Select the Best Bayard-Alpert Ionization Gauge for Your Application

An immense amount of research and development work, by many talented scientists and engineers, has led to a variety of new Bayard-Alpert Gauge (BAG) product designs. In fact, a high vacuum user looking for a new BAG might be surprised, and possibly overwhelmed, by the large number of new commercial options that have become available. Standardization of the BAG design has made it possible for generic ion gauge controllers, such as the IGC100, to control gauges from many different manufacturers.

This application note provides an overview of the current state of BAG technology to help high vacuum users choose the best hot-cathode ion gauge for their application.

In This Application Note

BAG Designs

This application note provides an overview of the current state of the BAG technology to help choose the best hot-cathode ion gauge for any application. For detailed information on the principle of operation of BAGs see the application note, 'Bayard-Alpert Ionization Gauges'.

Glass Tubulated Gauges

The glass tubulated BAG is the most commonly used gauge design in the world. Glass tubulated gauges are also the most inexpensive BAGs available.

The tubulated gauge has its electrodes surrounded by a glass envelope with a side tube that attaches to the vacuum system. The most common construction materials for the glass envelope are Nonex (an inexpensive glass used in old vacuum tubes) and Pyrex. Most tubulated BAGs are connected to the vacuum system through an O-ring compression fitting. Pyrex is the material selected when the side tube must be glass-blown directly on to the vacuum system. Kovar alloy is the material of choice when metallic tubulation is required for the side port. The thermal expansion coefficient of Kovar matches that of Pyrex producing strong glass-to-metal transitions. Kovar tubulation is sometimes combined with compression fittings, but most often it is welded to Klein or ConFlat® flanges for compatibility with standard vacuum ports. While slightly more expensive, flanged tubulated BAGs offer better vacuum integrity and higher bakeout temperatures than compression fitting options. Side tube diameters are set by standard compression fitting diameters to ½", ¾" and 1" OD. Whenever possible, choose the widest possible bore to assure structural integrity and maximum gas conductance between the vacuum chamber and the BAG ionization region.

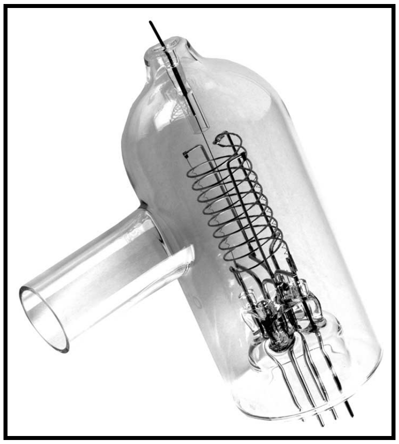

Figure E-1. Glass tubulated Bayard-Alpert ionization gauge, with glass side tube.

All glass tubulated gauges use the same bias voltages and similar emission currents, compatible with IGC100 electrical specifications, and provide pressure readings between 10^{-3} and $\approx 5x10^{-10}$ Torr (typical X-ray limit). Specification claims beyond this range must be approached with caution!

Typical sensitivity factors fall in the range of 8-10 Torr^{-1}. Both I^2R and EB degas are supported by most of these gauges. A typical outgassing procedure includes heating the envelope to 250-400°C for 1 hour followed by a 15 minute degas step.

The repeatability, short and long term stability, and gauge-to-gauge reproducibility of glass tubulated gauges have been the subject of many studies. Several reports show that tubulated BAG users must be careful not to rely blindly on the accuracy of their gauge pressure readings. Gauge-to-gauge sensitivity variations are not unusual for seemingly identical gauges and 25% accuracy at midrange should be considered good for any one gauge, even with new, unused tubes. Long term stability is highly dependent on gauge construction, filament material, operation conditions and environment. Sensitivity changes are usually in the direction of decreased sensitivity. Repeatability in glass tubulated gauges is affected by accumulated electrostatic charge (electrons from the filament) on the glass walls. Several gauge manufacturers offer internal precious metal coatings (Pt) in their BAG tubes. The coating is electrically connected to the filament to reduce electrostatic charge on the glass surface and improve repeatability providing a slight advantage over standard gauges. With uncoated glass, it impossible to control the potential of the internal surfaces, which results in uncontrolled electron and ion trajectories within the gauge and reduced measurement accuracy and repeatability. Long-term stability is affected by changes in the electrode structure, particularly after repeated thermal cycling.

