LE3 B7
1951 AB
R51V2
Cop. 1

THE VACUUM SYSTEM OF THE UNIVERSITY OF BRITISH COLUMBIA VAN DE GRAAFF GENERATOR AND A MASS SPECTROMETER LEAK DETECTOR

by

Eric Harvey Richardson

A thesis submitted in partial fulfilment of
the requirements for the degree of

MASTER OF ARTS

IN THE DEPARTMENT OF

Physics

We accept this thesis as conforming to the
standard required for the degree of Master of Arts:

Members of the Department
of Physics

The University of British Columbia
Vancouver, Canada

May 1, 1951

THE VACUUM SYSTEM OF THE UNIVERSITY OF BRITISH COLUMBIA VAN DE GRAAFF GENERATOR AND A MASS SPECTROMETER LEAK DETECTOR

ABSTRACT

The vacuum system of the Van de Graaff generator is described. Techniques in the construction of the high voltage vacuum tubes are indicated. The required performance of the system and the methods of attaining it are outlined, calculations being given in the Appendices. Vacuum pressure gauges are described and the indicated performance of the system recorded. Vacuum protection circuits are discussed.

Methods of leak detection are discussed and the University of British Columbia mass spectrometer leak detector described in detail. The theory of analysis by a spectrometer with a coterminous crossed electric and magnetic field is given. An operating procedure for the spectrometer is described in detail and some results recorded and discussed.

ACKNOWLEDGMENTS

This work was financed from the Van de Graaff grant of the National Research Council of Canada.

The author is pleased to express his gratitude to Dr. J. B. Warren for guidance and assistance throughout this work.

The author wishes to make it clear that he had nothing to do with the original design of the vacuum system of the Van de Graaff and that the majority of the work on the system was done by others. Special credit must go to Mr. Al Salone, in particular for his work in making final, exhaustive vacuum tests of the tube sections and in assembling and sealing the high voltage vacuum tubes.

The author wishes to acknowledge the work of Mr. A. J. Fraser of the Physics Department machine shop in constructing the mass spectrometer leak detector. Credit must also go to Mr. John Lees, glass blower.

C O N T E N T S

C O N T E N T S

(cont'd)

ILLUSTRATIONS

PLATES

TABLES

THE VACUUM SYSTEM OF THE UNIVERSITY OF BRITISH COLUMBIA VAN DE GRAAFF GENERATOR AND A MASS SPECTROMETER LEAK DETECTOR

I. Introduction

If the Van de Graaff generator is to produce a well defined beam, the pressure of the gas in the system through which the beam passes must be sufficiently low to prevent an appreciable number of collisions between beam particles and gas molecules. For example, a pressure of about $1.3\ 10^{-5}$ mms of Hg is required to pass 90 percent of a proton beam without collision through a path length of 20 feet in hydrogen gas. The calculation of this pressure is given in Appendix I.

Even without consideration of beam scattering, an upper limit of about 10^{-4} mm of Hg pressure is required throughout all parts of the high voltage vacuum tubes to pre-

vent flashovers when high voltage is applied. It is in a high voltage vacuum tube that the beam is accelerated through the voltage developed by the generator. This accelerator tube must be capable of withstanding 65,000 volts across each of 2.8 inch insulators and possibly 250,000 volts during surges. The diameter of the tube should be as large as possible to hasten outgassing and keep the pressure down despite the leak from the ion source. The tube must be sturdy enough to stand a pressure of 200 lbs per square inch while under vacuum and must be vacuum tight under these circumstances.

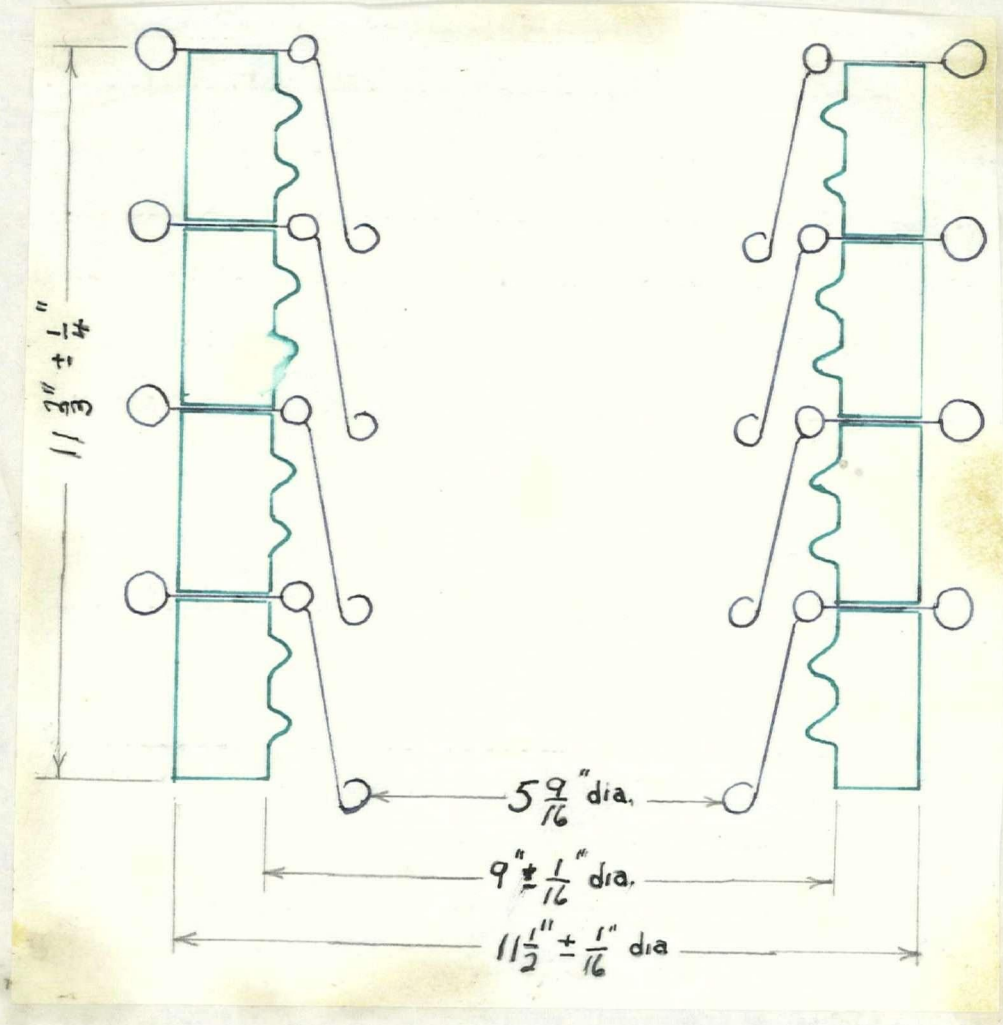
II. DESIGN AND CONSTRUCTION OF THE VACUUM SYSTEM

(a) The High Voltage Vacuum Tubes

The two high voltage vacuum tubes of the Van de Graaff generator are sixteen feet in height and consist of a succession of porcelain rings and steel lenses. The porcelain rings are glazed on the cylindrical surfaces and the plane ends are ground flat to within 0.002 inches and parallel to within 0.006 inches. The steel electrodes are shaped to shield the porcelain surfaces from particles scattered from the beam and edges are rounded and polished to eliminate avoidable corona and flash-overs.

Figure 1

Side View of a Tube Section



Key: Blue ink: steel
Green ink: porcelain

SCALE: 1/3 SIZE

The tubes are assembled in sections. Each section is made up of four pairs of lenses and rings cemented at 400°F under compression. A typical section is shown in Figure 1. The portion of the electrodes to which porcelain is cemented is made of thin stainless steel and is welded in only three places to reduce stress in the porcelain due to unequal expansion coefficients in lieu of using a cement having a lower setting temperature. The cement used was Vinylite Resin Solution, Blend 571, manufactured by the Bakelite Corporation.

Steel spacers are sealed between sections with flat Neoprene gaskets 3/64 inch thick and greased with high vacuum lubricant. The steel spacers have 0.005 inch ridges 3/8 inch wide to prevent the gaskets from being drawn in. Most spacers are 3/8 inch thick but about every tenth spacer was made $\frac{3}{4}$ inch thick to keep the tube electrodes at the same level as the stack electrodes.

The accelerator tube is paralleled by the second high voltage vacuum tube, the differential pumping tube. The bulk of the gas which diffuses into the system through the ion source orifice is pumped out through the tube at a sufficient rate to maintain a calculated equilibrium pressure of about 10^{-4} mm at the ion source. A second orifice is set below the first at the entrance to the accelerator tube to reduce the flow of gas into the tube. This pumping arrange-

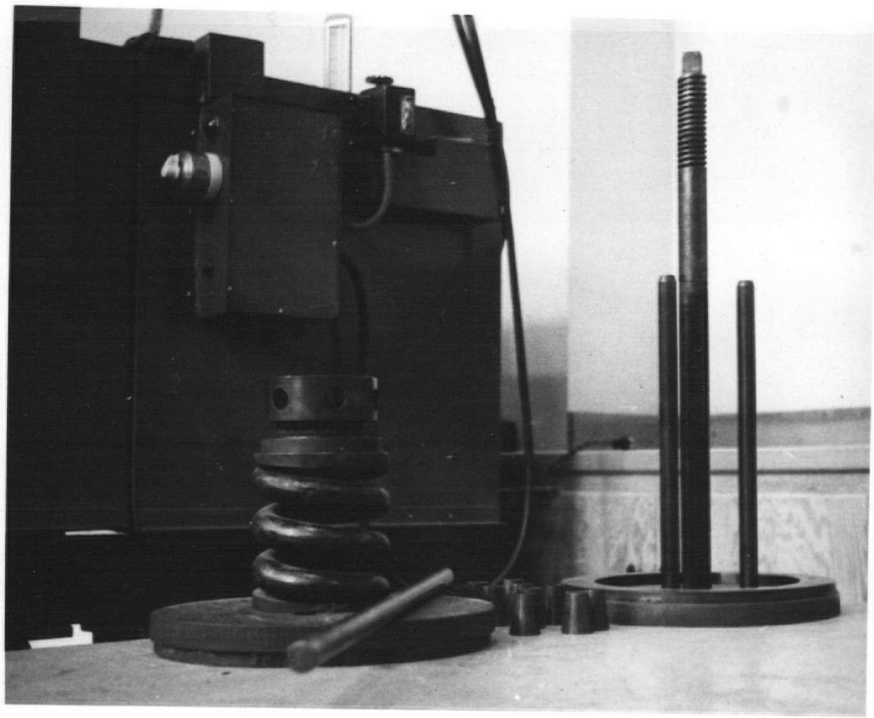


PLATE I

Cementing Press

ment produces a very much better vacuum in the accelerator tube than would be possible without the action of the differential pumping tube. Calculations involved are given in Appendix II.

From the bases of the tubes to the diffusion pumps the system is constructed of large welded and flanged iron ports painted with red glyptal. Each of the tubes is acted on by two diffusion pumps, and can be isolated from the pumps by a plate valve. The external portions of these valves are visible in Plate 2.

A holder providing compression and alignment facilitated the cementing of tube sections. An axial "compression" rod and three shorter "alignment" rods are mounted on an iron plate. Alignment of the lenses is produced by circular wedges dropped down the alignment rods. After a complete section is in place a second plate and a coil spring from a railway car are slipped down over the compression shaft. A brass head threads down the shaft and acts on the spring through ball bearings. The head is radially bored to fit levering rods.

Previous to the baking of an assembled section the cement applied to the ring and lens surfaces was dried either by warming to 150°F for a few hours or by applying the cement three days previous to the baking of the particular section.

