Long-term stability of two types of hot cathode ionization gauges

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We have monitored the nitrogen sensitivity of four gauges each of two selected types of hot cathode ion gauges over a 500-day test period. Gauges of one type, a tungsten filament conventional triode, changed by about 12% during this time, with most of the decrease caused by "high" pressure operation. Gauges of the second type, a twin tungsten filament Bayard–Alpert gauge, changed by no more than 6% and with no obvious correlation between sensitivity changes and "high" pressure operation or exposure to air. There were no significant differences in the sensitivity changes for the two filaments in a given Bayard–Alpert gauge, although their operating times differed by a factor of 10.

I. INTRODUCTION

In applications where the trouble must be taken to calibrate a hot cathode ion gauge, one is obviously concerned about the subsequent stability of the gauge sensitivity. An estimate of likely changes with time will be important in establishing recalibration intervals or estimating probable errors as a function of time. In many other cases accuracy is not important, but stability is. In our work at the National Bureau of Standards (NBS) on the performance characteristics of ion gauges, we have observed large differences in the short-term repeatability and other relevant performance characteristics for different types of ion gauges.[1–5] However, we have had only limited and fragmentary information on long-term stability. Little information is available in the literature. Data have been published[6–8] on the behavior over time of different gauge types that, unfortunately, are not completely described or are not commonly used and not generally available. The most extensive published study is that carried out by Poulter and Sutton at the National Physical Laboratory (NPL) on five conventional triode (CT) and six single tungsten filament Bayard–Alpert (BA) gauges.[9] They repeatedly calibrated the gauges with nitrogen at a pressure of 5×10^{-3} Pa over an unspecified period of time during which the gauges were operated for up to 1000 h, with indeterminate periods of storage while exposed to atmospheric conditions. They found a fairly uniform rate of change in the sensitivity for the CT gauges as a function of operating time, up to +0.45% per 100 operating hours. They found much larger and less predictable changes for the BA gauges, with rates as high as −1.4% per 100 operating hours. Less explicable were large changes, up to 25%, observed after the BA gauges were stored in air. Limited experience with this same type of BA gauge at the NBS had indicated that it was not particularly stable, but the NPL results after exposing the gauges to air were unexpected. Because of this and the general paucity of information on gauge stability, we decided to conduct a long-term stability test on two gauge types commonly used in the U. S. that in earlier[5] tests appeared to have superior short-term stability and uniformity of sensitivity from gauge to gauge.

II. EXPERIMENTAL CONDITIONS

The gauge types chosen, illustrated in Fig. 1, were a tungsten filament conventional triode, the filament being of the hairpin type, and a dual tungsten filament Bayard–Alpert type. The filaments in the BA gauge are located 180° apart about the central collector. Both types are glass tubulated and connected by a Kovar seal and copper-gasketed metal flanges to an all-metal vacuum system. The vacuum system was initially ion pumped, but subsequent failure of the ion pump occasioned the installation of a cryopump. Four gauges of each type were included in the study; two of each type could be isolated from the main system by an all-metal bakable valve. The latter gauges will be identified throughout this paper as "protected," the others as "unprotected."

The gauges were operated at 1-mA emission current with a 30-V filament bias, 180-V grid bias, and the collector at ground. The controllers used were designed and built at the NBS. These permit regulation of bias voltages to within 20 mV and emission current to better than 0.02%. All electrical parameters are measured with an uncertainty equivalent to less than 0.1% in the gauge sensitivity. The vacuum system and gauges were baked out at 230 °C at the start of the experiment and after two subsequent exposures to air. The gauges were degassed by resistance heating using 5 A through the grids after the initial bakeout. No additional outgassing was

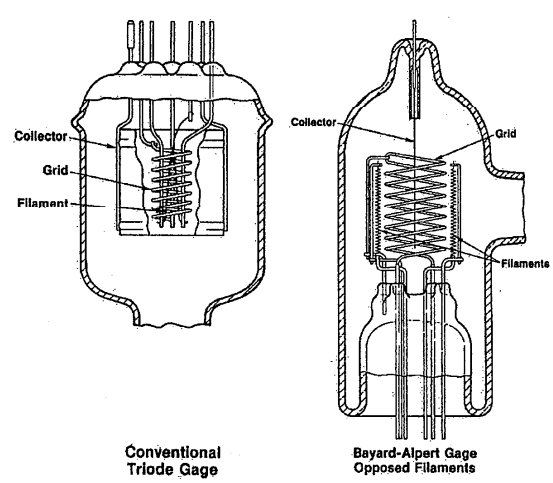

FIG. 1. Schematic of the two gauge types used for this test.

performed, although the gauges were operated during the subsequent bakeouts—a procedure we have found to be as effective or even more effective than standard degassing procedures.

