SRS Bayard-Alpert Gauge Calibration Service

Stanford Research Systems has established a High Vacuum Calibration Facility to generate high-accuracy, NIST-traceable, full-range calibrations for any new BAG operated with an SRS IGC100 controller. Two accuracy levels are available: a 6% accuracy full-range calibration and a high-precision 3% accuracy full-range calibration.

All calibration information generated at the SRS High Vacuum Calibration Facility is returned to the user in a 'memory card' that can be used to transfer the calibration data, including all necessary instrument setup information, into any IGC100 controller. With the calibration data transferred into the controller, any IGC100 can accurately measure and display unknown pressures in real time over the entire useful range of the BAG.

In This Application Note

Introduction

The calculation of pressure with a Bayard-Alpert gauge (BAG) relies on the knowledge of the gauge sensitivity factor, S_g, which is strongly dependent on (1) gauge geometry, (2) gas type and, to a lesser extent, (3) pressure and (4) emission current[1]. Once the sensitivity factor is known, the pressure, P, is calculated from the simple mathematical expression:

$$P = [\, I_c / (S_g \cdot I_e)] \qquad \text{(eqn. 1)}$$

where

S_g is the sensitivity factor for gas g [$Torr^{-1}$]

I_c is the ion collector current [amps]

I_e is the electron emission current [amps]

Sensitivity Factor

A common approximation, used by most ion gauge controllers, is to treat the gauge sensitivity factor as a constant, independent of pressure and electron emission current. A single sensitivity value, known as the sensitivity constant, is used to calculate and display pressures over the entire operating range of the BAG while ignoring pressure-induced non-linearities in the gauge response.

The sensitivity value stored in most controllers is the 'nominal' sensitivity constant, as specified by the manufacturer, for the specific gauge model connected to the controller. Nominal sensitivity constants are statistical averages calculated at mid-range ($\approx 10^{-6}$ Torr, typical) for nitrogen gas. Unfortunately, relaxed manufacturing tolerances cause large spreads of individual gauge sensitivities around their nominal value - i.e. no two commercial tubes have close to the same actual sensitivity even if they seem identical to the eye. As a result, only 'rough' pressure measurements can be obtained when nominal sensitivity constants are applied to pressure calculations.

Gauge-to-gauge variation in sensitivity constants is the biggest source of errors in ionization gauge pressure measurements. In order to avoid this source of error, the sensitivity constant for the *individual*, *specific gauge* connected to the controller must be known or obtained. A simple approach, used by some high vacuum practitioners, is to calibrate the gauge response at mid-range against a certified pressure standard and store the calibrated sensitivity constant in the controller. Alternatively, high-accuracy gauges with improved gauge-to-gauge reproducibility and well-known mid-range (nominal) sensitivity constants have recently become commercially available. Calibrated sensitivity constants can provide accurate results only at pressures below the upper limit of linear response. For most commercially available gauges, this upper limit is dependent on the gauge design and starts at $\approx 10^{-5}$ Torr.

In addition to gauge-to-gauge variations and pressure dependent non-linearities, BAG measurements are also affected by several aging mechanisms responsible for changes in

gauge sensitivity with operating time. Aging mechanisms affect the long term stability, accuracy and reproducibility of BAG pressure readings.

Full-range calibration

Full-range calibration of the BAG response, over the entire useful pressure range of the gauge, is the only sure way to effectively, and simultaneously, eliminate reading errors caused by (1) gauge-to-gauge variations, (2) pressure non-linearities and (3) aging-related instabilities. Full-range calibration is generated by comparison of the gauge response against a certified primary or transfer standard at many points spanning the entire useful pressure range. Typical transfer standards are NIST-traceable (1) spinning rotor gauges (SRGs) or (2) high-accuracy BAGs. The gas-dependent full-range calibration is often represented as a collection of sensitivity factors calculated at representative values of standard pressure at a known emission current. The IGC100 can store full-range calibration curves in its memory and use them for accurate, real time, pressure determinations across the entire useful pressure range of the gauge. Most other commercial controllers require the user to correct the displayed pressure readings outside the box, based on the manual interpolation of pressure-dependent correction factors derived from the full-scale calibration data.

The effect of pressure on gauge sensitivity has generally been ignored because its contribution to pressure measurement errors is small compared to the inaccuracies and instabilities caused by the electronics of conventional ion gauge controllers. This is also the reason why most calibration facilities require that the specific controller used for the actual measurements, be connected to the gauge during calibration. However, the BAG technology is rapidly evolving. High-quality controllers, such as the IGC100, can now provide stable and reproducible bias voltages, emission currents and electrometer readings that do not contribute to pressure display errors. The improved performance of these modern instruments, makes the presence of the specific controller unnecessary during the BAG calibration procedure.

