Sensitivity of hot cathode ionization gages

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As a part of an experimental program of some years duration we have attempted to characterize several hot cathode ionization gage types in the high vacuum range by the uniformity, linearity, and stability of their nitrogen sensitivity. Results for six commonly used types are summarized here. Of the gages tested, the most promising overall performance was obtained from tubulated Bayard–Alpert gages with two tungsten filaments mounted 180° apart about the grid. Conventional triode gages with tungsten filaments came close to this level of performance and have superior high pressure linearity.

I. INTRODUCTION

"Pressure" is a measurement of importance to the large and increasing number of scientific investigations and industrial processes that require a vacuum environment. Although the quantity of interest may really be the gas density or molecular flux, it can be related back to the force-per-unit-area pressure that we are familiar with at higher pressures. However, as the pressure is reduced, conventional mechanical pressure measurements become increasingly difficult. While capacitance diaphragm gages can be used into the high vacuum range, and molecular drag gages throughout the high vacuum range, both are eventually limited by lack of sensitivity as the pressure is reduced. Their application may be further restricted by cost and/or response time. For these reasons, ionization gages have been and will undoubtedly continue to be the most widely used vacuum gage below 10^{-1} Pa (1 Torr = 133 Pa). Many vacuum processes require only crude measures of the pressure, but an increasing number require uncertainties as small as a few percent (or better). Accurate measurements can be obtained only if the user appreciates the capabilities of the measuring instrument and, particularly in the vacuum range, the limitations of the measurement environment. In order to improve the state of knowledge in the first of these areas, the National Bureau of Standards has been acquiring data on the performance characteristics of vacuum instrumentation. Because of the large number of users, much of this effort has focused on ion gages in the high vacuum range. This paper summarizes the results to date and includes some recent data on gage performance down to 10^{-6} Pa.

II. PRINCIPLE AND LIMITATIONS OF IONIZATION GAGES

The results reported here are for hot cathode (hot filament) ion gages. In these gages a heated cathode emits a current of electrons that is accelerated through a modest voltage, (typically 150 V), between the cathode and a grid. The energetic electrons collide with and ionize gas-phase molecules. The ions are attracted to a collector which is negatively biased with respect to the cathode and the grid. The pressure in the gage, P, can be related to the emission current, I^e, and collector current, I^+, by

$$P=\frac{I^+ - I_r^+}{I^e S'}, \tag{1}$$

where S' is the gage sensitivity, and I_r^+ is a pressure independent residual current.

The residual current is primarily due to photoelectrons ejected from the collector by soft x rays generated by collisions of electrons with the grid. A secondary contribution is due to electron stimulated desorption of ions from the grid. The older conventional triode (CT) gage design, illustrated in Fig. 1, has a central cathode (filament) surrounded by a coaxial grid and cylindrical collector. The large area of the collector results in residual currents equivalent to a nitrogen pressure of the order of (1 to 3)$\times 10^{-4}$ Pa. The inverted triode geometry, commonly known as Bayard–Alpert (BA), has the cathode outside the grid and the collector is a fine wire along the axis of the grid. One configuration of this gage is illustrated in Fig. 1. Electrostatic forces maintain a high ion collection efficiency while the small geometric cross section of the collector results in residual currents three or more orders of magnitude smaller than those of CT gages.

Equation (1) and the mechanical simplicity of an ion gage may leave the impression that they are simple theoretically predictable devices. In fact, ion gage performance depends on a number of factors that are difficult to theoretically model and quantitatively evaluate: electrode geometry, electrical parameters, surface and bulk properties of electrode materials, emission characteristics of filaments, space and surface charges to name but the more obvious. The sensitivity in Eq.

