VACUUM INTERRUPTERS: PRESSURE VS. AGE
A Study of Vacuum Levels in 322 Service-Age Vacuum Breakers

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ABSTRACT

Millions of vacuum interrupters (VIs) are installed worldwide with hundreds of thousands of breakers and contactors in the field that have exceeded their vacuum design lifetime of twenty years. To determine the effect of VI age on its internal vacuum level (pressure) we measured the pressure of 815 VIs from 322 breakers which had been removed from service. All breakers we tested were a variety of ratings but were from a single manufacturer and type. The internal VI pressure was measured, with the pole assembly still fastened to the breaker, using a field portable magnetron (Magnetron Atmospheric Condition – MAC tester).

INTRODUCTION

Since the first large influx of equipment and breakers into the market based upon vacuum interruption in the early 1970s, the technology has become the most widely applied power interruption technique in the medium voltage range (2.4kV - 38kV). Vacuum technology now dominates the interrupter market throughout the world. There are millions of vacuum circuit breakers installed and probably on the order of 10 million vacuum contactors. There are hundreds of thousands of vacuum breakers and contactors in the field that were manufactured twenty or more years ago. The question arises as to how long these VIs manufactured many years ago will maintain the vacuum level required for proper operation.

All vacuum interrupters (VIs) increase in internal pressure over time. [Authors' note: In this paper the modern term *vacuum interrupter* will be used in lieu of the now obsolete *vacuum bottle*.] The pressure increase may be due to small, long-path leaks from outside to inside, diffusion through the container materials and/or virtual leaks from materials within the internal volume. VI manufacturers design and test their vacuum interrupters for a minimum lifetime of twenty to thirty years. VIs may successfully operate beyond this period but it is beyond their design life. With the large number of VIs in the field which were manufactured over 20 or 30 years ago it seems likely that in-service VI failures caused by vacuum loss have greatly increased over the last 10 years.

As part of their vacuum breaker maintenance routine manufacturers recommend a vacuum integrity test. This test consists of applying an AC power frequency rated voltage across the terminals of a VI at its rated gap. If the VI is able to withstand the voltage for the manufacturer specified length of time the VI is deemed to have good vacuum. Passing this test indicates that the VI vacuum is sufficient to successfully interrupt a fault but gives no indication of how close the VI is to having a vacuum level which would cause it to lose its capability for clearing a fault.

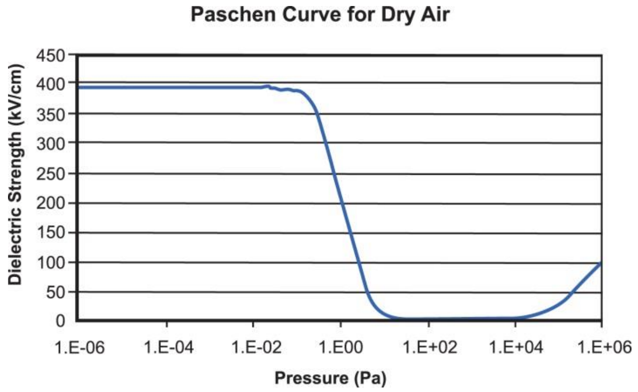
Until recently there was no technology that allowed field testing vacuum levels in VIs. Using a field portable magnetron, test technicians can now test vacuum level and thereby evaluate the VI condition based on that parameter. The vacuum level test is called the Magnetron Atmospheric Condition (MAC) test.

To further study the effect of VI age on its vacuum level, the authors performed vacuum level, as well as other, tests on 815 VI's installed in over 300 vacuum circuit breakers, covering a range of ratings, service histories manufacturing dates, etc., which have been removed from service. The breakers had nameplate manufacturing dates ranging from 1978 through 2014. It was assumed that the VI manufacturing dates were the same as the breakers in which they were installed due to sequential serial numbers.

