NBS TECHNICAL NOTE

298

A Survey of Ionization Vacuum Gages and Their Performance Characteristics

W. G. BROMBACHER

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards

THE NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] provides measurement and technical information services essential to the efficiency and effectiveness of the work of the Nation's scientists and engineers. The Bureau serves also as a focal point in the Federal Government for assuring maximum application of the physical and engineering sciences to the advancement of technology in industry and commerce. To accomplish this mission, the Bureau is organized into three institutes covering broad program areas of research and services:

THE INSTITUTE FOR BASIC STANDARDS . . . provides the central basis within the United States for a complete and consistent system of physical measurements, coordinates that system with the measurement systems of other nations, and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. This Institute comprises a series of divisions, each serving a classical subject matter area:

—Applied Mathematics—Electricity—Metrology—Mechanics—Heat—Atomic Physics—Physical Chemistry—Radiation Physics—Laboratory Astrophysics[2]—Radio Standards Laboratory,[2] which includes Radio Standards Physics and Radio Standards Engineering—Office of Standard Reference Data.

THE INSTITUTE FOR MATERIALS RESEARCH . . . conducts materials research and provides associated materials services including mainly reference materials and data on the properties of materials. Beyond its direct interest to the Nation's scientists and engineers, this Institute yields services which are essential to the advancement of technology in industry and commerce. This Institute is organized primarily by technical fields:

—Analytical Chemistry—Metallurgy—Reactor Radiations—Polymers—Inorganic Materials—Cryogenics[2]—Materials Evaluation Laboratory—Office of Standard Reference Materials.

THE INSTITUTE FOR APPLIED TECHNOLOGY . . . provides technical services to promote the use of available technology and to facilitate technological innovation in industry and government. The principal elements of this Institute are:

—Building Research—Electronic Instrumentation—Textile and Apparel Technology Center—Technical Analysis—Center for Computer Sciences and Technology—Office of Weights and Measures—Office of Engineering Standards Services—Office of Invention and Innovation—Clearinghouse for Federal Scientific and Technical Information.[3]

---

[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D. C., 20234.

[2] Located at Boulder, Colorado, 80302.

[3] Located at 5285 Port Royal Road, Springfield, Virginia, 22151.

NBS TECHNICAL NOTE 298

ISSUED FEBRUARY 3, 1967

A Survey of Ionization Vacuum Gages and Their Performance Characteristics

W. G. Brombacher

Institute for Basic Standards
National Bureau of Standards
Washington, D.C., 20234

ABSTRACT

The design of various types of ionization gages is outlined, with particular attention to the design elements important to performance. The performance and the many factors affecting the performance of the various gages are reviewed. Methods of calibration are discussed in some detail, including the use of volumetric pressure dividers, conductance pressure dividers and constant rate of pressure change methods. About 365 references to the literature are cited.

CONTENTS

CONTENTS (cont'd)

A SURVEY OF IONIZATION VACUUM GAGES AND THEIR PERFORMANCE CHARACTERISTICS

W. G. Brombacher

The design of various types of ionization gages is outlined, with particular attention to the design elements important to performance. The performance and the many factors affecting the performance of the various gages are reviewed. Methods of calibration are discussed in some detail, including the use of volumetric pressure dividers, conductance pressure dividers and constant rate of pressure change methods. About 365 references to the literature are cited.

KEY WORDS: Bayard-Alpert gages, cold cathode vacuum gages, conductance pressure dividers, hot cathode vacuum gages, ionization gages, vacuum gage calibration systems, vacuum gages, volumetric pressure dividers.

1. Introduction

It is of interest to note that experimenters in the field of vacuum technology are more concerned with development and evaluation of the ionization gage than any other vacuum gage. This situation follows largely because of its general use for measuring high and ultra-high vacuum and its shortcomings in performance. New developments can be expected, and one or another of today's experimental ionization gages may come into general use in the near future as evidence of its superior performance is accumulated.

Basic gage designs are decribed schematically, including some which may be classed as in the embryo state of development. The design elements of the gage and extraneous factors which affect performance are discussed in some detail. The electrical circuits external to the gage itself are briefly considered, with emphasis only on the elements involving performance in an unusual way. The performance of the various gages is reviewed in considerable detail.

In treating the various subjects relating to ionization gages it has usually been found expedient to describe the technical developments on a historical basis. Items of historical interest are discussed briefly. Details can be filled in by recourse to the literature to which extensive reference is made.

Methods of calibrating ionization gages, mainly the volume and conductance pressure dividers and constant rate-of-flow methods of determining linearity of gage response, are reviewed. The conductance pressure divider method of securing known pressures is now under intensive development. With it, known lower pressures are obtainable than from volumetric pressure dividers or are measurable with McLeod gages. The lowest pressure point obtainable with the conductance pressure divider still remains to be determined. The relation between a small population of molecules and the pressure certainly requires further investigation as pressures are lowered further and further.

Mass spectrometers essentially depend upon ionization phenomena, but differ from ionization gages in that partial pressures only of individual gases present can be determined. They will not be discussed in this survey.

Throughout the text, the terminology used has generally followed the American Vacuum Society "Glossary of terms used in vacuum technology," [58148][1] to which the reader is referred. Thus, in accordance with usage in the United States, the following classification of degrees of vacuum has been used:

Condition	Pressure
High vacuum	10^{-3} to 10^{-6} torr
Very high vacuum	10^{-6} to 10^{-9} torr
Ultra-high vacuum	10^{-9} torr and below

While the torr is the unit of pressure now commonly used in vacuum technology, the newton per sq m has recently been proposed as an international standard. It has seemed preferable to stay with the torr in this report in view of its wide use in vacuum literature up to the present. For all practical purposes under vacuum conditions a torr equals one millimeter of mercury. One standard atmosphere of pressure, equal to 760 torr, is defined to equal 1,013,250 dynes per sq cm and 101,325 newtons per sq m.

---

[1]Figures in brackets indicate literature references at the end of this paper.

The numbers given the references are, for convenience, the same as those given in the Bibliography, NBS Monograph 35 [6101] to which readers are referred for titles and indexed content. However, references published after 1960 and a few pre-1960 references, are not listed in Monograph 35. See Section 4 for more details on the numbering system used.

2. Ionization Gages

In its present state of development, the ionization gage gives indications dependent primarily on the concentration of the gas molecules present in a vacuum system in the vicinity of the gage. Insofar as the rate of ionization of these molecules varies continuously, preferably linearly, with pressure the gage indications are a function of the pressure. When the gage is calibrated in pressure units the indications are valid only for one gas, for which nitrogen is usually chosen.

For a definition of pressure here applicable see the "Glossary of terms used in vacuum technology" [58148].

The ionization gage is by far the principal gage used in measuring vacuum beyond the high vacuum range. It can provide an indication of the lowest density obtainable with diffusion pumps, in contrast with other types equally convenient to use which are limited on the low pressure end to about 10^{-7} torr. Further, the indication is continuous, with suitable safeguards. There are, however, limitations which will be discussed later. The gage was first described by Buckley [1601].

There are two rather diverse well established designs, the hot cathode, and the cold cathode. The hot cathode design includes the Bayard-Alpert modification. The primary cold cathode design in which a magnetic field is a necessary addition is often called the Philips or the Penning gage; the magnetron and inverted magnetron are design variations. Other designs involve the use of a radioactive material or an ultra-violet light to activate a photomultiplier as the source of electrons instead of the cathode filament.

2.1. Characteristics and Basic Design

All ionization gages have (a) a source of electrons, (b) a means for accelerating the motion of the electrons and (c) an ion collector at negative electrical potential.

The historically basic design of an ionization gage is shown schematically in Figure 1. In the envelope, closed except for a connection to the vacuum system the pressure of which is to be measured, the electrons are supplied by a wire filament or cathode F, the accelerating potential by grid G and the collector of positive ions or anode by plate A. As shown, the filament F is heated electrically. The grid G is maintained at an optimum positive potential, while the anode A is maintained at an optimum negative potential. The positive ion current I^+ is measured by electrical meter M which may be graduated in units of pressure. Electron flow to the grid G, gives rise to the electrical current I^- measured for control purposes by meter m. The electron current I^- is many orders larger than the positive ion current I^+.

Without considering at this point the many design modifications proposed for improving the performance or increasing the range of the ionization gage, it is obvious that a sensitive arrangement is obtained by making the grid G and the anode A cylindrical and by putting the filament at the axis of the cylinders.

Positive ions are generated from molecular impact with the accelerated electrons in quantity directly proportional to the molecular concentration provided the electron mean free path is long compared to gage dimensions, i.e., not more than one ionizing collision for each electron passage. In addition such quantity of positive ions would be directly proportional to the electron emission in the absence of space charge effects, i.e., for temperature limited emission. Thus, the positive ion current to the collector is essentially

$$I^+ = S \ I^- \ n$$

where n is the molecular concentration and I^- is the electron emission current. The probability for electron impact ionization increases with electron kinetic energy to a maximum value and then decreases with greater kinetic energy. Thus, the ion current- grid voltage characteristic of a hot cathode ionization gage is as indicated in Figure 1.1A. The operating point shown by the dotted line in the figure is usually selected to be on the plateau for reasons of stability. The dependence on collector potential is as shown in Figure 1.1B, where it is seen that the ion current is essentially independent of collector bias beyond a given value.

Since the probability of ionization of gases varies, it follows that the indication of an ionization gage depends upon the composition of the gas being ionized, as well as the density.

2.2. Major Gage Types

The geometry of the ionization gage has been modified through the years to improve performance, particularly to measure lower and lower pressures. One of the factors limiting the low pressure range is the appearance of a residual current at the collector. Thus, the collector current is $I^+ = SI^- n + Io$ where Io is the residual current. A second factor has been in the ionization efficiency itself, i.e., to generate sufficient ion current for detection. A third has been in the sensitivity of the ion current detector apparatus.

The basic major developments in gage design for measuring total pressure are outlined in this section. External electrical circuits are considered in a later section.

Of the gages to be discussed, the Bayard-Alpert gage is the most commonly used; for relatively rough measurements only in the high vacuum range, the Penning gage; and for applications in the high vacuum range, the radioactive gage. The two types of magnetron gages developed principally by Redhead, the hot cathode-magnetron gage developed by Lafferty, the photo-multiplier gage developed by Riemersma, et al, all for measuring ultra-high vacuum, are more recent developments. The latter two are without extensive application as yet, with the limits of their utility still to be fully determined. Other gages discussed may be classed as experimental.

Normally, the operating elements of a gage are enclosed in an envelope, either glass or metal, which is connected to the vacuum system by tubing. To minimize the differences in pressure between gage envelope and vacuum system caused by chemical reactions triggered by the gage elements, it is often the practice to dispense with the gage envelope and install the gage elements directly in the vacuum system. The gage without an envelope is called a nude gage.

2.2.1. Bayard-Alpert Gage. For some years after the development of the ionization gage a design, shown schematically in Figure 1, was found to be adequate for most applications. As lower and lower pressures had to be measured, it became more necessary to reduce residual currents. The triode gage was limited by this factor to approximately 10^{-8} torr. Dushman [B491] states that Nottingham suggested that the residual current was due to soft x-rays generated at the positive grid by electron bombardment which excite electron emission at the ion collector. Such current would have the form $i_o = CV^m$ and would be indistinguishable from the ion current. Here V is the grid potential and C and m are constants. The photo current effect was also noted by Richardson and Chalkin in 1926.

Bayard-Alpert [5012], Lander [5013] and Metson [5106] verified this suggested explanation and each proposed a design which greatly reduced the soft x-ray effect. The collector current-grid voltage dependence for a triode for a constant electron emission is shown in Figure 1.1C, as given by Dushman [B491, B621]. Curve a for higher pressures shows evidence of the normal ionization efficiency characteristic; whereas, curve b shows for pressures below 10^{-8} torr the distortion due to the photo current. The basic features of the Bayard-Alpert design predominate in the hot cathode gages now in use.

To reduce the effect of soft x-rays on the ion current both Bayard-Alpert and Lander reduced the physical dimensions of the ion collector, thus reducing the x-ray flux falling on the ion collector. The Bayard-Alpert gage is shown schematically in Figure 2. The hot wire electron source F is at one side of the enclosure; the electrically positive grid G is in the form of a helix enclosing the centrally located positive ion collector C which is simply a fine wire. It is obvious that the wire collector C has a greatly reduced target area for the x-rays from grid G than the plate or metal cylinder previously used. Lander's design had a disk, small in diameter and far from the grid, to achieve the same purpose. Both designs as described lowered measurable pressures from 10^{-8} to 10^{-10} torr.

The x-ray effect, electron emission constant, for the Bayard-Alpert gage is shown in Figure 1.1D (Dushman [B491, B621]). Curve a is the response of the gage when the x-ray effect is insignificant; curve b is the response when the x-ray effect contributes significantly to the ion current; and curve c shows that the x-ray current predominates over the ionization current. Note that curve c is obtained at all pressures below 5×10^{-11} torr; the normal operating value of e_g is shown by the dotted line.

Subsequent design improvements of the Bayard-Alpert gage will be considered below and in Sections 2.6.7. and significantly in 2.6.8.

2.2.2. Modulated Bayard-Alpert Gage. To measure the background currents, such as caused by soft x-rays, in Bayard-Alpert gages, Redhead [6079] added a fourth electrode called a modulator. By this addition Redhead was able to isolate the part of the ion current proportional only to pressure and lower the measurable pressure of the Bayard-Alpert design to 10^{-11} torr. The design is shown schematically in Figure 3. Here F is the hot wire cathode, A is the usual anode ion collector, M is the added ion collector or modulator and G is the grid, a helix, all placed about as shown in the figure.

In operation, when the modulator is at the same potential as the grid, the measured ion current I_1 is for all practical purposes the same as obtained in a Bayard-Alpert gage. When the modulator is at ion collector potential, it collects a constant fraction of the true ion current, independent of the background ion current and the normally measured ion current I_2 is correspondingly reduced.

Let 1-α equal the constant fraction of the true ion current diverted to the modulator, i be the true ion current and i_r be the background ion current. Then

$$I_1 = i + i_r \tag{1}$$

$$I_2 = \alpha i + i_r \tag{2}$$

consequently
$$i = \frac{I_1 - I_2}{1 - \alpha} \tag{3}$$

The value of α can be obtained by measurements at a higher pressure where i_r is insignificant compared to i. By eq (3) the true ion current can be computed.

Redhead also describes a procedure for measuring i_r, which involves making measurements at two pressures as defined by eq (1) and (2). Eliminating α and i from the four equations obtained gives i_r in terms of the measured ion collector currents.

The method depends on the value of i_r remaining constant when the potential of the modulator is changed. Appelt [6240] finds that a change of about 15 percent occurred in his modulated Bayard-Alpert gage, due to a change in radiation falling on the ion collector when the applied potential was changed. He shows how to take this change into account in making measurements.

Hobson [64143] in extensive experiments has investigated the constancy of the residual ion current i_r. A method of measurement was developed. Hobson concluded that i_r is not constant, that Appelt's method of correction gives no improvement in accuracy over Redhead's assumption of a constant value of i_r, and that Redhead's procedure is valid down to about 3×10^{-12} torr. Hobson's procedure for accurately determining i_r is not generally convenient for use in correcting the indications of the modulated gage. In a small aluminosilicate glass system, equipped with a finger which could be cooled by immersion in liquids, the lowest pressure obtained and measured was 3×10^{-15} torr when the cooling liquid was helium.

A modulated gage very similar in design to Redhead's is described by Lee [6326].

2.2.3. Penning (Philips) Gage. This is a cold cathode discharge diode developed by Penning [3705, 3706] in which the small electron emission current is offset by the use of a magnetic field to increase the effective mean free path and hence the number of ionizations per electron. It lacks some of the disadvantage of the hot cathode gage, in which the hot filament cannot withstand high pressures and is a source of undesired chemical interactions. On the other hand it is susceptible to electrical difficulties caused by insulating films formed in the high voltage field and by arc-over.

The first designs were found to have a low pressure limit of 10^{-5} torr and troublesome, erratic performance. A later design [4904] lowered the pressure limit to below 10^{-6} torr, had a more stable performance and had a ten-fold increase in sensitivity, that is output per unit pressure. A similar design was developed by Hayashi et al [4907]. A schematic diagram of the later Penning model is shown in Figure 4. Here the anode A is a tube and the cathode C consists of two circular disks covering the ends of tube A. A magnetic field M, about 370 gauss, is applied parallel to the axis of C, which keeps the electrons travelling in a circular path. About 2000 volts is applied between the cathode C and anode A, with a microammeter in the circuit to measure the ionization current. The ion current varies non-linearly with the pressure in the range 10^{-6} to 10^{-2} torr in the design considered by Conn and Daglish [5311] and linearly in the design proposed by Varičak and Vošicki [5561]. For electrostatic shielding a metallic film is sputtered on the inside wall of the envelope, if of glass.

For the gage to operate or "fire" some free electrons must be present; their acceleration by the high potential will ionize molecules in the gage and produce a flood of secondary electrons. The ionized molecules form the ion current, similarly as in hot cathode gages. Initiating a discharge when insufficient free electrons are available is discussed in Section 2.4.2.

To obtain a wide range of indication of pressure, Grigor'ev [58113] designed a gage which is essentially two gages in one case. Two anodes, a wire ring anode and a tube anode are installed with a common disk cathode placed between the two anodes. The current between the tubular anode and the cathode predominates at low pressures; that between the ring-shaped anode and the cathode at the higher pressures. The total current from the anodes to the cathode is a measure of the pressure in the range 10^{-7} to 10^{-1} torr. Another design using a sectionalizing anode in which the anode area is reduced as the pressure increases permits pressures up to 1 torr to be measured.

Young and Hession [6395] extended the lower pressure limit of the gage by using a hot filament to initiate electron production at pressures even below 10^{-10} torr. Getting the gage to strike or start operating is the primary difficulty in measuring low pressures. Indications down to 10^{-14} torr were secured. At this pressure the ion current was 10^{-14} amperes, which was amplified by an electron multiplier.

2.2.4. Inverted Magnetron Gage. Strictly speaking, the Penning gage, Section 2.2.3, is one of the family of magnetron gages. Two other designs, known as the inverted magnetron and magnetron gages, have been developed which have some advantages over the Penning design.

The earliest form of magnetron gage is described by Beck and Brisbane [5209] and Haefer [5485]. The major difference, inverted magnetron and magnetron, is that the positions of the anode and cathode are interchanged. It is probably easier to shield the central anode which is at high voltage in the inverted magnetron, than the larger diameter anode of the magnetron. The design to be discussed is that of Redhead [5867, 58134, 58136] who developed the gage to measure ultra-high vacuums.

In schematic diagram, Figure 5, A is the anode in the form of a solid rod; C is the cathode collecting the positive ions formed by bombarding electrons; C_1 is an auxiliary cathode which serves as an electrostatic shield; T are two short tubes to allow gas flow between the system and the inner chamber; and g is a galvanometer needed to measure the ionization current. Tubes T are welded to the auxiliary cathode C_1. Electrodes are cylinders with a vertical axis, with end plates. A magnetic field, designated by M, of about 2000 gauss, lengthens the paths of the electrons to increase their probability of striking the gas particles and creating positive ions. The anode is kept at 6000 volts, while the two cathodes C and C_1 are grounded. As shown in the figure only the ion current from C is measured. The range of the gages constructed is from about 10^{-13} to 10^{-3} torr. Some free electrons normally exist which, when accelerated by the electric field, initiate the ionization.

2.2.5. Magnetron Gage. This gage was also developed by Redhead [5867, 58136, 59107]. The anode A, Figure 6, is a cylinder with a number of holes to permit pressure equalization within the gage; the cathode C is in the form of a spool with the end plates mounted on tube T; S are two rings interposed between A and C for electric shielding; g is a galvanometer for measuring the ionization current. The magnetic field, M, about 1000 gauss, is applied in the direction shown in the figure and 6000 volts above ground potential is applied to the anode A. Cathode C and shields S are at ground potential. Cathode C is connected to a metallic film on the inside of the glass case to secure electrostatic shielding.

The established pressure range is from about 10^{-12} to 10^{-4} torr, with no limit on extension both upward and downward indicated, but a change in slope of the calibration curve occurs at 10^{-10} torr. Below 10^{-10} torr the ion current is directly proportional to pressure.

2.2.6. Hot Cathode - Magnetron Gage. Makinson and Treacy [4826] and Conn and Daglish [5409] added a magnetic field to a hot wire cathode ionization gage to increase the path length of the electrons and thus increase the sensitivity. The geometry of their electrodes and the measuring circuits were such that the low pressure limit of measurement was about 10^{-6} torr.

Following the preliminary work of Houston [5674], Lafferty [60160, 6104, 6181, 6311] has developed a hot cathode ionization gage with the addition of a magnetic field for making vacuum measurements down to 10^{-14} torr. In the earlier design [60160, 6104] there was difficulty in measuring the small ion current obtained below about 10^{-13} torr, which had to be kept small to minimize the residual x-ray photocurrent. To improve the sensitivity, the method of measuring the ion current was changed [6181, 6311]. The latter gage will be described.

The gage is shown schematically in Figure 7. The gage is divided into three parts: M, the gage, EL, the electrostatic lens system, and EM, the electron multiplier. The gage has a hot filament F, a disk shield S_1, at about -10 volts, a cylindrical anode A at +300 volts, and a cylindrical alnico magnet for producing magnetic field m of about 250 oersteds parallel to the anode axis. In earlier models of the gage a disk for collecting the ion current covered the open end of the anode similarly as shield S_1.

The electrostatic lens system has an ion accelerator grid G, at -45 volts and an ion focussing cylinder I at 50 volts. The positive ions, accelerated by -3000 volts, bombard the first dynode D, producing secondary electrons. This current is measured after amplification by the 10- stage multiplier. A cylindrical shield S_2 is provided. The gage was installed in a glass envelope.

The design minimizes the residual current produced by the soft x-rays and also enhances the ratio of the ion current to the residual current because of the amplification of the electron current produced in the electron multiplier.

The low pressure limit of the gage was estimated to be about 10^{-17} torr, [6311], with the indication linear with pressure up to about 10^{-4} torr.

A simpler design of the Lafferty gage is described by Hudson, Sears and Donnelly [6402]. An electron multiplier was used similarly as in the Lafferty gages but no magnetic field. Pressures as low as in the Lafferty design cannot be measured, but further experimentation is needed to set the limit.

2.2.7. Electron Beam Gage. A design developed by Klopfer [6178] for measuring ultra-high vacua has the electrode structure of the omegatron mass spectrometer but omits the radio frequency oscillator.

The design is shown schematically in Figure 8. Electrons are produced by a hot wire filament cathode C. These are accelerated by the positive voltages on electrodes G_1, G_2, G_3 and G_4 and pass through slits in these electrodes to electron trap T. The electron beam is focussed by a magnetic field M of 1000 gauss parallel to the beam. All of these electrodes are square plates. G_3, G_4 and H are integral and form a box held at +180 volts. H is a wire mesh in order to promote pressure equaliza- tion, gage and system. The positive ions are collected by square plate J and is shielded by tube Z. Electronic amplifier A amplifies the ion current. The electronic current is measured by meter M_1. The magnetic field is adjusted so that no electrons impinge on G_4, producing secondary electrons and x-rays; absence of the secondary current is indicated by a zero reading of the meter M_2.

The applied voltages are about as indicated in Figure 8. The glass case is 3.4 cm in diameter and 5 cm long.

Nitrogen pressures from 10^{-11} to 10^{-2} torr were measured, with a linear response. Calculations indicated practical extension down to 10^{-14} torr, with freedom from x-ray effects and very low ionic pumping. To prevent chemical pumping the use of a filament cathode with a low operating temperature is suggested. No data were presented for either a mixture of gases or pure gases other than nitrogen, but there is no apparent reason to expect other than the effect of gas composition typical of ionization gages.

2.2.8. Scintillation Detector Gage. This gage, proposed by Barnes [6070], is a cold cathode type (without a magnetic field) with an indicating means which avoids measuring residual currents produced by soft x-rays. Consequently, the lower pressures measurable are limited only by the sensitivity of the indication means which theoretically is about 10^{-15} torr.

The gage is shown schematically in Figure 9. Here A is a 50 mil tungsten wire to which is welded a number of short lengths of 5 mil tungsten wire. A positive voltage of 10 kv is applied, which produces positive ions near the wire points, as found by Mueller in his experiments on the field ion microscope. These ions are accelerated to wire loop B which is at ground potential, but most of them pass through the loop to impinge on the phosphor coat C on the inside of the glass envelope. The scintillations, or light intensity, resulting from the ion impact on the phosphor, is measured by a commercially available scintillation probe.

The scintillation probe must be shielded from extraneous light, a necessity which made impractical an earlier design [6070] using a hot filament to produce electrons. The indications of the experimental gage are pressure dependant down to 10^{-8} torr, the lowest pressure obtained, but sharp changes in sensi- tivity occurred at 10^{-4} and 10^{-6} torr. A major advantage is the probable effects caused by high energy positive ions, easily capable of sputtering, releasing gases and material damage. Pumping by the gage is expected, but no data are available now.

Nottingham [61199] indicates that Barnes has not proved that this gage measures pressure. The conclusion is based on Barnes' use of a Bayard-Alpert ionization gage as a reference without regard for the composition of the gases in the vacuum system.

2.2.9. Photomultiplier Gage. This gage, developed by Riemersma, Fox and Lange [60159, 6103] primarily to avoid, when necessary, chemical reactions between hot filaments and gases which affect the pressure being measured, is shown schematically in Figure 10. Ultra violet light from lamp U passes into the gage through quartz window Q and light shield L and is focussed by mirror M on the first dynode D_1 of a photomultiplier. The electrons produced at the first dynode are successively accelerated by a potential of 200 to 300 volts between each dynode, resulting in the production of a cloud of secondary electrons from each dynode after the first. The gas in the gage is ionized and the positive ions collected by a short wire I, shielded by tube S. The positive ion current ($10^{-8} - 10^{-13}$ amperes) is measured by appropriate means. The electrons are collected by two wire rings E, maintained at a poten- tial of 150 - 200 volts above that of the last dynode. The position and size of the collectors I and E are critical.

While chemical reactions are avoided and ion pumping is practically negligible, background currents of sufficient magnitude exist which prevent making pressure measurements at ultra-high vacuum. However currents produced by soft x-rays, leakage and direct photoemission from the ion collector are of opposite sign to the ion current produced by high energy reflected electrons striking the ion collector. Experiments to equalize these two background currents were successful, accomplished by adjusting the position of zero potential in the potentiometer controlling the dynode voltage as indicated in Figure 10.

Silver magnesium multipliers were found to deteriorate in gain when exposed to the atmosphere, but copper berryllium dynodes, found to give equal performance, are expected to be more stable.

An ion current, linear with pressure, was obtained in the range 10^{-10} to 10^{-5} torr, with no limit reached experimentally at the low pressure end.

2.2.10. Photocurrent Suppressor Gage. Schuemann [6283, 6325] has designed a gage for making measurements below 10^{-10} torr in which background currents are minimized. As shown in Figure 11, a hot wire filament F is roughly parallel to the axis of a cylindrical wire grid G at +200 volts. At the top of the tube there are a cylindrical shield A, a suppressor wire ring S at -300 volts, and a circular disk ion collector C. The shield prevents x-rays from reaching the suppressor ring which in turn repels photoelectrons. Schuemann has made measurements free from background currents down at least to 10^{-12} torr. The electron emission current was one milliampere.

2.2.11. Radioactive Gage. A vacuum gage using radium as a source of ionizing particles was first reported by Downing and Mellen [4608]. This type of gage, known as the alphatron, has the merit of great ruggedness. Alpha particles emitted by the radium are the principal means for ionizing the gas in the gage, with insignificant contributions from the emitted electrons or gamma rays. A review of design and performance developments of this design is given by Vacca [5664]. Designs for various purposes are described in references [5402, 5640, 5911, 59150]. The pressure range achieved is from 10^{-5} to 760 torr, in steps.

Only the radioactive gage developed by Vanderschmidt and Simons [58118, 5901] based on the use of tritium, the radioactive isotope of hydrogen will be described. Blanc and Dagnac [6348, 64247] have constructed a similar gage. Tritium emits only electrons, thus avoids the necessity for health safeguards required in using radium. It has a half life of 12 years. The gage is shown schematically in Figure 12. Here T is a plaque containing tritium, D is its support, A is the collector of the positive ions, in the form of a ring, B is the inner chamber, cylindrical in shape with holes in the upper disk to facilitate pressure equalization, E is an electrometer and C is the outer case. Amplification of the ion current is required. As shown, the inner chamber is at a positive potential of 100 volts with respect to the collector A.

The plaque T contains about 1 cc of tritium chemically bound to a thin film of titanium. Details of the plaque and of the electrical circuits are given by Roehrig and Vanderschmidt [59148].

The low pressure limit is about 10^{-5} torr limited by the effect of x-rays generated at the walls. The upper pressure linearly measurable is extended by using a second inner chamber B of the smallest practical size for pressures above 1 torr, so that the range of the emitted electrons is nearer that of the chamber dimensions. A selector permits seven ranges of pressure to be indicated on the same electrometer (voltmeter), the lowest 10^{-3} torr, the highest 760 torr. The indications above about 10 torr are not linear owing to more and more complete absorption of the emitted electrons by the surrounding gas.

Moreau [62121] uses an RaD and RaE mixture to avoid using radium 226. These all emit both beta and gamma rays in addition to alpha particles which is undesirable. He proposes the use of either Neodymium 144 or Samarium 147, when commercially available, since they emit only alpha rays.

All designs of radioactive gages are reviewed in some detail by Dagnac [64104].

2.2.12. Modified Hot Cathode-Magnetron Gage. Kantorowicz [6401] describes a magnetron gage in which electrons are supplied by a hot filament and have a long path length between two concentric cylindrical electrodes, one the ion collector and the other, the electron collector. A magnetic field parallel to the axis of the cylinders adds to the electron path length before collection. Either the inner or outer cylindrical electrode may be the ion collector. The cathode filament occupies a small sector of the space between the cylindrical electrodes. Advantages claimed are the absence of any effect of radio frequency oscillations, no background current due to soft x-rays and a relatively high sensitivity so that no amplifier of the ion current is needed at pressures above 10^{-9} torr. Lack of a complete evaluation forces classifying the gage as experimental.

2.2.13. Time-of-Current-Rise Gage. In this gage, proposed by Atkinson [6391], a drift space is set up having all surrounding surfaces at a positive potential. If an electron gun (a hot filament cathode) is fired to shoot electrons into the drift space, positive ions are formed and held in the drift space. The secondary electrons formed pass through an aperture to a target at positive potential and, as explained by Atkinson, the target electron current rises with time and finally levels off. The reciprocal of the time for a given rise in target current before equilibrium, say double the initial value, is found to be, within limits, proportional to the pressure of the gas in the gage. An oscilloscope is used to measure the time of rise; for the present design, this time is one microsecond at 10^{-4} torr and about 10 milliseconds at 10^{-8} torr. The utility of the gage remains to be demonstrated; its advantages for some applications and circuit simplicity may be balanced by the present disadvantage of lack of continuity in indication.

