# Cold cathode gauges for ultrahigh vacuum measurements

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Nine cold cathode gauges have been evaluated on ion-pumped ultrahigh vacuum systems operating at pressures down to the $10^{-11}$ Torr range. The test gauges included magnetrons, inverted magnetrons, and double inverted magnetrons from four different manufacturers as well as experimental variable-geometry gauges built especially for this project. Spinning-rotor and extractor gauges were used for calibration. The investigation covered repeated calibration over the $10^{-10}$ to $10^{-4}$ Torr range, stability over periods of up to 35 000 h of low pressure operation, tests for discontinuities in the current-pressure characteristics, stray magnetic field measurements, susceptibility to external magnetic fields, outgassing effects, and starting behavior at very low pressures. Our conclusion is that modern cold-cathode gauges are capable of giving far more accurate results than were possible with earlier Penning-type designs. Because of their extremely low outgassing rates, and their relative freedom from x-ray and electron stimulated desorption errors, they may in practice give results at low pressures which are more accurate than those obtained with typical hot-cathode gauges. © *1997 American Vacuum Society.*
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## I. INTRODUCTION

For several years we have been operating two ultrahigh vacuum systems, each equipped with clusters of various types of cold-cathode and hot-cathode ionization gauges. These systems are used primarily to evaluate new gauge designs and to study sources of error in high vacuum gauges.

The opportunity to compare simultaneous measurements from numerous different types of gauges revealed certain strengths of cold-cathode gauges which still do not appear to be generally recognized, despite a thorough and predominantly favorable review by Peacock *et al.*[1] several years ago. These observations led to a long term project to evaluate the ultrahigh vacuum performance of a group of modern cold-cathode gauges. Factors such as the output linearity, long term stability, discontinuities in the current-pressure characteristics, stray magnetic fields, susceptibility to external magnetic fields, outgassing effects, and starting behavior were investigated. A necessarily very condensed summary of this four year program is presented here.

## II. TEST APPARATUS

Two almost identical ion-pumped ultrahigh vacuum systems were used, one operating routinely around $2\times10^{-10}$ Torr and the other in the mid $10^{-11}$ Torr range. Each was pumped by a 400 *l*/s noble-gas ion pump.

One system had a spinning rotor gauge (MKS SRG-1) which was used to calibrate two extractor gauges (Leybold-Heraeus Ionivac 510 controllers with IE-511 gauge tubes), which in turn were used as references for the various test gauges. The extractor gauge range scales were individually calibrated with a current reference source. The gauges were grouped closely together, typically mounted on adjacent arms of five- and six-way crosses so that there was no line-of-sight between them. Gauge interactions were determined to be negligible at normal operating pressures, except in starting time measurements, which were done with all but the test gauge off. Gas inlet systems (one of them equipped for repetitive pressure sweeps) allowed controlled input of the nitrogen test gas. Conventional all metal design was used with stainless steel components and copper sealing gaskets. Special gasket polishing and cleaning was used on the $10^{-11}$ Torr system, along with a more aggressive bakeout schedule. For certain measurements above about $10^{-7}$ Torr, test gauges were transferred temporarily to a turbo-pumped system with a similar gas inlet system.

## III. TEST GAUGES

The gauges tested were limited to designs known to operate reliably down to at least $10^{-11}$ Torr. Nine gauges from four different manufacturers were studied. They included Redhead-type magnetrons,[2] inverted magnetrons,[3] and several examples of a recently introduced double inverted magnetron. In the double inverted magnetron a single set of electrodes is immersed in two opposed axial magnetic fields, to give the effect of two inverted magnetrons operating in parallel. Abbreviations M, IM, and DIM will be used to indicate gauges of the three basic types, each with a numerical suffix to identify a particular gauge tube. The numbering of individual gauges is consistent with that used in our recent study of the starting characteristics of cold-cathode gauges.

The test program also included extensive additional studies of voltage, magnetic field, and geometrical variations on several of these gauges, but space limitations allow only a brief selection of those results to be presented here.