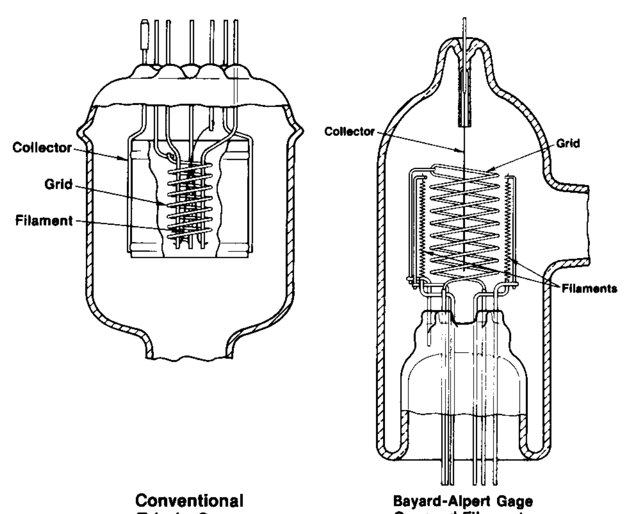

FIG. 1. Schematic of the electrode structure for tubulated conventional triode and Bayard–Alpert gages.

(1) thus depends on a number of variables. The probability that an electron will collide with a molecule depends on the length of the electron trajectory, which in turn depends on where and in what direction it was emitted, the electric fields, and the physical arrangement of the gage electrodes. The probability that an electron will ionize a molecule depends on the molecular species and the electron energy. The probability that an ion will be collected depends on where it is created, the component of its velocity orthogonal to a wire collector, and the surface condition of the collector. The theoretical difficulties of just part of this problem can be appreciated from Pittaway's analysis of electron orbits in BA gages.[1] The problem is compounded since many of these factors can change with time and conditions of use.

III. GAGE CHARACTERIZATION PROGRAM

The importance of ion gages to vacuum science and technology has prompted a considerable amount of research on their properties during the last 30 to 40 years. This work has been covered by several reviews[2–5] which we will not try to replicate. A common feature of much of this work was the emphasis on low pressure (ultrahigh vacuum) gaging problems, principally how to minimize or avoid the effects of residual currents. Accuracy or stability of gage sensitivity was generally a secondary concern. However, in the high vacuum range residual currents are negligble for BA gages, and the vacuum environment can be controlled well enough that measurement accuracy is often limited by the instrument performance. Users desiring small errors are then concerned with the accuracy, linearity, and stability of gage sensitivities and, in the many applications where the trouble and expense of gage calibration is not warranted, it is desirable to have some measure of the probable errors when uncalibrated gages are used.

Given the near impossibility of theoretically predicting ion gage performance, we have attempted to address these questions by obtaining calibration data for samples of several ion gage types, principally those of U.S. manufacture in common use. The initial emphasis has been on nitrogen sensitivities in the high vacuum range, although relative sensitivities for several gases have been obtained for some gages, and we have recently started obtaining data down to 10^{-6} Pa. One of our premises has been that gage types that show small unit to unit variations, in spite of manufacturing intolerances, would be more stable and predictable with time and use. The probable errors when using uncalibrated gages of such a type would be smaller as well.

The calibration apparatus has changed somewhat during the 5 years that we have been acquiring these data. Common to all of the measurements is that they have been obtained on all-metal calibration systems using either ion, mercury diffusion, cryogenic, or turbomolecular pumps, which have all produced system base pressures below 10^{-6} Pa. The gages and calibration chambers were baked at 230 °C before testing the gages. Most of the gages were outgassed by resistive or electron bombardment heating of the grid. However, we have discovered that operation of the gages during bakeout, with or without outgassing, produces base pressure readings that are lower and more stable than those obtained with conventional outgassing techniques. Presumably this is in part due to the material outgassed from the gages being quickly pumped from the hot chamber walls. The gages were operated on NBS-designed controllers, with control and measurement of bias voltages to within 20 mV, control and measurement of emission currents to within 0.02%, and measurement of collector currents to within 0.1%. Direct current cathode heating was used, and for gage types where it mattered the current direction was reversed and the results averaged. Unless the manufacturer specified otherwise the gages were operated with the collector at ground, the filament at + 30 V, the grid at + 180 V, and with 1 mA emission current.

Most of the gages were calibrated against spinning rotor gages (SRG), which in turn had been calibrated against an NBS primary vacuum standard.[6] Calibrations were performed from 10^{-4} to 10^{-1} Pa with two points per decade. Depending on their calibration history, the SRG measurement uncertainties varied from 1.5% to 3%, except at the lowest pressures where they varied from 2.5% to 5%. Some of the ionization gages recently measured were calibrated down to 10^{-6} Pa directly against an NBS primary standard of the orifice flow type. This system has a base pressure in the 10^{-8} Pa range. The uncertainty of these measuements varied from 5% at 10^{-6} Pa to 1% at 10^{-5} Pa and above. Residual gas analysis indicated no significant impurities in the nitrogen calibration gas for all cases.

