THE APPLICATION OF ION STORAGE IN ELECTRON SPACE-CHARGE FIELDS TO THE DESIGN OF A U.H.V. GAUGE AND MASS-SPECTROMETER ION SOURCE

PART I. THE DESIGN OF A NEW EXTRACTOR GAUGE FOR U.H.V. PRESSURE MEASUREMENTS

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Abstract

Computed potential distributions and ion trajectories are used to compare two existing gauge designs employing external collectors. The influence of field penetration through the grid of the Groszkowski gauge is described together with the modifications necessary to minimize its effect. The design of a new extractor gauge, employing a separate extractor electrode external to the grid, is described in detail. Advantages to be gained by the use of this system are discussed and the effects of varying parameters on the collected ion current are illustrated. A method is described of reducing the effect on the residual current of X-rays reflected from surrounding electrodes onto the collector. The addition of a modulation factor has been found to give a high modulation factor (0.95), which would enable the pressure range to be further extended.

1. Introduction

During the last few years we have carried out detailed theoretical and experimental studies of electrostatic ionization gauges designed to measure total pressures in the Ultra-High-Vacuum region below $10^{-10}$ Torr. Above this value, pressures are normally measured using the conventional Bayard–Alpert gauge in which positive ions generated by electron bombardment of the gas molecules within a wire grid, helically wound in the form of a cylinder, are collected on a negatively biased fine-wire collector placed along the grid axis. The ionizing electrons are emitted from a hot tungsten filament, usually in the form of a hairpin, which is mounted alongside the grid and spaced a few millimetres outside it. Emitted electrons are accelerated to approximately 100 eV by the applied potential before entering the grid volume. The ion current to the collector is proportional to the molecular concentration for a wide range of values and also to the ionization cross-section of the gas in the system. A measurement of pressure is therefore obtained for known gas mixtures and temperature over the range from approximately $10^{-4}$ Torr down to $10^{-10}$ Torr. The lower pres-
sure limit is determined by the presence of residual collector currents which are not linearly pressure-dependent.

Following an initial investigation of several different gauges designed by other workers in this field, our studies have been concentrated on the design of a gauge in which the ions are extracted to a fine-wire collector positioned outside the ionization region in order to minimize the residual currents. The major factors which influence the operation of such a gauge have been found to be the storage of ions in the confining electron space-charge field in which they are formed and their controlled extraction towards the ion collector.

It was soon realized that this type of ionization device could also form the basis of a low-energy ion source for mass-spectrometer applications. The advantages it offers are an anode structure which can be degassed by electron-bombardment heating and a beam of ions having low energy spread and small angular dispersion. The maximum sensitivity in A/Torr can be considerably higher than that of conventional sources, due to its ability to operate over a wide range of emission current up to 10 mA or more. An account of the earlier work on this ion source has been given in a previous paper.

The results of these studies are presented here in three parts:

Part I covers the choice of gauge type and the various aspects of the design of the electrode system in order to overcome the difficulties of low-pressure measurements.

Part II gives the results of experimental testing of the new gauge over a range of pressures from $10^{-4}$ to $10^{-11}$ Torr and compares its behaviour with that of a Bayard-Alpert gauge.

Part III describes the low-voltage extraction of ions using various types of mesh and aperture extractors, to form an ion source for mass-spectrometer applications.

In the theoretical study of the device operation considerable use has been made of existing computer programs designed to calculate the potential distributions, particle trajectories and space-charge effects in electrostatic systems.

2. Reduction of the low-pressure limitations

The lowest total pressure which can be measured to within 10% using the conventional Bayard-Alpert gauge is limited to approximately $10^{-10}$ Torr by the presence of residual collector currents which are not linearly pressure-dependent. Although the total residual current may be equivalent to a pressure reading of about $2 \cdot 10^{-11}$ Torr its presence will make the gauge reading become non-linear at pressures at least an order higher in magnitude. The residual currents are known to result from two separate effects; the collection of a small fraction of the ions desorbed from the grid or anode structure by electron bombardment, and the release of electrons from the collector caused by the incidence of soft X-rays produced at the grid surface by electron impact.
The measurement of very low pressures can be achieved only if some method is found of considerably reducing the relative magnitude of the residual current. Minor improvements can be made by optimising the gauge performance; for example, the use of a grid material having a low quantum yield for X-rays and a low sticking factor for incident gas molecules, focussing of the electron trajectories to give a maximum path length \(^{12}\) and reduction of the collector wire diameter to reduce the exposed area \(^9\). The latter is only marginally effective, since the collection factor for the ions also decreases with collector diameter \(^4\).