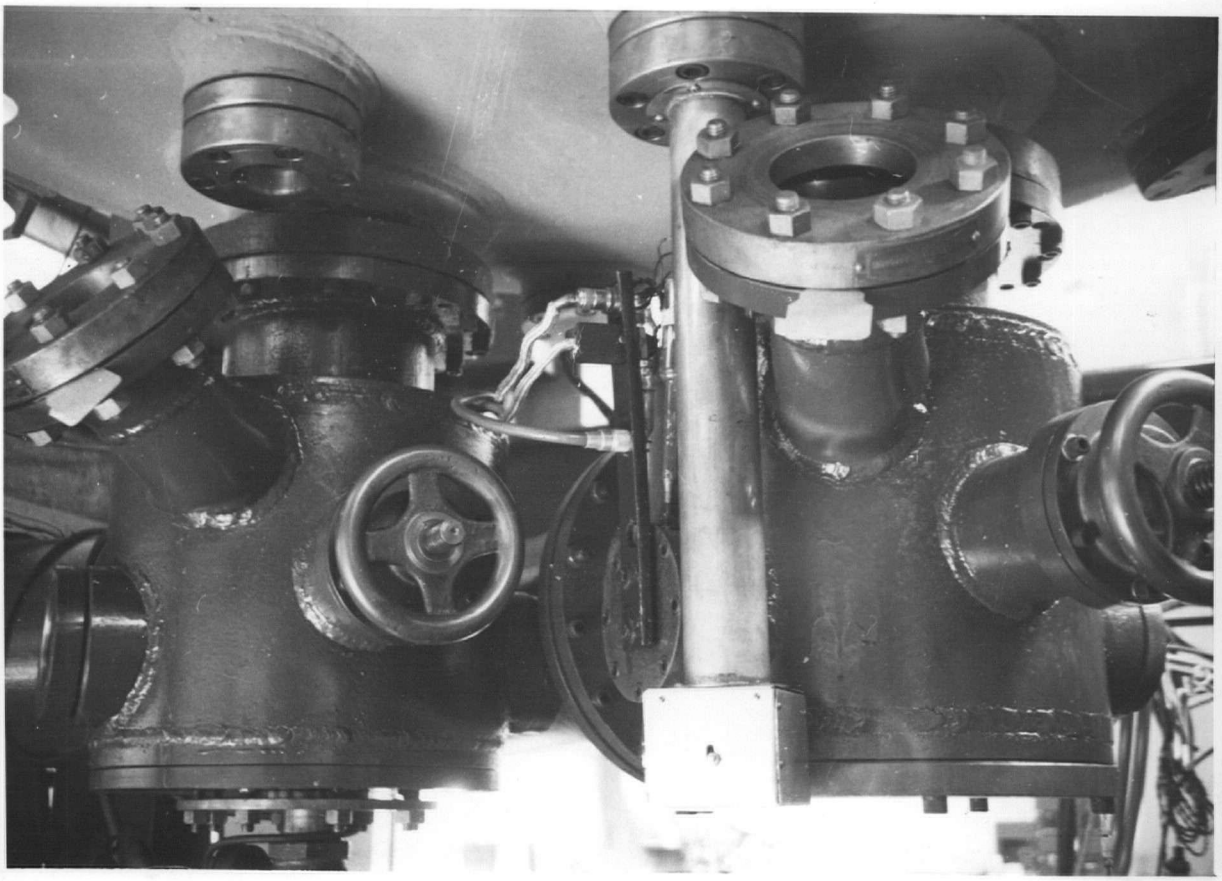


PLATE II

Pumping Port Pots

At the Base of the Van de Graaff

A very thin film of cement was used and both surfaces were coated.

Best results were obtained by heating the sections to 400°F and gradually cooling in the closed oven for about 14 hours to room temperature. To reach 400°F requires disconnection of the oven thermostats. Bubbles remain in the cement if a section has been under-baked; if over-baked, the cement is scorched and brittle.

Sections can be taken to pieces in a 150 degree oven. Cement is removed by soaking the lenses and rings in acetone in an especially designed tray.

(b) The Pumps

Each of the Distillation Products MCF 700 diffusion pumps has a rated pumping speeds given in Table 1. As calculated in Appendix II, these speeds are sufficient to maintain a pressure of about 10^{-6} mm at the base of the accelerator tube under normal operating conditions. Because of its extremely low vapour pressure, Octoil is used in the pumps. A water baffle is set above the intakes of each diffusion pump to reduce the diffusion of oil vapour into the vacuum system. Also, two liquid air traps having a combined capacity of about 8 litres are located in the ends of the ports above the diffusion pumps. The port ends and pumps are visible in Plate III. The pumps require a backing pressure

PLATE III

Vacuum System at the Pumps

of 50 microns or less.

TABLE 1

Rated Pumping Speeds of Diffusion Pumps

Speed (CFM)	Pressure (MMS)
1400	10^{-4}
1000	10^{-5}
100	10^{-6}

The common fore pump for the four diffusion pumps is a Kinney VSD 778. Its rated pumping speeds are given in Table 2. Calculations in Appendix II show that this pump should evacuate the entire vacuum system from atmospheric pressure to 50 microns in about 17 minutes and that it should maintain an equilibrium pressure of 10 microns while the system is outgassing $\frac{7}{\text{at/CFM}}$ (cubic feet per minute) as the rated pumping speed at this pressure is 7 CFM. Such a low equilibrium pressure is desirable if the system is to be left overnight with the diffusion pumps off. A drier is placed on the air intake to prevent water vapour from entering the pump oil. Also a silicagel drier is set in the tube between the diffusion pump and the Kinney pump.

TABLE 2

Rated Pumping Speeds of Fore Pump

Speed (CFM)	Pressure (MMS)
27	760
22	200
14	.05
7	.01

Data on the performance of the vacuum system is recorded in the next section.

III. PRESSURE MEASUREMENT

(a) General

Pressure in the vacuum system of the Van de Graaff generator is measured by a total of four Pirani and two VG-2 ionization gauges. "Forevac" pressures of the two sets of diffusion pumps are measured by two Pirani gauges located between the two diffusion pump pairs and the valves leading to the fore pump. "Hivac" pressures are measured by two Pirani and two ionization gauges set at the bases of the vacuum tubes. The plate valves separate the hivac gauges from the diffusion pumps.

An indication of pressure can be obtained by the application of a Tesla coil to the glow tubes next to the forevac gauges. No glow appears when the pressure is sufficiently low for operation of the diffusion pumps.

(b) Pirani Gauges

The Pirani Gauges are manufactured by Distillation Products Inc.

Measurement of pressure by means of a Pirani gauge is obtained by comparing two fine wire resistances incorporated in a bridge circuit. One of the resistances is in a vessel sealed at high vacuum and the other is in an identical vessel joined to the vacuum system. The presence of gases about the latter resistance servers to increase its cooling rate and thus lower its temperature and resistance. The sealed vessel is designed to compensate the effect caused by fluctuations in room temperature. The variation of pressure with current through the bridge galvonometer is approximately linear below 40 microns.

The Pirani gauges slowly move off calibration and thus require periodic adjustment of the bridge circuit resistances to maintain reasonably accurate pressure measurements.

The Pirani readings depend not only on the pressure of the gas but also on the molecular heat conductivity of the gas. Therefore, the introduction of a gas or vapour of dif-

ferent conductivity through a leak in the vacuum system would be detected by the Pirani which would thus serve as a leak detector as will be discussed later.

(c) Ionization Gauges

An ionization gauge is essentially a triode open to the vacuum system. The grid is maintained at about 150 volts positive and the plate at about 25 volts negative. A large percentage of the electrons which flow to the grid pass into the region between the grid and the plate before eventually being collected on the grid. Positive ions formed by collision of electrons with gas molecules in this region are collected at the plate or collector. The negative voltage on the plate overcomes thermal energies of the electrons and in combination with the grid voltage prevents electrons from reaching the plate. The positive ion current is almost directly proportional to the pressure, other factors being constant, but also depends on the ionization probability of the gas. This dependence makes the gauge useful as a detector in leak hunting when the pressure in the system is sufficiently low.

The ionization gauge cannot be operated at a pressure above 1 micron (10^{-4} cms. of Hg) without accelerated destruction of the filament.

Below 0.5 micron the VG-2 has a sensitivity for air of 32 microamperes per micron for a grid current of 10 milliamperes.

Thus, the collector current corresponding to 10^{-6} mms of Hg is only 0.32 microamperes which is too small to read with ease and accuracy on a panel microammeter. Also, the grid current fluctuates considerably causing undesirable collector current fluctuations. These difficulties are overcome by the Van de Graaff generator control unit which incorporates d.c. amplifier and a grid current stabilizer or emission regulator. A similar circuit is described by Elmore and Sands.[1]

By keeping the cathode at 25 volts positive, the grid at 175 volts positive, and the collector at zero volts, the ion gauge control circuit effectively provides the required operating voltages of the VG-2: cathode zero, plate 150 positive, and plate 25 negative.

The d.c. amplifier is built around a bridge circuit in which two branches are made up of the two halves of a 6SC7 double triode. One grid is permanently earthed; the other grid is connected to the common terminal of a six position selector switch. At "Zero" setting the grid is earthed and the circuit balanced by adjustment of the 3K rheostat which varies the relative magnitudes of the resistances of the other two branches of the bridge circuit.

With the switch at "Cal" about 0.2 volts is applied to the grid and the resistance in series with the microammeter adjusted to give full scale deflection. At position "1" full scale deflection corresponds to a pressure of 2 10^{-3} mms of Hg; that is, the grid is switched to a resistor across which a voltage producing full scale deflection developes when 64 microamps flows through the highly insulated collector lead. At each succeeding position, the pressure corresponding to full scale deflection drops by a factor of ten. At position "4" the zero setting of the amplifier is displaced by the voltage produced across the grid resistor by positive ion grid current. If the ion gauge filament and grid voltages are turned off, the bridge may be balanced to give zero deflection on the microammeter with the selector switch on position 4.

Grid current of the ion gauge is stabilized through regulation of the filament emission. A #273 Hammond transformer is connected in series with the filament transformer. The impedance of the #273 is affected by the secondary current which depends on the grid voltage of the two 2 A 3 tubes which act as load resistors. The 2 A 3 grids are connected to the 6SJ7 plate, the voltage of which is determined by the ion gauge grid current which produces the 6SJ7 grid voltage (which is also the positive bias on the ion gauge filament). Thus an incremental increase in ion gauge grid current

increases the plate current of the 6SJ7 and thus reduces the plate voltage which is the grid voltage of the 2 A 3 tubes. The corresponding decrease in secondary current raises the primary impedence of the #273 and the consequent incremental reduction in the filament emission tends to offset the rise in grid current.

The relay in the ion gauge grid circuit, when energized by an excessive current, disconnects the grid and applies the grid voltage across a resistor to the cathode to maintain the energizing current until the power is shut off or the "Out-gas" switch thrown.

The Out-gas switch shorts the relay energizing coil and switches the grid of the 6SJ7 to a rheostat which spans the voltage drop between the cathode and earth. Thus, the 6SJ7 grid voltage can be reduced to permit sufficient filament emission to provide 20 milliamps ion gauge grid current.

(d) McLeod Gauge

The McLeod gauge gives an absolute measurement of the pressure of the permanent gases present by compressing a known volume of gas from the vacuum system and measuring the resultant pressure manometrically. A glass tube runs from the vacuum system down to an evacuated mercury reservoir so that the level of Hg in the tube can be raised by letting air into the reservoir. The rising Hg enters a glass bulb which

tapers upward into a capillary tube sealed at the top end. Parallel to the capillary, the original tube narrows to a similar capillary in order to compensate the effect of surface tension on the levels of the two columns of Hg. (This capilliary is by-passed by a tube of normal diameter to increase pumping speed.) When the level of the Hg in the capillary reaches a point opposite the closed end of the sealed capillary, the pressure, P_b, of the compressed gas in cms of Hg equals the distance, h, from the top of the capillary down to the Hg level and the volume, V_b, is h times the area, A, of the capillary. Therefore, if the original volume of the gas is V_a, which is the volume of the bulb, then, the original pressure,

$$P_a = P_b V_b / V_a = Ab^2 / V_a$$

Thus, in order to measure low pressures, A/V_a should be as small as possible. In the low pressure gauge constructed for calibration of the Van de Graaff ion gauges, pressure of 10^{-5} corresponds to an h of 2.54 mms.

(e) Data on Performance of the Vacuum System

Observations on the performance of the vacuum system in the Spring of 1951 are given below.

(1) Pump down time from 760 mms to 25 microns: 15 minutes if system tight.

(2) Ultimate pressure with backing pump: 7 microns. When pump warms, Pirani readings rise to about 18 microns.

(3) Fore pressure with diffusion pumps operating: about 35 microns read on Pirani gauges.

