Comments on the stability of Bayard–Alpert ionization gages

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I. INTRODUCTION

A recent group of three articles presents stability testing results for ionization gages,[1] discusses the causes of gage instability,[2] and describes a new type of Bayard–Alpert (BA) ionization gage.[3] Although we are in general agreement with the analysis of gage instability presented by Bills,[2] we are concerned that the test results of Arnold and Borichevsky[1] and the discussion in all three references imply instabilities for existing types of BA gages that are much larger than we find to be the case. Here we briefly describe our experience with BA gage stability, indicate why we think our results are different from those of Arnold and Borichevsky, and describe the operating conditions that we believe will result in improved stability. We are encouraged by the effort of Arnold *et al.*[3] to understand and develop an improved BA gage, but do not have any additional comments on this gage.

Most of the test results presented by Arnold and Borichevsky are for commercially available nude and glass-envelope BA gages, all with hairpin-style, thoria-coated cathodes (filaments). The BA gages tested are referred to as "older design" gages, as distinguished from the "new design" or "new technology" gage described in the work of Arnold *et al.*[3] Observed changes in calibration (sensitivity) for the older design gages ranged from −57% to 72%.[1] Unfortunately, "older design" is such a broad characterization that readers might infer, and some statements in Refs. 2 and 3 imply, that these levels of instabilities can be attributed, in general, to all existing types of BA gages. Our experience, from both systematic testing and the results of repeated calibrations of gages used in industrial laboratories, using gage operating parameters and procedures that differ in some aspects from those described by Arnold and Borchevsky, is quite different; we find that the typical instabilities of some common BA gage types are significantly smaller than what is implied by Refs. 1–3, indeed, in some cases, an order of magnitude smaller.

II. NIST EXPERIENCE

We have previously presented results[4,5] showing significant differences between different ionization gage types for short-term stability, pressure dependence of sensitivity, and uniformity of sensitivity from gage to gage of the same type. Glass-envelope BA gages with tungsten cathodes, particularly those with two filaments spaced 180° about the central anode (grid), were found to be generally superior in all these attributes. This prompted a systematic testing of this type of gage, and we have reported the long-term stability results;[6] we observed maximum sensitivity decreases of 6% over an operation period of about 500 da (12 000 h).

Gage stability will depend in part on the choice and stability of operating parameters (determined by the gage controller) and conditions of use, and during our testing the gages were generally operated under well-controlled conditions: 1 mA electron–emission current, tight regulation of all electrical parameters, and most of the operation time at pressures of 10^{-7} Pa (1 Torr=133.322 Pa) or lower (see Ref. 6 for details). All of the gages were periodically operated with nitrogen pressures as high as 0.1 Pa, with some of the gages operated at nitrogen pressures as high as 0.5 Pa, in one case for a period of 10 da. They were also twice accidentally operated overnight at pressures of about 1 Pa. In all cases, the changes over the 500 da test period did not exceed 6%.

Any laboratory test, including those already discussed,[1,6] can be challenged as not typical of "real world" conditions, but we also have data on gage stability under conditions of actual use. NIST calibrates ionization gages for industrial and government-laboratory customers between 10^{-7} and 0.1 Pa, and, to date, 20 of these gages have been returned for repeat calibrations, typically after one or two years of use. Gages are calibrated as a system including the gage "tube" and a commercial gage controller. In some cases the performance of the gage is obviously compromised by deficiencies of the controller. However, all of the gages for which we have repeat calibrations were operated with high-quality controllers, as evidenced by the very good repeatability of the data obtained over the 500–1000 hour calibration cycle—standard deviations of the data are typically 1% or less, and in no case are they larger than 3%.

Our analysis[7] of these data indicates that the average change in the calibration of the tungsten–cathode gages, averaged over the calibration pressure range, was 3%, and the maximum change observed for all the gages and all pressures was 12%. Similarly, the average change for the thoria-coated cathode gages was 6%, and the maximum change was 18%. In most cases the changes were in the direction of decreasing sensitivity.

Usually we do not know the detailed conditions of the use of these gages between NIST calibrations, but most of them were used as reference standards for the calibration of process-control instrumentation. Overall, our experience with these industrial reference gages is entirely consistent with the results of our laboratory testing

III. TEST PROCEDURE DIFFERENCES

The question naturally arises, Why is our experience with BA gages so different from the results and conclusions presented in Refs. 1–3? We have no reason to question the ac-

curacy of these results and the controllers used to operate the gages[1,8] should contribute only negligibly to the observed instabilities. There are many factors that will influence ion gage performance, but we think three are particularly relevant in this case: cathode material, the combination of high emission current and high pressure, and degassing.