Proposed methods of improving the low-pressure performance of hot-cathode ionization gauges can be divided into two groups:

(i) Modulation of the ion current to the collector described by Redhead and Hobson \(^{15}\), for application to the Bayard–Alpert gauge. This technique can also be applied to other types of ionization gauge \(^{13}\).

(ii) The removal of the ion collector from inside the grid region to a suitable position outside, in order to minimize the incidence of desorbed ions and X-rays. This principle has been embodied in a number of proposed gauges which differ in other aspects; for example, Redhead's extractor gauge \(^{13}\), the bent-beam gauge of Helmer and Hayward \(^8\) and the hidden-collector gauges of Groszkowski \(^6\) and of Clay and Melfi \(^3\).

3. Gauges with external collectors

Having removed the collector to a position outside the grid region, some means must be devised of drawing out the gas-phase ions towards the collector, while leaving the energetic desorbed ions to be collected on or escape through the grid walls. Two different methods have been proposed. Redhead, Helmer and Hayward and also Clay and Melfi, have used an end-cap which is separate from the grid, at the end adjacent to the collector. This end-cap or shield contains a circular or rectangular aperture through which the ions are directed by the electrostatic field produced inside the grid region when the end-cap is biased between 100 and 250 V below the grid potential.

In the second method of ion extraction used by Groszkowski, the end-cap containing the aperture is attached to the main grid structure and has the same potential. The extraction field is formed by penetration of an external field through the aperture and into the grid region. Although, as will be shown later, the field inside the grid is much weaker than that obtained by the former method, gas-phase ions can still be drawn through the aperture. Furthermore, since the ions cannot be collected by the end-cap but must be either reflected or deflected through the aperture, the ion extraction can be more efficient.

The gas-phase ions, having been extracted by either of the above methods, may be collected on a fine-wire electrode mounted coaxially with the grid cylinder and spaced a small distance from the aperture. In Groszkowski's gauge
the collector wire is shielded by a glass tube whereas in Redhead's gauge it is surrounded by a hemispherical metal reflector at grid potential. Reduction of the residual currents depends upon the collector being in line of sight of X-rays emitted only from the far end-cap of the grid and upon the discrimination of the extraction system against desorbed ions.

Groszkowski 5) has made detailed calculations of the proportions of the X-rays emitted from the various parts of the grid walls which are incident on the collector wire, as a function of the collector position along the axis of the grid. His results show that a reduction in the X-ray-induced component of the residual current of about two orders of magnitude could be achieved if the collector is withdrawn from the grid to a position in line of sight of X-rays only from the far end-cap.

Helmer and Hayward have used a more sophisticated collection system in which the extracted ions are deflected by a cylindrical electrostatic deflection system and collected via a collimating slit on a shielded collector plate. This type of collection system, although providing greater protection of the collector against residual currents, introduces constructional complexities.

To assist in making an evaluation of the relative merits of the two methods of ion extraction outlined above, we have computed the potential distributions and the trajectories of a sample of ions in the gauges of Redhead and Groszkowski. The results are shown in figs 1 and 2 respectively. The published values of electrode dimensions and potentials have been used, except that the glass shield around the collector of the Groszkowski gauge has been placed at filament potential to simulate the effects of surface charging which will be described later. No account has been taken at this stage of the influence of electron and ion space charges on gauge behaviour but this is not expected to significantly alter the features shown. Figures 1a and 2a show the equipotentials in the gauge cross-section as dashed curves and also plots of ion-trajectory radii for six starting points distributed within the grid. The initial velocity of an ion will affect its trajectory in the extraction field and obviously a random sample from various starting points cannot be adequately represented by a small number of plots. However, the trajectories shown here for ions having initially only angular momentum, equivalent to an energy of 0.007 eV, give some indication of the relative behaviour of the two gauges. The ion trajectories plotted in Groszkowski's gauge all pass through the aperture and are focussed onto the collector wire. Whereas, in Redhead's gauge it is clear that ions formed at a radius greater than the aperture radius in the vicinity of the end-cap are less likely to be extracted.