(4) Time for diffusion pumps to begin pumping after being turned on: 30 minutes. Total time to reach 3 10^{-5}mms: 45 minutes.

(5) Pressures after prolonged pumping are recorded below. The diffusion pumps are shut off over night.

TABLE 3

Outgassing of Vacuum System

Pressure (mms)	Total Pumping Time Diffusion Pumps (hours)
3 10^{-5}	1
1 10^{-5}	8
8 10^{-6}	16
3 10^{-6}	24

Finally, upon filling the liquid air traps, a pressure of 1 10^{-6} mm was reached in both tubes.

(6) Pressures at the top and bottom of the differential pumping tube for various ion source leak rates are recorded below. Pressure in the hydrogen bottle was 100 pounds per square inch.

TABLE 4

Differential Tube Pressures vs Pd Leak Voltages

Pd Leak Voltage	Pressure (mms 10)	
	Top of Tube	Base of Tube
130	9.6	16
120	6.5	11
110	4.2	7
100	2.5	4
80	1.6	2.8
0	0.76	1.8

IV. VACUUM PROTECTION CIRCUITS

(a) Pressure Rise

As previously mentioned, diffusion pumps and ionization gauges should be operated at pressures less than 150 microns and 1 micron respectively. Operation of the diffusion pump at excessive pressures diffuses pump oil throughout the system causing a major cleaning problem. Heating of ion gauge filaments at too high a pressure greatly hastens their deterioration or destruction. Vacuum protection circuits have been designed to switch off the respective pieces of apparatus in the event of dangerous pressure rises.

Pirani controlled circuits are often used for the protection of diffusion pumps. T. S. Wang[2] has published a description of a satisfactory circuit design. The four Pirani gauges of the Van de Graaff are operated by two portable dual control circuit units. In order that pressures at the bases of the two accelerator tubes may be read simultaneously, each unit is wired to one hivac and one forevac gauge. Thus, the wiring and portability of the units makes them unsuitable as triggers for a relay circuit. I. Amdur[3] utilizes a thermocouple gauge and a very sensitive relay for the protection of diffusion pumps rather than a Pirani control circuit.

H. I. S. Allwood[4] employs a Geissler discharge tube

designed to operate from atmospheric pressure down to about 150 microns.

A very simple discharge tube consisting of only a Kovar seal is now incorporated in the vacuum system of the High Tension set used to test the ion source of the Van de Graaff generator. The discharge tube, in series with a 10 maa. d.c. relay energizing coil, operates satisfactorily on 500 volts A. C. when the pressure rises to 150 microns. Immediately that the tube strikes, voltage to the 500 volt transformer is cut off thus preventing damage to the Kovar, relay, or transformer.

Protection of thermionic filaments is provided in Allwood's circuit by a Penning type discharge tube which operates from 10mm of Hg to 1 micron in series with a relay. This protection can also be provided by a relay triggered by the potential of the ion gauge collector at the grid of the current amplifier. Such a circuit is used in the G. E. Leak Detector.[5]

(b) Water Failure.

Water failure in the cooling system of all diffusion pumps results in decomposition of the pump oil and eventual destruction of the heater elements. A "water switch" in series with a relay is an obvious remedy.

One of the first water switches involved a leaking container suspended on a coil spring which stretched sufficiently to close an electric contact when the cup became full of water.

At present, very sensitive "micro-switches" are available which react to the pressure exerted by a diverted stream of water.[6]

I. Amdur employs a bellows which is inflated by the pressure of water. Such bellows switches, however, may be pressurized even though no water is flowing should the drain be obstructed.

A simple and inexpensive water relay system was constructed for the vacuum system of the apparatus used for testing the ion source of the Van de Graaff. The resistance between two concentric cylinders is reduced sufficiently by the presence of water to enable energization of the power relay which is connected in series with the water resistance. Water flows in through the inner tube or cylinder and if the flow exceeds the outflow through the leak at the bottom of the outer cylinder, water rises between the cylinders until the overflow is reached.

(c) Power Failure

The return of power after failure could result in damage to the vacuum system due to the rise in pressure while

the power was off and/or due to the failure of the fore pump to come back on after the return of power. A comparatively small pressure rise could damage the ion gauge filaments. A larger pressure rise due to leakage through the fore pump might result in diffusion pump damage especially if the fore pump failed to come back on.

As the Kinney fore pump of the Van de Graaff is powered by a three phase motor fed by a standard magnetic switch the return of power would not start the motor. Thus, it was absolutely necessary to place in series with the diffusion pumps the contacts of a relay energized by the voltage of one phase of the fore pump motor so that voltage would not be applied to the diffusion pumps upon the return of power after a failure until the relay was reset.

V. LEAK DETECTION

(a) General

In any large vacuum system the detection of leaks can be extremely tedious and time consuming, so that each item as far as possible is separately checked (e.g. each tube section) before assembly. This may be done by pressurizing sections and placing them under water or painting over with soap solution to enable the location of leaks by the appearance of bubbles. Large leaks can be detected in this manner.

After a system is assembled leaks can be roughly localized by isolating sections (a process made easier by judicious choice of valve positions) and observing the change of pressure within or without the sections when the placement of valves in the system makes such isolation possible.

The spark from a Tesla coil applied to a glass system will enter the system through a hole, if it is large enough and close enough to the electrode, making the puncture clearly visible. As the color of the discharge of a glow tube depends on the nature of the residual gas, the absorbtion of an organic vapour applied to the system could be detected and the leak localized to the area of application. Acetone, or better ether, for example, would change the discharge color to bluish-white. The sensitivity of the Pirani

gauge to gas composition can be utilized in a similar manner if the pressure is within the practical range of the Pirani, i.e., from 1 micron to about 300 microns. Coal gas in a bag is useful for checking a gasket joint.

Below 1 micron, the ionization gauge may be used in leak detection. Stabilization of the grid current is especially necessary to prevent spurious fluctuations in the collector current. A jet of ether was used with the ion gauges as detectors during the assembly of the vacuum tubes of the Van de Graaff. The use of ether not only enables location of leaks but also often results in sealing the leaks possibly by reducing the viscosity of the vacuum grease which is then drawn in to perfect the seal.

The reduction of the emission of heated tungsten filaments by increasing concentrations of oxygen makes possible the use of diodes as detectors on vacuum systems with searching jets of oxygen. In a control circuit described by R. B. Nelson[7] the filament of the detector diode is wired in parallel with the filament of a control diode whose plate current is stabilized through emission regulation. This arrangement is designed to prevent spurious fluctuations in the plate current of the detector diode. A leak of 0.76 micron.litre per hour can be readily detected.

The principle involved in the detector described

by W. C. White and J. S. Hickey[8] is that red hot platinum emits positive ions, even at atmospheric pressure, and that the emission is increased markedly with the partial pressure of the vapour of a halogen compound. The system under investigation is usually pressurized with air or any other suitable gas containing a halogen vapour and the detector probe applied externally. General Electric Bulletin GEC-283 contains information on detector of this type which is especially convenient in testing refrigeration units as the detector is sensitive to Freon gas itself. Alternatively, the detector may be set internally between the diffusion pump and fore pump and a searching jet applied externally though no commercial detector designed for internal use is available. White and Hickey write, concerning the external detector, "the limit of sensitivity to small leaks is the same order of magnitude as that obtained with the mass spectrometer" which is about 0.57 micron.litres per hour for a 283 litre system according to Jacobs and Zuhr.[9]

(b) Improved Ion Gauge Leak Detectors

Brubaker and Wouk[10] have devised a sensitive auditory method of indicating changes in the collector current of ionization gauge detector fluctuations in collector voltage are amplified by a d.c. amplifier and used to bias a relaxation oscillator which feeds a loud speaker through an audio amplifier. A change in collector current will either bring

on the oscillator if it was originally biased off or change the frequency if the oscillator was originally operating. The arrangement enables one man to leak hunt. A change in partial pressure of 4×10^{-9} cms of Hg can be noticed.

H. Nelson's[11] hydrogen ionization gauge involves a palladium tube immersed in the vacuum system and sealed to an ionization gauge in which the pressure has been reduced to 10^{-7} mms of Hg with the aid of a getter. The system is pumped down to 10^{-4} cms of Hg and the palladium heated to 800°C at which temperature it is permeable to hydrogen exclusively. If hydrogen finds entrance to the system through a leak it is Preferentially admitted to the ionization gauge, the gas in which would then contain a percentage of hydrogen about one thousand times greater than the percentage of hydrogen in the gas of the vacuum system. It follows that the device can detect far smaller leaks than conventional ion gauges attached directly to the vacuum system. As the hydrogen is pumped from the system it diffuses through the hot Pd and out of the ion gauge against the 10^{-4} mm air pressure. The hydrogen gauge has the advantages of leak hunting at an extremely low pressure while the system under investigation is maintained at a relatively high and easily obtained pressure: in testing radio tubes on a small system a diffusion pump is not even required and a minimum leak of 10^{-4} litre.micron per second can be detected.

(c) Mass Spectrometer Leak Detectors

The most sensitive leak detectors involve a mass spectrometer and a probing jet of helium. The best of these instruments[12] can detect the presence of He in normal air which contains about 1 part He in 200,000 parts of air. This rarity of He plus its high rate of diffusion through leaks and its unique e/m ratio are the factors which result in the choice of He as the probe gas.

The mass spectrometer leak detector was developed during World War II to hasten the sealing of the extensive vacuum system employed in the United States Atomic Energy Project.

The mass spectrometer leak detector is not only extremely sensitive but also enables the location of leaks in a minimum of time as searching can be commenced while the system under investigation is at fore pump pressures and not yet outgassed.

A complete, portable mass spectrometer leak detector[5] with a sensitivity of 1 part He in 100,000 parts of air is available at a price considerably more than $4,000 from General Electric which also manufactures ion resonant and Bennet RF mass spectrometer tubes.[13] The ion resonant tube requires a magnet providing a uniform field of about 2000 gauss. The Bennet RF velocity selector tube requires no magnet but a

somewhat higher d. c. accelerating voltage. This tube is new and there is no record of its having been used in leak detection though it may prove well suited to such an application. It is sensitive to 1 part of He in 200,000 parts of air.

VI. A MASS SPECTROMETER LEAK DETECTOR FOR THE VAN DE GRAAFF GENERATOR

(a) Design

(i) General

A simple cheap version of a mass spectrometer leak detector has been designed for use with the University of British Columbia Van de Graaff. It uses a simple cold cathode ion source plus a straight through analyser, with cathode ray tube display.

The spectrometer is built in four sections: ion source, lower cathode, analyser, and collector. Except for the cathodes, the metal parts are brass.

(ii) Ion source

The ion source is a reflector type, as shown in Figure 2. What is termed the ion source section consists of a cylindrical anode sealed above and flanged at the base. The upper cathode is suspended by a kovar seal from the top of the anode where a connection is made to the gas feed apparatus through a ground glass joint separated from the ion source by a stopcock supported by a glass to copper seal.