We believe that the attention to system cleanliness and the control and measurement of electrical parameters generated optimum conditions, and the results presented below reflect the best performance of the gages themselves.

IV. RESULTS

The results presented here are primarily a summary of our nitrogen sensitivity results for commonly used gage types. Results for other gage types, and some of the results summarized here, have been presented elsewhere.[7–10] Additional results, including relative gas sensitivities are in Ref. 11, and a long term stability study is described elsewhere in these proceedings.[12]

Results are presented in terms of gage sensitivities, or sensitivity coefficients,

$$S = \frac{I^{+} - I_{0}^{+}}{I^{e}(P - P_{0})}, \tag{2}$$

where I_0^+ is the collector current at base pressure P_0. For CT gages I_0^+ is effectively the residual current, for BA gages it is negligible except at the lowest pressures. We have condensed the large amounts of data acquired by characterizing each gage by its average nitrogen sensitivity between 10^{-3} and 10^{-2} Pa. This number is then averaged for all the gages of a given type and that average is plotted, as a percent deviation from the manufacturer's specified sensitivity, in Fig. 2. The gage type is indicated at the bottom of Fig. 2, along with the number of gages (or filaments for dual filament gages) sampled. For each gage type $\pm$ 1 standard deviation of the sensitivities about the mean is indicated by the shorter rectangular box, while the range of sensitivities measured is indicated by the longer box. The results were obtained with "new" gages, typically with about 200 operating hours.

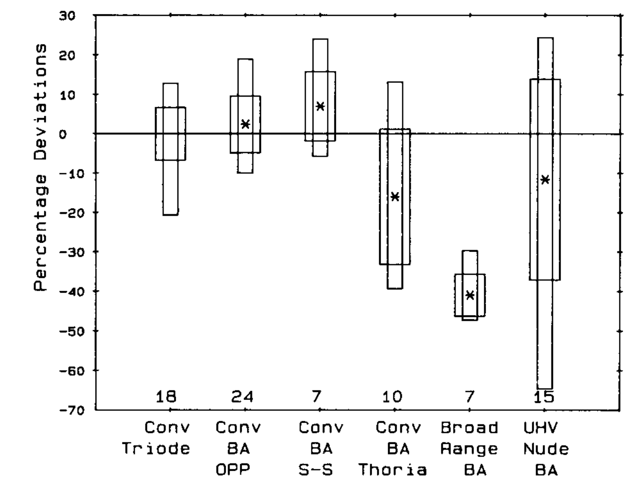

FIG. 2. Average offset from specified nitrogen sensitivity, standard deviation of sensitivities about the mean, and range of sensitivities for six different gage types. The gage types are designated at the bottom of the figure and explained in the text. The numbers at the bottom indicate the number of filaments tested. The mean sensitivity offset is indicated by the (*), $\pm$ one standard deviation by the wider box, and the range of sensitivities measured by the narrower box.

V. CONVENTIONAL TRIODE

Although limited at the low end of the high vacuum range by relatively large residual currents, CT gages are expected to be more uniform and stable because of their robust construction and cylindrical symmetry about the central cathode. The CT gage design is rather old and the suppliers' recommended -20 V collector bias, 0 V filament bias, 180 V grid bias, and 5 mA emission current are not compatible with most modern commercial controllers. Although we did verify good agreement between measured and specified sensitivities using the suppliers' recommended electrical parameters, the data for the 18 tungsten filament gages shown in Fig. 2 were obtained with the collector at ground, filament, and grid bias voltages of 30 and 150 V, and an emission current of 1 mA. Using these operating parameters we found an average nitrogen sensitivity of 0.138 Pa^{-1} (18.4 $Torr^{-1}$) and a somewhat improved linearity compared to that obtained with the older parameters. The range of sensitivities is dominated by three gages that have sensitivities significantly outside the range of the other 15. The standard deviation for all of the CT gages is 6.7%, which is consistent with other studies.[13,14] Day-to-day instabilities are on the order of 2% and the gages are linear to within a few percent through and beyond the upper part of the high vacuum range, although the nonlinearity increases with time.[12] Six thoria coated filament CT gages, not included in Fig. 2, had comparable sensitivities but with day-to-day instabilities a factor of 2 to 3 larger. The poorer results from the thoria coated filaments are, in our experience, typical. However, we did operate the coated filament gages up to 5 Pa with nonlinearities no greater than 15%. Bias voltage dependencies are comparatively large for CT gages, 0.5% change in sensitivity per volt of filament bias, -1.3% change per volt of grid bias.

