

Residual currents in several commercial ultrahigh vacuum Bayard-Alpert gauges

Albert R. Filippelli

Center for Basic Standards, National Bureau of Standards, Gaithersburg, Maryland 20899

(Received 18 April 1987; accepted 18 May 1987)

Residual currents have been determined for several commercial UHV Bayard-Alpert gauges, including two modulated gauges, by comparison against an extractor gauge. Residual currents in the modulated gauges were also determined by the modulation method (Redhead mode I) and these results are compared with those of the first method. Residual current modulation factors were estimated by combining the results of these two methods. A significant residual current modulation factor (1.33) was found for one of the modulated Bayard-Alpert gauges. One notable aspect of this work is the finding that residual current values can differ by more than a factor of 10 among nominally identical gauges. Another interesting and somewhat surprising feature of these measurements, which were performed in H_2 at pressures in the range 4×10^{-9} to 4×10^{-5} Pa, is that no hysteresis was detected in the gauges' response to large, rapid decreases in the H_2 pressure.

I. INTRODUCTION

As pressures become comparable to or less than about 10^{-8} Pa, large uncertainties will be present in absolute pressures determined with a Bayard-Alpert gauge (BAG) if the gauge's residual current is not known. For example, at an emission current of $I_e = 1$ mA, a typical BAG might have a residual current of 0.8 pA, which is equivalent¹ to a H_2 pressure of 1×10^{-8} Pa at room temperature (assuming a corresponding gauge sensitivity S of 0.08 Pa^{-1} for H_2).

The residual current is that current to the collector which is due to processes other than direct ionization of gas phase molecules. These other processes are generally dominated by the following: (1a) Photoejection of electrons from the collector by x-ray radiation generated when the energetic ionizing electrons collide with the grid (normal x-ray effect)^{2,3}: This current is independent of the gas density. (1b) A current of the opposite sign arises from the x-ray photoejection of electrons from the wall surrounding the gauge. It is possible for such electrons, when sufficiently energetic, to reach the collector (reverse x-ray effect).⁴ This reverse x-ray current to the collector is also pressure independent and can be eliminated by biasing the collector negative with respect to the wall. (2) Electron stimulated desorption (ESD)⁵: In the ESD process, energetic electron collisions with the grid can cause the release of adsorbed gas, both as neutrals and as ions. Some of the positive ions released in this way from the grid surface can reach the collector and contribute significantly to the measured collector current. ESD effects depend on the gauge materials, history of exposure to different gases, and operating voltages and emission current. For those cases in which the time dependence of this flux of ESD ions lags significantly behind the time dependence of the gas pressure (e.g., O_2 on Mo), this ESD current appears as part of the residual current since it is not proportional to the instantaneous gas pressure. However, if the time dependence of any part of the ESD current closely follows the time dependence of the gas pressure, it will be impossible to separate this ESD current from the gas phase component of the collector current, and they will both contribute to the measured gauge

sensitivity. (3) Leakage currents: These currents were found to be negligible in this work.

One approach to this pressure measurement problem is to make the residual current smaller. In BAG's, such a reduction may be realized in a number of ways: (1) The data of Refs. 6 and 7 suggest that it may be possible to find a grid material which is relatively inefficient for the generation of x radiation (e.g., Pt rather than W,⁶ or Pt-Ir alloy rather than Mo⁷). (2) Some advantage may be gained by using a grid material which exhibits a small ESD effect.⁸ (3) Reducing the electron impact energy may help, since the intensity of the x-ray radiation has been found to increase as some power of the impact energy.^{6,7} This may be appropriate for gases for which maximum ionization cross section occurs at an energy below the 100–150 eV range typically used in commercial BAG's, e.g., H_2 at 70 eV.⁹ (4) Using a shorter and/or thinner collector wire will yield some improvement because it reduces the fraction of x rays intercepted by the collector.^{10–12}

The other possible approach, and the objective in this work, is to measure the residual current. There are several methods to accomplish this: (A) compare the collector current of the BAG with that of another gauge for which the residual current is either known or negligibly small, (B) use a modulation method¹³ to obtain a measure of I_r , (C) use the variation of electron energy method,^{3,7} and (D) directly measure I_r by reducing the pressure to such a low value that the gas phase positive ion contribution to the collector current is negligible.

In the work discussed in the present paper, the first method (A) was used to determine I_r in several commercial BAG's and modulated Bayard-Alpert gauges (MBAG's) by comparison against an extractor gauge¹⁴ (EXG). This is the same method employed by Hseuh and Lanni¹⁵ in evaluating the performance of a large group of short/thin-collector BAG's, although in their work a modulated BAG was the reference gauge. In addition, the second method (B) is used here with the MBAG's assuming, as is common practice, that the residual current is not modulated. It is known,

however, that I_r is modulated to some extent.^{16,17} Finally, the results of method B are combined with those of method A to obtain an estimate of the residual current modulation factor for the MBAG's.

