Zero stability and calibration results for a group of capacitance diaphragm gages

Richard W. Hyland and Charles R. Tilford
Center for Basic Standards, National Bureau of Standards, Gaithersburg, Maryland 20899

(Received 24 January 1985; accepted 17 February 1985)

The lowest pressure which may be measured by a capacitance diaphragm gage is established by instabilities in the gage zero. In the systematic study of the stability of 14 different temperature-controlled gages we have observed that most of the instabilities are correlated with changes in room temperature. However, the magnitude of the changes for different gages differed by three orders of magnitude, underscoring the necessity for users to evaluate the stability of their own gages. We also observed small but steady zero drifts which extended over weeks, as well as occasional large, usually discontinuous, zero shifts that were precipitated by fast temperature changes. The most stable gage we observed changed by less than one part per million (ppm) of full range over periods of days; at the other extreme we have observed gages to change by 1000 ppm within an hour. At higher pressures the accuracy of gage readings will be determined in part by the long-term stability of the gage calibration factor. The calibration records for 17 gages, for which we have two or more calibrations separated by intervals on the order of 1 year, show shifts ranging from essentially no change to about 2% with an average value of 0.45%. With one exception, these do not appear as a steady drift with time, but as random shifts between calibrations.

I. INTRODUCTION

Capacitance diaphragm gages (CDG) are electromechanical pressure sensors in which the displacement of a stretched thin metal diaphragm is detected by a capacitance measurement. CDG's are configured either as absolute sensors with a sealed reference vacuum on one side of the diaphragm, or as differential sensors with pressure access to both sides of the diaphragm. The capacitance sensing technique results in a high degree of pressure sensitivity. Their design and construction provides the cleanliness and leak integrity required for many vacuum applications. These qualities, as well as little or no dependence of the gage reading on gas species, make these gages well, and in some cases uniquely, suited for many pressure measurements down into the high vacuum range.

In order to obtain the best performance from these gages, users need to know realistic lower pressure measurement limits and potential accuracies. The low pressure measurement limit of CDG's is seldom established by their sensitivities, but rather, by the instability of the zero reading. A measure of this instability can be obtained by applying "zero" pressure to the gage and monitoring the output as a function of time. At higher pressures the accuracy of CDG pressure measurements will be limited by the accuracy of the technique used for their calibration and variations in the gage calibration factor or response function with time. Calibration factor changes can only be determined by recalibration of the gage against a reliable standard.

We have systematically monitored the zero stability of 14 different CDG's on three occasions over the past 4 years. Evident from these tests are not only very large differences (up to three orders of magnitude) in the zero stability of different CDG's, but significant changes in the stability of individual gages over the time between tests. These data give a measure of the range and type of instabilities that might be expected, but users must monitor the stability of their CDG's in their environment if they are to realistically assess the low pressure performance of their gages.

We have also reviewed our calibration data for 17 CDG's for which we have repeated calibrations over period of weeks to years. Again, there are significant differences between individual gages. There do not in general appear to be steady drifts of the calibration factors, but rather random changes for which we have obtained an average value.

Although it is not the purpose of this paper to review low pressure calibration standards and techniques, we would like to note that a commonly used calibration technique for CDG's contributes errors as large as 2%–4% at absolute pressures below about 10 Pa (10^{-1} Torr, 1 Torr = 133.3 Pa). This is significantly larger than typical calibration factor instabilities. The technique involves the calibration of a differential CDG, generally using two piston gages, with a reference pressure between 1 kPa and atmospheric pressure. The reference pressure of the CDG is then reduced to zero so that the gage is effectively an absolute gage, which in turn is used as a transfer standard to calibrate other CDG's in the absolute mode. Apart from possible changes in the response of the differential gage when the reference pressure is changed, this technique makes no allowance for the low pressure thermal transpiration effects in heated sensors.[1] This effect will not appear in the "high" pressure differential calibration, but will have become significant for most gases for absolute pressure readings below about 10 Pa. As pressure is decreased farther, the error from thermal transpiration increases to 2%–4% of the reading, assuming typical differences between the CDG control temperature and system temperature.