High stability tubulated gauges with spring tensioned (sag-free) filaments and reinforced supports that provide improved measurement stability and accuracy without adding any significant cost are available from Stanford Research .

Glass-tubulated BAGs are fragile and present a safety hazard due to implosion if not adequately shielded. Whenever possible, place them where they cannot be bumped, and be particularly careful during installation. A common problem is crushed side tubes due to excessive tightening of compression fittings. If possible, install the gauge so that the filament is visible during operation. A quick visual check might save a tungsten filament from burnout during a venting or gas loading operation. The preferred mounting orientation is with the filament and anode grid in a vertical position, with the connection pins pointing up, to minimize the electrode distortion caused by gravity pull and thermal cycles.

Tubulated gauges with single and dual filament designs are available. Both tungsten and thoriated-iridium filament materials are offered. Gauges with opposed tungsten filaments have shown better long-term stability (about a factor of two) than gauges with thoriated cathodes. Filaments are not replaceable, making single filament gauges disposable after a burnout (an added cost that must be considered!).

Glass tubulated gauges may be significant sinks of gas molecules and exhibit a certain pumping capacity that is usually time-dependent. This pumping is due to both chemical and electrical effects. The effect usually saturates after approximately three months of operation. The best way to handle gauge pumping is to provide a large conductance connection between the gauge and the vacuum system. A glass envelope gauge with 1" tubulation is recommended for applications requiring pressure measurements down to the 10^{-10} Torr scale, ¾" tubulation is adequate for routine pressure measurements above 10^{-8} Torr.

Glass, when heated, permits permeation of helium from the atmosphere. Remember this effect while leak testing your vacuum system! If helium leak testing with the ion gauge is common practice in your facility, consider an all-metal gauge instead.

BAGs require few electrical connections; however, there is no standard mating socket that will work with all gauge designs. It is the user's responsibility to assure that the correct electrical connections are made at the gauge pins. Wrong connections can cause damage to equipment and may be dangerous for the vacuum system operator. Experienced users can usually identify the different pins by visual inspection; however, the use of pre-wired cables available directly from Stanford Research Systems is recommended to connect BAGs to the IGC100 controller.

Tubulated gauges owe their popularity to their low cost, convenient measurement range, and ease of mounting. Their limited accuracy is more than adequate for most vacuum applications since very often a 'rough' pressure indication (i.e. ±50%) is all that is required by the vacuum operator to characterize the status of a vacuum system.

Broad-Range Glass Tubulated Gauges

Broad-range glass tubulated BAGs are available from many different manufacturers, and under several different trade names. These gauges are designed to operate all the way up to 10^{-1} Torr (with 0.01 mA emission current above 10^{-3} Torr) while still providing a sensitivity factor of 8 Torr^{-1}. They are easily identified because of the narrow grid design (12 mm diameter x 46 mm long), a thoria-coated filament, and a grounded platinum coating on the inside of a reduced diameter (41 mm vs the traditional 57 mm) glass tube. However, they have been shown to be susceptible to large time-dependent instabilities and non-linearities that must be carefully considered during measurements.

In several independent studies, broad-range tubulated gauges have shown large gauge-to-gauge sensitivity variations and non-linearities that make reliable measurements impossible in the absence of individual calibration over the entire pressure range.

Nude Gauges

In nude BAGs the electrodes are not enclosed in a glass envelope. Instead, the electrode structures are welded onto insulating feedthroughs mounted on a vacuum compatible flange (typically a 2.75" ConFlat®), and inserted directly into the vacuum chamber environment. The gas molecules of the vacuum chamber can flow freely into the ionization volume of the gauge thereby eliminating the pressure differential normally associated with tubulated gauges.

The electrode arrangement, biasing voltages and emission current are similar (or identical) to the glass-tubulated BAG and the IGC100 controller can operate both gauge designs without any problems. A cable replacement is usually all that is required to switch from one gauge design to another.

Figure E-2. Nude Bayard-Alpert gauge, with standard electrode design.

Nude BAGs are more expensive than glass-tubulated designs. When connected to a suitable controller, they provide pressure readings between 10^{-3} and $4x10^{-10}$ Torr (typical X-ray limit), with extended UHV versions reaching a $2x10^{-11}$ Torr low limit. Typical sensitivities fall in the range of 8-10 $Torr^{-1}$ for standard gauges and 25 $Torr^{-1}$ for the extended UHV versions. Extended UHV versions are easily identified by the fragile 'squirrel-cage' design (i.e. closed ends) of their anode grid.