Figures 1b and 2b show the trajectories of desorbed ions from three points along the grid wall, with their initial directions perpendicular to and at 45° to the wall. The trajectories are shown as drawn curves for ions with 2 eV initial energy and as dashed curves for 7 eV. Although for the majority of desorbed
Fig. 1. The potential distribution and ion trajectories in Redhead's extractor gauge. (a) Equi-potentials and trajectory radius plots for gas-phase ions with initial tangential velocity. (b) Trajectories of ions desorbed from the grid wall with 2 eV (drawn curves) and 7 eV (dashed curves) initial energy.
Fig. 2. The potential distribution and ion trajectories in Groszkowski's hidden-collector gauge with the glass shield at filament potential. (a) Equipotentials and trajectory radius plots for gas-phase ions with initial tangential velocity. (b) Trajectories of ions desorbed from the grid wall with 2 eV (drawn curves) and 7 eV (dashed curves) initial energy.
ion types there is a peak in the energy distribution curve at 7 eV, there is still a significant proportion of ions which have a much lower energy (Redhead, Hobson and Kornelsen, ref. 16, p. 171). The desorbed ions shown have been given no angular momentum as this would prevent their reaching the collector unless very small. Figure 2b shows that the extraction field in Groszkowski’s gauge does not significantly deflect the desorbed-ion trajectories unless they enter the vicinity of the aperture. In Redhead’s gauge the influence of the extractor field is much greater, although many of the 7-eV ions deflected are either intercepted by the end-cap or collected on the reflector. Ions desorbed with 2 eV in this gauge, however, are more likely to be extracted and they will not reach the hemispherical reflector unless their velocity tangential to its surface on approach is equivalent to an energy less than 2 eV. In both gauges, ions desorbed from the top end-cap in the direction of the aperture are likely to reach the collector.

The above results indicate that a gauge having an external extractor electrode and integral end-cap and grid could well have a higher ion-extraction efficiency and a better discrimination against desorbed ions, than one having a separate end-cap negatively biased. The design details described in the following sections therefore relate to this type of system.

4. Grid-structure design and the influence of electron space charge

The system shown in fig. 2 has been discussed in some detail by Groszkowski 6). Gauges based on his design have also been investigated by Bernardet and Shaw 2) and Bernardet and Choumoff 1).

A number of gauges built to Groszkowski’s published drawings have been tested in our laboratory. The construction, shown schematically in fig. 2, contains a helically wound wire grid 30 mm in diameter and length, closed at one end with a spiral of wire and at the other with a metal disc containing a 10-mm diameter aperture. The fine-wire collector is coaxial with the cylindrical grid, placed a few millimetres outside the aperture and protected from unwanted radiation by a glass shield. The cathode filament in the form of a hairpin is situated alongside the grid. The significant difference in our assembly was that all gauges were flange-mounted in nude form inside a metal tube of 50 mm diameter, this being a form normally preferred for U.H.V. gauges, whereas those described by Groszkowski have been mounted inside an unscreened glass envelope 65 mm in diameter.

The gauge sensitivity was found to be rather poor, being in general less than 3 Torr$^{-1}$. Only under certain conditions of applied potentials and grid to filament spacing could the sensitivity be increased and then only for high electron currents. When a gauge is enclosed in an uncoated glass envelope and contains a glass collector shield these insulating surfaces would be expected to charge up by electron impact to approximately the potential of the cathode filament.
In order to simulate the conditions prevailing inside a charged glass envelope and to maintain constant ion-collection efficiency, we biased the filament 5 volts above the earthed metal screen and the collector 200 volts below the filament. The ion current was then measured as a function of grid potential for different values of the electron current. The resulting sensitivity curves are shown in fig. 3. It should be appreciated that while varying the grid potential the electron energy and the glass shield to grid potential were also varying. Measurements of sensitivity were made relative to a Mullard IOG20N Bayard–Alpert gauge at pressures in the region of $10^{-8}$ Torr.

