at 10 mA). The nitrogen bottle leak valve was opened and the system pressure allowed about one hour to come to equilibrium at a pressure of 1.9×10^{-9} torr. The anode voltage of both the T-119 and T-127 gauges was increased in steps from 2.5 kV to 6.0 kV in 0.5 kV intervals. The nitrogen leak rate was then successively increased to yield equilibrium pressures of 8.8×10^{-9} torr, 3.2×10^{-8} torr, 1.7×10^{-7} torr, and finally 1.5×10^{-6} torr. Voltage-current characteristics were measured for each of these pressure levels as described above. Currents were measured with Keithley Model 600 electrometers.

In the second test performed, a highly regulated John Fluke Model 408A high voltage power supply (in which the output voltage is adjusted digitally) was used to obtain a current-voltage characteristic for the T-127 gauge at 100 volt intervals over the voltage range from 2.5 kV to 6.0 kV. A nitrogen gas pressure of 8.0×10^{-9} torr was established in the system for this test. The general stability or instability of the gauge currents was noted.

A third test was performed that was identical with the second test above except that guage T-127 current-voltage data were obtained over the range from 3.9 kV to 4.1 kV at 10 volt intervals. The nitrogen gas pressure remained constant at 8.0×10^{-9} torr. Special attention was given to the stability of the gauge output current at each anode voltage.

Results

The data obtained in this experiment are shown graphically in Figures 9 and 10. At the higher nitrogen pressures of 10^{-6} and 10^{-7} torr, the gauge output current tended to increase more or less continually with increasing anode voltage. As the nitrogen pressure decreased, the gauge output current increased to a maximum for some voltage in the range between 2.5 kV and 6.0 kV. As the gas pressure decreased, the peak of the current-voltage characteristic shifted to lower values of voltage. At the lower pressures, there appeared to be a double maxima in the current-voltage characteristic. The characteristic taken at 100 volt anode voltage increments showed small scale variations in the gauge cathode current. These variations, of course, were not evident from the data taken at 500 volt anode voltage increments. The measurements of gauge current made at 10 volt anode voltage increments were rather remarkable in that they appeared to show that there were very small scale anode voltage regions in which the gauge current was either steady or erratic (noisy). An adequate theory of gauge operation should be able to explain this phenomenon.

Discussion

This test showed that the voltage for maximum gauge output current depended on the gas pressure. One might want to change the gauge voltage to obtain optimum gauge response in different pressure regions.

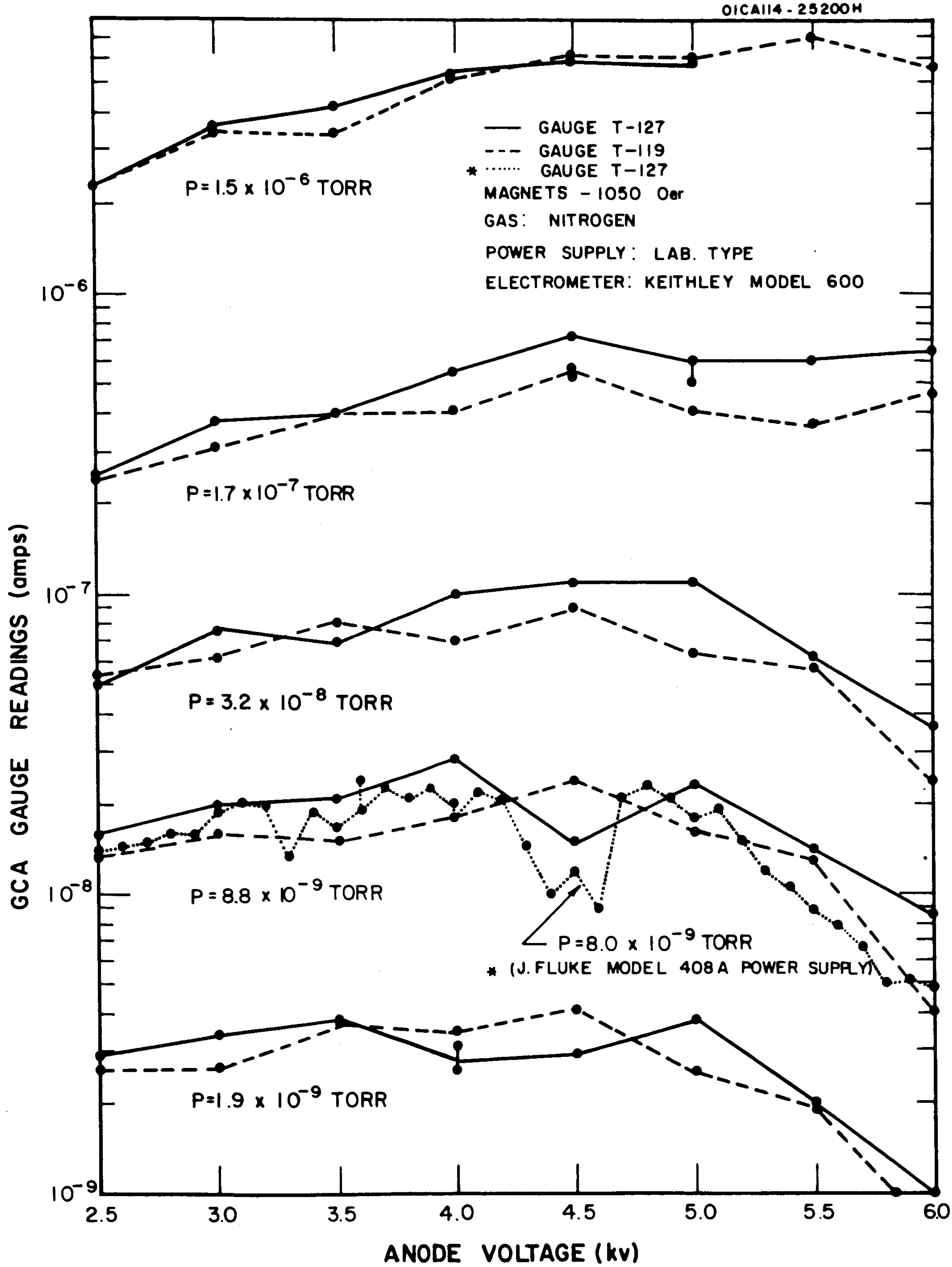

Figure 9. Current-voltage characteristics of two standard Model 1410 cold cathode gauges.

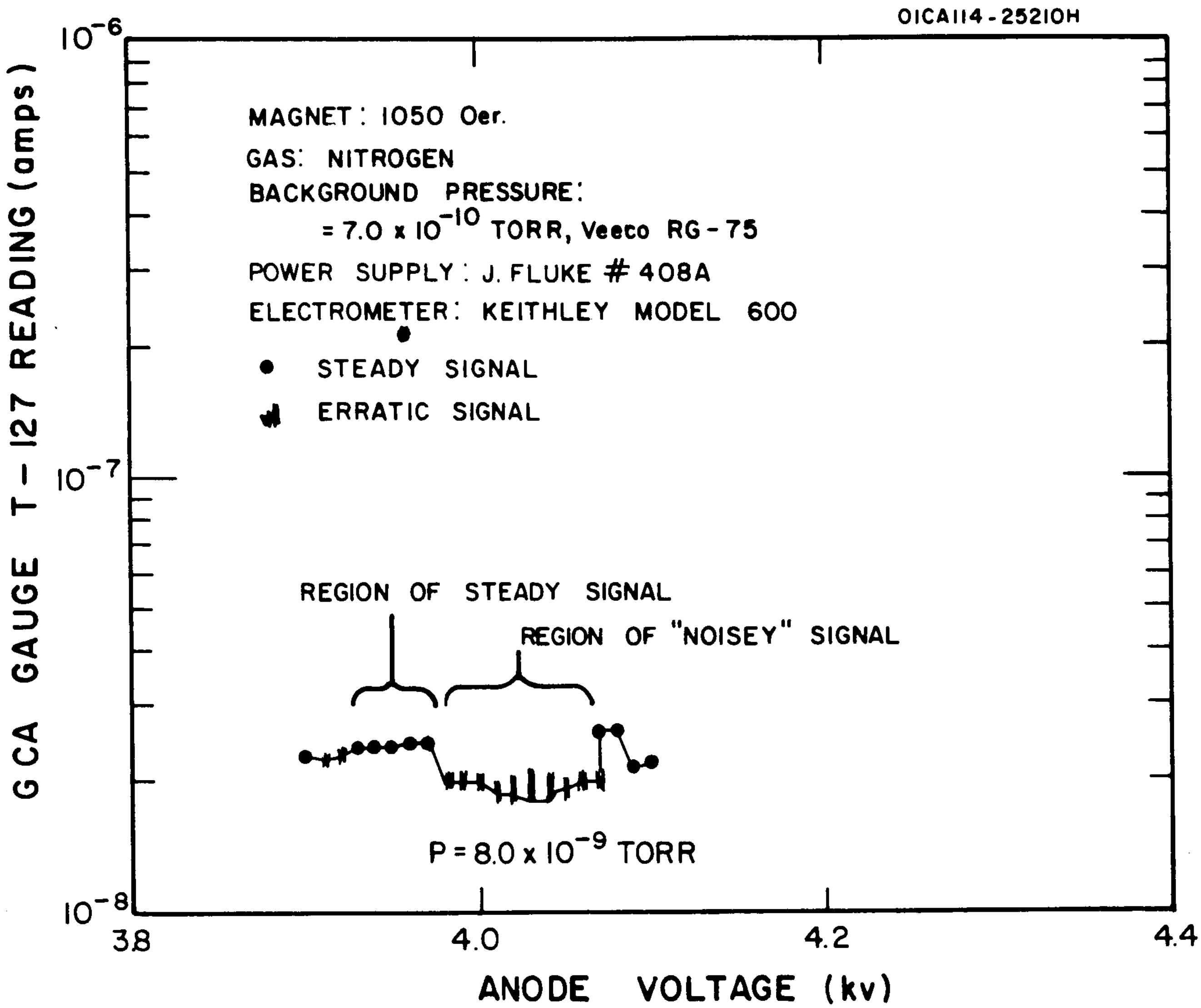

Figure 10. Detailed current-voltage characteristic of a GCA Model 1410 cold cathode gauge.

The detailed current-voltage characteristics clearly showed how the anode voltage can affect the stability of the gauge output current.

Current-Voltage Characteristics of a Typical Flight Model (Model R-4) Cold Cathode Gauge. The particular experiments described below were carried out to see if there was any important "fine structure" in the current-voltage characteristic of a typical magnetron type cold cathode gauge.

System Preparation and Tests Performed

This test was made on the vacuum test system after it had been baked overnight at 200 to 300°C. The main diffusion pump and the single cold trap following the pump were not baked. A Veeco Bayard-Alpert type RG-75 gauge (No. 248S31) was used to measure the system pressure. The system background pressure without liquid nitrogen in the spherical trap was about 3×10^{-8} torr. With the spherical trap filled, the background pressure was 3×10^{-9} torr. The system was operated overnight with a small flow of nitrogen gas to raise the pressure to about 5×10^{-8} torr. The cold cathode gauge being tested was the number 27 Model R-4 flight type gauge. This gauge was similar to the standard Model 1410 gauge except that the anode was positively positioned with the aid of ceramic spheres and was plated with radioactive material. The cathode was machined from a single piece of material and electropolished. The gauge was constructed to be mechanically rugged. The magnetic field for the gauge was supplied by the number 1 electromagnet. Anode voltage was furnished by a GCA unregulated power supply. The gauge current was measured with a Keithley Model 600 electrometer. After the nitrogen pressure in the system was established, the gauge anode voltage was varied from 2.5 to 5.0 kV in steps of 500 volts. Both the gauge current and its stability were observed.

Results

The results of this experiment are displayed in the graph of Figure 11. The gauge output current increased with increasing anode voltage over the range from 2.5 kV to 5.0 kV for nitrogen gas pressures ranging from 8.8×10^{-8} torr to 6.7×10^{-7} torr. The gauge output current was steady for anode voltages of 2.5, 3.0, 3.5, and 5.0 kV, but the current was erratic or noisy for anode voltages of 4.0 kV and 4.5 kV.

Discussion

The magnetic field used in this test was supplied by an electromagnet with larger pole pieces than those of the permanent magnets used in most of the other tests. The magnetic field was probably more uniform over the anode-cathode ionization region.

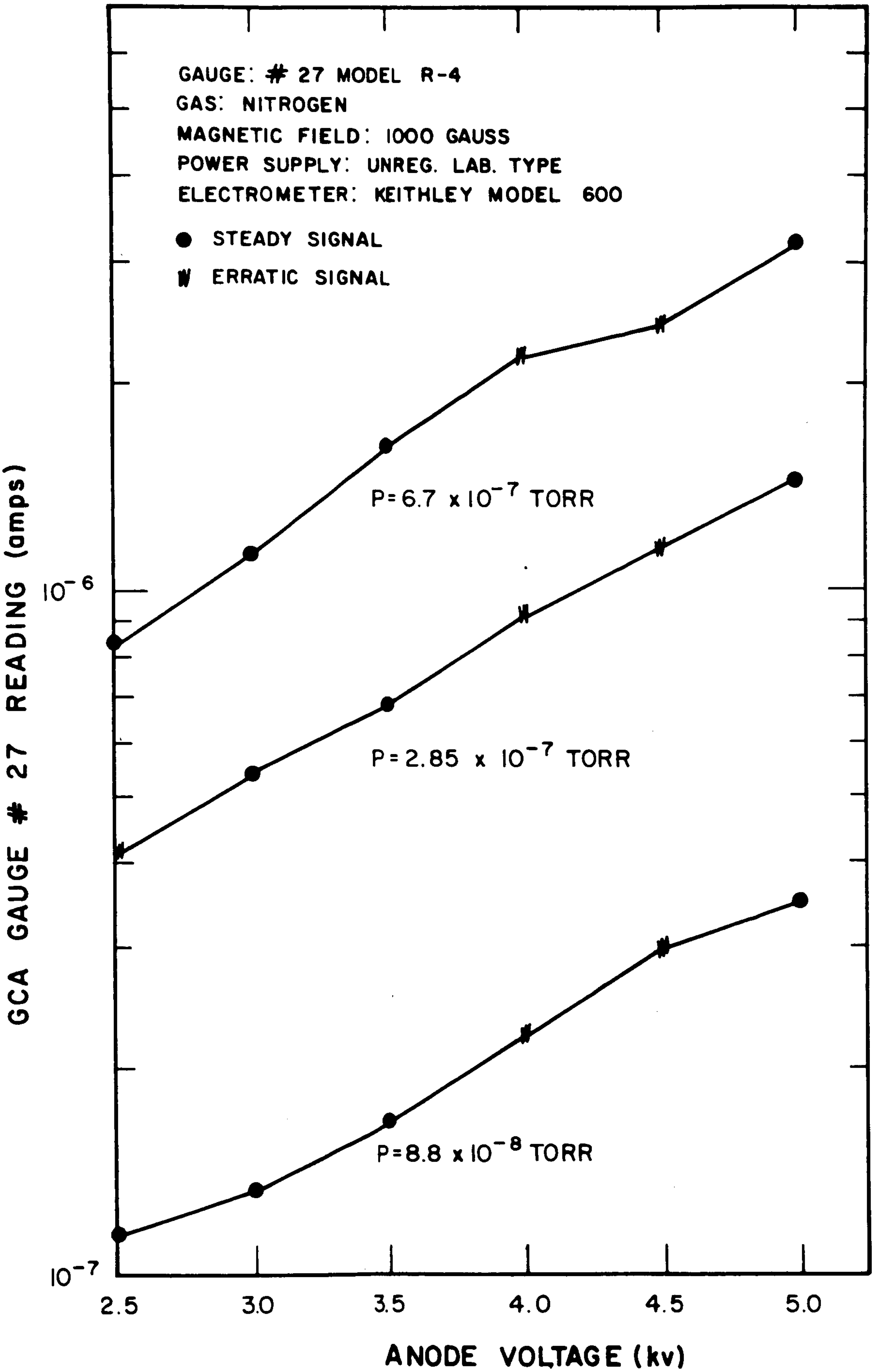

Figure 11. Current- voltage characteristics of a typical flight model cold cathode gauge.

The data confirmed the finding that stable operation was obtained for certain anode voltages.

The characteristics obtained in this experiment were different from those of the 1410 gauge -- no maxima were present -- chiefly because the nitrogen gas pressures used were higher.

Current-Magnetic Field Characteristics of a Typical Flight Model (Model R-4) Cold Cathode Gauge. This test was made to get an overall picture of the manner in which gauge response was affected by the magnitude of the magnetic field. Magnetic fields ranging from 700 to 1400 gauss were used.

System Preparation and Tests Performed

The output current of the number 27 Model R-4 cold cathode gauge was measured as a function of the magnetic field strength. The experimental conditions were the same as those described in test three above. The magnetic field was varied in steps of 100 gauss. The magnet air gap was 1-1/2 inches in diameter and 1-9/32 inches long. Data were taken for various anode voltages, but the data for an anode voltage of 4.0 kV were representative. The normal readings of the Veeco gauge (representing the system pressure) were somewhat disturbed by the fringing field of the electromagnet. Later tests showed that the Veeco gauge readings could have been as much as 40 percent greater if there were no fringing magnetic field. Data were taken for three different, (uncorrected) nitrogen pressures: 8.8×10^{-8} torr, 3.0×10^{-7} torr, and 6.9×10^{-7} torr.

Results

The data obtained in this experiment show a generally decreasing gauge output current with increasing magnetic field, with the exception that for the lowest pressure level investigated (8.8×10^{-8} torr), there was a minimum in the current-magnetic field characteristic. Other, less formal, experiments had shown that as the magnetic field dropped below 700 oersted, the gauge output current decreased and eventually went out. This behavior was also implied by the current values obtained at 700 and 800 oersted when the system pressure was 8.8×10^{-8} torr (refer to Figure 12). It was found that the stability of the gauge output current was a function of the magnetic field strength as well as a function of the anode voltage.

Discussion

Data of the type obtained in this test is necessary to select the best value of magnetic field strength for a given application. The stability of the gauge may be all important, and this experiment indicated that current stability depended on the value of the magnetic field. Constancy of the gauge output may be most important for a particular application (for maximum accuracy and reproducibility), and

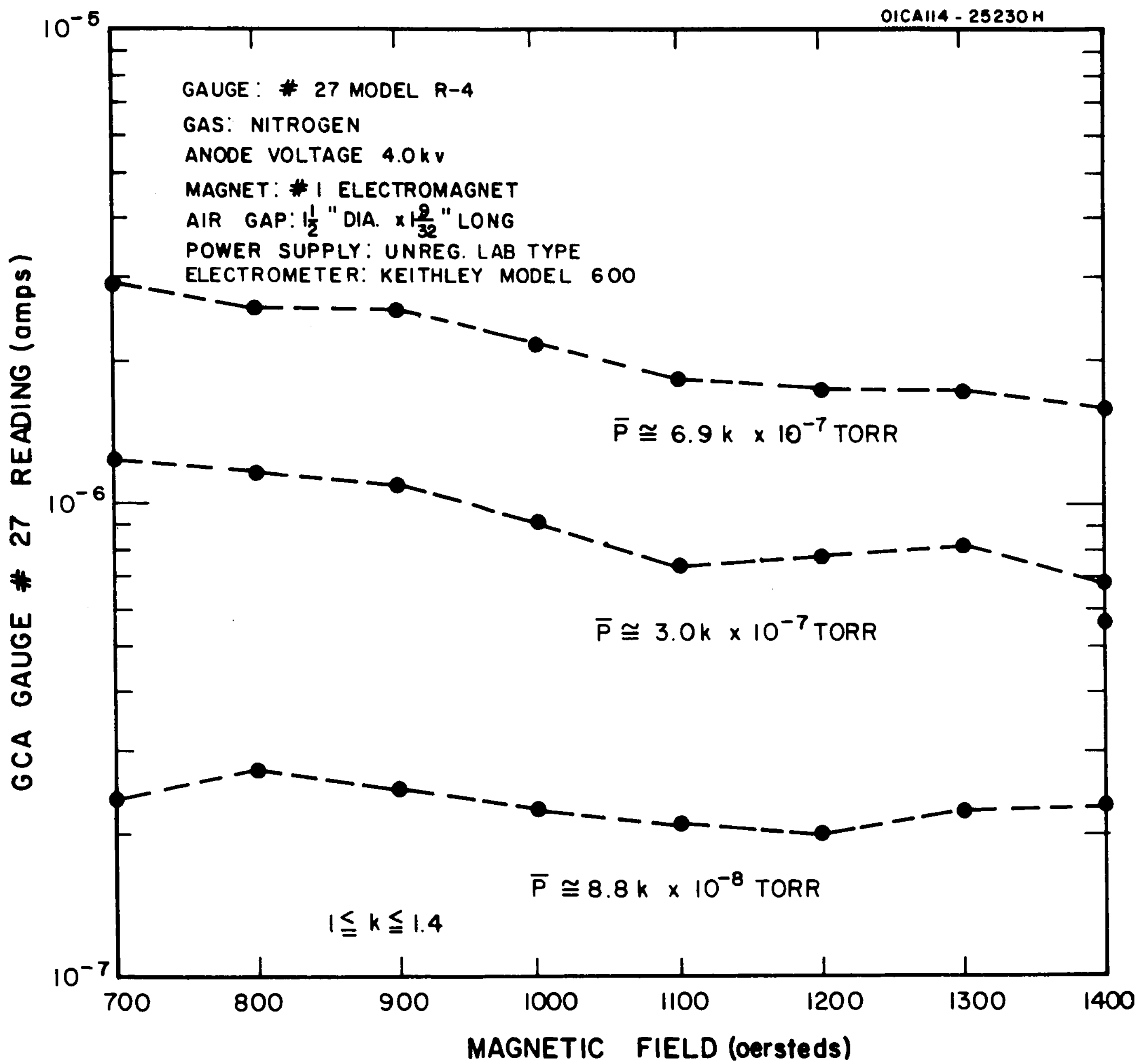

Figure 12. Current-magnetic field characteristics of a typical flight model cold cathode gauge.

one would then want to operate on a relatively horizontal portion of the current-pressure characteristic. In the same way, one might use a smaller magnetic field to get the maximum gauge output (at the higher pressures used in this test), or some value of the magnetic field that gives the "best" operation at very low pressures.

Detailed Current-Magnetic Field Characteristic of a Typical Flight Model (Model R-4) Cold Cathode Gauge. The experiment described below was performed to search for "fine structure" in the current-magnetic field characteristic of a typical magnetron type cold cathode gauge.

System Preparation and Tests Performed

This experiment was performed on the vacuum test system under conditions similar to those described in the third test. The number 27 Model R-4 cold cathode gauge was used together with the number 1 electromagnet. The magnet current was furnished by a regulated low voltage power supply and was read with a Triplett Model 630 NA ammeter. The anode voltage of 4.0 kV was supplied by a J. Fluke Model 408A high voltage power supply. The gauge current was read with a Keithley Model 600 electrometer. The system background pressure was 8×10^{-9} torr before the nitrogen gas was permitted to flow through the system to establish an equilibrium pressure of 5.2×10^{-7} torr in the test chamber. Gauge readings were taken for magnetic fields varying from 594 gauss to 1200 guass in 10 gauss intervals. All of the readings were stable.

Results

The results of this experiment are shown graphically in Figure 13. Even though the overall trend is such that there was a general decrease in the gauge output current as the magnetic field increased, it can be seen that there were small scale variations during which the gauge current increased with increasing magnetic field. It is noteworthy that all of the readings were steady, in contradiction to the results obtained in the previous test. A highly regulated high voltage power supply was used in this test while an unregulated power supply was used in the previous test. There are evidently regions of magnetic field strength, such as values near 1100 gauss, where small changes in the magnetic field hardly affect the gauge response. For maximum reproducibility, it would be advantageous to operate a gauge in a region where the output current does not vary much with the magnetic field.

Discussion

The detailed current-magnetic field data showed how small changes in the magnetic field could cause appreciable changes in the gauge output current. Such behavior should be predictable from an adequate theory of gauge operation.

Current-Pressure Characteristics for Three Typical Flight Model (Model R-5) Cold Cathode Gauges for Nitrogen. In the course of completing the contract work, it was necessary to calibrate a series of flight model

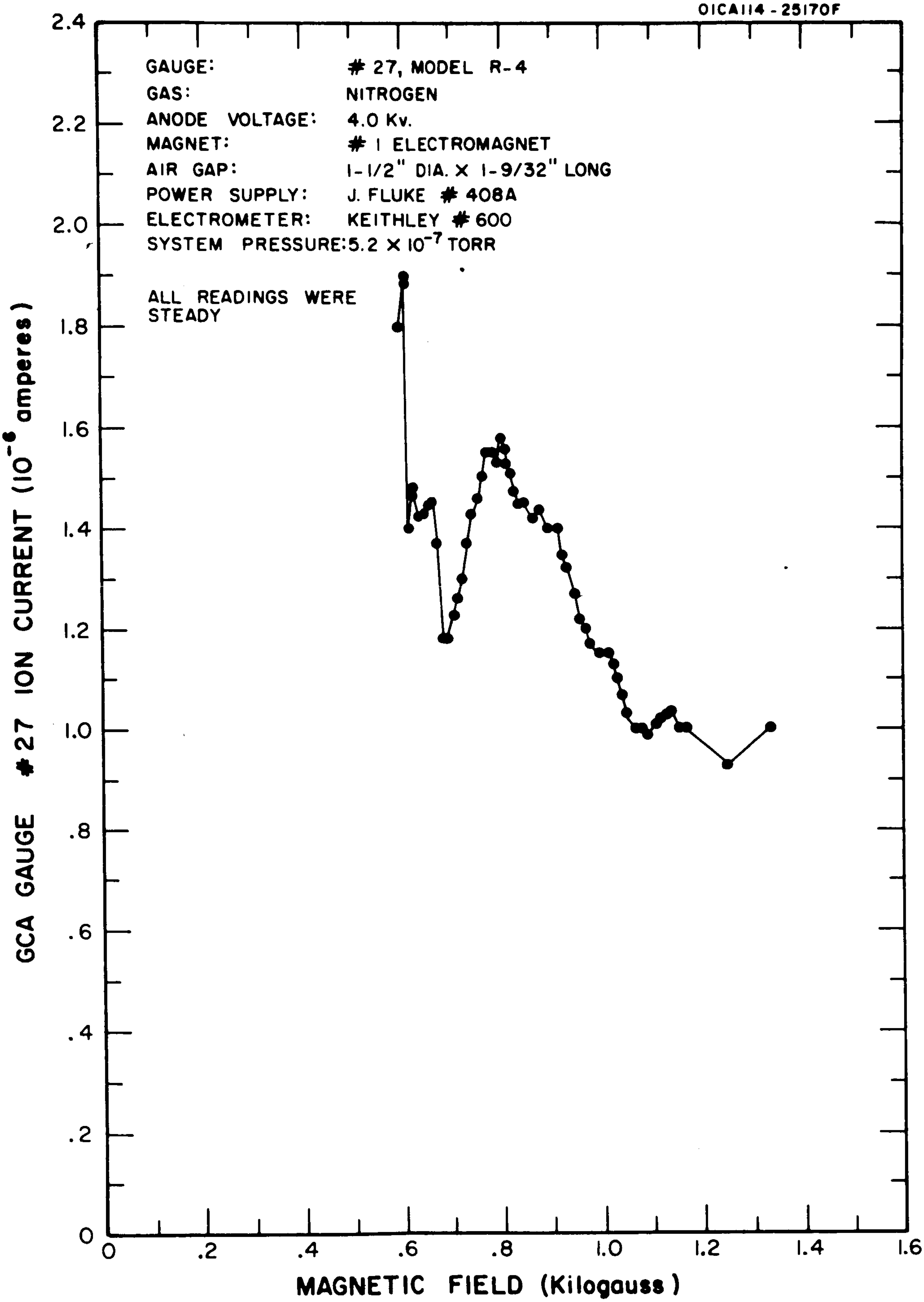

Figure 13. Detailed current-magnetic field characteristic of a typical flight model cold cathode gauge.

cold cathode gauges. The gauges were usually calibrated in groups of three to expedite the process and also to obtain a direct comparison of their behavior. During one such calibration, some interesting results were obtained. These are presented below:

System Preparation and Tests Performed

This test was an absolute calibration of three Model R5 cold cathode gauges for nitrogen gas over the pressure range from about 1.5×10^{-10} torr to 1.5×10^{-6} torr. The test was carried out with the number two all-glass Venema type calibration system that consisted of two mercury diffusion pumps in series with three Venema type re-entrant cold traps and a test chamber as described earlier. The three cold cathode gauges and a comparison hot filament gauge (Varian UHV-12P gauge) were connected to the test chamber. The test chamber, the three cold traps, and the upper part of the main diffusion pump were baked out overnight at $400^{\circ}C$. Pure nitrogen gas was admitted to the system at a point just below the test chamber from a gas inlet reservoir whose pressure was measured with a McLeod gauge. The nitrogen from the gas inlet chamber flowed through a calibrated small bore capillary tube of known vacuum conductance into the calibration system. The pumping speed of the system for nitrogen gas had previously been measured at higher pressures. The nitrogen gas pressure in the test chamber could then be simply calculated for equilibrium conditions -- at which time the total gas flow into the system had to be equal to the flow out of the system. Such "flow calibration" measurements were usually made for pressures up to about 1 x 10^{-7} torr. Calibrations above this pressure level were generally made by comparing the cold cathode gauge readings with the reading of a McLeod gauge calibrated Bayard Alpert "comparison gauge" located on the test chamber. In the test reported here, flow calibration was performed only over the pressure range from 1.5 x 10^{-10} torr to about 1.5 x 10^{-9} torr. Comparison calibration was performed in the 10^{-8}, 10^{-7}, and 10^{-6} torr regions.