II. DESCRIPTION OF THE GAGES

The CDG's discussed are commercially available gages from two different manufacturers with full-scale ranges of 1, 10, 100, and 1000 Torr. Common to all are welded sensors, lack of elastomers, and control of the sensor temperature between 35 and 45 °C. The complete gage consists of two or three components. The pressure sensor, pressure connections, temperature control, and part of the capacitance sensor electronics comprise a sensor unit. An electronics unit provides output amplification and range selection so that a full scale 10-V output is available for either 1, 0.1, 0.01, or, in some units, 0.001 times the full scale pressure range of the sensor. A third unit, used with some of the gages, allows the electrical outputs of up to three different sensor units to be multiplexed to a common electronics unit.

The importance of temperature stability for zero stability is readily apparent from our results. Therefore, we have categorized the gages by the type of temperature control and/or compensation employed. Gages referred to as type A employ a proportionally controlled heater wrapped directly around the sensor. Type B gages have the sensor and associated electronics mounted on a temperature-controlled thermal base and employ a compensating thermometer mounted near the sensor. Type C gages enclose the sensor in a cast aluminum shell on which is mounted a proportionally controlled heater. The sensor and electronics are enclosed in an outer cast aluminum shell. Type C gages also employ a temperature sensor mounted near the sensor for temperature compensation.

III. ZERO STABILITY TESTS

The three different zero stability tests ran for periods of between 3 and 7 weeks and involved ten differential and four absolute gages. The two pressure ports of the differential gages were either connected together at atmospheric pressure, or, as were the absolute gages, maintained at a pressure of about 10^{-5} Pa by ion pumps. Flexible tubing or bellows connectors were used to minimize mechanical strains at the gages. The gages were situated in close proximity to one another in order to minimize environmental differences. The outputs of the gages were monitored in the earliest test on strip chart recorders, and in the later tests by a digital data acquisition system which was monitored for voltage stability and found to make a negligible contribution to the observed instabilities. Because of the effects of temperature changes on gage stability evident during the first test, room temperature and the sensor temperatures of selected gages were monitored during the second two tests using platinum resistance thermometers. The room temperature thermometers were mounted near the gages in small aluminum blocks. The blocks were intended to approximate the thermal mass of the gage sensors.

The sensor zero adjustments, which compensate for changes in the sensor diaphragm and electronics, were set at the beginning of the tests and not changed thereafter. The zero and full scale adjustments, which correct only for electronic drifts, were periodically reset. These changes are relatively small compared to sensor drifts and the user can readily make these adjustments at any time.

The gage outputs were monitored for one or more days from a cold start with the temperature control left off. The temperature controls were then turned on and monitoring continued.

IV. ZERO STABILITY RESULTS

The results presented here are from the last two of the three zero stability tests. However, the results of the first test are consistent with those of the later two. In order to compare results for different range gages we present the zero instabilities for each gage as fractional parts of the full pressure range of that gage. Zero instabilities can be somewhat arbitrarily categorized into three types: random noise, drift, and discontinuous shifts. Random noise includes, but is not confined to, the short-term (seconds) noise obvious to anyone observing a CDG output. We will not be much concerned with short-term random noise since it is generally relatively small and can be readily reduced by filtering or averaging. The relative importance of the other contributions depends in part on the times between sensor zero checks. Therefore, where possible, we give a measure of the time span associated with different changes.

V. EQUILIBRATION AFTER TURN ON

Significant periods of time must be allowed after turn on from a cold start for the gage temperature to equilibrate and the gage output to stabilize. Even operating without temperature control, which may be desirable in certain applications, there is a significant sensor temperature increase caused by heat generated by the electronics mounted within the sensor enclosure. We found the increase for the type A and type B sensors to be about 0.5 °C; for the type C sensors it was 1.5 °C. A warmup period of about 4–10 h was required before a nominal temperature equilibrium was reached.

When the temperature control systems are turned on, the A and B gages again attained nominal temperature equilibrium in 4–10 h, while the type C gage required a somewhat shorter period. The temperature changes cause changes in the gage zeros which moderate as temperature equilibrium is achieved. However, significant drifts in the zeros may persist well after temperature equilibrium is reached. While the characteristics differ from gage to gage, typically several days are required for the output to stabilize. During this period we have observed changes as large as 400 ppm of full scale after temperature equilibrium was reached. For some gages, including some that eventually were found to be the most stable, we have observed steady monotonic drifts that persist for weeks after warmup. We have also observed that gages turned off for short periods (minutes) after being on for weeks, may, when turned back on, require times as long as a day before returning to their former equilibrium zero. Thus periodic checking of the zero reading is particularly important when a gage has just been turned on.

