A measurement of intrinsic outgassing rates in vacuum interrupters

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***Abstract*— In our paper *The effect of magnetron discharge pressure measurement on the actual pressure in vacuum interrupters* (ICEPE TS 2015) it was reported that in 2013 vacuum pressures in the 10^{-5} mbar range had been measured in a batch of old vacuum interrupters which had been sealed for more than 30 years. This measurement was then repeated in 2015 and found to be in the 10^{-6} or 10^{-7} mbar range. It was proposed that the discharge involved in the first measurements had the effect of permanently removing gas from the system to very low levels, and that the pressures seen two years later arose from intrinsic outgassing within the interrupters. Now in 2017 our equipment has been improved to measure low pressures better, and the pressures have been measured again after this additional two-year period. The new measurements confirm that permanent magnetron pumping occurs, and the new pressures are compatible with what was expected from the outgassing rates measured in 2015. We believe that these results also confirm our hypothesis that each vacuum interrupter has an intrinsic outgassing rate.**

***Index Terms*--Arc discharges, Gettering, Magnetron, Vacuum technology, Vacuum interrupter.**

I. INTRODUCTION

The inverse magnetron discharge method is widely used by manufacturers to check on the vacuum pressure inside newly made vacuum interrupters (VI), and is also sometimes used to check that VI which have been in service for many years still have a good enough vacuum and are therefore still safe to use.

The inverse magnetron test involves putting the VI inside a magnetizing coil and applying a voltage, typically 5,000V, across it. After a short wait a pulse of current in the micro-amp range occurs and the peak level of this pulse is taken as a measure of the vacuum level [1]. A typical example is shown in figure 1. After the peak the pulse dies away, which could be taken as an indication that the vacuum pressure is falling. This effect has been called magnetron pumping. It has been generally supposed that gas particles ionised by the discharge adhere to surfaces inside the VI, but over a few hours or days they pick up neutralizing charge and return to the vacuum, so that the pressure returns to its level before the test. However in 2015 we reported measurements that indicated that, although some VI did quickly recover their original pressure level, in the majority of a batch of VI that we tested the pressures in fact remained at a very low level.

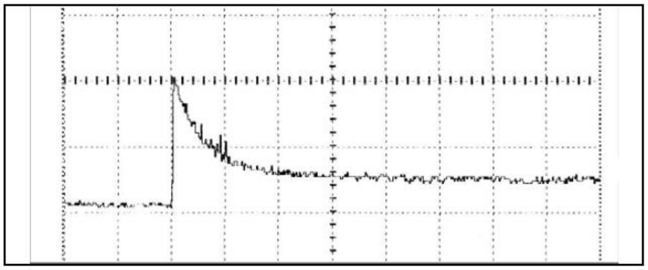

Figure 1. A typical magnetron pulse.

This "permanent" magnetron pumping has the potential to perform a gettering action in newly made VI and possibly to extend the lives of old VI by improving their vacuum levels.

When a magnetron test is applied by a manufacturer of VI, it is common practice to terminate a pulse by switching off the applied voltage or the magnetic field as soon as the peak value has been captured. In our 2015 measurements, which were made manually, it was seen that the longer a discharge was allowed to continue, the more the discharge current fell asymptotically towards zero, and thus towards zero pressure.

Although pressure can rise in a VI because of a leak of gas from outside due to a manufacturing fault or physical damage, this is a rare event. Most pressure rise occurs because of outgassing from within the VI due to surface contamination or gas evolved from the bulk of the metals and ceramics that the VI is made of. Gases trapped within inter-crystalline spaces of the solid parts gradually diffuse out and into the vacuum. This is normally termed a "Virtual Leak". Outgassing is a normal phenomenon in all vacuum systems, and this means that vacuum pumping can never be complete or permanent.

A. Observations reported in 2015

In 2015 we reported [2] the results of observations on a batch of 16 old VI whose pressures had been measured when they were received by us in 2013. The VI were around 35 years old in 2013. The 2013 pressures averaged 4.3x10^{-5} mbar. In 2015 these were measured again, to measure their expected rates of pressure rise, but it was found instead that the pressures had in fact fallen substantially, to an average of 6.3x10^{-6} mbar, which is comparable to the pressures that newly made VI are expected to have. We now believe that this was due to a permanent magnetron pumping effect due to the relatively long discharge times used in our measurements.