A high voltage of 4.0 kv was supplied to each of the three cold cathode gauges from GCA Model 1400 regulated and well-filtered 1410 gauge control power supplies. The gauge currents were read with Keithley Model 600 electrometers.

The Model R5 flight type gauges were similar to the Model R4 gauges except that the four ceramic spheres that supported the anode did not penetrate through the anode and hence, were not exposed to the gas discharge. The anode and tubulation of the Model R5 gauge were larger than their counterparts of the R4 gauge. The magnets used with the Model R5 gauges had a measured magnetic field strength of 1050 oersted at the center of the air gap.

Results

The results of the calibration of three typical flight model cold cathode gauges for nitrogen gas are shown graphically in Figure 14. The

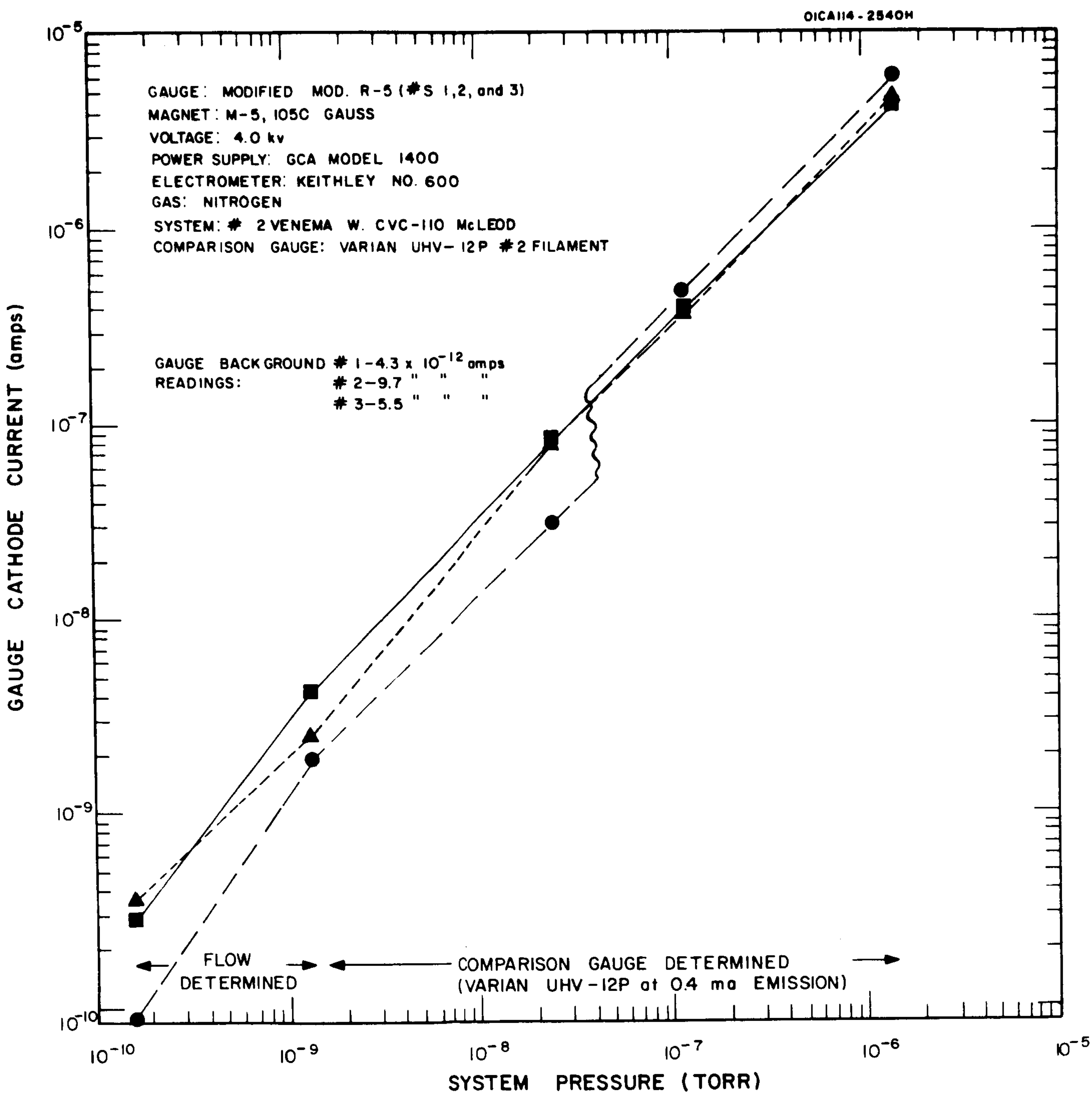

Figure 14. Current-pressure characteristics for three typical flight model cold cathode gauges.

two lowest pressure measurements were made by the flow calibration technique while the remainder of the measurements were made by comparison with a calibrated Bayard-Alpert type gauge. The three gauges involved were identical in construction, but the cathode of the No. 1 gauge had been accidentally scratched and subsequently polished with a fine abrasive material. The No. 2 and No. 3 gauges had electropolished surfaces.

It can be seen from the graph that the No. 2 and No. 3 gauges had approximately similar responses except for a pressure near 1×10^{-9} torr. The No. 1 gauge was unique in that its response was greater than that of the other two gauges for pressures above 1×10^{-7} torr, but was considerably less than that of the other two gauges for pressures of 2.5×10^{-8} torr and below. The sharp break in the current-pressure characteristic of the No. 1 gauge had not been observed previously in other flight model gauges, although it was observed later in some of the experimental gauges. The two undamaged gauges showed a fairly linear response in the pressure region from 1.3×10^{-9} torr to 1.45×10^{-6} torr.

Discussion

This experiment showed the importance of the cathode surface in determining the response of a cold cathode gauge. The roughening or contamination of the cathode surface affected its ability to emit secondary electrons and hence, had a marked effect on the electronic space charge build-up within the anode-cathode region. The decreased sensitivity of the No. 1 gauge at lower pressures indicated a reduction of secondary emission. The increased sensitivity at higher pressures cannot be explained at this time except to point out that the effective surface area of a "roughened" cathode is greater than that of a "smooth" cathode. Later experiments with the demountable gauge indicated that a larger diameter cathode (having a larger surface area) increased the sensitivity of a cold cathode gauge at pressures above 10^{-7} torr.

Comparison of Current-Pressure Characteristics of Model R5 Cold Cathode Gauges for Nitrogen and Helium. The objective of this test was to compare the behavior of typical flight model gauges with respect to their operation in two different gases.

System Preparation and Tests Performed

The No. 2 all-glass Venema calibration system was used in this test. The system test chamber contained three Model R5 cold cathode gauges, Nos. 8, 9, and 10, and a Vacuum Industries Model BA 100 Bayard-Alpert gauge that was quite similar in its construction to the Veeco RG-75 gauge used in other tests. The entire system was baked overnight at $450^{o}C$. The nitrogen flow calibration was carried out first, using both the "flow" technique and the comparison readings discussed in the previous test. Anode voltages of 4.0 kV to the cold cathode gauges were furnished by GCA Model 1400 gauge control power supplies. The gauge currents were read with Keithley Model 600 electrometers. The gas inlet Bayard Alpert gauge and the test chamber Bayard Alpert gauge were calibrated against the CVC Model GM-110 McLeod gauge for both nitrogen and helium gas.

Results

The data obtained in this experiment show that the behavior of a typical flight model cold cathode gauge is similar for nitrogen and helium gas. The gauge characteristics for the two gases contain both linear and non-linear portions. As can be seen in Figure 15, the ratio of gauge currents for equal pressures of nitrogen and helium is about five. There is a common transition region in which the gauge operation changed from linear to non-linear for both gases.

Discussion

The magnetron type cold cathode gauges used in this experimental program exhibited approximately the same ratio of sensitivities for nitrogen and helium gas as exhibited by hot filament ionization gauges. This indicated that the average energy of the electrons that created positive ions in the two devices was about the same. For a given gauge, if the transition point between the linear and non-linear current-pressure characteristics appeared at a fixed value of gauge current for different gases, it was an indication that the transition was purely an electronic phenomenon.

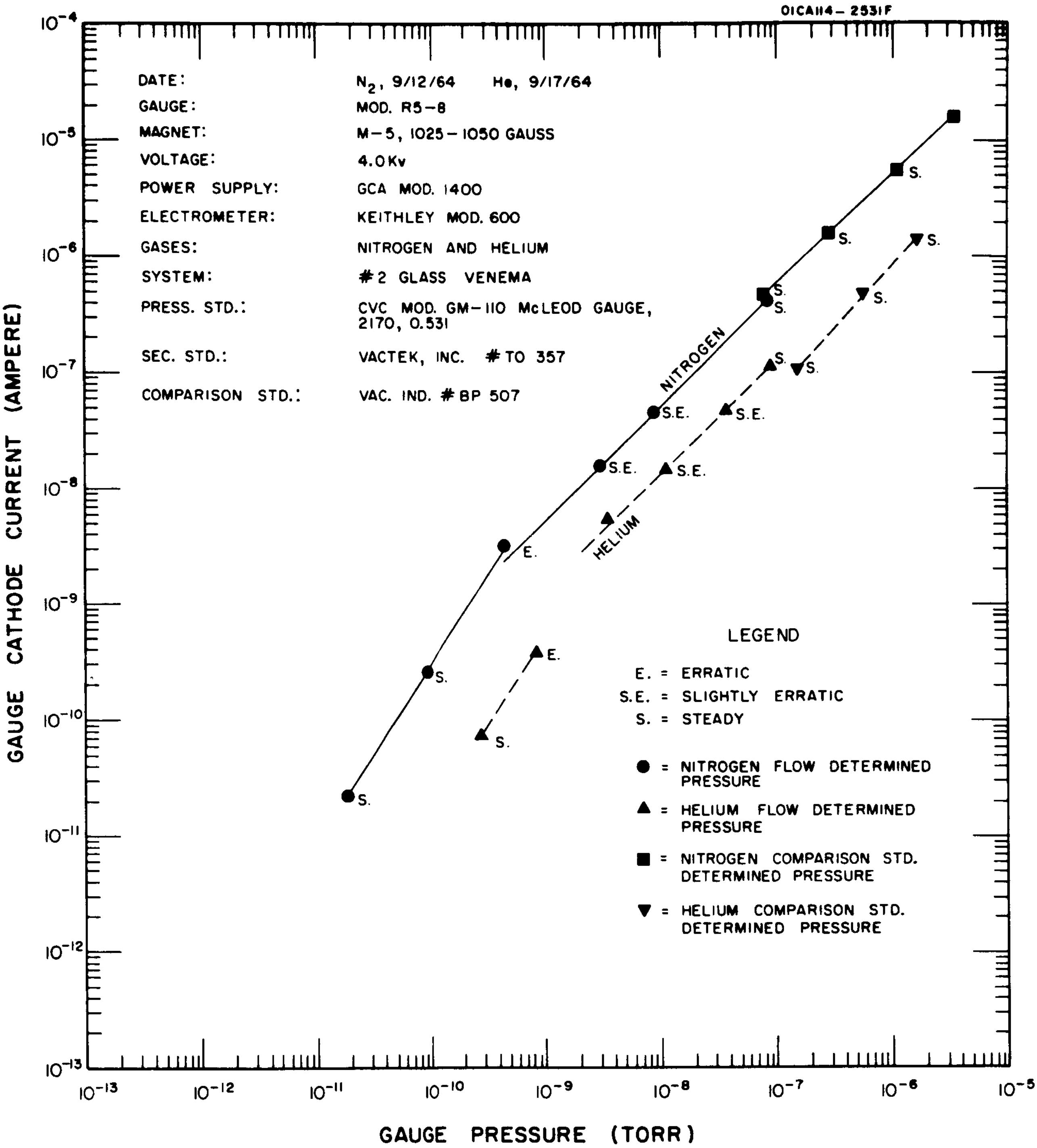

Figure 15. Comparative current-pressure characteristics of a typical flight model cold cathode gauge for nitrogen and helium gas.

Experiments With the Model X-1 Experimental Cold Cathode Gauge

The Model X-1 gauge was designed specifically to permit several different measurements to be made. The gauge was constructed with a radially divided anode to facilitate measurements of radio frequency that might be generated during its operation. This particular feature of the X-1 gauge has not been exploited as yet. A second objective of the gauge design was to place a small fixed probe adjacent to, but electrically isolated from, the slit in the gauge anode. Positive ions or electrons might then be drawn out of the discharge to the fixed probe. Such probe current measurements would then yield information about the radial movement of ions and/or electrons through apertures in the gauge anode. A third objective of the gauge design was to make use of a small aperture in the hollow cathode of the gauge. A movable, central ion probe was located within the hollow cathode. The aperture in the cathode would form a beam of positive ions which could be detected by the central probe. It was hoped that the curvature and spread of the positive ion beam for ions of a single species (mass) would yield information about the origin and energy of these ions within the discharge region. It was found that the energy of the positive ions that reached the gauge cathode could be measured by biasing the cathode negative with respect to the central ion probe.

The Model X-1 gauge, shown in Figure 16, was built with a radially divided anode and a movable, .010-inch diameter, tungsten, central wire probe located inside the hollow cathode. A bellows-sealed, micrometer-type

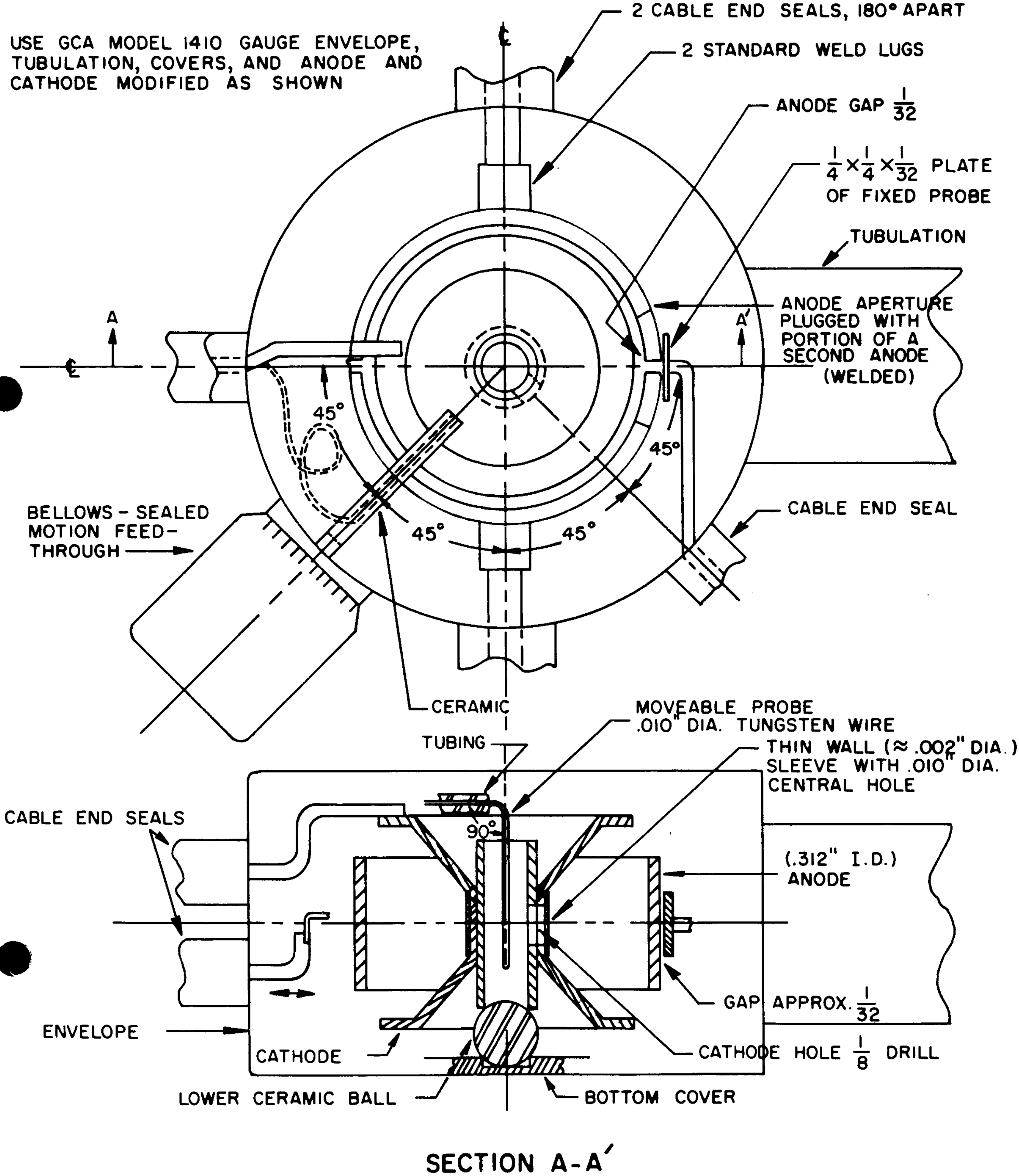

Figure 16. Model X-1 experimental cold cathode gauge.

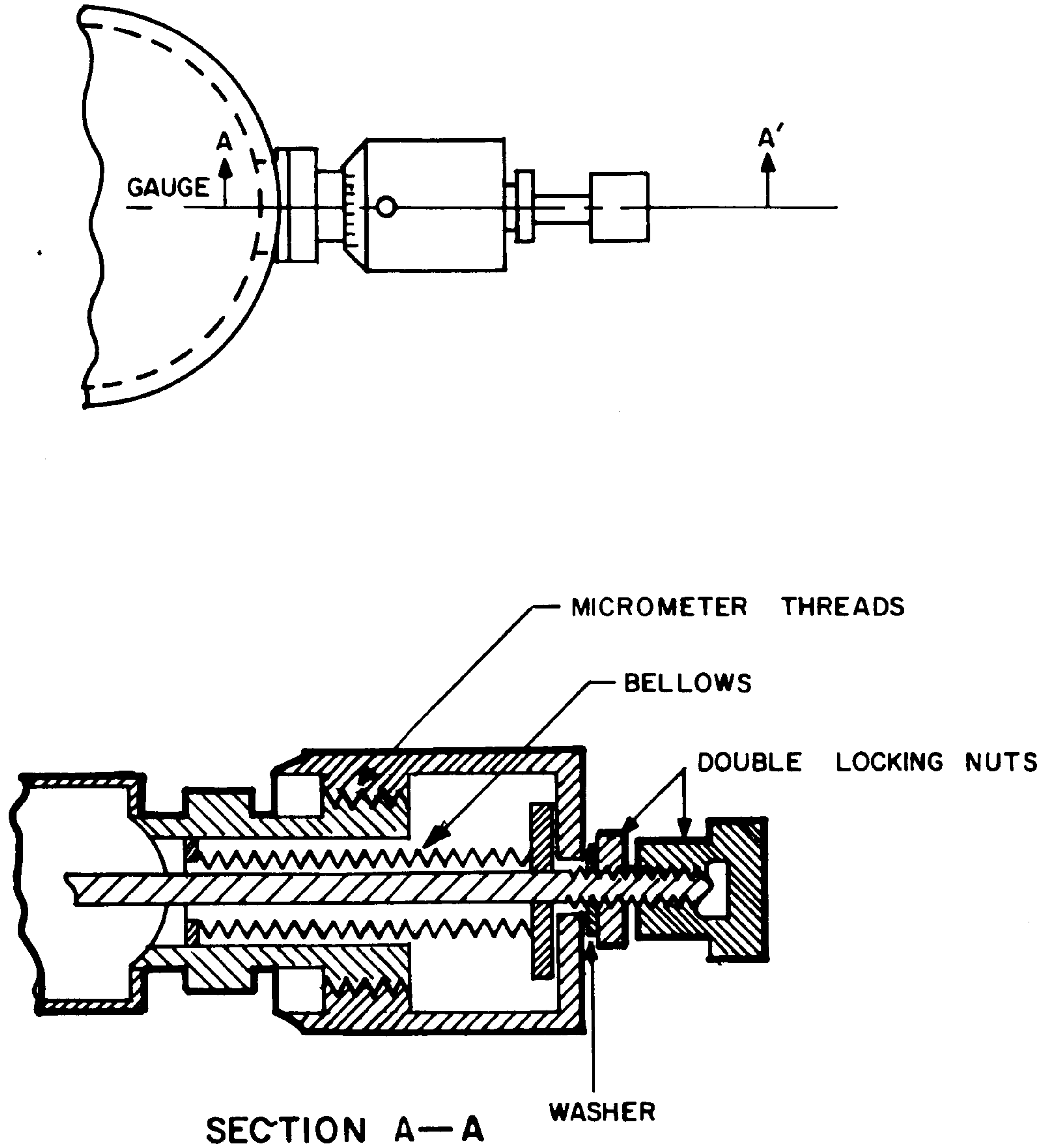

Figure 17. Bellows-sealed motion feedthrough.

motion feedthrough was used to move the central probe. A sketch of the motion feedthrough is presented in Figure 17. A hole 1/8-inch in diameter was drilled through the center of the cylindrical portion of the cathode. This hole was then covered with a sheet of thin wall stainless steel in which a .010-inch diameter hole had been drilled. The .010-inch diameter hole was centered over the 1/8-inch diameter hole and served as an aperture to permit positive ions from the discharge to enter the interior of the cathode. The positive ions that entered the cathode were collected by the movable .010-inch diameter tungsten probe.

A second probe, the so-called "Fixed Probe", was located just outside one of the two anode gaps that were created by dividing the anode into two radial segments. The function of the fixed probe was to draw either electrons or positive ions out of the discharge.

Notice that the upper ceramic ball that is normally used to support the cathode and keep it in a fixed position has been omitted in this gauge.

Current-Pressure Characteristics of the Model X-1 Gauge Electrodes For Nitrogen Gas. This initial experiment with the X-1 gauge was performed to determine the relationship of the positive ions collected by both the fixed probe and the movable central probe with respect to the total positive ion current to the gauge cathode.

System Preparation and Tests Performed

The experiment was performed with the X-1 gauge mounted on the vacuum test system. The system had been baked in the usual way with heating tape and had pumped for eight days after the bakeout period. The system pressure was measured with a Bayard Alpert Veeco RG-75 gauge (serial number 248S31) operated at 10 mA emission. The background pressure was 1.0×10^{-8} torr with the spherical cold trap filled before the nitrogen gas flow was started. The highly regulated J. Fluke Model 408A power supply furnished 4.0 kV to the gauge anode. Keithley Model 600 electrometers were used to measure the currents to the gauge cathode, the central ion probe, and the outer anode probe. A permanent magnet with a 1-1/4 inch air gap and a magnetic field of 1030 gauss was used. The nitrogen gas bottle valve was opened in steps to obtain a series of increasing equilibrium pressures in the system. Pressures from 1×10^{-8} torr to 1.5×10^{-5} torr were obtained.

The X-1 gauge was operated with the central ion probe in its zero position, that is, centered within the hollow cathode. The gauge cathode, central ion probe, and outer fixed anode probe were all connected to ground potential through their respective electrometers.