From the curves of fig. 3 the sensitivity can be seen to rise rapidly from zero in each case when the electron energy has reached 15 eV and then reach peaks whose amplitudes increase with electron current. For currents below 0.5 mA no peaks appear. The rising edges of these curves have a similar shape which is consistent with the increase of the gas-phase ionization cross-section with electron energy. With further increase in grid potential the sensitivity falls rapidly to a common residual value of approximately 2 Torr$^{-1}$. The sensitivity values shown here could be obtained only by using a grid-filament spacing of at least 5 mm. Under these conditions, space-charge limiting of the emission current prevented the use of currents much above 5 mA. A curve showing the variation of sensitivity with electron current, similar to that recently described by Groszkowski 7), can be obtained from the curves of fig. 3 at a constant grid potential.

![Fig. 3. Variation of sensitivity with grid potential $V_{gs}$ and electron current $i_e$ in the Groszkowski gauge.](image-url)
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It will become apparent later that the potential distribution inside the grid region is the main factor which determines the gauge behaviour and it is to this distribution that we must look for the cause of the sensitivity variations. For a given gauge structure there are four main contributing factors which govern the shape of this potential distribution. They are

(i) The potential difference between the glass collector shield and the grid giving a field penetration through the aperture.

(ii) Penetration of the field between grid and screen and between grid and filament through the grid structure into the interior.

(iii) The negative space-charge field produced by the cloud of electrons continually passing across the grid region.

(iv) A positive space-charge field resulting from an accumulation of ions within the grid region.

The first three factors are relatively independent of one another and their overall effect can be calculated. Since the field variation is too complex for an exact mathematical solution it is necessary to use computer methods which enable the dependence of these distributions on electrode potentials and space charge to be determined. Computations were made using digital-computer programs which calculate using relaxation techniques the potentials at regularly spaced points in cylindrically symmetric systems. The positive space-charge field depends on many factors and must be deduced from the computed results and the measured gauge performance.

The magnitude and distribution of the electron space charge can be determined by calculating the average number of electrons passing across the grid region at any time and by studying the electron motion and capture. The electron trajectories have been found to be fairly evenly distributed over the grid cross-section under the conditions used for these measurements \(^{13}\). Therefore, to a first approximation, the electron space-charge density can be assumed constant over the grid volume. The calculated space-charge density is of the order of \(10^{-6} \text{ C/m}^3\) for an electron current of 1 mA in this gauge. The average electron path length across the grid region depends on the angular momentum about the grid axis which the electrons gain in the field between the filament and grid \(^{14}\). With the filament at approximately the same potential as the surrounding screen the electron focussing is poor and for grid potentials from 50 up to 200 V gives the same average path length of about 0.7 times the grid diameter. We may conclude, therefore, that the rate of ion formation at a given electron current varies only with electron energy for the measurements shown in fig. 3.

Computed potential distributions are shown in fig. 4 for an electron current of 1 mA and two values of grid-to-screen potential 50 and 200 V. Distributions at a current of 0.1 mA have been given in an earlier paper \(^{11}\). These distri-
butions have been plotted by the computer in the form of oblique projections. Potentials are represented on the vertical scale from grid potential down to 20 V below the grid. The electrodes which are shown within this potential range are a half section of the end-cap containing the aperture and the grid wires. The overall picture is intended to illustrate the form which would be taken by a rubber-sheet model if this could have included space-charge effects and cylindrical symmetry. Superimposed on these distributions are a number of trajectories of ions starting with zero initial energy from the points indicated. They are shown as though reflected at the plane of symmetry.