The typical long term stability for the readings of a conventional BAG (as quoted by most High Vacuum Calibration Facilities) is between 1% and 6% per 1000 hours of accumulated operating time, but is strongly dependent on (1) operating environment, (2) gauge history, (3) gauge design, (4) gauge construction, and (5) filament material[2]. For a carefully treated ion gauge of high quality, a value of 3-6% over a one year period may serve as a reasonable estimate of its instability for this period[3]. The sensitivity value generally declines with time.

Note

High-accuracy gauges, with claims of improved long term stability, have only recently become commercially available[4] and no independent studies on their long term behavior have yet been reported.

Who Needs to Calibrate a BAG?

Different applications require different levels of accuracy. For many applications, the rough results provided by a pressure calculation based on the nominal sensitivity constant are sufficient. Mid-range accuracy: 25% at best, and worse above 10^{-4} Torr.

BAG accuracy can be easily improved by calibrating the mid-range gauge response against a certified transfer standard (i.e. NIST-traceable BAG or SRG) and storing a calibrated sensitivity constant in the controller. Even then, accurate readings are only possible below the upper limit of linear response - typically in the 10^{-5} Torr range. Mid-range accuracy: better than 15% under 10^{-4} Torr, but much worse at higher pressures.

In order to improve the accuracy over the *entire* useful pressure range of the gauge, full-range calibration against a certified pressure standard is required. Gauge sensitivity values calculated at several different reference pressures are then used to calibrate actual gauge response as a function of pressure. Mid-range accuracy: as good as ≈2% if calibration is performed against a primary standard, and ≈3-6% for calibrations performed against NIST-Traceable secondary standards.

Important

The accuracy of BAGs is ultimately limited by their intrinsic short-term repeatability which, for most conventional BAG designs, is between 1% - 2% (based on day-to-day random sensitivity variations).

Typical high vacuum applications requiring the accuracy of full-range calibrations include:

1. ISO 9000 applications requiring standards lab certification.
2. MIL-SPEC type applications requiring MIL-STD-45662A certification.
3. Government contracts requiring standards lab certification.
4. Transfer standards.
5. Process Control applications.
6. Basic vacuum technology research.
7. Scientific and research projects with tight pressure control requirements.
8. Measurement of fundamental physical parameters.

As a rule-of-thumb, accuracies better than 50% over the entire operating range of a BAG can only be assured through full-range calibration.

Every process engineer knows that vacuum conditions significantly affect yield. In the right process application, a calibrated BAG will generally result in increased throughput and yield and will pay for itself very quickly. For example, in semiconductor processing, an overestimated sensitivity constant could lead to high pressures that could then cause serious defects. On the other hand, an underestimated sensitivity constant could make

operators waste valuable time while achieving pressures lower than necessary. Both scenarios could be very costly!

Gauge calibration will often provide the lowest total cost-of-ownership (COO), even if the added gauge cost seems hard to justify at first!

A BAG with a specific calibration traceable to a standards lab (i.e. NIST) can provide a convenient in-house reference gauge, ideal for all work requiring certification. It is the only cost effective way to meet ISO 9000 requirements and be compliant with the MIL-STD-45662A standard.

Calibration Storage in the IGC100

The IGC100 controller has the capability to store in a full-range calibration curve and a sensitivity constant (for nitrogen[5]) for each BAG connected to its back panel. An intuitive, front-panel menu selection allows the user to switch between the two calibration sources during pressure measurements.

IGC100 users can have their ionization gauges calibrated at the certified SRS High Vacuum Calibration Facility. The BAG response is calibrated below 10^{-3} Torr by comparison against a NIST-traceable secondary standard and the information is stored in a Memory Card (Calibration Card) that is returned to the user with the gauge. The calibration curve, including all relevant instrument setup information, can then be easily transferred into the controller using the Memory Card Module on the front panel of the instrument.

Since all IGC100 instruments offer identical electrical performance, calibrated gauges can be operated from any IGC100 controller without any significant change in the accuracy of the results. For the same reason, the actual IGC100 controller used for real measurements does not need to be present at the SRS High Vacuum Calibration Facility during the calibration procedure.