VI. ZERO PRESSURE STABILITY

As will be seen below, room temperature variations have a significant effect on CDG zero stability. The CDG temperature control systems are intended to reduce these effects, which they do with varying degrees of success. During intentional large (3–7 °C) perturbations of room temperature, we have found the CDG sensor temperatures to track the room temperature changes, but with the magnitude of the change reduced by about a factor of 3–5 for type A and B gages, and by a factor of 15 for type C gages.

We have found significant differences between the manufacturer-specified CDG control temperature and actual temperatures when operated in a 23 °C environment. The type A and C gages are specified to operate at 45 °C, type B gages at 40 °C. We have found that the A and B gages operate between 35 and 39 °C, and the type C gages at 43 °C. While of no direct concern for gage stability, this difference from specified temperature could be of consequence when measuring condensable gases or calculating thermal transpiration corrections.[1]

It is clear from our tests that the stability of the gage output depends on more factors than just the stability of the sensor temperature. We show this in Fig. 1 which illustrates the room temperature as a function of time during an intentional perturbation, as well as the corresponding outputs of three gages chosen to illustrate different characteristic behaviors. These data were obtained in 1984, during the last of the three tests. The connected dots are the output of a 10-Torr type A gage. The correlation of this output with temperature is obvious. This highly correlated response is typical for type A gages, although, as discussed below, the magnitude of the response varies greatly from gage to gage.

The output of a 1-Torr type B gage (o) and the output of a 1-Torr type C gage (x) are also shown. We see some variant of these temperature responses for type B and C gages although both the magnitude and the shape of the response will vary, not only from gage to gage, but from time to time for a given gage. We believe that this is because both gage types employ thermal compensation sensors so that the thermal response depends not only on the matching of the thermal sensor and

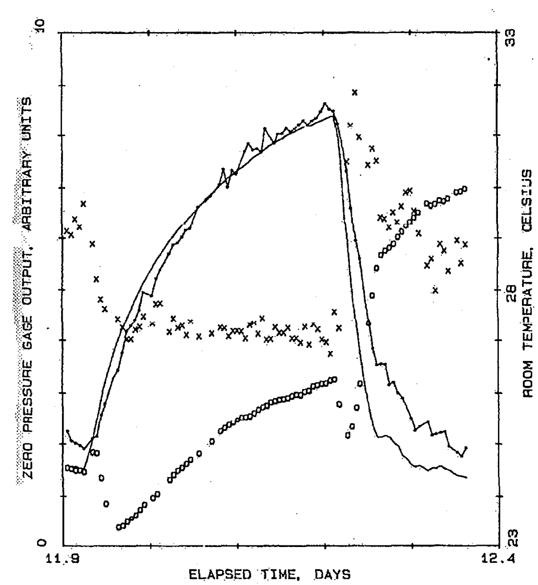

FIG. 1. Three different gage outputs during a large perturbation of room temperature. The solid line is the temperature. The connected dots are for a type A gage, the circles are for a type B gage, and the x's are for a type C gage. The extent to which these responses are typical of different gage types is discussed in the text.

the temperature coefficient of the pressure sensor, but also on their thermal time constants and the rate of change of temperature. The transients or offsets seen in Fig. 1 at the beginning and end of the temperature perturbation generally appear in our data during rapid temperature changes.

The upward trend of the type B gage output after the end of the temperature perturbation is the beginning of an extended drift. This is an example of temperature change induced instabilities that we have often observed for type B gages and on a number of occasions for type A gages as well.

The gage outputs illustrated in Fig. 1 are not plotted on the same scale. This particular type A gage, the most stable CDG we have tested, is plotted 1.5 ppm full scale. Changes of other type A gages during the same time were as much as 1200 times greater. The type C gage is plotted 100 ppm full scale, while that of the type B is 1500 ppm. As will be seen below, the magnitude of the temperature response also varies from gage to gage for the B and C gages. And for any given gage it may change significantly as a function of time. As an example, the temperature response of the type A gage illustrated in Fig. 1 was two orders of magnitude larger when the gage was monitored during the second text in 1983.