Figure 4a shows the conditions under which a reasonable sensitivity should be achieved. The potential hollow produced by the electron space charge can be clearly seen with its edges lowered several volts below the grid potential by

![Image](image.png)

**Fig. 4.** The potential distribution resulting from electron space charge and field penetration inside the grid of the Groszkowski gauge, with ion trajectories, for two values of grid-to-screen potential $V_{gs}$. 
field penetration from outside. All of the ion trajectories shown pass straight out via the aperture. However, many ions formed near the centre of the grid region oscillate to and fro inside the potential hollow and must therefore modify the shape of the potential distribution so that ions formed anywhere within the volume can escape either through the aperture or between the grid wires. Such trajectories have been omitted from the figure for reasons of clarity. In fig. 4b the grid-to-screen potential has been increased to 200 V and the correspondingly higher field penetration has lowered the average potential considerably and almost destroyed the space-charge hollow. Many of the ions formed can now escape between the grid wires in spite of the increased extraction potential and even after crossing the centre of the grid region. At lower electron currents the negative space-charge hollow is virtually non-existent.

These results lead to three important conclusions. First, field penetration through the grid wires from the region outside the grid is very detrimental to the operation of the gauge and is the main contributing factor to the behaviour shown in fig. 3. Penetration of the filament-grid field, not included in these calculations, has also been found to be an important factor. Second, the existence of the field produced by the electron space charge is necessary to prevent the ions escaping between the grid wires. Third, at higher electron currents the extraction field tends to produce a depression in the side of the potential hollow through which the ions can pass, rather than actually drawing them from the grid region. The implications of these conclusions will become more apparent later with the results obtained from a modified gauge structure.

In subsequent gauges we have replaced the open helically wound grid and spiral end-cap with a structure which has much smaller apertures to inhibit field penetration but which still has a high electron transparency. This has been achieved using a finely woven tungsten mesh, which has square apertures at a spacing of approximately 24 per cm and nearly 90% transparency. The effect which this structure has on the gauge performance is shown in fig. 5. These curves were produced using the same arrangement of potentials as in fig. 3 from which two curves have been reproduced (as dashed curves) for comparison. It can be seen that the performance is much improved although the sensitivity is not yet independent of the electron current under these conditions.

5. Ion extraction and collection

Typical collector characteristics measured for the gauge of fig. 2 are given in fig. 6. These curves show the variation in sensitivity with collector-to-grid potential for two values, -100 and -200 V, of the filament-to-grid potential. There is no ion current to the collector until its potential has reached that of the filament. With further increase of the collector-to-grid potential the current rises quickly over the next 100 volts and then continues to increase at a reduced rate. These results support the suggestion made by Groszkowski that the glass
Fig. 5. Variation of sensitivity with grid potential $V_{gs}$ and electron current $i_e$ in a gauge with a fine-mesh grid structure. Corresponding curves for the Groszkowski gauge are shown as dashed curves.

A better understanding of these curves and the collection mechanism can be obtained from a knowledge of the ion trajectories in this region.

Figure 7 shows such trajectories and equipotentials in a half cross-section of the collector region of the Groszkowski gauge. The lower boundary in each case is the axis of symmetry, and trajectories which would cross this axis are shown as though reflected from it. For the three cases illustrated the glass shield charges up to filament potential.
is given a potential 100 volts below that of the grid, thereby representing a surface charged to filament potential. In fig. 7a the collector and shield potentials are equal and virtually all of the ions go to the shield rather than the collector. With the collector biased 50 V below the shield, fig. 7b, about 50% of the ions are drawn to the collector. Even with a collector bias of 300 V below the shield, fig. 7c, a proportion of the ions still reach the shield. The ions for which these trajectories were computed had zero initial energy, the addition of angular momentum would make collection more difficult for weak fields and fine collector wires 4).

Another important feature which is apparent from the equipotential plots, is that the potential distribution in the region of the aperture is not significantly affected by the varying collector potential. This means that the collector plays no appreciable part in the extraction of ions from the grid region when the shield is at filament potential. By being placed at a sufficiently negative potential it draws a proportion of the ions away from the shield by which they would otherwise be intercepted. The extraction field is thus provided by the charged glass shield and can be changed only by varying the filament potential and may well be dependent on the condition of the glass surface.