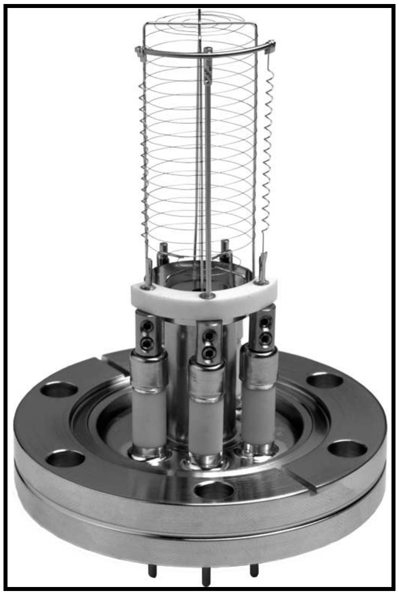

Figure E-3. Nude Bayard-Alpert Gauge, with UHV-extended design.

Gauge-to-gauge reproducibility has been shown to be worse than in tubulated gauges, particularly in UHV versions. Long term stability is comparable to that of tubulated gauges. Overall accuracies better than 30% should not be expected in general. Repeatability is improved in the absence of the insulating glass envelope.

Nude ion gauges are the definitive solution to the gauge pumping problems experienced in tubulated gauges. The unrestricted conductance to the vacuum system also provides faster response to pressure changes in the chamber.

Since the elements are exposed, and easily accessible, most nude ion gauges are designed with replacement filament assemblies. This allows filaments to be replaced after a burnout without having to dispose of the gauge (an important cost saving feature!). Unless a viewport is available, it is generally not possible to see the filament once the gauge is mounted on a port, making the filament more susceptible to accidental and catastrophic overpressures.

With the exception of extended range UHV gauges (EB only), all nude ion gauges provide both EB and I^2R degas options.

The sensitivity of nude ion gauges is affected by the way it is mounted on the system. This effect was recently demonstrated by a careful study, which showed that when the dimensions or shape of the gauge's metal envelope are changed there can be a dramatic effect (up to 2X) on the absolute magnitude of the gauge's sensitivity. There may also be a change in the relative dependence of its sensitivity on pressure. If these effects are not taken into account, the accuracy and consistency of the measurements performed with the gauge will be compromised. The envelope must be considered an integral part of the ionization gauge when specifying sensitivity. The practical consequence of these findings is that nude ion gauges must be calibrated in situ, or in an environment that exactly matches the one experienced by the gauge during its measurements.

Nude ions gauges are the choice of many UHV practitioners who appreciate the enhanced vacuum integrity provided by its mounting flange, the unrestricted conductance to the vacuum chamber, the reduced outgassing provided by its minimal surface area, and the higher bakeout temperatures that it can handle. Typical nude gauges can be baked to 450°C without any effect on performance.

Extended UHV gauges provide the most cost-effective alternative for pressure measurements in the low 10^{-10} Torr ranges typically seen in surface science and extreme high vacuum experiments. ThO_2Ir must be the filament material of choice for these applications.

High-Accuracy Gauges

One of the most significant developments in BAG design in recent years has been the introduction of the 'high-accuracy gauge' design. High-accuracy gauges operate based on the same ionization principles as nude and tubulated gauges; however, they provide highly accurate, reproducible and stable pressure readings by systematically avoiding the known problems associated with those gauge designs.

At the time of this writing, high-accuracy gauges are only available from one commercial source and the IGC100 controller is compatible with all available models. It is very likely that as a market is established, and the utility of the new design is demonstrated, other vacuum gauge manufacturers will follow with similar offers.

The long-term stability, accuracy and gauge-to-gauge reproducibility of pressure measurements in high-accuracy gauges are assured by the unique design and precise manufacturing applied to their construction.

In the commercially available design, dual, independent, thoria-coated, ribbon filaments are carefully positioned relative to the anode axis and maintained in tension by refractory metal springs. Consequently, the filaments exhibit negligible bow, sag or twist with use, assuring stable and reproducible electron trajectories over time. Partial end-caps are employed to extend the radial electric field over a much larger area of the anode grid, while at the same time, short filaments are used to introduce electrons away from the end regions of the anode, assuring stable ion production conditions within the ionizer. The end-capped anode is precision assembled and stress-relieved so that it maintains its exact shape and position even after high temperature degassing. Electrode positions relative to the walls are identical from gauge to gauge to ensure reproducibility of measurements. A grounded conductive shield completely surrounds the anode-cathode structure to provide a stable electrical environment for charged particle trajectories. The entire shield is designed to remain dimensionally stable over time and to have the same dimension from gauge to gauge within close tolerances. A grounded perforated high conductance shield over the port electrically isolates the electrode structures from the rest of the vacuum system.