For gages showing a consistent response to temperature changes, it is reasonable to compute a temperature coefficient. This has been done for the type A gages, using the change in gage output divided by the change in temperature during intentional perturbations of the room temperature during both the 1983 and 1984 tests. The results are given in Table I. Such a temperature coefficient has much less meaning for type B and type C gages, since the compensating thermometers cause responses which are much more dependent on the rate of temperature change. We have nonetheless, for comparison purposes only, computed in a similar manner a temperature response for type B and type C gages and included the results in Table I. Those values are enclosed in parentheses. Blanks are left where data were not obtained in a particular test. Also tabulated are standard deviations of the gage outputs, which we use as a comparative measure of gage instabilities. These standard deviations were obtained by selecting a period of approximately 1 week, well after the turn on and warm up period, when discontinuous changes in gage outputs were not observed. Room temperatures were typically stable to within ± 0.2 °C over a day's time except for 1 °C changes at the beginning and end of weekends. The data were divided into successive 6-h intervals, standard deviations computed for each interval, then averaged for the entire period to obtain the 6-h data in Table I. A similar procedure was followed for 24-h intervals, and a 7-day standard deviation was computed from all of the data.

Immediately apparent from Table I are the large differences in gage instabilities. One can also see a correlation between the 6-h standard deviations for different gages and their corresponding temperature coefficients, or temperature responses, particularly for the type A gages. Although the 6-h standard deviations differ by as much as a factor of 600, the 6-h standard deviation divided by the temperature response differs by less than a factor of 4 for the type A gages, and by less than a factor of 10 if the type B and type C gages are included. Examples can be seen in the data for large in-

TABLE I. Temperature coefficients and instabilities of different CDG's.[a]

Gage type range	Temp. coeff. ppm/K		Standard deviations, ppm full scale 6 h		24 h		7 days	
	1983	1984	1983	1984	1983	1984	1983	1984
A1	15	154	2.2	18.3	4.9	24	11.4	44
A1	34	−97	3.0	8.8	5.2	11.7	11.7	13.8
A10	16	0.13	3.0	0.03	6.0	0.06	19.0	0.16
A10	26.4	...	3.8	...	5.6	...	8.7	...
A10	9.0	...	1.4	...	2.9	...	7.7	...
A100	10.2	...	1.8	...	3.7	...	16.8	...
A100	25	...	8.5	...	13.1	...	18.8	...
B1	(79)	(85)	18.5	22.8	23.7	36.4	27.8	66.6
B1	(7.1)	...	10.7	...	13.8	...	49.8	...
B10	(21)	(3.6)	12.5	2.6	16.1	3.4	18.4	8.1
C1	...	(2.7)	...	2.8	...	3.5	...	9.5
C100	...	(1.6)	...	1.1	...	3.1	...	20.0
C1000	...	(7.0)	...	1.7	...	2.2	...	2.8
C1000	...	(1.2)	...	0.7	...	2.2	...	14.0

[a] Gage type, and range in Torr, are given in the first column. The next two columns give the temperature coefficients or temperature response (in parentheses). Standard deviations in ppm of full scale, obtained with zero applied pressure, are given over different time periods to illustrate the general correlation of short-term (6 h) instabilities with temperature coefficients or responses. Standard deviations obtained over longer periods indicate the increased instability arising from drifts. The first A10 listed is the type A gage of Fig. 1.

creases of the standard deviations for individual gages in increasing from 6-h to 24-h to 7-day periods. This is largely because of long-term drifts, which are not necessarily linear or even monotonic. This illustrates the increased gage instabilities that can be expected as the time between zero checks is extended, although the relative importance of short- and long-term instabilities varies from gage to gage. As an example, the 10-Torr type A gage illustrated in Fig. 1 has a relatively larger increase in standard deviation in going from 6-h to 7-day periods because the exceptional stability of this gage over 6 h allows us to observe a small 7-day drift which is large relative to its own instability, but insignificant when compared to the instabilities of the other gages.