From the above results it seems clear that a separate extractor electrode, which can be adequately biased, is essential. There are also the following important reasons for employing such an extractor electrode:

(i) A negative potential barrier must be provided across the gauge axis outside the aperture in the end-cap to prevent the passage of energetic electrons into the region surrounding the collector. Otherwise the arrival of these electrons at surfaces in the collector region will, we have found, give rise to residual currents which prevent low-pressure measurement.
(ii) At lower pressures the extraction of ions can be readily accomplished using a weak extraction field but at pressures above $10^{-7}$ Torr, satisfactory extraction requires increasingly stronger extraction fields.

(iii) As the pressure decreases below $10^{-9}$ Torr an increasing proportion of the ions, which are confined within the grid region prior to extraction, could become multiply ionized by sequential electron impact. The collection of such ions would increase the measured collector current. In order to prevent this effect, the ion residence time within the grid region must be kept to a minimum by the application of a sufficiently large extraction field.

We have investigated a number of extractor electrode arrangements, and an early version was described in a previous paper (11). The system which has evolved and has been used for recent experiments is illustrated in fig. 8, together with the equipotentials and a radius plot of typical ion trajectories. The aperture diameter and the internal diameter of the extractor electrode have been reduced to 4 mm, in order to shield the collector from the direct impact of X-rays emanating from the side walls of the grid, especially when using reduced grid dimensions. The extractor electrode is designed to provide an adequate extraction field and a suitable negative potential barrier when operating at collector potential, between 150 and 250 V below the grid potential. The collector wire protrudes through a hole in the centre of a closed cylindrical reflector electrode which is maintained at grid potential. The ion optical arrangement of the electrostatic lenses formed by these electrodes has been designed to focus the ion beam onto the collector wire, as shown in fig. 8.

The shape of the potential distribution in the extractor-collector region with both electrodes biased 200 V below grid potential is illustrated in fig. 9. The
position of the extractor electrode, which is hidden by the curvature of the potential surface, is indicated by a dashed line. The negative barrier across the mouth of the aperture can be seen together with a positive barrier between the extractor and collector. This positive barrier has a significant effect on the gauge characteristics in that its height controls the passage of ions to the collector. Since its height must be lower than that of the potential level inside the grid to avoid ion reflection, a limitation is imposed on the distance that a collector wire of a given diameter and potential can be withdrawn along the axis. A compromise must therefore be reached between adequate ion collection and the reduction of the X-ray limit.

Typical measured ion-extraction characteristics for nitrogen, using a collector wire diameter of 0.5 mm to provide a high collection factor, and a collector-to-grid potential of 200 V, are shown in fig. 10a for different electron currents. The ion current increases rapidly at first with increasing extractor-to-grid potential and then levels off as the maximum current is reached. Larger extraction potentials are required as the electron current is reduced and for values below 1 mA potentials in excess of 100 V are necessary as the influence of the negative space charge diminishes and ion extraction becomes increasingly difficult. In contrast, at 10 mA electron current the potential drop across the aperture diameter produced by the space charge and collector potential is sufficient to allow the ions to reach the collector using zero extractor bias. The influence of changing pressure on the extraction characteristics is shown in fig. 10b for an electron current of 1 mA. For pressures up to approximately $10^{-7}$ Torr the characteristic shape is virtually unchanged but as the pressure is raised towards the $10^{-5}$ Torr range the extraction of ions becomes increasingly more difficult until, at a pressure just above $10^{-5}$ Torr, a gauge with fixed extraction potential ceases to have a constant current-to-pressure ratio. The reason for this
Fig. 10. Ion-extraction characteristics showing the variation of sensitivity with (a) electron current, (b) pressure and (c) collector diameter.
effect is believed to lie in the conditions controlling the space-charge equilibrium and the ion-extraction mechanism and will be discussed in detail in a future publication. Additional effects which become apparent at very low pressures will be described in Part II.

Variation of the collector diameter for constant electrode potentials and spacing will alter the electric-field strength in the region between collector and extractor and hence the height and position of the positive potential barrier described above. Curves have been plotted for three values of the collector diameter (0·125, 0·2 and 0·5 mm) and a fixed spacing of 6·5 mm between the end-cap and the tip of the collector wire. In each case the length of the collector wire inside the reflector was 6 mm. Extractor characteristics for the three diameters are shown in fig. 10c for 1 mA electron current, a pressure of 10⁻⁷ Torr and a collector-to-grid potential of —200 V. In the case of the 0·5-mm collector the sensitivity rises rapidly as the extractor bias is increased and a relatively constant value is maintained above 100 V. For the 0·2-mm collector wire the sensitivity rises to a maximum at approximately 80 V and then falls to a lower level for potentials above 250 V. When the collector diameter is reduced to 0·125 mm, however, the sensitivity increases only slowly with increasing extractor bias, reaching a maximum at approximately 175 V and then slowly falling. Similar results were obtained for other values of the electron current.

