Long-term stability of metal-envelope enclosed Bayard–Alpert ionization gauges
James A. Fedchak, and Dana R. Defibaugh

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I. INTRODUCTION

Understanding the long-term stability of hot-filament ionization gauges is of critical importance to those who use these gauges as secondary references or transfer standards. For more than two decades, the National Institute of Standards and Technology (NIST) has offered a service for the calibration of hot-filament ionization gauges, in which vacuum gauges are compared against the NIST high-vacuum standard after calibration, shipped back to the gauge-owner, and were returned to NIST at a later date (more than one year) for recalibration. Gauge stability was determined using a pooled standard deviation (weighted root-mean-square average of individual gauge standard deviations) based on all calibration factors measured at NIST and was used to define the relative uncertainty component associated with long-term stability $u_{LTS}$. We determined $u_{LTS} = 1.9\%$ ($k = 1$) for gauges operated with 4 mA of emission current, and $u_{LTS} = 2.8\%$ ($k = 1$) for gauges operated with 0.1 mA emission current. [http://dx.doi.org/10.1116/1.4750482]

Long-term stability of metal-envelope enclosed Bayard–Alpert ionization gauges

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Ionization vacuum gauges are used as secondary standards by calibration laboratories and as transfer standards in intercomparisons among metrology laboratories. A quantitative measurement of gauge stability with respect to the gauge calibration factor is critical for these applications. We report the long-term calibration stability of hot-filament metal-envelope enclosed ionization gauges based upon the analysis of repeat calibrations of nine gauges over a 15 year period. All of the gauges included in the study were of the same type: Bayard–Alpert type ionization gauges of an all-metal construction with an integral metal-envelope surrounding the hot-filament, grid, and collector. All were calibrated repeatedly at the National Institute of Standards and Technology (NIST) using the NIST high-vacuum standard but are owned by organizations external to NIST. The gauges were removed from the high-vacuum standard after calibration, shipped back to the gauge-owner, and were returned to NIST at a later date (more than one year) for recalibration. Gauge stability was determined using a pooled standard deviation (weighted root-mean-square average of individual gauge standard deviations) based on all calibration factors measured at NIST and was used to define the relative uncertainty component associated with long-term stability $u_{LTS}$. We determined $u_{LTS} = 1.9\%$ ($k = 1$) for gauges operated with 4 mA of emission current, and $u_{LTS} = 2.8\%$ ($k = 1$) for gauges operated with 0.1 mA emission current. [http://dx.doi.org/10.1116/1.4750482]

I. INTRODUCTION

Understanding the long-term stability of hot-filament ionization gauges is of critical importance to those who use these gauges as secondary references or transfer standards. For more than two decades, the National Institute of Standards and Technology (NIST) has offered a service for the calibration of hot-filament ionization gauges, in which vacuum gauges are compared against the NIST high-vacuum standard over a $N_2$ pressure range of $10^{-7} - 0.1$ Pa. Customers of this service are typically government or private calibration laboratories that require direct traceability to NIST. Calibration laboratories use a variety of commercially available ionization gauges as transfer standards, including glass encapsulated Bayard–Alpert ionization gauges (glass BAGs); Bayard–Alpert type ionization gauges of an all-metal construction without an integral surrounding enclosure, often referred to as “nude” gauges; the extractor gauge; and the axial-transmission gauge. Previously, NIST reported long-term stability (LTS) results for glass BAGs based upon repeat calibrations of customer-owned gauges performed over a period of 10 years. Stability results were also reported for two “metal-envelope” Bayard–Alpert gauges, which were nude gauges mounted inside an electrically grounded metal tube during the calibrations. At that time, glass BAGs represented the majority of the gauges calibrated by NIST for external customers. Since then, a large portion of the calibrations have been for Bayard–Alpert style ionization gauges of an all-metal construction with the entire electrode structure (filament, grid, and collector) surrounded by an electrically grounded integral metal-envelope, referred to here as metal-envelope gauges (MEGs). In this work, the LTS of MEGs will be determined from the repeat calibrations of customer-owned gauges performed over a period of more than 15 years. All of the MEGs included in LTS study were of the same manufacturer and type described by Arnold et al. and, hereafter, MEG will only refer to that particular type of gauge. Between NIST calibrations, all of the gauges were removed from the high-vacuum standard, shipped back to the customer, and subsequently returned to NIST at a later date (more than one year) for recalibration. The gauges were possibly exposed to mechanical shock during the removal and shipment of the gauges, thermal shock during the high-temperature bake-out that is part of the NIST high-vacuum calibration procedure, and operated at $N_2$ pressures as high as 0.1 Pa during the calibration. The treatment of the gauges between calibrations is unknown, but we assume that all of the gauges included in the LTS study were used as transfer standards and handled and operated in a careful manner. The goal is to provide users of the MEG an estimate of the uncertainty in the gauge calibration factor due to long-term stability and to provide metrology labs interested in national or international comparisons a quantitative metric for gauge stability.