Results

As can be seen from Figure 18, the cathode, central ion probe, and outer anode probe currents of the X-1 gauge did not vary exactly

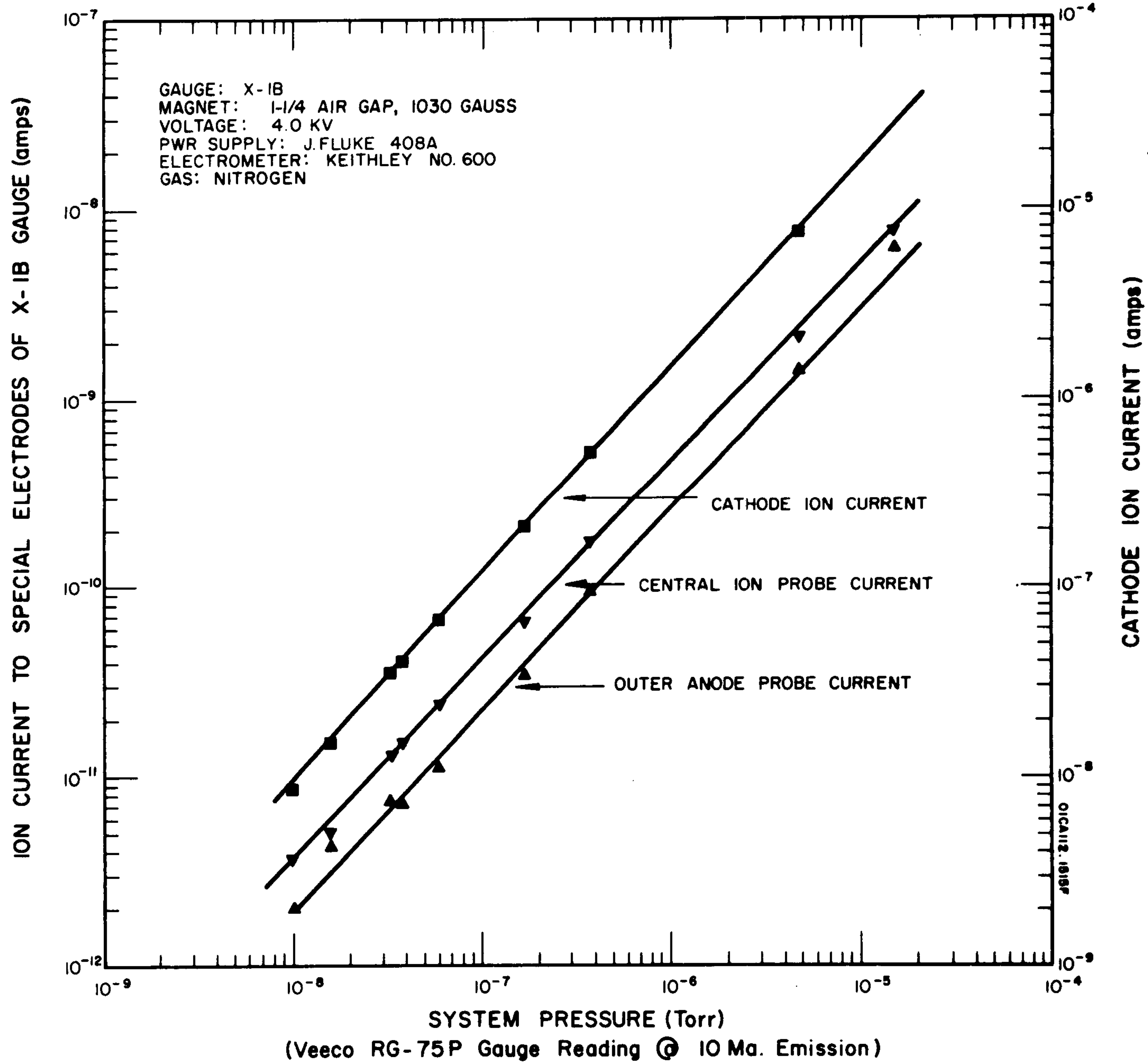

Figure 18. Current-pressure characteristics of the Model X-1 gauge electrodes.

linearly with pressure, assuming that the RG-75 Bayard Alpert gauge measuring the system pressure did vary linearly with pressure. The currents to both probes appeared to be positive ion currents. The ion currents to the central ion probe and the outer anode probe were proportional to the gauge cathode ion current over the entire pressure range. The gauge cathode current was about 3000 times greater than the current to the central ion probe and 6000 times greater than the current to the outer anode probe. The sensitivity of the X-1 gauge of 1.4 amperes per torr for nitrogen at a pressure of 1×10^{-6} torr appeared to be lower than the sensitivity of the standard Model 1410 cold cathode gauge. There were no mode changes apparent. Changing the outer anode probe potential from zero to 4.0 kV had no noticeable effect on the gauge discharge current.

Discussion

The proportionality between the currents to the two probes and the main discharge current in the gauge was expected. It was speculated that the positive ions that reached the outer anode probe were formed very close to the slit in the anode that was adjacent to this probe. The fact that the potential of the outer anode probe had no visible effect on the gauge discharge indicated that there was no strong "electronic ring current" immediately adjacent to the inner diameter of the anode. Such a current would have been disturbed by the probe potential.

Central Ion Probe Current of the X-1 Gauge as a Function of Probe Position for Various Gases.

System Preparation and Tests Performed

The experiment was performed with the Model X-1 gauge mounted on the vacuum test system. A 1030 gauss, 1-1/4 inch gap length permanent magnet was used to supply the magnetic field. An anode voltage of 4.0 kV was furnished by a GCA laboratory type unregulated but well-filtered high voltage power supply. Keithley Model 600 electrometers were used to measure the cathode current and the central ion probe currents. The system had been baked out mildly several days prior to the experiment. The background pressure in the system with the spherical trap filled with liquid nitrogen was about 1×10^{-8} torr (Veeco RG-75 gauge at 10 mA emission).

After the desired pressure of a particular gas had been established in the system in the usual way, the central ion collector probe was moved radially from a position .050 inches off-center to the center of the cathode (and gauge) and then .050 inches off-center in the opposite radial direction. The positive ion current to the probe was observed at .005 inches intervals of probe position. One experiment was conducted with a nitrogen pressure of 3.8×10^{-7} torr in the system. Another experiment was performed with a helium pressure of 7.2×10^{-6} torr equivalent nitrogen in the system. A third experiment was carried out with a 50% mixture of nitrogen and helium at a total pressure of 9.4×10^{-6} torr equivalent nitrogen. The last experiment was made with oxygen gas at a pressure of 8×10^{-6} torr equivalent nitrogen. In the last experiment, anode voltages of 4.0 and 2.0 kV were used. The cathode currents for each experiment were recorded.

Results

The data obtained for four different gases and gas mixtures are summarized in the graphs of Figures 19, 20, 21, and 22.

As is evident from the graphs, the positive ion current to the central ion probe formed a beam having dimensions determined primarily by the size of the cathode aperture. The beam was cut-off on one side by the geometry of the aperture and probe. It is believed that ions formed near the cathode consituted this edge of the beam that was closest to the gauge axis. The other edge of the beam was further from the gauge axis and contained somewhat more ions. It is believed that these ions come from regions near the anode. The nature of the beam indicated that positive ions were arriving at the cathode from all points within the inter-electrode space. The maximum beam current for nitrogen was about 7-1/2 times greater than the background current to the ion probe.

Figure 20 very clearly shows the displacement of the beam of light helium ions with respect to the center of the gauge cathode. The peak

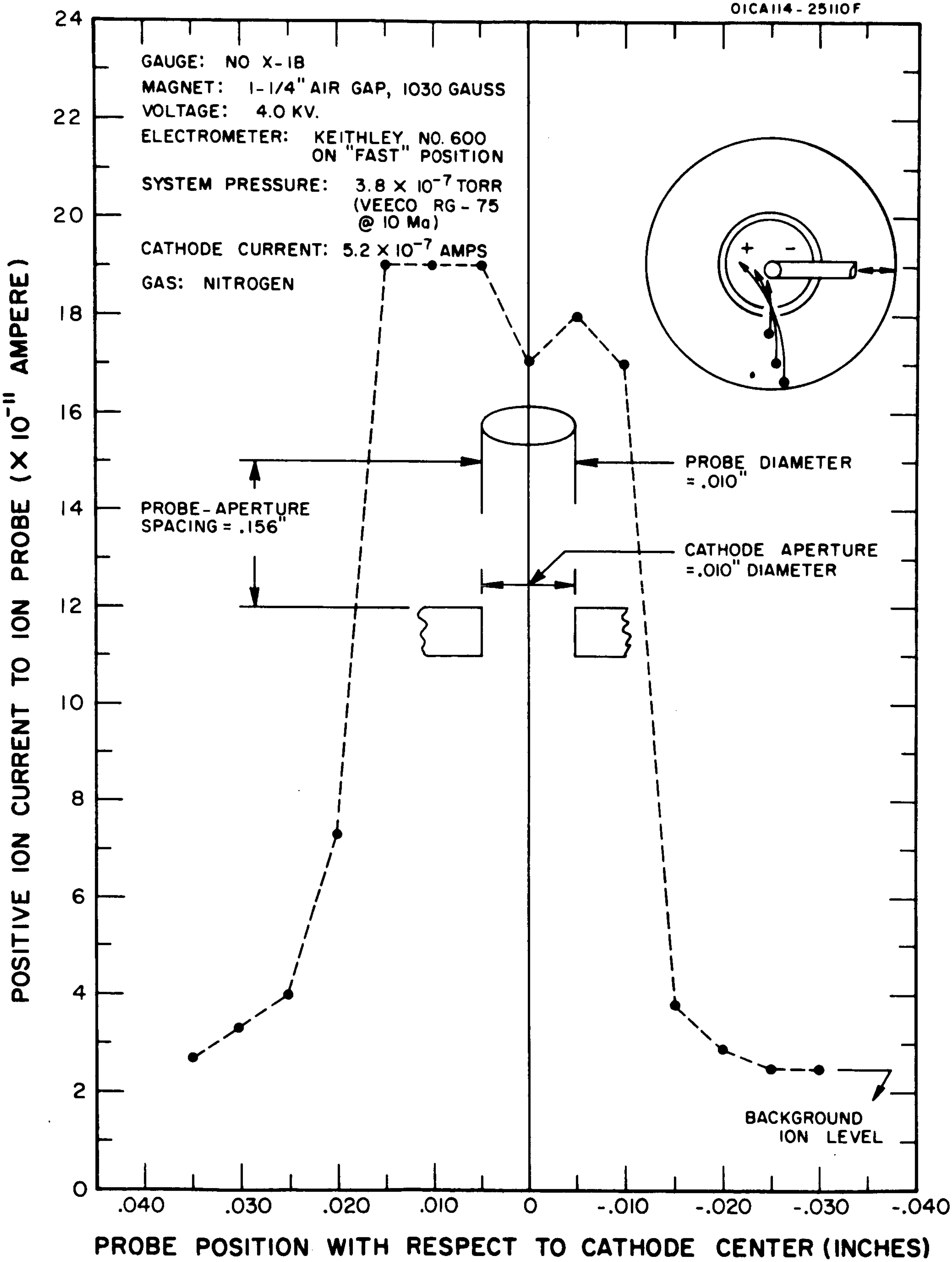

Figure 19. Central ion probe current-position characteristic for nitrogen gas in the X-1 gauge.

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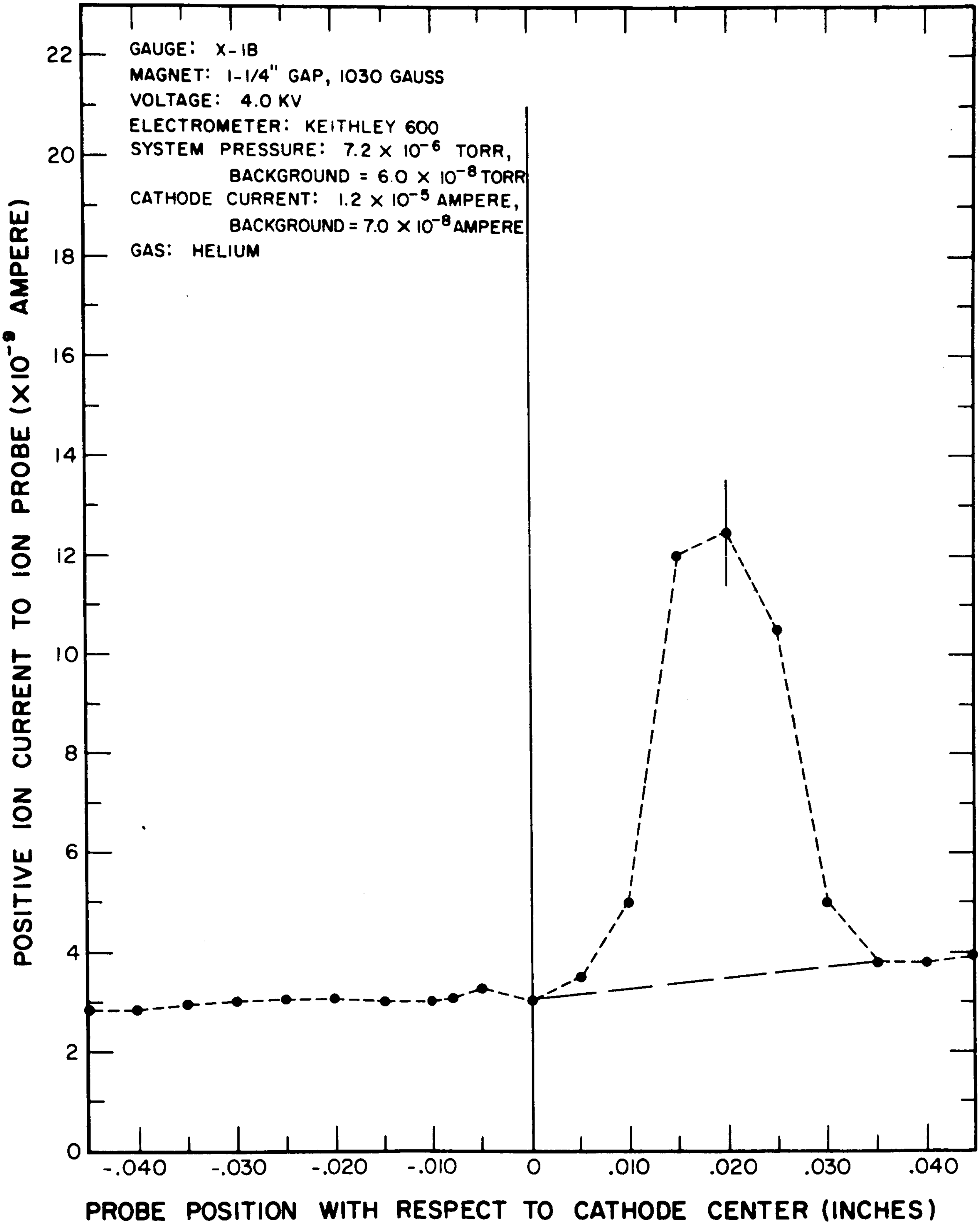

Figure 20. Central ion probe current-position characteristic for helium gas in the X-1 gauge.

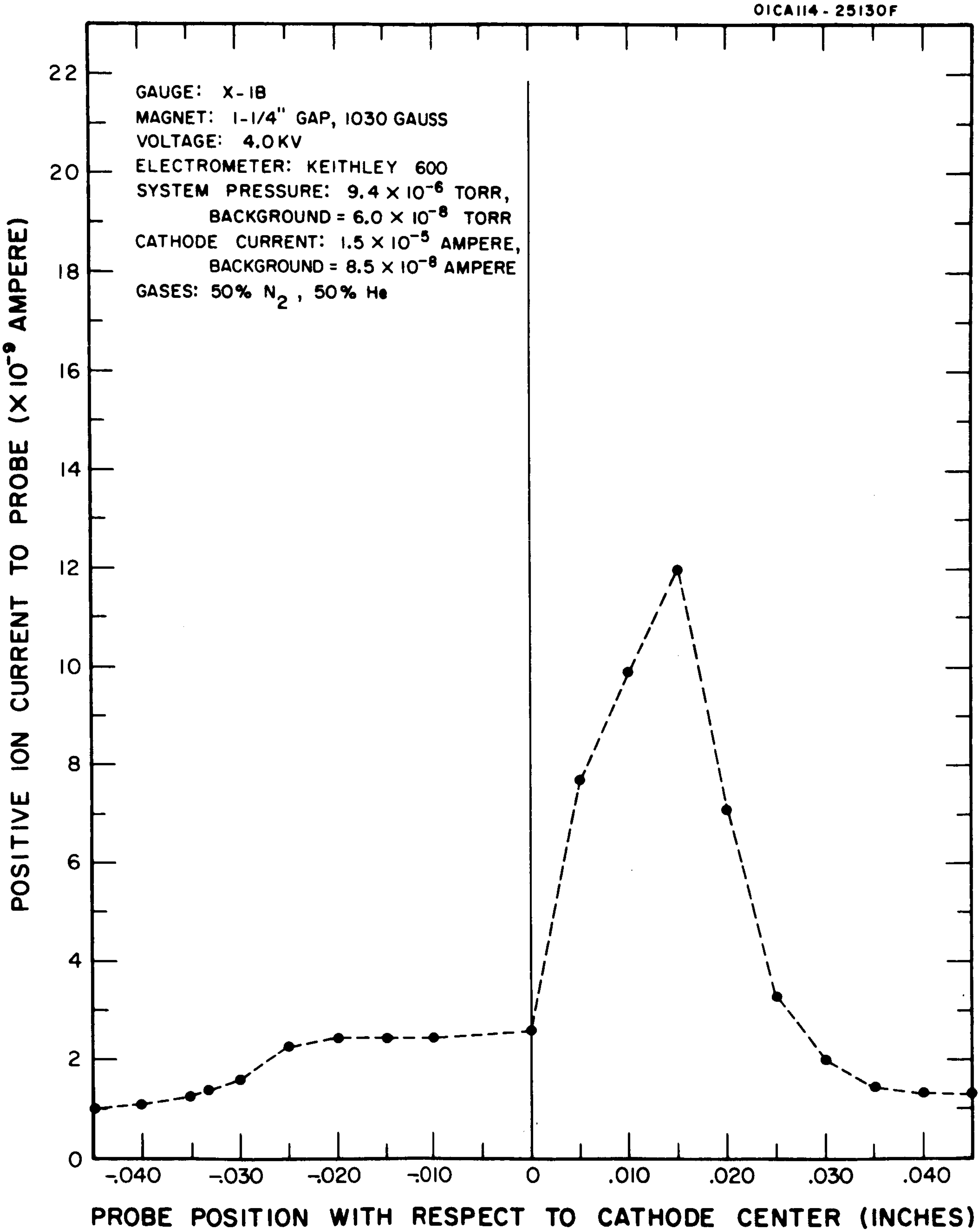

Figure 21. Central ion probe current-position characteristic for a 50% nitrogen-helium mixture in the X-1 gauge.

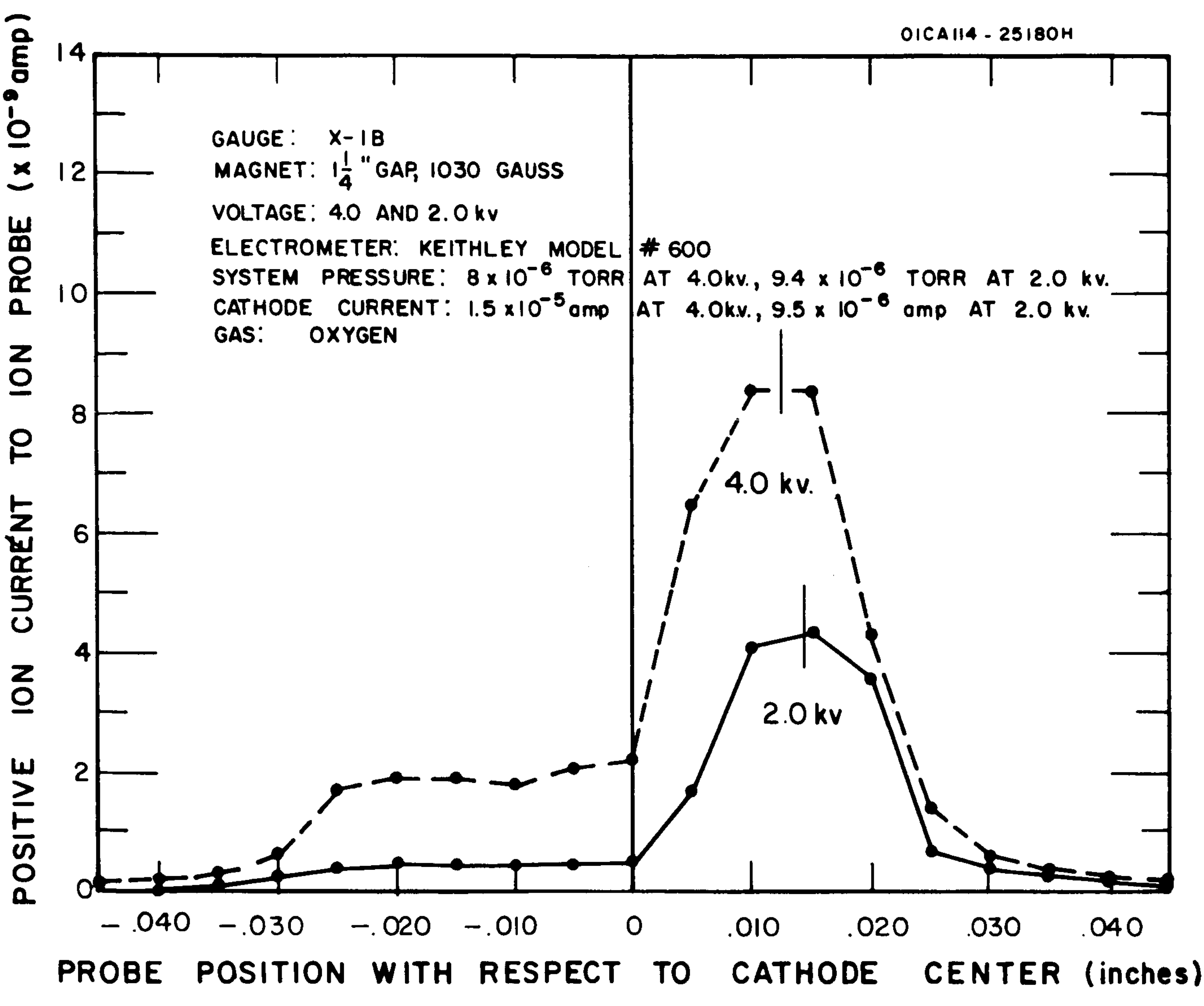

Figure 22. Central ion probe current-position characteristic for oxygen gas in the X-1 gauge.

current of the helium ion beam was only about 3-1/2 times greater than the ion background current within the cathode. Figure 21 shows the non-symmetrical shapes of an ion beam composed of helium and nitrogen. The resolving power of the device was obviously much too poor to separate the two constituents. Lastly, Figure 22 shows two oxygen ion beams, one formed with the gauge anode at 4.0 kV and the other with the anode at 2.0 kV. Not only was the maximum beam current less with the gauge anode operated at 2.0 kV, but the position of the beam maximum was shifted away from the gauge axis (center of the cathode) indicating that the average energy of the ions was less.

Discussion

The experiments that were performed with the Model X-1 gauge to obtain beams of ions of different masses show the future potential of such a device as a combination total pressure gauge and low resolution mass spectrometer. The original function of the X-1 gauge was to form beams of positive ions of a single mass species that could be analyzed to determine the origin of the ions within the discharge region. Unfortunately, a number of factors conspired to make measurements of this type impossible. First of all, the distance moved by the ions within the gauge cathode was very short, so that the amount of beam deflection was small. Secondly, one would have to know both the origin of an ion and its energy in order to be able to predict its trajectory within the cathode. While it is possible to assume various potential and space charge distributions within the gauge and then calculate corresponding beam patterns within the cathode, such a course of action would probably lead to ambiguous results. On the other hand, if the relative space charge distribution within the gauge were known -- for example, if it were determined with an experimental gauge such as the X-2 gauge -- then it should be possible to determine an absolute space charge distribution and the corresponding potential distribution that would lead to the measured beam pattern within the gauge cathode.

Measurement of Positive Ion Energy Distribution.

System Preparation and Tests Performed

The energy of positive ions that reached the cathode of the Model X-1 gauge could be measured to some degree by biasing the cathode negative with respect to the central ion probe. Starting with zero bias, the cathode voltage could be made more and more negative. In this way, the ion probe current as a function of retarding potential was obtained. It was found that for large bias voltages, relatively large leakage currents developed between the cathode and central ion probe. Large leakage currents, of course, obscured the positive ion current. However, significant information was obtained for retarding potentials up to 180 volts.

The test was performed on the vacuum test system with pure nitrogen at a pressure of 1.2×10^{-5} torr. A J.Fluke Model 408A power supply was used to maintain a potential of 4.0 kV between the gauge anode and cathode. A Kepco Model HB80M regulated power supply furnish the bias between the gauge cathode and the central ion probe. The ion probe was connected to ground through a Keithley Model 600 electrometer. The gauge cathode current was measured with a triplet Model 630 NA ammeter. The cathode potential was varied from zero to -300 volts at intervals of 60 volts. The probe current was recorded at each bias voltage for three positions of the probe -- at the beam maximum, and on the background at either side of the beam maximum. The resistance between the cathode and the ion probe was measured just prior to the experiment to determine the magnitude of the leakage currents that would develop. The positive ion currents to the probe at the beam maximum were computed on the assumption that the probe current was equal to the sum of the positive ion current and the leakage current, and that the leakage current could be calculated from the bias voltage and the measured cathode to probe resistance.

Results

The results of this experiment are summarized in Table I. It was found that 5.9% of the positive ions in the beam entering the interior of the cathode had energies less than 60 volts, 18.8% of the positive ions had energies less than 120 volts, while 34.7% had energies less than 180 volts. The presence of sizeable leakage currents

Table I

Distribution of Positive Ion Energies in a Cold Cathode Gauge

Cathode-to-Probe Retarding Voltage (Volts)	Cathode-to-Probe Leakage Current (Amperes)	Measured Probe Current (Amperes)	Positive Ion Probe Current (Amperes)	Decrease in Positive Ion Current (Percent)
0	$< 1.2 \times 10^{-12}$	3.40×10^{-8}	3.40×10^{-8}	0
60	7.1×10^{-11}	3.20	3.20	5.9
120	1.43×10^{-10}	2.75	2.76	18.8
180	2.14×10^{-10}	2.20	2.22	34.7

between the gauge cathode and the central ion probe was due primarily to the small space available within the gauge that necessitated the use of a small diameter glass bead as an insulator between the moving probe and the fixed cathode. The leakage resistance between these electrodes varied with the history of the gauge, but could be made as large as 8.4×10^{11} ohms by sparking the probe cable end seal with a tesla coil. In reducing the data, it was necessary to apply a correction for the leakage current.

Discussion

The Model X-1 gauge lent itself very well to the measurement of positive ion energies within a cold cathode type ionization gauge. The principal difficulty with the measurement revolved about the cathode-to-probe leakage resistance. There is no doubt but that a modified gauge of this type could be constructed in which the leakage resistance is increased by a factor of about 100. Under these circumstances, one could measure ion energies up to the full value of the anode voltage. The method is especially useful because secondary electrons emitted from the probe face a retarding electric field and also tend to be returned to the probe by the action of the magnetic field. Positive ions that miss the probe will strike the inside of the cathode and also release secondary electrons. These electrons face an attracting electric field, but the presence of the magnetic field must return most of these electrons to the cathode.

Experiments With the Model X-2 Experimental Cold Cathode Gauge

The Model X-2 gauge was designed to make several different measurements. The gauge was designed primarily to measure the radial electronic space charge distribution within the discharge region by drawing electrons out of the discharge in an axial direction parallel to the magnetic field. In addition to this, the gauge anode was divided axially into upper and lower cylindrical halves. This was done so that axial electronic oscillations could be detected and measured. Experiments of this kind, however, have not yet been performed. A fixed probe located just outside the gauge anode could draw either electrons or positive ions out of the discharge through the gap between the two halves of the anode.

As shown in Figure 23, a movable probe ending in a .010 inch diameter tungsten wire was located just outside one end plate of the cathode. A slot .010 inches wide and 3/16 inches long in a radial direction was cut in the cathode end plate just below the tungsten probe. The tungsten probe wire was oriented normal to the radial direction of the slot, but was moved radially. The probe could only be moved a distance of about 1/8 inch due to the design of the bellows sealed motion feedthrough that was used. This limited the radial region that could be explored. The photograph of Figure 24 gives some idea of the actual appearance of this experimental gauge. The dimensions in the photograph are roughly 50% greater than the full scale values.