Collector characteristics for a 0·5-mm collector wire are shown in fig. 11 as plots of relative sensitivity against collector-to-grid potential for 1 and 10 mA electron current. The variation of extractor sensitivity with $V_{cg}$ is also shown. As the extractor was not shielded from ions formed outside the grid region, the latter curves may include a component of current due to ions reaching its external surface, though this should not vary with collector potential. The sums of the ion currents to the two electrodes give total sensitivity curves

![Diagram](image-url)

Fig. 11. Ion-collection characteristics showing the variation of sensitivity $S$ at the collector and extractor with collector-to-grid potential $V_{cg}$. 
which, except for an initial dip, are relatively constant for varying $V_{eq}$. When using a 0·125-mm collector wire the ion current was found to rise more slowly with increasing collector bias than in the curves of fig. 11.

From the characteristic curves of figs 10c and 11 it is evident that the efficiency of ion collection depends on the height of the positive potential barrier between collector and extractor, relative to the potential level inside the grid region at which the ions are formed. It would appear that the decrease of sensitivity at high extraction potentials when using fine collector wires may well be due to the potential inside the grid region decreasing at a faster rate than the height of the potential barrier. In addition the barrier height may well be reduced by the presence of electron space charge which can penetrate into the collector-extractor region when the extractor is at a higher potential than the filament. This may well be the cause of an observed increase in sensitivity with electron current at extractor-to-grid potentials below 100 volts when using fine collector wires (see Part II).

The dependence of the ion-collection factor on the angular momentum of the ions, the collector-wire diameter and the applied electrostatic field, described by Comsa 4) for the Bayard-Alpert gauge is equally important in this type of system. The curves of fig. 11 show that ions prevented from reaching the collector, either by the potential barrier or as a result of their having excessive angular momentum, are collected by the extractor electrode. Ion collection using fine wires could probably be improved by moving the collector wire nearer to the aperture in the end-cap but only at the expense of a higher residual current due to the increased exposure to X-rays.

6. The effect of reflected X-rays on the residual current

Groszkowski has calculated the residual current in his gauge due to the direct incidence of X-rays on the collector to be equivalent to a nitrogen pressure in the region of $10^{-13}$ Torr. However, he has neglected the incidence of X-rays reflected towards the collector by the surrounding structure. In the ion-collection system we have described above, the collector is surrounded by a closed cylindrical reflector electrode made of stainless steel which is held at grid potential. The flux of X-rays through the aperture in the end-cap will be very much greater than the proportion which is intercepted directly by the collector wire and the majority of these X-rays will be incident on the reflector electrode. Although the reflection coefficient of most metals for soft X-rays is in the region of 0·1 to 0·2, the number of reflected X-rays reaching the collector after one or two reflections could well be considerably greater than the number which is directly incident.

In order to minimize this effect we have designed a modified reflector assembly in which the diameter of the reflector cylinder is slightly increased from 8 to 9 mm and the flat end-cap through which the collector protrudes is replaced by
Fig. 12. A modified reflector assembly designed to reduce the residual current due to X-ray reflection. The paths of two typical rays show multiple reflections at the reflector walls.

a cone, as shown in fig. 12. The angle and length of the cone and the cylinder diameter are chosen such that the majority of X-rays passing through the 4-mm aperture in the grid end-cap would have to be reflected many times before they could reach the collector. The low reflection coefficient ensures a considerable reduction in intensity for each additional reflection the X-rays undergo. In the low-pressure tests to be described in Part II a reduction in the estimated residual current of five times was obtained by replacing the previous reflector assembly with this system. A glass bead has also been placed on the collector wire to shield the collector support system from the direct impact of X-rays passing through the hole in the conical reflector.