To the authors’ knowledge, no other similar study of the long-term stability of MEGs, as defined here (i.e., covering a time period of more than one year, removing the gauges between calibrations, etc.), has been published. As previously stated, this lab reported stability results for two nude gauges surrounded by a metal tube, but these did not have the same electrode geometry as the MEGs, and they were...
not operated with the same electrode potentials or emission currents as the MEGs, described in Sec. II A. Yoshida et al.\textsuperscript{9} reported stability results for several types of ionization gauges including metal-envelope enclosed BAGs, but these were not identical to the MEGs in the current study and were operated under different electrical conditions. Additionally, in their long-term stability study, gauges were repeatedly calibrated over a period of about one year but were not removed from the vacuum chamber, although the chamber was periodically vented with N\textsubscript{2} gas. Li and Jousten\textsuperscript{10} studied the stability of a single MEG by performing repeat calibrations over a period of six months. This test covered a time period that was much shorter than our LTS and their calibration covered a pressure range of $10^{-7}$–$10^{-4}$ Pa. Arnold et al.\textsuperscript{8} and Arnold and Borichevsky\textsuperscript{11} performed repeat calibrations of MEGs three times over a period of roughly nine months. These results are somewhat comparable to our long-term stability study because the gauges were removed from the vacuum system and transferred to a different station for calibration; however, their MEG stability study differed from the present work in that their results cover a smaller time period, the MEGs were not subjected to shipping and were handled by a single laboratory, and most gauges were operated with 0.1 mA emission current (data are provided for a gauge operating at 4 mA emission current). The NIST study covers a much longer time period and provides LTS data on nine different gauges operating at 4 mA of emission current and seven operating at 0.1 mA of emission current. Finally, a MEG was one of the gauges used as a transfer artifact for the first international key comparison for the realization of absolute pressures in the range of $3 \times 10^{-6}$ Pa to $9 \times 10^{-4}$ Pa.\textsuperscript{12} During the key comparison, NIST calibrated the MEG four times using Ar gas over a period of four years, and the gauge was shipped to other calibration laboratories between the NIST measurements. Data from that study can therefore be used to obtain the LTS for the single MEG used in the key comparison; however, the calibrations were performed using Ar gas and covered a smaller pressure range that does the present results.

II. APPARATUS

A. Description of the MEG gauges

A detailed technical description of the MEG gauge is given by Arnold et al.\textsuperscript{8} Here, we point out a few of the features that differentiate the MEG from other Bayard–Alpert ionization gauges and which are relevant to this work. The arrangement of the collector, grid, and filament is similar to other Bayard–Alpert ionization gauges; however, in the MEG, these are completely surrounded by a cylindrical stainless-steel tube maintained at electrical ground potential. A metallic screen covers one end of the tube and allows gas to pass from the vacuum into the gauge. The opposite end of the tube is covered by a shield with feedthroughs for the collector, grid, and filament, and completes the grounded metal-envelope enclosure. The collector wire lies along the axis of a cylindrically shaped helical wire grid but lies slightly off the cylindrical axis of the metal envelope. Two ribbon-shaped iridium filaments are mounted in tension on a T-shaped central support post to prevent sagging or twisting with use. Both filaments are mounted parallel to the collector roughly midway between the envelope and grid, but only one filament is hot during use and is selectable by the user. The location of the envelope, filaments, grid posts, and collector are critical to the stability of the gauge since these affect the trajectory of the electrons emitted from the filament.\textsuperscript{13,14} The placement of the entire electrode structure off-axis from the surrounding envelope was done to prove better focusing of the emitted electrons through the grid volume at the operating potentials. The capped ends of the envelope also limits the length of the axial field (compared to, for example, a nude gauge), which also affects the electron trajectory and hence the stability and sensitivity of the gauge.\textsuperscript{15}