The 2015 measurements enabled calculation of the outgassing rate of each VI to be made, assuming that the VI had been pumped down to a negligible pressure in 2013.

B. *Shortcomings of the 2015 observations*

These 2015 observations had a number of shortcomings:

1. This was not initially a deliberately set up experiment, but rather based on a set of observations.
2. For the 2013 measurements no steps were taken to record the actual times the discharges were continued; it was simply that due to their manual nature these laboratory measurements happened to continue the discharges for many seconds after pulse capture.
3. The minimum measurable pressure of the magnetron equipment was limited by instrumental noise to about 3x10^{-7} mbar, which is fine for normal testing, but some of these unexpectedly small pulses were only a little larger than this, and so their peaks could not be read accurately.
4. For the smaller pulses the signal trace rapidly fell into the noise, and it was difficult to see how closely to zero the pressure had fallen in comparison to the peak value.

Before proceeding further, it should be pointed out that as well as the VI reported on in this paper, three others from the same batch definitely did show a return of pressure after magnetron pumping, and this could be repeated several times. For these VI the current did not fall to zero, but displayed a distinct remanent level after an extended period of magnetron pumping. These VI appear to contain gas which cannot be permanently pumped by this method, and these will be reported on in a later paper.

II. THE 2017 EXPERIMENTAL SETUP

In preparation for the 2017 measurements on permanently pumpable VI, the 2015 discharges were each continued for 60 seconds, which, based on the previous observed pumping rate, was thought to be more than enough for all significant magnetron pumping to occur.

The sensitivity of the magnetron was increased by a factor of 10. The magnetron current supply, the HT unit and outside machinery all produce instrumental noise signals, which adds to mains-derived noise. These were reduced by various means to a noise level allowing us to measure down to about 3x10^{-8} mbar, which meant that pulse heights only 10% of the previous limit could now be measured. The remaining noise consisted almost entirely of short pulses at 100 Hz, which we assumed to be derived from the mains frequency. In figure 2 for example this noise shows as a band of spikes, before the discharge peak, of a fairly constant amplitude.

This noise could be reduced further with a simple RC smoothing circuit, but if the time constant is too great the peak of the pulse is rounded, obscuring the peak level, and potentially affecting the reading. Because of this the RC time constant was set to a value which reduced noise as much as possible without changing the peak value.

It was of interest to see how complete the magnetron pumping was, so the remanent level at the end of the 60 seconds of discharge was also noted. In fact all of the remanent levels were as close to zero as could be distinguished, and so no value was recorded.

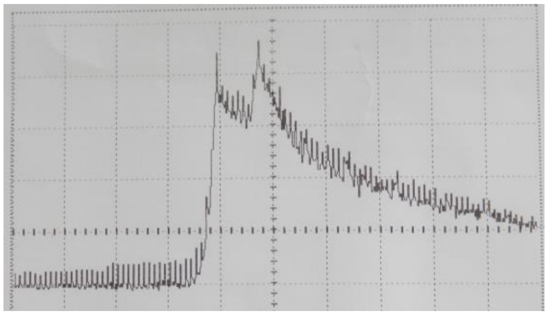

Figure 2. A pulse showing residual noise. The vertical scale is 2x10^{-7} mbar/div and the horizontal scale is 200ms/div. This is an example of a double peaked pulse. VI number T203.

A. *Comparison with the Penning Gauge*

The magnetron setup used for measuring vacuum levels in VI is similar to the well-known Penning gauge used in vacuum systems. The Penning gauge uses a permanent magnet instead of a coil, and measures continuously instead of by a single pulse. The data sheet for the Inficon PEG100 Penning gauge [3] gives its pressure range as 1x10^{-2} mbar to 1x10^{-9} mbar, so the commercial gauge is ten times more sensitive than the setup described above. However VI are not designed as pressure measuring devices, so the performance reported here for our magnetron system is very satisfactory.