2.2.14. Orbitron Gage. Mourad, Pauly and Herb [6418] have developed an ionization gage in which electrons from a hot cathode have long trajectories around a central wire anode at about 500 volts within a cylindrical cage. The cathode filament is placed between the anode and cylinder, near the lower end of the anode. A shield is placed between the filament and anode. The initial directions of motion of a substantial portion of the electrons and of the anode electrical field differ and produce long electron trajectories. The positive ions produced are collected on the cylinder. The chief

advantage is that a short cathode with a small electron output is sufficient. The x-ray effect is small. The output of the gage is linear with pressure up to the low pressure limit of the Bayard-Alpert gage. Full data on the performance of the gage is not available, hence its utility remains to be determined. Of more importance to the authors appears to be its use as a pump, for which purpose the design is modified so that the electrons can evaporate titanium and thus obtain a type of getter-ion pump [64156].

2.3. Specialized Designs

Ionization gages, particularly the hot wire filament types, have been designed for many specific purposes, not always directly associated with pressure measurement. Thus, ease of degassing, prevention of filament burnout, power supply stabilization, vacuum control, ease or convenience of indication, etc. have resulted in a diversity of minor deviations in design. Most of these more or less minor design variations will be discussed more pertinently in Section 2.6. The discussion here will be restricted to tube designs for high pressure measurement, leak detection, vapor pressure, dynamic measurement, and of subminiature size. The main stream of tube development as covered in the preceding section is largely that for measuring lower and lower pressure.

2.3.1. High-Pressure Measuring Gage. Schulz and Phelps [5718] state the conditions which must be met by a hot cathode gage in order to measure pressures exceeding about 10^{-3} torr. The limitations of the Bayard-Alpert gage in this respect are given by Schulz [5729]. These conditions are:

a. The electron paths must be well defined and not changed appreciably with pressure. The tube geometry must be such that the electrons move in straight lines from the filament to the electron collector.

b. The gage sensitivity must be small compared to the reciprocal of the highest pressure to be measured. This is met by making the distance, filament to electron collector small and by applying a low electron accelerating voltage.

c. The ion collector must be designed so that the efficiency of ion collection does not vary with pressure. To meet this requirement the surface of the ion collector should be large compared to that of the filament.

Thus, the early type of ionization gages based on the triode vacuum tube can be used. Schulz and Phelps obtained satisfactory data, except for lack of linearity, on two commercially available designs. These had a central hot cathode filament, a grid and outer metal cylinder concentric with the cathode. The positive accelerating voltage, about 150 volts, was applied to the outer cylinder, while the grid had a negative potential, about 5 volts, with respect to the hot cathode. The grid current was a measure of the pressure.

Two designs were constructed by Schulz and Phelps [5718]. In both, the hot filament cathode was between the collectors of electrons and positive ions. In one case the collectors were flat plates, in the other, two cylinders, with the electron collector having the larger diameter. The ion currents for both designs were linear with pressure in the range 10^{-5} to 10^{-6} to about 1 torr. The linear limit at high pressure differed with gas composition being above 1 torr for helium and below for nitrogen and hydrogen.

Futch [6130] used this design of gage for measuring the pressure of water vapor in the range 10^{-4} to 10^{-1} torr. Hinzpeter [6064] describes a design using flat plate collectors and obtains an ion current linear with pressure in the range 10^{-5} to 10^{-1} torr for air, argon, neon and nitrogen.

2.3.2. Miniature Gages. Miniaturizing of ionization gages has had two purposes. One is to reduce the overall size and weight of the complete instrument for use in high altitude rockets, where these factors are of primary importance. In the other, a small ionization tube is desired in order to measure the pressure in a small volume or cross section, as in a tube.

In the first case, the effort must be primarily directed to reducing the size and weight of the auxiliary apparatus, that is of the power supply, of the amplifier and indicating or telemetering means. Benton [5968] describes a circuit design to this end. The power supply comes from dry cells, since long time operation is not normally needed, and transistors are used where possible. Two complete control units in one chassis weighed 3.2 kg, and occupied 4400 cu cm, with further reduction in size held possible.

Second, a reduction in size of the Bayard-Alpert gage was achieved by Ramey [59149]. The tube elements would all fit into a cylinder 0.8 cm in diameter and 1.5 cm long, compared with a conventional tube roughly 2.5 by 2.5 by 2.5 cm. Since the sensitivity is much less, greater amplification of the positive ion current is required and obtained without difficulty. Following Bayard-Alpert, the hot wire filament is off-center in the tube, the positive ion wire collector is central and is surrounded by a helical accelerator grid. Owing to the background current due to soft x-rays, the lowest pressure measurable is above 10^{-9} torr. Theory useful in design is presented.

Newton, Pelz et al [6390] used a Bayard-Alpert gage 2.5 cm in diameter and a Redhead magnetron gage 3.0 cm in diameter is a satellite to measure ambient pressure. Both were modified from conventional designs and ruggedized. Details of the procedure to obtain pressure from telemetered data taken while the satellite was rotating are given.

2.3.3. Secondary Standard. Meinke and Reich [63238] found that a commercial design of hot cathode gage would not repeat its indications at a given pressure within ± 3 percent, as required for a calibration standard. The data were obtained after various operations, such as before and after opening the system to the atmosphere. A gage was constructed in which the hot cathode, very short, was central, with the grid between the cathode and cylindrical ion collector. Both the ion collector and grid were of platinum. The sensitivity obtained after an established operational procedure varied less than 3 percent. The gage was therefore considered useful as a secondary standard. The lowest pressure measurable is limited by the x-ray effect, which as a guess would be about 10^{-8} torr.

2.3.4. Leak Detection. Diverse methods and instruments are used to detect and locate leaks into vacuum system. Reviews are given in [5114, 5233, B491, B621]. The standard method is to spray a probe gas at a suspected point and detect the rise in the chamber pressure, or other effects.

Ordinarily, leaks are located with a mass spectrometer using helium as the probe gas. At ultra-high vacuums, the sensitivity commences to be inadequate and the use of an ionization gage may be preferable, using high sensitivity gases as carbon tetrachloride, acetone, or ether as the probe gas. Techniques are discussed by Alpert [5874], Huber [6372] and Lafferty-Dushman [B621].

Only discussion of modifications of ionization gages for leak detection are pertinent here. Inward leakage of both oxygen and hydrogen cause a decrease in the electron emission of the hot tungsten filament. Lawton [4009] and Nelson [4506] developed a diode for leak testing based on this fact using oxygen as the probe gas. A good sized tungsten filament was used, operated to secure saturated electron emission current flowing to an anode. Leaks as low as 10^{-5} torr liter per hour were detectable.

H. Nelson [4505] used a sealed off ionization gage with a palladium tube open only to the gage and projecting into the vacuum system. Provision was made for heating the tube to make it permeable to hydrogen which was used as the probe gas. Hydrogen entering the vacuum system passed through the palladium tube and gives a sharp change in indication of the ionization gage.

Hamacher [4617] describes a circuit in which an audio-frequency is controlled by the output of an ion gage. Using a probe, a large volume vacuum system can be tested for leaks with greater convenience which are indicated by a rise in the audio-frequency.

2.3.5. Vapor Pressure Measurement. To measure the vapor pressure of alkali metals (caesium, potassium, sodium and lithium) Lebedev and Stavisskii [62122] use a diode arrangement. These metal atoms in contact with the surface of a metal with a work function which exceeds their ionization potential leave the metal surface ionized. The ion current is a function of the pressure of the alkali metal. Measurements were made in the range 10^{-5} to 10^{-2} torr, using a tungsten filament surrounded by a cylindrical cathode.

2.3.6. Dynamic Measurement. The dynamic response of ionization gages in vacuum systems, particularly at pressures below 10^{-6} torr, is of lesser importance than adsorption phenomena or conductance lags. It may be important, however, in dynamic measurements at pressures above 10^{-6} torr. See Section 2.7.5.

Sicinski, Spencer and Dow [5402] used a radioactive gage to measure atmospheric pressures from a moving rocket. The low pressure end was about 10^{-2} torr. Spencer and Boggess [5911] describe a similar gage with the same lower pressure limit for such use.

Horowitz and LaGow [5769] used a cold cathode (Penning) gage for the same purpose, but to much lower pressures.

Newton, Pelz et al [6390] used both a Bayard-Alpert and a Redhead magnetron gage to measure ambient pressure in the range 10^{-11} to 10^{-6} torr. These gages were installed in rotating satellite.

An oscillograph was used by Dobbe and Schroeder [5378] in which the ion output of the gage was connected to the horizontal plates, the electron emission to the vertical plates. The slope of the line formed by the spot and the origin is proportional to the pressure. Circuit details and theory are presented.

Cobine and Burger [6114], to measure pressures in the range 10^{-4} to 10^{-7} torr in connection with an investigation of metal arcs, found that the time constant of Bayard-Alpert ionization gages was less than 10^{-3} seconds. Wire wound precision resistors ordinarily used in the electrical circuits increase the time constant to several seconds. To reduce stray effects, batteries were used as the power supply and the electrical circuit refined in many respects. The output was displayed on an oscillograph.

Vitkus [59150] for an installation of radioactive gages connected to pressure heads in a model in a wind tunnel found that equilibrium pressures were obtained in one second in the 30 to 3 torr range and in 4 seconds in the 0.3 to 0.03 torr range. The major part of the lag time was due to the connecting tubing.

Lewin and Martin [6211] describe in detail a modified Bayard-Alpert gage in a small enclosure for measuring the density of neutral gas in the presence of magnetically confined plasma. They [6327] added two grids, one for electrostatic shielding and one for modulation. The latter had a direct current bias with a superimposed sine wave which cut off the electron emission each half cycle. This gave a better zero at low ion currents.

Bannenberg and Insinger [6382] describe modifications to a commercial ionization gage to operate in a magnetic field of 8000 gauss, also for measuring the density of a neutral gas in the presence of a magnetically confined plasma. Screening was used to suppress plasma and radiation effects. The time constant of the gage was 160 microseconds for hydrogen.

Buser and Sullivan [6213] were interested in dynamic measurements in the pressure range 10^{-3} to 1 torr which is outside of the range of the common hot wire gage. They propose the use of the rectification properties of the hot wire gage. An audio-frequency voltage is impressed on the ion collector which results in a half wave rectified current displayed on an oscillograph. The fourth power of the amplitude of this output is proportional to the pressure. For dynamic measurements a frequency of 10 - 20 kc for the impressed voltage is recommended.

Dei-Ças and Valckx [63300] used a commercial pentode (3A4) to make dynamic measurements in the range 10^{-4} to 5×10^{-2} torr. A minimum response time of 100 μ seconds was obtained. The output of the pentode was displayed on an oscillograph.

Cambou, Cotin and Reme [64120] adapted a radioactive ionization gage, using either polonium 210 or tritium, so that the positive ion pulses per unit time could be counted. Details of the counting circuit are given. The pulses per unit time are proportional to the gas density. The instrument is for use on balloons or rockets in the altitude range 0 - 80 km (pressure range approximately 8×10^{-3} to 760 torr).

2.3.7. Disturbing Magnetic Field. Doran [61188] faced the necessity of securing operation of a hot cathode ionization gage in a pulsed magnetic field, duration two seconds and repetition rate ten seconds. The gage was placed so that the magnetic field is in the direction of the electron emission current, therefore not affecting it. To avoid the interaction of the magnetic field and the heater current of the filament, which are at right angles to each other, the filament was supplied with 5000 c/s current, well above the natural frequency of vibration of the filament. The heater current was stabilized to obtain a constant electron emission.

2.4. Electrodes

Electrodes are divided into two classes, those producing the electrons and those controlling the electrons and collecting the ion current. Most of the difficulties in securing adequate performance are associated with the electron producing electrodes. A large literature exists on the development and performance of the latter, largely in vacuum tubes but substantially applicable to ionization gages. The hot cathode filament is widely used as an electron source in ionization gages. Later developments are the cold cathode as developed by Penning, the two forms of the magnetron gage, the use of a radioactive material and a radical development, the use of photons to secure electrons. All of these to some degree overcome the performance limitations of the hot cathode.

On the other electrodes the situation is not critical. However, the arrangement of all electrodes within the enclosure is important and has received considerable attention, notably in reducing background currents, or securing a means of correcting for them. This is considered in Section 2.6.10.

The review of electron producing electrodes will be quite limited in scope. The mechanism and theories associated with the production of electrons by the hot and cathodes is not reviewed. On hot cathodes of all types a good review is given by Nottingham [5678], with copious references to the literature and more briefly by Tischer [6439]. Functioning of cold cathodes in the vacuum range where gaseous discharge does not ordinarily occur is given by Guthrie and Wakerling [B492] and Kreindel and Ionov [64170].

Details of the chemical activity associated with hot filaments are extremely pertinent but consideration here will be limited, with broader aspects considered in Section 2.6.4.

2.4.1. Hot Wire Cathodes. Desirable properties for a hot filament cathode may be summarized as follows:

a. Produces an adequate stable electron current with a minimum input of energy.

b. Has a minimum of the chemical activity at its surface of a type which may alter the gas composition or the pressure in the gage envelope.

c. Has a long service life.

d. Does not burn out when accidently subject to atmospheric pressure while hot.

e. Produces a vapor pressure in operation which is at least an order lower than the pressure being measured. This is of practical importance in measuring ultra-high vacuum.

Hot wire cathodes of many materials have been tried in order to obtain adequate performance as specified under b), c), and d) above. Complete success has not been secured, a fact which has led to experimentation with the cold cathode type of gage and to the use of photons.

Of considerable promise is the recently developed rhenium wire covered with lanthanum boride as a hot cathode for ultra-high vacuum use.

2.4.1.1. Tungsten Filament. More research has been done on tungsten than on any other filament material. It is probably the most commonly used material in the high vacuum range.

Recently Weissman and Kinter [6377] report on the increased efficiency as an emitter of a filament consisting of vapor deposited tungsten on a tungsten substrate. The technique of deposition is such that the deposited tungsten crystals are oriented to present the same face, instead of random-oriented.

Heating current is applied to secure an electron current in the milliampere range, resulting in a filament temperature in the 2000°K range. The useful life of the tungsten filament, maintained under vacuum while hot, is limited by chemical action with, or ion bombardment of, the filament. A decrease of 10 percent in diameter at any point causes a local hot spot, which produces burn out [B571]. Mueller [6260] states that the tungsten filament has a life of 10 to 20 hours when heated in the ambient pressure range of 10^{-2} to 10^{-3} torr; 1000 hours in the range 10^{-6} torr.

Alpert and Buritz [5448, 5874, B621] pointed out that at a tungsten filament temperature of 2300°K, the tungsten vapor was calculated to give a reading on an ionization gage, calibrated for nitrogen, of 10^{-12} torr. The vapor pressure of tungsten at 2300°K is about 10^{-8} torr. This is a low pressure limitation on the use of the tungsten filament.

Chemical activity at the surface of the tungsten filament may seriously alter the gas composition and ambient pressure. Details are deferred to Section 2.6.4.

Riddoch and Leck [58170] and Redhead [60162] stated that the tungsten filament should be flashed at high temperature to eliminate the alkali metals which are ordinarily present as impurities. Otherwise these metals are given off during normal operation of the gage, ionize, and give a spurious ion current of significant amount. This procedure needs to be followed on fresh filament. Denison, Winters and Donaldson [6392] found that the sodium or potassium impurities released from the hot filament are mainly neutral molecules which are adsorbed on the grid of Bayard-Alpert gages. The amount released depends on diffusion of the alkalies to the tungsten surface and is enormously increased when the tungsten surface is etched away by a chemically active gas such as oxygen, carbon monoxide, or oxide, or water vapor. Bombardment of the grid releases the adsorbed alkalies as positive ions, thus giving rise to an anomalous or background positive ion current. Tungsten filaments free of alkalies do not produce this anomalous current.

The hot filament is easily damaged by electrical or mechanical mishandling. Failure of the vacuum may destroy the hot filament (Leck [B571]). The chief defect of the tungsten filament in comparison with hot filaments of other materials is its shorter life and possibly its greater chemical activity due to its higher operating temperature.

To prolong the life of the ionization gage, some manufacturers equip their gages with a spare tungsten filament. When the primary filament burns out, it is only necessary to connect the spare filament into the electrical circuit, thus avoiding replacing the entire gage.

2.4.1.2. Rhenium Filament. Hall [5723] used a 10 mil rhenium filament in his ionization gage in place of a tungsten filament. Ammonia gas, present in his vacuum system, reacted with the tungsten filament, but not with the rhenium filament. Pertinent physical data on rhenium are given by Espe [6453] and Kotowski and Tischer [64127].

2.4.1.3. Thoriated Tungsten Filament. Thoriated tungsten was developed in 1914. Its electron emission and ductility exceed that of tungsten. Large crystals of tungsten do not form when the thoriated wire is heated. (Nottingham [5678]). The filament contains from 0.5 to 1.5 percent of thorium oxide. When the filament is flashed at above 2700°K some thorium oxide is reduced to thorium. At 2100 - 2200°K the thorium diffuses to the surface of the filament to form a monolayer. At 2000°K, thorium evaporates faster than thorium diffuses from the interior and the electron emission is reduced.

(Lafferty - Dushman [B621]). Presumably the normal operating temperature is below 2000°K. Langmuir [3307] states that the thorium film forms at 2000°K and evaporates at 2400°K.

Some data on the physical and chemical properties are given by Schneider [62129] and on thoriated rhenium tungsten by Jolly [62194].

The thoriated tungsten filament was used by Jaycox and Weinhart [3105] and Copley, Phipps and Glasser [3501], but apparently not by recent designers of ionization gages.

No specific study on its performance in an ionization gage permitting comparison that of other filament materials, appear to have been made.

2.4.1.4. Oxide Coated Filaments. These filaments were widely used in vacuum tubes, dating back to before 1920. Ridenour [4103] and Fogel [4616] used oxide coated filaments in their ionization gages, mainly because sudden vacuum failure did not cause burnout, as normally the case with tungsten filaments. Also, some reduction in chemical activity occurs due to the substantial reduction in operating tempera- ture of the oxide coated filament over that for the tungsten, and other pure metal types. The lower energy input is bound to be helpful. However the oxide-coated filament had to be reactivated after vacuum failure which could be difficult (Dushman [B491]).

Usually nickel wire was used which is covered with a mixture of barium and strontium (some add calcium) carbonates. Upon heating, the carbonates change to oxides, producing a monatomic film. Barium oxide breaks down to barium which produces the electrons from the hot filament. A 50-50 mixture of barium and strontium carbonate produces the best results (Nottingham [5678]). Nottingham raises some doubt as to whether the barium film forms and discusses at some length the relative possibilities of a "barium excess" or an "oxygen deficiency". No discussion was found on the function of the strontium.

Lafferty [B621] stated that the monatomic film of barium (if it is barium) of oxide coated filaments evaporates rapidly at a filament temperature of 1200°K whereupon the electron emission decreases. How- ever the normal operating temperature is well below this temperature.

Leck [B571] stated that oxygen, or a gas containing oxygen such as water vapor, reacts with the barium. Carbon monoxide and carbon dioxide also react at the low filament temperatures. The oxide coated cathode is "poisoned", reducing the electron emission. The effect is usually reversible, [4906] so that recovery is rapid if the oxygen or oxygen containing gases are eliminated by pumping. There is no reaction with the noble gases.

Kelly [6231] reported that the barium oxide coating of an oxide coated filament changes to barium hydroxide in a moist atmosphere at room temperature. The hydroxide is 21 percent less dense, there- fore particles of it flake off finally ruining the filament. If the filament is kept electrically heated to 120-130°C when exposed to a moist atmosphere, the reaction is suppressed. In tests, a heated filament survived over 50 pressure cycles; an unheated, only about 10 cycles.

Nottingham [5678] in his review stated that the reaction reducing barium oxide to barium requires the presence of impurities in the underlying nickel wire. However, Schuetze and Dlouhy [6293] in tests on the life of sealed vacuum tubes with oxide coated filaments, found that the tube life was greatly increased (to 60,000 hours) if chemically pure nickel wire was used. They found that the impurities in the nickel diffuse to the surface of the nickel at a filament temperature of 740°C. Probably con- taminants in the gases to which ionization gages, in contrast to sealed tubes, are ordinarily exposed are of far greater importance in controlling gage life than impurities in the nickel. See also Florio [62196].

DeGoer and Thibault [61183] considered the conduction mechanism within the oxide film and concluded that long pores across the entire film exist and that bottom layer of the film determines the electron emission.

It appears safe to conclude that the advantages of using a barium oxide coated filament instead of a tungsten filament in ionization gages are at best almost negligible.

2.4.1.5. Thoria Coated Filaments. Weinreich and Bleecher [5207] experimented with the use of thoria coated, heated iridium filaments. They are much more resistant to burnout when subjected to a sudden loss of vacuum. The filaments remain stable when subjected to oxygen up to a pressure of 10^{-2} torr. This is in contrast to the behavior of barium oxide coated and tungsten filaments. The life is at least 1000 hours at an operating temperature of 1875°K. The filaments are cleaned by pro- longed heating at 1550 to 1950°K.

Data are given on both thoria coated iridium and rhodium filaments by Weinreich [5110]. An iridium coated filament was used as described above probably because its melting point of 2350°C is about 400°C higher than that of rhodium.

Peters [5546] described a Bayard-Alpert type ionization gage with a thoria coated iridium filament. The filament operating temperature is 1875°K at which a useful life of several thousand hours could be expected. Calculations show that the vapor pressure of thoria at 1875°K is 8.5 x 10^{-9} torr. However, the brightness of the filament decreased 100 to 200°C when it was subjected to a vacuum which lowered the vapor pressure to about 10^{-10} torr, which is also approximately the x-ray limit. The effect on the indication of the gage of the sublimating thoria vapor is much less than 10^{-10} torr, if the effect of tungsten vapor given in Section 2.4.1.1 is valid.

The filament emission current was reduced about 60 percent by a pump oil and increased about 10 percent by a silicone pump oil, both present in liquid form. It was concluded that the thoria coating could be damaged by excessive amounts of hydrocarbons such as pump oil vapor, and less so by silicone oil vapors. Normal operation of the filaments were restored by heating in air.

Penchko [61135] experimented with a thoria coated iridium filament. Air at atmospheric pressure was admitted 20 times; the gage operated satisfactorily after evacuation. The filament life was 168 hours of continuous operation at a pressure of one torr. Similarly, for a thoria coated yttrium filament, the life was over 200 hours.

Futch [6130] used a thoria covered iridium filament in his ionization gage for measuring the pressure of water vapor at pressures as high as 0.5 torr because it was not easily poisoned.

2.4.1.6. Boride Coated Filaments. Lafferty [5168] determined the physical and electrical properties of seven borides with special reference to their use as hot filament cathodes. Of these, lanthanum boride (LaB$_6$) has the best properties for the purpose.

Young [59180] developed a tantalum filament coated with lanthanum boride. At a filament temperature of 1000°C no reaction with oxygen was observed. Hickmott [6002] avoided the dissociation of hydrogen by hot tungsten filaments by using a similar filament. No carbon oxides were produced in the presence of oxygen.

Lafferty [B621, 6297] used a rhenium wire coated with lanthanum boride as the filament in his ionization gage. Rhenium was selected because it did not react with the boride at the operating temperature which was 675°C. A rhenium wire, 5 mils in diameter, is spirally wound on a 10 mil rhenium wire. The space between the turns of the spiral wire is filled with a paste of lanthanum boride and amyl acetate. This is sintered in argon at 1600°C. At a filament temperature of 1425°K the electron emission was 25 ma/cm^2. The vapor pressure of the boride is about 10^{-4} torr below that of tungsten producing the same electron emission.

Paderno et al [63176] used a lanthanum boride coated cathode as an ion source. No details are available.

No data on the chemical activity of the filament in the presence of gases is published except for oxygen and hydrogen as noted above. No reaction is expected with the noble gases, but for hydrocarbons may be another story. No data on the life of the filament appears published.

2.4.2. Cold Cathodes. In cold cathode gages a high voltage between two electrodes produces an electrical discharge in the gas. In the Penning type there is difficulty in initiating the discharge, or striking, at pressure below about 10^{-5} torr. For a theoretical discussion see Valle [5267]. This has been eased by using a cathode with sharp pointed electrodes, Evans and Burmaster [5016], Barnes [6070] and Bernardet and Gourdon [63191]; by using an auxiliary heated filament to liberate gas, raise the pressure and permit striking, McIlwraith [4709]; by using an auxiliary heated filament to supply electrons and permit striking, Vanderslice [6352] and Young and Hession [6395]; and by using a higher accelerating voltage [B571]. Young and Hession extended the range of this gage to cover 10^{-14} to 10^{-3} torr. This difficulty is avoided even at ultra-high vacuum in the magnetron and inverted magnetron gages by trapping the available electrons by a strong magnetic field. (Redhead [58136]).

The choice of material for the electrodes is not critical. Evans and Burmaster [5016] used stainless steel disks for the cathode, Leck [5312, 5604] hard nickel electrodes in his Penning gage. Leck [B571] tried constantan, nickel and aluminum and obtained about the same sensitivity in a Penning type gage. Magnesium gave an erratic sensitivity. Recommends nickel because of ease in handling.

Hobson and Redhead [58134] used a tungsten anode and nichrome V for all other electrodes in the inverted magnetron gage.

2.4.3. Other Electrodes. The electrodes for magnetron gages has been discussed in the preceding section.

Copley, Phipps and Glasser [3501] in an ionization gage, using a thoriated tungsten filament, evaporated some thorium onto the glass envelope and used this film as the ion collector.

Morse and Bowie [4003] in a hot filament gage used a platinum film deposited on the inside of part of the glass envelope for the ion collector. A similar film, grounded, has been used by others to fix the potential of the glass envelope.

Fogel [4616] in a hot wire gage used nickel plates for the electrodes other than the filament.

Peters [5546] in a Bayard-Alpert gage used a molybdenum grid. Young [6128] found that molybdenum anodes, after degassing by heat or electron bombardment, produce a white layer on the glass envelope, probably molybdenum trioxide. The sensitivity of the gage was decreased thereby. He recommends the use of either tungsten or tantalum for the electrodes, since their films did not affect the gage performance.

The use of platinum electrodes in hot cathode gages to stabilize the sensitivity has been discussed in Section 2.3.3.

2.5. Electrical Circuits

The electrical circuit of the ionization gage has gradually evolved through the years to meet many demands and to stay in step with new developments in electronic technology. The primary need is to measure the positive ion current I^+ and to measure or maintain constant the electron emission currents I^-, for which the simplest circuit is indicated in Figure 1. In hot cathode gages

$$\frac{I^+}{I^-} = SP \qquad (4)$$

where S the sensitivity which is a constant or a unique function of the pressure. In cold cathode gages, $I^+ = KP$, since there is no controlled electron emission.

For the Bayard-Alpert Gage, Alpert [5874] gives 0.1 as a typical value for S for nitrogen and for P in torrs; for an electron emission current of 10 ma, also a typical value used in hot cathode gages, and a pressure of 10^{-6} torr, the ion current is then 10^{-9} amperes. To measure ion currents at this pressure, and lower, requires the use of an amplifier. In fact, ion current amplifiers are usually used for all types of ionization gages, including cold cathode and radioactive gages.

2.5.1. Electric Circuit Functions. The basic functions of the electrical circuit of modern hot cathode gages are as follows:

a) The positive ion current must be measured.

b) The electron emission current is automatically held constant at a value, which may be selected within a practical range. Means for measurement must be provided.

c) The electrical potentials on the electrodes must be controlled at values which can be selected.

Subsidiary, but desirable, additions to the circuit are:

d) Means for automatically operating relays which cut off the current to the gage filament and which operate valves to isolate parts of the vacuum system, if due to any cause, pressure in the gage rises to a value above the high pressure end of its range.

e) Special provision may be made to heat electrodes in the gage to facilitate outgassing, particularly at ultra-high vacuum.

Circuits have been designed for other needs, such as dynamic measurements, for recording or telemetering and even for measuring directly the ratio I^+/I^-. These are discussed in following sections.

For cold cathode gages of all types, direct control of the electron emission current, item (b) above, is not pertinent; all other requirements are valid.

2.5.2. Ion Current Measurement. The problem is primarily to amplify ion currents in the range 10^{-6} to 10^{-15} amperes so that they can be indicated on a panel microammeter or a microvoltmeter. As lower and lower pressures are being achieved the ion currents to be measured have become progressively lower, and are now bordering on the low practical limit of easy measurement of 10^{-15} ampere. This situation has required from time to time the utilization of new or improved designs of electronic amplifiers. The main interest is in the hot cathode ionization gage but the methods of ion current amplification apply equally well to other types of ion gages.

2.5.2.1. Ion Current Amplified. Where the ion current is measured directly by an electrical meter, the type of amplifier is principally of interest. The various types, many only of historical interest, will be indicated; details are omitted; background material can be obtained from many texts and handbooks such as [B525, B552]. Adaptations required to obtain other modes of indication are discussed later.

An electronic amplifier was probably first used by Found and Reynolds [2604, B491].

Huntoon and Ellett [3602] used an electronic amplifier in their gage in combination with a galvanometer to measure the current.

A dc amplifier commonly used in making measurements of a pressure as low as in the high vacuum range is described by Leck [B571], and by Dushman [B491] who stated that the circuit was developed by Lafferty. Bowie [4004], Bouwmeester and Warmoltz [5504] and others used this amplifier. See the above references for circuit diagrams or Figure 8-19 of Terman's book [B552]. A bridge arrangement is used to balance out in some measure changes in filament and other supply voltages. The output of two triode tubes and two resistors form the bridge, with means for balancing for zero; the unbalance is measured, normally with a microammeter.

An electrometer amplifier, which measures essentially a voltage, was used by Peters [5546] in the RG 75 gage of the Bayard-Alpert type. Reynolds and Lipson [5458] describe an electrometer circuit for Bayard-Alpert gages utilizing two pentode tubes. Allenden [58105] and Gavrilyuk and Kucherov [59110] also used electrometer amplifiers. Allenden's gage had a current of 2×10^{-12} amperes at 10^{-10} torr, which after amplification was measured by a 50 microampere meter.

Of special interest is the electrometer amplifier described by Roehrig and Vanderschmidt [59148] for use with a radioactive vacuum gage. Two electrometers, balanced to reduce the effect of power supply variations are used. Their output is fed to a differential voltage amplifier, the output of which is fed to a telemeter.

Beynon and Nicholson [5640] used an electrometer of the vibrating reed type and a dc potentiometer to provide a negative feedback to the electrometer in a radioactive gage. At zero on the meter, the dc potential is read and is proportional to the pressure. A sensitivity of 10^{-15} amperes was obtained, equivalent to a pressure of 10^{-6} torr.

Mueller [6260] described a Bayard-Alpert gage in which the same indicator was used to indicate (a) the ion current as a linear function of the pressure, (b) as a linear function of the logarithm of the pressure and (c) the electron emission current. Hand operated switches connect to the special circuits giving the desired measurement. The pressure range was 10^{-2} to 10^{-6} torr.