An inherent limitation of a long term test such as this is its inability to cover current production equipment. In over four years, most manufacturers will have made numerous minor electronic and software changes in the gauge controllers. We aim only to provide general guidance as to the performance of some typical gauges of the most common generic types.

## IV. CURRENTS AND PRESSURES

Over most of its pressure range, the output current $I$ of a cold-cathode gauge is given by

$$I=KP^x, \quad (1)$$

where $K$ is a constant, $P$ the pressure, and $x$ an exponent, typically close to unity for many magnetrons, but between 1.05 and 1.25 for most inverted magnetrons. The interpretation of this equation, and particularly the constant $K$, has been discussed by Peacock and Peacock.[4]

Our results indicate values of $x$ in the range 1.00 to 1.02 for both glass envelope and newer design metal envelope Redhead magnetron gauges over the pressure range from $10^{-5}$ to $10^{-9}$ Torr. Because of this linear relationship, first reported by Redhead,[2] the current in these gauges may be read directly in terms of pressure as in a typical hot-cathode gauge.

At pressures below about $10^{-9}$ Torr the exponent $x$ shifts suddenly to a higher value of 1.25 to 1.5, or more. The reason is obscure, but all of the gauges tested showed this characteristic. The shift in value of the exponent $x$ can be seen as a pronounced change of slope in the log current versus log pressure plot of a cold-cathode gauge. This knee, often called the "magnetron knee" irrespective of the specific gauge type, occurred between $5\times10^{-10}$ and $2\times10^{-9}$ Torr in the gauges tested, with the precise value being specific to a given gauge tube for a specific magnetic field and operating voltage.[5–8]

The user, of course, is only interested in the linearity of the indicated pressure as a function of true pressure. The conversion from the nonlinear current characteristic of inverted magnetrons at pressures above the magnetron knee is typically made via logarithmic converters or internal look-it-up tables and is essentially transparent to the operator.

There is no standard method for dealing with currents below the magnetron knee. Internal look-up-tables, a second stage of logarithmic conversion, or printed correction tables may be used. Gauge DIM-6, using the second of these methods, remained within 15% of extractor gauge pressure down to $8\times10^{-11}$ Torr, the ultimate pressure of the system with the extractor gauge operating.

## V. LONG TERM STABILITY

One of the ion-pumped vacuum systems was operated continuously for 50 months except for a period from the 38th to the 40th month when the system was stored under vacuum. Total operating time was just over 35 000 h. There were eight roughly evenly spread short exposures to atmosphere (after nitrogen venting) for modifications and interchange of test equipment. Inverted magnetron gauge IM-2 was on the system throughout. Inverted magnetron IM-1 was added at the 5th month and double inverted magnetron DIM-5 was added at the 23rd month. All gauges were operated continuously throughout their time on the system. No special gauge conditioning was carried out. The gauges and controllers were used as they came from the manufacturers, without calibration or sensitivity adjustment. An external circuit to correct for the "knee" in the DIM-5 characteristic below $10^{-9}$ Torr was used, preset on the basis of measurements on other double inverted magnetrons and not adjusted after these tests began. Calibrations were carried out using the extractor gauge, which was in turn calibrated at intervals against the spinning-rotor gauge in the $10^{-6}$ Torr range. An extractor gauge is the logical choice for low pressure reference applications because of its freedom from x-ray-induced errors.[9]

Variations in the cold-cathode gauge sensitivities over time are conveniently plotted as fractional deviations from the extractor gauge readings as a function of time for different pressure ranges. Figure 1 shows the results for pressures around $10^{-9}$ Torr, where knee corrections are minimal. The two inverted magnetron gauges remained within a range of $88\pm15\%$ of the extractor gauge reading for the entire test period, while the double inverted magnetron remained within $78\pm12\%$ for the 27 months following its first calibration.

Figure 2 shows the corresponding results for pressures around $2\times10^{-10}$ Torr, where knee corrections are likely to be substantial. Gauge IM-2 remained in the range of 131 $\pm20\%$ of the reference gauge readings, and IM-1 remains in the range of $89\pm11\%$. The double inverted magnetron remained in the range of $85\pm5\%$ (five readings over 27 months). Note the reasonably close correlation between the three sets of data taken over the final three months.