B. *Some difficulties of the work*

1. **Rarity of the specimens**. VI are very reliable and only a few spares are kept. Occasionally some VI become redundant when a substation goes out of use, but even then, the owner normally does not make them available for research, and may well scrap them.
2. **One-shot measurements**. The main conclusion from our 2015 measurements was that after an extended magnetron pulse in the majority of VI tested the residual gas in the vacuum of a VI disappears permanently. Fresh gas then appears due to outgassing, but at a very slow rate with each VI having its own inherent outgassing rate. This means that an extended magnetron reading can only be done once on a given VI, and if there is a failure to capture the data then the opportunity is lost. During VI manufacture this can be overcome by automatically switching the High Voltage (HV) off as soon as the peak has been passed.

3. **No-strikes occur**. After switching on the magnetron's HV voltage and magnetic field, it can take a while for the pulse to occur, and if no discharge is seen during the test period, this is termed a "No-strike". It is supposed that a first random ionisation sets off an avalanche discharge and that this first event may be due to a particle of radiation from a cosmic ray or the earth's crust. Sometimes there is a very long wait before a pulse arrives and the problem appears to get worse the lower the vacuum pressure to be measured. Quite often no pulse may occur in a reasonable time.

TABLE 1. MAGNETRON PRESSURE MEASUREMENTS ON VI AS RECEIVED WHEN ABOUT 35 YEARS OLD IN 2013, REPEATED IN 2015 AND AGAIN IN 2017

VI No.	**2013 measured pressure**	**2015 measured pressure**	**2017 measured pressure**	**Outgassing rates calculated from 2015 pressure**	**Predicted 2017 pressure, 2015 data**	**Ratio of predicted 2017 pressure to actual**	**Outgassing rates calculated from 2017 pressure**
	mbar	***mbar***	***mbar***	***mbar/year***	***mbar***	***mbar***	***mbar/year***
T198	4.6E-05	7.0E-07	8.20E-07	3.5E-07	7.8E-07	0.96	3.6E-07
T199	9.4E-05	3.4E-05	1.50E-05	1.7E-05	3.8E-05	2.55	6.7E-06
T203	2.3E-05	1.7E-06	7.00E-07	8.5E-07	1.9E-06	2.73	3.1E-07
T204	4.0E-05	1.6E-06	5.30E-07	8.0E-07	1.8E-06	3.42	2.4E-07
T206	1.8E-05	8.0E-07	3.60E-07	4.0E-07	9.0E-07	2.50	1.6E-07
T208	4.4E-05	2.4E-06	6.00E-07	1.2E-06	2.7E-06	4.50	2.7E-07
T210	6.0E-05	3.4E-06	1.10E-06	1.7E-06	3.8E-06	3.48	4.9E-07
T211	2.0E-05	1.8E-06	6.40E-07	9.0E-07	2.0E-06	3.16	2.8E-07
T213	4.0E-05	1.0E-05	7.40E-06	5.0E-06	1.2E-05	1.52	3.3E-06

4. **The pulses are erratic.** Sometimes there is a double peak, as in the example of figure 2. Possibly a first discharge sets up between one contact and one end of the shield and then a second discharge sets up between the other contact and the other end of the shield. Because of this it is sometimes difficult to know what value to take as the peak. Pulses can also be irregular in other ways.

III. THE 2017 FINDINGS

It was disappointing that although a pulse was obtained for all sixteen VI in 2015, this time there were seven no-strikes after wait times around six minutes, and therefore only nine VI gave a pulse. However, the nine readings gave a clear result. It is possible that some or all of the no-strikes had a pressure below the measurable range, and any discharge was not seen due to instrument noise.

The measurements for 2013, 2015 and 2017 are shown in Table 1, listing only those VI that gave a pulse in 2017. Looking at the average values it is clear that the pressures in 2017 are on average over ten times lower than in 2013, and half as much as in 2015. Furthermore in all cases the discharges in 2017 died away to a value too low to be measured, and so was actually much lower than in a newly made VI. We conclude that the magnetron pumping was permanent in these VI. We now expect it to be followed by continued normal outgassing at each VI's inherent outgassing rate.

A. *Outgassing rates and pressure calculations*

Annual outgassing rates were calculated from the 2015 data by assuming that the pressures were zero after the 2013 testing, and dividing by the two years between the two sets of readings, as shown in the fourth column of the table. These 2015 outgassing rates were then used to predict the pressures expected 2.25 years later, in 2017. These predictions varied from 0.95 times the predicted value with the average being 2.4 times the predicted value. This is in the same range as the accuracy of the measurement, and so we believe it to be a reasonable correlation.