A cylindrical magnet made up of three identical ring sections fits around the ion source. The magnet was magnetized as a unit and never subsequently taken apart in

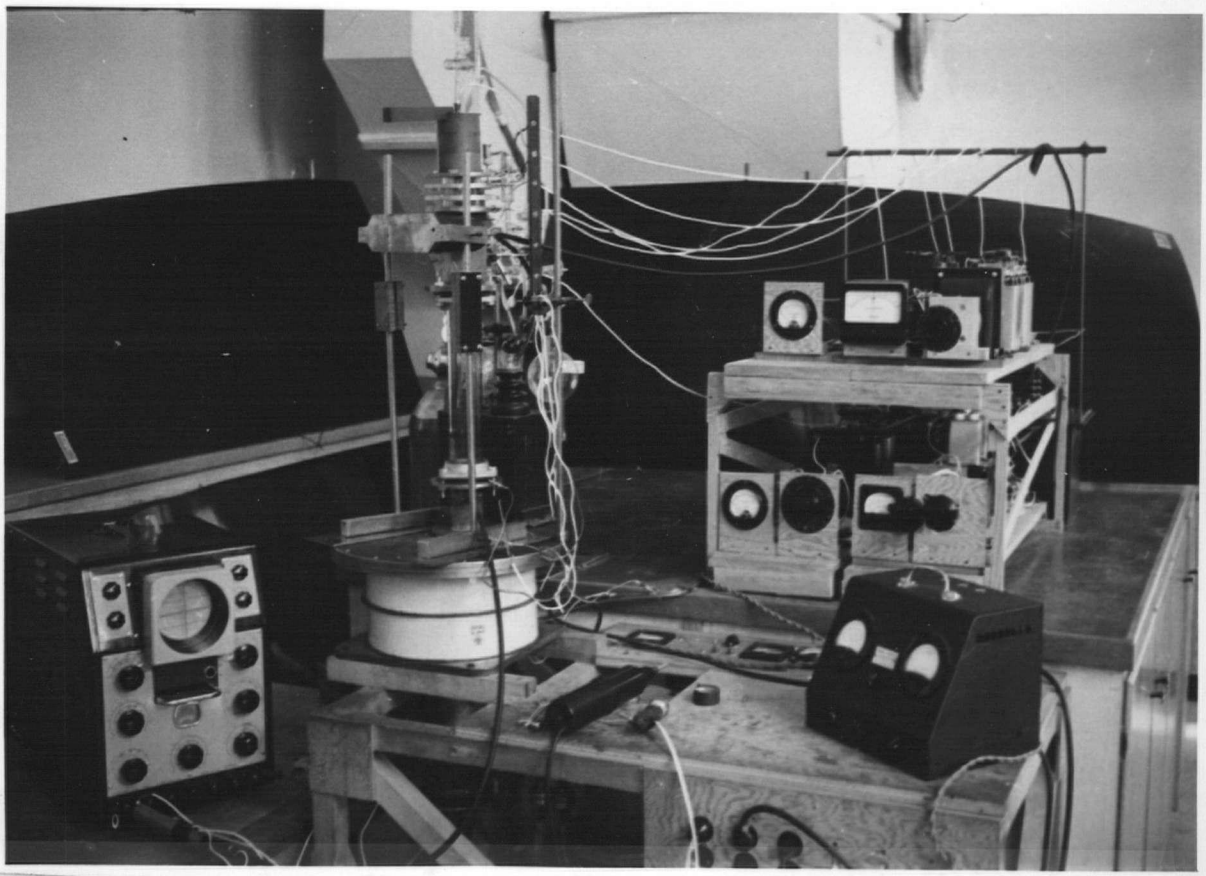


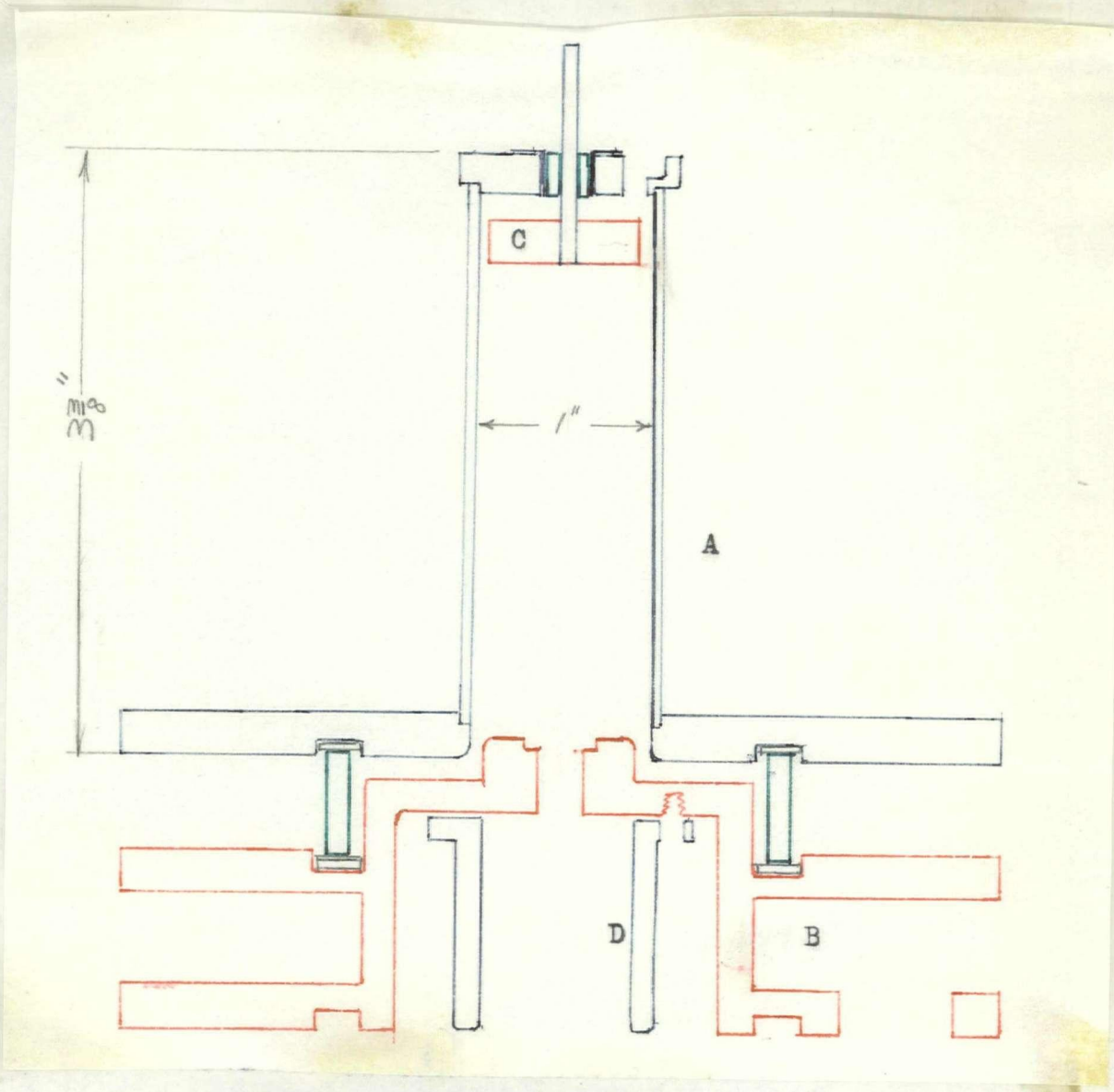
PLATE IV

Mass Spectrometer Leak Detactor

and Apparatus

Figure 2

Side View of Ion Source



A: Ion source section
B: Cathode section
C: Upper cathode
D: Upper electrode of first lens

Key: Blue ink: brass except for Kovar
Red ink: aluminum
Green ink: glass
Pencil: rubber gaskets

SCALE: FULL SIZE

order to ensure the greatest possible field strength which is about 200 gauss at its centre.

The ion source section is separated from the lower cathode section by a glass ring sealed with rubber gaskets set in the cathode and ion source flanges. The cathode section was turned from one piece of aluminum and contains the upper electrode of the first lens. The core of the cathode is removable to enable replacement by cores of various orifice diameters. All orifices are 7/16 inch long. The cathode section is sealed to the analyser by a second glass spacer.

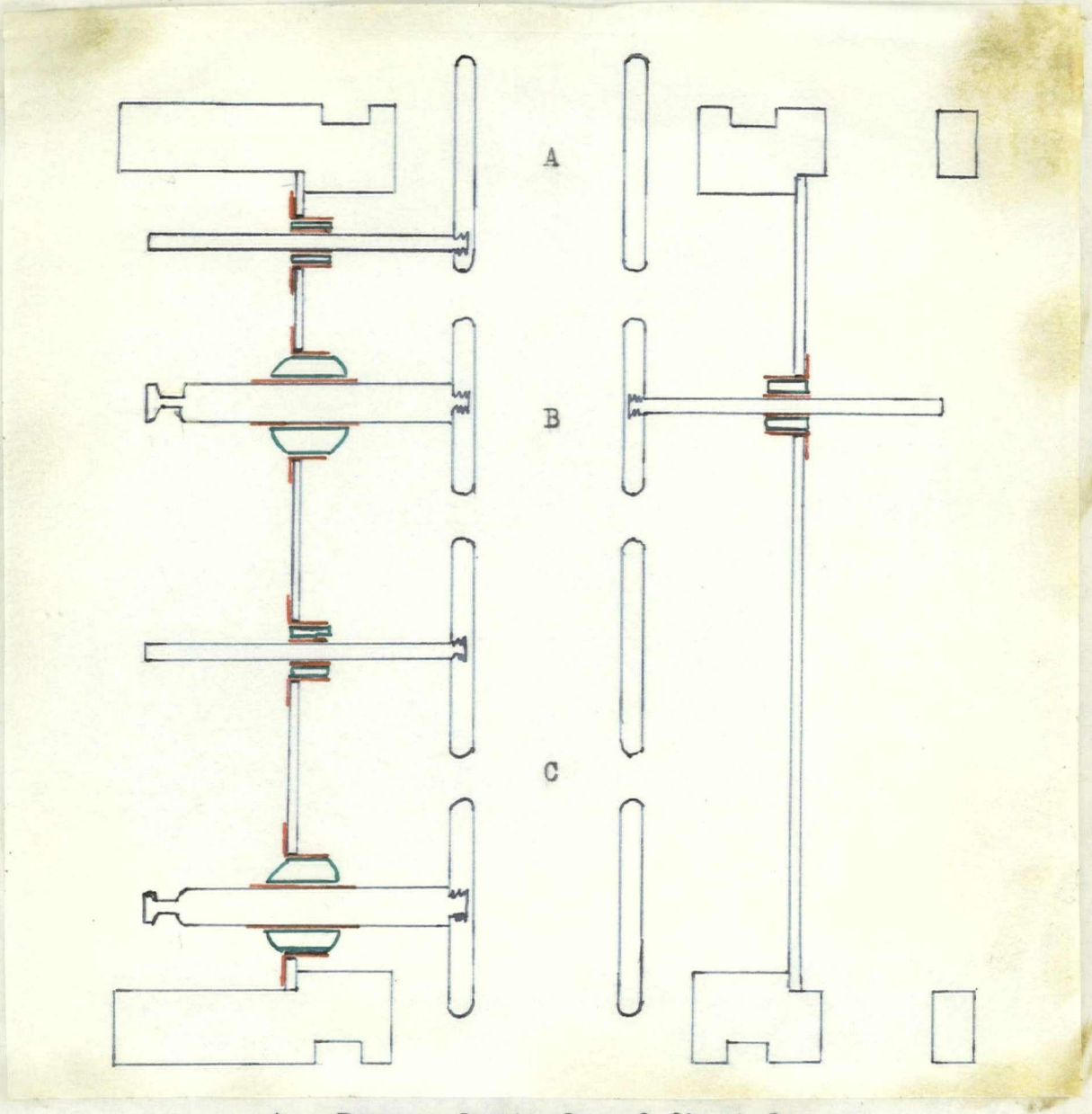
(iii) Analyser and Collector

The analyser electrodes are contained in a length of rectangular wave guide tube which includes the lower electrode of the first lens, the deflection plates, and the second lens, each electrode being held by horizontal rods supported by kovar seals as shown in Figure 3. A 1700 gauss magnet supported by an insulated stand fits about the analyser section at the deflection plates. A Corning glass tube section separates the analyser from the collector.