This paper describes the data gathering and analysis methodology, summarizes the results of the analysis, and discusses an interpretation of those results. Before describing our measurements and analyses, brief descriptions of vacuum insulation, methods of evacuating and sealing VIs, sources of leaks in VIs and how a magnetron tester determines the vacuum level in a VI are given below.

Vacuum Level vs. Interrupting Rating

From Paschen's Law (Louis Karl Heinrich Friedrich Paschen 1865-1947) we know that the dielectric strength between two electrodes is a function of the pressure of the gas between them.



Paschen Curve for Dry Air
Figure 1

Figure 1 shows Paschen's Law applied to dry air in a volume containing electrodes at spacing typical of those in a vacuum interrupter. The horizontal axis is the air pressure in Pascals (Pa), and the vertical axis is the dielectric strength in kilovolts per centimeter of electrode separation.

As the pressure in the interrupter is decreased from one atmosphere (≈1×10^5 Pa) the dielectric strength first drops to a very low level. Then, at around 10 Pa the dielectric strength starts to rise. At 10^{-2} Pa the dielectric strength has reached slightly less than 400 kV/cm and remains constant for all lower pressures.

Although manufacturer design specifications vary slightly, most newly made VIs have internal pressures in the range of 10^{-4} Pa to 10^{-7} Pa; however, all VIs leak to some degree, and as the pressure rises, the dielectric strength will start to decrease when the pressure exceeds approximately 10^{-2} Pa. At 10^{-1} Pa, the dielectric strength decreases rapidly.

Methods of Evacuation and Sealing of VIs

The construction and sealing of the enclosure which provides the high vacuum environment for the inner workings of the VI is achieved in one of 2 ways depending on the materials of which it is constructed.

VIs constructed of glass cylinders generally have metal flanges embedded on either end which permits their TIG welding to each other and to metal endplates to which the contact support structures and a copper tubulation has previously been brazed. In order to evacuate the VI, the tubulation is connected to a multistage vacuum system and pumped while baking the assembly at several hundred degrees. After achieving the required level of vacuum the VI tubulation is "pinched off" leaving a stub denoted as the pinch off tube.

VIs constructed of ceramic cylinders do not have metal embedments; rather, the ends are ground flat and metallized such that properly designed metal endplates (to which contact support structures have been previously brazed) can be brazed to their surfaces. In this type of construction the VI is evacuated and sealed in the same furnace and the same time that the ceramic cylinder(s) is brazed to the endplates. In this type of design there is no pinch off tube.

Leaks in a Vacuum Interrupter

The internal pressure of a vacuum interrupter can be increased by three main causes: gas permeation, virtual leaks, and real leaks.

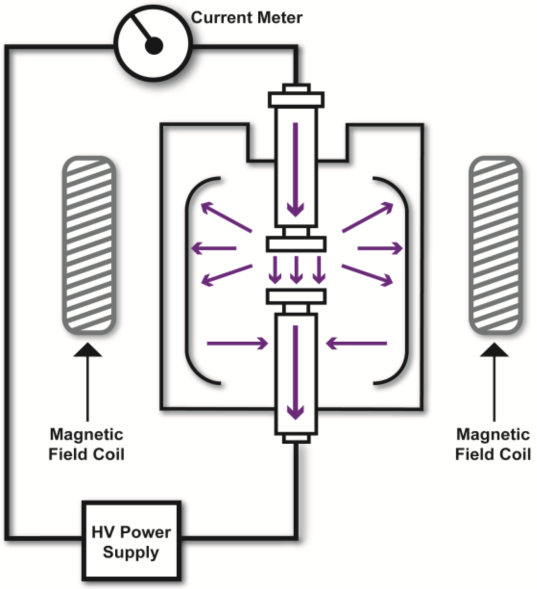
Gas permeation is the infiltration of gases into the vacuum interrupter volume through the insulation material and metallic surfaces by diffusion. Only very small molecules, such as hydrogen (H_2) or helium (He), can diffuse through these materials. The upper limit of the internal pressure that can be attained by diffusion is in the range of 10^{-2} Pa. [1] To help control the pressure increase from these leaks, a *getter* material is normally mounted inside the vacuum interrupter which provides a continuous pumping for low levels of H_2, N_2, O_2, and other various residual gases. [2] This getter material is activated by high temperatures during the final stages of the vacuum interrupter manufacturing process and will function until the getter surface has been saturated with gas molecules. Note that the getter is ineffective at pumping inert gases such as helium or argon.

