Long-term stability of Bayard–Alpert gauge performance: Results obtained from repeated calibrations against the National Institute of Standards and Technology primary vacuum standard

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This article presents and briefly discusses information on the long-term stability of the sensitivity of Bayard–Alpert ionization gauges with time and use, derived from an analysis of data for Bayard–Alpert gauge calibrations performed at the National Institute of Standards and Technology over a ten year period.

I. INTRODUCTION

For a variety of reasons, the sensitivity of a hot-cathode ionization gauge can change with time of use. These causes include filament and/or grid distortion, alteration in filament temperature and electron emission distribution from the filament, potential shifts in the envelope surrounding the gauge, and changes in the surface properties of its collector and grid. The magnitude of these effects will also depend upon actual operating conditions as well as the duration of operation. Such changes in sensitivity are of particular interest to those who rely on the stability of a gauge's pressure indication to make a decision regarding some process in vacuum, as well as to those who use a calibrated gauge to actually measure pressure. There are however, only a few published studies in which the long-term stability of hot-cathode ion gauge sensitivity has been systematically examined. This article presents some additional information on the long-term stability of Bayard–Alpert (BA) gauge sensitivity, as derived from an analysis of calibrations performed at the National Institute of Standard and Technology (NIST) over the past ten years. A preliminary summary of these results is given in Ref. 1.

II. PREVIOUSLY PUBLISHED WORK ON ION GAUGE STABILITY

Some limited information covering a three year period ($<$ 1000 hours of actual operation, however) is presented by Messer[2] for a specially constructed BA gauge operated at 0.1 mA emission current and for which the collector had been subject to special processing (annealing at high temperature). The six argon sensitivity values reported by Messer for this gauge during the three year period lay in an interval of about -1.1%–$+1.5\%$ with respect to their mean.

Poulter and Sutton[3] performed repeated N_2 calibrations of six nominally identical BA gauges at 5×10^{-3} Pa (1 Torr $\approx$133.322 Pa), for a total operating time of about 1000 hours each. These gauges, operated at 1 mA emission, had tungsten filaments and a glass envelope with a metallized interior surface held at ground potential. Their results are puzzling. The one BA gauge that was kept under vacuum for the entire test period exhibited a gradual decline in sensitivity with operating time at an average rate of roughly -1.4% per 100 hours. The other five, each exposed one or more times to atmospheric air during the testing, but with filament off (one stored on a shelf in the lab for 15 months), exhibited significant shifts in calibration (as large as 25%) that seemed to be correlated with the exposure to air. Yet these gauges seemed not to show any permanent shifts in calibration that were correlated with degassing or operation in N_2 at high pressure. In limited experience at NIST (not published), the particular make and model of BA gauge examined by Poulter and Sutton was also found to be relatively unstable in comparison with BA gauges of other manufacture.

Warshawsky[4] has examined stability of sensitivity for a group of nine glass-envelope BA gauges with ThO_2–Ir filaments by analyzing results for 64 calibrations among the nine gauges. For each calibration of a gauge, a *mean sensitivity* value was determined for that gauge (not all gauges were calibrated the same number of times, however). Each mean sensitivity value determined in this work[4] was obtained from sensitivity measurements made in N_2 over the pressure range 2×10^{-4}–2×10^{-1} Pa. For each gauge, the root-mean-square (rms) deviation of these mean sensitivity values from their average was computed. The average of these rms deviation values was about 1.1% and for any particular gauge the rms deviation never exceeded 3%. It is not clear from Ref. 4 how much time each calibration required, how much time elapsed between calibrations, and what emission current(s) were used. It was noted, however, that the gauges remained on the calibration system between calibrations and were almost continuously under vacuum.

NIST has previously reported the results of long-term stability testing of a group of four tungsten–cathode glass-envelope BA gauges[5] operated in N_2 with 1 mA emission current; over an accumulated operating time of about 480 days (11 500 hours) the sensitivity of the gauges tended to progressively decrease, but with maximum sensitivity decreases limited to no more than 6% .