II. APPARATUS AND PROCEDURES

Seven commercial gauges of three types, all with closed grids, were employed in this study: one extractor gauge (EXG), two modulated Bayard-Alpert gauges (MBAG-1 and MBAG-2), each of different manufacture, and four Bayard-Alpert gauges (BAG-1, BAG-2, BAG-3, and BAG-4) all of same manufacture and nominally identical. All the gauges had tungsten filaments except the extractor gauge which had a thoria-coated iridium filament. In Table I, operating parameters and other data are given for the gauges, which were all operated with bias voltages and emission current at or near the manufacturer's specified values. Collector current measurements were made with feedback-type electrometers with all gauges in simultaneous operation. The gauges were all mounted in the nude configuration on a 0.46-m-diam, 165-l cylindrical stainless-steel vacuum chamber pumped by a 500 l/s turbomolecular pump. A quadrupole residual gas analyzer, mounted between the chamber and the pump, was used to estimate the gas composition at base vacuum.

Prior to this study, and as part of a separate effort to reduce the H_2 component of the residual gas, the chamber and MBAG-1 had been subjected to a bakeout at 450 °C for 160 h. After that, MBAG-1 was removed, the four BAG's installed, and the chamber and gauges baked at 450–500 °C for 200 h. Just before the present study was started, MBAG-1 was reinstalled, the EXG and MBAG-2 added to the system, and the chamber and all gauges were baked at 250 °C for 24 h. During every bakeout, the gauges were operated at normal bias voltages and emission currents. This is the usual gauge-outgassing procedure followed in this laboratory. In addition, during the final bake (250 °C), the MBAG-1 and BAG-3 grids were electron-bombardment degassed (550 eV) at 40 W for about 1 h. After this final bake, the gauges were not subjected to any further degassing procedures.

The test gas (He or H_2) was introduced through the vent port on the turbomolecular pump and reached the chamber by backdiffusion through the pump. All gauges were calibrated absolutely for He in the range 1.3×10^{-4} – 1.3×10^{-2} Pa

by comparison against two molecular drag gauges (MDG's), also mounted on the chamber. Modulation factors for the MBAG's and sensitivity ratios of one gauge to another for the same gas were determined for all the gauges for both H_2 and He gas. The gauges were not calibrated for H_2 by direct comparison against the MDG's, because of initial concern about the effect on the base vacuum of exposure to a high pressure ($> 10^{-4}$ Pa) of H_2 . Instead, hydrogen (H_2) sensitivity for each gauge was determined from the He sensitivity with a nominal conversion factor 2.6, i.e., $S_{H_2} = 2.6 S_{He}$. Using the H_2 sensitivities determined in this way, and assuming the residual gas to be all H_2 , the lowest pressure achievable in the chamber was found to be $\sim 4 \times 10^{-9}$ Pa. Unless noted otherwise, the pressures quoted in this paper are H_2 pressures. Care should be exercised when comparing these results with other work in which collector currents or residual currents may be expressed as "Nitrogen equivalent" pressures. It should also be noted that atomic hydrogen and various derived molecules can be generated by reactions at the hot filament.⁵ Contributions to the collector current resulting from ionization of these species will be considered a normal part of the gauge's response to H_2 .

The following model equations for a single-component gas were used to interpret the data.

$$I_c = I_r + I_+, \quad (1)$$

$$I'_c = \mu I_r + M I_+, \quad (2)$$

$$I_+ = I_c S P. \quad (3)$$

In Eq. (1), I_c is the collector current, I_+ is the positive ion current to the collector, and I_r is the residual current.

Equation (2) applies to the modulated gauges. In the modulation method used here the modulator potential V_m in the MBAG's was alternately set at grid potential V_g (normal condition) and at collector potential V_c (modulated condition). This is the choice of potentials used by Redhead¹³ who was the first to propose the modulation method. In Eq. (2), I'_c is the collector current in the MBAG's when $V_m = V_c$, and μ and M are the corresponding modulation factors for the residual current and the ion current, respectively. [In some studies,^{18,19} $(1 - M)$ and $(1 - \mu)$ would be referred to as the modulation factors.] It is common practice to assume that $\mu = 1$ but, as will be shown, this assumption is not always true and may lead to significant error.

TABLE I. Operating parameters and other information for the gauges studied in this work.

Gauge	Grid bias V_g (V)	Filament bias V_f (V)	Emission current I_e (mA)	Modulator potentials V_m (V)	Grid diam. D_g (mm)	Grid length L_g (mm)	Grid material	Collector diameter D_c (10^{-6} m)	Collector material	Inside diam. of envelope ^a D_w (mm)
BAG's	180	30	1.000		23	45	Pt-Ir	178	W	35
MBAG-1 ^b	150	50	1.000	150,0	30	39	Pt-Ir	50	W	59
MBAG-2 ^c	190	47	0.994	190,0	25	45	Mo	127	W	35
EXG	220	100	1.36				Mo		W	35

^aThis is the inside diameter of the flanged 304 stainless-steel port in which the gauge was mounted.

^bTungsten (W) modulator, 500- μ m diameter, symmetrically positioned away from the filaments.

^cTungsten (W) modulator, 127- μ m diameter, asymmetrically positioned near filaments.

In Eq. (3) for a single-component gas, I_e is the emission current, S is the gauge's sensitivity for that gas, and P is the pressure of that gas.

The effects of ESD in ion gauges are well established, especially in the case of O_2 adsorbed on Mo,²⁰ and can lead to an increase in residual current.^{21,22} However, as will be discussed in Sec. IV, transient ESD effects were not observed in the present work in H_2 and it seemed more appropriate to consider any ESD current as part of I_+ , i.e., either as a negligible contribution or, as a contribution proportional to the instantaneous H_2 pressure. Therefore, I_r in Eq. (1) mainly represents the pressure-independent residual current resulting from the net effect of electrons photoejected from the collector (normal x-ray current) and electrons photoejected from the wall surrounding the gauge (reverse x-ray effect).