In addition to temperature correlated instabilities, we have also observed other types of instabilities which in some cases may be precipitated by temperature changes. Figure 2 includes the outputs of two different CDG's chosen to illustrate different instability modes over a common time period. The o's represent the output of a 1-Torr type A gage. The initial data show the drift caused by turn on and warm up. This is followed by smaller changes correlated with temperature changes (this gage has a negative temperature coefficient). At 11 days a discontinuous shift precipitated by a room temperature perturbation is evident. We have observed similar shifts for most of the A and B gages. We have observed this type of shift for type C gages as well, but the magnitudes are significantly smaller, typically 10 ppm of full range or less. We are unable to correlate the large upward drift evident at the end of the data with any known perturbation. Again, at the beginning of the data for a 10-Torr type A

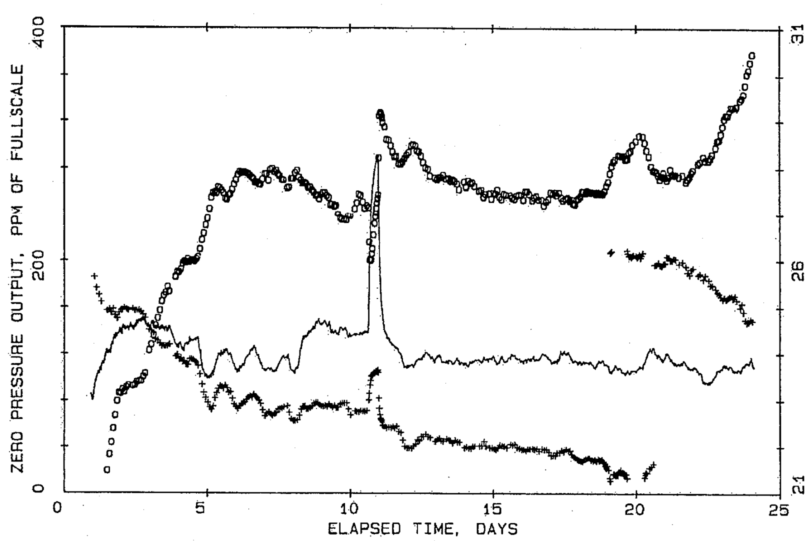

FIG. 2. Room temperature (solid line) and the zero pressure outputs of two type A gages, illustrating different zero instabilities observed in the three gage types. These include extended warm up drifts (all three types), smaller variations correlated with temperature (A and B), baseline drift (A, B, and C), discontinuous changes after temperature transients (A, B, and C), and discontinuous shifts apparently due to electronic instabilities (A). The illustrative examples are a 1-Torr type A(o) and a 10-Torr type A(+).

gage (+) shows the end of the warm up drift. Also evident are smaller continuous changes which are highly correlated with temperature. After 5 days a continual baseline drift is evident. We have observed these drifts for all three types of gages, although the magnitudes and directions vary. However, the shifts at the end of the figure which, on an expanded time scale can be seen to be a series of shifts, are somewhat unusual. Similar shifts occurred at precisely the same time for a second gage, not plotted, that was operated on the same multiplexer unit. The suspicion that these shifts may be due to a malfunction of the multiplexer unit is reinforced by the observation that a third gage on the multiplexer exhibited similar shifts at a later time.

We have occasionally observed shifts in pressure readings which can amount to 0.1% of reading when the range multiplier in the electronics units is changed. The user should check to see if zero readings and pressure readings are consistent when the range multiplier is changed. In addition, it is not unreasonable that significant zero shifts will occur if the sensor is pressurized beyond its range. Zero checks after such an occurrence are a reasonable precaution.

VII. EVALUATION OF CALIBRATION FACTOR STABILITY

At higher pressures the accuracy of gage readings will be largely determined by the accuracy of the calibration standard and the stability of the gage response. In our experience, CDG gage responses are typically stable to within 0.1% or better over periods of days or even weeks. However, over longer times, much larger shifts are typical. We have obtained a measure of this long-term stability by examining the calibration records of a number of CDG's calibrated against an NBS primary standard that is an extended range version of a high resolution mercury manometer previously described.[2] This standard has a total uncertainty of 0.01% at pressures considered here, with a long-term (on the order of years) reproducibility of better than 3 ppm at higher pressures.