Virtual leaks are the results of outgassing from internal surfaces and parts as well as diffusion of gases from “trapped” volumes (from poor brazes or welds) to the main VI volume. Research performed on one type of vacuum interrupter in 1978 showed that “gas evolved from the bulk of the material was the major contributor to pressure buildup.” [3] Improved manufacturing techniques have significantly reduced this type of leak by selecting well-refined, low gas content materials and by fully degassing parts in the production process of the vacuum interrupter. [4]

Real leaks are gases penetrating the interior of the vacuum interrupter through microscopic paths caused by manufacturing defects, mechanical damage, corrosion, and/or external flashover. With the exception of corrosion, the rate of internal pressure increase caused by real leaks is much greater that leaks caused by gas permeation and virtual leaks. Most real leaks cause failure due to inadequate vacuum in a short period of time. Corrosion can result in a slower leak which can take as long as a year to compromise the integrity of the vacuum. [1]

As vacuum interrupters age, a combination of the described factors cause an increase in internal pressure and, depending on the environmental, circuit, and mechanical conditions, may increase faster or slower for a given vacuum interrupter.

TESTING VACUUM LEVEL



Penning Discharge Principle
Figure 2

Determining the pressure in an enclosed, sealed chamber is done using a test based on the Penning Discharge Principle. (Frans Michel Penning 1894-1953) Penning showed that when a high voltage is applied to open contacts in a gas and the contact structure is surrounded with a magnetic field, the amount of current flow between the plates is a function of the gas pressure, the applied voltage, and the magnetic field strength. Figure 2 is a diagram of the test.

A magnetic field is set up by placing the VI into a field coil. The field is created by a direct current and remains constant during the test. A constant DC voltage, usually 10 kV or greater, is applied to the open contacts and the current flow through the VI is measured.

Since the magnetic field and the applied voltage (DC) are both known, the only variable remaining is the pressure of the gas. If the relationship between the gas pressure and the current flow is known, the internal pressure can be calculated based on the amount of current flow.

The test equipment used to perform this procedure is called a *magnetron*. Until recently, the magnetron was a very bulky and difficult to use in the field. It was, therefore, relegated to manufacturer laboratory testing.

In recent years, more portable equipment has become available and the vacuum level can be readily tested in the field. Figure 3 shows such a test set up. Note that this configuration does not require removal of the pole assembly from the breaker.

VI Vacuum Test (MAC Test)
Figure 3

OBJECTIVES

As the data collection and testing progressed it became clear that we had five basic objectives in mind:

1. What, if any, correlation exists between the VI age and its internal pressure.
2. What, if any, correlation exists between the VI age and its AC HiPot test results.
3. What, if any, correlation exists between the VI age and its contact resistance.
4. What, if any, correlation exists between the VI vacuum level and the AC HiPot results.
5. Do the AC HiPot test results have any predictive value as far as the VI serviceability is concerned or is the AC HiPot strictly a go no-go test?

EXPERIMENTAL METHODOLOGY

Test Population

The 322 circuit breakers were all the same model and from the same manufacturer but included a range of ratings and VI types. All of the breakers had been in actual service at some point in their history. None of the breakers or interrupters had been modified from the manufacturer's original specifications with the exception that some of the breakers had 1 or 2 VIs missing. The total number of VIs tested was 815.