Mainly to increase the current to be measured and to minimize the soft x-ray effect, an electron multiplier was used by Lafferty [6181, 6311], Riemersma et al [60159, 6103], and Hudson, Sears and Donnelly [6402]. These are discussed in Sections 2.2.6 and 2.2.9. Young and Hession [6395] used an electron multiplier similar to Lafferty's in a low pressure range Penning gage.

In Lafferty's gage the output electron current at 10^{-15} torr was 7.8×10^{-11} ampere when the emission current from the hot filament was 4×10^{-9} ampere, and correspondingly greater for increased emission currents. This output current is easily measurable by conventional methods.

Transistor amplifiers are particularly attractive if low weight is desirable, as in rocket installations. Benton [5968] designed a low weight amplifier, which is discussed in Section 2.3.2. The design and performance of 3-stage transistor amplifier for ionization gages is given by Lecorguillier [64121].

Krpata [61230] has devised an amplifier circuit whereby the indication on the electrical meter is proportional to the logarithm of the pressure. This enables measurements to be made over a wide range of pressure on a microammeter without adjustment of the amplifier or electron emission. Marechal and Octave-Prevot [64152] control the range of indication of the pressure by varying the electron emission current.

2.5.2.2. Null Methods. These are largely of historical interest. Ridenour [4103] developed a circuit in which the ion current ends in a 6E5 tube in which a fluorescent screen presents a bright circular field with a dark sector. The dark sector is kept unvaried in width by operating a potentiometer. The resistance required to maintain this null is a measure of the pressure.

Parkins and Higinbothan [4102] avoided stabilizing the electron emission current by using 6AF6G tube which has two dark sectors. One dark sector is adjusted to set the value of the emission current; the other is connected to the ion current and its dark sector maintained invariant by a potentiometer. Two resistances are thus obtained, the ratio of which is proportional to the ratio of the ion to the emission currents.

Making manual adjustments to obtain a reading is unattractive compared to a continuously indicating instrument, particularly when no gain in overall accuracy is obtained. Low cost was the reason for the development of the null methods just described.

2.5.2.3. Phosphorescent Screen. This method of indicating the ion current has been described in Section 2.2.8. See Figure 9.

2.5.2.4. Ratio, Ion to Emission Currents. This ratio can be obtained (a) by computation, since both currents are ordinarily measured, (b) by an adjustment of some sort plus a single measurement or (c) by a continuous single indication where circuits are used to obtain the ratio automatically. Ordinary practice is to stabilize the emission current whereupon the measured ion current in effect is proportional to the desired ratio.

Considering type (b) above, Sibata et al [5237] and Fitz Osborne [5350] used a potentiometer circuit in which a resistor was adjusted until the voltage drop across it due to the emission current equaled the voltage drop across a high ohmic resistor carrying the ion current. Zero voltage was detected by a vacuum tube voltmeter. The pressure was proportional to the value of the variable resistance. The need for an adjustment preparatory to making a reading of the pressure is a drawback.

Hiby and Pahl [5482] used a balanced wheatstone bridge circuit where the ratio of two resistances, one adjustable, equaled the ratio, ion to emission current.

Electronic circuits to obtain type (c), where the ratio of the two currents is continuously indicated, were developed both by Hariharan and Bhalla [5641, 5687] and by Frost [62104]. In both cases the output to the meter is the logarithm of the ratio, ion to emission current, proportional to the logarithm of the pressure. One advantage is that a large pressure range can be indicated without switching. Parenthetically, it is still worthwhile to stabilize automatically the emission current which both investigators have done.

Schutten [5770, 58140] obtains an intermittent reading of the ratio of the two currents by using a timing circuit to periodically discharge a condenser connected to the ion collector of the gage. The change in the potential of the condenser, proportional to the pressure, is measured by a peak reading voltmeter.

Schutten also proposes a circuit, which he states requires an excessive filament power, to obtain a continuous indication of pressure.

2.5.2.5. Recorders and Telemetering. Discussion of recorders and telemetering equipment are out-of-place here; it will be limited to electrical circuits for ionization gages especially tailored for recorders or telemetering.

An electrical recorder can be substituted for the electrical meters in an ionization gage, if desired. For example, Savage and Odom [6208] use two recorders, one for the ion current and the other for the emission current since the two currents normally differ more than ten-fold.

Vitkus [59150] used from 10 to 50 radioactive pressure sensors in wind tunnel experiments. The electrical circuits were designed so that the output of the gages was fed to a digitizing recording system.

Telemetering of necessity has to be used in measuring atmospheric and impact pressures during rocket flights. The gages must be rugged, hence cold cathode and radioactive type gages have been favored, since thus far the lower end of the pressure to be measured is within their range. Light weight circuitry is at a premium; battery power is obviously required. With due attention to the electrical circuits, the speed of response of the gages themselves appears adequate. However, as the pressures to be measured go lower, connecting tube conductance, adsorption and outgassing become serious if not unsurmountable bars to accurate measurements at rapidly varying altitudes.

Circuits designed to telemeter data from radioactive gages are described by Sicinski, Spencer and Dow [5402], Spencer and Boggess [5911] and in considerable detail by Roehrig and Vanderschmidt [59148]. The gage of the last named was based on the use of tritium, of the others on radium 226.

The electrical circuit for telemetering developed by Horowitz and LaGow [5769] was for a cold cathode gage of the Penning type.

As an indication of the direction development is taking in rocket applications, Benton [5968] has developed a control circuit, including output for a telemeter, around a hot wire filament gage (VGIA). Reliability, simplicity and low weight have been stressed. A dual unit control circuit weighed only 7 lb.

2.5.3. Electron Emission Current Measurement. Commonly the electron emission current of cathode filaments is in the range 1 to 10 ma, with some advocates of a value of a decade or more lower. This offers no difficulty in measurement by a portable meter without amplication. Even if this current is automatically stabilized, it is also measured as a check.

Lafferty [6297] apparently expects to use emission currents from the hot filament of his gage well below 10^{-6} amperes, the measurement of which will require the use of an amplifier.

2.5.4. Control of Electron Emission Current. Very early in the use of the hot cathode ionization gage, attempts were made to automatically control the value of the emission current. Manual adjustment was found to be inadequate.

Two fundamental approaches for emission current regulation exist. In the first, electrical circuits operate on the gage having the normal three electrodes and in the second, a grid is added to the gage.

In gages with the normal three electrodes, circuitry now only of historical interest include (a) the use of a relay which opened when the emission current exceeded a selected value and through a resistance so added, lowered the current (Found and Reynolds [2604]), Jaycox and Weinhart [3105]; the use of a saturable core transformer (Overbeck and Meyer [3408]); and the use of a thyratron (Hoag and Smith [3704]).

A break-through to a reasonably satisfactory and much used control for three-electrode gage tube is that developed by Ridenour and Lampson [3707]. This control depends on a feedback. Any change in the ac emission current changes the voltage across a resistor, which amplified, is fed to the grids of two electron tubes. Their output in series with the filament supply voltage through transformers, adjusts the filament current to return the resistor voltage, and thus the emission current, to their original values.

Modifications, either to simplify or improve the performance of the above described feedback circuit have been made by Nelson and Wing [4202], Nelson [4506], King [4607], Steckelmacher and Van Der Meer [5014], Richards and Tuthill [5108], Raible and Testerman [5564], and Reese [5750]. Allenden [58105] used two thryatrons and a series resistor in a circuit similar to, but simpler than that of a Nelson and Wing [4202], whereby a wider range control is obtained.

Hariharan and Bhalla [5641] designed a feedback circuit of some complication which is an improvement of the Ridenour-Lampson circuit in that it is operative over a much wider range of filament current.

Benton [5968] and Penchko [61152] used transistors in a dc amplifier feedback circuit to control the emission current of three-electrode gages. This design is light in weight and economical of power but only practical for a dc power supply. Winkler [6305] also developed a control based on the use of transistors.

Reynolds and Lipson [5458] regulated the emission current by means of a saturable reactor driven by a balanced dc amplifier.

Henry [58112] developed a novel electronic feedback circuit to control the emission current. Theory is included. He avoids the range limitations of a regulator based on the variation of the saturation of a magnetic circuit by regulating electronically the output of a transformer.

Yee and Carpenter [63110] have developed a circuit which stabilizes the electron current to better than 0.05 percent. Any change varies the difference in two voltages, which, amplified, controls a light source which acts on a photocell. The amplified photo current modifies the filament input to restore the set emission current. Transistor dc amplifiers are used.

The use of an additional grid to stabilize the electron emission was initiated by Montgomery [3805], used by Johnston [5003] and further developed by Warmoltz and Bouwmeester [5208, 5504], Penchko and Kharkin [59182], Schwerdtfeger [60132] and Edeline [6182]. The additional grid is placed between the filament and normal grid and is held at a potential slightly below that of the hot cathode. The combination, filament-extra grid-normal grid is in effect a triode, and by feedback to the extra grid in an appropriate circuit, the electron emission can be maintained constant.

In conclusion, present practice appears to favor the normal three electrode gage tube and a feedback electrical circuit controlling the power supply to the filament.

2.5.5. Power Supply Controls. In the early use of the hot cathode ionization gage, the power was obtained from storage and dry batteries. Only regulation of the filament current was needed, owning to changes in the filament performance with use, since the gage sensitivity is not greatly dependent on small variations in the voltages impressed on the grid or ion collector.

Kuper [3407] appears to have initiated the use of an ac power supply for the hot cathode gage. The alternating current had to be converted to direct current for application to the grid and ion collector. Some stabilization of the voltages to the grid and ion collector appear to be needed against normal line fluctuations. An early design of such regulation is described by Bowie [4004]; another design by Lafferty is described by Dushman [B491]. More modern stabilizers of the power supply are described by van der Scheer [5039], Redhead [5254], Allenden [58105] and Durm [6361].

Stabilizing the electron emission current is necessary always; methods are discussed above in Section 2.5.4.

In cold cathode gages high dc voltages are required, up to 6000 volts for the inverted magnetron gage. Generally, line ac voltage is the supply, stepped up in voltage by a transformer and then rectified. Stabilization of the line voltage may be necessary (Antal and Koenig [5782]). Safety against a short circuit of the high voltage and excessive currents at pressures above the vacuum range, can be obtained by a ballast resistance in the input line to the gage (Conn and Daglish [5410]).

2.5.6. Protective Circuits. Protection may be desirable (a) to protect the ion gage and mass spectrometer filament against a sudden increase in pressure which causes the filament to burn out, (b) to retain vacuum in the system if pump operation suddenly ceases and (c) to give a warning signal of loss of vacuum.

In all cases relays are operated by the element sensing the over pressure. To protect the hot wire filaments it is merely necessary to switch off their power supply. To retain vacuum in a system, the relay closes a valve in the line between the pumps and the system. A warning signal is auditory in nature, as a horn, which is put into operation by a relay.

Generally where it is only necessary to protect the vacuum gage or other equipment by switching off their power supply, the gage itself is used as the sensing element. Van Valkenburg [4619], Milner [4918], Pupp [5269], Reynolds and Lipson [5458], Allenden [58105], Mueller [5979, 6260], Winkler [6305] and others have described relay circuits for this purpose. Ryzhov [61197] used a thyratron circuit to cut the electrical circuit at the unusually low pressure in the 10^{-7} to 10^{-8} torr range.

In large vacuum systems where both electrical current and valves are to be controlled, pressure sensing elements for control should be chosen which will not be made inoperative when subjected to pressures beyond the high side of their normal range. Generally the electrical output of gages rises or becomes constant with rise in pressure, so that any failure of the gage to have output would nullify protection against pressure. Since its continuity of operation at high pressure is in doubt, the hot filament ionization gage is not suitable as a sensor.

The cold cathode gage is suitable as a sensing element, particularly the Penning type, which has a sudden large increase in output current in the pressure region, 10^{-2} to 10^{-3} torr. Allwood [4810] used the gage for this purpose. Haefer [58157] used the inverted magnetron gage as a sensing element in the range 10^{-6} to 5×10^{-3} torr, apparently in the linear part of the range.

For relay operation at a pressure at about 10^{-1} torr, Allwood used a Geissler tube, which became conducting at pressures above 10^{-1} torr. Haefer [58157] used a thermocouple vacuum gage as a sensor in the range 2×10^{-3} to 1 torr.

Hamilton [5858] developed a general purpose relay control circuit of the high gain magnetic amplifier type for use with any sensor with an electrical output.

2.5.7. Magnetic Fields. A magnetic field is required for cold cathode gages and in some other types. For Penning gages a field strength of 250-400 oersteds is required and for other magnetron types 1000 to 2000 oersteds. A uniform field in the gage is desirable. A permanent magnet, usually alnico, is most convenient for working gages, where the required value of the optimum field is known. In research work on gages, the flexibility of the electromagnet makes its use almost mandatory.

2.5.8. Vacuum Controllers. Vacuum controllers do not differ essentially in design from pressure controllers. A pressure sensor is needed which by a suitable mechanism or electrical circuit controls either one or two valves. In the two-valve vacuum control, overpressure causes the system to be connected to a pump; underpressure, to the atmosphere or a reservoir at a somewhat higher pressure than desired in the system.

Most often in vacuum work, the desired pressure is the lowest obtainable from the pumps. If higher pressures are desired, the rate of pumping, outgassing etc. are so slow, that any reasonable value of the pressure in the vacuum range exists long enough for most purposes. Controlling the intake of gas from an external source by valves while pumping is an effective, simple means of pressure control.

Linner, George, and McQuistan [6078] considered automatic vacuum control down to 10^{-8} torr. For pressures above 5×10^{-3} torr, a radioactive vacuum gage is used as the sensor; below to 10^{-8} torr, a Bayard-Alpert ionization gage. A voltage proportional to the desired pressure bucks the output of either of the two gages, depending on the desired pressure. Any deviation of the gage output from the set voltage causes a servomotor to operate switches and thus solenoid valves. Underpressure connects the system to a gas reservoir; overpressure to a fore pump or a diffusion pump, depending on the desired pressure.

2.6. Factors Affecting Performance

Many of the factors affecting the performance of ionization gages have to be "lived with" for each type of gage. On many of the factors for many gage designs information is incomplete.

Factors affecting the performance which are largely independent of the design of the ionization gage are (a) outgassing and degassing, (b) adsorption of gases, and (c) ionic pumping. Their influence may be minimized by operational procedures.

Other factors the influence of which can be greatly reduced by the design of the gage or of the vacuum system are (d) permeability of the gage envelope to ambient gases, principally helium; (e) high frequency oscillations; (f) background electrical currents; (g) pressure equilibrium with the vacuum system, and (h) gage envelope temperature and electrical potential. (i) Extraneous magnetic fields may need consideration.

To avoid (j) chemical reactions and (k) poisoning by certain gases requires the elimination of the commonly used hot wire filament for producing electrons. This has stimulated the development of other means of supplying electrons.

The last factor, that of (m) gage geometry for optimum performance, is solely a design problem for each type of ionization gage.

Outgassing, degassing, adsorption, ionic pumping and chemical reactions are often interrelated phenomena which of necessity will involve some crossover in the discussion.

2.6.1. Degassing and Outgassing. All vacuum systems and all types of ionization gages must be degassed; the lower the pressure to be measured, the more thoroughly. The principal method is by the application of heat while pumping out the gage. Pumping alone at room temperature at pressures below about 10^{-4} torr takes inordinately long to degas any material.

Special degassing procedures for hot tungsten filaments are discussed in Section 2.4.1.1.

Heat may be applied to the electrodes (a) by an external high frequency electrical source, (b) by subjecting them to infrared radiation, (c) by bombarding the grid and anode with electrons from the filament, (d) by passing an electric current through the electrodes or (e) by placing the entire instrument in a furnace.

Method (c) was used by Fogel [4616] and is still used (Todd et al) [6004]. Method (d) was used in whole or in part by Peters [5546], Schwerdtfeger [60132], Mueller [6260], Hwa et al [63165] and probably others. Method (a) although often used is more awkward in comparison with other methods; method (b) is discussed by Stewart [5048].

None of the methods just mentioned cover the necessity of heating the enclosure of the gage. Of course, heat can be applied externally by hit and miss methods as by torching, radiant heating etc., but for thorough degassing, the temperature of the entire gage must be controlled, for which heating in a furnace, method (e), is required. Heating of the electrodes by passing an electrical current through them may also be desirable in order to speed up the degassing process.

The volume of even a fractional monolayer of adsorbed gas if transferred to the system is equivalent to a pressure well above ultra-high vacuum. To prevent slow subsequent outgassing in this pressure range with its significant effect on the pressure, the envelope must be thoroughly degassed which requires subjecting it to the highest possible temperature. The safe high temperature limit on selected glass, if used for the envelope, is not much above 450°C, but glass manufacturers are developing glasses with a somewhat higher temperature limit [6014]. Csernatony [63158] stresses the necessity of removing films from glass by chemical means. Another expedient [6131] to reduce subsequent outgassing is to outgas at both the highest temperature possible and at a pressure much lower than the working pressure to be measured.

Redhead [60162] pointed out that thorough degassing of the grid of Bayard-Alpert gages is essential in order to prevent gas evolution from it due to bombarding electrons. Pressure inequalities, gage and vacuum system, otherwise results.

The literature is extensive on the composition of the gases released by degassing, both for metals and glasses. The gases released come from the surface and also diffuse from the interior of the material. The diffusion process increases the time to degas. For glasses, which is usually the gage envelope material, the principal gas evolved during degassing is water vapor Dushman [B491], Todd [5503], Garbe and Christians [6249]. Most of the water vapor is released at glass temperatures in the region 200-300°C. Carbon dioxide appears to be the next most abundant gas released. The amount of water vapor degassed differs for pyrex and soft glass [6249].

Dayton [59153, 6138, 6266] considered the degassing of metals, contaminated metals and plastics in considerable detail and has developed a theory which connects outgassing rate with metal temperature, diffusion and other factors. Again water vapor is important. It may form as many as 80 monolayers on contaminated layers, but is largely released by pumping. Oxide films form on many metals.

2.6.2. Adsorption. The effect of pure adsorption on pressure measurements with ionization gages is normally secondary, compared with that of ionic pumping and chemical activity of the gage.

The time rate of adsorption is of some importance in tubing, if initially degassed, followed by adsorption of a gas. The time required for the gas entering at one end of a tube to reach the other end may be quite large. Reich [60163] considered the case of pump oil vapor entering a tube from a vacuum system and leading to the envelope of an ionization gage.

Clausing [3009] (Dushman [B491]) developed a formula given below for the time t_o required for a monolayer of a gas to form in a tube of length L and radius r where $(r/L)^2$ is negligible. The tube surface is assumed initially free of the gas and the sticking probability is assumed equal to unity. Until this adsorption is completed, practically none of the entering gas reaches the tube exit.

$$t_o = \frac{3L^2 + 16\ rL}{2Fr^2\ \overline{nc}} = \frac{(3L^2 + 16rL)\ \sqrt{2\pi\ RMT}}{8\ Fr^2 P} \qquad (5)$$

where

$$\frac{\overline{nc}}{4} = \frac{P}{\sqrt{2\pi RMT}} \qquad (6)$$

Here F = the absorption cross-section of the gas molecule

$\frac{\overline{nc}}{4}$ = the number of gas particles incident at one end of the tube per unit area and time

P = pressure

T = temperature °K

R_o = universal gas constant

M = molecular weight

Reich calculated that 8.2 hours is required to form a monomolecular film of nitrogen in a tube 2 cm in diameter and 15 cm long at a pressure of 10^{-8} torr. For an oil vapor of molecular weight 450, the time would be about 32 hours. Here L/r = 15. If L/r = 2, and assuming that the formula holds for a ratio this small, the time for a monolayer of oil vapor to form on the tube wall would drop to about 1.6 hours. This indicates that waiting time for equilibrium would not be of great practical significance in ordinary laboratory sized vacuum systems. However, some attention needs to be given to adequately dimensioned connecting tubing to vacuum gages.

2.6.3. Ionic Pumping. Removal of gases within and by the ionization gage is by two main processes (a) by ionic pumping, sometimes called electrical removal or electronic pumping and (b) by chemical action. Ionic pumping is the entrapment by negatively charged, or neutral, electrodes or walls of ionized gases which have acquired energy (Alpert [5874], Redhead [60162], Bloomer [6061]). It includes adsorption of the ions, probably neutralized upon contact with the negatively charged surface, and permanent trapping of the ions by sputtered metal evaporated from the hot filament. For a review see Carter [5919], Cobic [61206] and Baker [6330].

Ionic pumping proceeds rapidly at first and then tapers off greatly, finally becoming constant with time [6172]. Desorption, or recovery of adsorbed gas after activation of the gage is interrupted, is of the order of 10 percent of the volume adsorbed, and decreases after each cycle of pump operation. This recovery is reduced by annealing the glass surface; this reduction is called secondary pumping by Baker [6172].

Schwarz [4405], Carter [5919], Baker [6172, 6330] and probably others indicate that the primary mechanism in ionic pumping of inert gases is due to the positive ions being shot into negatively charged solid surfaces. The energy lost by the ions produces lattice defects in the solid surface which prevents escape of the ions. Annealing out the lattice defects in glass traps the gas more permanently.

The above mechanism does not appear to hold for clean glass surfaces. Thus, for argon Blodgett and Vanderslice [6173] found that the mechanism applied only when a metal film had been deposited on the glass surface. See also Cavaleru et al [6412] on the mechanism of argon adsorption.

Similarly as for argon, Varnerin and Carmichael [5517] and Blodgett and Vanderslice [6173] found that helium is not trapped in the glass envelope of the gage until a metal film, normally deposited by evaporation from the hot filament, is present on the glass surface. Otherwise, helium pumping is by adsorption by the metal supports for the filament [5517], or metal screens or metallized wall of the gage (Baker and Yarwood [6340]). Young [5665] showed that the pumping speed of helium into a clean glass surface is about 1/5 of that into a sputtered metal surface. The rate of cleanup is exponential.

For nitrogen, Carter, James and Leck [6207], Cobic and Carter [61178, 62131], Carter [6356] and Florescu [6416] point out that the ionic pumping is too large to be explained by the above mechanism;

they suggest that the bombarding nitrogen molecules are dissociated or are in a metastable state and the pumping is therefore a chemisorption process. Jaeckel and Teloy [6174] report that the pumping is due mainly to the excitation of the metastable state of nitrogen.

Young [5665] and Robinson and Berz [58138, 5931] investigated the initial ionic pumping in hot cathode ionization gages. The latter experimenters obtained experimental data on ionization gages with a tungsten filament operated at the lowest practical temperature and includes the effect of the temperature of the glass envelope. The pressure range was 10^{-7} to 10^{-9} torr. A formula was given relating pressure change to pumping time. Both the pumping and recovering speeds were greatly affected if the glass surface had an evaporated titanium film.

Alpert [5874] derived a relation similar to that of Robinson and Berz assuming a rate of pressure reduction in the gage proportional to pressure.

It has been assumed this far that the surfaces were initially well degassed. A gas initially adsorbed on the surface by ionic pumping or otherwise, can be released by impinging ions of another gas. Thus Dushman-Lafferty [B621] in their review point out that impinging mercury ions cause hydrogen to be liberated from the surface, also that gas is released from the walls by impinging nitrogen, carbon monoxide and argon ions (Schwarz [4405]). See also [5878].

Ionic pumping of Penning cold cathode gages has been considered by Leck [B571, 5312]. For nitrogen and argon the pumping rate increases with the accelerating voltage, but not with pressure. The gas is adsorbed by the electrodes, not on the glass (Brown and Leck [5506]), and is desorbed at about 300°C. As expected, the pumping rate decreases with time. The pumping rate has been reduced by Lepekhin and Sheresheviskii [6443] by using a grid as the anode, thus reducing the area effective for pumping. Kawasaki [6410], using a radioactive tracer, Xe^{131}, found that inert gases are adsorbed principally at the cathode; about 20 percent at the anode. Continued erosion of the cathode releases previously adsorbed gas. This confirms Brown and Leck's observations.

Data on the ionic pumping speeds for various gases for various designs of ionization gages are particularly pertinent for pressure measurement and follow below. It is not always clear whether the data refer to initial pumping speed or the low stable pumping speed attained after operating the gage for some time. It is assumed that the pumping speeds given refer to liters per second at the ambient pressure; in any case the data are reasonably comparative.

For Bayard-Alpert gages, and probably of the same order of magnitude for hot wire gages of other designs, the pumping speeds are as follows:

(a) Nitrogen: 0.1 l/s [5665] 0.25 l/sec [60162]; 0.08 l/sec for well baked glass envelope and thin evaporated tungsten film, 0.20 l/sec for a similar condition of the glass envelope but with a freshly evaporated tungsten film (Bills and Carleton [5885]). Hobson [6124] in his extensive review of nitrogen pumping, gives 0.25 l/s after chemical pumping disappeared, which value fell sharply after 10^{-17} molecules were pumped.

(b) Oxygen: 11 l/s initially at a pressure of 1.25×10^{-5} torr; 1.8 l/s initially at 1.25×10^{-6} torr; finally, after 16 liters pumped, 0.01 l/s. [5885] In all cases a tungsten film was present on the glass envelope surface.

(c) Argon: 0.08 l/s [60172].

(d) Helium: Maximum pumping speed, 4×10^{-3} l/s [5665, 60162].

(e) Hydrogen: See Section 2.6.4.

Winters, Denison and Bills [6212] show that reducing the emission (electron) current from 1 ma to 1 μa reduces the pumping speed by a factor of 10^4. Practically, reducing the emission current increases the difficulty of output measurement and may enhance the importance of background currents.

Cold cathode gages of the Penning type have higher ionic pumping speeds than the Bayard-Alpert gage. For air, nitrogen, water vapor, carbon tetrachloride and ethyl ether, the initial pumping speeds vary from about 0.3 to 0.5 l/s, depending on the applied voltage; the final speed is from 0.1 to 0.2 l/s. For argon and hydrogen the total volume pumped is much less with about the same pumping rates. For argon the initial speed varies from 0.1 to 0.4 l/s, again increasing with the applied voltage; it falls quickly to a steady value varying from 0.01 to 0.04 l/s [B571, 5312]. Desorption after pumping is about 1 percent of that pumped; when the glass surface is heated to 400 - 500°C, a sudden burst of gas is released [5312].

Lafferty's hot cathode - magnetron gage [6104] has an ionic pumping rate of 3×10^{-10} l/s at very low electron emission levels (10^{-9} - 10^{-7} amperes), as here employed.

The electron beam gage [6178] has small ionic pumping rates. For nitrogen, the rate is 3×10^{-3} l/s, when the electron current is 1 ma.

For the magnetron gage, pumping rates are reported as follows:

a) Redhead [5867, 58135, 58136]: helium 0.15 l/s.

b) Rhodin and Rovner [60172]: nitrogen 0.14 l/s; argon, 0.018 to 0.34 l/s; oxygen, 0.15 to 0.36 l/s at about 10^{-5} torr for various conditions of the glass envelope surface.

c) Barnes and coworkers [6289]: helium, 0.15 l/s; nitrogen, 2.5 l/s; argon, 1.7 l/s; oxygen, 3.4 l/s; hydrogen, 2.0 l/s; and carbon dioxide, 2.4 l/s. All are averaged pumping speeds at about 5×10^{-6} torr. The values are about ten times higher for all gases except helium than those obtained by other workers, with the discrepancy unaccounted for.

From the standpoint of pressure measurement, it is seen that ionic pumping can be expected if the positive ions can bombard any surface, metal or glass, other than the ion collector. Further, the pumping rate is initially large and falls off with time to a steady value, and if the gage is isolated, comes rather rapidly into equilibrium with desorption from the walls, Smith [63101]. Assuming that the ionization gage measures the pressure in its envelope, two steps can be taken to minimize the difference in pressure in the gage envelope and the vacuum system. First, the conductance of any tubing connecting the gage and system must be large, resulting in a "nude gage" (Section 2.2) when pushed to the ultimate. See Leck [B571] for computations on this point. Second, to minimize the effect of all types of pumping it has been suggested that the grid and ion collector voltages of the gage be applied only for an interval of time sufficient to obtain a reading while the filament power supply is kept on. This procedure is largely ineffective because desorption is taking place in the absence of pumping and also because ionic pumping is a maximum when the accelerating voltage is first applied. Some data bearing on this conclusion are given by Groszkowski [63175] and Axler [64146]. If the electron emission in hot cathode gages is reduced below the commonly used value of 1 ma, the initial ionic pumping is greatly reduced (Steckelmacher [6282]). This reduction however introduces background current difficulties with certain gases (see Section 2.6.7.).

If readings are made after continual operation of a gage for an interval of time, the ionic pumping speed is reduced to a minimum, which is helpful in the absence of chemical reactions. In hot wire gages, this gain is usually overbalanced by chemical reactions, again leaving the validity of the pressure measurement in doubt.

2.6.4. Chemical Reactions. Chemical reactions largely occur only in ionization gages having a hot filament. Chemisorption is defined as the adsorption of a gas or vapor produced by the chemical interaction of the gases and solids in the gage usually initiated by the hot filament.

The chain of events involved in Blears effect starts with a chemical decomposition of pump oil vapor at the hot filament; it is discussed in the next section. Garbe [6379] points out however that molecules of pump oil DC 704 (at 6×10^{-8} torr) adsorbed on solid surfaces outnumber those in the free space. Therefore, in an ionization gage, cracking of the oil by accelerated electrons occurs mainly on solid surfaces. Experimental data bearing on this are given by Garbe.

In general, polyatomic molecules, such as water vapor, hydrogen and chlorine, dissociate when in contact with the hot filament and are subsequently adsorbed. The degree of dissociation is greatly reduced by reduction in the temperature at which the filament is operated. See Winters et al [6212] for data. Some of the voluminous, but still incomplete, data will be outlined.

The hot tungsten filament is oxidized if oxygen is present. Details are given by Becker and Brandes [6105], Ackermann and Rauh [63219], Gasser and Patterson [6423] and many other earlier investigators [4821, 5253]. The tungsten oxide is deposited on the cold surfaces of the gage, notably the glass walls. Thus oxygen is removed, or gettered, from the ambient gas, reducing the oxygen pressure in the gage envelope. Leck [B571] calculated the quantity of oxygen removed and obtains $Q/P = .02$ l/s at a tungsten filament temperature of $1400°K$ and 0.6 l/s at $2400°K$ where Q is the quantity and p is the pressure. This was experimentally confirmed by Riddiford [5109]. Leck [B571] concludes that the affect on the electron emission of tungsten is small, of the order of 10 percent; there remains, however, the effect on the oxygen pressure in the gage envelope. Leck states further that the erosion of the tungsten filament due to oxygen attack is generally uniform over the heated part and that filament breakage ensues only when the diameter is reduced by 1/2 to 2/3.

While probably of minor importance in pressure measurement, it appears that chemisorption of nitrogen by the hot tungsten cathode occurs. Investigations have recently been made by Oguri [63287, 6483], Ricca and Saini [6475], Bliven and Polanyi [63269] and Kornelson [6425].