The upper plate of the collector section is drilled with six $\frac{1}{2}$ inch diameter holes to increase the pumping speed. A slit of variable width fits above the centre hole of the plate below which is fixed a cylindrical screen which encompasses the Faraday cup which is supported by a rod fixed to a

Figure 3

Side View of Analyser Section



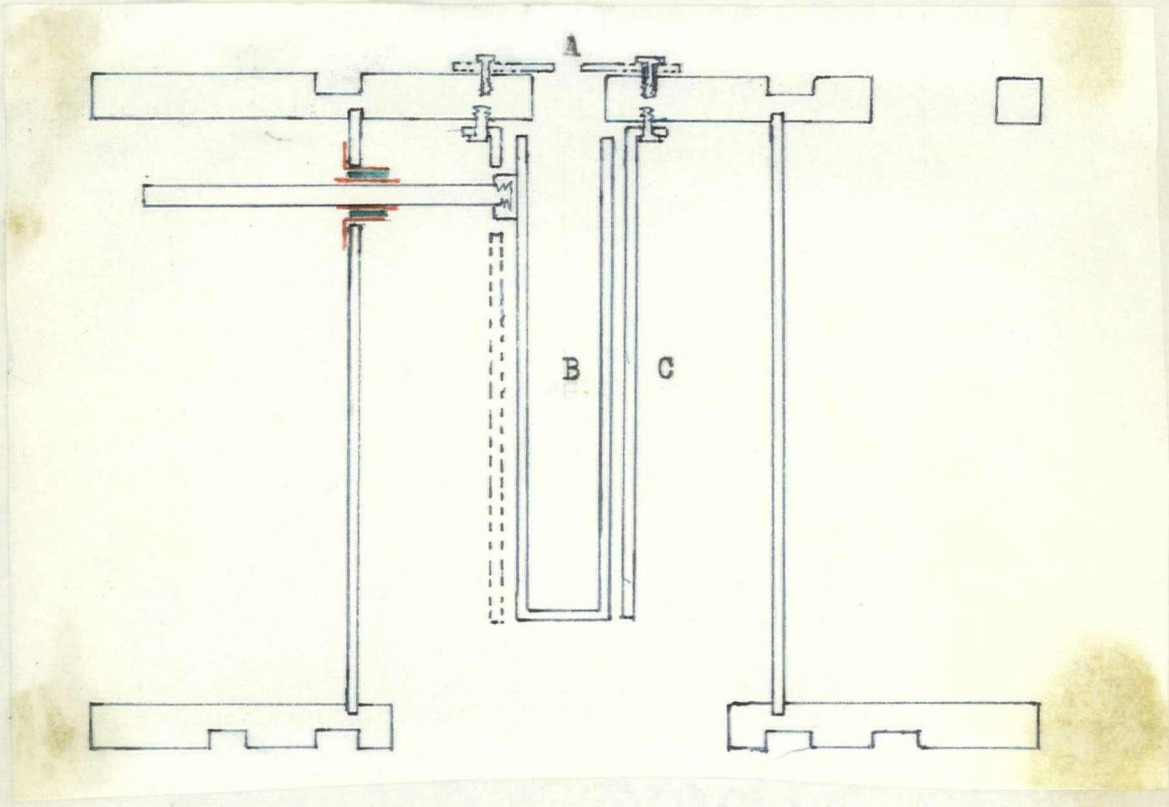
A: Lower electrode of first lens.
B: Deflection plates.
C: Electrodes of second lens.

Material: Brass except for Kovar seals

SCALE: FULL SIZE

Figure 4

Side View of Collector Section



A: Slit
B: Faraday cup
C: Shield

Material: brass except for Kovar seal

SCALE: FULL SIZE

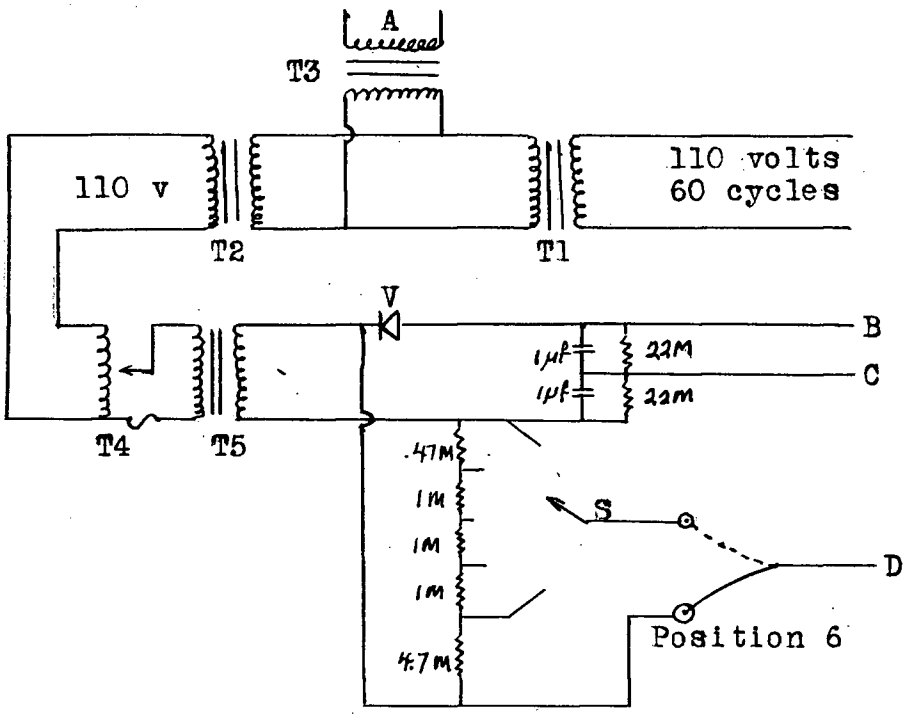
kovar seal set in the side of the collector section as shown in Figure 4 The base of the section is sealed to the vacuum system by a rubber gasket.

The collector can be connected to either a galvanometer or an oscilloscope depending on whether or not the deflection plate voltage has an a. c. component.

The deflection plate a. c. voltage pattern can be applied to the sweep of the oscilloscope through a 12,500 v. d. c. 0.25 microfarad condenser and potential divider.

(iv) Power Supplies

The voltages of the deflection plates are provided by a 7000 volt selenium rectifier which has a potential divider set across the secondary at the transformer. Filtering is done by two 1 microfarad 4000 v. d. c. condensers in series bled by a total of 44 megohms which draw a maximum of 0.16 milliamps which produce a ripple of 0.03%. The common terminal of the condensers is set at the potential of the analyser. One of the deflection plates is wired to the positive output of the rectifier and the other to the output of the potential divider to enable application of various a. c. voltages in the negative d. c. voltage of the rectifier. A five step rheostat capable of operating across a maximum of 3500 volts provides the lower a. c. voltages. To switch from the highest rheostat voltage to position 6 at the other end of the over-all potential divider necessitates manual



A: To ion source power supply.
B: To positive deflection plate.
C: To upper electrode of second lens, lower electrode of first lens, and analyser casing.
D: To negative deflection plate.

T1 = T2 = T3 = Maloney Filament Transformer; secondary, 11 v, 15 a, insulated for 25,000 volts.

T4 = Superior Electric Powerstat Type 20.

T5 = Hammond Type 26182, 87 VA, 2500 v, c.t.

S = selector switch

V = Selenium rectifier.

Figure 5

Circuit Diagram of Deflection Plate Power Supply and Isolating Transformers

unplugging and replugging of the line easily and rapidly done with the special insulated hook provided. See Plate VI. When the output of the potential divider is at position 6, the voltage between the plates oscillates between zero and twice the rectified voltage. Thus, a maximum voltage difference of 14,000 volts is available.

An identical 7000 volt rectifier without a potential divider supplies the second lens and a 7000 volt voltage doubler is applied to the first lens. The ion source supply delivers 0/3600 volts at 20 milliamps.

All transformer primaries are supplied by variacs which are themselves fed by isolating transformers when necessary. As isolating transformers insulated for 25,000 volts and giving a 15 volt secondary voltage were available, three such transformers were used to provide two isolated voltages of 110 volts by wiring the secondaries in parallel and applying the mains voltage to one of the primaries. One of the isolated voltages feeds the first lens and deflection plate power supplies and the other feeds the ion source supply.

The anode of the ion source may reach a maximum of 15,000 volts above the collector if a discharge does not occur through the gas in the tube connecting the ion source to the leak. This discharge is prevented by insulating the stand of the gas feed apparatus with a bakelite sheet.

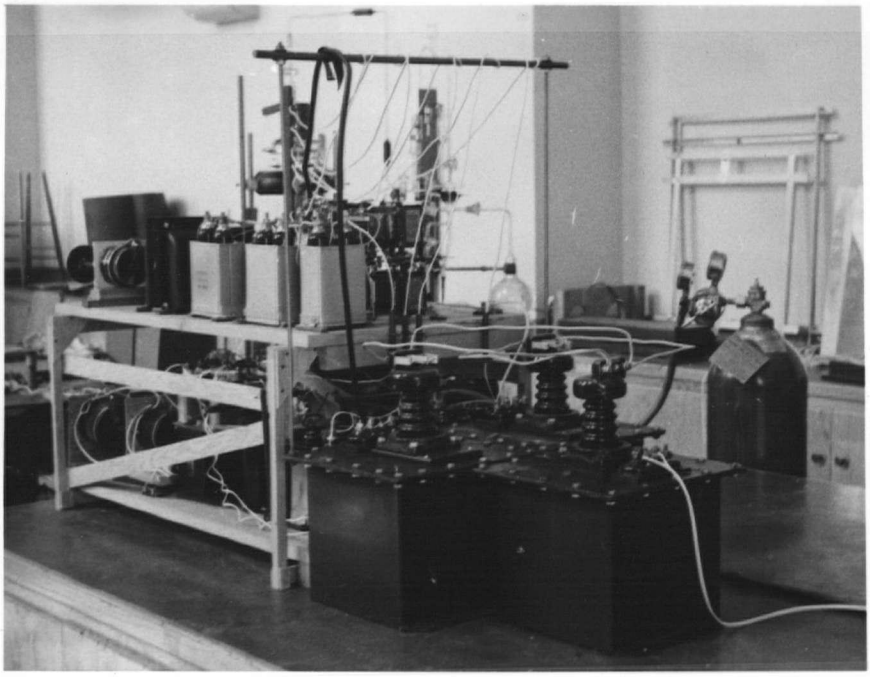


PLATE V

Isolating Transformers

and Power Supplies

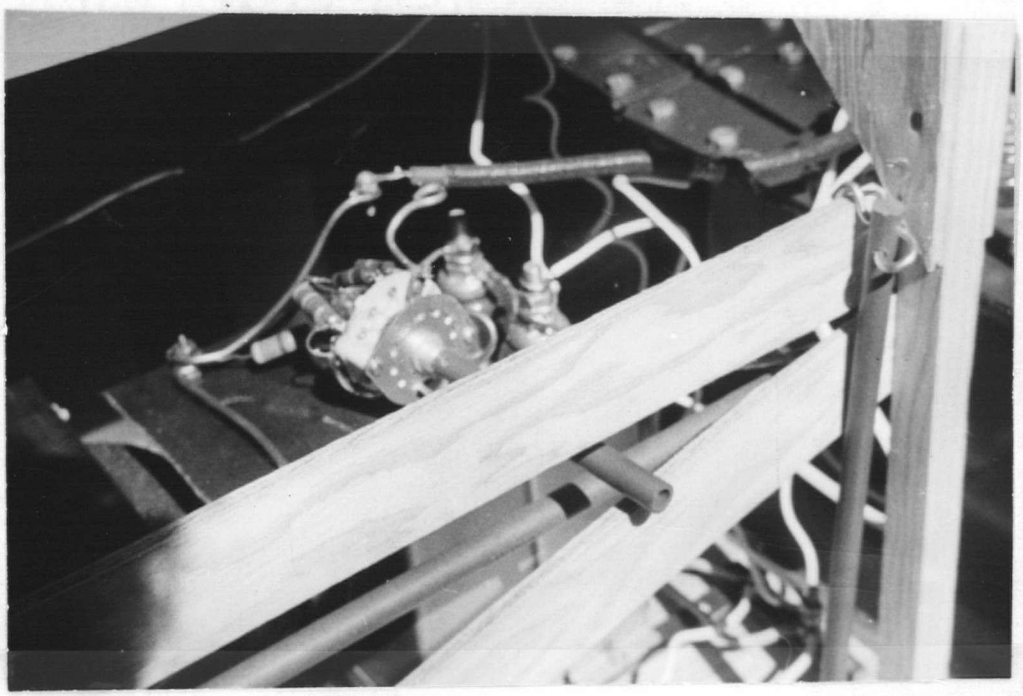


PLATE VI

The Deflection Plate Supply

(v) Gas Feed

The gas feed apparatus was designed to test the spectrometer and includes two 500 ml storage flasks, an open mercury manometer, a silica gel drier, a Pirani gauge, and a leak consisting of a flattened copper tube in series with a needle valve. Stopcocks are arranged so that the leak rate can be determined by allowing the gas to flow into a known volume and observing the rate of increase of pressure with the Pirani though such data is not necessary to determine the ability of the mass spectrometer to detect various percentages of helium in air. A separate mechanical pump permits changes in gas composition without interfering with the action of the diffusion pumps of the spectrometer vacuum system.