To obtain the highest degree of accuracy, BAGs must be calibrated directly at a National (or International) Standards Laboratory against a primary high-vacuum pressure standard[6]. The Calibration Report, supplied by the standards laboratory, can be submitted to the SRS High Vacuum Calibration Facility to have the calibration data transferred into a Memory Card compatible with the IGC100 controller. A nominal fee is charged for this procedure. Consult SRS directly for additional information on this alternative calibration option.

Warning

Although BAGs calibrated against primary standards offer the highest measurement accuracy (<2%), the cost of calibration can be excessive for most applications (>$4,000 per tube), and the turn-around time is usually very long. Full-range calibration against a NIST-traceable secondary standard, as provided by the SRS High Vacuum Calibration Facility, offers a very significant cost advantage, very fast response, and sufficient accuracy for most applications.

The IGC100 uses full-range calibration data to display accurate pressure readings in real time without the need for pressure-dependent corrections outside the box. The estimated

expiration date for the gauge calibration is stored in the memory card and transferred to the controller along with the rest of the calibration information.

Although in principle it should be possible to calibrate a gauge for one gas and use this calibration for another by simply multiplying by the corresponding gas correction factor, investigations have shown that this is not the case if high accuracy (<10%) is required. Specific calibration for each specific gas is recommended in that case.

SRS High Vacuum Calibration Facility

Stanford Research Systems has established a High Vacuum Calibration Facility to generate high-accuracy, NIST-traceable, full-range calibrations for any new[7] BAG operated with an IGC100 controller. Two accuracy levels are available: a 6% accuracy full-range calibration and a high-precision 3% accuracy full-range calibration.

BAGs are calibrated by the direct comparison method in a continuous flow calibration chamber[8] following the recommendations of well-established calibration standards[9] laboratories. During a calibration procedure, the test gauges and a reference gauge (NIST-calibrated secondary standard) are all exposed to a identical pressure environments in a carefully designed high-vacuum chamber[10]. The sensitivity of each test gauge is calculated, at specified pressure values of the reference gauge, using the well-known formula:

$$S = (I_c - I_{c0}) / [\, I_e \cdot (P - P_0)] \qquad \text{(eqn. 2)}$$

where

P_0 = pressure due to residual gases in the chamber as measured by the reference gauge.

P = pressure due to the residual gases plus the calibration pressure step generated by the gas delivery system, as measured by the reference gauge.

I_c = collector current at pressure P.

I_{c0} = residual collector current at residual pressure P_0.

I_e = emission current measured on the anode.

All calibrations start with a determination of I_{c0} and P_0 at base pressure, following an extensive overnight bakeout (>200°C) of the chamber and test gauges[11]. No return to base pressure takes place throughout the course of the calibration procedure[12].

Full-range calibration requires the determination of sensitivity constants at specified reference pressure set-points between 10^{-7} and 10^{-3} Torr. Three calibration points per decade are obtained over this range. The reference pressure readings must be constant to <0.5% for 5-10 minutes before any measurements can take place at a setpoint. The measurements are performed in a sequence of increasing pressures. The calibration information is represented as a table of calculated sensitivity factors (eqn. 2) vs. measured collector currents[13], in order of increasing reference pressure. Following the

standard, the sensitivity factor is assumed a constant below the lowest calibration pressure.

The time required to complete the process, and the accuracy requirements on the test equipment used, depend on the accuracy of the calibration. This is the reason, 6% accuracy calibrations are more affordable than the high precision (i.e. 3% accuracy) option.

Note

When the sensitivity is calculated according to eqn. 2, the residual current in the BAG caused by outgassing, ESD and X-ray limits is subtracted from the signal. When the gauge is in use, its residual current (or the equivalent pressure reading) must be subtracted from the signal as well to generate accurate results.

The standard calibration gas used at the SRS High Vacuum Calibration Facility is nitrogen. Calibration against other gases is possible by special order only. Consult Stanford Research Systems for details on this service.

All calibration information generated at the SRS High Vacuum Calibration Facility is returned to the user in a Memory Card that can be used to transfer the calibration data, including all necessary instrument setup information, into any IGC100 controller. With the calibration data transferred into the controller, an IGC100 can accurately measure and display pressures in real time over the entire useful range of the BAG. The microprocessor automatically interpolates the calibration data to find the sensitivity factor corresponding to the measured collector current, and uses eqn.1 to calculate and display the resulting pressure.