The electric fields within the MEG are well-defined and regulated by the gauge controller: the electric potentials are, nominally, $+30$ V for the filament, $+180$ V for the grid, and the collector is held near 0 V. All of the currents and potentials are operated in DC. The metal envelope is grounded through the metal flange that connects the gauge to the vacuum chamber. The controller allows the user to choose between two different pressure ranges corresponding to two different emission currents $i_{e}$: a low-pressure range (low-range) used for pressures less than 0.1 Pa and corresponding to $i_{e} = 4$ mA, and a high-pressure range (high-range), covering pressures from $5 \times 10^{-7}$ Pa to 3 Pa and corresponding to $i_{e} = 0.1$ mA. The maximum pressure limits are firmly set by the controller. The lower pressure limit of the low-range depends on the gauge version and is discussed in the following paragraph. The manufacturer recommends using the high-range for pressures above $1.3 \times 10^{-2}$ Pa, the low-range for pressure below $1.3 \times 10^{-5}$ Pa, and either range for pressures between $1.3 \times 10^{-2}$ Pa and $1.3 \times 10^{-5}$ Pa.

Two versions of the MEG gauge are included in this study: one has a thin collector wire that is 0.13 mm in diameter, and the other has a thicker collector wire, 1.02 mm in diameter. The smaller diameter collector has a lower x-ray emission limit\textsuperscript{4} and can therefore be used at lower pressures, whereas gauges with the larger diameter collector have an increased sensitivity.\textsuperscript{16,17} Gauges with a 1.02 mm diameter collector are known as “extended pressure range” (EXT) gauges and have a lower pressure limit of $3 \times 10^{-8}$ Pa, whereas gauges with a 0.13 mm diameter collector are designed for ultra-high vacuum measurements (UHV) and have a lower pressure limit of $3 \times 10^{-9}$ Pa. Either variety adequately covers the pressure range of the calibration service.

The pressure indicated by the controller is given to three decimal places in exponential format. The uncertainty due to the gauge resolution can be estimated by assuming that the true reading lies within a rectangular probability distribution\textsuperscript{18} around the last half-digit of the reading. For a mid-range reading of $5.00 \times 10^{-3}$ Pa, where $x$ is an integer from 1 to 7, the relative standard uncertainty due to the resolution of the pressure reading is thus estimated to be $\pm 0.06\%$ ($k = 1$). This value represents both the minimum type A uncertainty that is possible, and the maximum stability that
B. Calibration of the ionization gauges

The NIST high-vacuum standard utilizes a dynamic expansion technique and has been previously described in detail.1,2,19 It consists of a cylindrical high-vacuum chamber separated into an upper and lower chamber by an orifice of known conductance. The lower chamber is evacuated using a turbomolecular pump. A known flow of gas, \( \dot{n} \), is produced using one of NIST’s flowmeters20 and is injected into the upper chamber. The upper chamber pressure, \( P_{STD} \), is determined from the molar gas flow rate \( \dot{n} \), the orifice conductance \( C \), the universal gas constant \( R \), and the chamber temperature \( T \)

\[
P_{STD} = \left( \frac{R_P}{R_P - 1} \right) \frac{\dot{n}RT}{C^2}. \tag{1}
\]