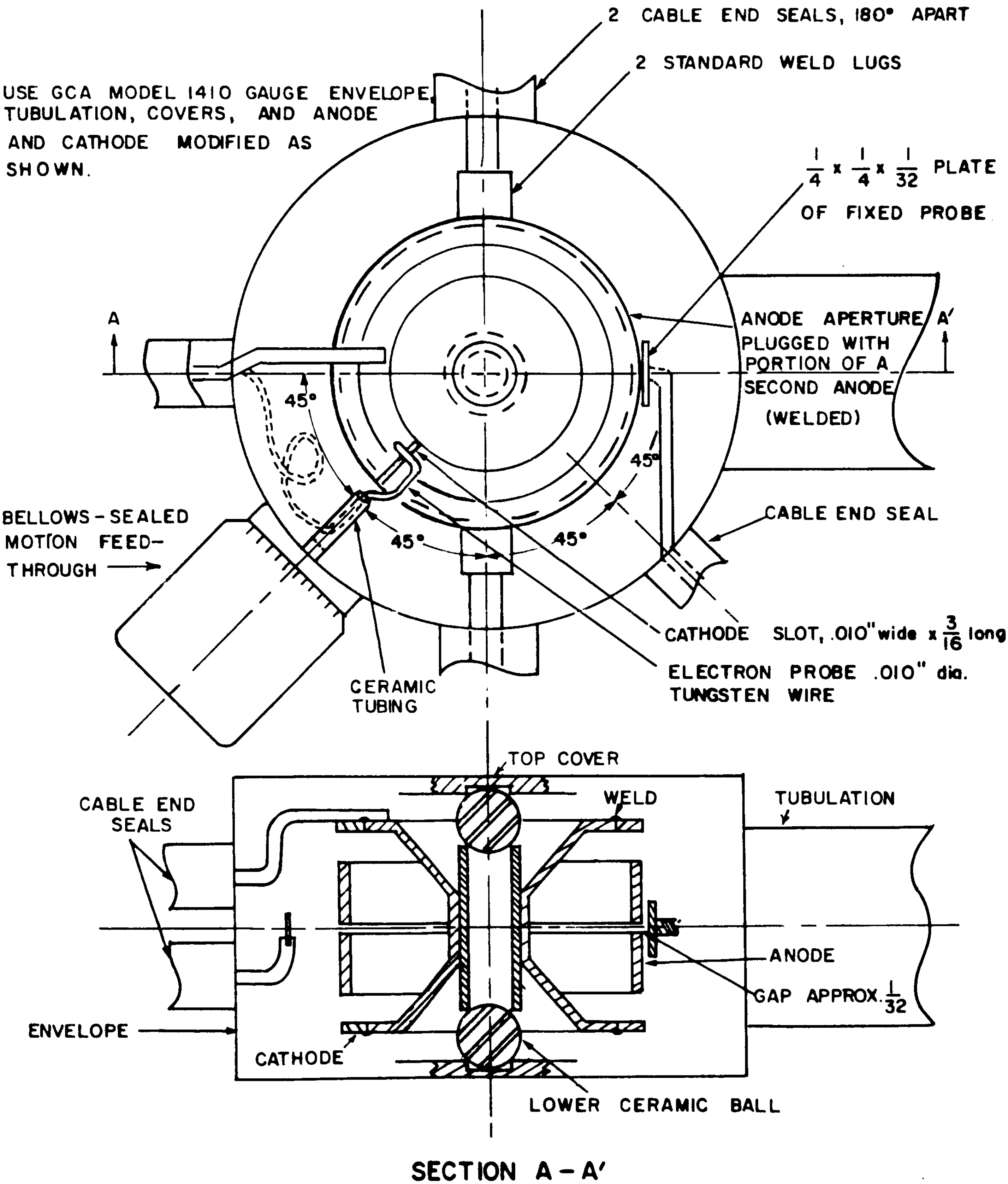

Figure 23. Model X-2 experimental cold cathode gauge.

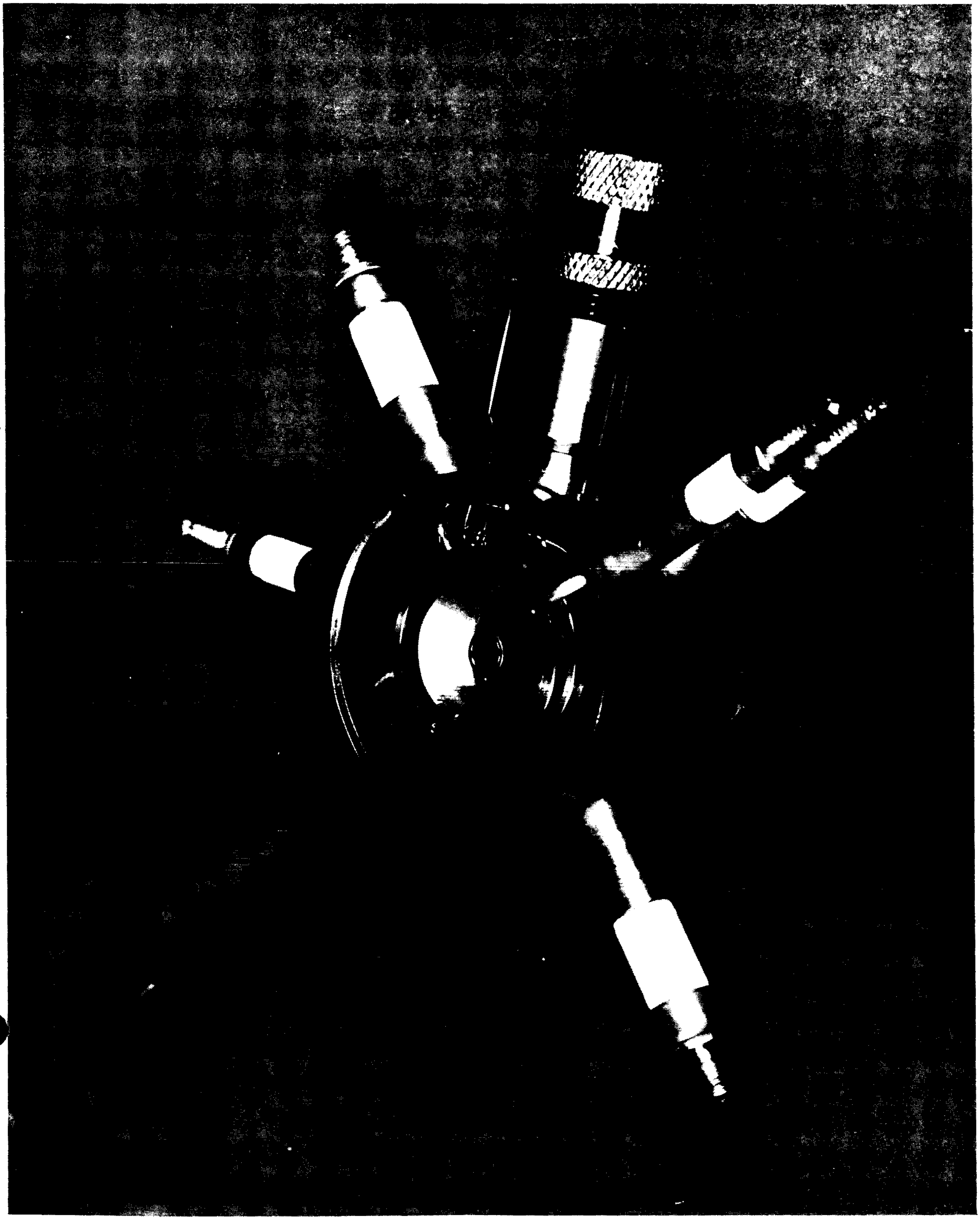

Figure 24. Photograph of the Model X-2 gauge.

Measurement of Net Radial Electronic Space Charge Distribution.

System Preparation and Tests Performed

This experiment was carried out on the vacuum test system using only background gas at a pressure in the mid 10^{-7} torr region. The model X-2 gauge was operated at an anode voltage of 1.9 kV. Early experimentation showed that the X-2 gauge operated stably only for a few values of anode voltage including the value of 1.9 kV. The anode voltage was derived from a GCA laboratory type unregulated high voltage supply. A 1030 gauss permanent magnet supplied the magnetic field. A Keithley Model 600 electrometer was used to measure the probe current. The probe was biased +22.5 Volts above ground (cathode) potential to draw electrons out of the discharge.

The experiment was performed by moving the probe radially inward starting from a position just above the outside edge of the gauge anode. The probe was moved radially inward a total of 0.100 inch in steps of 0.010 inch, and the probe current was recorded at each position. The gauge cathode current was 1.25×10^{-6} amperes.

Results

As mentioned earlier, the initial results of work with the X-2 gauge showed that this gauge would not operate for all values of anode voltage but only for certain regions of voltage. In particular, the gauge seemed to operate well at about 1900 volts and 3450 volts.

The data obtained at an anode voltage of 1.9 kV with the probe biased at a value of + 22.5 volts is summarized in Figure 25. It can be seen that the net flow of electrons to the probe was relatively constant in the region above the edge of the gauge anode. However, starting at the inner diameter of the anode, the electronic current flow to the probe increased as the probe was moved radially inward. The same sort of results were obtained in two separate tests. The limited motion of the bellows-sealed motion feedthrough prevented the probe from being moved farther inward.

Discussion

The results of this experiment showed clearly that electrons could be drawn out of a cold cathode gauge discharge in the direction of the magnetic field. It should be possible, with the proper instrumentation, to measure the relative electronic space charge distribution in either magnetron type, inverted magnetron type, or Penning type cold cathode gauges.

From the data obtained, it appears likely that the electronic space charge reached a maximum at some point between the anode and the cathode. Certainly, the space charge was not a maximum at the anode, and theoretical considerations indicate that it cannot be a maximum at the cathode.

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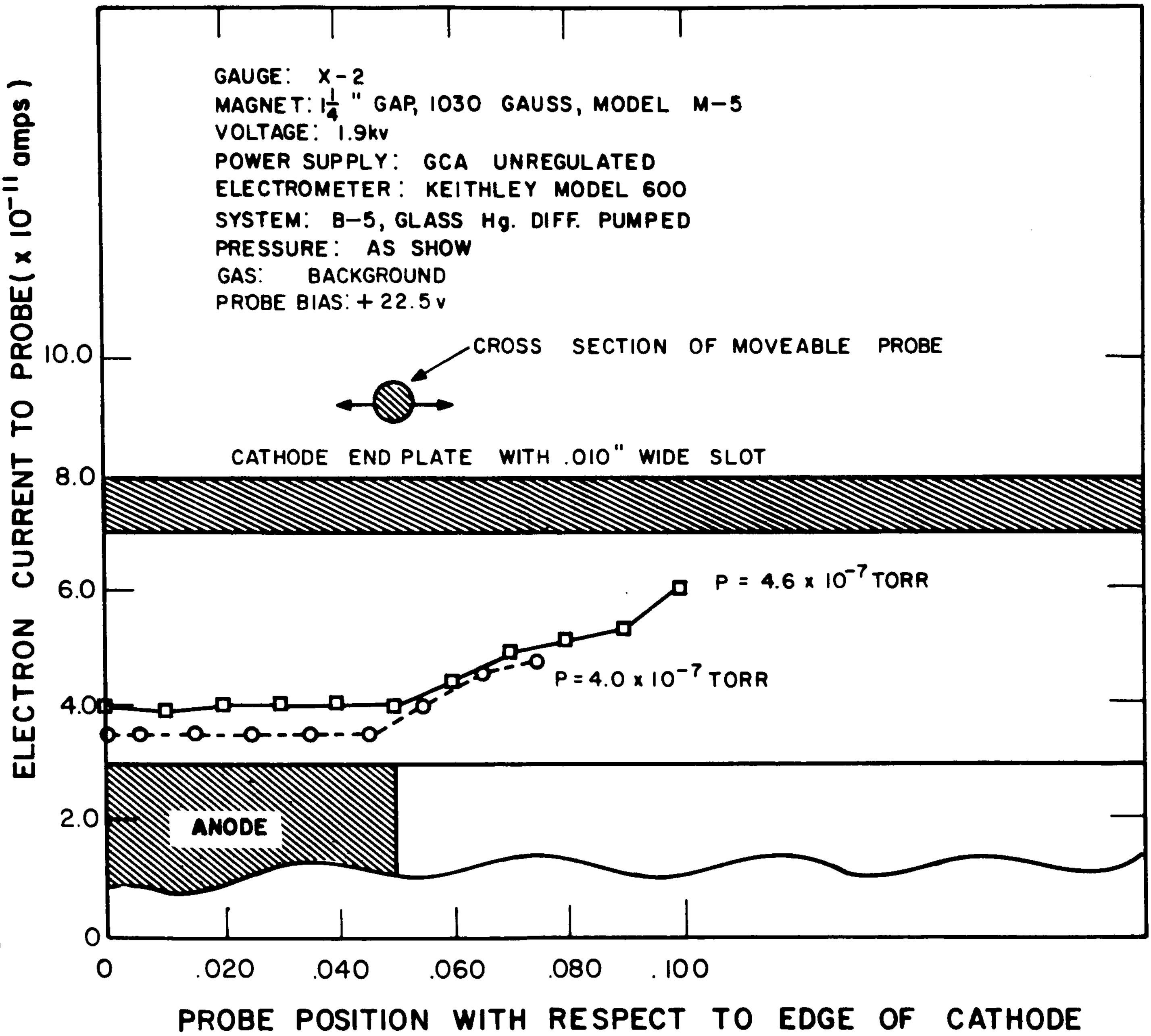

Figure 25. The net radial electronic space charge distribution in the X-2 gauge.

Measurement of Net Radial Positive Ion Distribution.

System Preparation and Tests Performed

The same system and conditions prevailed during this test as during the preceeding test with the following exceptions: first, the gauge anode voltage was increased from 1.9 kV to 3.45 kV, another value of anode voltage for which stable operation was obtained, and, second, the probe bias voltage was increased from + 22.5 volts to + 45 volts. Despite the higher bias voltage, the net current to the probe was positive. The probe outside the cathode end plate was moved radially inward a total distance of 0.080 inch in steps of 0.010 inch, and the probe current was recorded at each position. The system pressure (background gas) was 3.4×10^{-7} torr. The gauge cathode current was 1.9×10^{-6} amperes.

Results

With an anode voltage of 3450 volts, the probe of the Model X-2 gauge apparently collected a predominance of positive ions. As can be seen From Table II, the net positive ion current increased as the probe was moved radially inward in the region above the edge of the gauge anode. Starting at the inner diameter of the gauge anode, the net positive ion current began to decrease as the probe was moved further inward toward the gauge center. The data shown in Table II were taken with the probe biased at + 45 volts. There was evidence

Table II

Net Radial Positive Ion Distribution in a Cold Cathode Gauge

(Model X-2 Gauge operated at 3.45 kV with the probe at +45 Volts)

Probe Position Relative to Anode o.d. (Inches)	Probe Current (Amperes)
000	4.4×10^{-11}
.010	4.8
.020	4.9
.030	5.3
.040	5.5
.050	5.1
.060	4.6
.070	4.1
.080	4.1

that the bias on the probe affected the discharge somewhat. A change in the probe bias voltage from + 45 volts to zero volts caused the gauge cathode current to decrease about 10%. Changing the probe bias from zero volts to + 22.5 volts caused the net positive ion current to the probe to decrease by a factor of two.

Discussion

The contribution of positive ions to the net electronic current measured by the X-2 gauge probe could not be determined. It was assumed that there would be a minimum of positive ions near the gauge anode. On the other hand, when the gauge anode voltage was increased from 1.9 kV to 3.45 kV, the net flow of current to the probe was positive, indicating that many positive ions were created near the anode. The peak of the positive ion distribution coincided with the inner diameter of the anode. As the probe was moved further radially inward, the net positive ion current to the probe decreased. This decrease could have been caused by an increasing electronic component of current. The experiment indicated that the probe potential tended to change the nature of the discharge. There was evidently a considerable difference in the nature of the discharge when the anode voltage was changed from 1.9 kV to 3.45 kV in this particular gauge.

Experiments With the Model X-3 Experimental Cold Cathode Gauge

The Model X-3 gauge was designed in such a way that it could be used to separately measure the positive ion flow to the central and end portions of the cathode. It was speculated that changes in gauge operation, such as sensitivity mode changes and the transition from linear to non-linear operation, might be accompanied by changes in the space charge distribution and associated positive ion trajectories. Such changes would change the ratios of the positive ion flows to various parts of the cathode. In addition, due to the conical geometry of the cathode, the central cylindrical segment of the cathode collects only ions which have a radial component of velocity while the end cathode segments can collect ions that have only axial components of velocity. For this reason, current to the central cathode segment was termed radial current while current to the end segments was termed axial current.

The Model X-3 gauge was constructed in identical fashion with the standard GCA Model 1410 gauge with the exception that the cathode was divided into three segments, a central segment and two end plate segments. The two cathode end segments were mechanically and electrically separated from the central cylinder of the cathode by thin-walled pyrex glass sleeves and washers as shown in Figure 26. The two cathode end plates were connected together electrically inside the gauge, and a single conductor leading to these top and bottom cathode segments was brought out of the gauge.

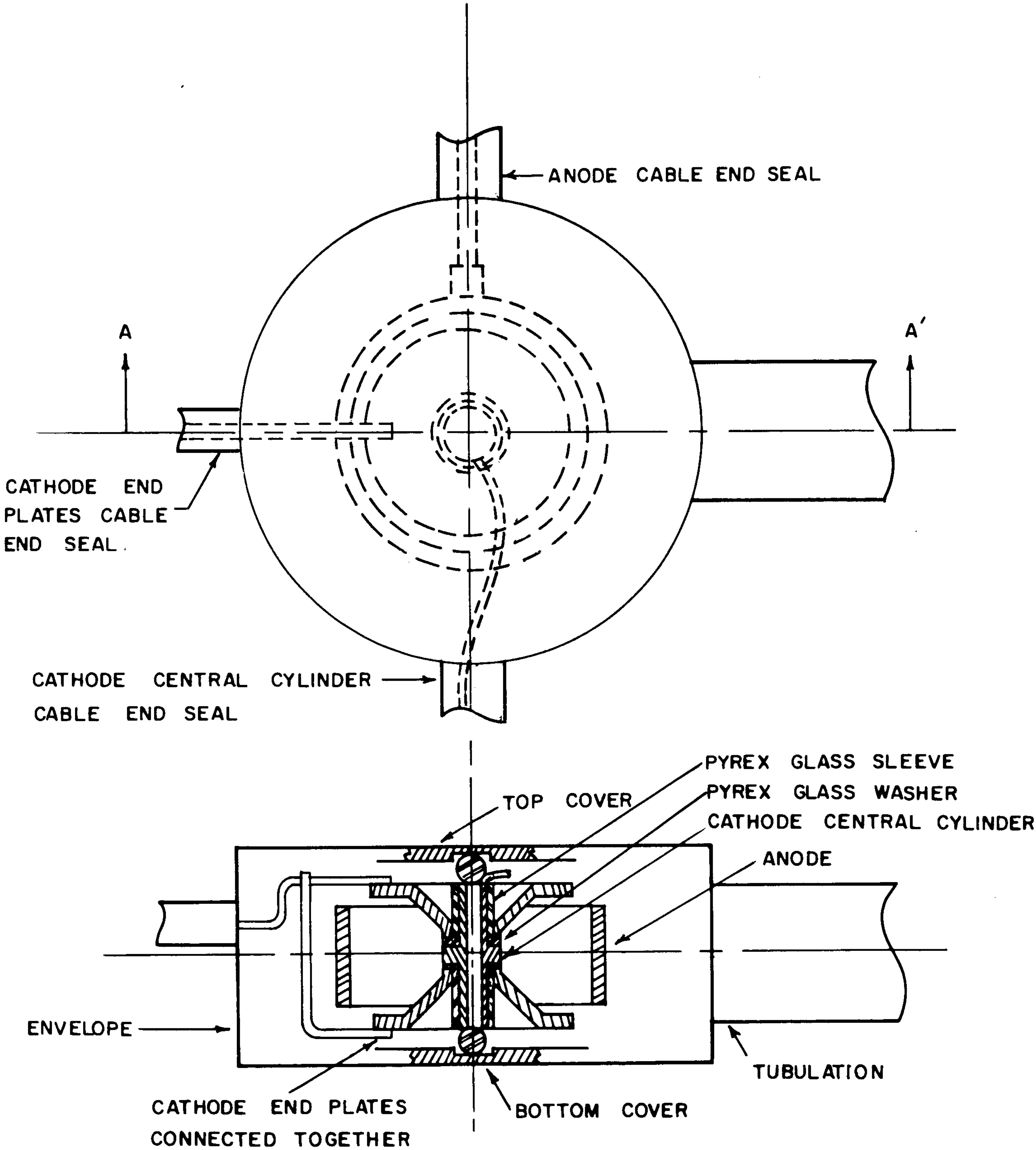

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Figure 26. Model X-3 experimental cold cathode gauge.

Comparison of Radial and Axial Positive Ion Currents in Nitrogen Gas at Higher Pressures.

System Preparation and Tests Performed

The vacuum test system was used for this experiment. The system had been under vacuum for several days and its residual (background) pressure was 3.5 x 10^{-8} torr with the spherical cold trap empty. When the spherical cold trap was filled with liquid nitrogen, the system pressure decreased to 1.6 x 10^{-8} torr. The Model X-3 gauge was first operated at 4.0 kV using a GCA laboratory type unregulated high voltage power supply. The standard 1100 gauss GCA commercial magnet used with the 1410 gauge supplied the magnetic field. Keithley Model 600 electrometers were used to measure the positive ion currents to the central and end portions of the cathode.

In the first test made, the nitrogen pressure was varied over the range from 2.8 x 10^{-7} torr to 2.17 x 10^{-5} torr. The radial ion current to the central portion of the cathode and the predominantly axial ion current to the end portions of the cathode were measured at four different pressure levels.

In the second test made, the nitrogen pressure was held constant at a value of 1.9 x 10^{-5} torr and the gauge anode voltage was varied from 2.5 kV to 5.0 kV in steps of 0.5 kV. The positive ion current to each part of the cathode for each anode voltage was recorded.

Results

The data obtained in these tests are displayed in Figures 27 and 28. The center segment of the gauge cathode collects radially moving positive ions. This segment is often termed the "magnetron" cathode segment. It can be seen from the graph that the current to the magnetron segment of the cathode varied approximately linearly with pressure for the relatively high pressures existing in the system. On the other hand, the end segments of the cathode, which collect predominantly axially moving positive ions, had a definitely non-linear current-pressure characteristic. The end segments were called "Penning" segments because of their resemblance to the cathodes of the original Penning cold cathode gauge. The current to the magnetron cathode segment was at least 1.7 times greater than the current to the Penning segments even though the surface area of the latter segments was many times greater than that of the magnetron segment. The difference in the behavior of the two cathode portions as a function of the anode voltage is shown quite clearly in Figure 28. The current to the magnetron segment of the cathode increased continually as the anode voltage was increased from 2.5 kV to 5.0 kV. By way of contrast, the current to the Penning segments of the cathode increased to a maximum at 4.0 kV and then decreased as the anode voltage increased beyond 4.0 kV.

Discussion

The experiments that were performed with the Model X-3 gauge were intended to yield information about the current distribution within the

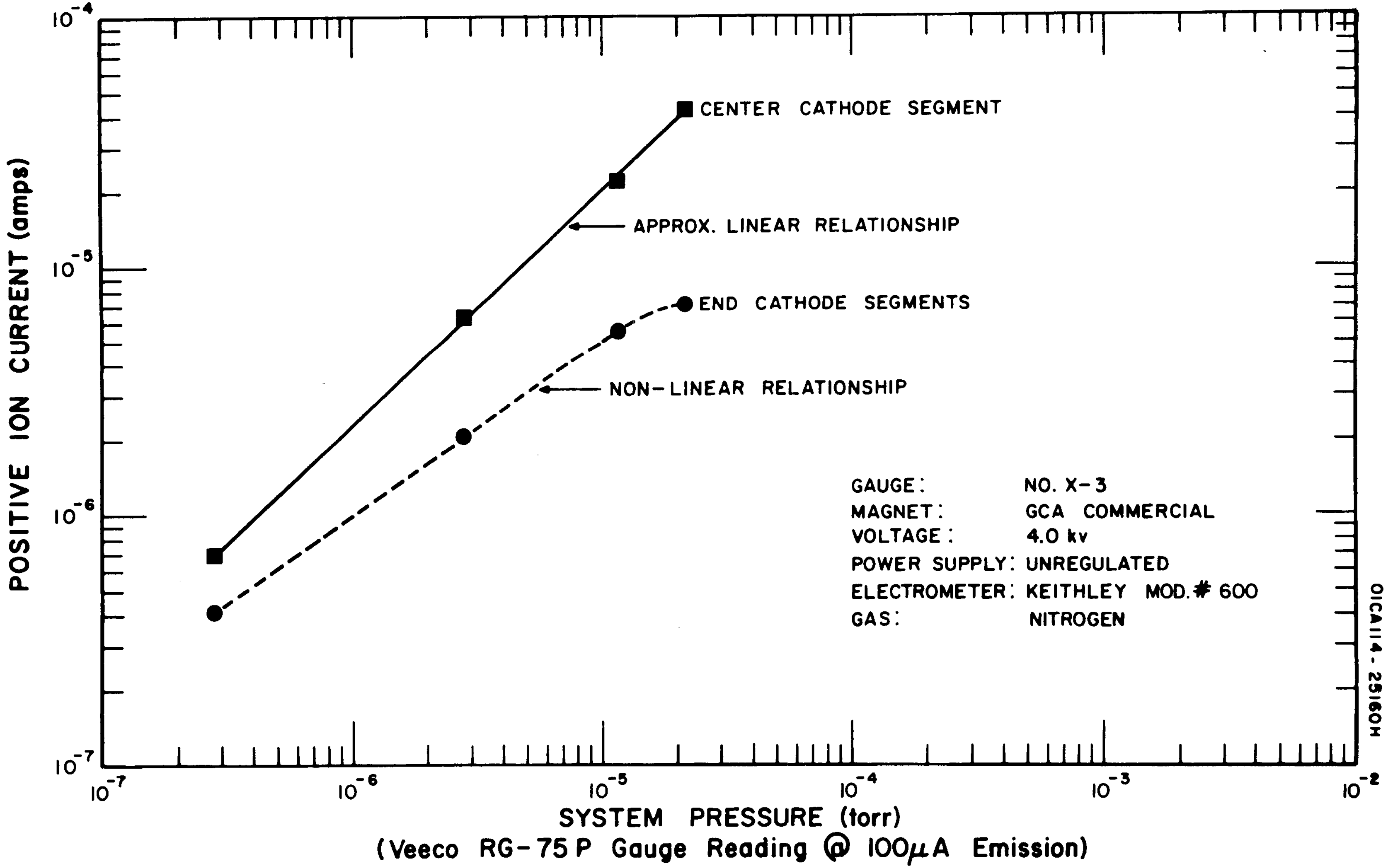

Figure 27. Current-pressure characteristics for the center and end cathode segments of the X-3 gauge for nitrogen gas.