Since the BAG measures gas density but the sensitivity is defined for pressure, the temperature at which the calibration was performed must always be specified. The mean temperature of the molecules in the chamber is determined by the average temperature of the chamber walls, which is measured at several points with ±0.5°C certainty. Ion gauges are internal heat sources and, depending on their number and configuration, can add uncertainty to the gas temperature value. This effect contributes less than 1% uncertainty to the sensitivity determination even under the worse possible conditions (this does not account for thermal transpiration corrections). It is common practice for calibration facilities to correct and state sensitivity factors for a temperature T_o=23°C. If the sensitivity factor, S, was determined at a temperature T_1, it is expressed as:

$$S(T_o) = S(T_1) \cdot (T_1 / T_o) \qquad \text{(eqn. 3)}$$

Important recommendations to be followed during and after all calibration procedures include:

1. Changes in gauge envelope can result in measurement errors as large as 50% with some BAGs[14]. Thus, the envelope must be considered a proper part of an ionization gauge, and a specification of nude gauge sensitivity is not complete unless the geometry and potential of its envelope are also given. ***Stanford Research Systems recommends that the calibration and operation of nude ion gauges take place inside a calibration nipple – 38 mm ID x 100 mm long tube with 2.75" CF flanges at both ends and a screen at the input port. Calibration nipples are available***

directly from Stanford Research Systems. Consult the factory for order part numbers, pricing and availability.

2. Due to the hot cathode, the temperature inside the gauge head (T_{ga}) is higher than the temperature of the chamber (T_{ch}). As a result, gas pressure and particle density are different in the chamber and the gauge head. The difference in temperature depends on too many factors and cannot be calculated. However, to make the calibration as useful as possible the ratio of temperatures T_{ga}/T_{ch} should be the same during calibration and actual use. This can only be accomplished if the gauge is enclosed in the same way in both cases, and is another reason to calibrate nude gauges inside calibration nipples. Additionally, the emission current (heating power) should not be changed from calibration to use.

3. The orientation of the gauge head should be identical during calibration and use, since geometrical deformations due to different orientations may affect the potential distribution and electron trajectories inside the gauge head.

4. The presence of the specific IGC100 controller used to operate the gauge is not required during gauge calibration procedures performed at the SRS High Vacuum Calibration Facility. However, the presence of the controller is usually required by Primary Laboratory Standards who routinely check the accuracy of the bias voltages and emission current before and after the gauge calibration procedure.

5. Calibrations are gas specific.

6. Gas purities for calibration gases are specified better than 0.1%.

7. Each IGC100 controller is individually tested and calibrated against NIST-traceable test and measurement instrumentation. Certificates of traceability for the controllers are available, free of charge, from Stanford Research Systems.

8. In order to obtain optimum stability, long periods of electron bombardment degas must be avoided. If it must be degassed, the gauge must be allowed to equilibrate for eight or more hours before accurate readings are obtained.

9. After exposure to air, the gauge must be thoroughly baked out at high temperature and allowed to equilibrate for 12-24 hours after bakeout.

Calibration reports are also available for those customers who require for their own records: (1) a complete description of the test procedure, (2) certification of results, including NIST-traceability information, and (3) a complete listing of the data recorded on their gauge

Calibration at a Standards Laboratory

Several laboratories, located throughout the world, offer calibration of ionization gauges against primary high-vacuum standards[15]. Calibration information obtained directly from a primary standards laboratory provides the highest level of measurement accuracy possible - typically better than 2%.

Most primary standards laboratories require the presence of the specific controller, used for actual pressure measurements, during the calibration procedure. The gauge and the controller are regarded as a unit and calibrated together for maximum accuracy of results. The bias voltages and emission current are checked before, and after, the calibration to get an estimate of the accuracy and stability of the controller's electronics.

The calibration procedures followed by most primary standards laboratories are very similar to those used at the SRS High Vacuum Calibration Facility[16]. Reference pressures are generated in carefully characterized vacuum systems consisting of (1) a high accuracy flowmeter (i.e. inlet system) of known throughput, and (2) an orifice-flow chamber, with an aperture of known conductance[17]. Reference pressure values are derived from fundamental quantities such as length, time and mass instead of being measured indirectly with a secondary standard.

The calibration results are summarized in a calibration report . A typical report describes the detailed conditions under which the tests were performed and lists the calibration data as a collection of pressure correction factors, graphed and/or tabulated as a function of the total pressure on the controller's display. When using conventional controllers, corrected pressure values are calculated as a product of the displayed pressure times the correction factor interpolated (usually by hand) from the report's graph or look-up table. This is usually slow and very inconvenient!