Some of the CDG's studied are used within the NBS pressure and vacuum group, some have been used as comparison artifacts between the NBS and other national standards laboratories, and some are used by industrial standards labs as calibration or transfer standards. Some, but not all, of the low range gages were equipped with isolation valves to protect them from pressures beyond their full range. A few were hand carried to NBS for calibration, but most were shipped by commercial carriers. For the industrial transfer standards, and to a lesser extent for the international transfer gages, we do not know the entire history of the instruments, and the concern exists that the manner of use could influence the stability of the instruments. We do see larger shifts for the type A gages used in industrial labs compared to those used chiefly by NBS, but our data are too limited to determine if this difference is significant. We see no such difference for the type B gages. Overall, we expect that the use of these gages by standards laboratories, whether industrial or national, typifies careful treatment and that the calibration results are characteristic of CDG performance under "good" conditions.

Before each calibration, gage zeros were checked and set. Scale factor or spans were not adjusted. All gages were calibrated in the absolute mode.

VIII. CALIBRATION FACTOR STABILITY RESULTS

Figure 3 shows the calibration curves obtained at the NBS over a period of 4 years for a 10-Torr type A differential gage. This gage was one of a set of four CDG's that were used to compare NBS standards with another national standards laboratory. After installation, this gage, and the other gages of the set, were protected at all times from pressures above their full scale ranges. The calibrations are represented as correction factors, the ratio of the pressures measured by the standard to those indicated by the gage. The results are presented down to only ~ 100 Pa (1 Torr) for clarity's sake, since large changes (2%–4%) in the correction factor occur in the thermal transpiration range.

The results shown in Fig. 3 are typical of most CDG's with respect to the magnitude of the calibration factor shifts illustrated and the lack of any apparent linear or even monotonic drift with time. However, if we try to correlate the shifts with handling of the gages we do not see a consistent pattern. For example, the results in Fig. 3 were for a gage shipped overseas and back in the interval between the August 1980 and the March 1981 calibrations, and again between the August 1981 and December 1982 calibrations. For this gage relatively large shifts were observed after the shipping while a shift of less than 0.1% was observed between March and August of 1981, during which time the gage never left our laboratory. However, another gage, shipped and handled at the same times and in the same manner, showed small ($\sim 0.1\%$) changes after shipment, but changed by 0.7% between March and August of 1981. As a further example of our inability to correlate calibration

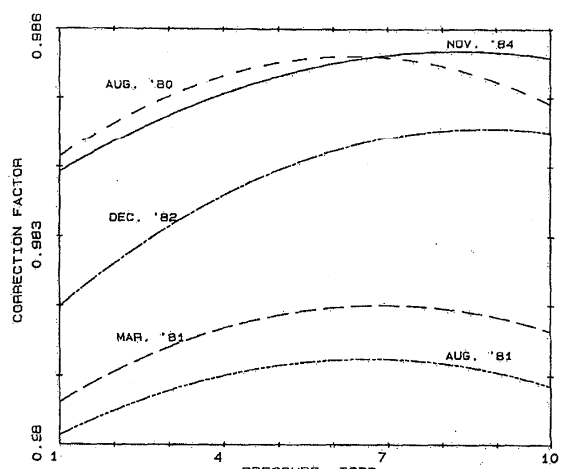

FIG. 3. Least-squares curves fitted to the ratio of the true to the indicated pressure obtained for a 10-Torr type A gage calibrated at NBS on the indicated dates. The magnitude of the changes and lack of a linear or monotonic drift with time are typical of results obtained for both type A and B gages. The scatter of the data to which these curves were fit is characterized by a standard deviaiton of 0.01% or better. This is a measure of the gage instability over the 4–6 h required for a calibration.

TABLE II. Percentage shift at midrange of different CDG's calibrated in the absolute mode at NBS.

Range (Torr)	Configuration[a]	Change (%)	Time (years)	Range (Torr)	Configuration[a]	Change (%)	Time (years)
	Type A				Type B		
1	D	−0.16	0.6	1	D	+0.91	0.6
		−0.10	0.4			−0.68	0.4
		−0.30	1.3			0	1.3
		+0.05	1.9			−0.11	1.9
1	A	−2.02	2.1	10	D	+0.42	0.6
						+0.86	0.4
1	A	−1.72	2.8			+0.11	1.3
						−0.11	1.9
1	D	−0.50	3.2				
				10	D	+0.29	4.5
10	D	−0.36	0.6				
		−0.07	0.4	10	D	−0.59	3.8
		+0.28	1.3				
		+0.12	1.9	10	A	−0.57	1.8
10	A	−0.69	2.8				
		+0.99	2.3				
10	A	−0.15	2.1				
10	D	−0.45	3.2				
100	D	+0.24	2.2				
100	D	+0.07	0.8				
100	D	+0.10	2.3				
1000	D	+0.86	1.5				
1000	A	+0.05	1.0				