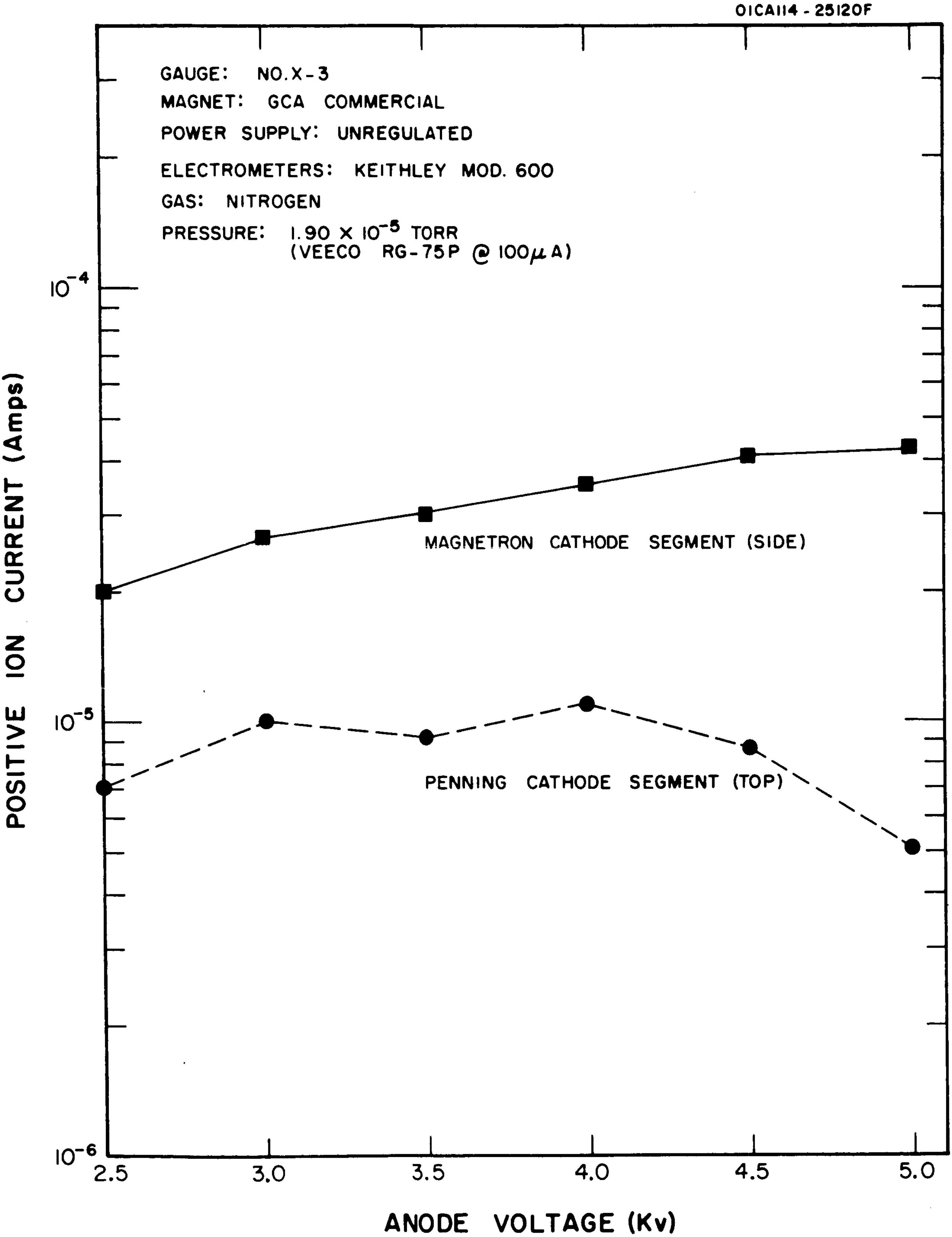

Figure 28. Current-voltage characteristics for the center and end cathode segments of the X-3 gauge for nitrogen gas.

gauge. It was desired to determine the relative effectiveness of the central and end portions of the cathode in the discharge process. The short cylindrical center portion (magnetron portion) of the cathode is oriented with its surface parallel to the magnetic field. Positive ions that move in a purely axial direction cannot be collected by the center portion of the cathode. A positive ion must have a radial component of velocity in order to reach the center of the cathode. The end portions of the cathode have surfaces that are either normal to the magnetic field or inclined to this field at an angle of about 45 degrees. The end parts (the so-called Penning portion) of the cathode can collect positive ions that move either radially or axially. It was assumed that the current to the Penning part of the cathode was predominantly axial. Of course, this assumption has no bearing on the results obtained, but would be involved in an interpretation of the data. It was primarily desired to find out if the ratio of the two cathode currents would remain constant over a wide range of pressure -- especially, above and below the transition from linear to non-linear operation. A change in the ratio of the two cathode currents, such as that found in the experiment with nitrogen gas at a higher pressure, would indicate a change in the space charge distribution within the discharge. It was speculated initially that operation at higher pressures might be predominantly axial current flow, Penning gauge type operation. Experiments with the X-3 gauge supplied no evidence to support this theory.

Comparison of Radial and Axial Positive Ion Currents in Oxygen Gas at Lower Pressures.

System Preparation and Tests Performed

The vacuum test system had been baked and placed in operation about one week prior to this experiment. The gauge anode voltage of 4.0 kV was furnished by a J. Fluke Model 408A regulated power supply while Keithley Model 600 electrometers were used to measure the currents to the central and outer end portions of the cathode. A standard 1100 gauss GCA permanent magnet supplied the required magnetic field.

After a background pressure of 2.2×10^{-9} torr had been established in the system with the spherical cold trap filled with liquid nitrogen, pure oxygen gas was introduced from a 1-liter flask. Oxygen pressures over the range from 4.6×10^{-9} torr to 2.4×10^{-7} torr (equivalent nitrogen reading) were established in the system. Readings of the cathode currents were taken at discrete pressure levels within the range mentioned above.

Results

The results of the experiment with oxygen gas at pressures above and below the transition point are given in Figure 29. It can be seen that there was a break in the current-pressure characteristics for

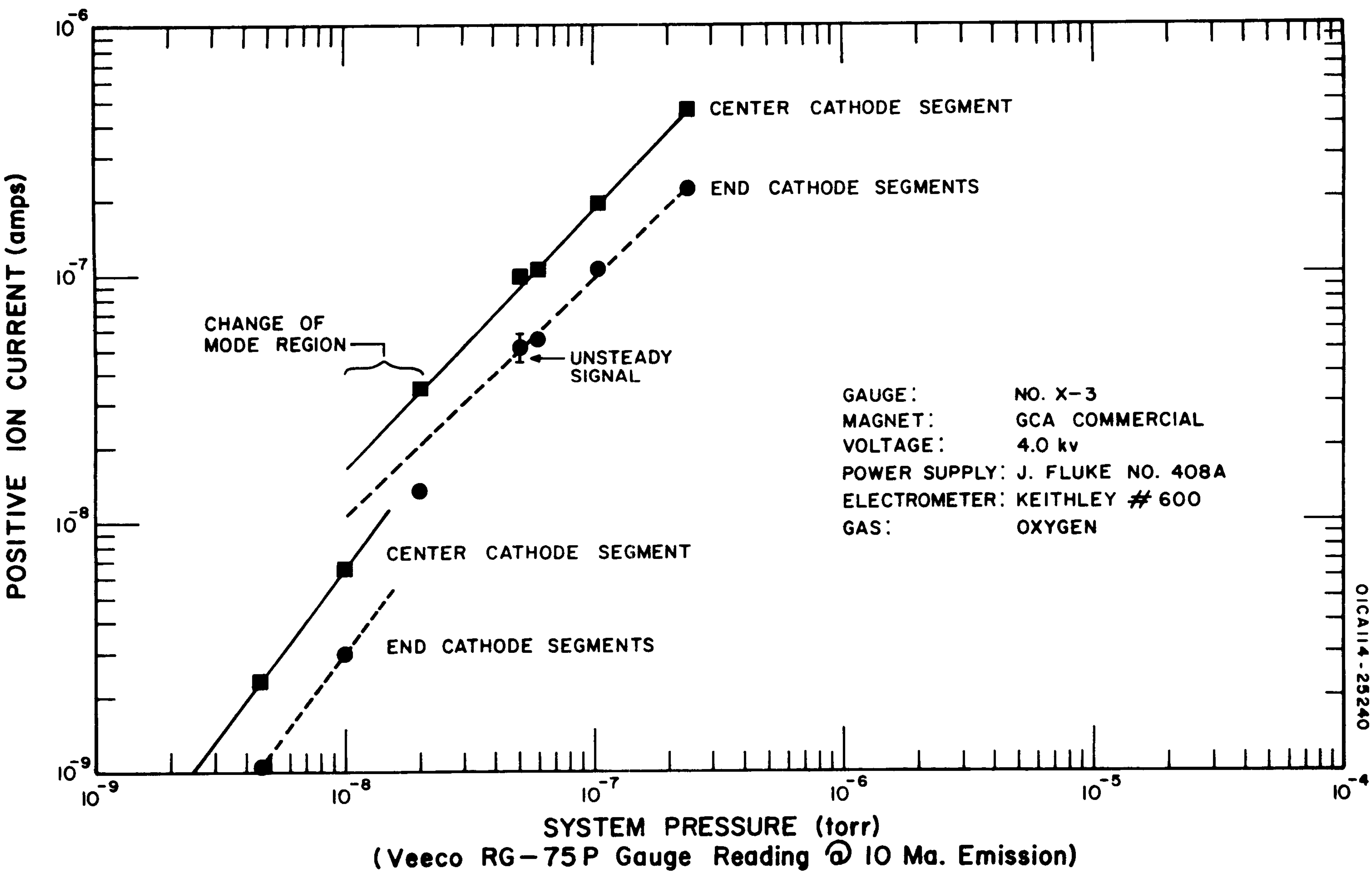

Figure 29. Current-pressure characteristics for the center and end cathode segments of the X-3 gauge for oxygen gas.

both cathode portions at about the same value of pressure -- between 1 and 2×10^{-8} torr equivalent nitrogen. The ratio of the two cathode currents remained essentially unchanged through the transition region (labelled the "change of mode" region in the figure). It appeared that the space charge within the gauge decreased considerably in passing through the transition region from higher to lower gas pressures, but the distribution of space charge and the resulting positive ion trajectories could not have changed appreciably. The current to the central part of the cathode was roughly twice that of the current to the end portions of the cathode.

Discussion

In the experiment with oxygen gas, it became clear that only the magnitude of the space charge within the gauge changed in passing through the transition region. The space charge configuration and the relative trajectories of positive ions did not change. In this test, there was a definite discontinuity in the current-pressure characteristics at the transition point.

Comparison of Radial and Axial Positive Ion Currents in Argon Gas at Lower Pressures.

System Preparation and Tests Performed

The vacuum test system had been baked and in operation about two weeks prior to this experiment. The Model X-3 gauge was being used with the GCA commercial 1100 gauss permanent magnet. A voltage of 4.0 kV was furnished to the gauge anode from a J. Fluke Model 408A regulated high voltage power supply. Keithley Model 600 electrometers were used to measure the ion currents to the central and outer end portions of the gauge cathode.

Prior to the introduction of argon gas, the system background pressure was 4.3×10^{-9} torr equivalent nitrogen reading. The spherical cold trap had been filled with liuqid nitrogen. Argon pressures over the range from 7.4×10^{-9} torr to 3.7×10^{-5} torr (equivalent nitrogen reading) were established in the system. The system pressure was increased in steps and the currents to the two cathode segments were recorded. The composition of the gas in the system was recorded with a General Electric Model 22 PT 110 partial pressure analyzer tube operated at 1 mA emission.

A second experiment using argon gas was performed that was practically identical with the first experiment discussed above, except that the range of gas pressures was somewhat greater. It was desired to see if the experimental results obtained in the first test could be repeated.

Results

The data obtained in this experiment are displayed in the graph of Figure 30. A relatively large pressure range was covered in this

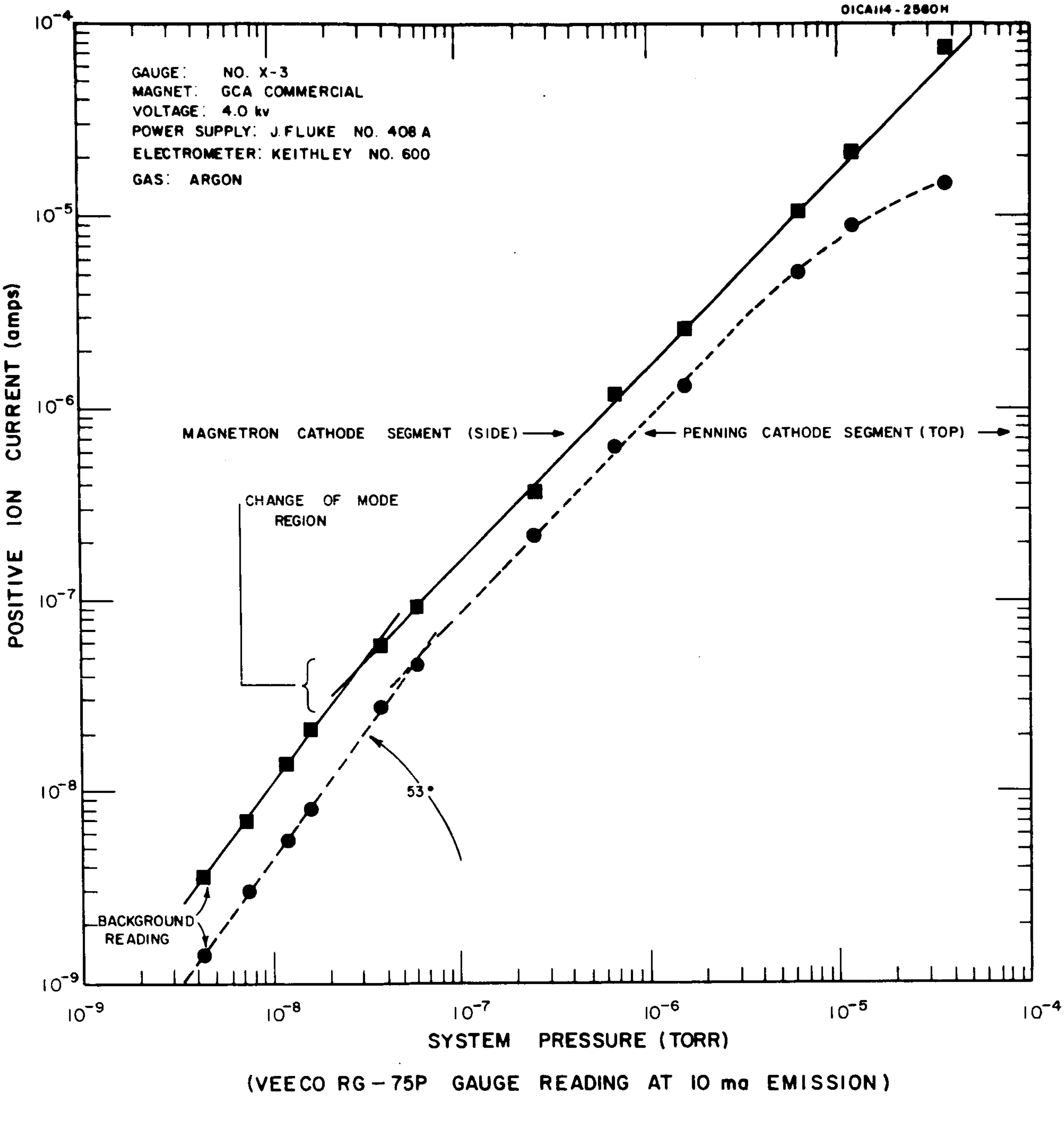

Figure 30. Current-pressure characteristics for the center and end cathode segments of the X-3 gauge for argon gas.

test, and it can be seen that the two cathode currents maintain a constant ratio up to pressures as high as 5×10^{-6} torr. According to the curves as drawn, the transition points for both the current to the central part of the cathode and the current to the end portions of the cathode occur at almost the same values of current, namely values of 4.5 and 5.0×10^{-8} amperes. The transition points do not seem to occur for a common value of system pressure. For argon pressures above 5×10^{-6} torr, the same divergence of cathode currents occurs as was observed for nitrogen gas at higher pressures. Notice that the gauge was operated at pressures as high as 4×10^{-5} torr. A great deal of sputtering apparently occurred during this higher pressure operation in argon. Mass spectra that were taken during this test showed that carbon monoxide and water vapor were the major residual gas peaks. The doubly ionized argon peak was equal to about 20 percent of the main singly ionized argon peak.

In the second test using the X-3 gauge with argon gas, an unexpected result was obtained. It was found that the current to the end portions of the cathode (the Penning cathode segment) had a limiting value of 4.4×10^{-9} amperes, as shown in Figure 31, even though the current to the central part of the cathode went as low as 5.9×10^{-10} amperes. It is postulated that this high limiting current resulted from cold field emission between the outer edges of the cathode and the anode. It is further postulated that strong sputtering from the central region of the cathode (where the current density was quite high) deposited something

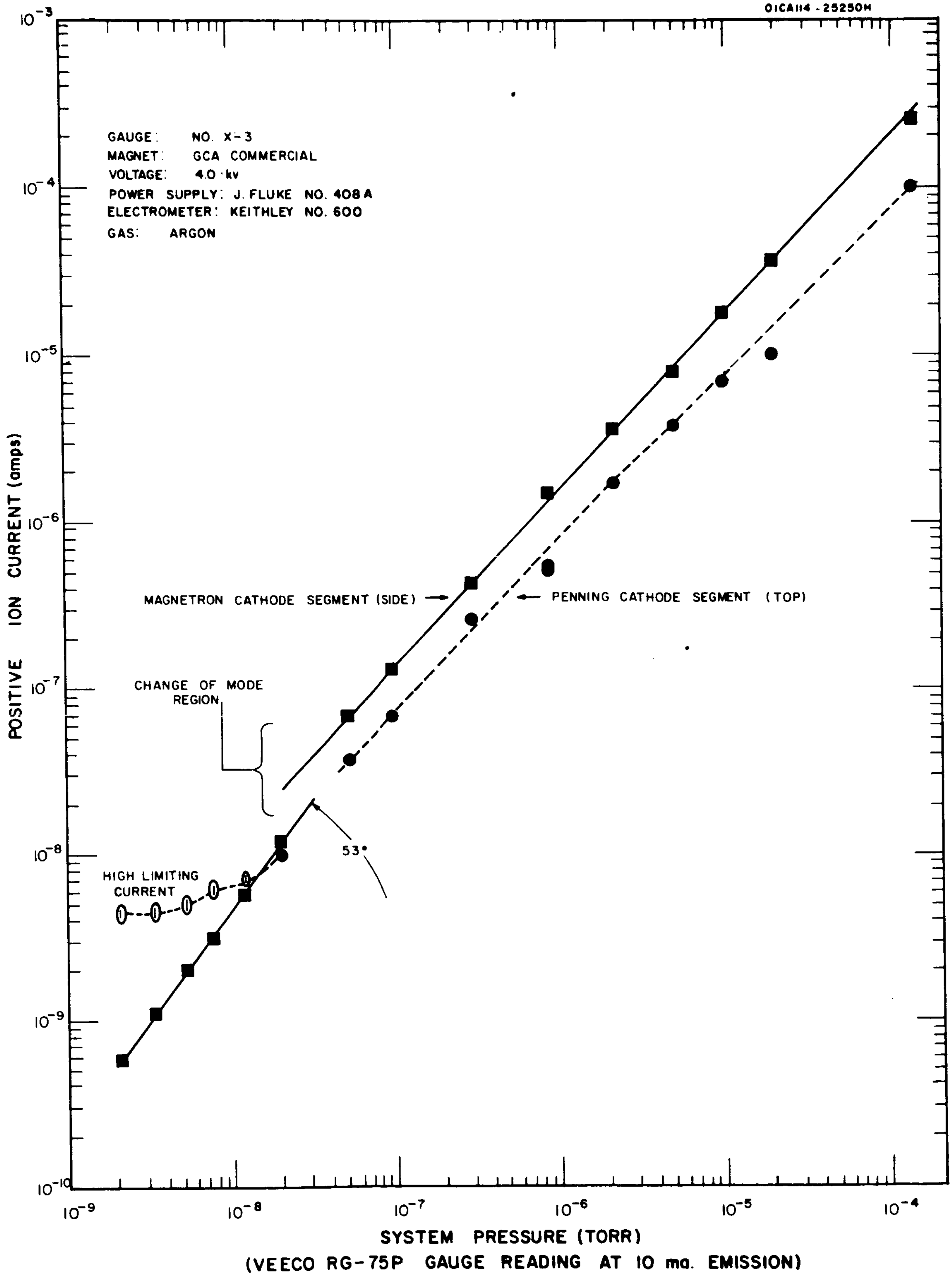

Figure 31. Development of cold field emission in the X-3 gauge for argon gas.

akin to metal "whiskers" at the edges of the cathode. These whiskers would then create a strong electric field sufficient to cause cold field emission. It should be noticed that the current to the magnetron (central) cathode segment exhibited a break at the transition point in this experiment, whereas there was no sharp discontinuity at the transition point in the earlier experiment with argon. Note also that the current to the Penning section of the cathode showed some mode changing or departures from the linear current-pressure relationship at pressures in the 10^{-7} torr region.

Discussion

The first experiment with argon gas indicated that the current-pressure characteristics in the vicinity of the transition point did not necessarily have to have a sharp discontinuity. The same general constant ratio between the two cathode currents obtained for oxygen gas was also obtained for argon gas over a wider pressure range. The second test with argon gas in the X-3 gauge showed a different characteristic for both the magnetron and Penning cathode segments. The Penning segment had developed cold field emission while the magnetron segment had developed a discontinuity at the transition region. The first effect can be attributed to the formation of metal whiskers at the edge of the cathode due to heavy sputtering by the argon. The second effect (the discontinuity) must also be attributed to a change in the surface characteristics of the central part of the cathode due to sputtering. Perhaps sputtering made the surface rough on a microscopic scale. It had been shown earlier that a roughened cathode surface seemed to cause a sharp discontinuity in the current-pressure characteristic of a flight model gauge.

Experiments With The Model X-4 Experimental Cold Cathode Gauge

The Model X-4 gauge was designed to determine how the (electronic) anode current was distributed in an axial direction, and how the anode length affected gauge operation. As shown in the sketch of Figure 32, the X-4 gauge was constructed in identical fashion with a standard GCA Model 1410 gauge with the exception that the anode was divided into three separate segments. The three anode cylindrical segments, a central segment, an upper end segment, and a bottom end segment, were spaced apart by pyrex glass rings. The top and bottom anode segments were connected together electrically and a single electrical connection was brought out of the gauge.

Measurement of Electronic Current to the Different Anode Segments in High Pressure Nitrogen Gas.

System Preparation and Tests Performed

The unbaked vacuum test system was used for this experiment. The gauge was allowed to operate at 4.0 kV at a background pressure of

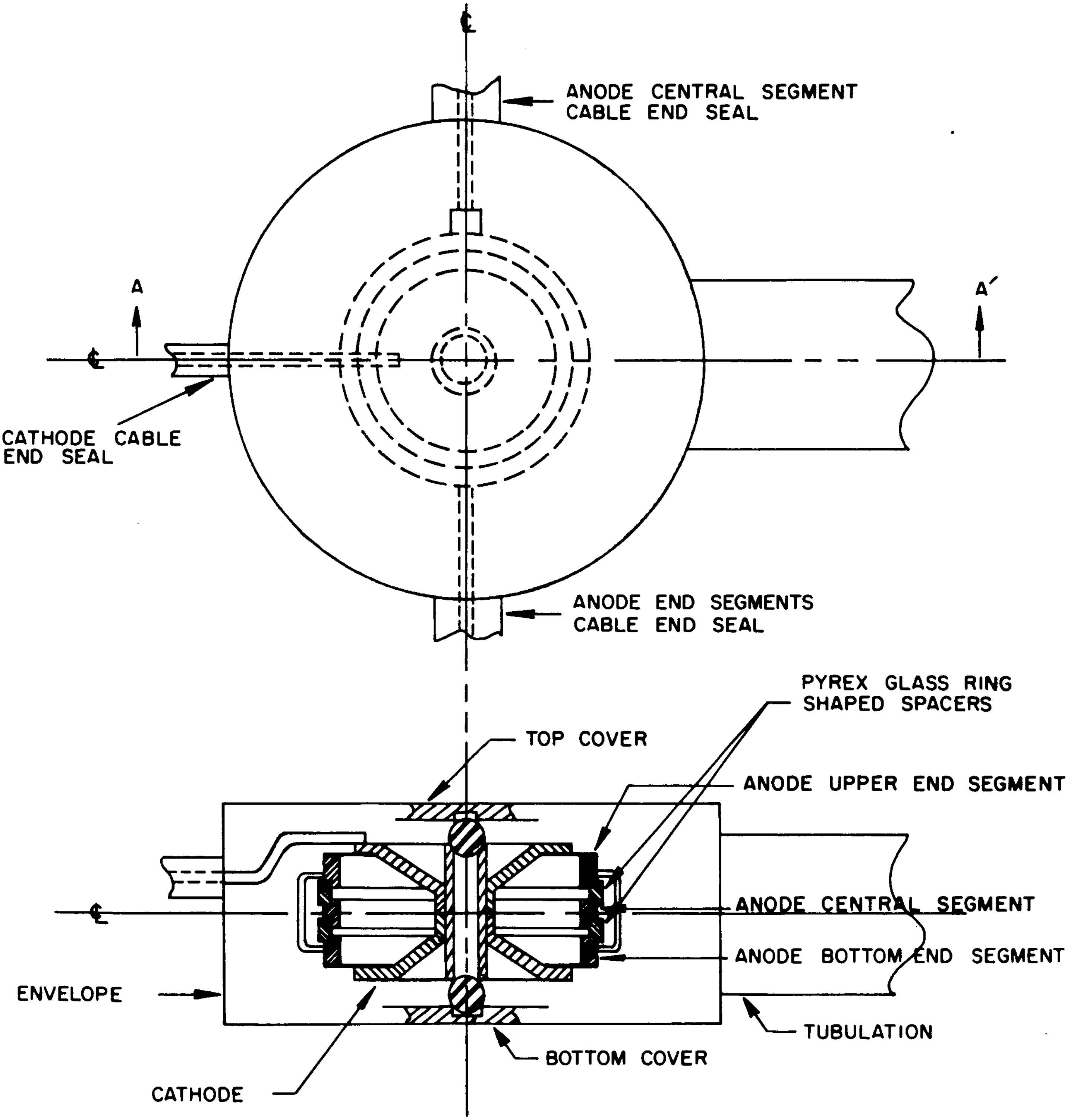

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Figure 32. Model X-4 experimental cold cathode gauge.

5×10^{-8} torr ovenight, and was heated for about 30 minutes with a hot air gun to outgas it prior to the test. A GCA standard 1100 gauss permanent magnet supplied the magnetic field. A GCA unregulated laboratory type high voltage power supply was used to furnish 1.5 kV to the gauge anode(s). The gauge cathode current was measured with a Model 600 Keithley electrometer while the anode segment currents were measured with Simpson Model 260 multimeters that were insulated from ground by teflon blocks. A nitrogen gas pressure of 2.35×10^{-6} torr was created within the system. Three basic connections were made to the X-4 gauge. In the first, the central anode segment was connected to the high voltage supply while the end anode segments were left floating electrically. In the second arrangement, the center anode segment was left electrically floating while the end anode segments were connected to the high voltage. In the third arrangement, the center and end anode segments were connected to the high voltage supply through separate ammeters. The various anode and cathode currents were recorded.