III. RESULTS

A. Method A

In this method, the first of the methods described in the introduction, two steps were followed. First, the collector current I_c for each gauge was measured as the test gas (H_2) pressure was varied over a sufficiently wide range (4×10^{-9} to 4×10^{-5} Pa) to cause a four-decade change in I_c of the extractor gauge. For every gauge, the plot of $[I_c]_{tg}$ vs $[I_c]_{exg}$, where "tg" stands for "test gauge", was found to be very well described by a least-squares-fit straight line (correlation coefficient > 0.99999). Assuming that the sensitivity ratio of the two gauges for each component of the residual gas is the same as the ratio for H_2 , it follows from Eqs. (1) and (3) that,

$$[I_r]_{tg} = [I_c]_{tg} - \left[\frac{[I_e S_{H_2}]_{tg}}{[I_e S_{H_2}]_{exg}} \right] [(I_c)_{exg} - (I_r)_{exg}] \quad (4)$$

In fact, residual gas analysis indicates that hydrogen is the dominant gas as base vacuum. At base pressure, about 80% of the total ion current to the Faraday cup detector of the uncalibrated quadrupole gas analyzer was due to $H_2^+ + H^+$, with the other 20% due to signals at $M/Q = 12, 16, 28,$ and 44 . Since the partial pressures of the residual gas

components are small with respect to that of H_2 then, even though the ratio of the sensitivities of the two gauges for other gases may differ slightly from the ratio corresponding to H_2 , the error in $[I_r]_{tg}$ associated with this difference can reasonably be expected to be quite small ($< 1\%$). The slope h of the fitted line was assumed to give the ratio of the H_2 sensitivity of the two gauges (when emission currents are equal).

$$h = \frac{[I_e S_{H_2}]_{tg}}{[I_e S_{H_2}]_{exg}} \quad (5)$$

Next, the collector currents I_c were again measured at base pressure and also at a H_2 pressure about 10 times the base pressure. At each pressure, these measurements were used in Eq. (4) together with the previously determined h values to obtain the residual current I_r for each gauge in terms of the residual current for the extractor gauge. At the two pressures, the I_r values so determined for each gauge agreed to within 0.006 pA or better. The extractor gauge manufacturer specifies the N_2 pressure equivalent to the residual current to be $< 1 \times 10^{-10}$ Pa which, for this gauge, means $[I_r]_{exg} < 0.007$ pA. Thus, assuming that this limit on $[I_r]_{exg}$ is correct, Eq. (4) yields an upper bound on $[I_r]_{tg}$. Upper bounds on the residual current in the tested gauges (MBAG's in unmodulated condition, i.e., $V_m = V_g$) determined in this way with Eq. (4), are given in Table II.

B. Method B

In the second of the methods listed in the introduction, the modulation technique alone is used to obtain a value for I_r in the MBAG's. Solving Eqs. (1) and (2) for I_r and I_+ yields

$$I_r = \frac{I'_c - MI_c}{\mu - M} \quad (6)$$

$$I_+ = \frac{\mu I_c - I'_c}{\mu - M} \quad (7)$$

The currents I_c and I'_c in Eqs. (6) and (7) are presumed to be equilibrium values corresponding to the instantaneous ambient H_2 pressure. As will be discussed in Sec. IV, this assumption appears to be valid. The ion current modulation

TABLE II. Relative sensitivities for H_2 and residual currents determined by method A.

Gauge	$\frac{[I_e S_{H_2}]_{gauge}}{[I_e S_{H_2}]_{exg}}$	Residual current ^a I_r (pA)	Equivalent H_2 pressure ^b P_r (Pa)	Manufacturer's nominal value for equivalent H_2 pressure ^c P_r (Pa)
BAG-1	1.404	0.13	2.6×10^{-9}	6×10^{-9}
BAG-2	1.706	0.86	1.4×10^{-8}	6×10^{-9}
BAG-3	1.974	1.58	2.3×10^{-8}	6×10^{-9}
BAG-4	1.831	0.38	5.9×10^{-9}	6×10^{-9}
MBAG-1	1.989	0.15 ^d	2.1×10^{-9}	7×10^{-10}
MBAG-2	1.374	0.21 ^d	4.2×10^{-9}	7×10^{-9}

^a These values are upper bounds determined in this work with Eq. (4) and assuming $[I_r]_{exg} = 0.007$ pA. The lower bound values, determined by assuming $[I_r]_{exg} = 0$, were found to be only about 0.01 pA smaller than the upper bound values.

^b The H_2 sensitivity was determined from the helium sensitivity S_{He} , measured in this work, by $S_{H_2} = 2.6 \times S_{He}$. Equivalent H_2 pressure $P_r = I_r / I_e S_{H_2}$.

^c These values for H_2 pressure were derived from the manufacturer's nominal or typical value for N_2 using $P_r(H_2) = (S_{N_2} / S_{H_2}) \times P_r(N_2) = 2.3 \times P_r(N_2)$.

^d Compare MBAG results here with those determined by method B and shown in Table III.