\( R_P \) is the pressure ratio and is defined as the ratio of the pressure above the orifice to that below and is determined in a separate measurement. Both \( R_P \) and \( C \) are constant in the molecular flow regime; for N\(_2\) gas at 296 K, \( R_P \) is approximately 60 and \( C \) is approximately 11 L/s. To generate pressures less than \( 10^{-5} \) Pa, a split flow technique is used. In that case, the gas flow from the flowmeter is directed into the lower chamber and \( P_{STD} \) is determined by substituting \( \dot{n}_L/R_P \) for \( \dot{n} \) in Eq. (1), where \( \dot{n}_L \) is the gas flow into the lower chamber and \( R_P \) is the flow ratio, defined as the ratio of \( \dot{n}_L \) to the upper chamber flow \( \dot{n}_U \), under the condition that the two gas flows produce the same pressure in the upper chamber. \( R_P \) is determined in a separate measurement and is constant in the molecular flow regime, \( R_P \approx 120 \).

Ionization gauges are calibrated by attaching them to the upper chamber and comparing the net pressure (above base pressure) given by the gauge controller, \( P_G \), to that generated by the standard. The calibration factor, \( F_{CF} \), is then determined from

\[
F_{CF} = \frac{P_{STD}}{P_G}. \tag{2}
\]

It is customary relate the gauge reading to a gauge sensitivity \( S \), by the relationship \( P_G = i_{ion}/(i_e S) \), where \( i_{ion} \) is the ion current to the collector and \( i_e \) is the emission current.21 The gauge sensitivity \( S \) is a property of the gauge, which depends on the geometry, dimensions, materials, and surface conditions within the gauge, as well as the gas that is being measured. Since the MEG controllers do not indicate \( i_{ion} \) and an independent measurement of \( i_{ion} \) is not typically performed during a calibration, the gauge sensitivity \( S \) is not determined during a routine calibration. Nevertheless, a change in gauge sensitivity will result in change in the measured \( F_{CF} \) since \( F_{CF} \propto S^{-1} \).

Calibrations are performed as a batch; in other words, several customer gauges are often calibrated at the same time. This will be referred to as a calibration cycle and the frequency of calibration cycles are greater than one year for all the gauges in the LTS.

Ionization gauge calibrations are typically performed over a pressure range of \( 10^{-7}–10^{-1} \) Pa with the \( F_{CF} \) measured at three pressure points per decade. Data are always accumulated in the order of increasing pressure, and each pressure point is typically taken twice. The entire data sequence is then repeated at least once on a different day, so \( F_{CF} \) is determined a minimum of four times per pressure point. It takes one to three days to complete the full data sequence, and it can take several days for the gauge readings to return to base pressure before the sequence can be repeated. For MEGs, two separate calibrations are performed: one for the low-range of the gauge covering \( 10^{-7}–10^{-2} \) Pa, and one for the high-range of the gauge covering the pressure range of \( 10^{-5}–10^{-1} \) Pa. Therefore, for calibrations covering both ranges, a minimum of four data sequences are acquired for MEGs. In some cases, usually upon customer request, calibrations are performed solely on the low-range.

Prior to accumulating calibration data, the gauges are mounted on the high-vacuum standard, the system is evacuated, and the entire system, including the gauges, is baked to about 260 °C for approximately 72 h. Gauges are operated during the bake-out. Often the gauges are degassed after bake-out; degassing was performed in 7 of the 28 calibrations included in the study. In recent years, the gauges have been preconditioned or “dosed” after baking by exposing them to a high pressure of N\(_2\), typically about \( 10^{-2} \) Pa, for at least 1 h. This procedure was performed on half of the calibrations included in the study and was introduced to produce a more consistent calibration factor at low-pressures. In this laboratory, we have noticed that exposing the gauges to high pressures of N\(_2\) reduces ion-gauge pumping effects and, possibly, produces other changes in the gauge, which affect the low-pressure calibration factor. Calibration data are not collected until the system returns a base pressure on the order of \( 10^{-8} \) Pa, which usually takes a minimum of two days.