Most recently, Arnold and Borichevsky[6] have published ion gauge stability testing results obtained over a 580 day period for a group of gauges that included 11 "widely used" BA gauges, all with ThO_2–Ir cathodes. Most (eight out of eleven) were operated at 10 mA emission current, and each of the 11 gauges was subjected to degassing for a cumulative

TABLE I. Relevant information about construction and operation of the gauges. The terms "eb" and "I^2R" denote electron bombardment degassing and resistive heating degassing, respectively. The term "wrt" stands for "with respect to."

						Intervening operation			
Gauge No.	Envelope	Filament material	I_{em} (mA)	Repeat calibration	Average |change| wrt previous calibration (%)	Total operating time (hours)	Type of degas	No. of degassings	Total degas time (hours)
1	Glass	W	0.934	First	0.8	Unknown	eb	Unknown	Unknown
2	Glass	W	1.12	First	10.2	1000	eb	250	21
				Second	1.2	1000	eb	250	21
3	Glass	W	0.94	First	0.6	Unknown	eb	Unknown	Unknown
4	Glass	W	1.027	First	2.6	1000	eb	250	21
5	Glass	W	1.004	First	1.0	Unknown	eb	Unknown	Unknown
6	Glass	ThO_2–Ir	1.036	First	7.3	1000	eb	250	21
7	Glass	ThO_2–Ir	1.019	First	11.2	Unknown	eb	Unknown	Unknown
8	Metal	ThO_2–Ir	10	First	2.6	100–200	I^2R	Unknown	Unknown
9	Metal	ThO_2–Ir	1.076	First	4.8	200–400	I^2R	Unknown	Unknown
10	Glass	W	1.015	First	2.0	< 35	None	0	0
11	Glass	ThO_2–Ir	2	First	11.8	1600	I^2R	200	67
12	Glass	ThO_2–Ir	1.06	First	6.0	~1000	eb	~250	~21
				Second	2.1	Unknown	eb	Unknown	Unknown
13	Glass	ThO_2–Ir	0.94	First	7.1	~1000	eb	~250	~21
				Second	1.0	Unknown	eb	Unknown	Unknown
14	Glass	W	1	First	3.1	1200–1400	None	0	0
15	Glass	W	1	First	3.0	1200–1400	None	0	0
16	Glass	W	1	First	4.3	1200–1400	None	0	0
17	Glass	W	1	First	1.7	1200–1400	None	0	0
18	Glass	W	1.0	First	3.7	1200–1400	None	0	0
19	Glass	ThO_2–Ir	1	First	2.7	36	eb	3	0.25
20	Glass	W	1	First	1.9	250	I^2R	10	3

time of about 150 hours. With respect to an original calibration, they observed changes in calibration that ranged from −57% to +72%.

III. RESULTS FROM REPEATED CUSTOMER GAUGE CALIBRATIONS AT NIST

Over the past ten years, the Vacuum Standards Laboratory at NIST has performed more than 165 BA gauge calibrations for a variety of industrial and government laboratories. The calibration pressure range is normally 10^{-7}–10^{-1} Pa. For 20 separate gauge "tube"/controller combinations, the calibration has been carried out more than once, with the time interval between the repeat calibrations typically one or two years. The observed changes in calibration, as well as some information about the gauge construction and operating conditions during the calibrations for these 20 gauges are given in Table I. Eighteen of these gauges had a glass envelope. The other two were mounted "nude" inside a grounded metal tube. Both ThO_2–Ir and tungsten (W) cathode gauges are included in this group. With two exceptions (gauges No. 8 and 11), these gauges were operated at an emission current of about 1 mA and, during our testing of them, they were never degassed. However, in the time period between our calibrations some of the gauges were degassed by the customer—see columns 8–10 of Table I. Analysis of our data shows (see column 6) that, relative to the previous calibration, the absolute value of the change in calibration exhibited by 11 of the 12 tungsten-filament gauges, averaged over the calibration pressure range, generally does not exceed 5% (the first recalibration of gauge No. 2 is an exception—10%). For the eight ThO_2–Ir filament gauges, the averaged changes are about a factor of 2 larger, but do not exceed 12%. It should be noted that, at pressures above 5×10^{-6} Pa, the total uncertainty (at the two-standard deviation level) in the NIST primary vacuum standard used in these calibrations is 1% or less.