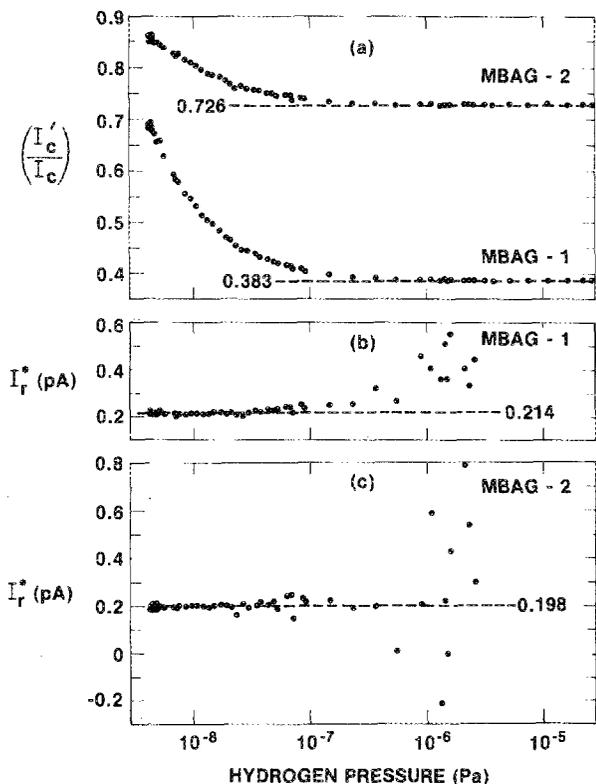


FIG. 1. (a) Collector current ratio (I'_c/I_c) vs H_2 pressure, where I'_c is collector current when modulator is at collector potential ($V_m = V_c = 0$) and I_c is collector current when modulator is at grid potential ($V_m = V_g$). The limiting value M of the ratio (I'_c/I_c) was determined as the arithmetic average of the ratio values obtained at the seven highest H_2 pressures. The standard deviation of the average values is 0.1% and 0.2% for the MBAG-1 and MBAG-2, respectively. The value M was used in Eq. (6) along with an assumed value of $\mu = 1$ to obtain the residual current values I_r^* shown in (b) and (c).

factor M was determined from the ratio (I'_c/I_c) at "high" pressure, i.e.,

$$\left(\frac{I'_c}{I_c}\right) \rightarrow \frac{MI_+}{I_+} = M, \quad \text{when } I_+ \gg I_r. \quad (8)$$

The approach of this current ratio to a constant value as the ion current becomes large with respect to the residual current is illustrated in Figs. 1 and 2, and the M values determined in this way for the MBAG's in H_2 are also listed in Table III. As reported by other investigators,^{23,24} M was found to depend significantly on gas species. This is illustrated in Fig. 2, which shows results obtained in this work for the MBAG's in H_2 and in He. The results for MBAG-2 in N_2 , obtained in an earlier experiment,²⁵ are included for comparison.

The residual current modulation factor μ could also be determined from the ratio (I'_c/I_c) at very low pressure, where I_+ approaches zero.

$$\left(\frac{I'_c}{I_c}\right) \rightarrow \left(\frac{\mu I_r}{I_r}\right) = \mu \quad \text{as } I_+ \rightarrow 0. \quad (9)$$

However, since the pressure could not be reduced sufficiently low for the ratio (I'_c/I_c) to reach the limiting value μ , the data analysis was carried out under the assumption that the

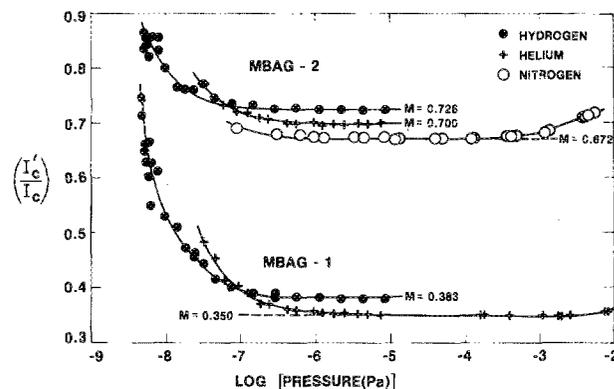


FIG. 2. (I'_c/I_c) vs pressure, where I'_c is collector current when modulator is at collector potential ($V_m = V_c = 0$) and I_c is collector current when modulator is at grid potential ($V_m = V_g$). The large scatter in the data for H_2 below about 10^{-7} Pa is due to exceptionally noisy coaxial collector cables. More precise measurements were obtained (see Fig. 1) when the measurements were repeated with low-noise cables. N_2 data for MBAG-2 were obtained on a different vacuum chamber. Since the ion current modulation factor M is gas specific, then when determining I_r for a MBAG in a clean UHV chamber (base pressure due to H_2) one should use M_{H_2} .

residual current was not modulated, i.e., $\mu = 1$. Thus, the quantities I_r^* and I_r^+ were calculated where

$$I_r^* = \frac{I'_c - MI_c}{1 - M}, \quad (10)$$

$$I_r^+ = \frac{I_c - I'_c}{1 - M}. \quad (11)$$

Values of I_r^* , calculated for both MBAG-1 and MBAG-2 using Eq. (10), are shown in Figs. 1(b) and 1(c), as a function of the H_2 pressure. The apparent high pressure dependence of I_r^* in the case of MBAG-1 [see Fig. 1(b)] is believed to be not real, but instead to be due to a small error in the numerical value 0.383 determined for M . Analysis of the calculation for MBAG-1 shows the values I_r^* calculated with Eq. (10) to be extremely sensitive to the value of M when I_c is larger than about 3 pA (H_2 pressure greater than about 4×10^{-8} Pa). Changing the value of M by only about 0.1% practically removes the apparent pressure dependence

TABLE III. Residual currents I_r^* determined in this work by the modulation method, and residual current modulation factors μ .