Results

The essential data obtained in this experiment are shown in schematic form in Figure 33. The total current through the gauge -- primarily the cathode current -- was divided between the two portions of the anode. When the currents to the two anode segments were measured

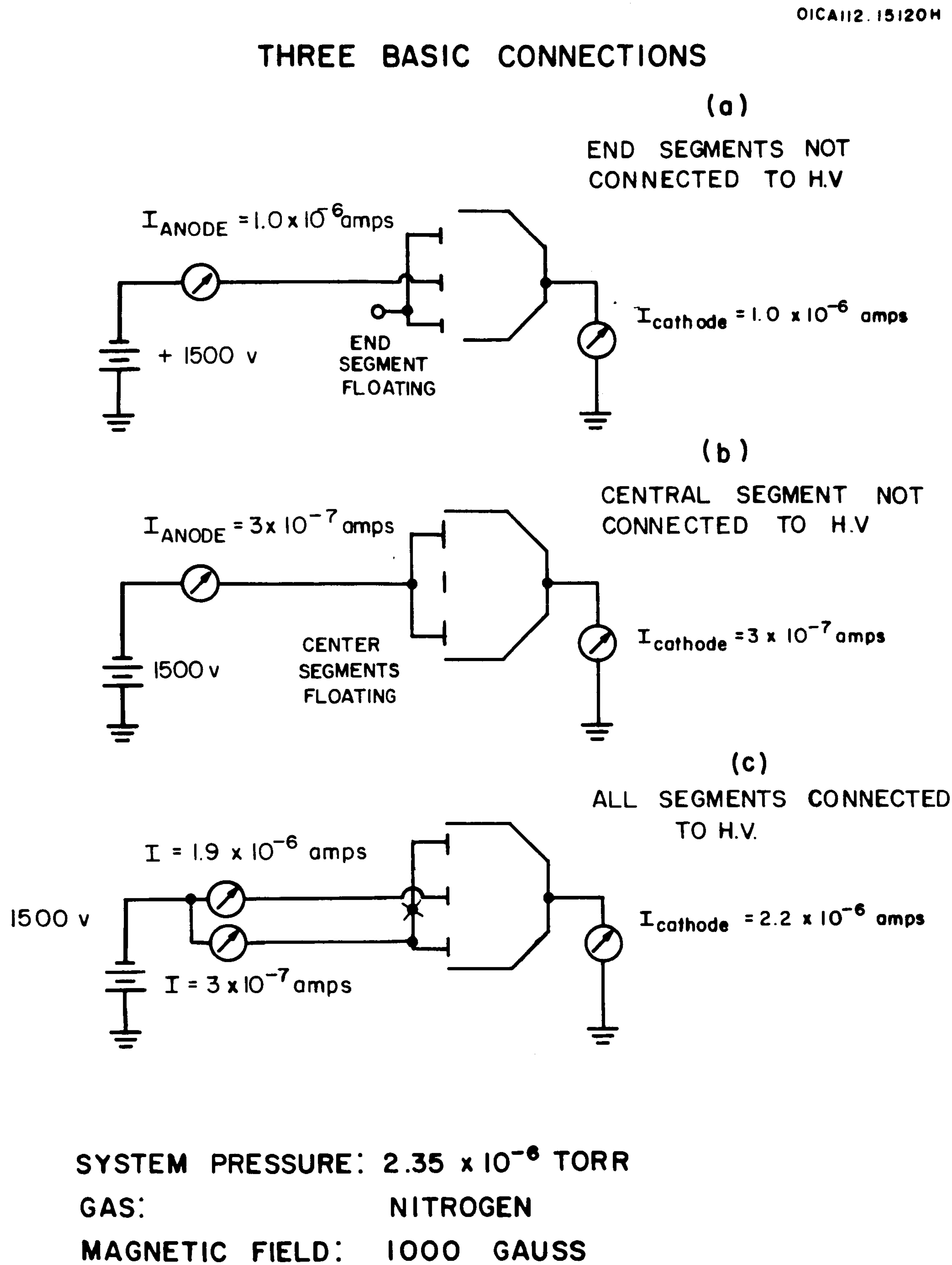

Figure 33. Schematic diagram of measurements of current to the central and outer portions of the X-4 gauge anode.

simultaneously, it was found that six times as much current was collected by the central portion of the anode compared with the end portions of the anode. When the end portions of the anode were left floating, the central segment collected roughly half of the current that it collected when all segments of the anode were at the same potential of 1500 volts. When the end portions of the anode were at a potential of 1500 volts, they collected the same small current independent of the potential of the central anode segment.

Discussion

A comparison of parts (a) and (c) of Figure 33 show that an anode of increased length yielded a larger ion current to a given cathode under the conditions of the test. Comparing parts (a) and (c) again, one can see that the presence of high voltage on the end segments actually increased the current to the central segment of the anode and did not just add a contribution of "end current" to that of the "central current". Finally, comparing parts (b) and (c) of Figure 33, it can be seen that the current to the anode end segments appeared to be independent of the potential on the anode center segment.

Comparison of Anode Central and End Segment Currents for a Range of Oxygen Pressures.

System Preparation and Tests Performed

The vacuum test system had been pumping for several weeks prior to this experiment. The system had been baked out in the usual way.

A GCA commercial 1100 gauss permanent magnet supplied the magnetic field. The anode central segment and end segments were connected to a J. Fluke Model 408A regulated power supply through separate Keithley Model 600 electrometers that were insulated from ground by teflon blocks. A third Keithley Model 600 electrometer was used to measure the gauge cathode current.

The background pressure in the system with the spherical cold trap filled was 3.2×10^{-9} torr. Oxygen gas was admitted to the system to establish pressures within the range from 6.2×10^{-9} torr to 1.7×10^{-5} torr (equivalent nitrogen reading). The cathode current and the currents to the two anode segments were recorded for various pressure levels.

Results

The data obtained in this test are displayed in Figure 34. It can be seen that the two currents to the Model X-4 gauge anode maintained a constant ratio over the pressure range from 2×10^{-8} torr to 5×10^{-7} torr equivalent nitrogen. For pressures above 2×10^{-6} torr, it was suspected that the Keithley electrometers were not operating properly. The indicated decreasing gauge currents from 5.5×10^{-6} torr to 1.7×10^{-5} torr were probably not real effects.

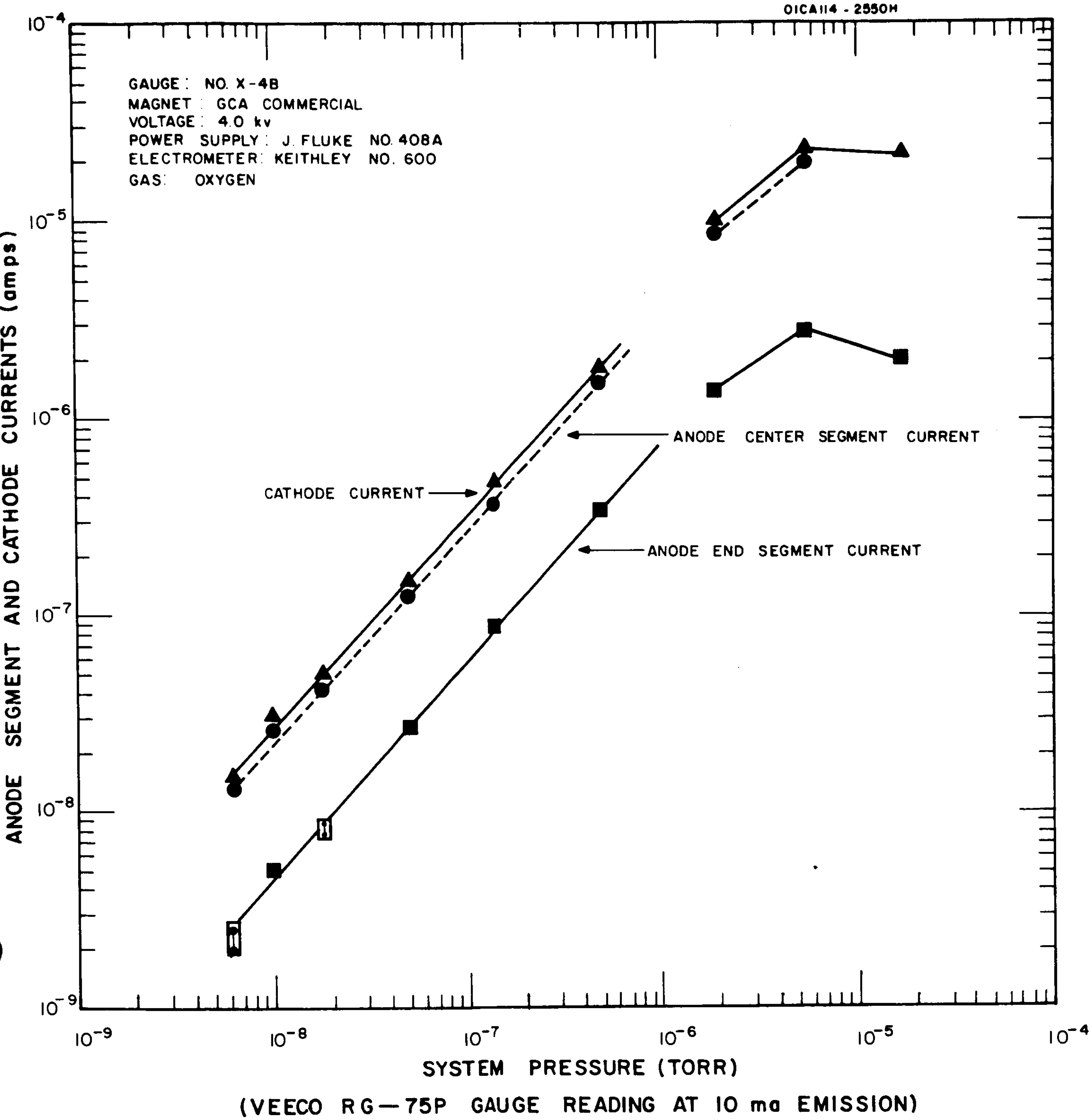

Figure 34. Current-pressure characteristics for the central and end anode segments of the X-4 gauge for oxygen gas.

Discussion

The constant ratio of the two anode segment currents over the pressure range in which linear operation was normally obtained was not unexpected. There was no indication that anything unusual was happening for pressures in the 10^{-9} torr region.

Experiments With The Model X-5 Experimental Cold Cathode Gauge

The Model X-5 gauge was designed to have cathode end plates that overlapped the anode and a fine mesh screened anode aperture in the hope that these geometrical changes would help prevent the loss of electrons from the discharge and hence help extend the linear portion of the current-pressure characteristic to lower currents (pressures). As illustrated in Figure 35, the X-5 gauge used the standard GCA Model 1410 gauge parts with the exception of the anode and cathode. The standard anode was modified by welding a fine wire mesh screening over the aperture. The standard cathode was modified by welding on overlap type end plate extensions. The anode and cathode were assembled as a single unit.

Current-Pressure Characteristic of the X-5 Gauge for Background Gas. System Preparation and Tests Performed

This experiment was performed on the No. 3 all glass Venema type calibration system. The system had been baked and was operating at a

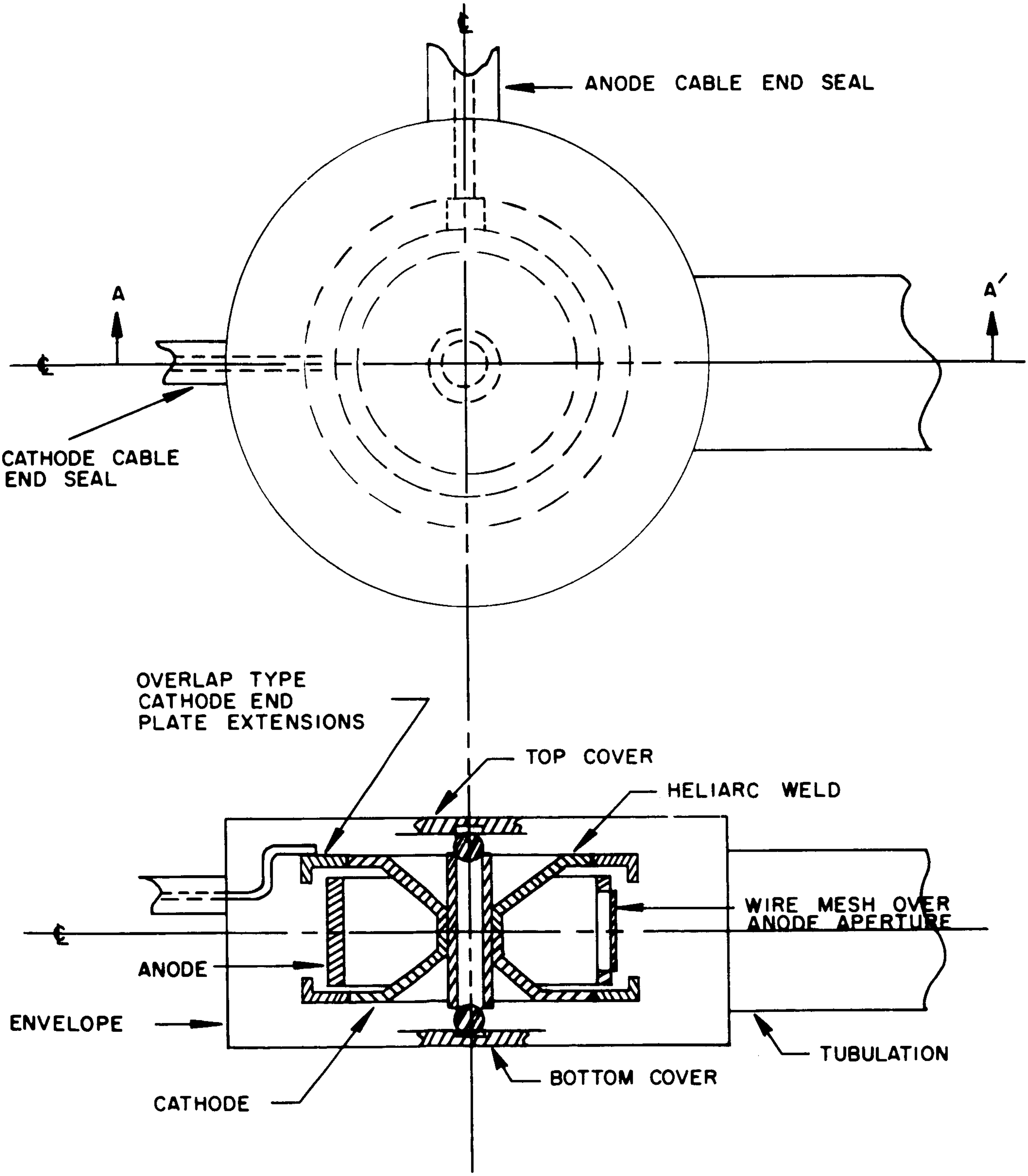

Figure 35. Model X-5 experimental cold cathode gauge.

low pressure background of 6.8×10^{-10} torr as read with a Varian UHV-12 glass Bayard Alpert type gauge. The X-5 gauge was being used with a GCA commercial 1100 gauss magnet. A GCA unregulated high voltage power supply furnished a voltage of 3.0 kV to the gauge anode. A Keithley Model 600 electrometer was used to measure the cathode current of the gauge. Starting with the lowest pressure, the background pressure in the system was permitted to increase by allowing the liquid nitrogen in the top Venema type cold trap to evaporate without replacement. Varian gauge readings and Model X-5 cathode (ion) current readings were taken at various pressure levels. It can be assumed that the background gas was predominantly carbon monoxide.

Results

The characteristic curve for the C-5 gauge is shown in the graph of Figure 36. The region of quasi-linear operation extended over an indicated pressure interval ranging from 1.3×10^{-9} torr to about 1×10^{-8} torr, the highest pressure attained in the test. The transition point for this gauge occurred at a gauge current of 1.6×10^{-9} amps corresponding to a pressure of about 1.3×10^{-9} torr. The non-linear portion of the curve is probably not very accurate due to the method used in the test. The data taken, however, does show the two regions of operation of magnetron type cold cathode gauges, and the method used may be a quick way to find the transition point.

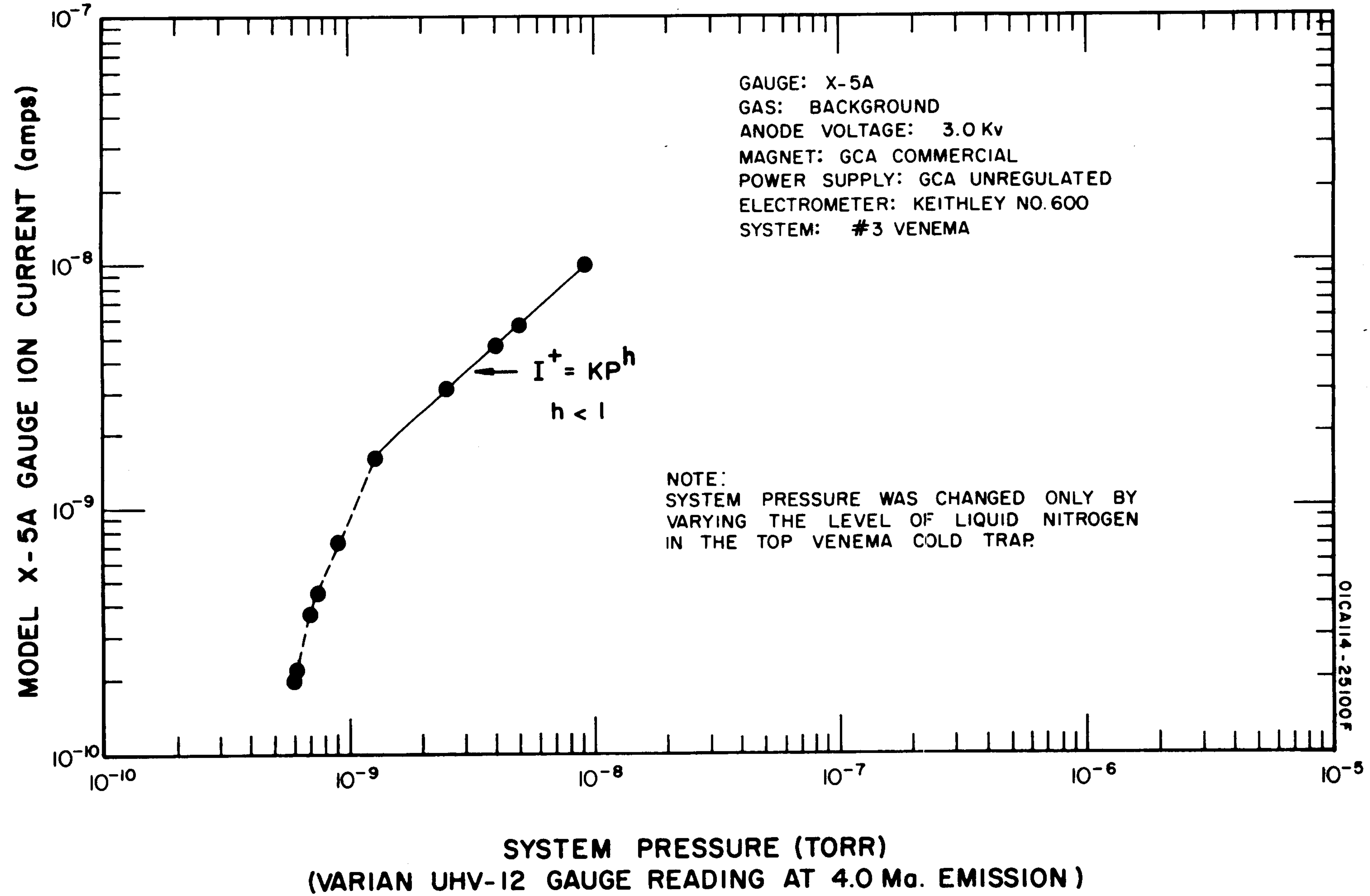

Figure 36. Current-pressure characteristic of the Model X-5 gauge for background gas.

Discussion

Judging from the results displayed in Figure 36, and those obtained with similar gauges not having the overlap cathodes, the Model X-5 gauge did have its transition point at a lower current and pressure. Gauges of the X-5 type should be tested in direct comparison with a standard (Model 1410) gauge to insure that unusual system effects do not give misleading results.

Experiments With the Model X-6 Experimental Cold Cathode Gauge

The Model X-6 gauge was constructed for the purpose of investigating the effect of shield rings in a magnetron gauge. It was especially desired to determine the shield ring current as a function of pressure, and to investigate the nature of the discharge in the vicinity of the shield rings.

As shown in the sketch of Figure 37, the Model X-6 gauge used all of the standard GCA Model 1410 gauge components. In addition, however, two electrically isolated shield rings were installed and positioned to lie between the edges of the cathode end plates and the top and bottom ends of the anode. The two shield rings were strapped together mechanically by three wire supports located 120 degrees apart. Pyrex glass insulating rings positioned the shield rings as shown.

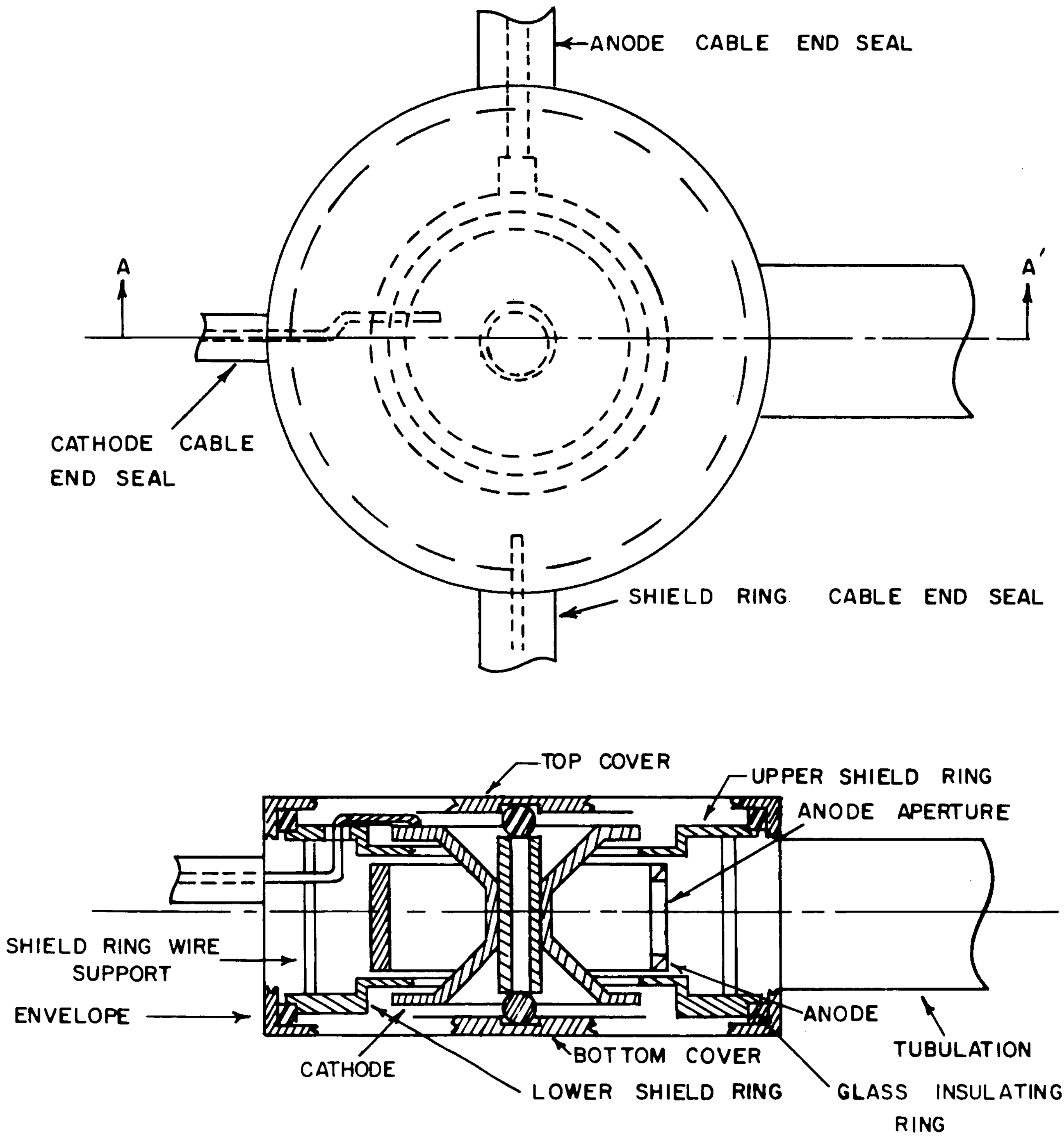

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Figure 37. Model X-6 experimental cold cathode gauge.

Cold Field Emission from the Gauge Shield Rings to the Anode.

System Preparation and Tests Performed

This experiment was performed on the No. 2 all glass Venema type calibration system. The system had been baked overnight at $400^{\circ}C$ and had been under vacuum approximately three weeks before the experiment was made. Anode voltages were being furnished by a J. Fluke Model 408A regulated high voltage supply. A standard GCA commercial 1100 gauss permanent magnet supplied the magnetic field. Keithley Model 600 electrometers were used to measure the shield ring and cathode currents. With the system background pressure at 4.0×10^{-10} torr equivalent nitrogen, uncorrected, the anode voltage to the gauge was varied in steps from 4.0 to 1.0 kV and the currents to the shield rings and the cathode were observed.

Results

The data taken during this test are displayed in Table III. The decrease in the shield ring current by over five decades for an anode voltage change from 4.0 kV to 2.0 kV is characteristic of cold field emission. It can be seen that the cathode current was relatively constant at about 3×10^{-13} amperes, independent of the anode voltage. Most likely the gas discharge in the gauge had gone out and the cathode current was a result of pickup or thermal e.m.f.'s. Another test, performed a few days later, yielded almost identical shield ring currents with the gauge magnet removed. There could not possibly have been a gas discharge in the gauge during this latter test.

Table III

Cold Field Emission from the Model X-6 Gauge Shield Rings to Anode

Anode Voltage (kV)	Shield Ring Current (Amperes)	Cathode Current (Amperes)
4.0	6.8×10^{-8}	---
3.0	6.5×10^{-10}	3.3×10^{-13}
2.5	3.7×10^{-11}	3.0
2.0	1.0×10^{-13}	3.8
1.5	1.8×10^{-14}	4.5
1.0	1.7×10^{-14}	3.0

Discussion

The development of cold field emission between the shield rings and the gauge anode was not surprising in view of the relatively close spacing between these electrodes. The exact magnitude of the current, of course, could not be predicted in advance. This experiment pointed up the danger of placing the anode too close to the cathode in a two element gauge.

Cathode and Shield Ring Current as a Function of Pressure for Nitrogen Gas.