Calibration reports, supplied by standards laboratories, can be submitted to the SRS High Vacuum Calibration Facility to have the calibration data transferred into a memory card, compatible with the IGC100 controller. Any IGC100 can then use the calibration data to obtain accurate, real-time pressure readings from the calibrated gauge, without any need for additional correction of the results displayed on the front panel. A nominal fee is charged for this procedure. Consult SRS directly for additional information on this calibration option.

IMPORTANT

For direct transfer of the primary calibration results into a memory card, *IGC100 users must request that all collector currents, measured by the controller at the different pressure setpoints, be added to the calibration report*. A proper report must include (1) ion current, (2) pressure display and (3) derived pressure step values for all available setpoints (including values for all relevant base pressure stops)[18].

Some of the standards laboratories offering Primary High Vacuum Calibration Services are listed in the following table.

Name	Address	Method	Country
National Institute of Standards and Technology[19] (NIST)	Center for Basic Standards National Measurement Laboratory National Institute of Standards and Technology, I-270 at Quince Orchard Road Building 220, Room A55 Gaithersburg, MD 20899-0001	Constant pressure flowmeter	USA
National Physical Laboratory-Teddington[20] (NPL-Teddington)	National Physical Laboratory Teddington, Middlesex TW11 OLW	Series expansion	UK
German Calibration Service (DKD[21]) accredited by PhysiKalisch-Technische Bundesanstalt[22] (PTB)	Physikalisch-Technische Bundesanstalt, Bundesallee 100 D-38116 Braunschweig, Postbox 3345 D-38023 Braunschweig	Constant pressure flowmeter	Germany
National Physical Laboratory-New Delhi (NPL-New Delhi)	National Physical Laboratory, New Delhi-110012	Constant pressure flowmeter and series expansion	India
National Research Council-Canada (NRC Canada)	Institute for National Measurement Standards Montreal Road, Building M-36 Ottawa, Canada K1A 0R6	series expansion	Canada

BEWARE!

Calibration information obtained directly from a primary standards laboratory offers the highest level of accuracy - typically better than 2%. However, the cost of calibration may be prohibitively high (>$4,000), and the response time is usually several months (i.e. fixed yearly calibration schedule). Full-range calibration against a NIST-traceable secondary standard, as provided by the SRS High Vacuum Calibration Facility, offers a very significant cost advantage, very fast response, and an accuracy compatible with most applications.

Important Terms

Calibration Standard
For a calibration device or instrument to qualify as a standard, its measurement performance should be predictable and thoroughly understood, and its random and systematic uncertainties should be well characterized and documented. Only if the above conditions are met can the comparison of the BAG with the standard be called a calibration.

Primary Standard
An instrument where pressure readings are derived from fundamental units such as length, time and mass. This would include measurement of a liquid column height or pressures produced by volume expansion.

Transfer Standard
An instrument that has been calibrated with traceability to a primary standard for the purpose of being used for a local calibration application. Examples of such transfer standards are calibrated high-accuracy BAGs and SRGs.

Secondary Standard
A transfer standard calibrated directly against a primary standard.

Working Standard
A working standard is a calibrated instrument used for routine calibrations of other instruments. For example this can be the transfer standard or a specific BAG.

Check Standard
A check standard is an instrument that may or may not be fully calibrated but which is known to have a stability comparable or better than the device being checked. For example, the check standard can be a specific BAG.

Static Calibration
Refers to producing known pressures by introducing a quantity of gas into the volume to which the gauge to be calibrated and the working standard are connected.

Continuous Flow (Dynamic Expansion) Calibration
Refers to producing equal pressures at the gauge under test and the working standard by establishing a steady-state gas inflow into the calibration chamber against high speed pumping through one or more orifices.

References

[1] C. R. Tilford, "Sensitivity of hot cathode ionization gauges", J. Vac. Sci. Technol. A 3(3) (1985) 546.

[2] C. R. Tilford, A. R. Filippelli, and P. J. Abbot, "Comments on the stability of Bayard-Alpert ionization gages", J. Vac. Sci. Technol. A 13(2) (1995) 485; C. R. Tilford, "Reliability of high vacuum measurements", J. Vac. Sci. Technol. A 1(2) (1983) 152; P. C. Arnold and S. C. Borichevski, "Nonstable behavior of widely used ionization gauges", J. Vac. Sci. Technol. A 12(2) (1994) 574; D. G. Bills, "Causes of nonstability and nonreproducibility in widely used Bayard-Alpert ionization gauges", J. Vac. Sci. Technol. A 12(2) (1994) 574.