VI. CONVENTIONAL BA GAGES

Glass tubulated BA gages with a 21 mm diameter, 43 mm long grid are widely used. These gages can be further subdivided by filament arrangement. The type designated as "CONV BA OPP" has two tungsten filaments 180° apart, or opposed, about the central collector, and a coaxial grid, as illustrated in Fig. 1. The "CONV BA S-S" has two tungsten filaments side-by-side or 8 mm apart on one side of the grid structure. The "CONV BA THOR" has one thoria-coated filament. All three have a specified sensitivity of 0.075 Pa^{-1}, or 10 $Torr^{-1}$.

The 24 filaments of the 12 opposed filament gages tested have shown a remarkable degree of uniformity and the average sensitivity differs from the specified sensitivity by 2.4%. As with the CT gages, the range of sensitivities is dominated by two gages (four filaments) that are well outside the range of the other gages. The standard deviation for all gages is 7.2%. The gages tested were obtained from three different suppliers. It is of interest that the gages from one supplier all had sensitivities above the stated value, those from the other two were all below. Day-to-day instabilities are of the order of 2% and linearity is within a few percent up to about 5×10^{-2} Pa, after which the sensitivity may drop precipitously. Long-term stability is better than any other gage type for which data have been published.[12] Bias voltage dependences of the sensitivity are an order of magnitude smaller than for CT gages, but increasing the emission currents to 10 mA can decrease low pressure sensitivities by up to 20% with much larger changes above 10^{-3} Pa.

As can be seen from Fig. 2, the side-by-side filaments have a slightly greater variability in sensitivity (standard deviation of 8.8%) and a 7% difference on the average from the specified sensitivity. Not shown in the figure is a systematic difference in sensitivity between the two filament positions. We believe that is due to electric field differences caused by an asymmetric filament support structure. Furthermore, one of the two filaments positions (same position for each gage) showed a characteristic instability above 10^{-2} Pa that reduced the sensitivity by as much as a factor of 3.

The thoria-coated filament BA gages had a much larger variability of sensitivity (standard deviation = 25.5%) and the average sensitivity is offset by -11.6% from the specified sensitivity. Day-to-day changes were on the order of 4% to 5% and some gages had significant high pressure nonlinearities as low as 10^{-2} Pa. We believe the instabilities are due to changing thermal contact between the filament coating and the substrate, with consequent changes in emission characteristics.

VII. BROAD RANGE BA GAGES

Various attempts have been made to extend the range of BA gages above 10^{-1} Pa. One such design, available under several trade names, uses a narrowed grid, which is 12 mm in diameter and 46 mm long, a thoria-coated filament, and a grounded platinum coating on the inside of the glass tube. Although the range of sensitivities indicated in Fig. 2 is small, the average sensitivity for the seven gages was 41% below the specified value. Of more concern, we found large instabilities and nonlinearities for some of the gages,[9] with sensitivity changes with time and pressure exceeding the range shown in Fig. 2.

VIII. UHV NUDE BA GAGES

Although designed to minimize residual currents and maximize sensitivity for improved performance in the ultrahigh vacuum range, the UHV nude BA gage is often used in the high vacuum range. This gage has a small diameter collector, typically 0.125 mm, a fine wire grid with end "caps," and two replaceable filaments. Most manufacturers specify a sensitivity of 0.188 Pa^{-1} (25 $Torr^{-1}$) for a 4 mA emission current. Recommended bias voltages vary. The results summarized in Fig. 2 were obtained with gages from two different manufacturers with both tungsten and thoria-coated filaments. The thoria-coated filaments were operated at 1 mA, the tungsten at 4 mA. All gages were mounted inside 1 3/8 in. i.d. stainless steel tubing. Since these gages become very nonlinear at higher pressures, the results presented here are based on average sensitivities between 10^{-4} and 10^{-3} Pa. The large variation in sensitivities (standard deviation = 26%) shown in Fig. 2 would be increased had the thoria-coated filaments been operated at 4 mA since this would have decreased their already low sensitivities by about 9%. One expects that the variation from gage to gage is due at least in part to the fragile construction and possible mounting variations in the replaceable filaments. Some of the gages employ an asymmetric mounting structure for the two filaments. For these gages we observed systematic sensitivity differences for the two filament positions that were similar to the differences observed between the asymmetrically mounted filaments of the side-by-side conventional BA gages.