[a] Range in Torr and configuration (absolute—A or differential—D) are indicated along with the interval between calibrations. The average magnitude of the shifts for type A gages is 0.46%; average for type B gages is 0.42%.

shifts with treatment of the gages, we have accidentally overpressured a CDG in our laboratory beyond specified limits, but found it to repeat its calibration to within 0.07%, an order of magnitude better than the stability observed for some other gages treated in an exemplary manner.

Prudence dictates that gages should be protected from the rigors of shipping as much as possible, and, if possible, not subjected to pressures beyond their range. However, our experience to date indicates that CDG's are typically subject to calibration shifts that are random in sign and magnitude but which cannot be correlated with obvious perturbations.

Table II summarizes the results of repeated NBS calibrations of 18 different type A and type B gages. Repeated calibrations are not yet available for type C gages. The results are presented as the percentage differences at the midrange pressure between successive calibrations, along with the time between calibrations. Apparent from the table are the large differences in the shifts observed for different gages (from near 0%–2%), and the random nature of the shifts for individual gages at different times. The average magnitude of the shifts tabulated in Table II for the type A's is 0.45%, and for the type B's is 0.42%. These numbers are consistent with the instabilities reported by other standards laboratories for times on the order of a year. Poulter[3] of the National Physical Laboratory, Teddington, England, has observed 0.4% long-term instability. Reich[4] quotes 0.3% as the long-term stability given by the Physikalisch-Technische Bundesanstalt, Berlin, West Germany. An analysis of the calibration records for 12 type A CDG's over times of up to 11 years obtained by Taylor[5] of the Sandia Primary Standards Laboratory showed shifts ranging from 0.01% to 1.3% with an average shift of 0.40%. This average included 21 differences between successive calibrations with typical times between calibrations of 12 to 15 mos.

IX. CONCLUSIONS

The large differences in zero stability for different CDG and the changes in the zero stability with time for a particular gage, make it imperative that users monitor their own gages to obtain stability estimates. Monitoring should continue for long enough periods to allow for extended warmup drifts and occasional discontinuous shifts. Errors arising from zero drifts and shifts can be minimized by frequent ezeroing. The appropriate interval will be determined by he requirements of the user and the stability of the gage ised. Attention should be paid to providing a stable thermal nvironment since temperature instabilities are the major, although not the sole, source of zero instabilities. The user nay choose to forgo the built-in temperature regulation and control the gage at system temperature. This has the advantage of eliminating thermal transpiration effects. Variations of the calibration factor with temperature should be taken nto consideration, although these are generally rather small.

The calibration factors can vary significantly over periods of a year or less. Therefore, users should compare their accuracy requirements with the observed instabilities reported here and plan recalibration intervals accordingly. Confidence in CDG stability can be increased if more than one gage is employed and the gages periodically intercompared. Changes in the relative indications mean that one or both gages have changed. No change in the relative readings increases the probability that neither gage has changed. Users should also be cognizant of possible significant calibration errors below 10 Pa (0.1 Torr) absolute for most CDG's, arising from linear extrapolations of calibration curves into the thermal transpiration region.

ACKNOWLEDGMENTS

We appreciate partial support of the work by the Office of Fusion Energy, Department of Energy. We thank Warren Taylor of Sandia National Laboratory for making available numerous CDG calibration records.

[1]K. F. Poulter and P. J. Nash, Vacuum 33, 311 (1983).

[2]P. L. M. Heydemann, C. R. Tilford, and R. W. Hyland, J. Vac. Sci. Technol. **14**, 597 (1977).

[3]K. F. Poulter, Le Vide **207**, 521 (1981).

[4]G. Reich, in *Proceedings of the Ninth International Vacuum Congress*, Madrid, Spain, edited by J. L. de Segovia (Imprenta Moderna, Madrid, 1983), p. 195.

[5]Warren Taylor (private communication), Sandia National Laboratory, Albuquerque, NM.