IV. PROCEDURES

For the 20 gauge/controller combinations discussed in this article, the term *calibration* means determination of CF, the correction factor to the pressure indication on the gauge's controller, such that

$$CF*\text{indicated pressure}=\text{true pressure}, \tag{1}$$

where the *true pressure* is that generated with the NIST primary standard[7] or measured with a spinning rotor gauge that has been calibrated against the primary standard. The correction factor, as defined, is inversely proportional to the gauge's *sensitivity*. Correction factor values are determined (with N_2 gas in the present article) as a function of either the indicated pressure or the true pressure, and depend on the operating parameters (emission current and bias voltages). These CF results are then represented analytically by least-squares fitted polynomial functions. Typically, a gauge is in continuous operation for about 1000 hours during such a calibration at NIST. For about 90% of this time, the pressure in the calibration system is at its base value (10^{-8} Pa). During the other 10% of the time, the gauge is actually being

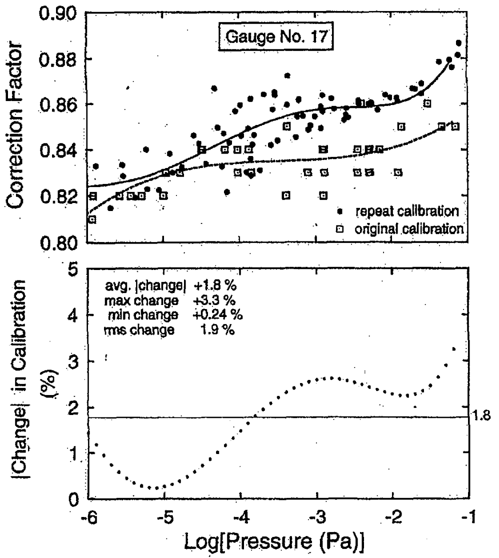

FIG. 1. Example of calculation of average absolute value of change in calibration. |change| in the lower panel denotes the absolute value of the change.

calibrated. Usually, five to ten independent measurements are made in each pressure decade of the measuring range.

In a repeat calibration, the same combination of gauge tube, filament, and controller (with controller operating parameters also set the same as for the previous calibration) was again calibrated against the primary standard. In a few cases, gauge No. 2, for example, there are two repeat calibrations. As indicated in Table I, detailed knowledge of a customer's treatment of the gauge during the time interval between the calibrations is usually not well known. The values given in column 6 of Table I for the average absolute percentage change in calibration with respect to (wrt) a previous calibration were calculated using the definition of absolute change given in Eq. (2).

$$\text{absolute change } (\%)=\left|\frac{(\mathrm{CF})_{\text{repeat}}-(\mathrm{CF})_{\text{previous}}}{(\mathrm{CF})_{\text{previous}}}\right|100. \quad (2)$$

The value of this change was calculated at 10 uniformly spaced (on a logarithmic scale) pressure values per decade over the pressure range common to the two calibrations being compared, typically 5 to 6 decades. In column 6 of Table I we give the average of the 50 to 60 absolute change values yielded by this procedure. The calculation of the average value of the absolute change in calibration is illustrated in Fig 1 with calibration data for gauge No.17. The smooth and dashed curves in the upper part of Fig. 1 are the polynomial fits to the repeat and original data, respectively. The plotted dots in the lower frame of Fig. 1 show the absolute change between the two curves in the upper frame, calculated using Eq. (2) at 10 uniformly spaced points per decade along the logarithmic pressure scale. Figure 2 gives a graphical summary of the maximum and minimum changes in calibration [using Eq. (2) *without* the absolute value operator] as well as the average value of the absolute change in calibration. In

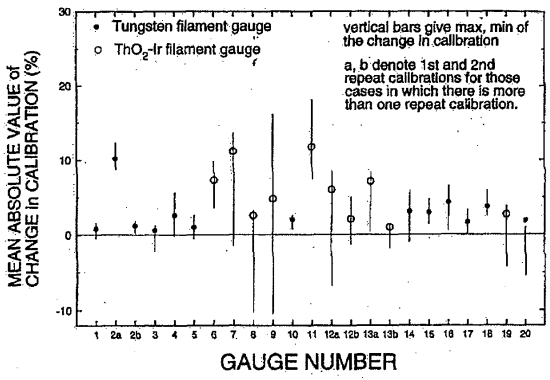

FIG. 2. Graphical representation of the observed average changes in calibration.

order to give a more complete picture of the calibration data themselves, some statistics for them are tabulated in Table II.