After the data are collected, the calibration factor, \( F_{CF} \), is calculated as a function of \( P_G \) using Eq. (2). The calculated calibration factor \( F_{CF} \) is then fit to a polynomial function of \( \log(P_G) \)

\[
f_{CF}(P_G) = \sum_{i=0}^{n} A_i \log(P_G)^i. \tag{3}
\]

The polynomial coefficients \( A_i \) are reported to the customer. In the long-term stability analysis, we use the coefficients \( A_i \) to calculate \( f_{CF} \), thus allowing a comparison of the calibration results at a given gauge reading \( P_G \).

An example of the measured \( F_{CF} \) and the derived calibration function is shown in Fig. 1, and the uncertainty of a typical calibration is given in Table I. The type B uncertainty \( u_B \) is a function of \( P_{STD} \) and is associated with the realization of the standard pressure. The type A uncertainty is calculated from the standard uncertainty of the polynomial fit given by Eq. (3) and will depend on the gauge; the values given in Table I can be considered to be typical. Two dominant contributors to the type A uncertainty are the goodness of the
polynomial fit and the repeatability of the gauge reading during the calibration cycle. From Fig. 1, it is seen that the non-repeatability in the data is rather large at some pressure points. The repeatability of the gauge readings during the calibration depends on temperature and gauge stability. Random variations in $P_{STD}$ are expected to be $<0.1\%$ over a calibration cycle, which is too small to make a relevant contribution to the repeatability. The temperature dependence of $F_{CF}$ is less than $0.3%/K$. In the example low-range data of Fig. 1 the temperature varied by 0.3 K, thus one expects the $F_{CF}$ variation due to temperature to be less than 0.1%. Changing the gauge pressure range from low to high changes the filament power and can cause a change in the chamber temperature, but the chamber temperature is typically stable to well within 1 K over the course of the calibration for either range.

III. RESULTS AND ANALYSIS

A. Low-range long-term stability

Nine MEGs owned by five different organizations external to NIST had repeat calibrations and were included in this study, as summarized in Table II. We chose to analyze the LTS at six pressure points for the low-range: $1.3 \times 10^{-2}$ Pa and $6.7 \times 10^{-3}$ Pa, where $x = 7, 6, 5, 4, 3$. The calibration factors $f_{CF}$ were taken from Eq. (3). The goal is to obtain a measurement of gauge stability, $u_{LTS}$, which represents what a user can expect from a typical gauge. The percent change in $f_{CF}$ from the first calibration is often used as a figure-of-merit for gauge stability. This is shown in Fig. 2 as a function of the number of years since the first calibration. More gauges show a positive change in the calibration factor than negative but, given the small number of gauges and calibrations in the study, it cannot be concluded that there is a significant trend or drift over time that is common to all the gauges. Figure 3 shows the fractional change of $f_{CF}$ relative to average calibration factor, <$f_{CF}$>, for each gauge at each pressure; the data appears to be randomly distributed at all pressure points. Therefore, for our analysis, we will assume that the calibration factor changes in a random direction from the value measured in the previous calibration, and that neither the magnitude nor direction of the change depends on time. Since the authors have no reason to conclude that some gauges are more stable than others (based on knowledge of the manufacturing or design, for example), the data from all gauges will be treated as originating from the same statistical distribution. Therefore, to measure gauge stability, we use the pooled standard deviation [23], $s_{pooled}$, given by

$$s_{pooled} = \sqrt{\frac{\sum_{i=1}^{9} (n_i - 1) s_i^2}{\sum_{i=1}^{9} (n_i - 1)}}.$$  (4)