	MBAG-1	MBAG-2
Ion current modulation factor M_{H_2}	0.383	0.726
Residual current I_r^* (pA)		
determined assuming $\mu = 1$	0.21 ^a	0.20 ^a
Method A value for I_r (pA) ^b	(0.15)	(0.21)
Upper bound ^c on μ	1.33	1.00
Lower bound ^c on μ	1.24	0.99

^a See Eq. (10) and Fig. 1.

^b Shown in parentheses, for comparison, are the corresponding residual current values I_r determined by method A.

^c See Eq. (12). Upper and lower bounds on μ here correspond to $[I_r]_{\text{exg}} = 0$ and $[I_r]_{\text{exg}} = 0.007$ pA, respectively.

of the I_r^* values in Fig. 1(b) at higher pressures, but has no noticeable effect at the low pressures. An error of about 0.1% in M also is consistent with the standard deviation (0.1%) of the M values. Average I_r^* values for the data shown in Fig. 1 are also given in Table III.

C. Residual current modulation factor μ

As can be seen in Table III, a significant difference exists between the residual currents determined for MBAG-1 by the two methods A and B, while those determined for MBAG-2 agree rather well. Since the same input data (collector current values) were used in both methods, this indicates that either one or both of the assumptions made in the analysis were incorrect, viz., in method A, that $0 < [I_r]_{\text{exg}} \leq 0.007$ pA and/or in method B, that $\mu = 1$. Examination of the data shows that there is no single choice for the value of $[I_r]_{\text{exg}}$ which will make method A yield the same I_r values for the MBAG's as were given by method B, under the assumption $\mu = 1$. In the case of MBAG-1, the choice $[I_r]_{\text{exg}} = 0.036$ pA is required to make method A yield a value of 0.214 pA for I_r of MBAG-1. For MBAG-2, the choice $[I_r]_{\text{exg}} = 0.001$ pA is required for method A to yield the value 0.198 pA for I_r of MBAG-2. Since there must be a single value for $[I_r]_{\text{exg}}$ which will make the method A results agree with the method B results when the correct values of μ are used, then the assumption $\mu = 1$ for both MBAG's cannot be correct. It is not possible though, from the present data, to determine the values of all three of the quantities: $[I_r]_{\text{exg}}$ and the two μ values. However, by assuming the actual value $[I_r]_{\text{exg}}$ does lie in the range 0–0.007 pA, as was done in method A and that the corresponding method A residual current values I_r are therefore correct (Table II), we can obtain an estimate for the residual current modulation factors μ as follows: The values I_r^* and I_+^* , calculated assuming $\mu = 1$, differ from the true values I_r and I_+ given by Eqs. (6) and (7) by amounts which depend on the actual values of both μ and M , viz.,

$$I_r^* = \left(\frac{\mu - M}{1 - M} \right) I_r, \quad (12)$$

$$I_+^* = I_+ + \left(\frac{1 - \mu}{1 - M} \right) I_r. \quad (13)$$

The residual current values determined for the MBAG's by method A are substituted for I_r in the right-hand side of Eq. (12), where I_r^* on the left-hand side is the corresponding method B value determined with Eq. (10). Equation (12) can then be solved for μ . Basically, this gives the value of μ needed to make method B yield the same answer for $[I_r]_{\text{tg}}$ as was obtained by method A. These estimates of μ are included in Table III for both MBAG-1 and 2 for two different assumed values of $[I_r]_{\text{exg}}$, 0 and 0.007 pA, the upper bound specified by the manufacturer. Both choices for $[I_r]_{\text{exg}}$ give essentially the same value for μ , and in the case of MBAG-2, indicate virtually no modulation of the residual current.

The works of Appelt¹⁶ and of Hobson¹⁷ appear to be the only other published measurements of residual current modulation in a BAG. Appelt, apparently the first to recognize I_r modulation, combined the technique of variation of electron

energy^{3,7} with that of collector current modulation¹³ to obtain a value $\mu = 0.85$ for a MBAG with geometry and operating parameters similar to those used in the present work. Appelt also estimated the expected value of μ , by calculating the change in solid angle subtended at the collector by the bombarded grid surfaces when the modulator potential was changed. Later, Hobson,¹⁷ using a technique which allowed an estimation of the true ion current independent of any modulation, obtained μ values from 0.941 to 1.025. Most recently, Lange and Singleton²⁶ calculated an estimate of 2.9% for the residual current modulation effect in a gauge similar to MBAG-1 of the present work, but with a Mo grid. This estimate was based upon the gauge's geometry and electron current distribution.

IV. DISCUSSION

History-dependent behavior is not evident in the data for gauge operation in H_2 shown in Figs. 1 and 2. For example, the data in Fig. 1 were obtained in five independent sets over a period of 12 days. The hydrogen pressure was increased by as much as four orders of magnitude and measurements were made for pressure increasing and for pressure decreasing. After exposure to H_2 at a pressure as high as 4×10^{-5} Pa, followed by evacuation, collector currents on all gauges within 10 min dropped to within a factor of 2 of base readings and always returned after 24 h to within a few percent of the base vacuum (4×10^{-9} Pa) values. The very slow decline in the gauge readings is believed to result from a very slow return of the gas phase H_2 pressure to its base vacuum value. The reason for this very slow pumpout is currently under investigation.