At higher pressures, the calibration records showed rather less variation with time and moved closer to the reference gauge readings. In the $10^{-5}$ Torr range, gauges IM-1 and DIM-5 were each within a few percent of the reference gauge readings.

It should be remembered that these gauges were tested "as delivered," without calibration. There may have been a slight tendency to drift downward in sensitivity with time, as has been reported for operation at higher pressures. The observed results necessarily included any drifts in their electronic circuitry during the long test period. Any one of these gauges would have given adequate accuracy for all normal purposes, particularly if a postinstallation calibration had been carried out.

Similarly stable results were obtained by Hyatt and Peacock[10] for a two year test on a single gauge tube connected to laboratory grade electronics.

## VI. DISCONTINUITIES

Although modern cold-cathode gauges are far less likely to exhibit discontinuities in their current-pressure relationships than earlier Penning based designs,[11,12] the elimination of these discontinuities continues to present a major challenge to the gauge designer.

Discontinuities are very easily missed when pressures are varied manually. This is particularly so when digital displays

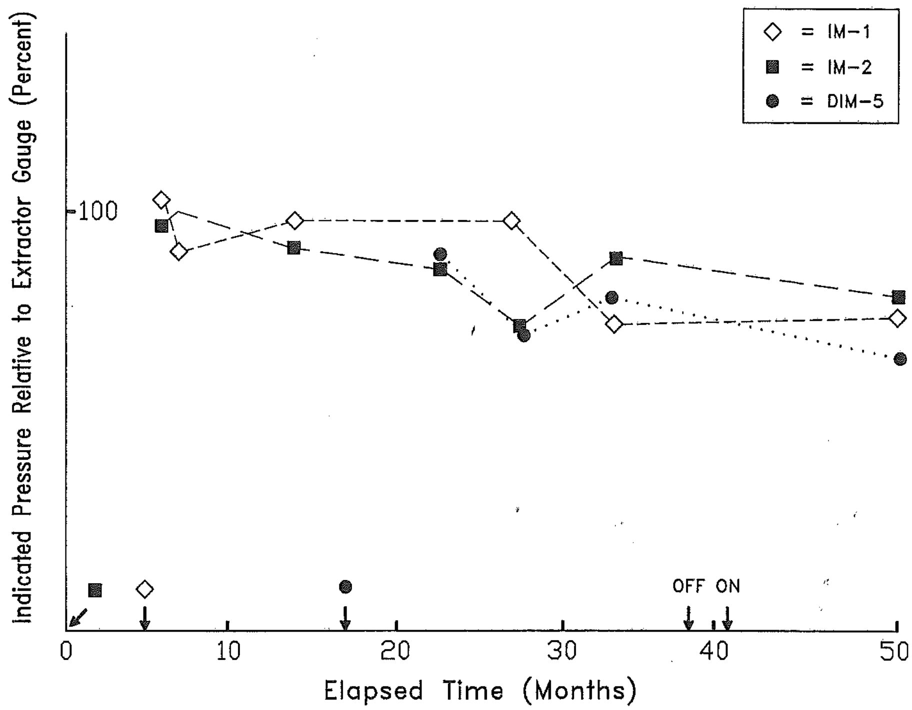


FIG. 1. Variations in indicated pressures relative to extractor gauge reference at 10 $^{-9}$ Torr over a 50 month period. Installation times and period of power off storage indicated on time axis.