The gauges were calibrated at the beginning of the test and up to 12 times thereafter with nitrogen between 10^{-4} and 10^{-1} Pa (1 Torr = 133 Pa). During the 500 days of the test, the gauges were operated continuously except for occasional interruptions totaling 20 days. One of the two filaments in each BA gauge was designated "primary" and the gauge was operated during more than 90% of the test on that filament. The second filament, designated "reserve" was used only during its calibrations, which immediately followed the calibration of the primary filament.

The ion gauges were calibrated at two points per decade, starting at the lowest pressure, over a period of about 4 h. After the highest point was finished, the system was pumped back down to base pressure, which was below 10^{-6} Pa nitrogen equivalent, and left there until the next experiment or calibration. Two spinning rotor gauges were used as calibration standards. The calibration constant of one was determined by the NBS primary high vacuum standard[10] with a total uncertainty of less than 1.5%. The calibration constant of the other was determined by an initial comparison with the first. Midway through the test, the calibrated spinning rotor was replaced with another which had just been calibrated against the high vacuum standard. With the exception of one calibration, where apparently an incorrect offset was used, comparisons of the pressure readings for the two spinning rotor gauges showed consistent agreement throughout the experiment to within $\pm 0.6\%$, except at the lowest pressures where random errors increased the limit of the differences to $\pm 2\%$. Thus, we believe the spinning rotor gauges provided a calibration reference stable to within $\pm 0.6\%$ at higher pressures, and $\pm 2\%$ at 10^{-4} Pa.

During the course of the test, the unprotected gauges were deliberately exposed to atmospheric air (filaments off) or extended operation with "high" (typically 5×10^{-1} Pa) nitrogen pressures. The protected gauges were maintained at a low pressure behind a bakable valve and served as a base line from which changes in the exposed unprotected gauges could be measured. All or part of the gauges were accidentally exposed to various perturbations caused by pump failure, electrical outages, etc. All of these deliberate experiments and accidental perturbations and their effects are discussed below. The experiment was unintentionally terminated by a system failure during bakeout. The operating filaments were burned out and the gauges were baked at 230 °C in air at some pressure well above their operating range for all or part of a weekend.

III. RESULTS

All results are presented in terms of ion gauge sensitivity, or sensitivity coefficient, S, where

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

I^{+} is the collector current at pressure P, I_{0}^{+} is collector current at base pressure P_0, and I^e is the electron emission current.

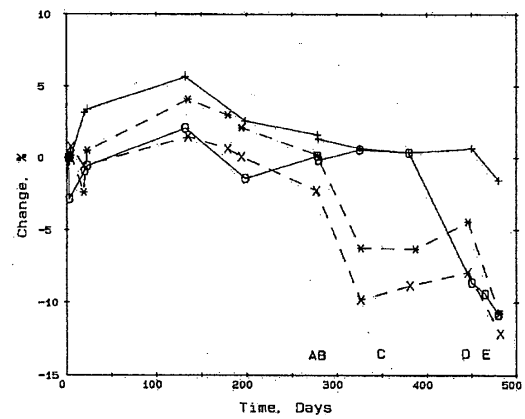

FIG. 2. Changes in the nitrogen sensitivities between 10^{-3} and 10^{-2} Pa as a function of time for the four CT gauges in this test. Protected gauges are indicated by solid lines, unprotected by dashed lines. Letters indicate specific changes in the operating environment that are discussed in the text.