We have consistently obtained the best results, even when operating with noninert gases such as water or sulfur hexafluoride, for gages with tungsten cathodes while the results reported in Ref. 1 are all for thoria-coated hairpin-cathode gages. Significant changes in both the geometry and the surface condition of these cathodes are evident to the naked eye after extended use and, as discussed in Ref. 2, these will cause changes in gage sensitivity. However, this is not a full explanation as our limited results with this type of cathode still show significantly smaller instabilities than those reported in Ref. 1.

A second possible reason is the calibration of the "older design" gages with combinations of high pressures and high electron–emission currents. Some of the results presented in Ref. 1 were obtained with 10 mA emission currents at pressures as high as 2×10^{-3} Torr (0.3 Pa). Under these conditions the gages are strongly affected by space charge, become highly nonlinear, and the effects of potential changes discussed by Bills[2] are likely to be significantly enhanced. The consequences are evident in that the largest changes of sensitivity, presented in the figures of Ref. 1, occur at the high-pressure extreme. It should also be noted that most of the gages were operated at 10 mA for extended periods (10 000 h) between calibrations. Most of our experience was obtained under different operating conditions; as a general rule, we restrict BA gage operation to 1 mA emission current and do not attempt operation at pressures above 0.1 Pa. However, high emission currents and high pressures cannot be the entire explanation since large shifts are also tabulated[1] for "older design" gages calibrated with emission currents as low as 1 mA.

A third possible reason is that the "older design" gages of Ref. 1 were degassed for 20 min each day during the first 458 da (11 000 h) of testing. Sustained high-power degassing can cause significant distortion of the grid structure and evaporate thin films of variable-conductivity material (depending on the oxidation state) on the gage electrodes, insulators, and gage enclosure. Electron-bombardment degassing will further stress the cathode, causing additional distortion, cathode-surface modification, and deposition of cathode material. As has been pointed out,[2] changes in geometry, electrical potentials, and electron emission density distributions will all cause sensitivity changes.

Thus we believe that the differences between our results and those of Ref. 1 are due at least in part to the choices of gage operating parameters and test procedures. The test conditions used[1] for the "older design" gages were selected in part because some industrial users operate with 10 mA emission at high pressures and with frequent outgassing.[8] Whatever the reason, we believe these operating conditions are unnecessary and ill-advised. We find that, with reasonable precautions, it is possible to reduce BA gage instabilities well below the levels discussed in Refs. 1–3 to the point where they will not be a limiting factor for many measurements.

IV. RECOMMENDED OPERATING PROCEDURES

To achieve better stability we recommend the following: (1) Of the common gage types on the U.S. market, we have obtained the most stable and linear results with glass-envelope BA gages with two tungsten filaments located on opposite sides of the collector and grid structure. Of course, these gages will not be satisfactory if mechanical integrity of the gage housing is critical or if the gage is likely to be exposed to high pressures (above 1 Pa) while operating. Again, we do not have experience with the "new technology" gage described by Arnold *et al.*[3] (2) Operate the gage with 1 mA, or less, emission current. The only reason to operate a modern gage with 10 mA emission is to increase the temperature of the gage and speed outgassing. (3) Monitor gage controllers to ensure that they maintain bias voltages to within a few volts and emission currents to within a few percent (emission current instabilities will cause corresponding instabilities in gage readings). In order to improve gage linearity it is also desirable to use noise-free direct current (dc) filament current supplies,[9] and the gage collector should be maintained within a fraction of a volt of ground. The use of controllers that employ field effect transistor (FET)-input, feedback controlled current-to-voltage converters to measure the ion current will maintain the collector at ground and with proper feedback resistors will also provide good linearity and stability in the measured current.

Finally, it is of course important to keep the gage clean, avoid leaks (we strongly recommend metallic seals), and minimize the evolution of gas within the gage structure. However, even though it has become a firmly established part of vacuum lore, for most BA gage applications we do not recommend degassing by direct high-temperature heating of the grid, whether resistive or electron-bombardment heating. In addition to causing the structural and surface changes previously discussed, high-temperature heating of the grid can deposit a metallic film on the gage enclosure, turning the gage into a getter pump and causing erroneous low pressure readings. In general, for baked systems we find that gages can be effectively outgassed by operating them at normal emission currents while the gage and system are baked. For unbaked systems, the gage can be baked and outgassed by thermally insulating the operating gage; fiberglass building insulation and normal filament power will increase the temperature of the gage by 100–150° C. If the gage is heavily contaminated or operated at very low pressures after exposure to surface-active gases such as oxygen, then bombardment of the grid with high-energy electrons may be necessary. In these cases the collector should be degassed as well by connecting it to the grid potential during electron bombardment. Since electron-bombardment degas depends on the flux and energy of the electrons rather than on the temperature, damage to the cathode and grid can be minimized by reducing the electron–emission current and extending the degas time.

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