If the tungsten filament contains carbon as an impurity, and an oxygen layer exists on the surface, carbon monoxide and carbon dioxide will form, and continue to do so as the carbon in the tungsten diffuses to the filament surface. Young [59180] states that a filament containing 0.012 percent carbon pro-

duced at 2000°K an increasing amount of carbon monoxide and dioxide for 10 minutes and then no change for several hours. In extensive experiments Becker and Brandes [6105] found that these gases formed if an oxide layer was present on the tungsten and if the temperature was high enough. The amount of carbon oxides formed did not account for the drop in oxygen pressure. The carbon in a tungsten filament is removable by prolonged heating at 2200°K under vacuum containing oxygen at a pressure of 10^{-6} torr.

Water vapor is dissociated by a hot tungsten filament. This sets up a cycle according to Langmuir (Dushman [B491]). The oxygen combines with the tungsten and the hydrogen may be dissociated to atomic hydrogen. The tungsten oxide distills to the glass envelope surface, is deposited as a film. It is reduced to metallic tungsten by the atomic hydrogen with water vapor again produced. The end result is a continual increase in the tungsten deposit on the glass surface. These reactions are reduced by lowering the filament temperatures and eliminated by removing water vapor from the gage. The error in measuring the pressure of gases containing water vapor does not appear to have been investigated. In measuring the pressure of water vapor, Futch [6130] avoided this chemical activity by using a thoria coated iridium filament in his gage.

The atomic hydrogen forms at an appreciable rate when the tungsten filament temperature exceeds about 1000°K Langmuir [1501], Hickmott [6002, 6083]. The hydrogen atoms are adsorbed, particularly on a glass envelope, and as might be expected, strongly at low glass temperatures (80°K) and less so at glass room temperature [6083]. After a monolayer is adsorbed much of the incident atomic hydrogen converts to molecular hydrogen and is re-emitted Langmuir [1501]. This adsorption of atomic hydrogen gives rise to an abnormally high pumping rate at least initially which Schwarz [4405] found to 0.02 l/s. Also, to complicate the situation, the impinging atomic hydrogen reacts with glass to produce water vapor, methane and to a greater extent carbon monoxide.

Redhead [60162] advocated reducing the filament temperature and finds that little carbon monoxide is produced when using a lanthanum boride covered rhenium filament operated at 1300°K. If a hot filament is used, he suggests interposing a metal surface between the glass envelope and the filament, where the hydrogen atoms will recombine. See also Hickmott [6002].

Chlorine molecules were found by Langmuir [B491] to dissociate similarly as hydrogen molecules when in contact with a hot tungsten filament. This gas is seldom present in vacuum systems; if so, metal chlorides will be formed.

Oxygen does not appear to be removed if a lanthanum boride covered wire filament is used (Young [59180]).

The breakdown of methane was discussed by Baronetzky and Klopfer [58130]. Their data indicated that the methane pressure remains constant when the oxycathode filament temperature was 800°C, fell significantly when a thoria coated platinum iridium filament was a 1280°C, and fell rapidly when a tungsten filament was at 1900°C.

In general cold cathode gages do not initiate or accelerate chemical reactions and from this point of view are superior to all hot filament designs.

2.6.5. Blears Effect. In a mixture of gases, particularly those containing hydrocarbons, such as pump oils, the rate of adsorption in connecting tubing will influence the ionization gage readings. Blears [4708] pointed out that two ionization gages, one connected to the vacuum system by glass tubing, the other installed "nude" in the vacuum system, will differ in indication by as much as several orders of magnitude, if oil diffusion pumps are used. The nude gage indicates the higher pressure. It occurs at pressures below about 10^{-6} torr. This difference in performance is known as the Blears effect.

If pump oil vapors are absent from the vacuum system, Hartman [6304] found that readings of either a nude or tube connected Bayard-Alpert gage had no significant difference in indication. The pressure was 10^{-6} - 10^{-9} torr and the gas composition was 70 percent carbon monoxide, 15 percent hydrogen, water vapor 7 percent, with a scattering of other gases. Incidentally, he varied the electron emission current from 10^{-6} to 10^{-2} amperes and secured a linear response over a wide range of these emission currents; the positive ion current indications were corrected for leakage current (no filament current, accelerating voltages applied) and the x-ray current.

Reich [60163] assumed that initially all of the pump oil vapor has been degassed from the surfaces, particularly those of the tube connecting the gage to the vacuum system. The constant lower reading of the tube connected gage is due to the fact that no pump oil vapor reaches the gage envelope. Reich concludes that a long time is required for the connecting tube to adsorb a monolayer of the pump oil vapor, which he computes by Clausing's formula (see Section 2.6.2) and finds to be of the right order of magnitude to account for his experimental results. The gradual rise in indication of the nude gage presumably is due to the rise in oil vapor pressure which is hindered by adsorption in the vacuum system and decomposition by the nude gage.

In fact, Reich confirmed the theoretical and experimental work of Hayashi [5754] on the rate of adsorption of pump oils in tubes initially having clean surfaces. While Hayashi pointed out that application of his equations to pump oils is questionable (but valid for lighter molecules) he showed by a simple experiment that the rate of flow of dibutyl phthalate through a tube is inordinately less than the molecular flow computed from the Knudson equation.

To speed up pressure equilibrium Reich suggested heating the connecting tube to prevent adsorption, illustrated by experiments on water vapor.

Reich calls attention to the fact that the ionization gage sensitivity for pump oil vapors is at least 12 times higher than for nitrogen. Differences in reading in the two gages if due to oil vapor are thus magnified.

Haefer and Hengevoss [60156, 6312] investigated equilibrium conditions. Briefly, thorough degassing brought the initial readings of the nude and tube connected gages to the same reading. At pressure equilibrium, the nude gage read about ten or more times higher with the vacuum system at room temperature. At temperatures below about $-10°C$ of either vacuum chamber in which the gages were installed the gage readings were nearly the same, with differences depending upon the particular pump oil used. The adsorption time required for connecting tubing as considered by Reich was not evaluated, but the Haefer data indicates that pressure equilibrium was probably obtained.

Their explanation of the Blears effect follows. Initially it is assumed that both gages are subjected to the same oil vapor pressure, but is is only necessary to start with both subjected to the same pressure. Both gages decompose the hydrocarbon oil vapor to smaller molecules, which are ionically pumped into the surrounding surfaces. This process does not appear to significantly affect the pressure in the vacuum system owing to its large volume, evidence for which is Reich's observation of the constancy of reading of the nude gage with time. In the tube connected gage, it appears likely that all of the pump oil vapors are cracked, and that at least most of the craked products are ionically pumped. The oil vapor has a conductivity through the connecting tubing less by a factor of the order of 10^{-4} than that of the gases produced by cracking. This means that any inequality in the pressure of the permanent gases is much more rapidly equalized by conduction and that a deficiency of pump oil vapor exists and grows with time in the envelope of the tube connected gage. The latter ultimately indicates the system pressure minus the pressure of the pump oil in the system. Thus, a deficiency of oil vapor in the tube connected gage, produced by cracking and its inadequate replacement by conduction account in the main for the Blears effect.

Haefer and Hengevoss apparently have given the mechanism involved in the Blears effect under equilibrium conditions. Reich's contribution is to call attention to a transient condition, the duration of which is perhaps still in some doubt.

2.6.6. High Frequency Oscillations. Radio frequency oscillations of the type first described by Barkhausen-Kurtz in 1920 are set up in some measure in all ionization gages. Their effect on the indication of ionization gages can be largely reduced by modifying the electrode geometry of the gage (Jaycox and Weinhard [3105]) and by reducing the power input into the gage, either or both the filament current and grid voltage [B621]. Other expedients are effective as mentioned below.

In his review, Redhead [60162] indicated that the Barkhausen-Kurtz oscillations occur in Bayard-Alpert ionization gages under many conditions and always when the electron current exceeded 1 ma. These cause some electrons to gain sufficient energy so that

   a) electrons reach the ion collector, and

   b) electrons strike the gage envelope.

Also any radio frequency output can be rectified at the grid of the first stage of the ion current rectifier. Extraneous and erratic indications result which are independent of pressure.

Redhead practically eliminated the effect of the oscillations on the gage indications by a conducting coating on the inside of the gage envelope. Transparent tin oxide was used. However, radio frequency oscillations could still be detected.

Pierre [61180] described the generating mechanism of the oscillations and outlines ways of preventing them.

Conn and Daglish [5311] and Dumas [5505] found high frequency oscillations to occur in the Penning type cold cathode gage, which gave rise to fluctuating indications. Conn and Daglish found experimentally that electron oscillations were not the cause and concluded that the cause was plasma oscillations. No cure was suggested.

Vasileva and Reikhrudel [62184] developed a theory to account for the high frequency oscillations in a Penning gage of a specified design. Kaganskii, Kaminski and Klyucharev [64139] find that

oscillations in the range 10 to 10,000 kHz occur. These are intense at pressures around 10^{-3} torr and result in additional output currents comparable to that expected for the pressure. The oscillation currents are a function of the ratio of anode voltage to magnetic field strength.

Hobson and Redhead [58134] reported that high frequency oscillations, varying from 400 Hz to 150 kHz, are always present in inverted magnetron gages in the pressure range 10^{-7} to 10^{-4} torr. Discontinuous jumps in the mode of the oscillations occurred which resulted in small discontinuous jumps in the collector current of the gage. The frequency of the oscillations increased with increase in the collector current of the gage independent of the gas composition, with the magnetic field and applied voltage maintained constant.

Worrell [6389] describes an instability in the magnetron gage at pressures near 10^{-9} torr. It manifests itself as a jitter, usually followed by a discontinuous jump in the ion current, that is to another mode of stable operation. The cause of the change in mode of operation was not investigated, but their origin in high frequency oscillations is highly probable.

2.6.7. Background Currents. These currents, also called residual currents, are that part of the electrical output of the gage which is independent of the pressure. If this extraneous output does not vary with pressure, it merely limits the lowest pressure which can be measured by the gage; if not so constant, pressure measurement becomes difficult.

Background currents may have many sources. These are principally soft x-rays and high frequency oscillations, both produced in the tube. The latter has been considered in Section 2.6.6; consideration here will be on other sources, principally the soft x-rays.

Mention should be made of background currents in Bayard-Alpert gages due to the effect of ultra-violet radiation from the hot filament and from sources external to the ionization tube (Redhead [60162]). This background current, on which no data appears available, is probably small. The ionization tube can be shielded from external ultraviolet radiation to eliminate the effect. The use of a cathode operating at relatively low temperatures, such as a lanthanum boride covered rhenium wire, would reduce the ultraviolet light from the hot cathode to a negligible amount.

Historically, hot wire gages available before 1950 had a background current due to soft x-rays which had a value equivalent to that for a pressure of about 10^{-8} torr (Alpert [5874]). Bayard and Alpert [5012] and others recognized the source of this bar to low pressure measurement. See Section 2.2.1. for the design of the Bayard-Alpert gage.

Other workers have further reduced the diameter of the ion collector wire in Bayard-Alpert gages in order to reduce the target area for incident soft x-rays. Redhead and McNarry [5428] reduced the ion collector to a wire 0.003 inch in diameter; Venema and Bandringa [59181] reduced the wire diameter to 25 microns (0.001 inch) in diameter; and Van Oostrom [6179] reduced it to four microns to secure an x-ray effect equivalent to about 10^{-12} torr. Schuetze and Stork [6296] reduced both the length and diameter of the ion collector and concluded by experiment and theory that the x-ray effect can be reduced to be equivalent to below 5×10^{-11} torr.

Schuemann [6283, 6325] designed a hot cathode gage for making measurements below 10^{-10} torr specifically to reduce the x-ray effect. See Section 2.2.10.

Hayward, Jepson and Redhead [6394] uncovered a reverse x-ray effect in Bayard-Alpert gages. Soft x-rays from the grid cause photo currents to be emitted from the gage walls, some of which will reach the positive ion collector if it is at or near the wall potential. This current to the positive ion collector, opposite in sign to the normal x-ray current, is termed the reverse x-ray effect. At best it can only partially compensate for the normal x-ray current.

Redhead [60162, 6226] found that the background current of the gage increased as much as 400 fold when certain gases, particularly oxygen, water vapor and carbon monoxide are chemically adsorbed on the electrodes. This effect was absent with hydrogen and nitrogen. With a well outgassed Bayard-Alpert gage the background current was equivalent to that for a pressure of 6×10^{-11} torr.

Oxygen, the worst offender in this respect, was admitted to the gage for one minute to secure a pressure of 10^{-7} torr and then pumped out. The background current at 5×10^{-9} torr rose to a value equivalent to 2.4 x 10^{-8} torr. When the electron emission current was 8×10^{-5} ampere, 60 hours were required to lower the background current to its initial value; when the emission current was 10^{-3} ampere, the time was 50 minutes. Heat is insufficient to release these gases from either molybdenum or tungsten grids; electron bombardment is required. The background current is caused by positive oxygen ions released from the grid by electron bombardment (Redhead [6337], Schuemann, de Segovia and Alpert [6393], and Hartman [63167]).

The experiments of Redhead, and Huber [63205], lead to the conclusion that the electron emission current of the Bayard-Alpert gage cannot be indefinitely lowered to avoid ionic pumping; to avoid long-continued high-valued background currents, the value must be one milliampere or above. Further [6337,

6393], thorough outgassing of the grid is essential to secure reliable measurements in the ultra-high vacuum region. However, Redhead [6337] and Hobson [64143] point out that correction for stable background currents can be made from the indications of a modulated gage. Hobson [64143] developed procedures for obtaining pressure measurements with the modulated gage down to 7 x 10^{-15} torr. See Section 2.2.2.

Huber [63205] determined this change in the x-ray limit of three designs of Bayard-Alpert gages with changes in the electron emission current. Redhead's results were confirmed in that the grid released previously adsorbed carbon monoxide principally (apparently oxygen was not present in the vacuum system) at rates dependent on the size of the emission current. Experiments showed that the carbon monoxide was not dissociated, which left unexplained the excess in gage current output over that of the Lafferty hot cathode magnetron gage which was used as a monitor.

The photocurrent suppressor gage developed by Schuemann [6283, 6325] has been described in Section 2.2.10.

No separable background current due to soft x-rays is produced in the cold cathode gage such as the Penning or magnetron gages (Redhead [58136]). Background currents of opposite sign exist in the photomultiplier gage, Riemersma et al [60159, 6103], which permits compensating for the x-ray produced current. In the electron beam gage, adjustment of the magnetic field strength is possible to prevent the production of soft x-rays (Klopfer [6178]). Lafferty [6104, 6181], in the design of the hot cathode magnetron gage reduces the effect of the x-ray produced current to a value far below that in the Bayard-Alpert gage.

2.6.8. Gage Envelope Problems. Three performance problems are discussed: a) permeability of gases through the walls, b) effect of electrical condition of inner surfaces, and c) effect of envelope temperature. Effects b) and c) are particularly important in gages having a hot cathode.

2.6.8.1. Envelope Permeability. The gases of low atomic number such as hydrogen and helium diffuse through non-crystalline materials, such as glass, rubber, plastics, etc., at significant rates. The data accumulated by many have been reviewed by Dayton [59153], Diels and Jaeckel [B581] and others.

The diffusion of atmospheric gases through glass is significant only in ultra-high vacuum measurement. Only the diffusion of helium in the atmosphere through the glass envelope into the gage is of practical importance at the present time. Norton [6136] and Altemose [6134] presented data on the rate of diffusion of helium through many compositions of glass. The logarithm of the permeation rate decreases with decrease in temperature of the glass and is linear with the reciprocal of the absolute temperature. The permeation rate is highest for quartz and falls many orders of magnitude for Corning glass 1720, [6134] and for a lead borate glass [6136]. Approximately, the permeation rate through various glasses is directly proportional to the percent content of $SiO_2 + B_2O_3 + P_2O_5$. The permeation constant for pyrex is about ten times of that for soft glass. Norton [6136] gives a curve of time against pressure of helium diffused through silica, pyrex, soft glass (soda lime) and Corning 1720 bulbs. In one hour this pressure in the bulbs would be respectively about 10^{-8}, 10^{-9}, 10^{-12}, and 10^{-14} torr. The effect of helium diffusion can thus not be ignored in making ultra-high vacuum measurements.

Three ways of eliminating the permeation of helium have been proposed. Varnerin and White [5435] surrounded a Bayard-Alpert gage with an enclosure which could be evacuated. By this arrangement the pressure of helium external to the gage envelope could be reduced to an insignificant amount, practically eliminating diffusion of helium into the gage since its rate is proportional to the difference in the pressure of helium on the two wall surfaces. As an ultimate refinement, the external helium pressure of helium could be maintained identical with the internal helium pressure, this eliminating diffusion in either direction. Incidentally Varnerin and White lowered the measurable pressure of their gage to 10^{-11} torr. Rivera and Riche [59143] used a double chamber, principally to reduce leakage effects.

The second method, experimented with by Lafferty [60160], involved a change in the envelope material. A combination of a ceramic and titanium was used instead of glass. The permeation of all gases for these materials is very low, permitting extension of pressure measurements many decades lower than with an envelope of the most favorable glass composition.

The third way is to use all metal envelopes to the extent possible. These are favorable both with respect to gas permeation and ease in fixing its electric potential. Compared to a glass envelope, insulating the electrode leads is somewhat more complicated, which is a minor disadvantage.

Some reduction in permeation is obtainable by reducing the temperature of the gage envelope as discussed in Section 2.6.8.3.

All of the three methods discussed above will control permeation of gases through the gage envelope within acceptable limits. Other factors control the choice of method. It should be mentioned that the development of glasses with low permeation rates for gases is also proceeding and their use may be an acceptable alternate in many cases.

2.6.8.2. Electrical Potential of Envelope. Glass is normally an insulator and therefore can be expected to collect or lose electrical charges, depending on such factors as adsorption or desorption of gases by impinging molecules, ions or electrons generated in the gage. Control of the phenomena is essential to the reliable operation of the hot cathode gage.

Carter and Leck [59102, 61128] found a double sensitivity to occur in Bayard-Alpert glass-enclosed gages, which they state are due in some manner to electrical charges on the glass surface and perhaps to the assymmetry of the gage electrodes, more probably a high frequency effect (see Section 2.6.6.). The two sensitivities differed by a factor of three. A metal screen inserted between the glass envelope and the gage electrodes aided in eliminating the ambiguity in sensitivity, but better, is holding the electron collector voltage below 250 volts.

Nottingham [5474, 6188] and Redhead [60162] found that sensitivity of the Bayard-Alpert gage was increased and high frequency oscillations reduced, by enclosing the entire electrode system by metal grids, including top and bottom. This facilitates positive ion collection and prevents chemical action involving hydrogen occurring at glass surfaces, but not at metal surfaces. The electrical potential of the metal grids is made negative to repel electrons and thus increase their path length.

An evaporated metal film on the inside of the glass envelope, used by Bouwmeester and Warmoltz [5504] and Frost [62104] is just as effective as the metal grids, but probably is less practical. Frost recommends an exterior grounded coating of silver paste as almost as effective. A tin oxide coating is used commercially. A practical solution is the use of an all metal case.

2.6.8.3. Envelope Temperature. It is generally assumed, at least to a first approximation, that the rate of ionization in the gage is proportional to the gas density. Safely, minor changes in envelope temperatures will not appreciably affect the rate of ionization, and therefore not affect the gage indication. Two assumptions will be made: first, that the gas and envelope temperatures are the same, and second, that equilibrium conditions exist in the gage and vacuum system. If the temperature of the envelope is changing, adsorption and degassing in the gage are far more significant on the indication of the ionization gage than the direct effect of changes in gas temperature.

If the envelope temperature differs from that at which the gage was calibrated, the pressure $P = P_i T_o / T$ where P_i is the indicated pressure and T_o is the envelope temperature at which the gage was calibrated and T the envelope temperature. Ordinarily this correction is not applied, first, because the additional accuracy obtained is usually insignificant, and second, because envelope and gas temperatures are not necessarily related, particularly in a hot cathode gage. It is impractical to measure the gas temperature.

Another situation may exist, in which the vacuum system and the gage temperature differ. In this case thermal transpiration occurs [B491, B621] if the two are connected by tubing or an orifice of a bore small compared with the mean free path of the gas, resulting at equilibrium in a difference in pressure in the gage, P_g, and in the vacuum system, P. At equilibrium $P/P_g = \sqrt{\dfrac{T}{T_g}}$ where T is the gas temperature in the vacuum system and T_g in the gage. Miller [63211] and Takaishi and Sensui [63229] investigated special cases of thermal transpiration both theoretically and experimentally which may be of some interest in pressure measurement. It should be noted that the gas temperatures in the ionization gage, particularly in the hot cathode type, and in the vacuum system will always differ somewhat because of the energy input into the gage. If the error is considered significant, correcting gage readings is impractical so recourse is to methods of equalizing the pressures. This is facilitated greatly by an adequately large conductance between the gage and system, in the ultimate, a nude gage. However, in view of the greater magnitude of residual errors due to other causes, a fine-grained consideration of gage envelope temperature errors is hardly warranted in practice.

Far more important practically are the increase in permeation of helium through the glass envelope and increase in outgassing from the envelope surface with increase in envelope temperature. These are of particular importance in measuring ultra-high vacuum. Redhead [60162] found that the envelope of a Bayard-Alpert gage is heated to about 50°C due to radiation from the hot filament. He obtained data at about 10^{-10} torr on gas composition in the gage when the envelope was about 50°C and when a cooling air-blast was directed against the gage envelope. The absolute pressure in the cooled tube fell to about one-half, the hydrogen pressure fell five fold and the helium pressure fell 30 percent. These two gases were the main components present. The reduction in helium pressure was ascribed to reduction in the permeation of helium through the envelope. At the lower wall temperature, water vapor desorption was reduced, therefore less was dissociated by the hot filament, resulting in a significant reduction in the hydrogen present.

Redhead suggests as remedies that the gage envelope size be large (about 8 cm in diameter), that the envelope be cooled (an air blast is suggested) and last, and perhaps more fundamental, that the operating temperature of the filament be reduced by using a lanthanum boride coated filament.

For reasons discussed in Section 2.6.8.2, a metal grid interposed between the glass envelope and the gage electrodes is recommended. If this grid and the glass envelope are well outgassed while at temperatures well above the equilibrium temperatures during normal operation of the gage, the subsequent outgassing can be held to limits which would not greatly interfere with reasonably accurate pressure measurements with a hot filament gage.

Steckelmacher [6282] points out that in addition to the effects just discussed, glass becomes electrically conducting at high temperatures. This leads to the use of an envelope of metal or a ceramic if pressure measurements at high gage temperatures are to be made.

2.6.9. Pressure Equilibrium. The pressure in a vacuum system is never static, varying from point to point, and most of all in the ionization gage, the energy input into which is a serious disturbing factor. The phenomena in the gage which interfere with securing equilibrium are:

a) Adsorption and desorption of gases

b) Ionic pumping of the gage

c) Chemical reactions in hot filament gages

d) Permeability of glass envelope to helium

   The system pressure may be affected by the following phenomena:

e) Adsorption and desorption of gases

f) Permeability of system enclosure to helium

g) Interactions between gages

h) Pressure drop along flow path during pumping

i) Interactions between system and gage

The adsorption and desorption of gases, item a) and e) above, occur in both the system and gage envelope. Due to the difference in the volumes of the system and gage and more significant, the energy input into the gage, the pressure in the gage envelope is affected much more than that in the system, so that a pressure difference, gage and system, can normally be expected due to this cause. For details see Sections 2.6.1. and 2.6.2.

Permeation of gases, mainly helium, through the gage and system envelope, items b) and f), is important at ultra-high vacuums, and again occurs differentially. More pressure-effective permeation occurs through the gage envelope because the ratio, envelope surface to volume, is greater than for the system and because the system envelope often is made of a material more impermeable than glass. Permeation of helium changes the composition of the gas in the gage, as well as increasing the gas pressure in the gage relative to that in the system. See Section 2.6.8. for details.

Ionic pumping, item b), occurring in all gage designs, lowers the pressure in the gage envelope and since the ionic pumping rate differs for various gases, changes the composition of the gases in the gage from that in the system. See Section 2.6.3. for details.

Chemical reactions in hot filament gages, item c), are a legion, changing both the pressure and gas composition in the gage envelope from that in the system. It is largely eliminated in gage designs without a hot filament and greatly reduced by lowering the operating temperature of the hot filament by various means. These are discussed in Section 2.6.4 and a special case, the Blears effect, in Section 2.6.5.

On item g), Worrell [6388] installed five ionization gages in various positions around a sphere 20 cm in diameter. He found that some of the positive ions produced in one gage could migrate to the ion collector of another gage. This interaction, while existing here in a rather unusual set up, may occur in practice if positive ions are produced by more than one electronic stream in a vacuum system.

Item h) is the pressure drop in the system during pumping. The pressure is lowest at the pump entrance and rises with distance from the pump. The flow pattern varies with the geometry of the system. The axis of the tube connecting the gage and system should preferable be at right angles to the flow direction but could be such as to head into or away from the flow direction; the pressure measured will vary with the tube heading. Theoretically at least, the pressure of the system is measured only at the point where the gage is connected. In the case of nude gages baffles need to be placed near pump openings to avoid flow effects.

The final item i) is the interaction between the vacuum system and the gage. This can be illustrated by what would occur in a closed system with a nude gage installed. The pressure and gas composition in the system will be altered by the presence of the operating gage by b) ionic pumping, and c) chemical reactions triggered by hot cathodes. If the gage is connected to the system by a tube, gas flow between the gage and system occurs in addition, generally making the pressure measurement even less valid.

Due to these various causes, both the pressure and composition of the gases in the gage will vary from that in the vacuum system. Use of low temperature cathodes in Bayard-Alpert gages or use of cold cathode gages greatly reduces the lack of equilibrium. Further reduction is achieved by making the conductance of the tubing connecting the gage and system as large as practical, in the ultimate resulting in a nude gage. However, even with a large conductance, transfer of gases in the higher vacuum ranges requires a long time, hours in fact, to obtain any semblance to pressure equilibrium. Pumping by the gage is an interfering factor, no matter how or where the gage is installed.

Redhead [60162] and other experimenters seem to agree, that "Total pressure measurements below 10^{-8} torr with an ionization gage give only a rough indication of the system which are useful for comparative purposes."

2.6.10. Gage Geometry. The discussion of gage geometry will be limited to investigations of the effect of the size and configuration of the electrodes in the ionization gage largely to increase or stabilize the sensitivity of the gage. Hot cathode gage geometry primarily to lower the measurable pressure is discussed in Section 2.6.7.

Kinsella [5471] obtained data for hot cathode gages with a cylindrical ion collector, obviously limited by the x-ray produced background current to pressures in 10^{-7} - 10^{-8} torr range. He found that the length and diameter of the hot filament were not important in affecting the sensitivity. Optimum dimensions and designs are presented for the anode wire helix grid and the ion collecting cylinder.

Kobayashi [58115] in experiments with a hot cathode gage design with a cylindrical ion collector, found that moving the hot wire filament to a position close to the ion collector greatly increased the gage sensitivity. Wire anodes in linear array were used. The pressure range of the experiments was in the range 10^{-5} - 10^{-3} torr.

Nottingham [6188] found that, in a Bayard-Alpert gage, the gage sensitivity varies with the distance of the filament from the electron collector and that this distance must be controlled to obtain gages with identical sensitivities.

Schuetze and Stork [6237] and Freytag and Schram [63259] as a result of experiments, specify the values of pitch, wire diameter and helix diameter for the grid and of the filament-grid distance for obtaining maximum sensitivity from Bayard-Alpert gages. The collector wire position inside the grid is stated not to be critical. For a low x-ray limit [6296] the ion collector wire has to be short; practically, pressures down to 5×10^{-11} have been reported by this procedure. See Section 2.6.7.

Enclosing the electrode structure of the Bayard-Alpert gage with metal screens, added by Nottingham [5474], is discussed in Section 2.6.8.2.

Montgomery [3805] added a fourth electrode to the hot cathode gage to serve as a grid between the hot filament and the normal grid anode. Utilizing a negative feedback to this extra grid, the electron emission from the filament could be stabilized at saturation value, and notably reduces its variation with pressure. See Section 2.5.4.

Gage geometry to measure pressures up to a torr with hot cathode gages, which requires shortening the electron path, is discussed in Section 2.3.1.

Conn and Daglish [5412, 5705] presented considerable data on various arrangements and shapes of the electrodes for the Penning cold cathode gage. One arrangement of multiple electrodes was found to have promise for eliminating the extraneous shifts in sensitivity (hysteresis) experienced with the Penning gage. The experiments were made in the pressure range 10^{-5} to 5×10^{-2} torr.

Hayashi et al [4907] found that increasing the dimensions of the electrodes and base permitted extension of the lower pressure limit of the cold cathode gage to below 10^{-6} torr, but several modes of discharge still occurred. On the other hand decreasing the dimensions of the gage permitted higher pressure to be measured, to above 0.1 torr; increasing the magnetic field strength was required, to over 1000 oersteds.

2.6.11. Magnetic Field. The concern here is only with effect of extraneous magnetic fields, not with magnetic fields normally forming part of a gage.

Martin [6185] investigated the effect of both static and pulsed magnetic fields of various strengths upon the sensitivity of hot wire filament gages. By analysis he finds that only magnetic fields normal

to the tube axis and parallel to the plane of the axis of the filament and ion collector, permit pressure measurements to be made. By experiment he found that the sensitivity of a Bayard-Alpert gage in the above orientation was increased by the magnetic field, 4-to 8-fold by a constant magnetic field .027 to .2 webers per square meter for an electron emission current of one microampere and up to 14-fold by a pulsed field in the range 0.3 to 1.5 webers per square meter. (One weber per sq m = 12,600 oersteds.) For any one value of a pulsed magnetic field the sensitivity was found to be practically independent of the electron emission. The sensitivity, magnetic field held constant, increased with decrease in electron emission below one microampere which was inferred to be partially due to heightened gage pumping.

Normand [6193] also obtained data on the magnetic field effect on two designs of Bayard-Alpert gages. A minimum change in sensitivity of the gages was obtained when the magnetic field was normal to the tube axis and parallel to the plane of the filament and ion collector axis, similarly as found by Martin. The change in sensitivity took place at magnetic fields below 100 oersteds; it remained practically constant up to 300 oersteds. In agreement with Martin's theory at other orientations of the magnetic field, Normand's data shows that the sensitivity decreased markedly with increase in magnetic field strength to such an extent as to make the gage useless.

In conclusion, any hot filament gage can be oriented with respect to a uniform magnetic field so that reasonably reliable indications of pressure can be obtained. However, calibration of the gage while subjected to the particular magnetic field is essential.

The lowest magnetic field strength for which data were obtained by Martin is over 500 and by Normand about 100 times the strength of the earth's field. Undoubtedly the earth's magnetic field has some effect on gages not requiring a magnetic field for its operation, but experiments on how significant have not been made.

2.6.12. Protective Traps. Traps, such as cold liquids, copper foil, activated alumina, and zeolites, are used as auxiliary pumping means as well as traps of unwanted gases. These pumps or traps are ordinarily installed between the pumps and the vacuum system. The discussion will be limited to traps used to trap unwanted gases.

Ionization gages should be protected from backstreaming vapors from the diffusion pumps, mainly either mercury or oil vapors, since these are normally not present in vacuum systems. Oil vapors react with the hot filament of the gages. Also, it is desirable in some cases to eliminate water vapor from the vacuum system at a rate greater than by normal pumping.