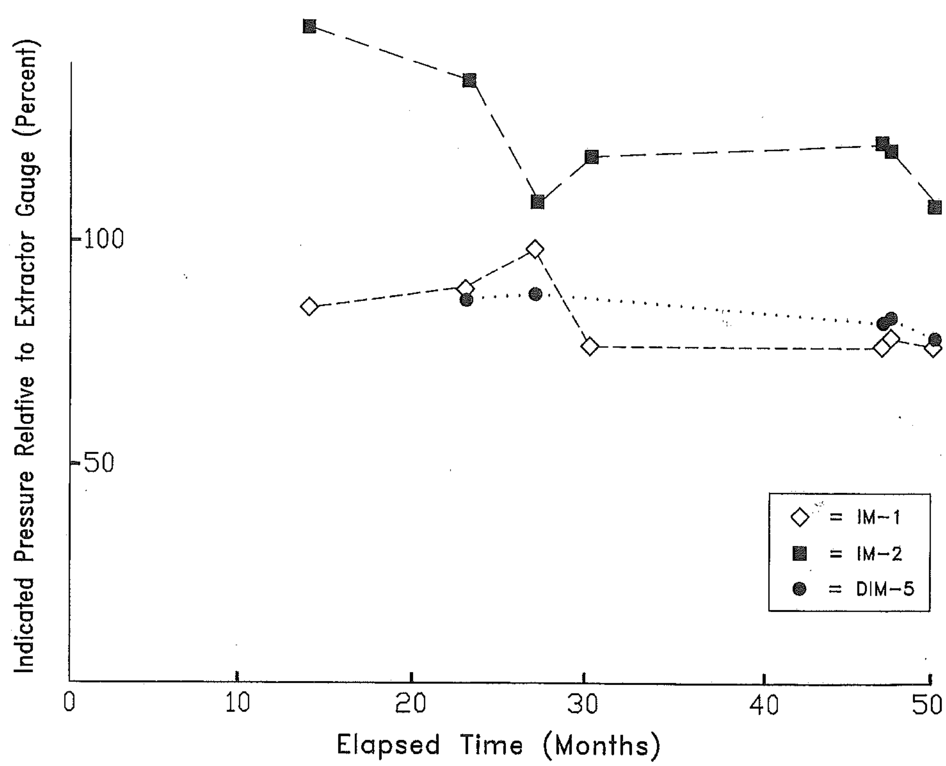


FIG. 2. Variations in indicated pressures relative to extractor gauge reference at $2\times10^{-10}$ Torr over a 50 month period. Note reproducibility of separate measurements in final three month period.

are being observed and the reading is near unity; a 5% discontinuity is easily missed as the display shifts from, say, 1.0 to 1.1 during a slow pressure increase.

To properly test for discontinuities, we developed a swept leak generator analogous to an electronic waveform generator. It produces linear or exponential sweeps over successive decades of pressures from $10^{-3}$ to $10^{-9}$ Torr in a typical vacuum system. Sweep times are adjustable from 10 s to 1 min per decade.

The pressure scanning technique has yielded large amounts of data but, so far, no simple answers. Individual gauges of the same type may have very different discontinuity patterns. In contrast to some other reports, we find these patterns to be generally quite reproducible, sometimes over long periods of time. Close attention to magnet homogeneity and geometrical accuracy of the gauge structure reduces but does not eliminate the incidence of discontinuities.

By viewing the gauge discharge through an optical window and using sensitive photographic film, it was established that at least some of the remaining discontinuities were associated with axial movements of the discharge. By modifications aimed at stabilizing the axial position of the discharge, an experimental double inverted magnetron was eventually constructed in which there was only one medium sized (10%) discontinuity detectable in the upper test range ($10^{-3}$ to $10^{-4}$ Torr), and no detectable discontinuity over 3% in the lower decades down to $10^{-9}$ Torr. Manual sweeps down to $3\times10^{-11}$ Torr disclosed no additional discontinuities.

## VII. OUTGASSING AND PUMPING EFFECTS

Users are so accustomed to the outgassing of hot-cathode gauges at very low pressures that it is often barely recognized as being a potentially large source of error when such gauges are used under ultrahigh vacuum conditions. As Young[13] and others[1,5,14] point out, the gas composition and pressure in even a large vacuum system may be dominated by gases released from a single hot-cathode gauge and its surroundings. This is particularly true when nude hot-cathode gauges are used, because of heating of the metal system in the vicinity of the gauge filament.

With cold-cathode and extractor gauges on adjacent arms of a cross or tee fitting, the relative outgassing rates may readily be measured by switching each gauge off alternately and observing the change in reading of the other.