This gas supply in active operation will be the gas immediately above the valve above the Kinney Pump--closed to give a high enough pressure for the ion source to operate.

(b) Theory

(i) Straight through analysis

If ions of velocity, $\vec{v}$, and charge, Q, having been accelerated through a voltage, V, enter a coterminous, crossed electric and magnetic field, they are acted upon by parallel forces F_e and F_m of the electric and magnetic fields respectively. If these forces are equal and opposite the ions will pass straight through without deflection.

$$F_e = cEQ/300 = 10^8 EQ$$

where F is in dynes
E in volts/cm
& Q in emu. Also

$$F_m = HQv$$

where H is in gauss and v in cms/sec. If

$$F_e = F_m$$

$$\underline{E = 10^{-8} H v} \qquad (1)$$

The energy of the ions in joules is 10VQ as Q is in emu; the energy in ergs is $10^8 VQ$.

$10^8 VQ = \frac{1}{2} Mv^2$, M in grams.

Therefore, $v = (2VQ10^8/M)^{\frac{1}{2}}$ (2)

Let the charge, Q, expressed in electronic units be q.

Then,

$q = Q/e$ where e is the charge of an electron in emu.

and $Q = 1.6\ 10^{-20}\ q$.

Also, $M = m/6.023\ 10^{-23}$

where m is the molecular wt.

Substituting for Q and M in (2)

$$v = (2Vq\ 10^8\ 1.6\ \ 10^{-20} 6.023\ 10^{23}/m)^{\frac{1}{2}}$$

$$v = 1.39\ 10^6\ V^{\frac{1}{2}}\ \ (q/m)^{\frac{1}{2}} \qquad (3)$$

Substituting (3) into (1)

$$\underline{E = 1.39\ 10^{-2}\ V^{\frac{1}{2}}\ \ (q/m)^{\frac{1}{2}}\ \ H} \qquad (4)$$

For V = 7000 volts and H = 1700 gauss, the voltage across the deflection plates,

$$Vd = E/2.54$$

where 2.54 cms is the plate separation. Finally

$$Vd = 5000\ (q/m)^{\frac{1}{2}} \qquad (5)$$

(ii) Dispersion

If f_e does not equal F_m, the beam moves off the axis and the velocity, v, acquires a horizontal component, V_y, the vertical component being V_x. Therefore the magnetic field exerts a vertical force, F_{mx} in addition to the horizontal component F_{my}. Let the resultant force, F, exerted by the crossed field be resolved into F_x and F_y and the origin taken on the axis at the upper boundary of the field, the downward direction of x being considered positive.

$$F_y = F_{my} - F_e = HQv_x - 10^8EQ = \frac{M\ dv}{dt}_y \qquad (6)$$

$$F_x = F_{mx} = HQv_y = -M\ \frac{dv}{dt}_x \qquad (7)$$

Differentiating (6) and substituting for dv_x/dt in (7),

$$HQv_y = -M\ (M/HQ\ d^2v_y/dt^2\ )$$

Integrating,

$$v_y = a \cos\ (HQ/M\ t + \phi)$$

Let $t = 0$ at the origin where $v_y = 0$.

Then, $\phi = \pi/2$

and $$v_y = (a \sin) HQt/M \qquad (8)$$

Differentiating and substituting for dv/dt in (6),

$$v_x = 10^8 \, E/H + a \cos HQt/M \qquad (9)$$

As $v_x = v$ at $t = 0$,

$$a = v - 10^8 \, E/H \qquad (10)$$

Equations (8) and (9) show that the motion consists of a downward translation of constant velocity in combination with a circular rotation of radius

$$r = a/w = aM/QH$$

Integrating (8), the horizontal deflection,

$$y = aM/HQ \, (1 - \cos HQt/M)$$

as $y = 0$ when $t = 0$.

If T is the passage time through the field, then the total deflection, s, at the lower boundary of the field is

$$s = aM/HQ \, (1 - \cos HQT/M) \qquad (11)$$

The relative motion of ions when only slightly deflected from the axial path will determine the dispersion of the instrument. For these ions, it is obvious that only a very small portion of the circular motion will have been executed before the ions pass out of the field, i.e., HQT/M is small, and approximations can be made.

Using (11) and the relation $\cos x = 1 - x^2/2! + \ldots$

$$s = aM/HQ\ (HQT/2M)^2 \text{ approximately}$$

As $a = v - 10^8 E/H$ from (10)

$$s = \tfrac{1}{2}\ HQvT^2/M - \tfrac{1}{2}\ 10^8 EQT^2/M$$

Also $v_x = v$ approximately from equations (9) and (10). Therefore, $T = L/v$ where L is the length of the field which is assumed equal to the length of the deflection plates. Thus,

$$s = \tfrac{1}{2}\ HQL^2/Mv - \tfrac{1}{2}\ 10^8 EQL^2/Mv^2 \qquad (12)$$

This approximation can also be derived by assuming initially that $F = F_y$ and $v = v_x$ and making use of the equations $F = ma$ and $s = \tfrac{1}{2}\ at^2$, setting

$$F_e = Ma_e = 10^8 EQ$$

$$F_m = Ma_m = HQv$$

Whereupon,

$$s = \tfrac{1}{2}\ a_m t^2 - \tfrac{1}{2}\ a_e t^2 = \tfrac{1}{2}\ HQL^2/Mv - \tfrac{1}{2}\ 10^8 EQL^2/Mv^2$$

Substituting from (2) $v = (2VQ10^8/M)^{\frac{1}{2}}$

$$s = \tfrac{1}{2}\ HL^2\ (Q/M)^{\frac{1}{2}}/\ (2V10^8)^{\frac{1}{2}} - \tfrac{1}{2}\ EL^2/2V \qquad (13)$$

As $s = (\text{constant})\ L^2 x = C\ L^2$

$$ds/dL = 2\ C\ L = 2s/L$$

Therefore, if D (cms) is the separation from the centre of the plates to the collector, the deflection S, at the collector is

$$S = (2D/L)s$$

The difference in the deflections, s_a and s_b of two ions having ratios Q_a/M_a and Q_b/M_b is

$$\Delta s = \tfrac{1}{2} HL^2((Q_a/M_a)^{\frac{1}{2}} - Q_b/M_b)^{\frac{1}{2}})/(2V10^8)^{\frac{1}{2}} \quad (13a)$$

Converting to q/m and taking H = 1700 gauss L = 2.54 cms, and V = 7000 volts,

$$\Delta s = 0.456\ ((q_a/m_a)^{\frac{1}{2}} - q_b/m_b)^{\frac{1}{2}}) \quad (14)$$

For a D of 30 cms,

$$\Delta S = 10.8\ ((q_a/m_a)^{\frac{1}{2}} - (q_b/m_b)^{\frac{1}{2}}) \quad (15)$$

As an example, the dispersion between He^+ and its nearest likely neighbor, C^{++} is

$$S = 10.8\ \ ((1/4)^{\frac{1}{2}} - (2/12)^{\frac{1}{2}}) = 10.8 \begin{matrix}(0.500 - \\ (0.408)\end{matrix}$$

$$= 0.99 \text{ cm}$$

$$= 9.9 \text{ mms}$$

As the beam diameter is much less than this, judging by the results, such a dispersion is quite satisfactory.

(c) Operation

As a guide to future operators of the spectrometer as it is now set up for testing on the vacuum table of Room 122, the following operating data are given with pertinent descriptions of the apparatus and its perdormance.

(1) The spectrometer should be evacuated down to about 0.1 micron with the ground glass joint connecting the spect-

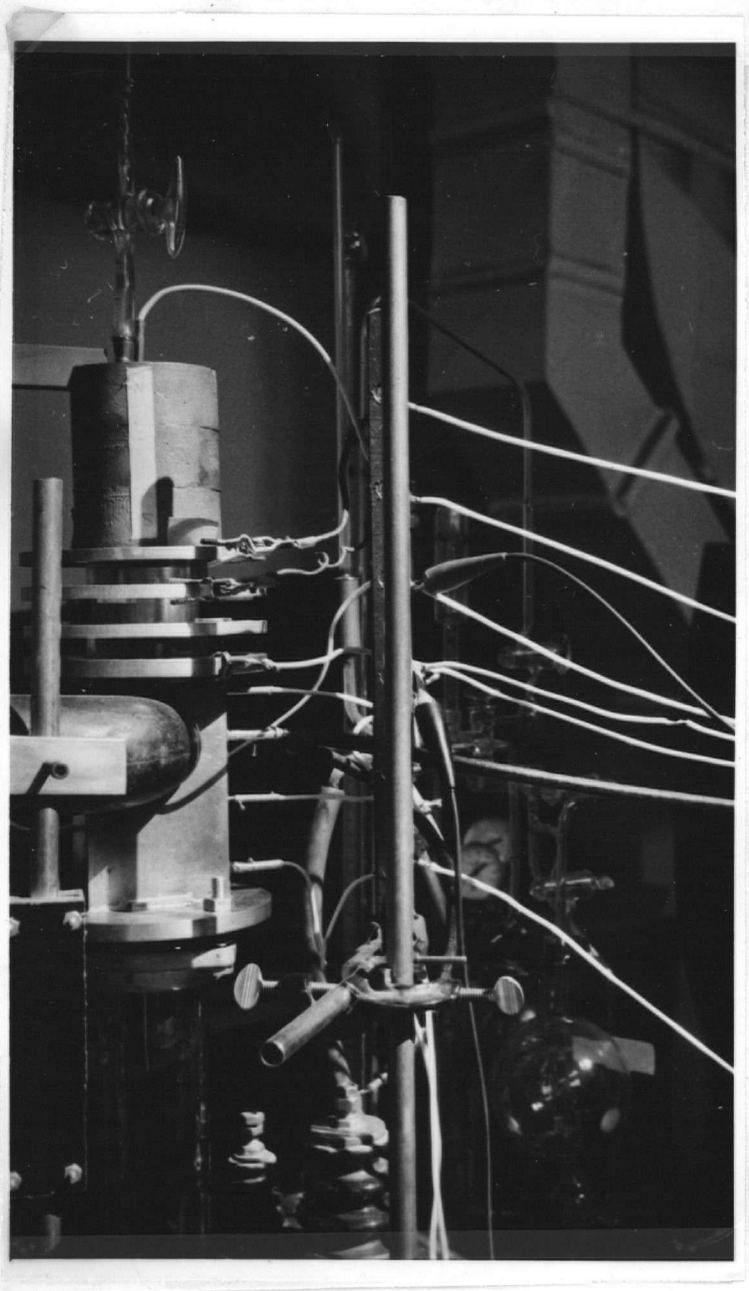


PLATE VII

Wired ion Source and Analyser

rometer to the gas feed apparatus in place and the ion source stopcock located between the spectrometer and the ground glass joint open. The "end" stopcock which connects the Pirani gauge section of the gas feed apparatus to either the tube leading to the spectrometer or the hose to the gas feed apparatus pump may be closed as the "feed" system beyond it can be evacuated by the feed pump. Should the spectrometer be evacuated with the ion source stopcock closed, it should be opened very gradually so as not to flood the vacuum system.

(2) Gas is fed into the ion source by opening the leak needle valve about a quarter of a revolution for a few seconds before closing three sixteenths of a turn or so. An easily visible discharge between the leak and the ion source should occur upon application of a Tesla to the feed stand if the ion source is wired. A pressure of 20 cms on the high side of the leak is easy to work with using the 1/16 inch diameter orifice of the cathode though pressures up to one atmosphere have been used. When setting the stopcocks care should be taken not to turn the "central" feed stopcock, which connects the Pirani section to either the high or low pressure sides of the leak, to the high pressure sections while the end stopcock is opened to the spectrometer.

(3) The ion source power supply is turned up until a current flows. Flash-overs sometimes occur inside between the cathode section and the ion source section but are sometimes

reduced in frequency on decreasing the pressure by closing the needle valve a little. The flashes may cease altogether after prolonged operation. Also, a permanent breakdown sometimes occurs between the upper cathode and the top of the anode, the kovar becoming sufficiently contaminated to have a measurable resistance whereupon it is necessary to turn off the voltage, remove the upper cathode connection, ground the anode, and apply to the upper cathode a Tesla which usually cleans up the contamination and begins sparking across the outside of the kovar. After reconnection, if the ion source is working properly the current will stop flowing upon disconnection of the lower cathode. Before performing this test a careful check was made to ensure that the lens voltages were off; it was found necessary to form the habit of applying a grounded wire to any metal part of the spectrometer before touching with the hands.