Copper foil, Alpert [5330], Rivera and Le Riche [59143] and probably others, placed in the line between the pump and vacuum system, refrigerated by liquid air or nitrogen, adsorbs pump oil vapor backstreaming from the diffusion pump. It can be reactivated by heating to the degree needed for normal degassing of the vacuum system. Alpert [5330] and Carmichael and Lange [5853] found that in small vacuum systems unrefrigerated copper foil is also effective in removing pump oil vapors. The latter investigators state that saturation of the copper foil results in carbon monoxide being evolved. It is effective in removing the silicones, octoil, octoil-s, convoil-20 and Litton type C oil vapors, but not for convactor 8 or convoil-10 oil vapor. The time it is effective reduces with increase in the state of deterioration of the pump oil.

Continuing with oil vapor traps, liquid nitrogen or air is also effective. Milleron [5864] and probably others, states that such traps are preferable to copper foil for large vacuum systems. Blears, Greer and Nightingale [58159] also considered large vacuum systems and found activated carbon superior to alumina, copper foil and refrigerated baffles in trapping pump oils. However, an annoying deposit formed on the envelope surfaces and water vapor was evolved in excess from the carbon, the latter presumed eliminated by more thorough initial degassing. On the whole, they concluded that refrigerated chevron baffles are more effective than carbon.

Biondi [5906, 60147] switched from copper foil to an artificial zeolite (alkali metal alumina silicate) or activated alumina, both porous in order to have a greater effective surface area, which improved trapping the pump oil vapors. These materials do not trap mercury vapor. Levenson and Milleron [6143] found that artificial zeolites adsorb carbon dioxide and n-butane also, but not helium, hydrogen, nitrogen, argon, carbon monoxide or methane.

Harris [6011] prefers alumina pellets as a trap material instead of a cold trap for pump oil vapors.

Finally on trapping oil vapors, Haefer [61161, 6254] prefers for the purpose a magnetron gage arrangement called an ion baffle. In the 10^{-6} torr range all components of the residual gas are pumped, as well as the oil vapors.

Liquid nitrogen, or lower temperature liquid traps, are effective in preventing mercury vapor from pumps backstreaming into the vacuum system (Alpert [5874]). Carbon monoxide, carbon dioxide, methane and other hydrocarbons with appreciable vapor pressure at liquid nitrogen temperature (-186°C) will desorb after several monolayers are adsorbed. Warming of the cold adsorbing surfaces must be avoided by maintaining a constant liquid level in the trap.

Thomas [5370] describes a stainless steel foil, refrigerated by liquid air, to prevent mercury vapor backstreaming. No applicable performance data appear to have been published. This is a substitute for copper foil since the latter (McFarland and McDonald [5820]) does not trap mercury vapor.

In connection with protection against water vapor, Robson [6123] has investigated desiccants under vacuum conditions. For removing water vapor he rates their effectiveness in the following order: phosphorus pentoxide, molecular sieves (artificial zeolite pellets) activated alumina and silica gel. Considerable pertinent performance data are given.

2.7. Performance of Ionization Gages

The performance of ionization gages considered here is restricted to inherently measurable constants such as sensitivity, linearity, variation of sensitivity with gas composition, pressure range of valid indications and dynamic characteristics. Almost all of these quantities need to be determined with more or less care for each individual gage of most designs. As discussed in Section 2.6, many factors adversely affect the performance of the gage. The discussion here will be limited to the pressure range in which the gage readings have validity.

2.7.1. Theory. Leck [B571] reviewed the theoretical calculations of sensitivity of the hot cathode gage made by Morgulis [3404] and Reynolds [3102] which were based on experimental values of the number of ions produced in various gases by electrons having various energies. He concludes that the theory is based on simplifying assumptions which are not sufficiently applicable to practical gages. Ionization gage design rests upon experimentally derived data; calibration of the gage is always necessary.

The sensitivity S of an ionization gage in which an electron emission exists which is both measurable and controllable, is generally defined by the relation

$$S = \frac{I^+}{I^-} \frac{1}{P} \tag{7}$$

where I^+ and I^- are respectively the positive ion and electron current, and P is the pressure. Customarily, S is given in terms of torr^{-1}, which infers that I^+ and I^- are expressed in the same unit of current. To the extent that the output I^+/I^- is linear with pressure, achieved only if the proportion of gas ionized and collected for measurement is independent of the pressure, S is constant.

In ionization gages where either the ionizing particle current is not measurable or not of great significance a sensitivity K may be defined as follows:

$$I^+ = PK \text{ or } P^n K \tag{8}$$

The unit of K is not standardized but in many cases amperes per torr is convenient.

The sensitivity S or K varies with the composition of the gas in the gage. Independent of the value of S or K of a gage for a particular gas, and reasonably so, of the design or type of the ionization gage is the ratio R defined by

$$R = \frac{S}{S_n} \text{ or } \frac{K}{K_n} \tag{9}$$

where S or K is the sensitivity for a particular gas and S_n or K_n is the sensitivity for a reference gas, usually nitrogen, sometimes argon.

Nottingham [5474, 60164] has amplified formula (7) in order to investigate the performance of Bayard-Alpert ionization gages at the high pressure end of their range. He was interested in checking the validity of extrapolation of calibration data obtained at these high pressures to lower pressures. His modification is

$$\frac{I^+}{I^-} \frac{1}{P} = S = \alpha\beta \, L_e \, \overline{P}_i \tag{10}$$

$$i^- = \alpha I^- \tag{11}$$

$$i^+ = \frac{I^+}{\beta} \tag{12}$$

where i^- and I^- are respectively the true and observed electron current; i^+ and I^+ are respectively the true and observed positive ion current; L_e is the length of the average electron path; $\overline{P}_i$ is the effective ionization efficiency factor. The relation indicates broadly the factors which may affect the constancy of the sensitivity S.

Schuetz and Stork [6237] have developed a theory covering the influence of the electrode geometry of the Bayard-Alpert gage. The sensitivity depends on the grid and ion collector voltages, on the pitch and diameter of the grid and the diameter of the grid wire. The theory was checked by experiments.

Hwa [63163] develops a general theory on the linearity of hot cathode gages. Surprisingly this results in an exponential function for I^+/I^-, which breaks down to eq (7) when I^+ is small compared to I^-.

Shroff [63189] gives theoretical relations for both sensitivity and the x-ray effect for Bayard-Alpert gages. As a result a gage design was developed with the x-ray limit at 10^{-10} torr.

The theory of the modulated Bayard-Alpert gage given by Redhead [6079] is presented in Section 2.2.2.

An overall theory of cold cathode gages, including the Penning and magnetron types has been developed by Jepson [61190]. Some phases of the discharge mechanism, including theory and experiment have been covered by Knauer [62116], Dow [6319] and Kreindel and Ionov [64170]. Earlier theoretical work by Garrod and Gross [4809] and Moesta [5639] are probably now only of historical interest.

The simple theory for the Penning type cold cathode gage given by Grigor'ev [58113] is worth mentioning. The ion current I^+ relation is:

$$I^+ = \frac{E - U_o}{R_a + R_d} \qquad (13)$$

Here E is the anode voltage

  U_o is the discharge voltage at the maximum pressure measured by the gage,

  R_a is the resistance of the anode circuit (ballast resistance largely),

  R_d is the equivalent resistance of the discharge gap.

At some limiting higher pressure the gap resistance R_d greatly exceeds the anode circuit resistance R_a so that the output I^+ becomes constant at higher pressures. To extend the usefulness of the gage to higher pressures the resistance R_d is reduced by reducing the size of the anode and the distance between the cathode plates.

Redhead [58133] has developed theory which is applicable to the inverted magnetron gage. Jepson's theory [61190] covers both magnetron types.

Vacca [5664] presents a theory covering the operation of the electronic circuits used in the six-range radioactive gage using radium 226.

Lafferty [6311] has developed an expression for the sensitivity of the hot cathode - magnetron gage. For the gage without the photomultiplier the expression for the sensitivity S is given by eq (7). For the gage with the photomultiplier,

$$I^+ = G \ (I_r + nr \ SI^- P) \qquad (14)$$

where I^+ is the final output of the gage,

  S is the sensitivity of the gage without the photomultiplier;

  I_r is the background current in the multiplier, which limits the measurable low pressure;

  G is the current amplification for n-1 multiplier stages;

  n is the fraction of the ion current that reaches the first dynode of the photomultiplier;

  r is a factor to cover the case where positive ions, instead of electrons, strike the first dynode;

  I^- is the electron emission current;

  P is the pressure.

2.7.2. Range Limits of Gages. The high and low pressure limits of ionization gages of various designs are shown graphically in Figure 13. The gage nomenclature is that used in Section 2.2, with the exception of the hot cathode, high pressure gage which refers to the design proposed by Schulz and Phelps [5718].

The data on all gages represents the present state of development. Emphasis in development is now on measuring even lower pressures, with no reason to believe that the limit indicated in the figure is necessarily final. Dashed lines in the figure on the low pressure end indicate theoretical limits, not yet realized for one reason or another in experimental work. Redhead and Hobson [65150] conclude that the lowest pressure measurable with the modulated Bayard-Alpert gage is about 3×10^{-13} torr, if it is assumed that the soft x-ray effect remains constant.

The range for the Penning gage shown in Figure 13 as a solid line was claimed for their designs by both Sharev'skyi and Nikolayev [6435] and Lepekhin and Sheresheviskii [6443]. The dotted line at the high pressure end is an indication that other designs have valid indications at higher pressures. Classical designs have a pressure range of about 10^{-5} torr. Grigor'ev [58113] developed a design with two tube geometrics in one tube and achieved a range from 10^{-7} to 1 torr.

Data shown in Figure 13 for "Penning hot cathode fired" refers to the design of Young and Hession [6395] where a hot filament was used to strike a discharge at low pressures.

The data on the high pressure limits, except where a deliberate effort was made to extend it, is less firm than the low pressure limits. At pressures above about 10^{-3} torr, other methods of measurement became competitive with ionization gages and, except for convenience in some cases, are usually preferred.

2.7.3. Linearity of Pressure-Ion Current. The ion current is in most cases proportional to the pressure over the useful range of the gage. For some gages it is proportional to the pressure raised to some power as given by eq (8). In either case the gage is equally useful. Practically, the useful pressure range of the gage is pretty much restricted to that where the ion current-pressure relation is invariant. Continuous or erratic variation is almost intolerable.

Figure 13 shows the range of pressure over which commonly used gages have either a linear response or a response given by eq (8) where the exponent n is a constant near unity. The pressures are for nitrogen.

Except for the magnetron gage, all types of gages have an ion current-pressure relation which is constant for any chemically inert gas at the low pressure end of their range. Extension of the range to lower pressure, where possible, is not expected to change this situation.

Achieving constancy in the ion current-pressure relation of the usable range of the hot cathode types of gages in the pressure ranges 10^{-4} to 10^{-2} torr offers some difficulty, but is practically important.

Nottingham [60164, 6188] investigated the linearity of the MIT version of Bayard-Alpert gages in the high pressure range 10^{-5} to 10^{-1} torr. At lower pressures the gages had an output linear with pressure; for some data see Davis [6399]. The practical objective was to check the validity of calibration of the gage which requires comparison against a McLeod gage in the pressure range given above. Valid extrapolation to lower pressures requires that the sensitivity S remains constant. In the above high pressure range Nottingham found that the value of the sensitivity was affected by the value of the electron emission current, greatly so at high values. However if the gage had a shielding metal screen between the electrodes and the glass envelope, and the positive ion current to the screen was also measured, the sum of the ion current to the usual collector and the screen gave a value of the sensitivity reasonably independent of pressure up to 10^{-2} torr for electron emission currents as high as 1 ma. The percentage of the ion current collected on the screen decreases with decrease in pressure.

Ackley, Lothrop and Wheeler [6299] report that the sensitivity of Bayard-Alpert gages, in glass envelopes without the Nottingham shielding screen, shifts at pressures below 10^{-2} torr when the electron emission current is reduced. Reducing the emission current from 4 ma to 20 microamperes at constant pressure, increased a reading of the gage from 10^{-9} to 2×10^{-8} torr in 10 minutes and to 1×10^{-7} torr in from 200 to 2000 minutes. The effect was ascribed to an enhanced x-ray effect or possibly to a change in the rate of a chemical reaction. Pending further investigation, changes in the emission current from that at which the gage was calibrated are inadvisable.

As noted in Section 2.7.2, data for two designs of Penning gages are given in Figure 13 for both of which the ion current is linear with pressure. Linear response was also obtained by Varićak and Vošicki [5561] (10^{-5} to 10^{-2} torr) and Varghese [61204] (5×10^{-7} to 3×10^{-3} torr) from gages designed by them. On the other hand earlier designs had a response given by $I^+ = KP^n$ where n = 1.3 in the data obtained by Conn and Daglish [5311], and n was somewhat less, by Bernardet and Gourdon [63191]. It should be mentioned that the multiple gage designed by Grigor'ev [58113] has a nonlinear response over its entire pressure range. The high pressure end of the range of linearity terminated with a sharp increase in the ion current, useful to use for pressure control.

The magnetron gage has an output for helium and nitrogen which is linear with pressure down to 5×10^{-10} torr as shown in Figure 13; below this pressure $I^+ = SP^{1.7}$ (Redhead [58136, 59107]). This relation is modified by Torney and Feakes [6386, 63100] to $I^+ = SP^{1.6}$ at pressures below 2×10^{-10}, nearly to 10^{-14} torr.

33

The inverted magnetron gage over its range has an output given by $I^+ = KP^n$, where n is between 1.10 and 1.15 (Redhead [58136]). This is probably for nitrogen and is applicable to other noble gases. Somewhat different values of n are given by Feakes and Torney [63100], who show that n depends on the strength of the magnetic field.

The radioactive gage output is nonlinear to some degree only at the higher pressures of its range, 10 to 1000 torr, a range not important in vacuum measurement.

2.7.4. Sensitivity. The sensitivity S or K defined by eq (7) or (8) are listed in Table 1 for various designs of ionization gages. The hot cathode-magnetron gage when without the photomultiplier actually has a sensitivity defined by S, but for comparative purposes is listed under class B with a sensitivity K; with the photomultiplier as a complicating feature, this choice seems more appropriate.

Table 1. Sensitivity of gages for nitrogen.

A. Gages for which $S = \dfrac{I^+}{I^- P}$

	S	Positive ion current, amperes		
		$I^- = 10^{-2}$ amp	$I^- = 10^{-3}$ amp	$I^- = 5 \times 10^{-5}$ A
	per torr	$P = 10^{-5}$ torr	$P = 10^{-5}$ torr	$P = 6$ torr
Hot cathode	4 to 40	$(4 \text{ to } 40)\ 10^{-7}$	-	-
Hot cathode, Schulz	0.6	-	-	3×10^{-5}
Bayard-Alpert	4 to 40	$(4 \text{ to } 40)\ 10^{-7}$	-	-
Bayard-Alpert, modulated	(No data; same as B-A gage)		-	-
Electron beam	15	-	1.5×10^{-7}	-
Photomultiplier	2 (3)	-	5×10^{-9}*	-

*$I^- = 165 \times 10^{-6}$ amp

B. Gages for which $PK = I^+$

	K	Positive ion current, amperes		
	Amperes/torr	$P = 10^{-12}$ torr	$P = 10^{-5}$ torr	$P = 1$ torr
Penning [5561]	$I^+ = K \log P$	-	4×10^{-5}	-
Magnetron	10	-	10^{-4}	-
Hot cathode-magnetron with photomultiplier	0.10 (=S) 10^6	10^{-13} 10^{-6}	-	-
Photomultiplier	5×10^{-4}	-	5×10^{-9}	-
Radioactive (Ra 226)	2×10^{-10}	-	-	2×10^{-10}
Radioactive (Tritium)	2×10^{-10}	-	-	2×10^{-10}

	n	K Amperes/torr	Ion current $P = 10^{-5}$ torr Amperes
Inverted magnetron	1.10	30	10^{-4}
Magnetron (below 5×10^{-10} torr	1.7	-	-
Penning [5311]	1.3	300 - 30	$10^{-4} - 10^{-5}$

Obviously, it is desirable that S and K be as large as possible, almost essential that S be a constant over the measurable pressure range, and essential that S remain constant with time and use of the gage.

The sensitivities S and K listed in Table 1 are mainly for nitrogen and in a few cases for air, for which the sensitivity should theoretically not differ significantly from that for nitrogen. Discussion of the sensitivity for other gases is deferred to Section 2.7.3.

For all individual gages of any one design, wide range of values of either S or K may exist. The choice of tube geometry, the accelerating voltages, and other disturbing factors influence the value of S or K for a given gage. It is common experience, particularly with the hot cathode gage, that the sensitivity of instruments of apparently identical design varies widely. The range of this variation is indicated in Table 1 for the hot cathode gage. For other designs, a single value of S or K is given, based on the best values of the affecting parameters. Data are sparse on many designs, since broad experience on many designs is lacking. The single values given for S and K can only be considered as representative; a many-fold variation is easily possible.

On the relative sensitivities of the various gage designs it is obvious from Table 1 that the radioactive gage as now designed has the lowest sensitivity, followed closely by the more or less experimental photomultiplier gage. For the other designs, the values of either S or K are not practically restrictive, since even at ultra-high vacuums the positive ion current is measurable.

Experience with gages of the hot cathode, Bayard-Alpert, modulated Bayard-Alpert, hot wire-magnetron, electron beam and photomultiplier type indicates that the sensitivity S (eq (7)) is a constant within definite pressure limits, that is, the output is linear with pressure. This hold for all gases if no chemical action takes place in the gage. Outgassing, pumping by the gage and some forms of chemical action may be proportional to the gas pressure and therefore may not affect the apparent linearity; however, these phenomena may cause a lack of equilibrium between the gage tube and the vacuum system unless the conductivity between the two is adequate.

The sensitivity S is proportional to the ratio of the positive ion current to the electron emission in the gages listed in the above paragraph. In practice the electron emission current is held constant at some value and the positive ion current indicator is calibrated in terms of pressure. Customarily the electron emission current is held at some value between 1 and 10 milliamperes in the hot cathode gages; at about 10^{-9} amperes in the hot cathode-magnetron gage in order to avoid instability and excessive pumping (Lafferty [6311]); and from the microampere range to one milliampere in the electron beam gage (Klopfer [6178]). A maximum pressure range of linearity is desired coupled with ease in measuring the positive ion current.

2.7.5. Sensitivity for Various Gases. The indication of all types of ionization gages varies substantially with the composition of the gas in the gage. The sensitivity S or K as defined in Section 2.7.1 varies widely for all types of gages and also for gages apparently identical, while on the other hand the ratio R, either

$$\frac{S}{S_n} \quad \text{or} \quad \frac{K}{K_n} \qquad (9)$$

is more nearly constant, both for all gage types and for gages of the same design. This ratio is generally used to express the effect of gas composition on the gage indication. Generally the reference sensitivity S_n or K_n is for nitrogen, although some experimenters prefer argon.

The values of the relative sensitivity with reference to nitrogen obtained through the years for various gases are presented in Table 2 for relatively stable gases, and in Table 3 for hydrocarbons and halogens. The numbers in brackets refer to the papers from which the data were obtained.

While the values of the relative sensitivity for a given gas vary somewhat for the different gages, it is seen in Table 2 that the relative sensitivity of any one gas is unique, for example the value for helium is always less than that for hydrogen.

It is evident that if a gage is calibrated in terms of its output for nitrogen, the indication at a given pressure reduces to 1/5 for helium for example, and increases threefold for mercury.

Table 2. Relative Sensitivity $R = S/S_n$ or K/K_n

Gage	N_2	H_2	He	Ne	O_2	A	Kr	Xe	Hg	Cd	I_2	H_2O	CO	CO_2	Dry Air
Hot Cathode															
[2802]	1.00	.38	.15	.23	-	1.11	-	-	2.1	-	-	-	-	-	-
[3102] (an average)	1.00	-	.16	.18	-	1.56	-	-	2.70	-	-	-	-	-	-
[4503, B491] (average)	1.00	.38	.15	.24	-	1.19	1.86	2.72	3.44	-	-	-	-	-	-
[B491]	1.00	-	-	-	-	-	-	-	-	2.0	4.4	-	-	-	-
[5106]	1.00	.52	-	-	0.79	-	-	-	-	-	-	2.0	1.05	1.36	-
[5109]	1.00	.38	.25	-	1.14	1.06	-	-	-	-	-	-	-	-	.81
[5145] (average of 3)	1.00	.53	-	-	0.85	-	-	-	-	-	-	.89	1.07	1.37	-
[61189]	1.00	.53	.17	.32	-	1.20	2.74	2.74	-	-	-	-	-	.62	.70	-
[63154]	1.00	-	-	-	.90	1.89	-	-	-	-	-	-	.90	-	-
Bayard-Alpert															
[5729]	1.00	.42	.21	.33	-	1.5	-	-	-	-	-	-	-	-	-
[6095] (an average)	1.00	-	.21	-	-	1.37	-	-	-	-	-	-	-	-	1.13
[60164]	1.00	-	.10	-	1.16	1.16	-	-	-	-	-	-	-	-	-
[6237]	1.00	.48	-	.3	-	1.8	1.9	2.7	-	-	-	-	-	-	-
[6258]	1.00	.36	.20	.36	-	1.30	-	-	-	-	-	-	-	-	-
[6399]	1.00	-	.19	-	-	1.6	-	-	-	-	-	-	-	-	-
[63189]	1.00	.53	.16	.40	.85	1.2	-	-	-	-	-	-	-	-	1.0
[63204]	1.00	.41	.19	.34	-	1.33	-	-	-	-	-	-	1.12	-	-
Modified B-A															
[5474]	1.00	-	-	.23	-	1.25	-	-	-	-	-	-	-	-	-
Schulz High Press.															
[5718]	1.00	.53	.15	-	-	-	-	-	-	-	-	-	1.03	-	-
[6064]	1.00	-	-	.25	-	2.0	-	-	-	-	-	-	-	-	-
[6130]	1.00	-	-	-	-	-	-	-	-	-	-	1.4	-	-	-
[6457]	1.00	.53	.15	-	-	-	-	-	-	-	-	-	1.05	-	-
Penning															
[5311]	1.00	.49	.25	-	.95	-	-	-	-	-	-	-	-	-	-
Magnetron															
[58136]	1.00	-	.15	-	-	-	-	-	-	-	-	-	-	-	-
Radioactive															
[4608] Ra 226	1.00	.23	.21	.5	-	1.2	-	-	-	-	-	.88	-	1.5	-
Hot-cathode magnetron															
[6399]	1.00	-	.20	-	-	1.8	-	-	-	-	-	-	-	-	-

Table 3. Relative Sensitivity R for Hydrocarbons and Halogens

Gases

Gage	N_2	Air	Octoil-S	Amoil-S	Butyl Sebacate	Silicone	Naphthalene	Calor	Coal	Propane	N-butane	Iso-butane
Hot cathode												
[B491]	1.00	-	5.0	7.1	6.6	3.7	.85	-	-	-	-	-
[5791]	1.00	-	-	-	-	-	-	-	-	4.6	5.0	4.7
[6063]	-	1.00	-	-	-	-	-	4.6	1.25	-	-	-
Bayard-Alpert												
[6063]	-	1.00	-	-	-	-	-	3.7	-	-	-	-
Penning												
[6063]	-	1.00	-	-	-	-	-	5.4	-	-	-	-

Gases

Gage	N_2	Air	CH_4	Cl_2	Br_2	HCl	CCl_4	SF_6	Freon	CF_3
Bayard-Alpert										
[58169]	-	1.00	-	0.8	0.85	0.38	0.7	0.54	0.26	0.21
[63204]	1.00	-	1.56	-	-	-	-	-	-	-

Complicating factors enter in obtaining data for gases which are chemically active when in contact with a hot cathode. In Table 2 these gases are hydrogen, oxygen, carbon monoxide, carbon dioxide, iodine and water vapor. The variation in the data for these gases appears to be no greater than for the others and testifies to the care taken by experimenters in obtaining their data.

On theoretical grounds the data in Table 2 for the Schulz type high pressure gage might be expected to be out-of-line with the data for other types of gages. The data are sparse, but are reasonably in line. As indicated in Table 1, the sensitivity S for this gage is at least no more than 1/10 of that of the Bayard-Alpert gage.

Some discrepancies exist and could also be expected for the radioactive gage in which the ionizing particles are alpha particles from radium 226. No data are available on the gage in which tritium supplies the electrons.

The data in Table 3 are mainly for pump oil vapors and halogens and their compounds. On the pump oils care was necessary in obtaining data so that decomposition of the vapor by the hot cathode was kept at a minimum. The relative sensitivities are high which means that a pressure much too high is indicated by a gage calibrated for nitrogen when these oil vapors are present and since correction is impractical, the vapors must be prevented from reaching all types of gages. Decomposition of the vapor by the hot cathode will lower the indication at a given pressure, but gives rise to other difficulties as has been discussed in Section 2.6.5.

Dushman [B491, B621] discusses at some length possible relations governing the relative sensitivity R for various gases. A natural assumption is that R is some function of the ionizing potential of the gas. No simple relation holds and none so far developed is generally valid.

Without any satisfactory theoretical basis, Dushman found that a straight line was obtained by plotting R or S against the total number of electrons in the outer shell of the neutral molecule. This relation holds reasonably for both monatomic and diatomic gases, listed in Table 3 except for neon and helium, for which the observed R is too small. Schuetze and Stork [61155, 6237] also show that this relation is valid for the gases for which their data are given in Table 3 except for neon. The degree of agreement is surprising in view of the diversity of the gages and in their operating conditions.

Ghosh and Srivastava [61189] compute the relative sensitivity of hot cathode gages based on the probability of ionization. They secured fair agreement for helium, hydrogen, neon, argon and nitrogen. Their computations appear to account for the low values of the relative sensitivity for neon and helium mentioned in the paragraph just above.

Moesta and Renn [5791] have derived an empirical expression for S in terms of the effective cross-sectional area of the gas molecule, which appears to be of limited application.

It seems evident that further work needs to be done on the sensitivity of the gages to various gases. No adequate theory exists for the variation in relative sensitivity with the total number of electrons in the outer shell of the molecules, not to mention the abnormal values of the relative sensitivity for helium and neon. More valid data on the sensitivities of the commonly used gages is desirable. Data are almost completely lacking for the gages recently developed for measuring ultra-high vacuums.

2.7.6. **Nude Versus Tubulated Gages.** The differences in indication of nude and tubing-connected gages when pump oil is present in the vacuum system, known as the Blears effect, is discussed in Section 2.6.5. These differences in indication of Bayard-Alpert gages in the absence of oil vapor in an all-metal system is considered in some detail by Apgar [63204]. Comparative readings were made on a nude gage and three gages connected to the vacuum system by 12 mm bore tubing, 7, 28 and 114 cm long. In the pressure range 10^{-10} to 10^{-5} torr, the nude gage indicated a much higher pressure of carbon monoxide, smaller for hydrogen and nitrogen, and none for helium. The differences were less at pressures above 10^{-7} torr and were reduced by heating the tubing. The differences in indication are ascribed to slow gas adsorption in the tubing combined with its low effective conductance. Ionic pumping by the gages did not appear to be an important factor.

2.7.7. **Dynamic Performance.** Thus far the speed of response of an ionization gage is important only in measuring atmospheric pressure from rockets or satellites, in rare laboratory research work and to a limited extent in operating safety relays controlled by the gage. The latter case can be dropped from consideration since the gage response is sufficiently rapid and attention needs to be given only to the auxiliary apparatus.

First, the response time of the ionization gage itself is quite rapid. With an oscillograph for the indicator, Cobine and Burger [6114] obtained a rise time as short as 10 microseconds in the pressure range 10^{-4} to 10^{-7} torr. Lewin and Martin [6211, 6327] reported a time constant of 130 microseconds at 10^{-4} torr for deuterium using a modified Bayard-Alpert gage.

Bernardet and Gourdon [63191] investigated the dynamic response of a Penning cold cathode gage. Using an oscillograph as the indicator, the rise time was 1 millisecond in the pressure range 10^{-7} to 10^{-3} torr. The calibration of their gage was independent of the magnetic field strength in the range 1800 - 3500 oersteds.

With an oscilloscope indicator Vacca [5664] found that the radioactive gage using radium 226 has a response time of the order of microseconds. With a high speed strip recorder the response is as low as of the order of 0.01 second. He reports that the chief source of lag in the gage is in the current amplifier, giving a response time of 0.03 second for the gage. A theory covering the time response of the electrical circuit was presented.

The most serious obstacle to low time lag is the low conductance of any tubing normally used to connect the gage to vacuum to be measured. This is particularly true in the case of measuring atmospheric pressure from rockets or satellites which the altitude is changing. The most ambitious theoretical analysis is by Soo and Huang [6298] who conclude that only a nude gage will enable pressure measurements to be made with adequate accuracy. Their conclusion is questionable. Schaaf and Cyr [4925], Harris [5577], Ainsworth and LaGow [5623], Danilin et al [5787], and Spencer et al [5957] have also considered the conductance lag.

Newton, Pelz et al [6390] using 2 Bayard-Alpert and 2 Redhead magnetron gages, all miniaturized, in a rotating satellite to measure ambient pressure obtained telemetered indications which appear reasonably reliable. The connecting tubing was 0.938 cm in bore with a conductance of 9.38 liters/ second for nitrogen. The indications changed during the period of rotation of the satellite which was 0.67 second. The computed densities from the four gages agreed within ± 30 percent. The dynamic response of the gage and telemetering equipment was adequate; out-gassing remains a problem here because the altitude of the satellite varied. Presumably, if the altitude remained reasonably constant while orbiting, the procedures used would nullify the conclusions of Soo and Huang as to the effect of the conductance and outgassing.

For additional details see Section 2.3.6.

2.7.8. **Overall Accuracy.** The effect of many factors upon the accuracy of ionization gages is indeterminate, particularly at ultra-high vacuum; so that a quantitative evaluation of its performance as a pressure or density measuring instrument can be at best only an estimate, particularly in the ultra-high vacuum range. The development of calibration methods is now in the very high vacuum range, while ionization gages now available indicate pressures more than five decades lower. Methods of checking the linearity of the gages can be delusive, since some of the disturbing factors may also vary linearly with pressure and thus the slope of any curve obtained will not be a true function of the pressure in the vacuum system.

The major difficulties which make assessment of the accuracy of its indication practically impossible are the variation in indication with gas composition and the promotion of chemical activity and ionic pumping, both varying with gas composition, by the energy supplied to operate the gage.

The ionization gage in its present state of development measures pressures qualitatively and then only of a gas composition reasonably stable and constant. Failure to use the safeguards of good vacuum techniques may make the gage indications irrelevant as to the pressure. The development of the ionization gage into a more reliable instrument for many applications is unfinished business upon which considerable work is in progress.