When this was done after brief exposure to air and subsequent bakeout, the extractor gauge usually began at several orders of magnitude higher outgassing rate than the cold-cathode gauge. This improved only with very aggressive electron bombardment for periods far longer than the manufacturer's maximum recommended times, plus additional thermal degassing. Even after several weeks, the differential outgassing rates were typically still different by more than an order of magnitude at the system's ultimate pressure. At $8\times10^{-11}$ Torr, switching off the cold-cathode gauge typically reduced the extractor gauge reading by about 1%, but switching off the extractor gauge reduced the cold-cathode gauge reading by 20%–30%.

If the background pressure is increased, clean gauges may act as pumps. Pumping speeds for the gauges studied in Secs. IV and V were measured by comparison with a pumping orifice of known dimensions and found to be in the 0.1 to 0.3 $l\ s^{-1}$ range immediately after a large stepwise pressure increase, falling to a small fraction of these figures after several hours. These results are in general agreement with data reported by Redhead[15] and others.[1,14,16] Pressure errors due to gauge pumping are therefore likely to be negligible if normal gauge connections are used.

TABLE I. Field strengths at points 10 cm from centers of cold-cathode gauges. Side-on points are in the midplanes of the magnet systems. Field directions are indicated by "a" (axial or parallel to axis) or "p" (perpendicular to axis).

| | Stray field (G) | |
|---|---|---|
| Gauge | On axis | Side-on |
| IM-1 | 16 a | 10 a |
| IM-2 | 31 a | 19 a |
| IM-3 | 38 a | 23 a |
| DIM-6 | 6 a | 4 p |
| DIM-7 (with shielding) | 0 a | 1 p |

## VIII. MAGNETIC FIELDS NEAR COLD-CATHODE GAUGES

The magnitude and effects of the stray magnetic fields produced by cold-cathode gauges are of concern to some potential users. We obtained samples of typical commercial gauges from four manufacturers and mapped the stray fields around them with a Hall effect gaussmeter. For simplicity, we show in Table I only the on-axis and side-on fields measured at 10 cm from the centers of the gauge magnet systems.

The three inverted magnetrons showed substantial stray fields at this relatively short distance. Both on-axis and side-on measurements gave field directions parallel to the axis. As expected, the opposed magnets of the standard double inverted magnetron gave greatly reduced fields in both positions. Here the side-on position gave a field perpendicular to the axis. Addition of a simple sleeve of 0.020 in. Conetic AA shielding material reduced the stray fields by an additional factor of approximately 5, yielding stray fields below about 1 G.

An alternative form of low field gauge using radially magnetized elements has been described by Lethbridge and Asl.[17]

## IX. OPERATION IN EXTERNAL MAGNETIC FIELDS

In some applications, the ability of a gauge to operate correctly in an external magnetic field may be important. For performance comparisons in external fields, a large magnet was placed in fixed positions relative to each of eight gauges. Least affected were the magnetrons and the double inverted

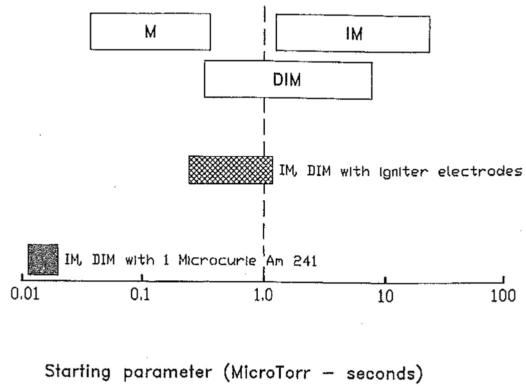


FIG. 3. Starting parameter ranges for typical cold-cathode gauges, operating in ion-free conditions.