(4) After checking the oscilloscope and turning on the lens voltages the deflection plate supply is slowly turned up with the potential divider set on position 6. The first lens supply is set at 60 meter divisions and the second at 0.1; the voltages corresponding to these scale readings can be obtained from the calibration curves. The oscilloscope sweep generator is synchronized at a multiple of 60 cycles and the shielded collector lead connected at an input giving two stages of amplification and bled externally through a 2

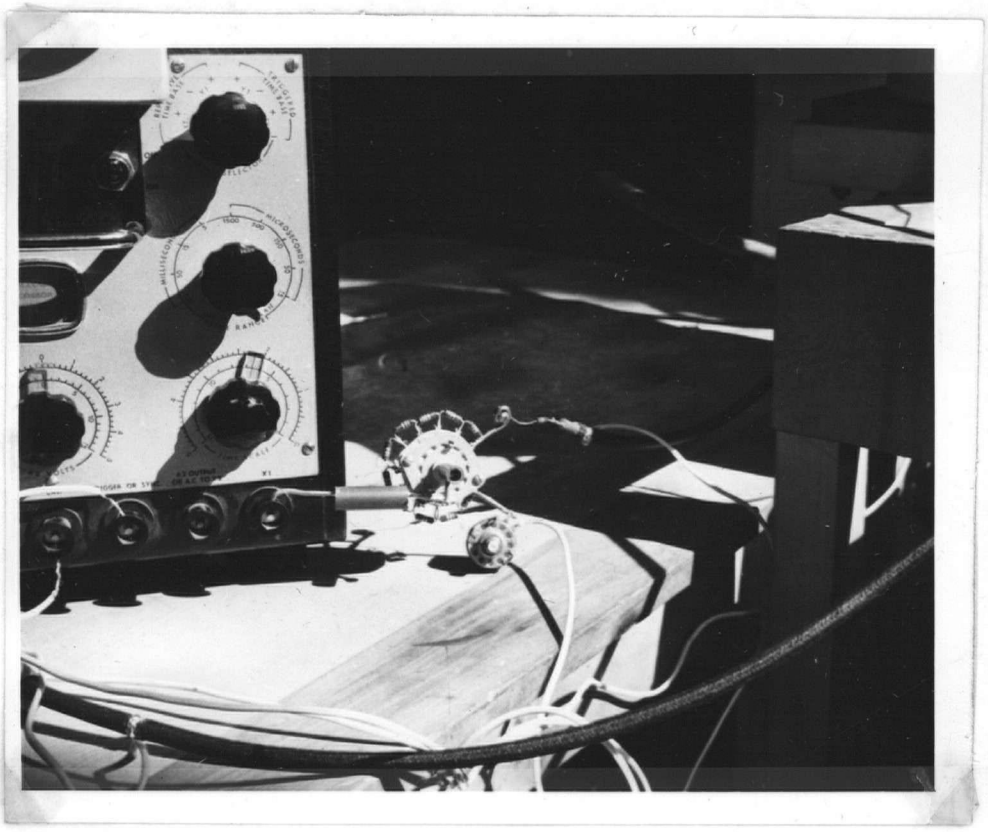


PLATE VIII

Oscilloscope External Sweep

Voltage Supply at Oscilloscope

megohm resistor. If a voltmeter is set between the analyser and the positive deflection plate which is always at a pure d. c. voltage, the air spectra should have appeared on the scope screen by the time the meter reads 1000 volts. If the pattern fails to appear, it is necessary to check that a pick-up voltage appears on the screen when the input is touched with a finger; failure usually means that the collector lead is shorted to a shield. If the scope is functioning it is necessary to check the ion source as described above, making sure that the lens voltages are off and the condensers discharged. Even the gas feed apparatus should not be touched while the lens voltages are on; adjustment to the needle valve should be made with an insulated screw driver. An external sweep voltage of the same pattern and phase as the deflection voltage is available at the oscilloscope. The relative magnitude of the voltage in comparison with the deflection plate a. c. voltage can be varied by the multiple position switch to compensate for changes in the deflection plate a. c. voltage.

(5) Vary the positions on the a. c. potential divider of the deflection plate supply so that small segments of the total mass spectrum can be examined. In this way it is possible to sweep the helium peak along in which case any peak appearing on the screen during leak hunting is known to be helium.

(6) When the a. c. potential divider is switched to give a pure d. c. voltage across the plates, the collector current can be fed through a sensitive galvanometer if absolute readings are desired. It has proven convenient to set the spectrometer on a certain peak by centering the peak on the externally generated sweep before adjusting for a galvanometer reading.

(d) Results

Currents in the ion source and unanalysed beam currents are given in Tables 5 and 6. Oscilloscope traces for Position 6 deflection voltages of various magnitudes using an internally generated scope sweep voltage are shown in Figure 6. As a reference, the a. c. deflection voltage is displayed on the lower trace of the double beam scope. The crests correspond to zero voltage between the plates as the a. c. voltage is then maximum positive and raises the negative plate to the same potential as the positive plate which is at a pure d. c. potential with respect to the analyser. This d. c. potential of the positive plate is measured and equals one half of the average voltage difference, Vd', between the plates.

In diagram (a) of Figure 6 three peaks appear per cycle indicating that the spectrum displayed consists of one and one half peaks, that is, during the rise in plate voltage from zero to its maximum value during the first half of a

TABLE 5

Performance of the Ion Source

Orifice: diameter d = 0.25
length = 0.312 inches

Gas: air

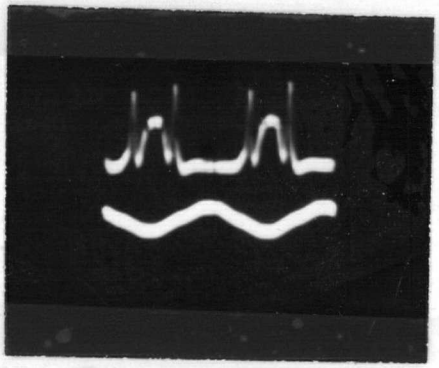
Anode Voltage	Anode Current (m.a)	Upper Cathode Current (m.a)	Lower Cathode Current (m.a)	Total beam Current (microamps)
1110	2	0.81	1.15	.5
1250	2.7	1.10	1.50	20
1550	3.8	1.6	2.1	26
1770	5.6	2.35	2.85	33
2120	8.1	3.3	4.1	44

TABLE 6

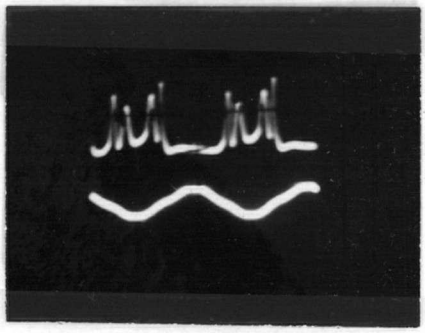
Unanalysed Beam Currents

d = 0.25
l = 0.312 inch
Gas: air
Anode voltage: 3100
Anode Current: 4.5 m.a.
First Lens Voltage: 0
Width of Collector Slit: 0.25 inch

Second Lens (Volts)	Total Beam Current at Collector (microamps)	Beam Current into Faraday Cup
2030	100	3
4000	200	5.1
5250	250	6.7



(a)



(b)

Figure 6

Photographs of Oscilloscope Displays

of Air Peaks on a Time Base

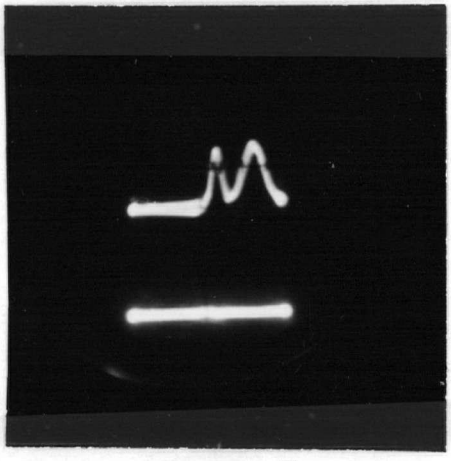


Figure 7

Photograph of an Oscilloscope Display

of Air Peaks on a Voltage Base

cycle one beam passes over the collector slit and a second beam reaches the slit at the deflection plate voltage, 2Vd. During the second half of a cycle the spectrum is swept in reverse order and a "reflected" spectrum appears on the screen thus resulting in the display of three peaks per cycle. An increase in Vd completes the sweep of the third beam and resolves the central peak into two peaks as shown in diagram (b) of Figure 8.

After furthe increase in Vd' the He^+ peak appears if Helium is present in the gas mixture and the air peaks are displaced towards the centre as would be expected. However, they are also diminished in height. Also the second lens voltage, having been adjusted when the air spectrum first appeared to give maximum peak height and definition, can now be readjusted to increase the height of the helium peak. The effect is displayed in parts (a) and (b) of Figure 8. In part (a) the Helium peak is dominant. When the second lens voltage is decreased, the air peak and the helium peak assume equal predominance and the height of the "reflected" helium peak becomes greater than the helium peak of the first half of the sweep cycles. The operating voltages for the displays of Figure 8 are given in Table 7.

When the external 60 c/s Ac sweep voltage supply is applied to the horizontal plates of the oscilloscope a single doubly traced spectrum appears, the second trace being that of the reflected spectrum. Figure 7 displays in this new

way the identical air spectrum shown in Figure 6 (b). Because the same sweep voltage pattern is used for both the spectrometer and the oscillioscope, the x-axis of the scope trace is linear in Vd rather than time as is the case for the internal sweep or "time base." Therefore, from equation 5 the x-axis should be linear in $(q/m)^{\frac{1}{2}}$ when the "voltage base" is used.

The phase of the voltage sweep is such that Vd is a minimum at the left end of a displayed pattern and a maximum at the right end.

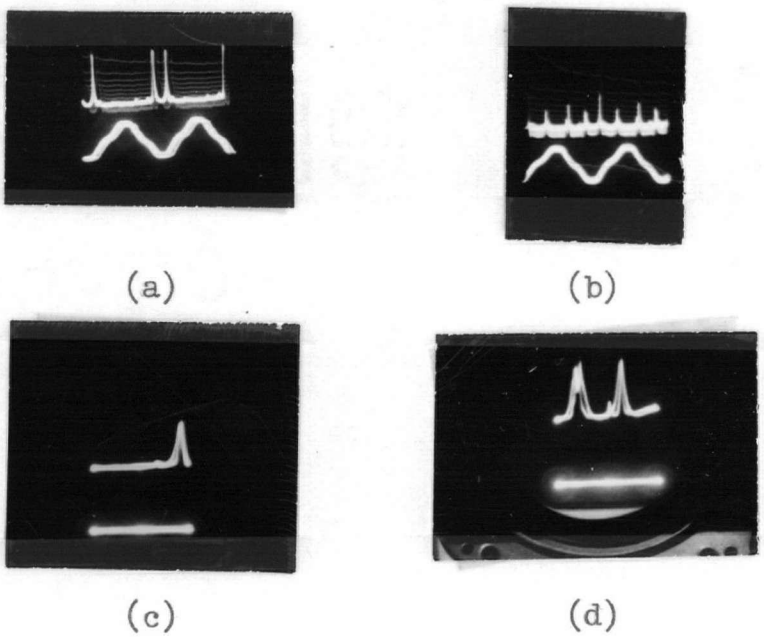


Figure 8

Photographs of Oscilloscope Displays

Figure 8 (c) displays the spectrum of Figure 8 (a) on a voltage base; the helium peak is definitely predominant.