It should further be noted that, although the observed changes in calibration apply to the gauge tube/gauge controller as a *system*, we feel that instability in the controllers has made no significant contribution to the observed changes in calibration of each system. Measured grid and filament bias voltages before, during, and after the calibrations have been constant to typically within a few tenths of a volt. Comparison of the data for gauge No. 10 was a special case because the pressure display on its controller was proportional to emission current and the original and repeat calibration results were obtained at different emission currents. To make the repeat CF calibration results obtained at 1.015 mA emission current directly comparable to the original results obtained at 1.000 mA, the repeat CF values were first scaled by a factor of (1.015/1.000) before the comparison.

V. DISCUSSION

There are several observations about our results that mav be worth noting.

(1) As is evident in Fig. 2, the changes in correction factor for these 20 gauges tended to be positive in an algebraic sense: The vertical line associated with each plotted point connects the maximum and minimum absolute values of the change in calibration; these vertical lines lie mostly above the 0% line. That is, the correction factors tended to increase with time and use, or correspondingly, the *sensitivity* of the gauges tended to *decrease*. This is consistent with the observations given in Ref. 5 for a group of four BA gauges with W filaments, where overall decreases in sensitivity of 6% or less were measured during a 480 day operating period.

(2) The gauges with ThO_2–Ir cathodes tended to be less stable than those with tungsten cathodes. This is shown in the second column of Table III, where we give the average value of the average absolute changes listed in column 6 of Table I for the 12 W cathode gauges (2.8%), and for the 8 ThO_2–Ir cathode gauges (5.7%). Thus, for this particular set of results, we can say that the changes in correction factor or sensitivity for the ThO_2–Ir cathode gauges were about twice

TABLE II. Polynomial fits to calibration results.

	Original calibration				1st repeat calibration				2nd repeat calibration			
Gauge No.	Std. dev. of residuals (%)	Mean residual (%)	Max. residual (%)	Min. residual (%)	Std. dev. of residuals (%)	Mean residual (%)	Max. residual (%)	Min. residual (%)	Std. dev. of residuals (%)	Mean residual (%)	Max. residual (%)	Min. residual (%)
1	1.54	0.00	3.88	−3.51	0.81	0.05	2.33	−2.10				
2	1.03	−0.02	2.93	−1.81	1.12	−0.04	2.17	−3.23	0.86	−0.16	1.50	−3.02
3	1.08	−0.05	2.19	−2.90	0.64	0.03	1.73	−2.07				
4	0.37	0.01	0.71	−0.97	0.58	−0.08	1.87	−1.69				
5	0.30	0.01	0.71	−0.76	0.46	0.03	0.77	−1.33				
6	0.78	0.00	2.10	−2.18	0.75	−0.06	2.53	−2.30				
7	0.62	0.01	1.20	−1.51	0.53	−0.01	1.14	−1.41				
8	2.25	0.00	4.89	−5.85	1.05	0.00	2.63	−2.56				
9	1.89	0.01	5.52	−4.25	1.69	0.03	4.83	−4.18				
10	0.79	−0.08	1.52	−2.80	−0.58	−0.01	1.39	−1.16				
11	1.84	0.03	3.92	−4.23	1.63	0.00	1.90	−6.06				
12	1.03	0.03	2.57	−2.55	0.96	−0.02	2.66	−2.63	1.25	−0.06	2.98	−2.55
13	3.19	−0.77	3.30	−13.38	0.38	0.03	1.13	−0.98	0.66	0.02	1.85	−1.76
14	0.76	−0.07	2.56	−2.52	1.51	0.00	3.32	−2.47				
15	0.52	−0.03	1.73	−1.21	1.22	−0.13	2.60	−1.67				
16	0.90	0.00	2.25	−1.79	0.94	0.00	3.25	−2.44				
17	0.90	0.00	2.66	−1.90	0.98	0.00	3.01	−2.66				
18	0.58	0.00	1.22	−1.43	0.53	0.02	1.34	−0.91				
19	0.54	0.07	1.18	−0.96	1.61	−0.02	3.73	−3.83				
20	1.18	−0.14	2.76	−2.49	2.39	−0.49	5.09	−4.89				