As will be shown, the sensitivities were relatively constant with pressure, and therefore we have characterized the gauges by the average sensitivity obtained from the three calibration points between 10^{-3} and 10^{-2} Pa. Figure 2 presents the percent deviation of this average sensitivity from the first calibration for the four CT gauges as a function of time. Figure 3 presents this same data for the primary filament of all four of the protected BA gauges and the reserve filament for three of the BA gauges. Unfortunately, the reserve filament for one of the BA gauges was erratic throughout the entire test; control of the emission current was inadequate, and the sensitivity varied randomly by 10% or more. The data for this filament were not inconsistent with the other filaments, but the data were left out to improve the

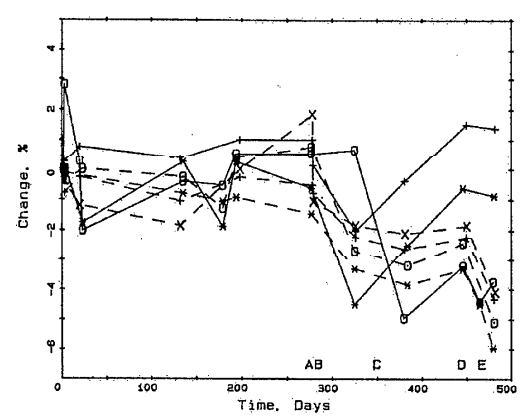

FIG. 3. Changes in the nitrogen sensitivity between 10^{-3} and 10^{-2} Pa as a function of time for the four BA gauges in this test. Protected gauges are indicated by solid lines, unprotected by dashed lines. Primary filaments are * and O, reserve are + and ×. Results for one reserve filament were left out to improve the clarity of the figure. Letters indicate specific changes in the operating environment that are discussed in the text.

clarity of the figure. The primary filament for this gauge was marginally less stable than the other gauges, and by the end of the test had deposited a visible coating on the gauge envelope not apparent on the other gauges.

The letters on the figures refer to specific experiments or incidents that will be explained below. Immediately apparent from the figures is the fact that the BA gauges were more stable than the CT gauges, that in both cases the sensitivity changes were rather small, and that for the BA gauges the changes were markedly smaller than the NPL results considering the 11 000 h of operation. It is also of interest that the BA sensitivities for the primary filaments varied no more than those of the reserve filaments, even though the former operated ten times as long as the latter.

From the beginning of the test the gauges were operated at base pressure except during the calibrations and occasional power interruptions. On day 275, indicated by *A*, a power transient caused the ion pump to cease operation but left the gauges on and operating at some unknown pressure above 10^{-1} Pa. The calibrations immediately following indicated no significant changes in the sensitivities. Starting on the 279th day, indicated by *B*, the unprotected gauges were operated for 10 days at a nitrogen pressure of 5×10^{-1} Pa. The protected gauges did not experience the high pressure. Unfortunately, immediately following this, and before the gauges could be recalibrated, the ion pump failed. Its replacement with a cryopump exposed the unprotected gauges to atmospheric air for 14 days. The calibration following this showed only a small decrease for the BA gauges, with the largest change occurring in one of the protected gauges. However, it is apparent from Fig. 1 that a significant decrease in sensitivity, about 6% occurred in the unprotected CT gauges.

On day 349, indicated by *C*, during a test and regeneration of the cryopump, the unprotected gauges were operated for 10 h at 5×10^{-1} Pa of helium. All gauges were then exposed to atmospheric air for one day while a recalibrated spinning rotor gauge ball was installed. The following calibration indicated a significant change only for the two protected BA gauges. Since these gauges were not operated with helium, and the other gauges exposed to air at the same time did not show a significant change, we do not have a ready explanation. On day 444, indicated by *D*, a power transient caused the cryopump to shut down and allowed the pressure to rise to 10 Pa before it was discovered. All of the gauges shut off except one of the CT gauges that was operated by a controller with a defective interlock. This gauge, previously protected from perturbations, showed a 9% drop in sensitivity at the next calibration. Starting on day 467, indicated by an *E*, the unprotected gauges were again operated at 5×10^{-1} Pa of nitrogen for 10 days, but not exposed to atmospheric air before the next calibration. All but one of the BA gauges decreased in sensitivity by about 2%–3%. The CT gauges decreased by 2% to 6%, with the protected gauges decreasing less than the unprotected ones. The last calibration of the CT gauges and the primary filaments of the BA gauges was on day 482.