The subscript $i$ corresponds to the nine gauges in the study, each with $n_i - 1$ degrees-of-freedom, where $n_i$ is the total number of calibrations per gauge $i$. For each gauge, a standard deviation $s_i$ is calculated at each pressure point for the $n_i$ calibrations, and $s_{pooled}$ is the weighted average of the variances (the squares of the standard deviations) for all nine gauges. The pressure dependence of $s_{pooled}$ is shown in Fig. 4. The uncertainty bars in Fig. 4 represent the statistical uncertainty in each result as a set of simultaneous 95% confidence intervals for the entire family of six results. In other words, to obtain a set of confidence intervals with a confidence level of 95% for the entire family of six $s_{pooled}$ results shown in Fig. 4, the confidence interval of each result is adjusted to $(0.95)^{1/6}$ [24]. The asymmetry in the error bars arises from the asymmetry in the chi-squared distribution, which is more pronounced for small values of the degrees-of-freedom. In principle, $s_{pooled}$ includes variations due to the standard as well as the gauge. However, since, from Fig. 4, $s_{pooled} \sim 0.02$ and, from Table I, $h_{CF} < 0.007$ ($k = 1$), we see that $s_{pooled} > h_{CF}$. Therefore, the long-term stability uncertainty should be well approximated by $h_{LTS} \approx s_{pooled}$.

The pressure dependence of $s_{pooled}$ is not strong. As a result, it seems reasonable to use the root-mean-square (RMS) of $s_{pooled}$ over all pressures to calculate a typical variation of a gauge’s calibration factor: <$s_{pooled}$> RMS = 0.019. Therefore, the relative standard uncertainty associated with long-term stability for a MEG with $F_{CF} \approx 1$ is $u_{LTS} = 1.9\%$ ($k = 1$).

B. High-range long-term stability

The gauges included in the LTS study for the high-range are the same as those included in the LTS study for the

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**TABLE I. Relative standard uncertainty in $F_{CF}$ for a typical MEG calibration.**

<table>
<thead>
<tr>
<th>$P_{STD}$ (Pa)</th>
<th>$u_A$ (k = 1; percent)</th>
<th>$u_B$ (k = 1; percent)</th>
<th>$U_{CF}$ (k = 2; percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6.7 \times 10^{-7}$</td>
<td>0.2</td>
<td>0.6</td>
<td>1.3</td>
</tr>
<tr>
<td>$6.7 \times 10^{-6}$</td>
<td>0.2</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>$6.7 \times 10^{-5}$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>$6.7 \times 10^{-4}$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>$6.7 \times 10^{-3}$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>$1.3 \times 10^{-2}$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
</tr>
</tbody>
</table>

---

**Fig. 1. Example of low-range calibration data. The dark circles are the measured $F_{CF}$, the solid line represents a polynomial function $f_{CF}$ fit to the data, and the dashed lines represent the expanded uncertainty interval ($k = 2$).**

---

**Fig. 2. Example of low-range calibration data. The dark circles are the measured $F_{CF}$, the solid line represents a polynomial function $f_{CF}$ fit to the data, and the dashed lines represent the expanded uncertainty interval ($k = 2$).**
low-range. There are a total of seven gauges owned by four organizations included in the high-range study, as summarized in Table III. Gauges 4 and 8 were not included because they did not have repeat calibrations on the high-range, and gauges 2, 5, and 9 had fewer calibrations on the high-range than on the low-range. Only a narrow range of calibration pressures were common to all the high-range calibrations. Two pressure points near the minimum and maximum of the range were chosen to perform the LTS analysis: $1.0 \times 10^{-2}$ Pa and $2.7 \times 10^{-2}$ Pa.

Similar to the low-range LTS study, the pooled standard deviation $s_{\text{pooled}}$, defined by Eq. (4), is used as a measure of the LTS. For the two pressures considered, $s_{\text{pooled}} (10 \text{ mPa}) = 0.028$ and $s_{\text{pooled}} (27 \text{ mPa}) = 0.027$, with an a RMS average of $s_{\text{pooled}} = 0.028$. Over the limited pressure range covered, the relative standard uncertainty for the high-range is approximately $u_{\text{LTS}} = 2.8\%$ ($k = 1$).