In a separate experiment, the collector currents of the two MBAG's (unmodulated operation, $V_m = V_g$) were continuously recorded as a function of the extractor gauge collector current during the evacuation of the chamber following gauge operation for 11 min in H_2 at a pressure 1000 times the base pressure. During the initial phase of this evacuation, in which the H_2 pressure as indicated by $[I_c]_{\text{exg}}$ dropped by more than a factor of 200 in less than 30 s, there was no evidence of hysteresis in the gauge responses. That is, $[I_c]_{\text{MBAG-1}}$ and $[I_c]_{\text{MBAG-2}}$ were linear functions of $[I_c]_{\text{exg}}$ even though the H_2 pressure was rapidly changing. The recording was continued for six more hours during the much slower phase of the evacuation. Still, a linear relation was observed among the collector currents. The slope of the $[I_c]_{\text{MBAG-2}}$ vs $[I_c]_{\text{exg}}$ data agreed to within 1% of the corresponding value obtained during the very fast part of the pumpout. For MBAG-1, the slope in the slow part of the pumpout was inexplicably about 20% larger than the value obtained during the fast pumpout. Aside from this discrepancy, which may be due to an undetected experimental error, the behavior observed here for the operation of BAG's and EXG's in H_2 differs markedly from that seen by Redhead¹⁴ for a gauge operation in O_2 . There, the ratio of a BAG's collector current to that of an EXG was found to be 30 times higher after pumpdown following exposure to O_2 at $P = 10^{-5}$ Pa. These observations seem to be very strong evidence that any ion current to the collector resulting from ESD of adsorbed hydrogen is either (i) negligibly small or

(ii) is always proportional to the instantaneous H_2 gas pressure.

The residual current values I_r^* are seen to be highly reproducible and independent of the H_2 pressure [see Figs. 1(b) and 1(c)]. As mentioned in Sec. III, the apparent pressure dependence of I_r^* in MBAG-1 above about 10^{-7} Pa is believed to be due to a small error in the M value, since an error as small as 0.1% could produce this appearance. The increasing scatter in the I_r^* values for both MBAG-1 and 2 for H_2 pressure larger than about 10^{-7} Pa can reasonably be attributed to the fact that the calculation requires the small difference between the two quantities I_c' and MI_c , each of which increases linearly with the pressure.

Transient behavior associated with switching the modulator potential, and requiring longer than about 5 s to decay, was not observed. For both MBAG's, recording of the collector current was started about 5 s after the modulator potentials were changed. For either case, $V_m = V_c \rightarrow V_m = V_g$ or the reverse, there was no evidence of time-dependent behavior of the current during the 2–4 min recording interval. At the same time, no changes were detected in the collector current of any of the other gauges, including the continuously recorded gas analyzer's H_2^+ signal. This behavior differs from that observed by Lange and Singleton²⁶ in which the collector current and H_2^+ signal did exhibit a transient increase by a factor of about 2 when the modulator was returned to grid potential after 7.5 min at collector potential, and which required about 5 min to decay away. In Ref. 26 this transient behavior was attributed to ESD of H_2 from the modulator. The apparent discrepancy between the observations of Ref. 26 and those of the present work is probably due to different characteristics of the vacuum systems. The present apparatus, with chamber volume 165 l and H_2 pumping speed 500 l/s, has an associated time constant of about 0.3 s. This is comparable to the time constant of 0.6 s associated with Lange and Singleton's apparatus, which had a volume of 1.5 l and a H_2 pumping speed of about 2.5 l/s. However, because the chamber volume in the present apparatus is over 100 times larger than that used in Ref. 26, the magnitude of the pressure step associated with ESD from the modulator would be much smaller for the same ambient H_2 pressure.

ESD of H^+ ions could also have contributed to the BAG transient seen in Lange and Singleton's work. Hobson and Earnshaw²⁷ performed a fairly detailed study of ESD effects in ionization gauges operated in H_2 at pressures 10^{-9} – 10^{-8} Pa. By including measurements in which the grid and filament biases could be removed and reapplied while maintaining the filament at normal operating temperature, they were able to distinguish the thermal desorption and ESD effects. One important conclusion they drew from their work is that under the action of ESD, a flux of H^+ ions is produced from the bombarded grid surfaces. This H^+ flux was found to exhibit a near linear relationship to the pressure of gas phase H_2 while the pressure was increasing and, it was concluded that in modulated BAG's the flux of H^+ ions was modulated, as well as the ions produced by ionization of the gas phase H_2 . The H^+ ESD current, which was found to be at least an order of magnitude smaller than the H_2^+ gas phase current, did exhibit some hysteresis when the H_2 pressure

was rapidly decreased.