[3] A. R. Filippelli and P. J. Abbott, "Long term stability of Bayard-Alpert gauge performance: Results obtained from repeated calibrations against the NIST primary vacuum standard", J. Vac. Sci. Technol. A 13(5) (1995) 2582.

[4] P. C. Arnold, D. G. Bills, M. D. Borenstein and S. C. Borichevsky, "Stable and reproducible Bayard-Alpert ionization gauge", J. Vac. Sci. Technol. A 12(2) (1994) 580.

[5] A gas correction factor is also available to correct the sensitivity factor for gases other than nitrogen.

[6] Peter Nash, "The use of hot filament ionization gauges", Vacuum 37(1987) 643. See section 7.8. titled "Calibration" on page 648.

[7] In order to avoid the risk of contamination of the HV Calibration Chamber, only new gauges are accepted for calibration.

[8] W. Steckelmacher, "The calibration of vacuum gauges", Vacuum 37(1987) 651. This is an excellent review paper on gauge calibration, including all known standards documents as of 1987.

[9] "Standard Method for Vacuum Gauge Calibration by Direct Comparison with a Reference Vacuum Gauge", DIN 28418, Beuth Verlag, Berlin, 1976. Note: other standards have been developed but none of them made it to an official state. See for example, "Calibration by Direct Comparison with a Reference gauge", ISO/DIN 3567 draft, and related ISO 3568 (calibration of ion gauges by comparison) and 5300 (calibration of thermal conductivity gauges by comparison).

[10] The vacuum system is designed following all the recommendations found in: J. M. Lafferty, "Foundations of Vacuum Science and technology", Wiley-Interscience, 1998, section 12.2. "Calibration by the comparison method", p. 673. Note; this chapter of the book was written by Karl Jousten a prominent metrologist at PhysiKalisch-Technische Bundesanstalt, Berlin, Germany, and is required reading for anybody involved in BAG calibrations.

[11] The base pressure in the chamber must be less than 2% of the lowest calibration pressure before a gauge calibration procedure can proceed.

[12] Sharrill Dittmann, "NIST High Vacuum Standard and its use", NIST Special Publication 250-34 (1988). This document describes NIST's BAG calibration procedure in detail, and shows that no return to base pressure takes place during the primary standard calibrations. Base pressure is only established once daily in that lab.

[13] All measured collector currents included in the table are background corrected to eliminate all residual (i.e. calibration gas unrelated) contributions.

[14] Albert Filippelli, "Influence of envelope geometry on the sensitivity of "nude" ionization gauges", J. Vac. Sci. Technol. A 14(5) (1996) 2953.

[15] K. Jousten, et. al. "Comparison of the standards for high and ultrahigh vacuum at three national standards laboratories", J. Vac. Sci. Technol. A 15(4) (1997) 2395. This is a useful comparison between calibration results from three different international facilities.

[16] Sharrill Dittmann, "High Vacuum Standard and its use", NIST Special Publication, 250-34, National Institute of Standards and Technology, Gaithersburgh, Maryland.

[17] P. D. Levine and J. R. Sweda, "Development of a primary standard ultrahigh vacuum calibration station", J. Vac. Sci. Technol. A 12(4) (1994) 1727. See also: : J. M. Lafferty, "Foundations of Vacuum Science and technology", Wiley-Interscience, 1998, p. 668.

[18] Consult Stanford Research Systems or your local representative to obtain information on the most effective way to collect all this information with the IGC100 controller during the measurements.

[19] C. R. Tilford, S. Dittmann and K. E. McCulloh, "The National Bureau of Standards primary high-vacuum standard", J. Vac. Sci. Technol. A 6(5) (1988) 2853.

[20] K. W. T. Elliott, D. M. Woodman and R. S. Dadson, Vacuum 17 (1967) 439. This describes part of an earlier implementation of the standard.

[21] The DKD comprises calibration laboratories in industrial firms, research institutes, technical authorities, inspection and testing institutes. They are accredited and supervised by the Physikalisch-Technische Bundesanstalt (PTB). They calibrate measuring instruments within the framework of the PTB accreditation. The DKD Calibration Certificates issued by these laboratories prove traceability to national standards as required in the ISO 9000 and EN 45 000 series of European standards.

[22] G. Grosse and G. Messer, Vacuum 20 (1970) 373; K. Jousten and G. Rupschus, Vacuum 44 (1993) 569; K. Jousten, G. Messer and D. Wandrey , Vacuum 44 (1993) 135.