3. Calibration Methods

As better and better vacuums are obtained, the question arises as to the meaning of any measurements made in terms of pressure. In the laboratory confining walls are necessary. D. P. Johnson in his paper at the conference on "Fundamental Problems of Low Pressure Measurements" at Teddington in 1964 (unpublished as yet) points out that in a spherical chamber three meters in diameter with gas at a pressure of 1×10^{-8} torr, each gas molecule collides with the walls a few thousand times for each collision with another molecule. In this chamber a monomolecular layer on the wall would contain about 50,000 molecules for each molecule of free gas. Thus, the momentum and energy changes involved in establishing an equilibrium takes place primarily on the walls.

The pressure measuring instruments used at ultra-high vacuum in no case measure pressure as customarily defined. Further, their input of energy and of electrons and extraneous molecules introduce a disturbance into any confined vacuum space which becomes more serious as the vacuum is bettered.

Graduating the dial of the vacuum gage in the ultra-high vacuum range in terms of pressure is a matter of convenience, or perhaps of necessity. The interpretation of the indications of the gage will in the end not be in terms of pressure. With the reservations above stated, the term pressure will be used in the discussion of calibration methods.

Calibration of ionization gages involves knowledge secured in some way of the pressure to which it is subjected. Down to pressures of about 10^{-6} torr some instruments are available for use as standards. For calibration at pressures below about 10^{-6} torr the pressure is determined by methods more or less indirect. These indirect methods include, a) volumetric pressure dividers, b) constant rate-of-pressure-change method, c) conductance type pressure dividers, and possibly d) vapor pressure cells.

Volumetric pressure dividers have not been used extensively to calibrate ionization gages. This is a static method and therefore, is uncertain in accuracy to the degree that adsorption and degassing takes place, fixing the lower pressure limit in the neighborhood of 10^{-6} torr.

Historically, the next development was the constant rate-of-pressure-change method, generally used to determine the linearity of response of ionization gages at pressures below those measurable with a McLeod gage. This method is usable to pressures perhaps as low as 10^{-12} torr. To the extent that the gage indication was linear, a high pressure calibration, for example, using a McLeod gage as a standard, could be extrapolated to lower pressures.

Recently, interest in the absolute calibration of vacuum gages has resulted in the development of the conductance type pressure dividers. Those available cover the vacuum range down to about 10^{-9} torr. Cryogenic adsorption pumping holds promise for extension deep into the ultra-high-vacuum range. This method is dynamic, that is, pumping is continuous. Readings can be made after pressure and flow equilibrium conditions exist.

One other method of securing a known pressure, as yet unrealized in practice but with some promise for the future, is the vapor pressure cell.

All of the above three methods will be discussed below.

3.1. Standard Instruments

Standard pressure-measuring instruments are those from which the pressure can be calculated for a given indication from a knowledge of either the significant dimensions or physical constants. Corollary to this, a calibrated instrument can serve as a secondary standard for calibrating other instruments if its performance is adequate.

The primary standard instruments of interest include a) McLeod gages, b) oil manometers, and c) radiometer gages. Of these McLeod gages are the most widely useful. U-tube manometers using a low vapor pressure oil in which interference fringes of a monochromatic light beam are counted to measure the column height can perhaps be developed for pressures down to 2×10^{-6} torr [62103].

Under some conditions, the accuracy of the McLeod gage is adequate' in the range 10^{-4} to 10^{-3} torr and tapers off at lower pressures. This pressure range is exactly where the Bayard-Alpert gage and the cold cathode gages are likely to have a nonlinear response, so that obtaining a calibration which can be extrapolated with certainty to the normal low pressure range of the ionization gages, requires care.

The Moser-Poltz design of the McLeod gage [5776] is claimed to permit accurate measurements down to about 10^{-7} torr. It is based upon the use of a sharp edged orifice at the entrance to a fixed compression volume in order to obtain a flat mercury surface. This permits eliminating troublesome capillarity effects. It is a more expensive instrument to construct than the conventional McLeod gage and the procedure of obtaining a pressure determination is quite a bit more complicated. Its utility requires further investigation.

The other instruments of possible utility in standards will not be discussed here. It is sufficient to say here that none have a useful range below 10^{-6} - 10^{-7} torr.

Of the secondary standard instruments, reliance for rough or qualitative work is mainly upon the ionization gage, particularly at very low pressures.

3.2. Volumetric Pressure Dividers

Several forms of volumetric pressure dividers have been devised to meet special needs [4909, 5310], all depending on expanding a permanent gas at a known pressure and volume into a known volume. Boyle's law is assumed to apply and noncondensable gases must be used. As examples, two designs will be considered.

3.2.1. Knudsen-Dunoyer. The design is shown schematically in Figure 14 [1403, B261] in which V, with subscripts, designates the volumes; P, the pressures in each; c, the valves; G_s, the gage, either a barometer or a McLeod gage to measure the pressure P_1, and G, the gage to be calibrated.

To make a calibration, the system is evacuated with all valves open except C_1; this may include a prior bake out of the system, since the residual pressure must be insignificant relative to the final pressure P_5. Valve C_2 is now closed, gas is admitted through valve C_1 and valve C_1 is closed. The pressure in V_1 is measured by gage G_s. With all valves closed, valve C_2 is opened and the gas in V_1 expands into volume V_2 giving pressure P_2 in volumes V_1 and V_2. Valve C_2 is then closed, and valve C_3 opened, giving pressure P_3 in volumes V_2 and V_3. This procedure continues until pressure P_5 is obtained in volume V_5.

It follows from Boyle's law that

$$P_5 = \frac{V_1 V_2 V_3 V_4 P_1}{(V_1 + V_2)(V_2 + V_3)(V_3 + V_4)(V_4 + V_5)} \tag{15}$$

In a practical case, if volumes V_2 and V_4 are equal and V_1, V_3 and V_5 are nearly equal and 1/100 as large as V_2 and V_4, pressure P_5 becomes approximately

$$P_5 = \frac{P_1}{(101)^2} = 10^{-4} P_1 \tag{16}$$

The volumes included between the valves must be measured, which is customarily done by weighing before and after filling with a liquid.

The ratio of the volumes, in the simplest case, $V_1/V_1 + V_2$, which is all that is needed, may be determined by using an initial gas pressure high enough so that the final gas pressure can be measured to sufficient accuracy. For this method, choice of a gage is practically limited to a mercury barometer and perhaps to a McLeod gage for the lower pressure. The additional volume introduced by the measuring instrument is a complicating factor.

To obtain various pressures, gas, usually nitrogen, is expanded into known volumes and the pressure computed from Boyle's law. Schuhmann [62102] has produced pressures by this procedure in the range 10^{-7} to 10^{-4} torr and obtained readings on an ionization gage. The gage readings, plotted against the computed pressures, lie on a straight line with only minor deviations. Further, the value of the ionization gage sensitivity remained reasonably constant. It can be concluded that the gage output is linear with pressure. A somewhat greater scatter in the pressure decade 10^{-7} to 10^{-6} torr, indicated by a standard deviation of 0.11, compared to about 0.03 for the other two pressure decades, probably indicates that sorption in the measuring volumes was beginning to be a significant factor. Schuhmann estimates the overall accuracy of the calibration over the entire pressure covered to be ± 10 percent, probably sufficient for most purposes in view of the variability in sensitivity of the ionization gage which can be expected with time and the various conditions of use.

This method of calibration has a more or less definite low pressure limit due to adsorption and degassing phenomena. The pumping action of most ionization gages is another serious disturbing factor in their calibration. This pressure limit is unlikely to be much below 10^{-6} torr.

3.2.2. Vermandé. While this method is ascribed to Vermandé [5242], it is likely to have been developed earlier. It has been also described by Alpert [5310], Kreisman [60136], and Flanick and

Ainsworth [6111]. The essentials of the design are shown schematically in Figure 15. In operation, the system from a to c is initially outgassed. With valve b closed, dry gas is admitted to V_1 and its pressure measured. Valve c is closed, valve b opened, whereupon

$$P_{21} = \frac{V_1 P_1}{V_1 + V_2} \qquad (17)$$

where P_1 is the initial pressure in volume V_1 and P_{21} the final pressure in volumes V_1 and V_2. P_1 is measured by gage G_s, usually a mercury manometer. It is assumed here that Boyle's law applies and that the initial pressure in V_2 is negligible compared to P_2.

The gage under calibration is read, giving one point. Another point is secured by evacuating volume V_2 with valve b closed, and then again connecting volumes V_1 and V_2. Then

$$P_{22} = \frac{V_1 P_{21}}{V_1 + V_2} = \frac{V_1^2 P_1}{(V_1 + V_2)^2} \qquad (18)$$

This process can be repeated until adsorption affects the pressure, thus achieving lower and lower final pressures.

The volumes V_1 and V_2, including connecting tubing up to the valves, must be determined, and pressure P_1, measured.

The remarks made in Section 3.2.1 relative to the possible effects of adsorption phenomena on the calibration pressure also apply here.

The procedure is modified by Flanick and Ainsworth [6111] so that the pressure in volume V_2 is gradually increased from a pressure of 10^{-2} to 10 torr. Volume V_1 in Figure 15, always initially brought to atmospheric pressure, is repeatedly connected to volume V_2. In this pressure range adsorption phenomena will cause no particular trouble.

3.3. Determining Linearity of Indications

3.3.1. Alpert-Buritz. A simple method, an extension of that used by Dushman and Found [2101], for determining whether the indications of a gage are linear down to ultra-high vacuums, was developed by Alpert and Buritz [5448, 5874]. In this method a rate of rise in pressure proportional to a function of time is established. Alpert and Buritz use two, instead of one, conductances in order to make the calibration at ultra-high vacuums within a reasonable time.

In Figure 16, P, P_1 and P_2 are pressures in the volumes V, V_1 and V_2, C_1 and C_2 are the conductances of the restrictions indicated, and G_1 and G_2 are the pressure gages to be calibrated, up to now only ionization gages. After outgassing the entire system, gas is admitted to volume V, the pump and gas inlet valves are closed and the gas allowed to flow into V_1 and V_2 through restrictions C_1 and C_2 causing pressures P_1 and P_2 to rise. The indications of gages G_1 and G_2 against time are then obtained.

The following relations hold on the assumptions that P_1 is negligibly small compared to P, that P remains sensibly constant while measurements are made and that the nature of the flow, usually molecular, through C_1 and C_2 remains unchanged. These assumptions can be met by selecting suitable values of V and P.

$$V_1 \frac{dP_1}{dt} = C_1 P \qquad (19)$$

From which it follows that

$$P_1 = at + P_{10} \qquad (20)$$

where $a = C_1 P / V_1$ and P_{10} is the pressure in V_1 at $t = 0$.

Similarly,

$$V_2 \frac{dP_2}{dt} = C_2 P_1 = C_2 (at + P_{10}) \qquad (21)$$

From which it follows that

$$P_2 = P_{20} + bt^2 \qquad (22)$$

where P_{20} is the pressure in V_2 at $t = 0$ and $b = \dfrac{C_2 a}{2V_2}$.

In deriving eq (22) the term P_{10} was dropped since in practice its value is negligible compared to at^2.

Assuming the indication of the gage is a measure of the initial value P_{20}, readings against time are plotted against t^2; to the extent the points lie on a straight line, the gage indications are linear with pressure.

Adsorption and outgassing in the vacuum system should be considered. Outgassing in significant amounts must be prevented by thorough prior degassing of the system. Since output data linear with time or the square of the time are obtained from ionization gages, and exact compensation for the lack of linearity of the gage output by adsorption is unlikely, it is safe to assume that adsorption is ordinarily not a significant factor. From another view point, the rate of adsorption, up to the point where a monolayer of gas molecules is present on the solid surfaces, is proportional to the gas density and hence its pressure. If the adsorption rate is significant in amount, its effect is only to change the slope of the straight-line, time-out-put relation.

The effect of gage pumping is minimized by operating the accelerating voltages of the gage just long enough to obtain a reading. See, however, Section 2.6.3.

3.3.2. Little-Whitney. They describe a procedure based on the use of a field emission microscope to determine the linearity of ionization gages [62100]. Briefly, at any constant pressure the time required for an equilibrium pattern to form on the field emission microscope after the field emission point was cleaned was compared with the indication of the ionization gage. It was found that this time plotted against the indication of a Bayard-Alpert gage was linear for oxygen, nitrogen and hydrogen in the pressure range 10^{-10} to 5×10^{-7} torr. The time required for a pattern to form varied from minutes to about one hour.

3.4. Conductance Pressure Dividers

These pressure dividers depend upon the computation of a conductance or conductances, and primarily upon either a pressure measurement in the range of a McLeod gage or other standard instrument, or measurement of the throughput.

3.4.1. Fundamental Theory

There are three general types of gas flow: a) free molecular, where the mean free path of the molecules definitely exceeds the distance between the confining walls of a system; b) viscous flow, where the mean free path is definitely less than the distance between the confining walls; and c) transition flow, where the mean free path is of the same order as the confining dimension. There are also subdivisions of the two latter flows, laminar and turbulent. The geometry of the tubing is another variable; the tubing may be circular or square or otherwise in cross section; or be an aperture or orifice. Transitional flows exist while pumping down the system, and through gas leaks into the evacuated system from the ambient atmosphere. In calibration systems it is only important to consider pressure drops within a system due to the free molecular flow of gases.

The gas throughput Q through any system is defined by the relations:

$$Q = \frac{PV}{t} = PF = C(P_1 - P_2) \tag{23}$$

It is related to the mass flow F_m as follows:

$$F_m = \frac{\rho V}{t} = \rho F = P \rho_1 F = Q \rho_1 \tag{24}$$

Here P is the pressure at some point along the line of gas flow in the system, $P_1 - P_2$ is the pressure drop between the two points along the line of gas flow, C is the conductance between points at pressure P_1 and P_2 (the resistance to flow $W = 1/C$), t is the time required for a volume V to flow past the point when the pressure is P, ρ is the gas density at pressure P, and ρ_1, the density at unit pressure, say 1 dyne/cm^2.

The throughput Q is a convenient function of continuous flow, since it is a constant at any point in a vacuum system, if there is no gain or loss of gas at any point in the system such as that due to adsorption or degassing.

The equation $Q = C(P_1 - P_2)$ was derived by Knudsen [B491] based on Maxwell's distribution law applied to free molecular flow. The conductance C has the dimensions of volume flow and may be usually considered as the volume flow per unit pressure difference.

The conductance C will be discussed briefly for a cylindrical tube and an aperture or orifice, since these shapes are specifically of interest. For a more complete discussion see [B491, B621].

3.4.1.1. Conductance of Cylindrical Tube

The conductance C_t of a long cylindrical tube ($L/a > 100$) connecting two volumes is, when the flow is molecular. [B491, B551, B621, 61113]

$$C_t = \frac{8\pi a^3}{3L} \sqrt{\frac{R_o T}{2\pi M}} \quad cm^3/sec \qquad (25)$$

$$= 30480 \frac{a^3}{L} \sqrt{\frac{T}{M}} \quad cm^3/sec \qquad (26)$$

$$= 3810 \frac{D^3}{L} \sqrt{\frac{T}{M}} \quad cm^3/sec \qquad (27)$$

$$= 9702 \frac{Aa}{L} \sqrt{\frac{T}{M}} \quad cm^3/sec \qquad (28)$$

Here a = radius of tube bore in cm,

   D = diameter of tube bore in cm,

   A = area of tube bore in cm^2,

   L = length of tube in cm,

   T = temperature of gas in °K,

   M = molecular mass in grams (molecular weight),

   R_o = universal gas constant,

Q can be expressed in any desired unit of PV/t by converting the values of C_t given above to the desired unit of flow and using the desired unit of pressure as indicated in eq (23). To obtain Q in terms of the torr liter per second, the pressure unit is the torr and the values of C_t given above must be divided by 1000.

As derived by Clausing [B491], in order to correct for end effects, eq (28) is modified as follows:

$$C = 3638 \, KA \sqrt{\frac{T}{M}} \quad cm^3/sec \qquad (29)$$

$$= 11428 \, Ka^2 \sqrt{\frac{T}{M}} \quad cm^3/sec$$

where K is a factor depending upon L/a, the ratio of the length of the tube to the radius of its bore.

A few values of K are given in Table 4; for more complete data see [B491, B621].

Table 4

Clausings Factor K

L/a	K	L/a	K	L/a	K
0	1	2.0	0.5136	40.0	0.0613
0.2	0.9092	4.0	0.3589	60.0	0.0420
0.4	0.8341	6.0	0.2807	80.0	0.0319
0.6	0.7711	8.0	0.2316	100.0	0.0258
0.8	0.7177	10.0	0.1973	1000.0	0.00266
1.0	0.6720	20.0	0.1135	Greater	8a/3L

Computations show that C_t in eq (28) and C in eq (29) give identical values for high values of L/a.

Kennard [B381, B491] has shown that K is in good agreement with the empirical relations:

For L/a between 0 and 1.5,

$$K = \frac{1}{1 + 0.5 L/a} \tag{30}$$

For L/a above 1.50,

$$K = \frac{1 + .04 \; L/a}{1 + 0.95 \; L/a + 0.15 \; (L/a)^2} \tag{31}$$

3.4.1.2. Conductance of Apertures

The conductance of an aperture or orifice between two volumes or tubes is given by eq (29). In this case L/a is small and K approaches unity, becoming unity when L/a is practically zero.

From data given in [B491, B621] based on eq (29), a few representative values of the conductance of apertures (low values of L/a) and tubing for air at 25°C are given in Table 5.

The effect of the conductance of the tubing in which the aperture or orifice is installed needs some amplification. In his calibration system, Normand (Section 3.4.3.1) used the relation proposed by Bureau et al [5274] as follows:

$$C = a \sqrt{\frac{RT}{2\pi M}} \; F \tag{32}$$

where F, a correction factor applied to the common aperture formula varying in practical cases from .97 for large values of a/A, to 1.0 for values of a/A less than about 0.01, equals:

$$\frac{1}{F} = \frac{1 - \frac{a}{A}}{k} + \frac{3}{4} \frac{aL}{AD} \tag{33}$$

In the above M is the molecular mass of the gas; R, the gas constant; T, the absolute temperature; a, the orifice area; A, the crossectional area of chamber A (Figure 18); L and D, respectively, the length and diameter of chamber A; and k, a constant given in [5274], which varies between 1 for small values of a and 4/3 for a = A.

Table 5

Aperture Conductance in Liters/sec for Air at 25°C

Bore								
Radius	L/a	.01	.1	1	5	10	20	30
cm	K	.995	.952	.672	.315	.197	.113	.0797
0.1		.365	.349	.246	.116	.0722	.0414	.0292
.2		1.46	1.40	.986	.462	.289	.166	.117
.3		3.28	3.14	2.22	1.04	.650	.373	.263
.4		5.84	5.58	3.94	1.85	1.16	.663	.468
.5		9.12	8.72	6.16	2.89	1.81	1.04	.730
1.0		36.5	34.9	24.64	11.6	7.22	4.14	2.92
5.0		912.	872.	616.	289.	18.1	10.4	7.30
10.0		3648.	3490.	2464.	1155.	722.	414.3	292.2

3.4.2. Fundamental Design. The design of a conductance divider is shown schematically in Figure 17. Here C_1 and C_2 are conductances, here shown as apertures, but could be any computable conductance, such as a tube. G_1 and G_s are vacuum gages, the first to be calibrated, the latter used as standard to measure P_1.

In operation gas is admitted through a controlling valve into chamber A. The pumps are run continually, finally establishing a constant flow into test chamber B through a restriction of conductance C_1 and to the pump line C through conductance C_2. Pressure P_1 exceeds P_2, and P_2 exceeds P_3. The lower limit of pressure P_2 in the test chamber B is limited by the lowest pressure, P_3, producible by the pumps.

Referring to Figure 17,

$$Q = C_1(P_1 - P_2) = C_2(P_2 - P_3) \tag{34}$$

from which it follows, if the throughput Q is constant

$$P_2 = \frac{C_1 P_1 + C_2 P_3}{C_1 + C_2} \tag{35}$$

Normally, pressure P_3 is kept small relative to P_1 and C_1 and C_2 are not greatly unequal, so that $C_2 P_3$ can be neglected. Finally

$$P_2 = \frac{C_1 P_1}{C_1 + C_2} \tag{36}$$

The effect of pumping by an ionization gage (G_1 in Figure 17) has not been considered in deriving eq (36). This can be done by adding an additional conductance C_g to C_2, but using techniques for minimizing its importance appear more desirable.

To determine P_2 (eq (36)), P_1 must be measured and the conductances C_1 and C_2 computed.

From eq (34),

$$P_2 = \frac{Q}{C_2} + P_3 \tag{37}$$

Again assuming P_3 negligible with respect to P_2, measuring the throughput and computing conductance C_2 determines P_2.

Applications of the above fundamental vacuum circuit are discussed below but it should be mentioned here that Normand [6193] uses a circuit which requires the measurements of throughput Q and a pressure ratio as well as computation of a conductance.

3.4.3. Design of Calibration Systems. A number of the designs proposed or built will be outlined. In most earlier designs throughput is measured while later designs have favored a pressure measurement.

Historically the first system based on a conductance appears to have been the Metropolitan-Vickers [B571]. It required the measurement of a throughput but had very little flexibility in providing more than one pressure.

A method for measuring pumping speed proposed by Oatley [5445] was used by Henry [5609] to obtain a calibration system for ionization gages. Throughput had to be measured. To obtain readily more than one calibration pressure Henry following in the footsteps of Oatley, used four orifices bored in a single plate. The plate was rotatable so that any one orifice could be connected into the system.

To secure a number of calibration pressures, Florescu [59147] proposed using the conductance of a long tube. The gas inlet, of special design to secure radial gas flow, could be raised or lowered so that the effective length of the conductance tube was variable. At a single throughput, the pressure range obtainable is unlikely to exceed about 10 to 1, a severe limitation on utility. Linearity of response of a gage could be determined by measuring only the position of the gas inlet with respect to the gage connection. To determine the pressure requires the measurement of throughput.

Florescu [6190] has also suggested a novel method of obtaining an additional value of the conductance in a calibration system which permits obtaining two calibration pressures. The system is as shown in Figure 17 except for the use of conductance tubes instead of orifices. Pressure P_1 is measured. Simply, the conductance of tube C_2 is reduced by sliding a tube of smaller cross section into a socket in tube C_2. The plug is movable magnetically from a position outside the flow region to its active position.

Dohmann [6490] and Narita [64131] describe calibration systems which depend on a computed value of the conductance of a single aperture. The calibration pressures obtained were above 10^{-6} torr.

Bergsnov-Hansen et al [64144] depend on the computed value of the conductance of a tube and the measurement of throughput by a leak detector in their calibrating system. The sensitivities of ion gages for helium and deuterium were obtained in the pressure range $10^{-5} - 10^{-7}$ torr.

Three other calibration systems, the Normand, the Roehring-Simons, and the Hobson are worth discussing in more detail.

3.4.3.1. Normand. The elements of his gage calibration system [6193] are shown in Figure 18. Here G_1 is the gage or gages to be calibrated; G_2 is a nude gage to be calibrated; G_3 is a calibrated gage used in determining pumping speed; O is an orifice; A is the test chamber; C, the high vacuum chamber; and B is a baffle.

Initially the system, with the gas inlet valve closed, is evacuated, resulting in a pressure P_o in chambers A and C, usually about 2×10^{-7} torr. Gas is then admitted to chamber A at a constant rate while the pumps are operating, resulting in equilibrium pressures P_1 in chamber A. It follows that,

$$\Delta P = P_1 - P_o = \frac{Q}{S} \tag{38}$$

where S is the pumping speed. The differential pressure ΔP is compared with $\Delta g = g_1 - g_o$ where g_o is the gage reading at pressure P_o and g_1 at P_1. The highest pressure P_1 obtained is about 4×10^{-2} torr. It is evident that this calibration essentially determines the linearity of response of the gage, that is, if

$$f = \frac{\Delta P}{\Delta g}$$

is constant, the response is linear. If one value of P_1 is measured accurately, say with a McLeod gage the calibration is absolute, not relative.

The throughput Q of gas entering the system is computed from measurements of the rate of change of readings of an oil manometer caused by trapped gas being admitted to the system through a control valve. With three manometers of different bores in the system, Q can be varied to secure pressures in the test chamber varying by a factor of at least 10^3.

The pumping speed S is determined from the relations,

$$Q = (P_1 - P_2) \, C \tag{39}$$

$$S = \frac{Q}{P_1} = (1 - \frac{P_2}{P_1}) \, C \tag{40}$$

where C is the conductance of orifice O.

It is seen in eq (40) that the pressure ratio P_2/P_1 is also required to determine the pumping speed S. Normand measured these pressures for one pumping speed by means of two ionization gages which had been calibrated to ensure that the pressure ratio would be sufficiently accurate.

3.4.3.2. Roehrig-Simons. This is a cascade calibration system [6131, 63304] developed to have for the moment a pressure range from 10^{-4} to 10^{-9} torr, with possibilities for extension to lower pressures. The overall plan is to measure the highest pressure with a McLeod gage and to secure ratios of the calibration pressures to the measured pressures as a function of the conductance of a number of apertures. The conductances are computed, but can be checked to some degree at the lowest pressure accurately measurable.

The calibration system designed by Roehrig and Simons is shown schematically in Figure 19. The system is divided into a system of chambers A, 1, 2, 3, and 4. The chambers are successively connected by apertures, the size of which can be selected by rotating a disk to secure one of three apertures. For purposes of analysis only one aperture in each connection is considered, the conductance of which is C_1, between chambers 1 and 2, C_2 between chambers 2 and 3, etc. The three possible apertures between chamber A and 1 are used to control the pressure in chamber 1 at values measurable by the McLeod gage. As a check on the calculations, an additional McLeod gage is connected to chamber 2 to measure, if feasible, pressures P_1.

The gage G to be calibrated is connected to chamber 4. A mechanical pump controls the pressure in chamber A, and diffusion pumps connected to chambers 1, 2, and 3 through fixed apertures, serve to lower the pressure in these chambers. Conductances are indicated by C and pressures by P, with subscripts as shown in Figure 19.

For checking leaks, contamination and composition a radio frequency mass spectrometer MS was connected to chamber 1.

In the system actually constructed the rotatable orifice plates were alike. The hole diameters were 3.96, 8.74 and 31.75 mm; plate thickness 6.22 mm; Clausing's factor K (see Section 3.4.1.1) was respectively 0.410, .593, and .837; and the computed conductances (see Section 3.4.1.1) 592, 4160, and 77500 cm^3/sec. Other choices for aperture size and number are obviously possible.

Chambers 3 and 4 can be enclosed in an oven for bakeout. The entire system was made of stainless steel pipe, 10 inches in diameter.

Consider the throughput in chamber 2, with a steady flow of gas from chamber 1 and a steady outflow into chamber 3 and into diffusion pump D_2. The flow into chamber 1 equals the outflow under equilibrium conditions. Then

$$(P_o - P_1) \, C_1 = (P_1 - P_2) \, C_2 + (P_1 - P_{p1}) \, C_{p1} \tag{41}$$

It follows that

$$\frac{P_o}{P_1} = \frac{C_1 + C_2 + C_{p1}}{C_1} - \frac{C_2}{C_1} \frac{P_2}{P_1} - \frac{C_{p1}}{C_1} \frac{P_{p1}}{P_1} \tag{42}$$

The pressure ratios in eq (42) are small quantities and each term containing the pressure ratios can be further reduced by selecting the conductances. Thus these terms can be neglected and there is obtained

$$\frac{P_o}{P_1} = \frac{C_1 + C_2 + C_{p1}}{C_1} \tag{43}$$

Progressively for chambers 3 and 4, there is similarly obtained

$$\frac{P_1}{P_2} = \frac{C_2 + C_3 + C_{p2}}{C_2} \tag{44}$$

and finally

$$\frac{P_2}{P_3} = \frac{C_3 + C_4}{C_3} - \frac{P_4}{P_3} \frac{C_4}{C_3} \tag{45}$$

where again the last term in equation is made negligible by choice of values for C_3 and C_4.

Thus if pressure P_o is measured, P_3 can be determined from eq (43), (44), and (45), using computed values of conductances.

If equilibrium conditions are obtained and maintained, adsorption phenomena will not affect the results. Other pertinent details for securing successful operation, such as pump capacities, are discussed by the authors.

Feakes and Torney [63100] have extended the above described calibration system to a pressure of about 4×10^{-13} torr. Cryopumping was used in addition to oil diffusion pumps.

Davis [6399] describes a simpler cascade system of conductances than that developed by Roehrig and Simons, but obtained pressures ranging from 10^{-10} to 10^{-3} torr. It was used to calibrate a Lafferty hot cathode-magnetron gage and a Bayard-Alpert gage.

3.4.3.3. Hobson. Hobson [6146] calls attention to the advantage of a cryogenic pump, based upon adsorption of a gas upon the cooled walls of the container in an ultra-high vacuum gage calibration system. Much lower pressures can be obtained than with a diffusion pump. At any one constant temperature the pressure remains constant in the cooled chamber, if apparently, less than a monolayer of gas has been adsorbed on its wall.

The following empirical isotherm equation, proposed by Dubinin and Rodushkevich in 1947, was found by Hobson to govern the equilibrium pressure in the cooled adsorption chamber.

$$\log_{10}\sigma = \log_{10}\sigma_m - D(\log_{10} \frac{P}{P_o}) \, 2 \tag{46}$$

Here σ is the number of molecules adsorbed per cm^2,

σ_m is interpreted as the number of molecules adsorbed per cm^2 in a monolayer.

$D = AT^2$ (A is a constant and T, the absolute temperature of the coolant).

P = the pressure above the adsorbed layer, and

P_o = the vapor pressure of the adsorbed gas above its liquid at temperature T.

Hobson presents data for helium, nitrogen and argon at various coolant temperatures below 100°K, which indicate the validity of eq (46). To indicate the low pressures attainable, the equilibrium pressure of helium, when the coolant temperature is 4.2°K, was computed to be of the order of 10^{-33} torr, physically of course quite meaningless.

While no experimental effort has been made to use this pump in a gage calibration system, it can be applied either to one in which throughput and a conductance are measured or computed, or one in which a pressure and two or more conductances are measured or determined. Experimental procedures, based on these methods, are discussed by Hobson.

Figure 20 shows an experimental arrangement considered by Hobson. A is the adsorbing chamber of pyrex glass, C_1 is the conductance of the tubing between A and the chamber at pressure P_1, G is the pressure gage to be calibrated, the pumping speed of which is S_g, C_2 is the conductance of a valve, P_2 is the gas inlet pressure, and Q is the throughput of the incoming gas. Chamber A is maintained at a temperature sufficiently low so that P_o is negligible compared to P_1.

If the throughput Q is measured,

$$P_1 = \frac{Q}{C_1 + S_g} \qquad (47)$$

Hobson's method of measuring the small throughputs here of interest is discussed in Section 3.4.4.

If the pressure P_2 is measured,

$$(P_2 - P_1) C_2 - P_1 S_g = (P_1 - P_o) C_1 \qquad (48)$$

from which it follows that,

$$P_1 = \frac{P_2 C_2}{C_1 + C_2 + S_g} \qquad (49)$$

The computation of conductances is discussed in Section 3.4.1.