Figure 3 illustrates the nitrogen sensitivities of a sample of three different nude gages, along with an opposed filament tubulated conventional BA gage for comparison. The crosses are a tungsten filament nude gage operated at 4 mA. The "knee" at 10^{-3} Pa and the rapid drop in sensitivity at higher pressures is quite typical. Preliminary data indicates that these gages are linear at low pressures down to at least 10^{-7} Pa. The gage illustrated has the asymmetric filament mounting and the sensitivity difference between the two filaments is also typical. The *'s are a gage of the same type, but with thoria-coated filaments operated at 1 mA. We are at a loss to explain the improved high pressure linearity. Operating tungsten filament gages of the same type at 1 mA reduces the sensitivity by about 8%–9% and extends the linear range a factor of 4 or 5 higher in pressure, presumably because of reduced space charge near the collector. However, the linear range of the thoria-coated filament gage appears to extend about a factor of 50 higher. The ×'s are a nude gage that is very similar in design to the tubulated side-by-side filament conventional BA gages. Data for this gage are not included in Fig. 2. It was both linear and stable, although after about 1500 h of operation one filament distorted with use to the point that it was useless.

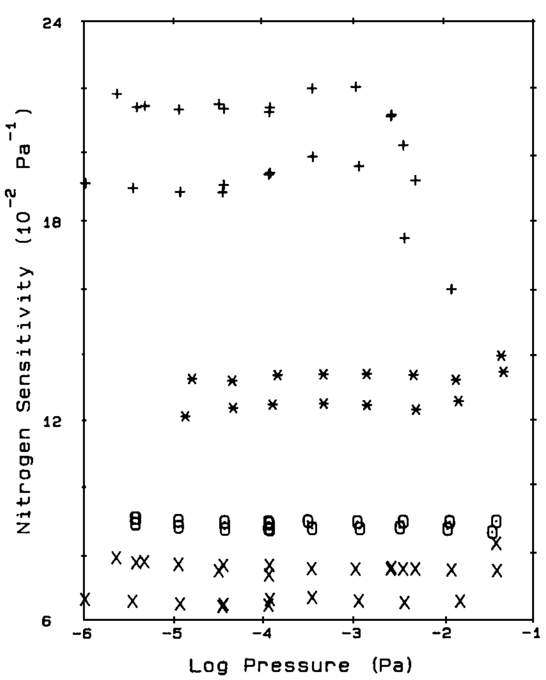

FIG. 3. Nitrogen sensitivities as a function of pressure for nude UHV BA gages with tungsten filaments (+) and thoria-coated filaments (*), one nude "conventional" BA gage (×), and one tubulated BA gage (O). Sensitivities of the tungsten filament UHV gage above 10^{-2} Pa have been deleted for clarity's sake since they drop rapidly with pressure and are below the scale of the graph at 10^{-1} Pa.

IX. CONCLUSIONS

Judging by predictability of sensitivity, stability, and linearity we find, of the gages we have tested, that the tubulated opposed tungsten filament BA gages perform best throughout the high vacuum range except at the highest pressures. Conventional triodes with tungsten filaments are a close second and maintain their linearity through and above the upper limit of the high vacuum range. They are limited at the lowest pressures by their large residual currents. We believe that the relatively poor performance of the thoria-coated filament gages may be due to changing thermal contact between the thoria coating and the hot flat hairpin substrate, with consequent changes in emission characteristics. We have no evidence as to whether or not this problem exists with coated filaments of other designs. Users of UHV nude gages should assume that gage sensitivity may differ significantly from stated values, particularly for tungsten filament gages above 10^{-3} Pa.

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