IV. DISCUSSION

It was suggested in our 2015 paper that permanent magnetron pumping of VI is due to the extreme cleanliness of the copper parts, because the normal passivating oxide layer has been etched away during manufacture, leaving exposed pure copper, which is a fairly reactive metal. Ionised gas particles are very reactive and so form solid compounds with the copper. Perhaps also ions accelerated to 5000V can become buried in the copper. Chromium vapour from the contacts faces deposited during arcing operation of the VI may also play a role. Chromium, like copper, forms a self-passivating layer of oxide in air, but an arcing deposit will expose the pure metal.

Whether this is the mechanism or not, the results presented here confirm that permanent magnetron pumping is a real phenomenon. We propose that both in post-production testing and in the testing of old VI, magnetron pumping can be used as a form of gettering.

A. *Some implications of the findings*

An average outgassing rate of 1.3×10^{-6} mbar/year was measured for these particular VI, which were all of the same type from the same manufacturer. This implies that a VI that had a pressure of 1×10^{-6} mbar when new would have a pressure of 2.7×10^{-5}mbar when 20 years old, which is the usual manufacturer's stated product life. A conservative estimate of the pressure at which a VI could fail to hold volts is 1×10^{-3}mbar. At the measured outgassing rate it would take 770 years to reach this pressure. Outgassing rate of course depends strongly on furnace temperature and time as well as the materials the VI is made of, but we conclude that it should be perfectly feasible to make VI with a product life of 100 years, assuming that we exclude other factors such as corrosion or damage.

The normal practice in manufacture for leak detection consists of measuring the pressure of newly made VI with a magnetron pressure measuring machine and then storing them for a few days and measuring again, in order to detect any leakage [4]. These results suggest that a greater understanding of the magnetron test would lead to a more diagnostic interpretation of such tests and perhaps a reduction of the storage time required, or even elimination of the need for a second test.

B. *Are magnetron pulses correctly interpreted?*

It can be seen from table 1 that there is there is quite a wide scatter of pressure values among the VI in the sample, and the pressures for individual VI are not consistent between 2015 and 2017. It was also observed that some pulses seem to be much narrower than others, as shown in figure 2. We suppose that a pulse continues until all the free gas particles in the VI have moved by thermal motion into the region of the discharge, become ionized and eventually settled on the walls of the container. Each ion can be expected to transport one or perhaps two units of positive electric charge, with electrons transporting corresponding negative charge the other way, so that an amount of charge proportional to the number of gas particles is transported. The number of gas particles equates to the pressure. This implies that it might be better to measure the time integral of the current in a magnetron pulse, and that this would give a pressure reading independent of pulse shape. We intend to investigate this and report at the next conference in 2019.

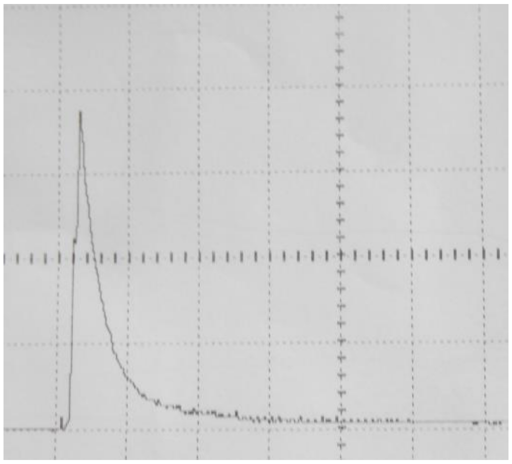

Figure 2. The pulse for specimen T199. This is narrower than other pulses, and its peak value is higher than that of other VI in the batch. This occurred both in 2015 and 2017, suggesting that particular VI may have particular pulse shapes.

V. CONCLUSIONS

We conclude that it is possible and useful to measure VI outgassing rates in this way, but it does take a year or so. We also conclude from these findings that the concept of each VI having an inherent outgassing rate is correct.

All but one pressure measurement made in 2017 showed that the pressure estimate was pessimistic, with the actual outgassing rate being lower than predicted. It may be that the inherent outgas rate is not linear as assumed but instead reduces slowly with time. We shall investigate this further in another paper.

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