TABLE 7

Mass Spectrometer Operating Conditions for the Spectra Displayed in Figure 8

Ion Source Voltage: 1825
Anode Current (m.a.): 1.5

Gas: Mixture of air and helium

Orifice: d = 0.062 inch
L = 0.312 inch

Spectrometer Sweep: Position 6

	Figure 8			
	(a)	(b)	(c)	(d)
First lens voltage	6800	6800	6800	4650
Second lens voltage	2400	5400	2400	3400
Vd'	4400	4400	4400	4565
Oscilloscope sweep	time base	time base	voltage base	voltage base

However, a change of the lens voltage improves the helium peak and brings up the air peak as shown in Figure 7 (d). The helium peak is shifted to the left in comparison with its position in Figure 8 (c) because the first lens voltage has been decreased, as given in Table 7, whereupon the helium beam, having less energy, is collected at a lower deflection voltage (from equation (4).) By measuring the length, S, of a pattern and the distance, s, of a certain peak from the

TABLE 8

A comparison of measured and calculated values of Vd for the collection of N_2 + and He^+

Pattern	Ion	Vdc (Calculated)	Vdm (Measured)	Vdc/Vdm
Figure 7(d)	N_2^+	9?08	2125 ±50	.426 ± 0.01
Figure 7(d)	H^+	2400	5750 ±100	.417 ± 0.01

origin (the left end of the trace), the Vd required to collect this beam can be determined if the maximum Vd per cycle is known. This voltage equals 2 Vd' as mentioned earlier. (Vd' is the average value of the deflection plate voltage and Vd is the instantaneous value). Thus, Vd = 2 Vd' (s/S). In Table 8, the massed air peak of Figure S(d) is taken as N_2^+ and the measured values of Vd for N_2^+ and He^+ are compared with values calculated from equation (4) using the data of Table 7.

Using only the amplification provided by the two stage amplifier of the oscilloscope, about 1 part of He in 50 parts of air can be detected.

(e) Interpretation of Results

Results show a considerable discrepancy between the predictions of theory and the operation of the spectrometer. The discrepancy is no doubt due chiefly to the fact that the electric and magnetic fields are neither coterminous nor confined in vertical dimension to the length of the deflection plates. The pole separation of the magnet is one and a half inches and the diameter of the pole face is one inch; thus, the flux leakage is of the same order of magnitude as the confined flux. As the deflection plates are one inch square and separated by one inch, the end effect is very considerable.

A possible explanation of the variation of the heights of the air peaks with Vd and the second lens voltage is that the unsymmetric potential gradient between the positive deflection plate and the lower electrode of the first lens effects the focus of the beams and that the effect on a certain beam is influenced by how far the beam is deflected from the axis towards the positive plate by the stray magnetic field. Thus, the lens voltage for best focus of a beam depends on Vd and on q/m.

That the deflection plate voltages are not always balanced around the analyser voltage which is also the voltage of the lower electrode of the first lens and the

and the upper electrode of the second lens does not have a significant effect on the focus as the air peaks continue to diminish as they move through the centre of the voltage sweep at which position the deflection plate voltages are balanced.

As seen in Figures 7(a) and 8(b) the spectrum of the second half of a sweep cycle is not an exact reflection of that of the first half. This distortion may be partly due to the amplifier as it is more pronounced on different scopes and the pre-amplifier increases it tremendously. However, part of the trouble must be in the spectrometer as the second lens voltage has an effect on the exactness of the reflection in height correspondence. Imperfect reflection due to distortion in the deflection voltage of the spectrometer was thought to have been eliminated by tapping this voltage with negligible phase shift onto the scope x-plates in preference to the use of a separate supply of sine voltage for the scope. However, if the distortion is not symmetrical a given voltage difference between the plates corresponding to the collection of a certain beam may be accomplished by different individual plate voltages at the two points of collection in a cycle thus effecting the focus in different degrees.

(f) Suggestions for improvement

A well shielded high gain amplifier must be built if the spectrometer is to be used as a sensitive leak detector. Shielding the rod supporting the shielded Faraday cup might be necessary to reduce noise voltages when high gains are used. Also, a higher vacuum in the spectrometer would probably reduce noise; the vacuum in the pumping table on which the spectrometer sat was about 10^{-4}mm while that of the spectrometer was no doubt higher. The pressure at which the G.E. Leak detector operates is about $7_0 10^{-6}$mm.

Alteration of the ion source is definitely required for improved performance. Redesign of the upper half of the source to resemble the cathode arrangement of the lower half might permit reliable operation. The upper flanges of the redesigned source would have to be small enough to allow the magnet to pass over. The magnet could be shortened to insulate it from the upper cathode through the centre of which the gas could be introduced.

BIBLIOGRAPHY

1. Elmore, W. C., Sands, M., Electronics Experimental Techniques, McGraw-Hill Book Company, Inc., 1949, p. 397.

2. Wang, T.S., Indust. Engn. Chem. (Analyt. Edit.)(1945) pp. 17,67.

3. Amdur, I., Rev. Sci. Instr., 18, 66 (1947)

4 Allwood, H.I.S., J. Sci. Inst. Phys. Ind. 28, 207-8 (1947)

5. United States Atomis Energy Commission Instructions, Cei - 18293A, p. 17

6. Pupp, W., Phys. Zeits, 33, 530, (1932)

7. Nelson, R. B., Rev. Sci. Instr. 16, 55, (1945)

8. White, W.C., and Hickey, S., Electronics, 21, 100, (1948)

9. Jacobs, R.B. and Zuhr, H.F., J. Applied Phys., 78, 34, (1947)

10. Brubaker, W.M. and Wouk, V. Rev. Sci. Instr.17, 97,(1946)

11. Nelson, H., Rev. Sci. Inst., 16, 273 (1945)

12. Thomas, H. A., Williams, T.W., and Hipple, J.A., Rev. Sci. Inst. 17, 368, (1946)

13. General Electric, Bulletin G.E.C. - 696, p. 6.

14. Dushman, S., Scientific Foundations of Vacuum Technique. p. 43.

APPENDIX I.

Scattering from a Proton Beam

Let a beam of energetic protons enter a volume of hydrogen gas. As the velocities of the protons are much greater than the velocities of the gas molecules, the molecules can be considered stationary. The diameter of proton is negligible in comparison with the diameter, d, of a hydrogen molecule and the approach of the centre of a proton within d/2 of the centre of a molecule can be considered a collision. On the average, a collision will occur when the volume of the cylinder of radius d/2 and length, L, where L is the distance travelled by the proton, equals the volume containing one molecule on the average.

Thus,

$L\pi(d/2)^2 = 1/N$ where N is the number of molecules per cm^3

The mean free path

$$L = 4/N\pi d^2 \qquad (1)$$

Let us consider, at t = 0, a group of N_o tagged protons of velocity, v. Let N denote the number of protons which have not been scattered after a period t.

Appendix I

(cont'd)

The collision frequency is v/L. Then

$$dN = N(vL)\, dt$$

Integrating and setting vt = s,

$$N = N_o\, e^{-s/L}$$

As current, I = Nev,

$$I = I_o\, e^{-s/L} \quad \text{and} \quad \underline{L = s/\ln (I_o/I)} \quad (2)$$

Taking s = 20 feet and requiring $I/I_o = 0.9$.

L = 192 feet = 58.6 meters.

Taking $d = 2.2\ 10^{-8}$ as obtained from electron collision experiments[13]

$N = 4.5\ 10^{11}$ molecules/cm^3 from (1)

The number of molecules per cm^3 in a gas at N.T.P. is $6.023\ 10^{23}/2.24\ 10^{4} = 2.68\ 10^{19}/cm^3$

Therefore, the pressure exerted by 4.5 molecules at T = 0 $p = 760\ (4.5\ 10^{11}/2.68\ 10^{19}) = 1.3\ 1^{-5}$ mm of Hg.

APPENDIX II

Times for Pump Down and Equilibrium Pressures

(i) Formulae

The time in minutes required to pump down a volume V from P1 to P2 at a constant pumping speed of S CFM (cubic feet per minute) if the system is tight and outgassing at a rate much less than S is

$$t = 2.3\ (V/S)\ \log\ P1/P2 = (V/S)\ \ln\ P1/P2 \quad (1)$$

If the pressure range is divided up into increments over which S is constant,

$$t = V((1/S1)\ \ln\ (P1/P2) + \ldots + (1/Sn)\ \ln\ (Pn/pn')) \quad (2)$$

where Sn is the pumping speed between Pn and Pn' and n' = n + 1.

The conductance of a tube for air measured in CFM at the high pressure end of the tube of diameter D inches and length L inches is

$$F = 166\ D^3/\ (L + (4/3)D) \quad (3)$$

if the pressure at one end of the tube is a negligible fraction of that at the other end and if the higher pressure is less than 2.5/D microns.

APPENDIX II

(cont'd)

The equilibrium pressure in a system,

$$P\ (mm) = Q/S \qquad (4)$$

Where Q, the outgassing and/or leak rate, is measured in CFM at 1 mm and S in CFM at P.

The conductance F or a series of tubes of conductances F1, F2, ... Fn, is

$$1/F = 1/F1 = 1/F2 + \ldots + 1/Fn$$

As the conductances are measured at the high pressure ends of the tubes a pump can be considered a tube of conductance S. Thus, the pumping speed S' at the end of a tube of conductance F when acted on by a pump of speed S is

$$1/S' = 1/F + 1/S$$

and

$$S' = FS/(F + S) \qquad (5)$$

(ii) Diffusion Pumps

After the diffusion pumps have been turned on for about one half hour the oil begins to boil with increasing intensity and the speed of the pumps increases in stages to the rated pumping speed causing the pressure to drop in steps. However, in calculating the time to pump down the accelerator tube and ports from 50 to 10^{-2} microns let us assume that the pumps have reached their rated speed and that the conditions of equation (1) hold. As two pumps act in the

APPENDIX II

(cont'd)

tube, the average speed is about 2000 CFM. From equation (3), the average F of the accelerator tube is about 360 CFM taking D = 9 inches and L = 8 feet which is one half of the height of the tube. Thus, from equation (5), S' = 305 CFM, and from equation (1) taking V = 12 cubic feet,

$$t = (12/305) \ln 50/10^{-2} = 0.3 \text{ minutes}$$

Taking the conductance of the ion source orifice as 1/5 CFM and the pressure in the source as 100 microns,

$$Q = (1/5)\ 0.1/1 = 2\ 10^{-2} \text{ CFM (at 1 mm)}$$

and

$$P = Q/S' = 2\ 10^{-2}/180 = 1\ 10^{-4} \text{ mm}$$

where S' is the speed of the differential pumping tube which is one half of 360 CFM and P is the pressure at the ion source when the differential pumping tube acts alone. The pumping speed of the accelerator tube at the ion source is negligible as a second orifice is placed over the top of the accelerator tube to reduce the flow of gas into the tube and thus enable it to maintain a lower pressure. If this orifice also has a conductance of 1/5 CFM, the leak through the second orifice into the accelerator tube is

$$Q = (1/5)\ 10^{-4}/1 = 2\ 10^{-5} \text{ CFM}$$

as the pressure above the orifice in this case is only 10^{-4} mm. Also,

$$P = Q/S' = (20/S)\ 10^{-6} \text{ mm}$$

APPENDIX II

(cont'd)

Thus even if S' dropped to only 2 CFM as the pressure at the top of the tube approached that at the bottom and the conditions of equation (3) were no longer satisfied, a pressure of 1 10^{-5} mm could still be maintained.

The maximum Q against which the diffusion pumps could maintain a pressure of 10^{-6} mm at the base of the tube taking S to be 100 CFM at 10^{-6} mm is

$$Q = PS = 10^{-4} \text{ CFM}$$

This gives a service factor of 5 taking the leak through the second orifice to be 0.2 10^{-4} CFM as calculated above.

(iii) Fore Pump

Rated S (average) (CFM)	Pressure Range (mms)
24	760--200
18	200--0.05
10	0.05--0.01

Substituting the above rated average pumping speeds into equation (2), the pump down time for the differential tube and its ports, of estimated volume 12 cubic feet, from 760 mms to 50 microns (0.05 mm) is

$$T = 2.3\ 12\ ((1/24)\ \log\ 3.8 + (1/18)\ \log\ 4000 + (1/10)\ \log\ 5)$$

$$= 8.3 \text{ minutes}$$

APPENDIX II

(cont'd)

The maximum permissable Q at 10 microns given that S is 10 CFM at 10 microns is

$$Q = PS = 0.1 \text{ CFM}$$

which is five times greater than the ion source leak into the differential tube as calculated above.