Hobson and Earnshaw's work suggests that the present results may be reinterpreted as follows: The equilibrium H_2 sensitivity S in Eq. (3) can be considered to be the sum ($S_\gamma + S_\sigma$) of two parts where S_γ is the contribution due to ionization of gas phase H_2 and S_σ is the contribution due to ESD of H^+ ions from hydrogen adsorbed on the grid. However, there is no way in the present work to distinguish between these two contributions. The ion current modulation factor M in Eq. (2) can be viewed as representing the net effect on I_+ of the modulation of each of the two components of I_+ . Since time-dependent behavior of gauge response was not evident in the present work this seems to indicate that if equilibrium ESD effects do make a significant contribution to the gauge response, a short time (seconds) is required to establish a new equilibrium in the H^+ current following a change in H_2 gas pressure. The interpretation of μ and I_r would not change. In short, the results of the present work do not appear to be influenced by transient effects due to ESD, and are representative of gauge behavior under equilibrium conditions.

The large spread in the residual current values for the four nominally identical BAG's seems to be the most significant finding in this work, with the largest value (BAG-3) being about 12 times larger than the smallest (BAG-1). See Table II. Even if the extractor gauge residual current had been assumed to be 10 times larger (i.e., 0.07 pA instead of 0.007 pA), the residual currents in the BAG's determined by method A would then still differ by a factor of 8 between the largest and smallest value. With respect to the typical value of I_r , ~ 0.5 pA at $I_c = 1$ mA indicated on the manufacturer's specification sheet for the BAG's, the I_r values determined in this work are seen to range from about $\frac{1}{4}$ to 3 times this typical value. The conclusion then, is that the actual residual current in nominally identical samples of this gauge can differ significantly from the manufacturer's typical value and consequently, the user should be aware of the potential for large pressure measurement errors when a nominal or typical value is used for the residual current.

The difficulty of predicting I_r is illustrated by the results for the MBAG's. Of all the BAG's, MBAG-1 was expected to have the lowest residual current because it had a very fine (50- μ m-diam) collector wire, the lowest grid-filament potential difference (100 V), and a Pt- I_r grid. Recall also that MBAG-1 is one of the two gauges which were electron-bombardment degassed for 1 h during the final bake. The manufacturer's specified residual current for MBAG-1, about 0.06 pA (corresponding to $I_c = 1$ mA), is the lowest value specified for the three types of BAG's studied. However, the residual current (0.15 pA) determined for MBAG-1 by method A, while next to lowest of any of the gauges studied, is about $2\frac{1}{2}$ times the manufacturer's value. MBAG-2, which has a Mo grid, a 143-V grid-filament potential difference, and a 130- μ m-diam collector, would be expected to have a much larger residual current, and the value specified by the manufacturer is 10 times larger than that specified for MBAG-1. Yet, their residual currents were found to differ by less than a factor of 2. The residual current in MBAG-1 is even larger than that determined for BAG-1, which has a

180- μ m-diam collector. In the case of MBAG-2, the residual current determined at $I_c = 1$ mA is about $\frac{1}{4}$ the value indicated by the manufacturer's specifications. Since residual currents in the two MBAG's differed from the manufacturer's values by factors similar to those seen in the sample of four BAG's, it is not unreasonable to expect similar wide variation in residual current from gauge to gauge within a given type of MBAG.

It should be noted that significant errors can arise from the use of an inappropriate modulation factor. Suppose the model Eqs. (1), (2), and (3) are generalized to account for a gas composed of several independent components, and suppose the ion current modulation factor M is determined for one gas only, say N_2 , which is generally not a significant component of the residual gas in a clean, baked stainless-steel chamber. Assuming further, for simplicity, that the residual current modulation factor $\mu = 1$, then the residual current value I_r^* obtained from Eq. (10) using for M the value determined for N_2 , would be equal to I_r plus a number of extra terms as shown in Eq. (14).

$$\left(\frac{I_c' - M_{N_2} I_c}{1 - M_{N_2}} \right) = I_r + I_c \sum_i \left(\frac{M_i - M_{N_2}}{1 - M_{N_2}} \right) S_i P_i \quad (14)$$

Using data from this work to evaluate the extra term in the right-hand side of Eq. (14) at base vacuum, where H_2 is the dominant component of the residual gas, shows the extra term for the MBAG-2 to have a value 0.03 pA, which is about 15% of the I_r value determined in this work. Repeating the calculation, with M_{He} in the left-hand side of Eq. (14), shows the extra term to be about 0.02 and 0.01 pA for MBAG-2 and MBAG-1, respectively. These values are 10% and 7% of the corresponding I_r values determined in this work. Since this error term is proportional to pressure, then there is the potential for very large errors (> 100%) when using an inappropriate M value (say M_{N_2}) to determine I_r from measurements of I_c and I_c' in H_2 at higher pressures (say 4×10^{-8} Pa).

It is apparent now that assuming $\mu = 1$, as is done in the manufacturer's instructions for using the MBAG, could lead to significant error when determining residual current in a modulated BAG. In the case of MBAG-1, the present results show that roughly a 30% error would result. The present results, however, do not allow a determination as to whether the difference in μ for MBAG-1 and MBAG-2 is due to differences between individual gauges, or design and/or material differences. It should also be noted that the consequences of the error in μ became progressively more serious as the pressure is reduced because I_r will make up a progressively larger part of I_c . Thus knowledge of μ is crucial to accurate use of a MBAG at very low pressures. Finally, it should be recognized that modulation factors, μ , M , and residual currents I_r are generally dependent on the emission current I_e . See, for example, the work of Poulter²³ on the dependence of M on I_e .