IV. DISCUSSION

The combined standard uncertainty for a calibration factor, $u_{\text{CF}}$, is the uncertainty of the calibration factor at the time the gauge was calibrated. The long term-stability uncertainty, $u_{\text{LTS}}$, represents the uncertainty due to a change or

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Collector type</th>
<th>Owner identifier</th>
<th>Filament type</th>
<th>Calibration cycle (years since previous calibration)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge 1</td>
<td>EXT</td>
<td>A</td>
<td>Thoria-coated iridium</td>
<td>3.6 3.3 4.7 1.8</td>
</tr>
<tr>
<td>Gauge 2</td>
<td>EXT</td>
<td>A</td>
<td>Thoria-coated iridium</td>
<td>2.7 4.5 2.9</td>
</tr>
<tr>
<td>Gauge 3</td>
<td>EXT</td>
<td>A</td>
<td>Thoria-coated iridium</td>
<td>4.5 2.9</td>
</tr>
<tr>
<td>Gauge 4</td>
<td>EXT</td>
<td>A</td>
<td>Thoria-coated iridium</td>
<td>2.4</td>
</tr>
<tr>
<td>Gauge 5</td>
<td>EXT</td>
<td>B</td>
<td>Thoria-coated iridium</td>
<td>1.5 2.7 7.5</td>
</tr>
<tr>
<td>Gauge 6</td>
<td>EXT</td>
<td>B</td>
<td>Thoria-coated iridium</td>
<td>7.9</td>
</tr>
<tr>
<td>Gauge 7</td>
<td>UHV</td>
<td>C</td>
<td>Yttria-coated iridium</td>
<td>2.9</td>
</tr>
<tr>
<td>Gauge 8</td>
<td>EXT</td>
<td>D</td>
<td>Thoria-coated iridium</td>
<td>4.6</td>
</tr>
<tr>
<td>Gauge 9</td>
<td>EXT</td>
<td>E</td>
<td>Thoria-coated iridium</td>
<td>1.3 1.9 2.7</td>
</tr>
</tbody>
</table>

![Fig. 2](image-url) Relative change in calibration factors since the first calibration as a function of time. Graphs (a) through (f) represent the relative change in the low-range calibration factors determined at six different gauge pressures: (a) $6.7 \times 10^{-2}$ Pa, (b) $6.7 \times 10^{-5}$ Pa, (c) $6.7 \times 10^{-3}$ Pa, (d) $6.7 \times 10^{-4}$ Pa, (e) $6.7 \times 10^{-3}$ Pa, and (f) $1.3 \times 10^{-3}$ Pa.
drift in the calibration factor since the last calibration. This change could be due to, for example, exposing the gauge to the ambient atmosphere, shifting of electrodes during transportation of the gauge, removal of the gauge from the calibration chamber, or other effects that change surface conditions or the geometry within the gauge. For the user, the combined standard uncertainty of the calibrated gauge reading is $u_{\text{Gauge}} = \sqrt{u_{\text{CF}}^2 + u_{\text{LTS}}^2}$. Typical short-term or day-to-day stability is included in $u_{\text{CF}}$ through the type A uncertainty evaluation, and so an additional short-term stability component is not necessary unless particular conditions at the user site warrant an additional component.

Arnold et al.\textsuperscript{8} present results from three repeat calibrations of five MEGs over a period of nine months. Their calibrations cover a pressure range of $10^{-4}$–$1$ Pa for the high-range. These gauges were not in continuous operation between calibrations but were operated each workday and routinely exposed to $10$ mPa of N$_2$, Ar, or air. From their graphical presentation of the high-range data, it appears that the calibration factors remained within about a 6% band around the initial value. Stability tests were performed in a similar manner on a single MEG by Arnold and Boreshevsky;\textsuperscript{11} they report the range of relative sensitivity changes for the low-range to be from $-2.0\%$ to $2.5\%$ after $6700$ h, and, similarly, to be from $-3.0\%$ to $3.0\%$ for the high-range. All of these results are in reasonable agreement with our value of $u_{\text{LTS}} = 2.8\%$ for the high-range and $u_{\text{LTS}} = 1.9\%$ for the low-range.