System Preparation and Test Performed

The No. 2 all glass Venema type calibration system was used for this experiment. The system had been baked overnight at $400^{\circ}C$ and had been operating at low pressures for several weeks. The gauge anode voltage of 2.0 kV was supplied by a J. Fluke Model 408A regulated power supply. A GCA commercial 1100 gauss magnet furnished the magnetic field. The Model X-6 gauge cathode and shield rings were connected through separate Keithley Model 600 electrometers to ground. Only the lower and middle Venema type cold traps on the system were filled with liquid nitrogen. The Varian UHV-12 glass Bayard Alpert type gauge was reading at its X-ray limit of 2.7×10^{-10} torr. The 0.2 mm diameter calibrated capillary on the system was being used for the flow calibration. A Veeco RG-75 Bayard Alpert type gauge operated at 100 μA was used to measure the pressure in the gas inlet system. Pressures from about 1 x 10^{-12} torr to 1 x 10^{-6} torr of nitrogen were established in the system. Test chamber pressures between 1 x 10^{-12} torr and 4 x 10^{-10} torr were determined by flow calibration techniques. Pressures above this value were determined by the Varian gauge. Both the gauge cathode current and the shield ring current were observed for each pressure level in the test chamber.

Results

The results of this test were most interesting and are displayed in graphical form in Figure 38. A background pressure in the low 10^{-12} torr region had been established in the Venema-type calibration system. It was found that at the calculated background pressure, the shield ring and cathode currents were equal and had a value of 3 x 10^{-13} ampere. As the nitrogen pressure in the system was increased, the cathode current first increased slowly in a non-linear fashion, varying approximately with the 0.38 power of the pressure, until a pressure of 3 x 10^{-11} torr was reached. After this, the cathode current increased approximately with the 1.5 power of the pressure until a pressure of 3 x 10^{-8} torr was reached. The cathode current then varied linearly with pressure from 3 x 10^{-8} torr to 1 x 10^{-6} torr, the highest pressure of nitrogen employed.

The shield ring current, on the other hand, remained constant at a value of 3 x 10^{-13} ampere from the background pressure to a nitrogen

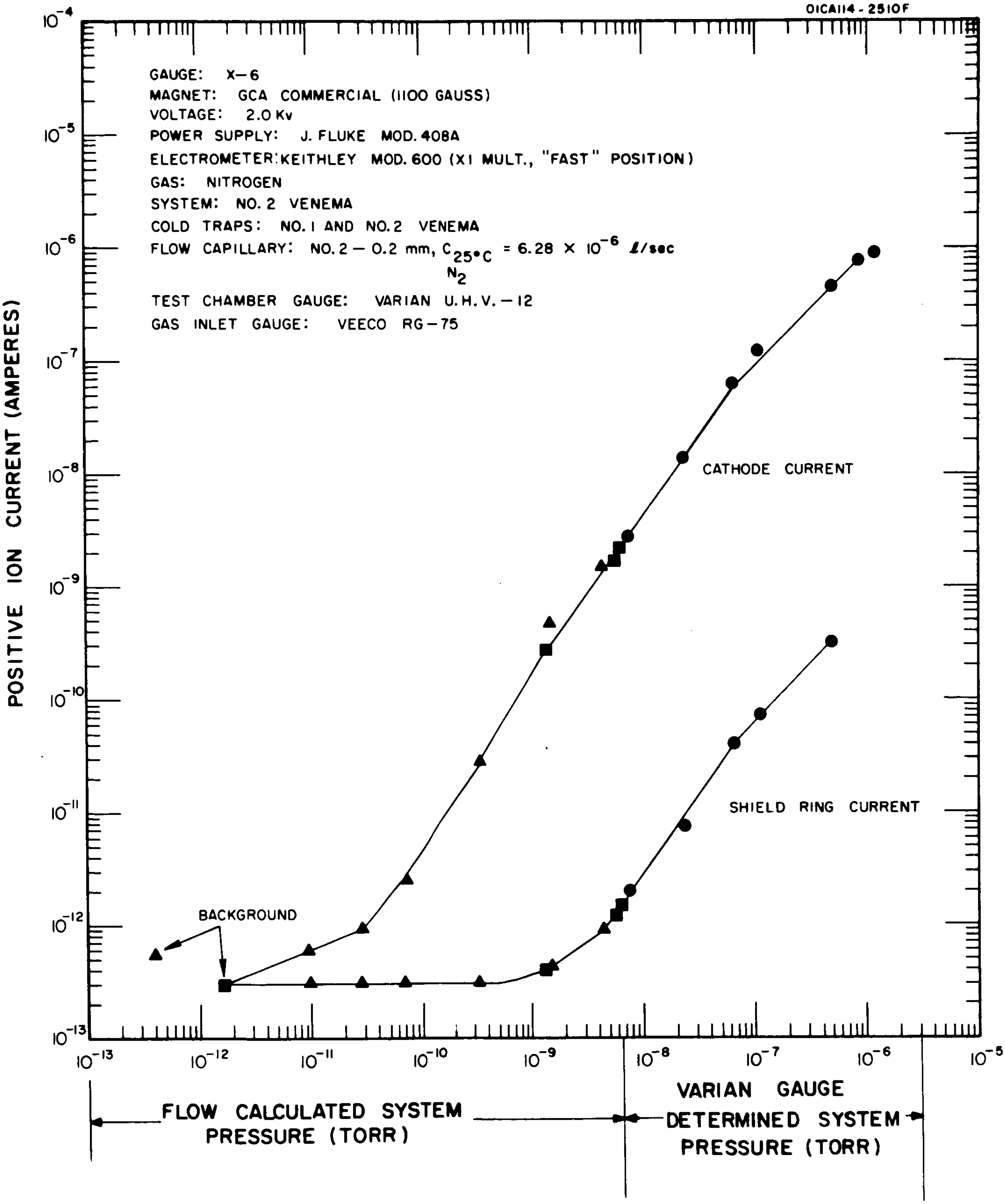

Figure 38. Current-pressure characteristics of the cathode and shield rings of the Model X-6 gauge.

pressure of about 4 x 10^{-10} torr. From 4 x 10^{-10} torr to about 4 x 10^{-9} torr, this current varied approximately with the 0.4 power of the pressure. From 4 x 10^{-9} torr to 6 x 10^{-8} torr, the current increased approximately with the 1.5 power of the pressure. From 6 x 10^{-8} torr to 5 x 10^{-7} torr, the shield ring current varied linearly with the pressure. For pressures greater than about 1 x 10^{-9} torr, the shield ring current was at least three orders of magnitude smaller than the cathode current.

Several new results were obtained in this particular experiment. First, the equality of the currents to the shield rings and the cathode is significant and indicates a common origin of the two currents. Second, a cold cathode gauge current-pressure characteristic with the current varying as the 0.4 power of the pressure had never been observed prior to this test. It appears that there can be a third mode of operation at very low pressures. Third, the shield rings do not appear to play any fundamental role in the operation of the gauge.

Discussion

The Model X-6 gauge was operated at an anode voltage of 2.0 kV for two reasons: first, the cold field emission was sufficiently low so that small positive ion currents to the shield rings could be measured, and second, an auxiliary test indicated that the gauge cathode current was a maximum at low pressures for this anode voltage.

A study of the data taken in this experiment shows that the shield ring current exhibited the same sort of pressure dependence as the cathode current, except at low pressures where the shield ring current was relatively constant and independent of pressure. Thus, one might say that the shield rings acted somewhat as probes located adjacent to the discharge, and collected a constant fraction of the positive ions produced in the discharge. Since the shield ring current was many orders of magnitude smaller than the cathode current, it must be concluded that only a very small number of positive ions were created in the region adjacent to the shield rings and the edges of the gauge anode.

Experiments With the Model A Experimental Cold Cathode Gauge

The Model A gauge was created to determine whether or not a gauge with a larger ionization volume between anode and cathode would automatically yield a higher sensitivity for the same values of magnetic field and anode voltage. The Model A gauge contained a larger anode and cathode than the other gauges used in the experimental program. There were no apertures at all in the gauge anode, and the cathode end plates closely approached the edges of the anode in this structure, leaving an annular gap between anode and cathode about .045 inches wide. Elimination of the anode aperture and narrowing of the annular gap between the anode and the cathode end plates were expected to reduce the possibilities of electron and positive ion escape. A sketch of the Model A gauge is presented in Figure 39.

Current-Pressure Characteristic for Nitrogen Gas.

System Preparation and Tests Performed

The vacuum test system was used for this experiment. The system had been baked and had been under vacuum for two days prior to the experiment. The gauge had been on and operating at 4.0 kV overnight before the experiment was performed. The anode voltage of 4.0 kV was supplied by a GCA unregulated high voltage power supply. A Keithley Model 600 electrometer was used to measure the cathode current. A permanent magnet with a 1-1/4 inch air gap and a magnetic field of 1030 gauss was used in the test.

The background pressure in the system was 1.0×10^{-8} torr with the spherical cold trap filled with liquid nitrogen. Pure nitrogen gas was then permitted to flow into the system to establish a series of pressures ranging from 1.6×10^{-8} torr to 1.5×10^{-5} torr. Gauge current readings were taken at each pressure level.

Results

The data obtained in this experiment are displayed in the graph of Figure 40. It can be seen that the gauge response was approximately linear within the pressure region covered from 1×10^{-8} torr to

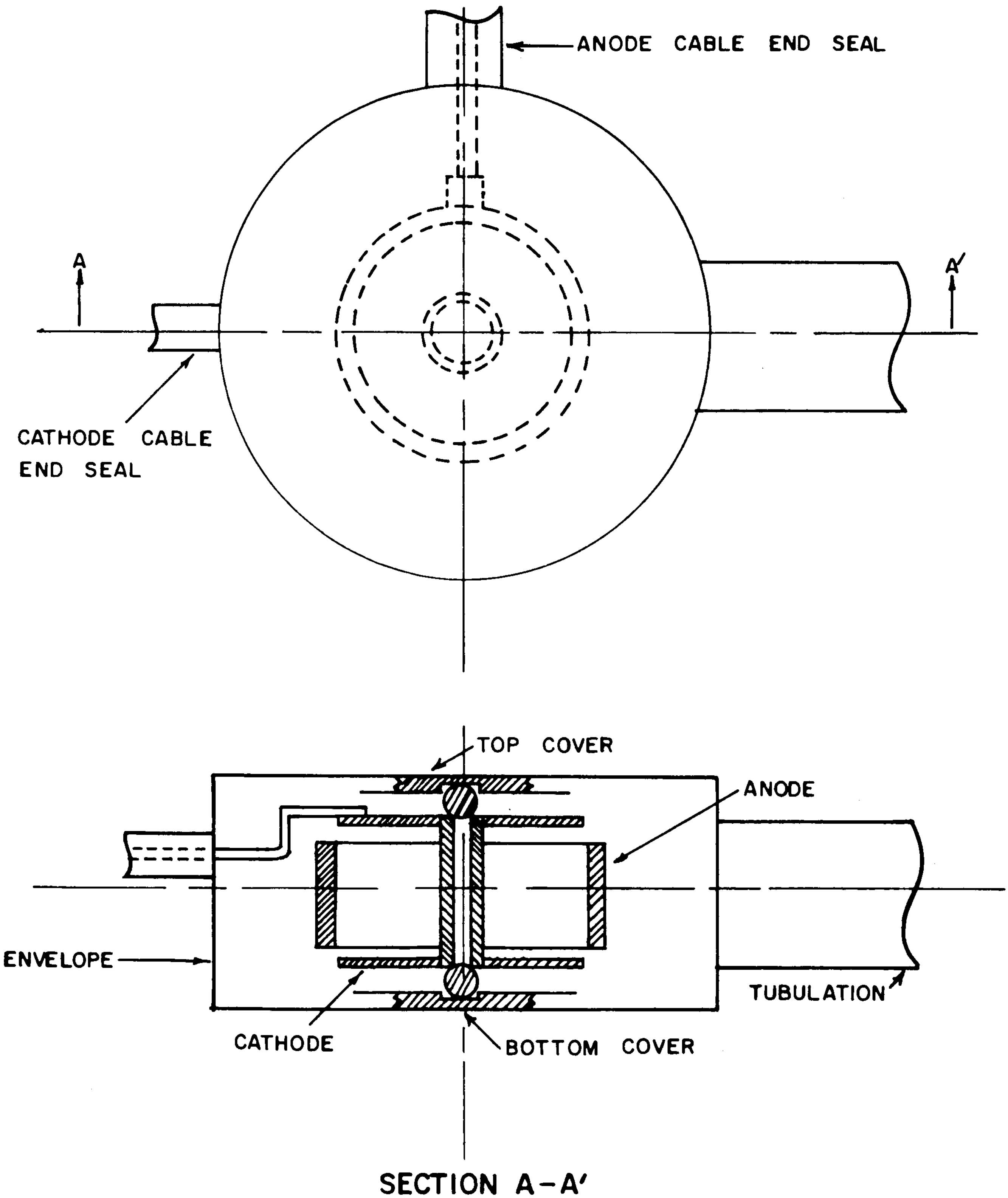

Figure 39. Model A experimental cold cathode gauge.

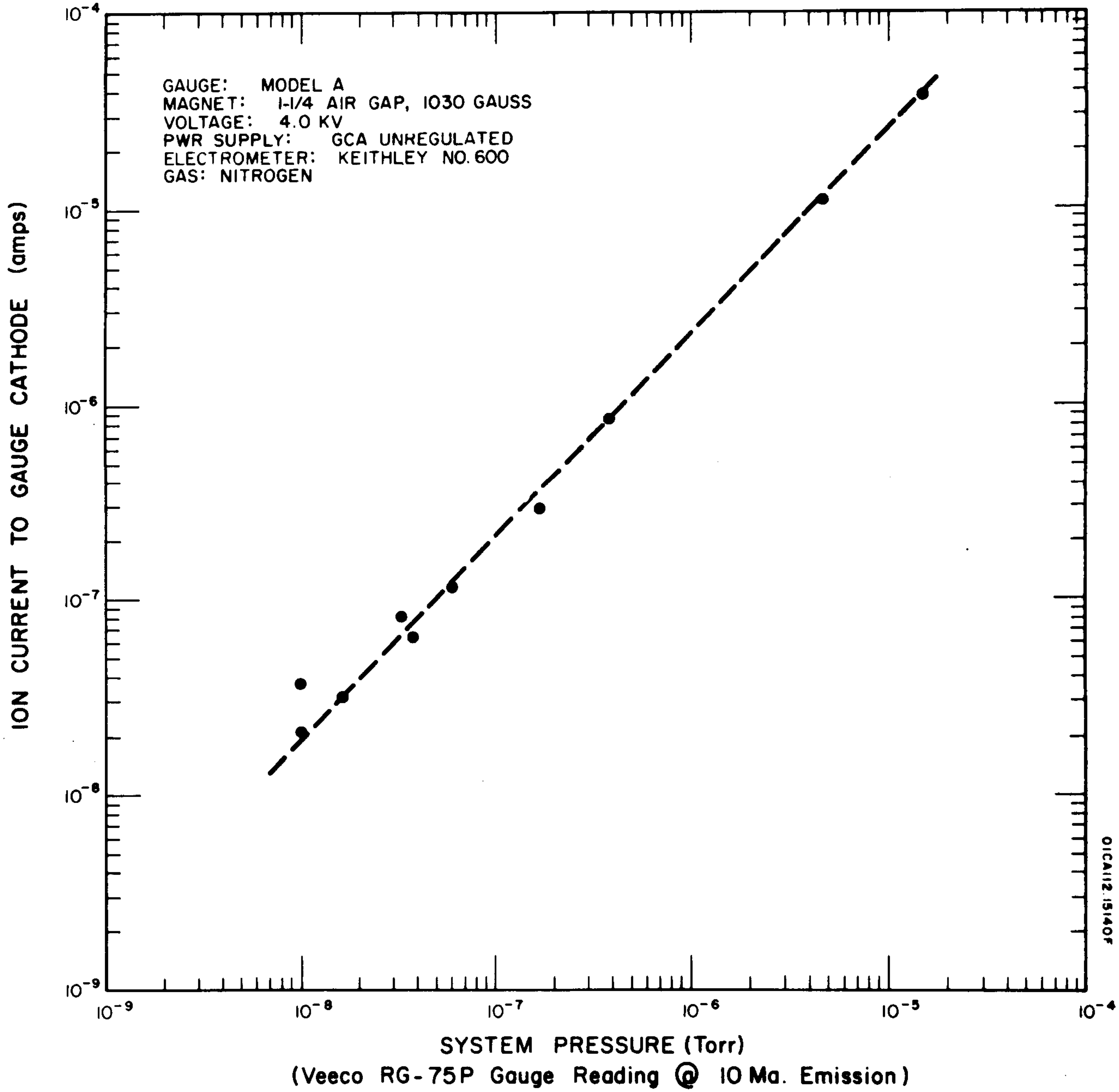

Figure 40. Current-pressure characteristic of the Model A gauge for nitrogen gas.

about 1.5 x 10^{-5} torr. The relative sensitivity of this gauge of about 2.5 amps per torr was somewhat greater than that of the standard 1410 gauge. Mode changes were observed in the Model A gauge in the 10^{-8} torr pressure region, changes very similar to those observed in other magnetron-type cold cathode ionization gauges.

Discussion

The results obtained in this experiment indicated that the Model A gauge did have a higher sensitivity than the standard GCA Model 1410 gauge. In other respects, the Model A gauge operation appeared to be quite similar to the 1410 gauge operation.

Experiments With the Demountable Cold Cathode Gauge

The demountable gauge was designed to permit various gauge elements, such as cathodes and anodes of different sizes, to be tested conveniently and quickly. In addition, sputtering studies could be made quite easily with this gauge. As shown in the sketch of Figure 41, the demountable, experimental gauge was constructed to make use of two 2-3/4 inch O.D. Conflat flanges. Two covers were provided to permit the use of different cathodes. The gauge tubulation was necessarily of small diameter (3/8 inches O.D.) due to the thickness of the flanges and the overall height limitations.

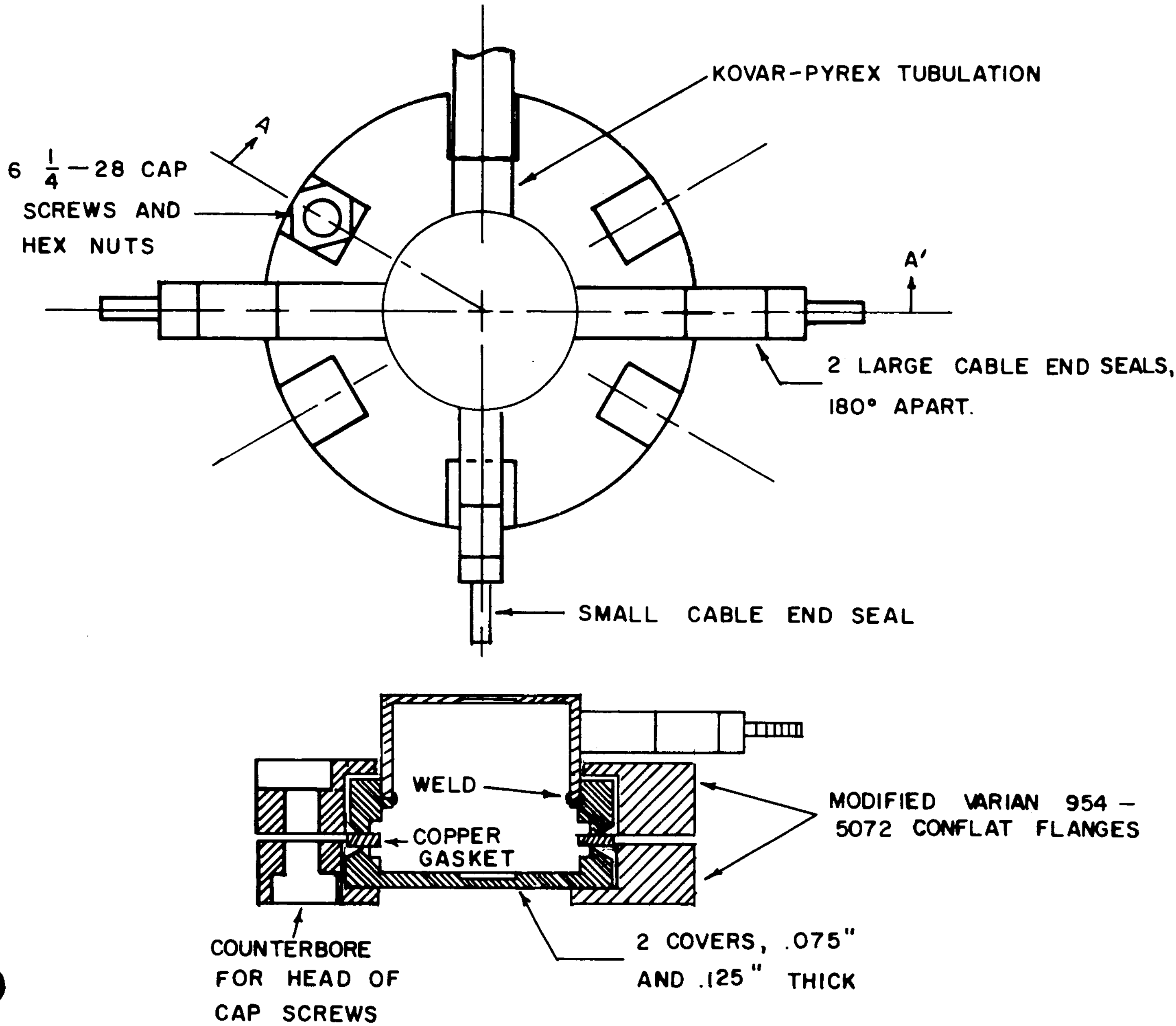

Figure 41. Demountable, experimental cold cathode gauge.

Current-Pressure and Current-Voltage Characteristics of the Standard Model 1410 Gauge With a Small Diameter Cathode.

System Preparation and Tests Performed

The vacuum test system was used for this experiment. The test system had been under vacuum for two weeks prior to this experiment. The gauge was used with a 1000 gauss permanent magnet (NRC Model No. 46756). Various voltages from 1.0 to 4.0 kV were supplied to the gauge anode from a GCA laboratory type unregulated high voltage power supply. The cathode current of the gauge was measured with a Keithley Model 600 electrometer. The cathode of this gauge had a diameter of .100 inches as compared with the standard cathode diameter of .156 inches.

The background pressure in the system with the spherical cold trap filled was 4×10^{-8} torr. Nitrogen gas was flowed into the system to establish a series of fixed pressure levels. At each pressure level, the anode voltage was varied from 4.0 to 1.0 kV in steps of 0.5 kV. The gauge cathode current corresponding to each anode voltage was recorded. The nitrogen pressure levels within the system were established in a sequence of increasing pressures, while the anode voltage levels were established in a sequence of decreasing voltages for each pressure level.

Results

The data that were obtained in this experiment are displayed graphically in Figures 42 and 43. It was found that this gauge took

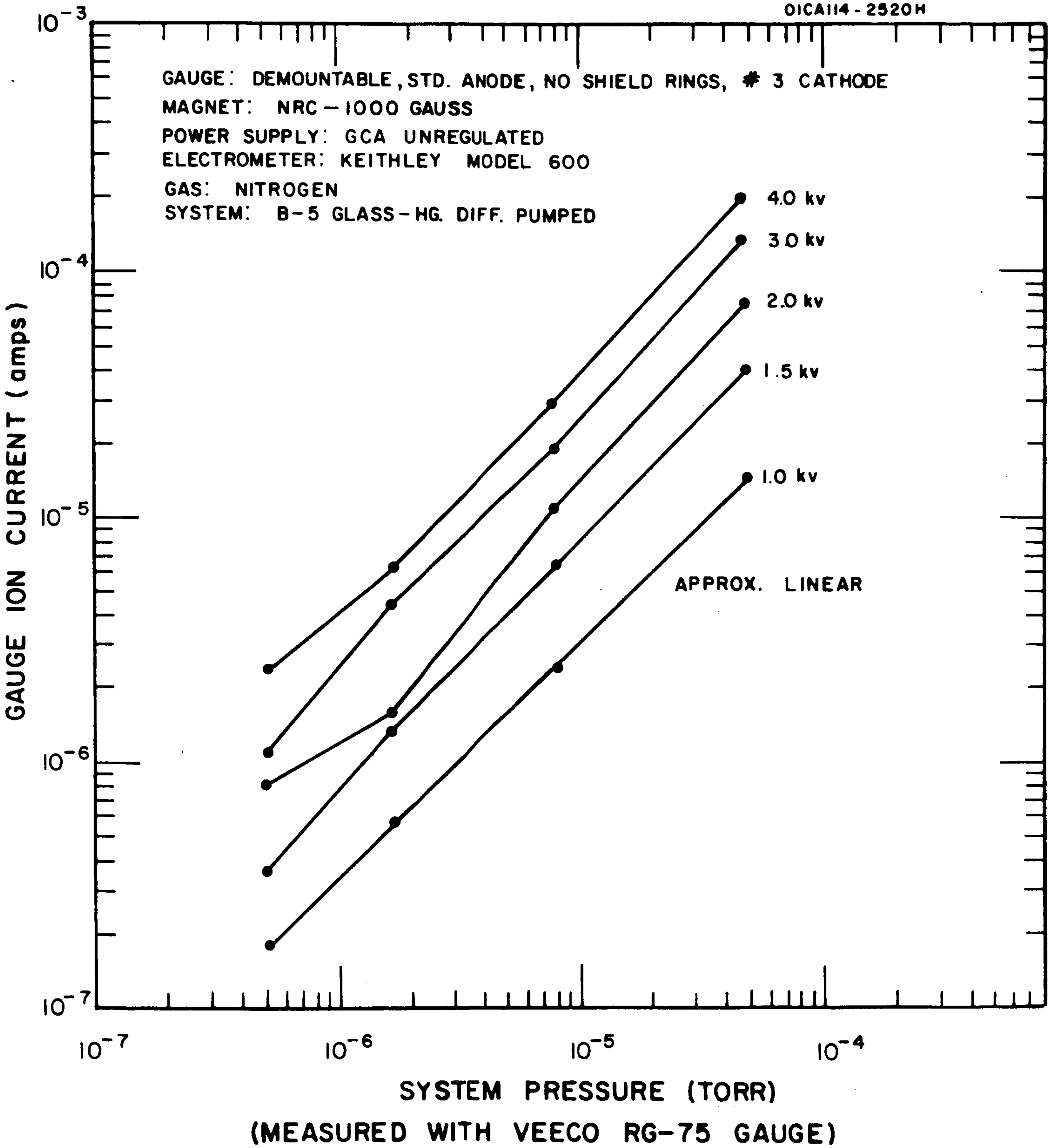

Figure 42. Current-pressure characteristics of a standard GCA Model 1410 gauge with a small diameter cathode.