3.4.4. Measurement of Throughput. In calibration systems depending upon knowledge of conductances, gas at a relatively high pressure continuously enters the system and is pumped through one or more intermediate chambers until it enters the pumping system. Throughput is defined by

$$Q = \frac{PV}{t} \qquad (50)$$

where at any one point in the calibration system, if no sources or sinks exist in the flow system, P is the pressure and V/t is the volume flow rate. Obviously, Q can be most accurately measured at a point where P is the highest, that is at the gas inlet end of the calibration system.

An important part of the gas inlet system is a variable leak of some sort to vary the throughput. This is usually secured by a sensitive needle valve [6193]. As throughput lowers with lower calibration pressures, other types of leaks may find application. A crack in a glass tube, leak volume controlled by the degree of coverage of the crack by mercury, was used by Henry [5609]. Another possible method of securing low flow rates is to use a permeable membrane to admit a particular gas, as a quartz tube for helium or a palladium tube or membrane for hydrogen. The rate of flow could be computed, based on the diffusion constant and the dimensions of the tube or membrane.

Volume flow rate into the calibration system is ordinarily determined by timing the change in volume of gas trapped in one arm of a U-tube manometer. To secure reasonably constant sensitivity over a large variation in flow rates, a bank of four or five manometers is used, in which the diameter of the leg in which the gas is trapped differs. Details of such a system, and its performance are discussed by Stevenson [6196].

All that need be said about the required pressure measurement is that it must be within the accurate measuring range of a liquid U-tube manometer or barometer or of a McLeod gage.

Hobson [6146] proposes methods of measuring very small throughputs. In Section 3.4.3.3 the adsorption pump is discussed where adsorption is a unique function of temperature. In one method gas is admitted through conductance, C_1. When the gas leak was closed, the pressure fell immediately by an amount P, measured by an ionization gage. Then $Q = C_1 P$. The effect of pumping by the ionization gage also enters, but could be minimized, as well as measured. Other indirect methods were used as checks, with good agreement. In one, the adsorption cell (Figure 20) at a given temperature was operated for a measured time; then the temperature was changed back to room temperature and the change in pressure above the pressure at zero time was measured. From these data and a knowledge of the system volume, the leak rate or throughput was computed, with minor correction needed for pumping by the ionization gage.

3.5. Vapor Pressure Cell

The vapor from a solid could be used to produce continuously a gas at a definite pressure which would serve to calibrate vacuum gages. This requires that the temperature of the solid be controlled and measured. Also that the vapor pressure-temperature relation be known; extrapolation of an established curve to lower vapor pressures is often possible to the accuracy sufficient in vacuum work.

The chief difficulty is in locating substances having known vapor pressures in the vacuum range in convenient temperature ranges. Additionally the vapor may interact chemically with ionization gages, which are almost solely used in the high and ultra-high vacuum ranges. Since reproducibility is imperative in the application, which seems to exclude most vacuum greases and pump oils, if not excluded for their chemical activity.

Another problem is the necessity of eliminating significant amounts of gases other than the selected gas from the system. At ultra-high vacuums this may be difficult, but cryogenic pumping may be a solution.

Thus far, few experiments with this method of calibration have been reported. Futch [6130] has used the vapor pressure of ice, temperature controlled by a dry ice-acetone both surrounding the ice container, to calibrate an ionization gage from 10^{-4} to 10^{-1} torr. The purpose was to secure a calibration of an ionization gage for water vapor specifically, but the technique described is of more general application. Published vapor pressure data were used to obtain the pressure. Continuous production of the water vapor permits continuous pumping, permitting the elimination of the effect of degassing and adsorption.

Obviously, lowering the bath temperature by using liquid nitrogen would lower the vapor pressure of the ice down into the ultra-high vacuum range, but raises the question as to the exact value of the vapor pressure, owing to the enormous extrapolation of available data required.

At the moment it appears that the adsorption of a gas at low wall temperatures, as proposed by Hobson (Section 3.4.3.3) offers not only less difficulty, but will produce lower known pressures.

3.6. Evaluation. The various types of calibration systems can best be evaluated by considering their low pressure limit. Due to adsorption and desorption effects the volumetric pressure divider presently is useful down to no lower than 10^{-6}, perhaps 10^{-7} torr.

Calibration systems depending either upon computation of a conductance and measurement of throughput or a cascade system involving conductance computation and one high pressure measurement are useful down to 10^{-9} - 10^{-10} torr. The limitation on the low pressure end appears to be the low pressure limit of diffusion pumps, since the pump should be able to maintain a pressure at least 10^{-2} torr below any desired calibration pressure. This limit is about 10^{-12} - 10^{-13} torr.

To obtain pressures below 10^{-12} torr in a calibration system, a molecular pump might be used, but it is believed that cryogenic adsorption pumping as discussed in Section 3.4.3.3. is the answer, where the low pressure end is far below any value now of practical interest.

In developing either calibration system, one pressure must be kept at least high enough so as to be accurately measurable with a McLeod gage.

Data on the accuracy of calibration systems are not as yet reliable; not enough work has as yet been done. As a rough estimate, the uncertainty in pressures at 10^{-6} torr delivered by the cascade system is about ± 10 percent.

4. References

The numbers given the references are, for convenience, the same as those given in the Bibliography, NBS Monograph 35, [6101] to which readers are referred for titles and indexed content. A few references previous to 1960 and all subsequent to 1960 are not listed in the Bibliography. These are planned for inclusion in an addition to the Bibliography using the same identifying numbers. This system of identification accounts for the fact that the reference numbers listed below for any one year omit identifying numbers listed in [6101] which are not here pertinent.

In the following list, book numbers are prefixed by B, the first two digits indicate the year of issue and the last digit distinguishes those listed for any one year.

Papers in journals or reports have numbers the first two of which identify the year of issue, and the remaining digits distinguish those listed for any one year. Thus [62103] indicates publication in 1962 and 103 is the identifying number.

4.1. Books

B261 L. Dunoyer, Vacuum practice; D. Van Nostrand, New York, (1926).

B381 E. H. Kennard, Kinetic theory of gases; McGraw-Hill Book Co., New York, (1938).

B491 S. Dushman, Scientific foundations of vacuum technique; John Wiley and Sons, New York, (1949).

B492 A. Guthrie and K. R. Wakerling, Vacuum equipment and techniques; McGraw-Hill Book Co., New York, (1949).

B525 F. K. Harris, Electrical measurements; John Wiley and Sons, New York, (1952).

B551 J. Yarwood, High-vacuum technique; John Wiley and Sons, New York, 3d Ed., (1955).

B552 F. E. Terman, Electronic and radio engineering; 4th Ed., McGraw-Hill Book Co., New York, (1955).

B571 J. H. Leck, Pressure measurement in vacuum systems; Inst. Physics, London, (1957); 2d Ed., Chapman and Hall, London, (1964).

B581 K. Diels and R. Jaeckel, Vacuum handbook for laboratory and industry; Springer-Verlag, Berlin, (1958).

B621 S. Dushman and J. M. Lafferty, Scientific foundations of vacuum technique; John Wiley and Sons, New York, revised, (1962).

4.2. Papers

1403 M. Knudsen, Ann. Phys. $\underline{44}$, 525 (1914).

1501 L. Langmuir, J. Am. Chem. Soc. $\underline{37}$, 417 (1915).

1601 O. E. Buckley, Proc. Nat. Acad. Sci., $\underline{2}$, 683 (1916).

2101 S. Dushman and C. G. Found, Phys. Rev. $\underline{17}$, 7 (1921).

2502 K. T. Compton and C. C. Van Voorhis, Phys. Rev. $\underline{26}$, 436 (1925).

2604 C. G. Found and N. B. Reynolds, J. Opt. Soc. Am. and Rev. Sci. Inst. $\underline{13}$, 217 (1926).

2607 F. Durau, Zt. Phys. $\underline{37}$, 419 (1926).

2802 I. Langmuir and H. A. Jones, Phys. Rev. $\underline{31}$, 357 (1928).

3009 P. Clausing, Ann. Phys. $\underline{7}$, 489 (1930).

3102 N. B. Reynolds, Phys. $\underline{1}$, 182 (1931).

3105 E. K. Jaycox and H. W. Weinhart, Rev. Sci. Inst. $\underline{2}$, (1931).

3307 I. Langmuir, Chem. Revs. $\underline{13}$, 147 (1933).

3404 N. Morgulis, Phys. Zt. Sowjetunion $\underline{5}$, 407 (1934).

3407 J. B. H. Kuper, Rev. Sci. Inst. $\underline{8}$, 394 (1937).

3408 W. P. Overbeck and F. A. Meyer, Rev. Sci. Inst. $\underline{5}$, 287 (1934).

3501 M. J. Copley, T. E. Phipps and J. Glasser, Rev. Sci. Inst. $\underline{6}$, 371 (1935).

3602 R. D. Huntoon and A. Ellett, Phys. Rev. $\underline{49}$, 381 (1936).

3704 J. B. Hoag and N. M. Smith, Jr., Rev. Sci. Inst. $\underline{7}$, 497 (1937).

3705 F. M. Penning, Philips Tech. Rev. $\underline{2}$, 201 (1937).

3706 F. M. Penning, Physica $\underline{4}$, 71 (1937).

3707 L. N. Ridenour and C. W. Lampson, Rev. Sci. Inst. $\underline{8}$, 162 (1937).

3805 C. G. Montgomery and D. D. Montgomery, Rev. Sci. Inst. $\underline{9}$, 58 (1938).

4003 R. S. Morse and R. M. Bowie, Rev. Sci. Inst. $\underline{11}$, 91 (1940).

4004 R. M. Bowie, Rev. Sci. Inst. $\underline{11}$, 265 (1940).

4009 E. J. Lawton, Rev. Sci. Inst. $\underline{11}$, 134 (1940).

4102 W. E. Parkins and W. A. Higinbotham. Rev. Sci. Inst. $\underline{12}$, 366 (1941).

4103 L. N. Ridenour, Rev. Sci. Inst. $\underline{12}$, 134 (1941).

4202 R. B. Nelson and A. K. Wing, Rev. Sci. Inst. $\underline{13}$, 215 (1942).

4405 H. Schwarz, Zt. Phys. $\underline{122}$, 437 (1944).

4505 H. Nelson, Rev. Sci. Inst. $\underline{16}$, 273 (1945).

4506 R. B. Nelson, Rev. Sci. Inst. $\underline{16}$, 55 (1945).

4607 A. H. King, J. Sci. Inst. $\underline{23}$, 85 (1946).

4608 J. R. Downing and G. Mellen, Rev. Sci. Inst. $\underline{17}$, 218 (1946).

4616 C. M. Fogel, Proc. Inst. Rad. Eng. $\underline{34}$, 302 (1946).

4617 E. A. Hamacher, Rev. Sci. Inst. $\underline{17}$, 281 (1946).

4619 H. E. Van Valkenburg, Gen. Elect. Rev. $\underline{49}$, 38 (June, 1946).

4708 J. Blears, Proc. Inst. Roy. Soc., London $\underline{A188}$, 62 (1947).

4709 C. G. McIlwraith, Rev. Sci. Inst. $\underline{18}$, 683 (1947).

4809 I. R. Garrod and K. A. Gross, J. Sci. Inst. $\underline{25}$, 378 (1948).

4810 H. I. S. Allwood, J. Sci. Inst. $\underline{25}$, 207 (1948).

4821 E. A. Gulbransen and W. S. Wysong, Trans. Am. Inst. Mining and Met. Eng. $\underline{175}$, 611 (1948).

4826 R. W. Makinson and P. B. Treacy, J. Sci. Inst. $\underline{25}$, 298 (1948).

4904 F. M. Penning and K. Nienhuis, Philips Tech. Rev. $\underline{11}$, 116 (1949).

4906 G. Herrmann and O. Krieg, Ann. Phys. Leipzig $\underline{4}$, 441 (1949).

4907 C. Hayashi, K. Hashimoto, et al, Rev. Sci. Inst. $\underline{20}$, 524 (1949).

4909   G. C. Fryburg and J. H. Simons, Rev. Sci. Inst. 20, 541 (1949).
4918   C. J. Milner, J. Sci. Inst. 26, 159 (1949).
4925   S. A. Schaaf and R. R. Cyr, J. Appl. Phys. 20, 860 (1949).
5003   J. E. Johnston, Atom. Energy Res. Establ. Grt. Brit. Report G/R 480, (1950).
5012   R. T. Bayard and D. Alpert, Rev. Sci. Inst. 21, 571 (1950).
5013   J. J. Lander, Rev. Sci. Inst. 21, 672 (1950).
5014   W. Steckelmacher and S. Van Der Meer, J. Sci. Inst. 27, 189 (1950).
5016   E. C. Evans and K. E. Burmaster, Proc. Inst. Rad. Eng. 38, 651 (1950).
5039   J. W. A. van der Scheer, Het PTT-Bedrijf, Holland 3, 24 (1950).
5048   A. B. Stewart, Rev. Sci. Inst. 21, 258 (1950).
5106   G. H. Metson, Brit. J. Appl. Phys. 2, 46 (1951).
5108   P. A. Richards and W. A. Tuthill, Rev. Sci. Inst. 22, 841 (1951).
5109   L. Riddiford, J. Sci. Inst. 28, 375 (1951).
5110   O. A. Weinreich, Phys. Rev. 82, 573 (1951).
5114   J. Blears and J. H. Leck, J. Sci. Inst. 28, Suppl. No. 1, 20 (1951).
5145   S. Wagener and C. B. Johnson, J. Sci. Inst. 28, 278 (1951).
5168   J. M. Lafferty, J. Appl. Phys. 22, 299 (1951).
5207   O. A. Weinreich and H. Bleecher, Rev. Sci. Inst. 23, 56 (1952).
5208   N. Warmoltz and E. Bouwmeester, Appl. Sci. Research 2B, 273 (1952).
5209   A. H. Beck and A. D. Brisbane, Vacuum 2, 137 (1952).
5233   N. Ochert and W. Steckelmacher, Vacuum 2, 125 (1952).
5237   H. Sibata, Y. Tuzi and H. Kumagai, Rev. Sci. Inst. 23, 54 (1952).
5242   M. J. Vermandé, Le Vide 7, 1145 (1952).
5253   R. Palme, Glas-und-Hochvakuum Tech. 1, 134 (1952).
5254   P. A. Redhead, Nat. Res. Council, Canada, Report No. ERB275 (1952).
5267   G. Valle, Nuovo Cimento 9, 145 (1952).
5269   W. Pupp, Glas-und-Hochvakuum Tech 1, 3 (1952).
5274   A. J. Bureau, L. J. Laslett and J. M. Keller, Rev. Sci. Inst. 23, 683 (1952).
5310   D. Alpert, J. Appl. Phys. 24, 860 (1953).
5311   G. K. T. Conn and H. N. Daglish, Vacuum 3, 24 (1953).
5312   J. H. Leck, J. Sci. Inst. 30, 271 (1953).
5330   D. Alpert, Rev. Sci. Inst. 24, 1004 (1953).
5350   F. J. Fitz Osborne, Canad. J. Phys. 31, 11 (1953).
5370   E. Thomas, Vacuum 3, 413 (1953).
5378   G. Dobbe and B. Schroeder, Glas-und-Hochvakuum Tech. 2, 285 (1953).
5402   H. S. Sicinski, N. W. Spencer and W. G. Dow, J. Appl. Phys. 25, 161 (1954).
5409   G. K. T. Conn and H. N. Daglish, J. Sci. Inst. 31, 412 (1954).
5410   G. K. T. Conn and H. N. Daglish, J. Sci. Inst. 31, 433 (1954).
5412   G. K. T. Conn and H. N. Daglish, Vacuum 4, 136 (1954).
5428   P. A. Redhead and L. R. McNarry, Canad. J. Phys. 32, 267 (1954).
5435   L. J. Varnerin, Jr. and D. White, J. Appl. Phys. 25, 1207 (1954).
5445   C. W. Oatley, Brit. J. Appl. Phys. 5, 385 (1954).
5448   D. Alpert and R. S. Buritz, J. Appl. Phys. 25, 202 (1954).
5458   J. H. Reynolds and J. Lipson, Rev. Sci. Inst. 25, 1029 (1954).
5471   J. J. Kinsella, Vacuum Sym. Trans. (1954), Committee Vac. Tech. 65 (1955).
5474   W. B. Nottingham, Vacuum Sym. Trans. (1954), Committee Vac. Tech. 76 (1955).
5482   J. W. Hiby and M. Pahl, Zt. Naturforsch. 9a, 906 (1954).
5485   R. Haefer, Acta Physica Austriaca 8, 213 (1954).
5503   B. J. Todd, J. Appl. Phys. 26, 1138 (1955).
5504   E. Bouwmeester and N. Warmoltz, Philips Tech. Rev 17, 121 (1955).
5505   G. Dumas, Revue Gén. Elect. 64, 331 (1955).
5506   E. Brown and J. H. Leck, Brit. J. Appl. Phys. 6, 161 (1955).
5517   L. J. Varnerin and J. H. Carmichael, J. Appl. Phys. 26, 782 (1955).
5546   J. L. Peters, Vac. Sym. Trans. (1955), Committee Vac. Tech. 71 (1956).
5561   M. Varićak and B. Vošicki, J. Sci. Inst. 32, 346 (1955).
5564   R. W. Raible and M. K. Testermann, Electronics 28, 210 (Feb 1955).
5577   E. L. Harris, Univ. Toronto, Inst. Aero Phys. Tech. Note No. 6 (1955).
5604   J. H. Leck and A. Riddoch, Brit. J. Appl. Phys. 7, 153 (1956).
5609   R. P. Henry, Le Vide 11, 54 (1956).
5623   J. Ainsworth and H. E. LaGow, Rev. Sci. Inst. 27, 653 (1956).
5639   H. Moesta, Zt. angew. Phys. 8, 598 (1956).
5640   J. H. Beynon and G. R. Nicholson, J. Sci. Inst. 33, 376 (1956).
5641   P. Hariharan and M. S. Bhalla, J. Sci. Inst. 33, 488 (1956).
5664   R. H. Vacca, Vacuum Sym. Trans. (1956), Committee Vac. Tech. 93 (1957).
5665   J. R. Young, J. Appl. Phys. 27, 926 (1956).
5674   J. M. Houston, Bull. Am. Phys. Soc. (II) 1, 301 (1956).
5678   W. B. Nottingham, Handbuch der Phys. Springer Verlag V. 21, 1 (1956).
5687   P. Hariharan and M. S. Bhalla, Rev. Sci. Inst. 27, 448 (1956).
5705   G. K. T. Conn and H. N. Daglish, Vacuum 7-8, 72 (1957).
5718   G. J. Schulz and A. V. Phelps, Rev. Sci. Inst. 28, 1051 (1957).
5723   L. D. Hall, Rev. Sci. Inst. 28, 653 (1957).

5729 G. J. Schulz, J. Appl. Phys. 28, 1149 (1957).
5750 M. P. Reece, J. Sci. Inst. 34, 513 (1957).
5754 C. Hayashi, Trans. 4th Natl. Sym., Am. Vacuum Soc. (1957) 13.
5769 R. Horowitz and H. E. LaGow, J. Geophys. Res. 62, 57 (1957).
5770 J. Schutten, Appl. Sci. Res. B6, 276 (1957).
5776 H. Moser and H. Poltz, Zt. Instrumentenk. 65, 43 (1957).
5782 J. Antal and A. Koenig, Acta Phys. Hungar. 7, 117 (1957).
5787 B. S. Danilin, V. V. Mikhneyich et al, Soviet Phys., Advances in Phys., SSSR Acad. Sci. 63,
      (Sept 1957). Transl., Russian lit. of Satellites, II, Int. Phys. Index, Inc., N. Y. 21 p (1960).
5791 W. Moesta and R. Renn, Vakuum-Tech. 6, 35 (1957).
5820 R. H. McFarland and D. G. McDonald, Rev. Sci. Inst. 29, 530 (1958).
5853 J. H. Carmichael and W. J. Lange, Trans. 5th Natl. Sym., Am. Vacuum Soc. (1958) 137.
5858 A. R. Hamilton, Trans. 5th Natl. Sym., Am. Vacuum Soc. (1958) 123.
5864 N. Milleron, Trans. 5th Natl. Sym., Am. Vacuum Soc. (1958) 140.
5867 P. A. Redhead, Trans. 5th Natl. Sym., Am. Vacuum Soc. (1958) 148.
5874 D. Alpert, Handbuch der Phys. Springer Verlag V. 12, 609 (1958).
5878 J. H. Carmichael and E. A. Trendelenburg, J. Appl. Phys. 29, 1570 (1958).
5885 D. G. Bills and N. P. Carleton, J. Appl. Phys. 29, 692 (1958).
58105 D. Allenden, Le Vide 13, 247 (1958).
58112 R. P. Henry, Proc. 1st Int. Cong. on Vacuum Tech. (1958) 299.
58113 A. M. Grigorêv, Proc. 1st Int. Cong. on Vacuum Tech. (1958) 308.
58115 S. Kobayashi, Proc. 1st Int. Cong. on Vacuum Tech. (1958) 271.
58118 G. F. Vanderschmidt and J. C. Simons, Jr., Proc. 1st Int. Cong. on Vacuum Tech. (1958) 305.
58130 E. Baronetzky and A. Klopfer, Proc. 1st Int. Cong. on Vacuum Tech. (1958) 401.
58133 P. A. Redhead, Canad. J. Phys. 36, 255 (1958).
58134 J. P. Hobson and P. A. Redhead, Canad. J. Phys. 36, 271 (1958).
58135 J. P. Hobson and P. A. Redhead, Proc. 1st Int. Cong. on Vacuum Tech. (1958) 384.
58136 P. A. Redhead, Proc. 1st Int. Cong. on Vacuum Tech. (1958) 410.
58138 N. W. Robinson and F. Berz, Proc. 1st Int. Cong. on Vacuum Tech. (1958) 378.
58140 J. Schutten, Proc. 1st Int. Cong. on Vacuum Tech. (1958) 414.
58157 R. Haefer, Proc. 1st Int. Cong. on Vacuum Tech. (1958) 508.
58159 J. Blears, E. J. Greer and J. Nightingale, Proc. 1st Int. Cong. on Vacuum Tech. (1958) 473.
58170 A. Riddoch and J. H. Leck, Proc. Phys. Soc. London 72, 467 (1958).
5901 G. F. Vanderschmidt, Electronics 32, 60 (June 19, 1959).
5906 M. A. Biondi, Rev. Sci. Inst. 30, 831 (1959).
5911 N. W. Spencer and R. L. Boggess, J. Am. Rocket Soc. 29, 68 (1959).
5919 G. Carter, Vacuum 9, 63 (1959).
5931 N. W. Robinson and F. Berz, Vacuum 9, 48 (1959).
5939 J. Eisinger, J. Chem. Phys. 30, 412 (1959).
5957 N. W. Spencer, R. L. Boggess, et al, J. Am. Rocket Soc. 29, 290 (1959).
5968 H. B. Benton, Rev. Sci. Inst. 30, 887 (1959).
5979 K. G. Mueller, Le Vide 14, 250 (1959).
59102 G. Carter and J. H. Leck, Brit. J. Appl. Phys. 10, 364 (1959).
59107 P. A. Redhead, Can. J. Phys. 37, 1260 (1959).
59110 V. M. Gavrilyuk and Y. M. Kucherov, Pribory i Tekh. Eksper. No. 2, 83 (1959). Transl. ISA Inst
      and Exp. Tech. No. 2,264 (1960).
59124 N. W. Robinson, Electronic Engg. 31, 759 (1959).
59143 M. Rivera and R. Le Riche, Trans 6th Natl. Sym., Am. Vacuum Soc. (1959) 55.
59147 N. A. Florescu, Trans. 6th Natl. Sym., Am. Vacuum Soc. (1959) 75.
59148 J. R. Roehrig and G. F. Vanderschmidt, Trans. 6th Natl. Sym., Am. Vacuum Soc. (1959) 82.
59149 R. L. Ramey, Trans. 6th Natl. Sym., Am. Vacuum Soc. (1959) 85.
59150 P. L. Vitkus, Trans. 6th Natl. Sym., Am. Vacuum Soc. (1959) 89.
59153 B. B. Dayton, Trans. 6th Natl. Sym., Am. Vacuum Soc. (1959) 101.
59180 J. R. Young, J. Appl. Phys. 30, 1671 (1959).
59181 A. Venema and M. Bandringa, Philips Tech. Rdsch. 20, 153 (1959).
59182 E. A. Penchko and L. P. Kharkin, Pribory i Tekh. Eksper, No. 1, 128 (1959). Transl. Inst. and
      Exper. Tech. No. 1, 132 (Jan. 1960).
6002 T. W. Hickmott, J. Appl. Phys. 31, 128 (1960).
6004 B. J. Todd, J. L. Lineweaver and J. T. Kerr, J. Appl. Phys. 31, 51 (1960).
6011 L. A. Harris, Rev. Sci. Inst. 31, 903 (1960).
6014 J. Herbert, Le Vide 15, 197 (1960).
6061 R. N. Bloomer, Vacuum 10, 260 (1960).
6063 L. Ellsworth, Vacuum 10, 266 (1960).
6064 G. Hinzpeter, Experim. Tech. Phys. 8, 89 (1960).
6070 G. Barnes, Rev. Sci. Inst. 31, 608 (1960).
6078 L. R. Linner, R. I. George and R. B. McQuistan, Rev. Sci. Inst. 31, 650 (1960).
6079 P. A. Redhead, Rev. Sci. Inst. 31, 343 (1960).
6083 T. W. Hickmott, J. Chem. Phys. 32, 810 (1960).
6095 W. McGowan and L. Kerwin, Can. J. Phys. 38, 567 (1960).
60132 P. Schwerdtfeger, Vacuum 10, 330 (1960).
60136 W. S. Kreisman, Geophysics Corp. of Am. Tech. Report 60-2 (1960).

60147   M. A. Biondi, Trans. 7th Natl. Sym., Am. Vacuum Soc. (1960) 24.
60156   R. A. Haefer and J. Hengevoss, Trans. 7th Natl. Sym., Am. Vacuum Soc. (1960) 67.
60159   H. Riemersma, R. E. Fox and W. J. Lange, Trans. 7th Natl. Sym., Am. Vac. Soc. (1960) 92.
60160   J. M. Lafferty, Trans. 7th Natl. Sym., Am. Vac. Soc. (1960) 97.
60162   P. A. Redhead, Trans. 7th Natl. Sym., Am. Vac. Soc. (1960) 108.
60163   G. Reich, Trans. 7th Natl. Sym., Am. Vac. Soc. (1960) 112.
60164   W. B. Nottingham and F. L. Torney, Jr., Trans. 7th Natl. Sym., Am. Vac. Soc. (1960) 117.
60172   T. N. Rhodin and L. H. Rovner, Trans. 7th Natl. Sym., Am. Vac. Soc. (1960) 228.
6101   W. G. Brombacher, Nat. Bur. Stds. Monograph 35 (1961).
6103   H. Riemersma, R. E. Fox and W. J. Lange, Rev. Sci. Inst. $\underline{32}$, 218 (1961).
6104   J. M. Lafferty, J. Appl. Phys. $\underline{32}$, 424 (1961).
6105   J. A. Becker, E. J. Becker and R. G. Brandes, J. Appl. Phys. $\underline{32}$ 411 (1961).
6111   A. P. Flanick and J. E. Ainsworth, Rev. Sci. Inst. $\underline{32}$, 408 (1961).
6114   J. D. Cobine and E. E. Burger, Rev. Sci. Inst. $\underline{32}$, 717 (1961).
6123   E. M. Robson, Vacuum $\underline{11}$, 10 (1961).
6124   J. P. Hobson, Vacuum $\underline{11}$, 16 (1961).
6128   R. D. Young, Rev. Sci. Inst. $\underline{32}$, 1255 (1961).
6130   A. H. Futch, Jr., Rev. Sci. Inst. $\underline{32}$, 1263 (1961).
6131   J. R. Roehrig and J. C. Simons, Jr., Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 511.
6134   V. O. Altemose, J. Appl. Phys. $\underline{32}$, 1309 (1961).
6136   F. J. Norton, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 8.
6138   B. B. Dayton, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 42.
6143   L. L. Levenson and N. Milleron, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 91.
6146   J. P. Hobson, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 146.
6172   F. A. Baker, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 395.
6173   K. B. Blodgett and T. A. Vanderslice, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 400.
6174   R. Jaeckel and E. Teloy, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 406.
6178   A. Klopfer, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 439.
6179   A. Van Oostrom, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 443.
6181   J. M. Lafferty, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 460.
6182   J. C. Edeline, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 464.
6185   G. D. Martin, Jr., Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 476.
6188   W. B. Nottingham, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 494.
6190   N. A. Florescu, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 504.
6193   C. E. Normand, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 534.
6196   D. L. Stevenson, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 555.
61113   W. Dong and L. A. Bromley, Trans. 8th Natl. Sym., Am. Vac. Soc. (1961) 1116.
61128   B. Cobic, G. Carter and J. H. Leck, Vacuum $\underline{11}$, 247 (1961).
61135   E. A. Penchko, Pribory i Tekh. Eksp. 170-173 (Jan-Feb 1961) Transl. Inst. and Exp. Tech. 174-
        178 (Sept 1961).
61152   E. A. Penchko, Pribory i Tekh. Eksp. 99-100 (Jul-Aug 1961) Transl. Inst. and Exp. Tech. 720-
        722 (Feb 1962).
61155   H. J. Schuetze, Vakuum-Tech. $\underline{10}$, 73 (1961).
61161   R. A. Haefer, Vakuum-Tech. $\underline{10}$, 95 (1961).
61178   B. Cobic and G. Carter, Brit. J. Appl. Phys. $\underline{12}$, 384 (1961).
61180   J. Pierre, Le Vide $\underline{16}$, 18 (1961).
61183   A. M. DeGoer and N. Thibault, Le Vide $\underline{16}$, 167 (1961).
61188   G. A. Doran, J. Sci. Inst. $\underline{38}$, 355 (1961).
61189   S. N. Ghosh and B. N. Srivastava, Can. J. Phys. $\underline{39}$, 373 (1961).
61190   R. L. Jepson, J. Appl. Phys. $\underline{32}$, 2619 (1961).
61197   V. A. Ryzhov, Pribory i Tek. Eksp. 135 (Nov-Dec 1961) Transl. Inst. and Exp. Tech. 1172
        (July 1962).
61199   W. B. Nottingham, Rev. Sci. Inst. $\underline{32}$, 464 (1961).
61204   T. G. Varghese, J. Sci. Ind. Res. India, $\underline{20D}$, 427 (1961).
61206   B. Cobic, Bull. Inst. Nucl. Sci. "Boris Kidrich", Belgrade, $\underline{11}$, 45 (March 1961).
61230   V. Krpata, Slab. Obzol. $\underline{22}$, 480 (1961).
6207   G. Carter, L. H. James and J. H. Leck, Vacuum $\underline{12}$, 213 (1962).
6208   W. R. Savage and W. J. Odom, Vacuum $\underline{12}$, 221 (1962).
6211   G. Lewin and G. Martin, Rev. Sci. Inst. $\underline{33}$, 447 (1962).
6212   H. F. Winters, D. R. Denison and D. G. Bills, Rev. Sci. Inst. $\underline{33}$, 520 (1962).
6213   R. Buser and J. Sullivan, Rev. Sci. Inst. $\underline{33}$, 562 (1962).
6226   P. A. Redhead, Vacuum $\underline{12}$, 267 (1962).
6231   J. W. Kelly, J. Sci. Inst., $\underline{39}$, 473 (1962).
6237   H. J. Schuetze and F. Stork, Vakuum-Tech. $\underline{11}$, 133 (1962).
6240   G. Appelt, Vakuum-Tech. $\underline{11}$, 174 (1962).
6249   S. Garbe and K. Christians, Vakuum-Tech. $\underline{11}$, 9 (1962).
6254   R. A. Haefer, Vakuum-Tech. $\underline{11}$, 41 (1962).
6258   E. O. Loecherbach and F. J. Schittko, Vakuum-Tech. $\underline{11}$, 51 (1962).
6260   G. S. Mueller, Vakuum-Tech. $\underline{11}$, 77 (1962).
6266   B. B. Dayton, Trans. 9th Natl. Sym., Am. Vacuum Soc. (1962) 293.
6282   W. Steckelmacher, Trans. 9th Natl. Sym., Am. Vacuum Soc. (1962) 421.