as large as those for the W cathode gauges. The relative magnitude of these one-directional long-term changes in sensitivity for the W cathode and ThO_2–Ir cathode gauges is just about the same as the relative magnitude of day-to-day changes in sensitivity observed by Tilford[8] for a group of seven glass-envelope BA gauges with W cathodes (2%), and a group of 10 glass-envelope BA gauges with ThO_2–Ir cathodes (4%–5%).

(3) The spread between the maximum and minimum values of the difference between two successive calibrations, represented by the vertical line associated with each plotted point in Fig. 2, is considerably larger for the gauges with ThO_2–Ir cathodes. This spread information is summarized in Table III.

(4) As shown in Table I and Fig. 2, in the three cases for which a gauge has been calibrated three times, the change in sensitivity between the second and third calibrations is always significantly smaller than the change between the first and second calibrations: between the first and second calibrations the observed changes in calibration factor for gauge Nos. 2, 12, and 13 were 10.2%, 6.0%, and 7.1%, respectively. The changes in CF value for these same gauges between the second and third calibrations were 1.2%, 2.1%, and 1.0%, respectively. This suggests that the change in a gauge's sensitivity may not occur in a uniform manner with time of use.

VI. CONCLUSIONS

As shown in Table I under the heading "Intervening Operation," for about one-half of the gauges, we have missing and/or uncertain information as to how the customer treated the gauge, between our calibrations. Yet, as shown in Fig. 2, for all the gauges of one type (W or ThO_2–Ir cathode) the magnitude of the absolute changes in calibration are comparable. For this reason, we think it is valid to consider these results as indicative of what level of long-term stability can typically be expected of these types of BA gauges when used as reference standards in what we believe to be the relatively benign environment of a secondary calibration laboratory. On the other hand, no conclusions can be drawn from these data with regard to stability of Bayard–Alpert gauges when

TABLE III. Differences between successive calibrations for W and ThO_2–Ir cathode BA gauges.

	Avg. value of absolute change in calibration (%)	Avg. value of maximum difference between successive calibrations (%)	Std. dev. of maximum difference between successive calibrations (%)	Avg. value of minimum difference between successive calibrations (%)	Std. dev. of minimum difference between successive calibrations (%)
W cathode gauges	2.8	4.2	3.1	0.4	3.2
ThO_2–Ir cathode gauges	5.7	8.8	5.7	-2.4	5.7

operated in "active" gases, e.g., oxygen. Recommended operating conditions and procedures, based on our experience, are given in Ref. 1.

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[1]C. R. Tilford, A. R. Filippelli, and P. J. Abbott, J. Vac. Sci. Technol. A **13**, 485 (1995).
[2]G. Messer, *Proceedings of the 8th International Vacuum Congress, Cannes, 1980*, Supplément à la Revue Le Vide, les Couches Minces, No. 201 (Societe Francaise du Vide, Paris, 1980), p. 191.
[3]K. F. Poulter and C. M. Sutton, Vacuum **31**, 147 (1981).
[4]I. Warshawsky, J. Vac. Sci. Technol. A **3**, 430 (1985).
[5]S. D. Wood and C. R. Tilford, J. Vac. Sci. Technol. A **3**, 542 (1985).
[6]P. C. Arnold and S. C. Borichevsky, J. Vac. Sci. Technol. A **12**, 568 (1994).
[7]S. Dittmann, *The NIST High Vacuum Standard and Its Use*, NIST Special Publication No. 250-34 (NIST, Gaithersburg, MD, 1989).
[8]C. R. Tilford, J. Vac. Sci. Technol. A **3**, 546 (1985).