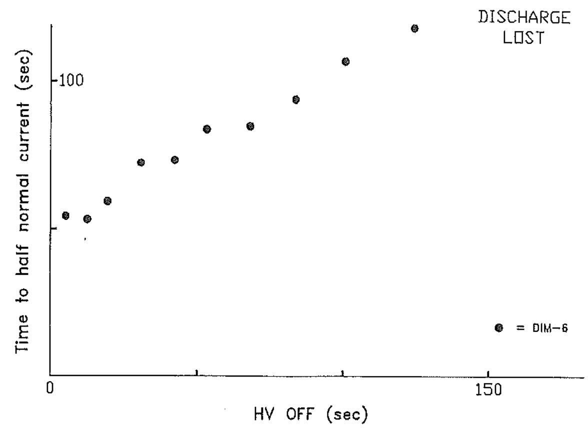


FIG. 4. Time for discharge recovery at $10^{-10}$ Torr as a function of period for which high voltage lead was physically removed. Original discharge did not recover for periods greater than about 120 s. A new discharge would eventually begin.

magnetrons, with shifts in readings of 2%–27%. Slightly larger effects were observed with the inverted magnetrons, with shifts of 16%–38%, and the most affected were the hot-cathode gauges with 50%–100% drops in sensitivity.

It appears that the sensitivity of the cold-cathode gauges is not drastically affected by external field conditions which make most hot-cathode gauges unusable. For operation in very high fields, special gauge designs have been developed.[18,19]

## X. STARTING AND RESTARTING

A traditional objection to the use of cold-cathode gauges has been the inherent delay in the ignition of the discharge at very low pressures.

The measured starting time has been shown to consist of a statistically distributed dormant period followed by a reproducible growth period after ignition occurs. In most simple situations the dormant period is dominant, but it can be reduced to negligible levels by the use of radioactive sources and in various other ways. A review of the various starting techniques and their relative effectiveness has been given elsewhere.[20]

Because both the dormant and growth times appear to be approximately inversely proportional to pressure, the product of the median starting time of a gauge and the pressure is a useful parameter for describing its starting behavior. Convenient units are $\mu$ Torr seconds, easily remembered by analogy with the definition of the langmuir. The langmuir, a unit of exposure to gas molecules used in surface science, corresponds to 1 s of exposure at a pressure of 1 $\mu$ Torr.

Figure 3 shows the range of starting parameters for the different families of gauges. These data are based on measurements in our laboratory on approximately 20 gauges from four manufacturers. They include our previously published results for nine cold-cathode gauges[20] and are consistent with figures provided by other researchers.[8,21] Each median starting time at a given pressure was itself determined from a group of at least 12–21 individual starts, rising to as many as 49 individual starts at the higher pressures. This statistical treatment is necessary because of the natural scatter in the dormant periods.

The double inverted magnetrons tend to start somewhat faster than conventional inverted magnetrons, presumably because ignition in either half of the symmetrical system will ignite the other. The fast ignition of the magnetrons (both traditional glass envelope and modern metal envelope types) is probably caused by their relatively high operating voltage and an efficient internal field distribution.

The data given in Fig. 3 apply to essentially ion-free conditions. We used completely ion-free turbo-pumped systems for all work down to about $10^{-8}$ Torr and for most measurements down to $10^{-9}$ Torr. After tests showed no significant difference when the experiments were repeated on a special ion-pumped system fitted with multiple ion baffles, this system was used for the remainder of the measurements below $10^{-8}$ Torr. Starting data are currently being gathered at pressures in the mid $10^{-11}$ Torr range.

In a practical situation, starting may be hastened by the presence of ion pumps, hot-cathode gauges, or other cold-cathode gauges operating on the same system. Charged particles or photons from these other sources then initiate the discharge in an average time much shorter than given by Fig. 3.

Recent work in our laboratory[20] and also by Welch *et al.*[21] at Brookhaven has shown that the starting problem can be completely eliminated by the use of weak radioactive starters such as 1 $\mu$ Ci of the alpha emitter, Americium 241. This essentially eliminates the dormant period. The small remaining starting times then represent the time for the gauge discharge to grow to its equilibrium value. This is quite reproducible and typically amounts to about 100–200 s at $10^{-10}$ Torr for modern commercial gauges.

A related issue is the loss of ignition caused by brief power interruptions. At very low pressures the electrons in the gauge may circulate for substantial periods with the power off, ready to restart the gauge when power is reapplied. Redhead[22] has reported a case of electron circulation for 1 h in a glass magnetron gauge at a very low pressure.