6283   W. C. Schuemann, Trans. 9th Natl. Sym., Am. Vacuum Soc. (1962) 428.
6289   G. Barnes, J. Gaines and J. Kees, Vacuum 12, 141 (1962).
6293   H. J. Schuetze and F. Dlouhy, Vakuum-Tech. 11, 221 (1962).
6296   H. J. Schuetze and F. Stork, Trans. 9th Natl. Sym., Am. Vacuum Soc. (1962) 431.
6297   J. M. Lafferty, Trans. 9th Natl. Sym., Am. Vacuum Soc. (1962) 438.
6298   S. L. Soo and A. B. Huang, Trans. 9th Natl. Sym., Am. Vacuum Soc. (1962) 443.
6299   J. W. Ackley, C. L. Lothrop and W. R. Wheeler, Trans. 9th Natl. Sym., Am. Vacuum Soc. (1962) 452.
62100   R. P. Little and W. T. Whitney, Trans. 9th Natl. Sym., Am. Vacuum Soc. (1962) 456.
62102   S. Schuhmann, Trans. 9th Natl. Sym., Am. Vacuum Soc. (1962) 463.
62103   A. M. Thomas, D. P. Johnson and J. W. Little, Trans. 9th Natl. Sym., Am. Vacuum Soc. (1962) 468.
62104   H. B. Frost, Trans. 9th Natl. Sym., Am. Vacuum Soc. (1962) 474.
62116   W. Knauer, J. Appl. Phys. 33, 2093 (1962).
62121   J. Moreau, Le Vide 17, 222 (1962).
62122   S. Y. Lebedev and Y. Y. Stavisskii, Inst. and Exp. Tech. 143 (Sept 1962).
62129   P. Schneider, Le Vide 17, 182 (1962).
62131   B. Cobic and G. Carter, Le Vide 17, 320 (1962).
62184   M. N. Vasil'eva and E. M. Reikhrudel, Zh. Tekh. Fiz. 32, 725 (1962); Transl. Soviet Phys. -
        Tech. Phys. 7, 528 (1962).
62194   J. A. Jolly, Adv. in Electron Tube Tech., Proc. 6th Nat. Conf. 2, 185 (1962). Pergamon Press
        (1963).
62196   J. V. Florio, Adv. in Electron Tube Tech., Proc. 6th Nat. Conf. 2, 241 (1962).
6304   T. E. Hartman, Rev. Sci. Inst. 34, 281 (1963).
6305   H. Winkler, Rev. Sci. Inst. 34, 295 (1963).
6311   J. M. Lafferty, Rev. Sci. Inst. 34, 467 (1963).
6312   R. A. Haefer and J. Hengevoss, Vacuum 13, 123 (1963).
6319   D. G. Dow, J. Appl. Phys. 34, 2395 (1963).
6325   W. C. Schuemann, Rev. Sci. Inst. 34, 700 (1963).
6326   D. Lee, Rev. Sci. Inst. 34, 816 (1963).
6327   G. Lewin and G. Martin, Rev. Sci. Inst. 34, 942 (1963).
6330   F. A. Baker, Vakuum-Tech. 12, 1 (1963).
6337   P. A. Redhead, Vacuum 13, 253 (1963).
6340   F. A. Baker and J. Yarwood, Le Vide 18, 26 (1963).
6348   D. Blanc and R. Dagnac, Le Vide 18, 322 (1963).
6352   T. A. Vanderslice, Science 142, 178 (1963).
6356   G. Carter, Vakuum - Tech. 12, 47 (1963).
6361   M. Durm, Vakuum-Tech. 12, 112 (1963).
6372   W. K. Huber, Vacuum 13, 469 (1963).
6377   I. Weissman and M. L. Kinter, J. Appl. Phys. 34, 3187 (1963).
6379   S. Garbe, Vakuum-Tech. 12, 201 (1963).
6382   J. G. Bannenberg and F. G. Insinger, Vakuum-Tech. 12, 210 (1963).
6386   F. L. Torney, Jr., and F. Feakes, Rev. Sci. Inst. 34, 1041 (1963).
6388   F. T. Worrell, Rev. Sci. Inst. 34, 1352 (1963).
6389   F. T. Worrell, Rev. Sci. Inst. 34, 1384 (1963).
6390   G. P. Newton, et al, Trans. 10th Natl. Sym., Am. Vacuum Soc. (1963) 208.
6391   H. Atkinson, Trans. 10th Natl. Sym., Am. Vacuum Soc. (1963) 213.
6392   D. R. Denison, et al, Trans. 10th Natl. Sym., Am. Vacuum Soc. (1963) 218.
6393   W. C. Schuemann, et al, Trans. 10th Natl. Sym., Am. Vacuum Soc. (1963) 223.
6394   W. H. Hayward, et al, Trans. 10th Natl. Sym., Am. Vacuum Soc. (1963) 228.
6395   J. R. Young and F. P. Hession, Trans. 10th Natl. Sym., Am. Vacuum Soc. (1963) 234.
6399   W. D. Davis, Trans. 10th Natl. Sym., Am. Vacuum Soc. (1963) 253.
63100   F. Feakes and F. L. Torney, Jr., Trans. 10th Natl. Sym., Am. Vacuum Soc. (1963) 257.
63101   H. I. Smith, Jr., Trans. 10th Natl. Sym., Am. Vacuum Soc. (1963) 263.
63110   K. W. Yee and R. J. Carpenter, Rev. Sci. Inst. 34, 1101 (1963).
63154   H. U. Anderson, Rev. Sci. Inst. 34, 703 (1963).
63158   L. de Csernatony, J. Sci. Inst. 40, 504 (1963).
63163   C. Y. Hwa, Acta Phys. Sinica 19, 73 (1963).
63165   C. Y. Hwa, S. Y. Wang and Z. C. Chang, Acta Phys. Sinica 19, 83 (1963).
63167   T. E. Hartman, Rev. Sci. Inst. 34, 1190 (1963).
63175   J. Groszkowski, Bull. Acad. Polon. Sci. Ser. Sci. Tech. 11, 31 (1963).
63176   Y. B. Paderno, L. I. Pomanyuk and V. C. Fomenko, Ukrayin Fiz. Zh. 8, 707 (1963).
63189   A. M. Shroff, Le Vide 18, 460 (1963).
63191   H. Bernardet and C. Gourdon, Le Vide 18, 472 (1963).
63204   E. Apgar, Proc. 2nd European Vac. Sym. 223 (1963) R. A. Lang Verlag.
63205   W. K. Huber, Proc. 2nd European Vac. Sym. 240 (1963).
63211   G. A. Miller, J. Phys. Chem. 67, 1359 (1963).
63219   R. J. Ackermann and E. G. Rauh, J. Phys. Chem. 67, 2596 (1963).
63229   T. Takaishi and Y. Sensui, Trans. Faraday Soc. 59, 2503 (1963).
63238   C. Meinke and G. Reich, Proc. 2nd European Vac. Sym. 233 (1963), R. A. Lang Verlag.
63259   J. P. Freytag and A. Schram, Nuovo Cim. Suppl. 1, No. 2, 405 (1963).
63269   C. M. Bliven, T. G. Polanyi, Nuovo Cim. Suppl. 1, No. 2, 452 (1963).
63287   T. Oguri, J. Phys. Soc., Japan 18, 1280 (1963).

63300 R. Dei-Cas and F. P. G. Valckx, Le Vide 18, 408 (1963).
63304 J. R. Roehrig and J. C. Simons, Jr., Inst. and Control Syst. 36, 107 (April 1963).
6401   K. Kantorowicz, Rev. Sci. Inst. 35, 126 (1964).
6402   J. B. Hudson, G. W. Sears and T. L. Donnelly, Rev. Sci. Inst. 35, 127 (1964).
6410   K. Kawasaki, T. Sugita, I. Kohno, J. Watanabe and N. Hayashi, J. Appl. Phys. 35, 479,
       Erratum 2787 (1964).
6412   A. Cavaleru, G. Comsa and B. Iosifescu, Brit. J. Appl. Phys. 15, 161 (1964).
6416   N. A. Florescu, Vacuum 14, 47 (1964).
6418   W. G. Mourad, T. Pauly and R. G. Herb, Rev. Sci. Inst. 35, 661 (1964).
6423   R. P. H. Gasser and T. F. Patteson, Vacuum 14, 141 (1964).
6424   D. Blanc and R. Dagnac, Vacuum 14, 145 (1964).
6425   E. V. Kornelson, Vakuum-Tech. 13, 6 (1964).
6435   B. A. Sharevskyi and H. T. Nikolayev, Ukrayin Fiz. Zh. 9, 66 (1964).
6439   K. M. Tischer, Vakuum-Tech. 13, 105, 155 (1964).
6443   A. T. Lepekhin and R. M. Sheresheviskii, Pribory i Tekh. Eksp. 151 (Jan-Feb 1964); Transl.
       Inst. and Exp. Tech. 160 (Sept 1964).
6453   W. Espe, Exper. Tech. Phys. 12, 1 (1964).
6457   R. J. Melling, Inst. and Control Syst. 37, 119 (Sept. 1964).
6475   F. Ricca and G. Saini, Ann. Chimica 54, 572 (1964).
6483   T. Oguri, J. Phys. Soc. Japan 19, 83 (1964).
6490   H. D. Dohmann, Vakuum-Tech. 13, 118 (1964).
64104 R. Dagnac, Le Vide 19, 135 (1964).
64120 F. Cambou, F. Cotin and H. Reme, Ann. Geophys. 20, 346 (1964).
64121 J. Lecorguillier, Le Vide 19, No. 109, 626 (1964).
64127 J. W. Kotowski and K. M. Tischer, Vakuum-Tech. 13, 214 (1964).
64131 S. Narita, J. Vacuum Soc. Japan 7, 331 (1964).
64139 M. G. Kaganskii, D. L. Kaminskii and A. N. Klyucharev, Zh. Tekh. Fiz. 34, 1050 (1964);
       Transl. Soviet Phys.-Tech. Phys. 9, 815 (Dec 1964).
64143 J. P. Hobson, J. Vac. Sci. and Tech. 1, 1 (1964).
64144 B. Bergsnov-Hansen, N. Endow and R. A. Pasternak, J. Vac. Sci. and Tech. 1, 7 (1964).
64146 M. F. Axler, J. Vac. Sci. and Tech. 1, 17 (1964).
64152 M. M. Marechal and M. R. Octave-Prevot, Le Vide 19, No. 109, 638 (1964).
64156 J. C. Maliakal, P. J. Limon, E. E. Arden and R. G. Herb, J. Vac. Sci. and Tech. 1, 54 (1964).
64170 Y. E. Kreindel and A. S. Ionov, Zh. Tekh. Fiz. 34, 1199 (1964); Transl. Soviet-Phys.-Tech.
       Phys. 9, 930 (1964).
65150 P. A. Redhead and J. P. Hobson, Vacuum 15, 25 (1965).
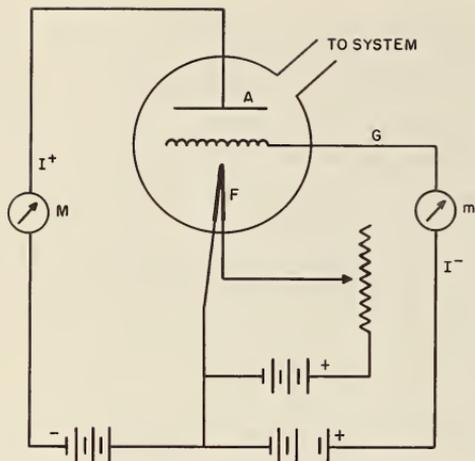
Figure 1. Basic ionization gage. F, hot cathode filament; G, grid; A, positive ion collector; m, meter for electron current; and M, meter for positive ion current.

Figure 1.1. Ionization gage characteristics. 1.1A, 1.1B, 1.1Ca, 1.1Da normal characteristics in measurable pressure range. 1.1C, triode gage. 1.1D, Bayard-Alpert gage. 1.1Cb, 1.1Db, c, X-ray effect predominates.

ION CURRENT I^+

GRID VOLTAGE e_g (A)

I^+

NEGATIVE COLLECTOR VOLTAGE e_c (B)

a 10^{-5} torr
b $< 10^{-8}$
GRID VOLTAGE e_g (C)

I^+
a 10^{-5} torr
b 10^{-9}
c $< 5 \times 10^{-}$
e_g (D)

56
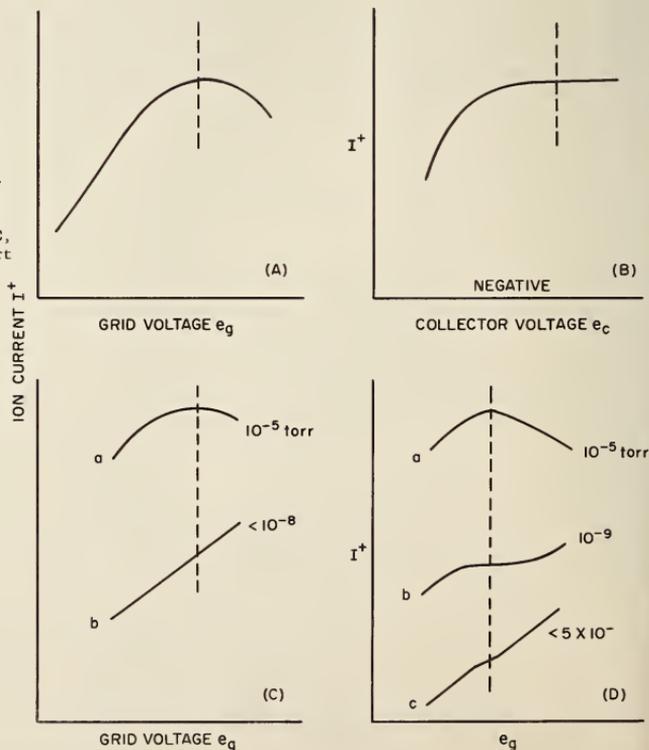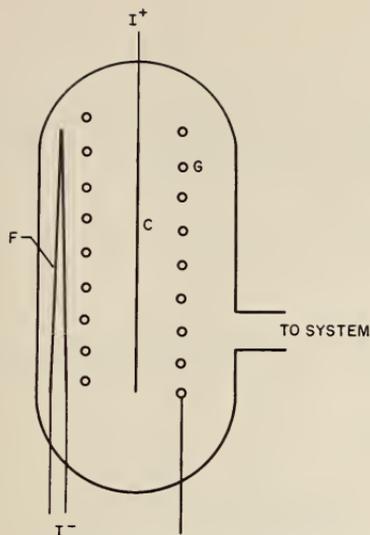
Figure 2. Bayard-Alpert ionization gage. C, positive ion collector; F, hot cathode filament; and G, grid.

Figure 4. Penning (Philips) gage. A, cylindrical anode; C, disk cathodes; I, microammeter; and M, the magnetic field.

Figure 3. Modulated Bayard-Alpert gage. A, normal positive ion collector; F, hot cathode filament; G, grid; and M, modulator.
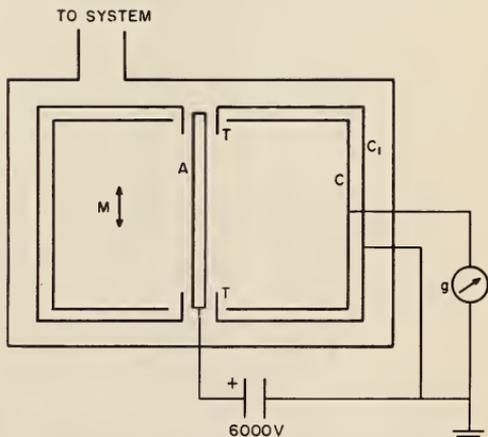
Figure 5. Inverted magnetron gage. A, rod anode; C, cathode collector of positive ions; C_1, electrostatic shield; g, meter for positive ion current; M, the magnetic field; and T, short tubes for pressure equalization and shielding.
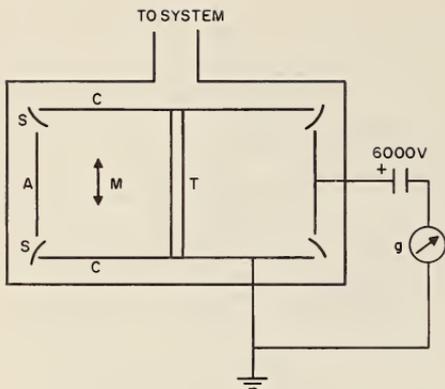
Figure 6. Magnetron gage. A, cylindrical anode; C, cathode; g, meter for positive ions; M, the magnetic field; S, electrostatic shields; and T, rod support for disks C.

Figure 7. Hot cathode-magnetron gage. M, the gage; EL, the electrostatic lens system; and EM, the electron multiplier. A, cylindrical anode; D, dynode; F, hot cathode filament; G, accelerator grid; I, ion focusing cylinder; m, the magnetic field; and S_1, S_2, shields.
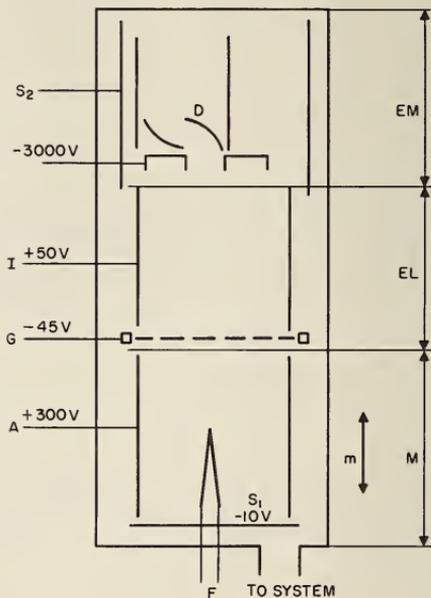
Figure 8. Electron beam gage. A, amplifier of positive ion current; C, hot cathode filament; G_1, G_2, G_3, G_4, electron accelerators with slits; H, disk with holes for pressure equalization; J, positive ion collector; M, the magnetic field; M_1, meter for electron current; M_2, meter for extraneous electron current; T, electron collector; and Z, shield.
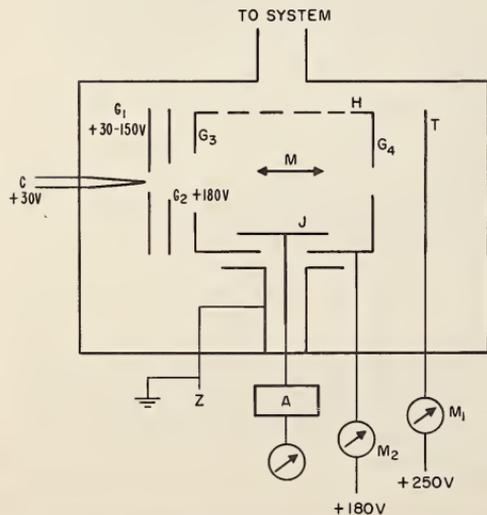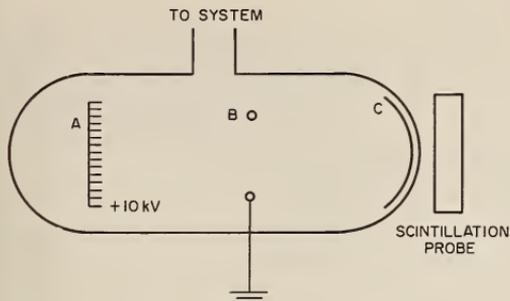
Figure 9. Scintillation detector gage. A, sharp pronged anode; B, wire loop; C, phosphor coating.
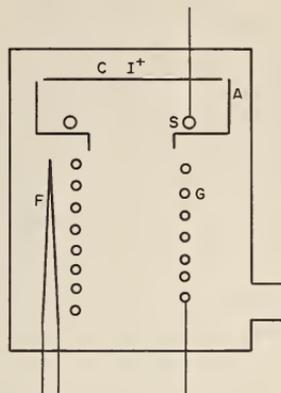
Figure 11. Photocurrent suppressor gage. A, a shield; C, ion collector; F, hot wire filament; G, cylindrical grid; and S, wire ring photocurrent suppressor.
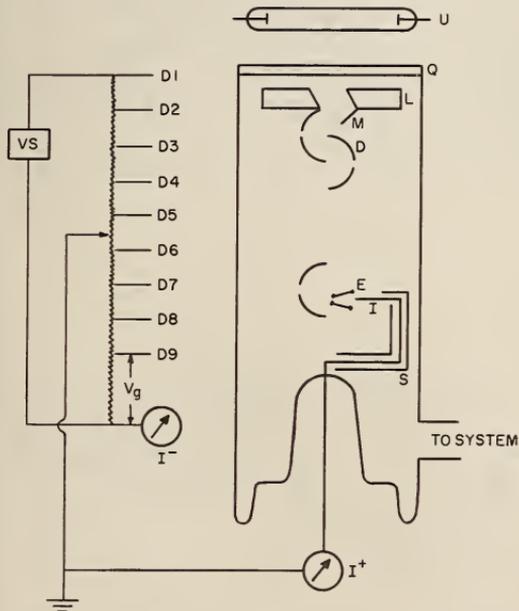
Figure 10. Photomultiplier gage. D, dynodes; E, wire ring electron collectors; I, positive ion collector wire; L, light shield; M, focusing mirror; Q, quartz window; S, electrostatic shielding; U, an ultraviolet light source; and VS, voltage supply.
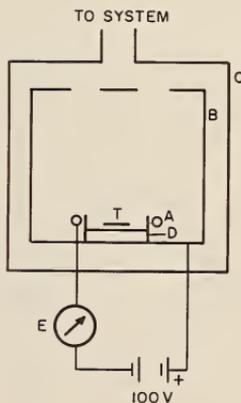
Figure 12. Radioactive gage. A, wire ring positive ion collector; B, cylindrical inner chamber; C, case; E, meter; T, radioactive material in support D.
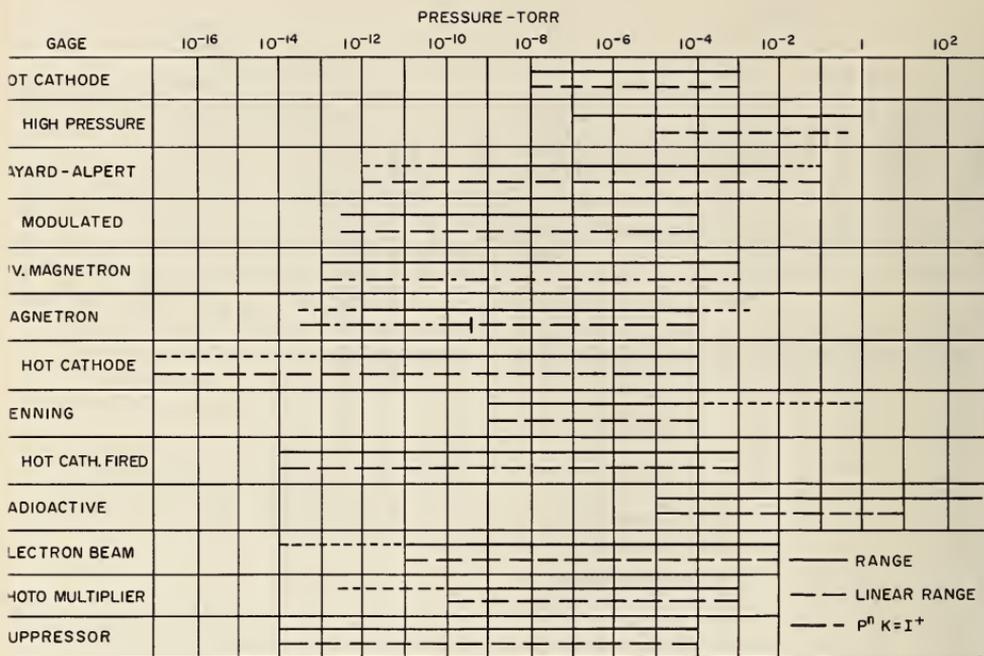
Figure 13. Pressure range and linearity for nitrogen of various designs of ionization gages.
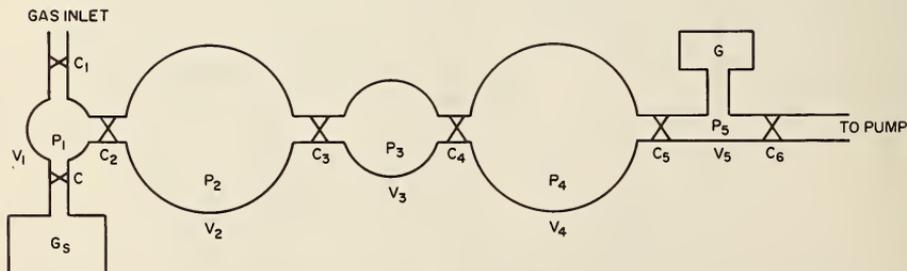
Figure 14. Knudson-Dunoyer pressure divider. The volumes are designated by V, pressures by P, valves by c; G_s is a manometer for measuring P_1, and G is the gage under test.

Figure 15. Vermandé pressure divider. V_1 and V_2 are volumes; P_1 and P_2 are pressures; a, b and c are valves; G_s is a gage for measuring P_1 and G is the gage under test.
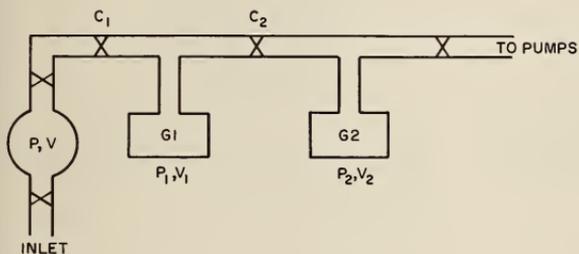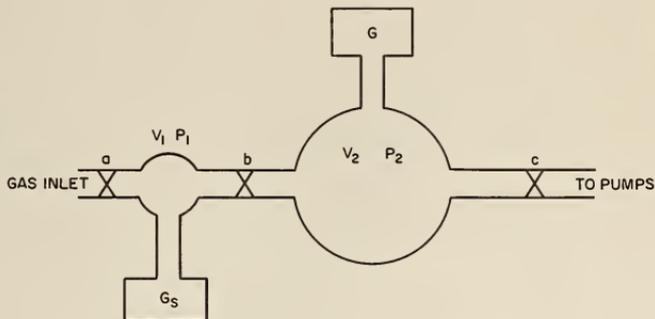
Figure 16. Alpert-Buritz pressure divider. G_1 and G_2 are vacuum gages, C designates valves, P designates pressure and V, volumes.

Figure 17. Design of conductance calibration system. A, B, and C are chambers connected by orifices C_1 and C_2; G_s is a standard vacuum gage; G_1 is the gage under test; and P_1, P_2 and P_3 are pressures.

61
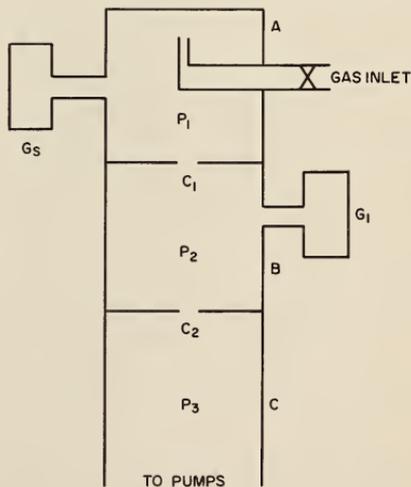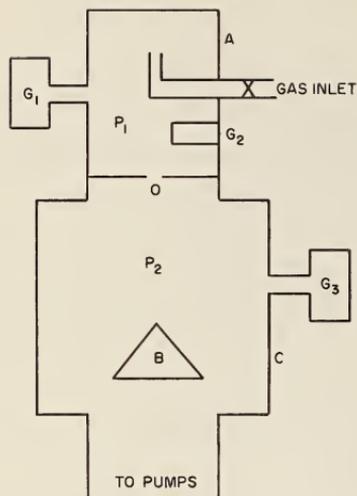
Figure 18. Normand calibration apparatus. A and C are chambers connected by orifice O; B is a baffle; P_1 and P_2 are pressures; G_1 and G_2 are gages under test; and G_3 is a gage used in measuring pumping speed.
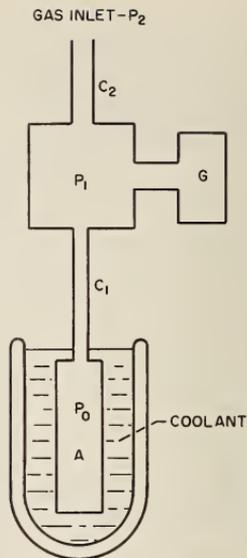
Figure 20. Hobson calibration apparatus. A is an adsorbing chamber; C_1 and C_2 are conductances; G is a vacuum gage under test; and P_0, P_1 and P_2 are pressures.
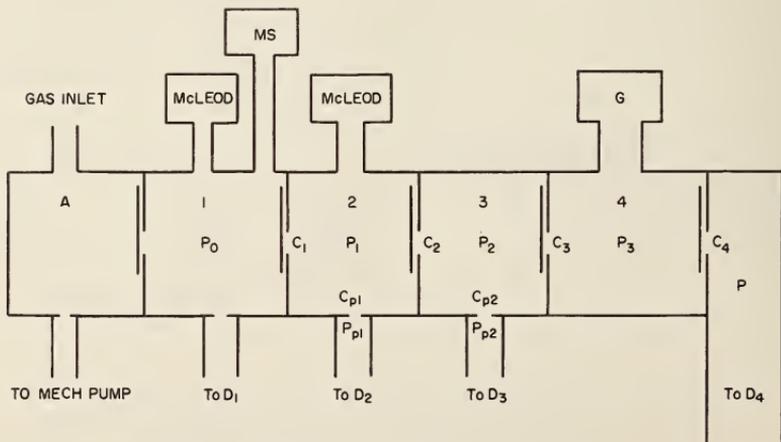
Figure 19. Roehrig-Simons pressure divider. C designates conductance of orifices; D designates diffusion pumps; P designates pressures; G is the gage under calibration; and MS is a mass spectrometer.