7. Modulation of the ion current

A modulator electrode has been incorporated in our experimental gauges as a means of assessing the low-pressure performance. The modulator used was in the form of a tungsten wire protruding a distance of approximately 2 mm into the grid region through a small central aperture in the mesh of the end-cap opposite the extraction aperture. This type of structure is similar to that used by Redhead in his extractor gauge and has the advantages of presenting a small cross-section for electron capture and having little influence on the electron trajectories when placed at collector potential. The electron current to the modulator and its support wire when placed at grid potential was found to be only 1·3\% of the total emission current. The electron current to the mesh end-cap through which the modulator enters the grid was measured using a grid with a separate end-cap. The proportion of the emission current reaching the end-cap at 1 mA was found to be approximately 20\% with the modulator at grid potential, falling to 19\% when the modulator was biased 200 V below the
grid. Current changes of this order should have little effect on the number of X-rays reaching the collector.

The shape of the potential distributions inside the grid region, assuming a uniform negative space-charge distribution, are illustrated in figs 13a and b for 1 mA electron current and the modulator at grid potential and 200 V below grid potential respectively. The extractor electrode which is also biased 200 V below the grid is outside the voltage range included in these figures. The effects of field penetration through the grid mesh and positive ion space charge have not been included in these calculations. The potential depression at the centre of the grid region is 3·4 V without modulation and the extractor potential provides an extraction field towards the aperture. The effect of reducing the modulator potential by 200 V is to make the potential distribution nearly symmetrical about the centre plane across the grid region, as shown in fig. 13b. The collection of ions formed in this near symmetric field would be expected to be divided almost equally between modulator and collector, indicating a modulation factor of about 0·5. However, from the measured modulation characteristics of the

Fig. 13. Potential distributions inside the grid region resulting from 1 mA electron current and 200 V extractor bias showing the effect of modulation when ion space charge is neglected; (a) modulator at grid potential; (b) modulator biased 200 V below grid potential.
gauge shown in fig. 14, it can be seen that the actual modulation factor is approximately 0.95 for a 200-V change in modulator potential. This obvious discrepancy illustrates the importance of the positive ion space charge in the interpretation of the gauge behaviour.

Of the ions desorbed from the grid structure by electron bombardment those originating from the top end-cap and having little or no angular momentum are more likely to reach the collector. In this case the change in the field distribution in this region, due to modulation, may have some effect on their trajectories. This effect has not been studied experimentally, though possible alternative siting of the modulator will be discussed later.

![Fig. 14. Typical modulation characteristics obtained from an experimental gauge showing the variation of collector current with modulator-to-grid potential at different electron currents.](image)

8. Conclusions

Having considered the two proposed methods of producing an ion-extraction field, we have chosen for further study the method in which the field penetrates into the grid region via the aperture from an external electrode. This system would appear to have two advantages in that the desorbed ions are not strongly drawn towards the aperture in the end-cap and therefore less reliance is placed on the collimating effect of the aperture to prevent their entering the collector region. Secondly, as the end-cap containing the aperture is at grid potential only energetic ions can be collected on it, the low-energy ions being directed towards the aperture. Consequently, the efficiency of extraction of the low-energy ions could well be consistently higher.

The large variation in sensitivity with electron current previously reported for gauges of this type results from ion loss due to penetration of external fields through the gaps in the coarse-grid structure used. This problem can be overcome by the use of a fine-mesh grid with high transparency.

The ion-extraction system has been designed to give controlled extraction over a wide pressure range. It also provides a negative potential barrier prevent-
ing electron penetration into the collector region, which would cause a considerable increase in the residual current. An ion-collection system has also been developed and incorporates a simple reflector assembly which can considerably reduce the residual current caused by reflected X-rays, while shielding the collector from external radiation. Tests have shown that a high modulation of the ion current of approximately 95% can be achieved using a simple modulator electrode which does not significantly affect the electron trajectories.

In Part II, the results of tests carried out on a gauge of this design are described for pressures down to $10^{-11}$ Torr and its performance is compared with that of a modulated Bayard–Alpert gauge.

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REFERENCES