A striking example of continued electron circulation is shown in Fig. 4 where the high voltage cable to the gauge tube has been physically removed for increasing periods at $10^{-10}$ Torr and the time taken for the current to reestablish itself after reattachment of the cable is plotted on the vertical axis. Even a brief power interruption at the gauge tube apparently causes a substantial drop in the discharge intensity. The reason is not clear. Increasing "off" periods cause a general increase in restarting time (indicating a dwindling supply of orbiting electrons in the gauge) until eventually the last electrons are lost and the original discharge does not recover when the power is reapplied. The operator must then await the normal processes of starting a new discharge, with a median time delay for this unassisted gauge of many hours at $10^{-10}$ Torr.

In an attempt to determine the role of capacitively stored charge in continuing the operation of the gauge, the experiment was repeated with the gauge anode grounded during the off period. The maximum time before the discharge was extinguished completely was now reduced to about 20 s. In this case, of course, the electron paths within the gauge become small circular orbits instead of cycloids.

To further investigate the role of capacitively stored charge in maintaining the discharge, we then removed the 2 m high voltage cable at the power supply end for increasing periods, leaving it connected to the gauge tube. The initial drop in discharge intensity was not present in this case. The discharge continued for several hours before being completely extinguished. This surprising result is actually quite consistent with the amount of charge stored in the approximately 200 pfd cable capacitance, combined with the extremely low gauge current of just under $10^{-10}$ A. This may explain occasional reports of anomalously short and uniform starting times at very low pressures.

One occasionally hears concerns about spontaneous loss of ignition from steady state conditions at low pressures. We have never seen such an event with any of the modern gauges tested, despite monitoring them for tens of thousands of hours at pressures at and below $10^{-10}$ Torr and recording almost 1000 starts at low pressures. One case was observed where an inverted magnetron lost ignition during the very early stages of a discharge growth period during a start in the $10^{-11}$ Torr range, but it restarted and operated normally shortly afterwards.

## XI. CONCLUSIONS

The nonlinear relationship between current and pressure seems to have been accurately allowed for in modern inverted magnetron gauges, either by the use of logarithmic converters or internal look-up tables, for pressures down to the magnetron knee at about $10^{-9}$ Torr. Below the magnetron knee special precautions need to be taken to allow for the more pronounced logarithmic response of both magnetrons and inverted magnetrons. With their use, reasonable accuracy is possible down to at least the low $10^{-11}$ Torr range. Wherever possible, the specific gauge tube/controller combination should be calibrated against a reliable transfer gauge to allow for individual variations in gauge sensitivity.

Stable operation appears to be possible over periods of several years under clean, low pressure working conditions. Further research to establish stability under less favorable conditions is desirable.

Elimination of discontinuities in the current-pressure relationship continues to present a major challenge to designers of cold-cathode gauges. Although modern magnetrons and inverted magnetrons are far less likely to exhibit large discontinuities than earlier Penning based gauges, there is still substantial variability between designs and also between gauge tubes which are nominally identical. This is another area where additional research and development effort is needed. The use of pressure-sweep test equipment makes such studies much easier.

Concerns about the stray magnetic fields of modern cold-cathode gauges are essentially unfounded. The use of either of the new opposed field designs reduces the stray fields to only a few gauss. Addition of simple shielding sleeves further reduces the stray fields to levels comparable with background effects in a typical laboratory.

Sensitivity to externally produced magnetic fields is typically far lower than for unshielded hot-cathode gauge tubes, and therefore unlikely to be a problem under normal conditions.

Starting times at very low pressures can be reduced greatly by the use of weak radioactive sources. In many cases, however, no special starting devices are needed because charged particles or high energy photons are present in the system in sufficient numbers to give quick starting, or because starting can be performed at temporarily elevated pressures.

Outgassing rates are typically very much lower and more predictable than for hot-cathode gauges, resulting in recent use of cold-cathode gauges for critical material outgassing studies.[14] Measured pumping speeds are also low, so that pressure measurement errors should be insignificant provided the connecting tubulation is short and of a diameter at least comparable with the gauge inner diameter.

We conclude that modern cold-cathode gauge designs avoid many of the problems associated with the early Penning configurations, while offering unique advantages at very low pressures because of their low outgassing rates and their freedom from x-ray and electron stimulated desorption effects.

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