In short, before failure of the ion pump and consequent high-pressure operation and exposure to atmospheric air, the operation of the BA gauges at base pressures or high nitrogen pressures, and their exposure to atmospheric air caused very little change. The small changes that we observed occurred almost equally for the primary and reserve filaments, indicating that the changes were associated with elements of the gauge other than the filaments. This was somewhat surprising since we have seen evidence from other gauges that changes in the filament with time cause significant changes in gauge characteristics.[4] The changes in the CT gauge were larger than those of the BA gauges, although still respectably small considering the long operating period. The CT gauge sensitivity does definitely seem to be decreased by high pressure operation, and there is some evidence of a limited recovery of sensitivity with continued operation at base pressure for the unprotected gauges between days 330 and 450. These results are significantly different from those of the NPL study.[9]

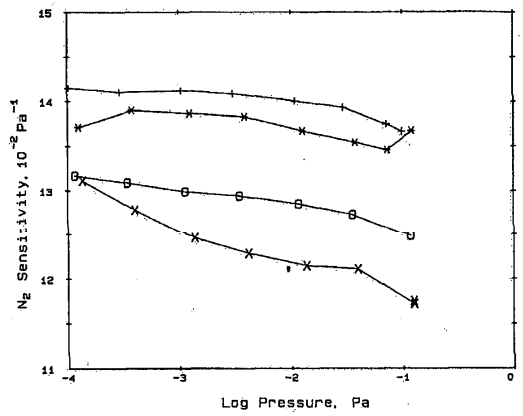

FIG. 4. Nitrogen sensitivities for one of the unprotected CT gauges during different phases of the test. Initial calibration, *; 180 days later, +; 325 days later after high-pressure nitrogen operation and exposure to air, O; last calibration before burnout of filament, ×.

Figure 4 illustrates a sequence of calibrations from the first to the last for one of the unprotected CT gauges. Apart from a small increase between the first and the second calibrations, the sensitivity decreases with time and the gauge becomes less linear as well. These results are quite typical for the CT gauges.

Figure 5 illustrates the initial and last calibrations for both filaments of an unprotected BA gauge, and, for the reserve filament, a calibration after baking at an elevated pressure and subsequent burnout of the primary filament. Again, these results are typical for the BA gauges. The initial calibrations generally showed a precipitous drop in sensitivity close to 10^{-1} Pa. After a period of operation this disappeared, or more likely, moved to higher pressure, and essentially constant sensitivity was observed for the unprotected gauges up to 10^{-1} Pa. For the protected gauges the sensitivity actually increased by 5% to 7% at higher pressures. As discussed earlier, the sensitivity of both filaments declined by a small amount during the test. After the high-pressure baking the sensitivity of the reserve filaments decreased by 10% to 20%. Subsequent calibrations after an additional 35

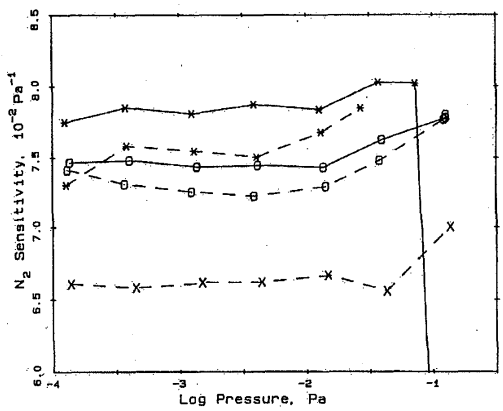

FIG. 5. Nitrogen sensitivities for one of the unprotected BA gauges during different phases of the test. Primary filament results are solid lines, reserve filaments are dashed. Initial calibration, *; last calibration before burnout of primary filament, O; calibration after high pressure baking, × (reserve filament only).

days of operation at base pressure showed virtually no change in sensitivity, except for one gauge which increased by 6%.

V. CONCLUSIONS

Although all gauges in this test showed smaller changes than we had expected for one and one-half years of operation, the BA gauges clearly showed less change in sensitivity than the CT gauges with time and operation. Thus, this particular type of BA gauge appears to be more promising in applications where stability is important, except at the highest pressures where the CT gauges had superior linearity. In this test the largest changes in gauge sensitivity appear to have been a result of operating or baking the gauges above 10^{-1} Pa.

We do not expect that our results are typical of all ion gauges. Even within our small sample one filament of one BA gauge was decidedly inferior to the others and, on the basis of shorter term tests, we would expect that other gauge types would show inferior long-term stability.[5] To put these results in perspective, we have observed day-to-day changes in sensitivity for thoria coated filament BA gauges that are comparable to those observed during 500 days for the BA gauges in this test.

Even for these well-behaved gauge types abuse can cause significant sensitivity changes, and even with the best of instrumentation, accurate results will be obtained only if the vacuum environment is controlled and understood. Confidence in gauge stability can be increased by periodically intercomparing with a check gauge. This will be more effective if the check gauge(s) is of proven stability and/or is protected from abuse or unnecessary use.

ACKNOWLEDGMENTS

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