V. SUMMARY

- (1) Residual currents I_r have been determined for four

nominally identical commercial Bayard-Alpert gauges and two modulated Bayard-Alpert gauges, by comparing their collector current with that in an extractor gauge (method A). Among the BAG's, I_r values ranged from a factor of $\frac{1}{3}$ to 4 times the manufacturer's specified values. In one of the MBAG's, I_r was 3 times the specified value.

(2) Residual currents I_r have also been determined in the MBAG's by the modulation method (method B). This required knowledge of the ion current modulation factor M , values of which were determined for MBAG operation in H_2 , He, and N_2 .

(3) Residual current modulation factors μ for the MBAG's were estimated by combining the MBAG data from methods A and B. In one gauge the modulation effect was negligible ($\mu \approx 1$). In the other MBAG it was quite significant ($\mu = 1.33$).

(4) In the results obtained in this work for gauge operation in H_2 , no hysteresis was detected in the response of any of the BAG's with respect to the response of the extractor gauge when large, rapid decreases in the H_2 pressure were made. This result may be interpreted to mean that (i) whatever its dependence on the history and instantaneous value of the H_2 pressure, the H^+ ion current due to ESD is always much smaller than the ion current of $H^+ + H_2^+$ due to gas phase ionization or, (ii) the current of H^+ ions due to ESD is always proportional to the instantaneous H_2 gas pressure and thus its contribution cannot be distinguished from that due to gas phase ionization.

(5) No collector current transients were observed in connection with changes in the modulator potentials. This finding seems to lend support to interpretation (4i) above.

ACKNOWLEDGMENTS

This work was partially funded by the U. S. Department of Energy, Office of Fusion Energy. The author thanks Dr. Charles R. Tilford and Dr. Theodore Madey for critically reading the manuscript and for valuable discussions, and S. D. Wood for providing the data on MBAG-2 operation in N_2 .

¹For a single-component gas, the pressure equivalent to the residual current I_r is that pressure P_r for which the positive ion current is equal to the residual current. This pressure is given by $I_r = I_e S P_r$, where I_e is the emission current and S is the gauge's sensitivity for that gas. This pressure is sometimes referred to as the x-ray limit of the gauge.

²W. B. Nottingham, in *Proceedings of the 7th Annual Conference on Physical Electronics* (M.I.T., Cambridge, MA, 1947).

³R. T. Bayard and D. Alpert, *Rev. Sci. Instrum.* **21**, 571 (1950).

⁴W. H. Hayward, R. L. Jepsen, and P. A. Redhead, *Transactions of the 10th National Vacuum Symposium* (MacMillan, London, 1963), p. 228.

⁵P. A. Redhead, J. P. Hobson, and E. V. Kornelsen, *The Physical Basis of Ultrahigh Vacuum* (Chapman and Hall, London, 1968); P. A. Redhead, *J. Vac. Sci. Technol.* **7**, 182 (1970).

⁶H. J. van Ark and J. van de Rotte, *Vak. Tech.* **17**, 173 (1967).

⁷Z. Hulek, in *Proceedings of the 7th International Vacuum Congress and the*

- 3rd International Conference on Solid Surfaces* (Berger & Söhne, Vienna, 1977), p. 145.
- ⁸R. W. Lawson, *Br. J. Appl. Phys.* **18**, 1763 (1967).
- ⁹H. S. W. Massey, *Electronic and Ionic Impact Phenomena*, 2nd ed. (Oxford, London, 1969), Vol. II, p. 910.
- ¹⁰A. Verema and M. Bandringa, *Philips Tech. Rev.* **20**, 145 (1958).
- ¹¹A. G. J. van Oostrom, *Trans. AVS Vac. Symp.* **8**, 443 (1961).
- ¹²H. J. Schuetze and F. Stork, *Trans. AVS Vac. Symp.* **9**, 431 (1962).
- ¹³This method was introduced by P. A. Redhead, *Rev. Sci. Instrum.* **31**, 343 (1960).
- ¹⁴P. A. Redhead, *J. Vac. Sci. Technol.* **3**, 173 (1966).
- ¹⁵H. C. Hseuh and C. Lanni, *J. Vac. Sci. Technol. A* **5**, 3244 (1987) (this issue).
- ¹⁶G. Appelt, *Vak. Tech.* **11**, 174 (1962).
- ¹⁷J. P. Hobson, *J. Vac. Sci. Technol.* **1**, 1 (1964).
- ¹⁸P. A. Redhead and J. P. Hobson, *Br. J. Appl. Phys.* **16**, 1555 (1965).
- ¹⁹T. Kanaji, S. Nakamura, T. Urano, and S. Nagata, in Ref. 7, p. 133.
- ²⁰P. A. Redhead, *Can. J. Phys.* **42**, 886 (1964).
- ²¹P. A. Redhead, *Vacuum* **12**, 267 (1962).
- ²²T. E. Hartman, *Rev. Sci. Instrum.* **34**, 1190 (1963).
- ²³K. F. Poulter, National Physical Laboratory, Teddington, Report No. MC5, 1970.
- ²⁴L. G. Pittaway, Philips Research Laboratories, Report No. 3189, Redhill, Surrey, 1981.
- ²⁵S. D. Wood (private communication).
- ²⁶W. J. Lange and J. H. Singleton, *J. Vac. Sci. Technol.* **3**, 319 (1966).
- ²⁷J. P. Hobson and J. W. Earnshaw, *Can. J. Phys.* **46**, 2517 (1968).