Note

It must be noted at this point that the gauge-to-gauge reproducibility and long-term stability claims associated with high accuracy gauges have not been verified by any independent vacuum calibration laboratory. The only experiments performed and data published on these gauges come directly from the manufacturer. SRS has not directly verified any of their claims.

Two different collector wire diameters, 0.005" and 0.040", are used. The thicker collector wire, precisely located at the anode axis, is so effective at collecting ions ($\approx$50 Torr^{-1} nominal sensitivity) that it extends the upper pressure limit to 10^{-2} Torr while keeping the X-ray limit at mid-10^{-10} Torr. The thinner collector wire, while providing a lower sensitivity ($\approx$ 25 Torr^{-1}), extends the X-ray limit into the low 10^{-11} Torr range for performance compatible with ultra- and extreme-high vacuum applications.

The premise is simple - high-accuracy gauges provide long-term, stable, accurate, gauge-to-gauge reproducible measurements in a way that is unmatched by any other BAG design. Current state-of-the art midrange accuracy specifications for uncalibrated gauges are ≈6%, and they get better for individually calibrated gauges. However, this increased performance comes at a price! High-accuracy gauges are expensive, costing up to 10 times as much as a glass tubulated gauge.

High-accuracy gauges are stable and reproducible enough, that it makes sense for their controllers to store gauge specific sensitivity data. In fact, it is possible to perform NIST traceable calibrations on individual gauges and store their calibration information in the IGC100 controller memory. Stored values of gauge sensitivity track the actual gauge sensitivity across the entire pressure range, providing real time correction for the non-linearities that lead to errors in traditional gauge systems. Individually calibrated high-accuracy gauges offer midrange reading accuracies better than 3% (close to spinning rotor gauge performance).

High-accuracy gauges make a lot of sense in strictly controlled vacuum process environments where pressure reading inaccuracies can lead to reduced yields and increased production costs. The gauge-to-gauge reproducibility is a welcome feature when forced to switch to a new gauge before trying to reproduce a production run. Calibrated high-accuracy gauges are also cost-effective NIST traceable transfer standards, providing accuracies comparable to spinning rotor gauges over a larger pressure range. It is common practice for pressure calibration laboratories to use high-accuracy gauges as transfer, check and working standards.

Tiny Gauges

Miniaturization has not escaped BAG designs. Almost every vacuum gauge manufacturer now offers a version of 'tiny' ionization gauge. The principle of operation remains the same, the advantages and disadvantages must be considered carefully.

Their goal is clear - replace the unreliable and fragile glass envelope gauges with much smaller and rugged designs without any compromises in performance and specifications.

The new tiny gauges accomplish most of that. They are small, occupying as little as 5% of the volume of a traditional glass envelope gauge. They eliminate glass gauge accidents by relying in all-metal construction. They offer an operational range that overlaps or sometimes exceeds that of traditional tubulated designs. The reduced size also minimizes the power requirements of the filament resulting in less heat being dissipated into the vacuum chamber.

No independent reports on the repeatability, short and long term stability, and gauge-to-gauge reproducibility of tiny gauges are currently available since the gauges have only been recently introduced into the market. However, it is probably fair to estimate that their accuracy specifications will be comparable to those of tubulated ion gauges.

Tiny gauges are more expensive than tubulated designs (up to 4 times). Tiny gauges are usually only available with thoria (burn-out resistant) filaments. Filaments are not replaceable, making the gauges disposable after filament failure. Both flanged and tubular mounting options are available.

Tiny gauges are a perfect match for applications requiring a small rugged gauge, with low power dissipation. They are often found as hidden components of portable systems including mass spectrometers, leak detectors, small sputtering systems, etc. It is possible that all-metal tiny gauges will some day become preferred over traditional glass tubulated gauges. However, in the meantime, traditional designs still offer a significant price advantage that cannot be easily overlooked. An advantage of glass envelope gauges, rarely mentioned by tiny gauge marketers, is that their use is so widespread that it is possible that your facility, or your next door neighbor, will have a spare on a shelf when you desperately need one in the middle of an experiment.