Li and Jousten\textsuperscript{10} performed six repeat calibrations of a single MEG operated on the low-range over a period of 6 months. Calibrations were performed with N$_2$, Ar, He, and H$_2$ gas, and covered a pressure range of $10^{-7}$–$10^{-3}$ Pa. The gauges were initially baked, degassed, and dosed with $10^{-4}$ Pa of Ar and were left in continual operation at base pressure between calibrations, except for times that other tests were performed. Using the standard deviation of the six calibrations as a measurement of stability, they report a relative standard uncertainty for calibration stability of $1.9\%$ ($k = 1$) for N$_2$. This value is the same to our value of $u_{\text{LTS}}$ even though the study is different because they did not remove the gauges from the system between calibrations, nor did they rebake or degas before every calibration.

During the CCM.P-K3 key comparison, NIST calibrated a single MEG four times with each calibration more than

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**Fig. 3.** Fractional change in calibration factors relative to the average calibration factor for each gauge, $f_{\text{CF}}/(f_{\text{CF}}) - 1$, as a function of the calibration cycle. Each calibration cycle is separated from the previous calibration by more than one year. Graphs (a) through (f) represent the fractional change in the low-range calibration factors determined at six different gauge pressures: (a) $6.7 \times 10^{-7}$ Pa, (b) $6.7 \times 10^{-6}$ Pa, (c) $6.7 \times 10^{-5}$ Pa, (d) $6.7 \times 10^{-4}$ Pa, (e) $6.7 \times 10^{-3}$ Pa, and (f) $1.3 \times 10^{-2}$ Pa.

**Fig. 4.** Plot of $S_{\text{spooled}}$ as a function of pressure for the low-range. $S_{\text{spooled}}$ is a measurement of long-term stability since $u_{\text{LTS}} \approx S_{\text{spooled}}$.
one year from the previous. The calibration was performed over a pressure range of 3 \times 10^{-6} \text{ Pa} to 9 \times 10^{-4} \text{ Pa} using Ar gas and was shipped to other national metrology institutions between calibrations. The standard deviation for the four NIST calibrations ranged from 0.7% at the lowest pressure to 1.6% at the highest. These values are less than the present result for nine gauges combined, but do lie within the distribution of stability results for the nine individual gauges discussed here, and therefore agree with the results of the present LTS study.

V. SUMMARY AND CONCLUSIONS

The long term stability of metal-envelope enclosed Bayard–Alpert ionization gauges of the type described by Arnold et al. was determined from the repeat calibrations of gauges over a 15 year period of time. The relative standard uncertainty in the calibration factor due to LTS was found to be \( u_{LTS} = 1.9\% \) (\( k = 1 \)) for the low-range and \( u_{LTS} = 2.8\% \) (\( k = 1 \)) for the high-range. The present values are in reasonable agreement with other published stability values of MEGs, even though those studies do not cover the same time span and the gauges were exposed to different operating conditions from the present work. Even so, it is still possible that our LTS results could be different from those obtained by repeat calibrations performed by other metrology labs, and so the best practice for the user is to estimate \( u_{LTS} \) based upon historical data from the particular laboratory that performed the calibration. In absence of such data, the above values for \( u_{LTS} \) should provide a reasonable estimate of \( u_{LTS} \) for calibrations performed with N\(_2\).

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Note 1: \( u_{LTS} \) designates gauges with a 0.13 mm diameter collector, optimized for ultra-high vacuum measurements. The total number of calibrations is 21.

Note 2: \( u_{LTS} \) designates gauges with a 1.02 mm diameter collector are designated by EXT (extended pressure range), whereas UHV designates gauges with a 0.13 mm diameter collector, optimized for ultra-high vacuum measurements. The total number of calibrations is 21.

Note 3: \( u_{LTS} \) designates gauges with a 0.13 mm diameter collector, optimized for ultra-high vacuum measurements. The total number of calibrations is 21.

Note 4: \( u_{LTS} \) designates gauges with a 0.13 mm diameter collector, optimized for ultra-high vacuum measurements. The total number of calibrations is 21.

Note 5: \( u_{LTS} \) designates gauges with a 0.13 mm diameter collector, optimized for ultra-high vacuum measurements. The total number of calibrations is 21.