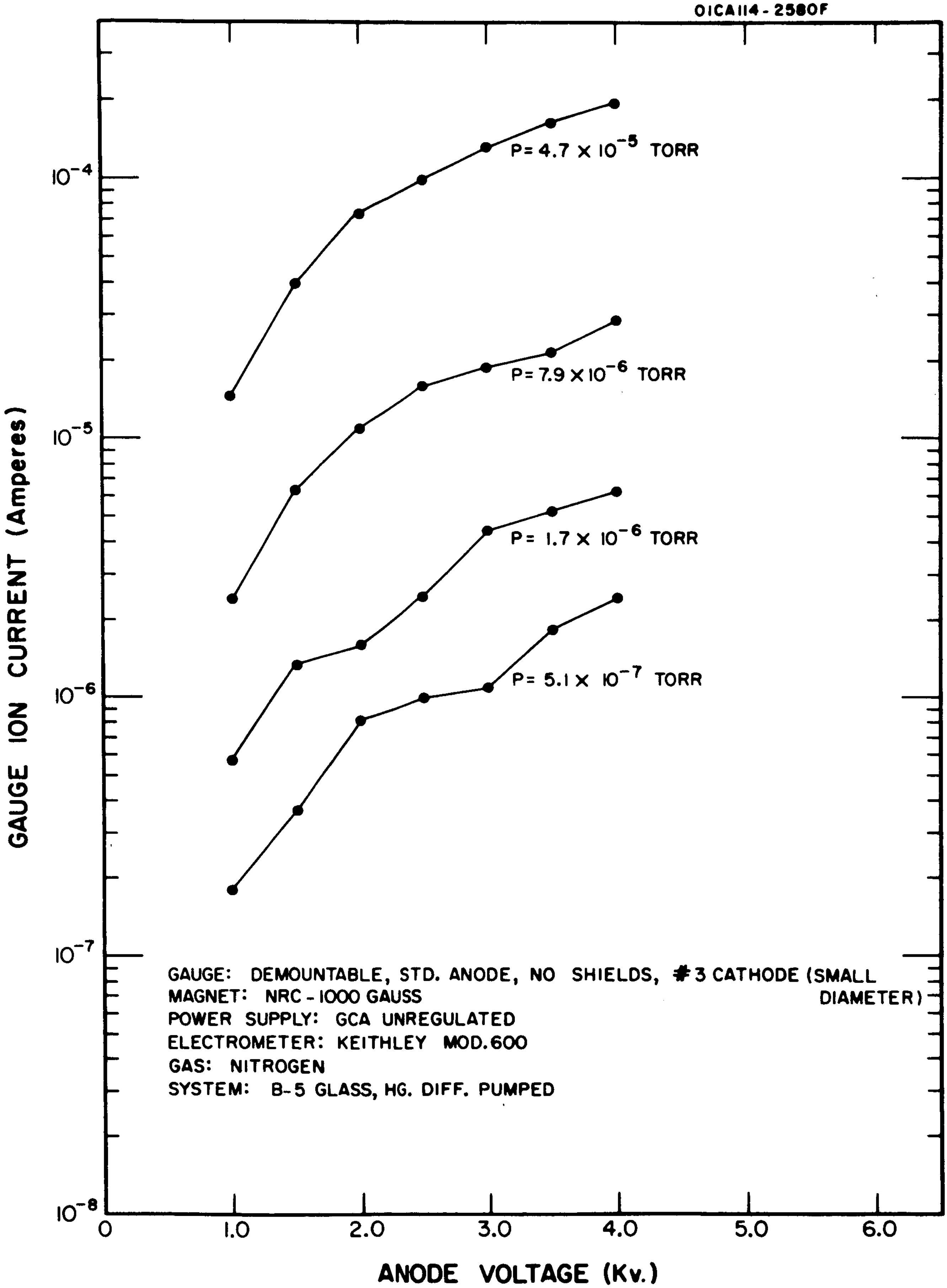

Figure 43. Current-voltage characteristics of a standard GCA Model 1410 gauge with a small diameter cathode.

one to two minutes to fire after a voltage of 4.0 kV was applied to the anode with a system pressure of about 4×10^{-8} torr. At this pressure level, a cold cathode gauge containing the regular diameter cathode fires in less than one second.

The current-pressure gauge characteristics shown in Figure 42 indicated that this gauge was very nearly linear for anode voltages of 1.0 or 1.5 kV, but had departures from linearity at higher voltages. At a pressure of 1×10^{-6} torr and with an anode voltage of 4.0 kV, the gauge had a sensitivity of 4.0 amperes/torr, about twice that of an equivalent gauge containing the larger diameter standard cathode. There were no indications of mode changes in this gauge, but this result was inconclusive since the lowest pressure attained was a background pressure of 4.0×10^{-8} torr, and mode changes generally occurred below this pressure level.

The current-voltage characteristics of the gauge displayed in Figure 43 show that within the ranges of pressure and anode voltage employed, the ion current continually increased with increasing anode voltage. There was no leveling-off of the curves at the higher voltages, as exhibited by gauges containing the standard cathode.

Discussion

The demountable cold cathode gauge proved to be very convenient to work with. The gauge cathodes could be changed quickly and easily without disturbing the other elements of the gauge. The results obtained with the small diameter cathode indicated that starting such a gauge could be a problem at low pressures. A gauge with a small diameter cathode seemed to demand a higher anode voltage in order to attain maximum sensitivity. At the same time, the gauge response become non-linear at these higher anode voltages. There was no difficulty operating this gauge over the entire range of pressures and anode voltages employed.

Current-Pressure and Current-Voltage Characteristics of the Standard Model 1410 Gauge With a Large Diameter Cathode.

System Preparation and Tests Performed

The vacuum test system was used for this experiment. The system had been under vacuum for one week prior to the test. A 1000 gauss permanent magnet (The NRC Model No. 46756 magnet) was used to furnish the necessary magnetic field. Anode voltage from 1.0 to 4.0 kV were supplied by a GCA laboratory type unregulated high voltage power supply. A Keithley Model 600 electrometer was used to measure the cathode current. The cathode of this gauge had a diameter of .392 inches as compared with the standard cathode diameter of .156 inches.

The background pressure in the system was 4.0×10^{-8} torr. Nitrogen gas was flowed into the system to establish three separate pressure levels in an increasing sequence. At the lowest pressure level, the anode voltage was first varied from 4.0 kV to 0.4 kV in a decreasing sequence in steps of 0.2 kV. After this, the same measurements were repeated, but now the anode voltage was varied from 1.5 kV to 4.0 kV in an increasing sequence in steps of 0.2 kV. The gauge current corresponding to each anode voltage was recorded. For the next two higher pressure levels, the anode voltage was varied from 4.0 kV to 0.5 kV in a decreasing sequence in steps of 0.2 kV.

Results

The data obtained in this experiment for nitrogen gas are summarized in the graphs of Figures 44 and 45. It was found that this gauge fired immediately upon application of a voltage of 3.0 kV to the anode at a system pressure of 4.5×10^{-8} torr. Using just the residual gas in the test system (at an indicated pressure of 4.1×10^{-8} torr), the gauge anode voltage was varied from about 500 volts to 3.5 kV. It was found that the discharge went out for voltages below 500 volts and above 3.5 kV.

Prior to performing the nitrogen gas experiment, tests were made using just the residual gas in the test system. Anode voltages were first applied in an increasing fashion and then in a decreasing fashion. With an increasing voltage, the ion current output increased to a maximum value for a voltage of 2.4 kV and then slowly decreased as the voltage was raised to 3.5 kV. On the other hand, with a decreasing voltage that started at 3.3 kV, it was found that the ion current

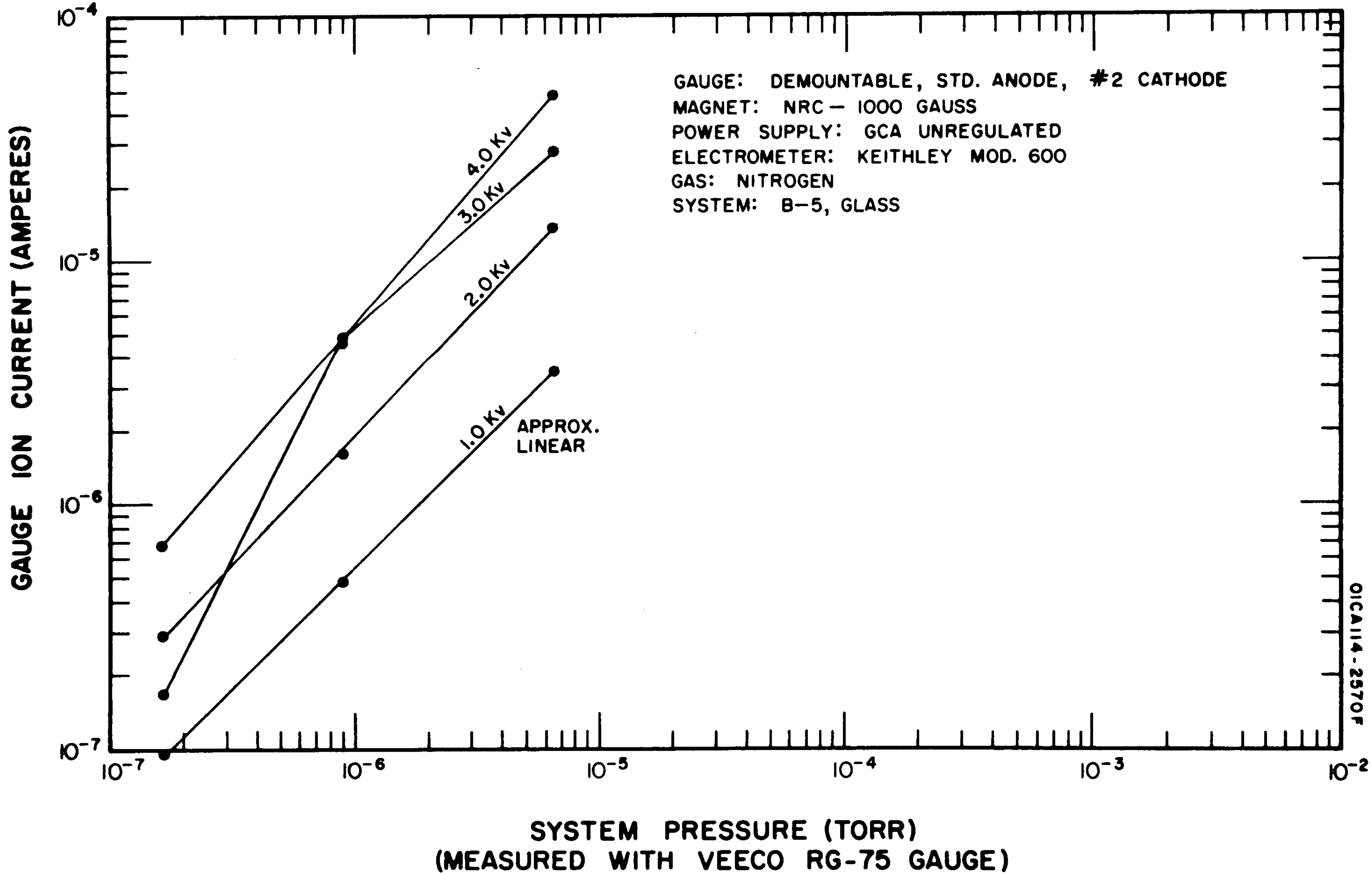

Figure 44. Current-pressure characteristics of a standard GCA Model 1410 gauge with a large diameter cathode.

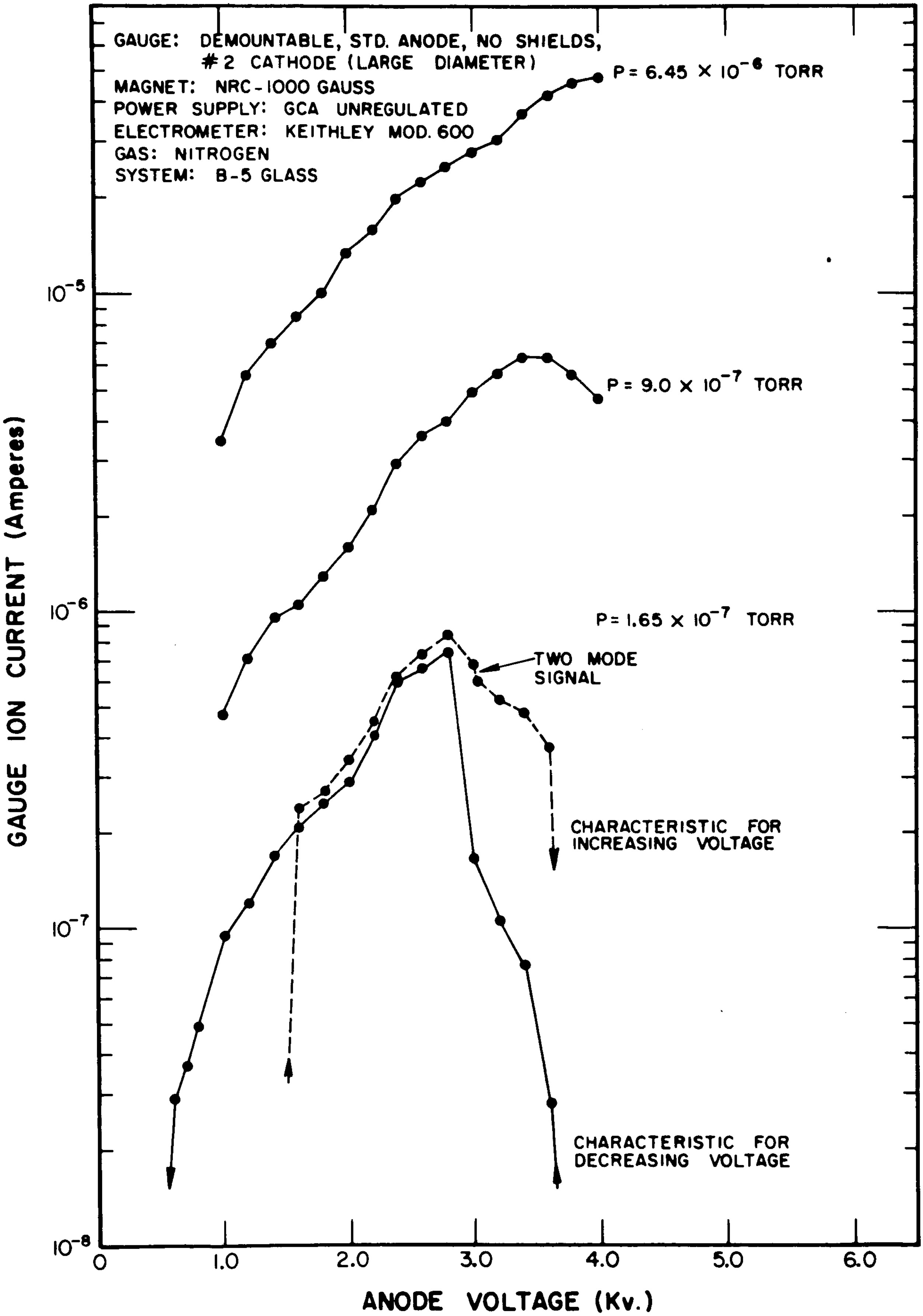

Figure 45. Current-voltage characteristics of a standard GCA Model 1410 gauge with a large diameter cathode.

remained very small, although it continued to increase, until a voltage of about 2.8 kV was reached, at which voltage the ion current increased suddenly by a factor of almost five and approached the values obtained earlier with the increasing voltage. In other words, there was a sort of hysteresis-type effect associated with the decreasing portion of the current-voltage characteristic (ion current decreasing as the anode voltage increased). It seems that in the case of an increasing voltage, the space charge established at the peak of the characteristic is mostly maintained as the voltage gets larger, while in the case of a decreasing voltage that starts at high values, the space charge does not build up until the peak of the characteristic is approached.

When nitrogen gas was introduced into the system, the maximum in the current-voltage characteristic was shifted to higher values of anode voltage, but the same hysteresis effect occurred, for example, at a nitrogen pressure of 1.65×10^{-7} torr. As shown in Figure 45, the maximum in the current-voltage characteristic at a pressure of 6.45×10^{-6} torr occurred for some anode voltage greater than 4.0 kV.

The current-pressure characteristics plotted in Figure 44 show that this gauge was approximately linear for anode voltages ranging from 1.0 to about 2.5 kV, but was non-linear for voltages greater than this. At a pressure of 1×10^{-6} torr and an anode voltage of 4.0 kV, the gauge sensitivity was 5.3 amperes/torr.

Discussion

The gauge with the larger diameter cathode would only operate within a limited voltage range. This effect was undoubtedly due to the relatively close spacing between the anode and cathode of the gauge. Perhaps one of the most significant findings of the entire research program was the discovery of the strong hysteresis effect for the gauge containing a large diameter cathode. This effect can form the basis of a theory explaining the existence of "current jumps" and "mode changes" in a magnetron type cold cathode gauge, as well as the transition from linear to non-linear behavior. The theory would go something like this: it is well-established that the maximum in the current-voltage characteristic of a magnetron type cold cathode gauge shifts to lower values of voltage as the pressure decreases. One simple way of explaining this phenomenon is to recall that a lowering of the pressure in the gauge reduces both the generation of new electrons at the cathode and the speed with which electrons are transported (by means of collisions) from cathode to anode. The magnitude of the anode voltage strongly affects the rate at which electrons are removed from the space charge. Hence, if there is a decrease in the generation and transport of electrons into the space charge region, there must be a corresponding decrease in the rate at which electrons are removed from the space charge region if an optimum (maximum) space charge is to be attained.

Having established a logical explanation for the shift of the current-voltage maximum to lower values of voltage as the pressure decreases, it remains to point out that changing the pressure in a magnetron type gauge at a fixed value of anode voltage in the vicinity of a current-voltage maximum, leads to a situation of hysteresis identical with that found for the gauge with the large diameter cathode.

As an example, consider the curves of Figure 45. Assume that the gauge is operated at 3.0 kV. If one starts with a high pressure in the gauge, say 6.45×10^{-6} torr, and then decreases the pressure, say to 9.0×10^{-7} torr, the gauge response will be linear since the slopes of the two current-pressure characteristics are both positive and have about the same value. In addition, there should be no mode switching since the space charge is relatively constant and any increase in the anode voltage will cause more space charge to be stored within the gauge, a normal, stable condition.

Now, if the pressure is reduced below a value of 9.0×10^{-7} torr, at some point in pressure greater that a pressure of 1.65×10^{-7} torr, the peak of the current-voltage characteristic shall have been reached. Under these circumstances, the gauge response is no longer linear since the slope of the current-voltage characteristic has gone from a positive value to zero. As the pressure is decreased still more, the slope of the characteristic becomes more and more negative. In addition to the loss of gauge response linearity when the peak of the current-voltage characteristic has been reached, the region of hysteresis is also at hand. At this point, any increase in gauge voltage will cause a decrease in the space charge within the gauge. Once the space charge has been decreased, it takes an appreciable time to replenish it, if the voltage should increase again. Two mode oscillation occurs when pressure or voltage fluctuations cause an alternation between the two current-voltage characteristics - one characteristic valid for increasing voltages, and the other for decreasing voltages.

CONCLUSIONS

During the course of the experimental program, a number of interesting and important results were obtained, permitting certain conclusions to be drawn about magnetron type cold cathode gauge operation.

The operating characteristics of cold cathode gauges will be grouped into several categories in order to unify conclusions made on the basis of different experiments.

Gauge Sensitivity

1) Experiments with several gauges showed that gauge sensitivity depended strongly on the anode voltage used. For higher gas pressures, the sensitivity generally increased with increasing voltage in the range from 1.0 to 5.0 kV. At lower gas pressures, a maximum value of sensitivity would be reached at some intermediate anode voltage. The peak in the current-voltage characteristic shifted to lower values of voltage as the gas pressure decreased.

2) Experiments with a flight model cold cathode gauge showed that gauge sensitivity generally decreased as the magnetic field was increased, except at lower pressures where a sensitivity minimum occurred for some intermediate value of the magnetic field used (500 to 1400 gauss).

3) The experiment with the model A gauge indicated that increasing the ionization volume of a gauge increased its sensitivity.

4) The highest sensitivity obtained for nitrogen gas at a pressure of 1×10^{-6} torr was obtained with a gauge that had a large diameter cathode (as used in the demountable gauge).

5) Geometrically identical gauges did not necessarily have the same sensitivity. A roughened cathode surface on a flight model gauge increased its sensitivity for higher gas pressures but lowered its sensitivity for lower gas pressures.

6) A hysteresis effect that was observed with a gauge that had a large diameter cathode indicated that gauge sensitivity could depend on whether the anode voltage or the gas pressure was raised or lowered to its final value.

Gauge Stability

1) An experiment with a GCA standard 1410 cold cathode gauge showed that there were small scale anode voltage regions in which the discharge was either stable or unstable. These voltage regions were of the order of 50 to 100 volts in extent.

2) Many experiments with different gauges indicated that at higher pressures, where the current-voltage characteristic had a

continuous positive slope, the discharge was stable, while for some intermediate pressure region, where the current-voltage characteristic exhibited a change in slope (such as passing through a maximum), the discharge became unstable. At very low pressures, the discharge was usually stable.

3) Evidence was obtained that the magnetic field strength affected the gauge stability as well as its sensitivity.

4) The stability of the discharge seemed to be independent of the gas present in the gauge.

5) The stability of the discharge was found to depend on the nature of the cathode surface in two separate experiments. A roughening of a flight model gauge cathode caused instability to occur at the transition region (region in which the gauge response changed from linear to non-linear). Sputtering by argon gas in another gauge also caused instability in the transition region.

6) The hysteresis effect discovered for the gauge that had a large diameter cathode appeared to be associated with gauge instability.

7) The rather large circumferential air gap in the X-2 gauge anode not only caused instability but prevented the gauge from operating except for certain values of anode voltage.

Linearity of Gauge Response

1) It was found that gauge linearity depended in good part on the anode voltage used. In the case of the demountable gauge that was used with both large and small diameter cathodes, linearity was achieved only for the lower anode voltages up to about 2.0 kV.

2) The experiment performed with the X-5 gauge (that contained overlap cathodes and a screened anode aperture) showed that the linear range of a cold cathode gauge could be extended to lower pressures by proper geometrical design.

3) The slope of the non-linear portion of the current-pressure characteristic was found to depend on the condition of the cathode surface. Roughening the surface increased the slope of this part of the characteristic.

4) A sharp discontinuity in the current-pressure characteristic in the transition region was obtained for both a roughened cathode and a well-sputtered cathode.

5) A second non-linearity was discovered for the X-6 shield ring gauge at very low pressures approaching a background pressure in the low 10^{-12} torr region.

6) An experiment with two apparently identical GCA standard 1410 gauges showed that the response of one gauge was linear in the usual way in the high pressure region above 10^{-8} torr while the other gauge was non-linear. Contamination of the gauge cathode was believed to have caused this discrepancy.

Development of Cold Field Emission

1) During one experiment with argon gas it was found that sputtering had evidently caused cold field emission to develop between the edge of the cathode and the anode.

2) The model X-6 gauge in which electrically isolated shield rings were installed, exhibited cold field emission between the shield rings and the anode.

Gauge Starting

1) When the demountable gauge was used with a small diameter cathode, it was found that it took several minutes to start. The same gauge with a larger diameter standard cathode usually starts in less than one second.

2) When the demountable gauge was used with a large diameter cathode, the gauge would not start at all when the anode voltage was either less than 500 volts or greater than 3500 volts.

Ion Energy Distribution

As was shown in Table I, it was found that 34.7 percent of all positive ions had energies of less than 180 volts. With some modifications, the method used could be extended to determine the complete ion energy distribution within the gauge.

Electronic Space Charge Distribution

The relative radial space charge distribution was determined for a small region adjacent to the gauge anode. It was found that the electronic space charge increased in a radially inward direction, starting at the inner diameter of the gauge anode. Motion limitation of the probe prevented measurements from being made over the entire anode-cathode region.

Current Flow to Center and Ends of Gauge Cathode and Anode

(1) It was found that the current to a small region at the center of the gauge cathode was several times larger than the current to the outer portions of the cathode including the end plates. The ratio between the currents to the central and end parts of the cathode was about the same for both the linear and non-linear parts of the gauge current-pressure characteristic. This result indicated that the space charge distribution did not change when the gauge response changed from linear to non-linear. Apparently only the magnitude of the space charge changed.

(2) The experiments performed with the multiple anode segment gauge (the X-4 gauge) yielded the same sort of results as those obtained with the multiple cathode segment gauge. The current to the center of the anode was several times greater than the current to the end portions of the anode. The presence of the end portions of the anode, however, caused the anode center segment to collect more current. In other words, a longer anode increased the discharge current through the gauge. It was found that the current to the end portions of the anode was independent of the potential of the center anode segment.

Use of a Cold Cathode Magnetron Gauge As A Low Resolution Mass Spectrometer

Experiments performed with the model X-1 gauge (in which there is a movable probe located inside the hollow gauge cathode) showed that a beam of positive ions was formed by a pinhole in the gauge cathode. This beam of ions was bent by the magnetic field of the gauge, lighter ions such as helium being bent more than heavy ions such as oxygen. The mass resolution of this particular gauge was so poor that helium and oxygen ions could not be resolved, but improvements in the device could lead to a useful low resolution mass spectrometer.

Explanation of Instability, Mode Changing, and the Transition From Linear to Non-Linear Gauge Response

A new theory was put forth to account for the phenomena of instability, mode switching, and the transition from linear to non-linear operation of a cold cathode magnetron type gauge. Very briefly, the theory is based on the two following phenomena: First, the shift in the maximum of the current-voltage characteristic to lower values of anode voltage with a decreasing gas pressure. This shift is explained in terms of the supply and loss of electrons and the equilibrium electronic space charge distribution resulting therefrom. Second, the hysteresis effect observed in connection with increasing and decreasing anode voltages in a region in which there is a maximum in the current-voltage characteristic. When the anode voltage is increased, the current increases to a maximum and then begins to decrease gradually as higher anode voltages are used. In effect, the electronic space charge density builds up to a maximum as the electron supply rate increases with increasing voltage. Finally, the electron loss rate, which also increases with increasing anode voltage, becomes dominant and begins to decrease the equilibrium space charge. On the other hand, when the gauge is started with a high value of anode voltage, the electronic loss rate is dominant, and the equilibrium space charge must be very small. As the voltage is decreased, the loss rate decreases but so also does the supply rate so that the space charge builds up very slowly. When the anode voltage approaches the value corresponding to the maximum in the current-voltage characteristic, there is a sudden increase in the space charge almost up to its former level. The two portions of the decreasing current-voltage characteristic (i.e. gauge current decreasing as the anode voltage increases) are believed to be responsible for the instability and mode jumping observed in and near the transition region of gauge operation. Small changes in gauge voltage or pressure cause an oscillation between the two characteristics. The non-linearity in the gauge response follows from the rapidly changing negative slope of the current-voltage characteristic as the maximum of this characteristic shifts to smaller values of voltage with decreasing gas pressure.

RECOMMENDATIONS FOR FURTHER STUDY

Among other studies and a continued collection of experimental data pertaining to cold cathode gauge operation, it is recommended that the following specific research be performed:

1. Make additional measurements of detailed current-voltage characteristics (especially observing the presence of noise) for various gas pressures and magnetic fields.

2. Search for new hysteresis effects at various pressures for various gauge designs.

3. Study low voltage operation of gauges with the objective of extending the range of linearity to lower pressures.

4. Extend the method developed to determine ion energy distribution so that the complete ion energy distribution within the gauge can be measured.

5. Extend the method developed to determine the relative radial space charge distribution in order to measure this distribution over a wider radial region.

6. Investigate the feasibility of using a cold cathode magnetron-type ionization gauge as a low resolution mass spectrometer.

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