One manufacturer was used to eliminate any statistical differences that might occur due to different manufacturing methods. Future tests will be performed on other manufacturers and the differences, if any, will be noted.

Test Procedure

1. Document the condition of the breakers and all components visually using digital photography. Note any differences and classify pinch tubes if present.
2. Record all nameplate information. Take high resolution digital photos.
3. Thoroughly clean all dust and contaminants from the breaker
4. Check primary contact erosion
5. Perform contact resistance tests
6. Perform MAC Test
7. Perform AC High Potential Test and measure/record leakage current at the recommended test voltage.

COLLECTED DATA

Nameplate data collected for all circuit breakers includes manufacturer, breaker type, serial number, rated max voltage, impulse voltage, rated amps, cycles, hertz, rated voltage range, close and latch compatibility, date of manufacture, close coil details, trip coil details, connection diagram, mechanism type, vacuum interrupter type, phase serial numbers, phase pinch tube details, and weight.

Inspection data collected includes the breaker mechanical operations before and after testing, ambient temperature, humidity, and the technician ID.

Test data collected for each of the three phases includes the MAC Ion Current, Contact Gap, Contact Resistance, AC HiPot Test (pass/not pass and the leakage current), and Contact Time Open and Close results.

Approximately ten percent of the tested population (84 out of 815) exceeded the maximum pressure measurable with the MAC tester (~5 x 10E-1 Pa – high pressure). These units were not included in the analysis since our analysis method requires continuously variable data.

The percentage of VIs with high pressure increases with VI age as illustrated below:

Table 1
VI Percentage of High Pressure Increases by Age

Age (Years)	High Pressure	Measurable Pressure
1 – 10	4%	96%
11 – 20	3%	97%
21 – 30	7%	93%
> **30**	20%	80%

DATA ANALYSIS

Correlation of Data Sets

The correlation coefficient (*r*) measures the direction and strength of the linear relationship between two quantitative variables. It is computed as follows:

$$r = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{x_i - \bar{x}}{s_x}\right)\left(\frac{y_i - \bar{y}}{s_y}\right)$$

Where:
r is the correlation coefficient
n is the sample size
x and *y* are the independent and dependent variables respectively
$\bar{x}$ and $\bar{y}$ are the means of *x* and *y*
s_x and s_y are the standard deviations of *x* and *y*

Due to the small sample size, we performed an additional calculation to offset any bias, seen here:

$$r_{adj} = r[1 + \frac{1 - r^2}{2(n-1)}]$$

Where:

r_{adj} is an unbiased estimator of *r*.

Note that for large values of n, $r_{adj} \approx r$. [5]

Properties

- For $r > 0$, there is a positive relationship between x and y; that is, when x increases, y increases. For $r < 0$ there is a negative relationship between x and y; that is, when x increases, y decreases.
- Correlation is always a number between -1 and 1. Values near -1 or 1 indicate a strong relationship and values near 0 indicate a weak relationship.
- The square of the correlation coefficient, r^2, is the fraction of the y values whose variance can be explained by a change in x.
- As with mean and standard deviation, r is heavily influenced by outliers.

DISCUSSION OF RESULTS

A Magnetron Atmospheric Condition test (MAC) was performed on 815 vacuum interrupters of varying age to determine the internal pressure. The MAC test measures the current generated by ionized gas molecules inside the vacuum interrupter and converts this value to a pressure using formulas (curves) based on experimental data. A set of curves was produced to maintain a high degree of accuracy when testing VI's of different diameters. Vacuum interrupter manufacturers use the same procedure when performing quality control tests on new vacuum interrupters. For the calculations, a normalized MAC Pressure result in Pascals was used. Of those 815 vacuum interrupters, 772 were also given a High Potential test for comparison.

Data Distributions

Figures 4 through 7 are scatter plots of the various comparisons performed in the analysis of the VI data. Correlation coefficients were calculated for each of the data sets that are shown with the curve fits most commonly found in nature, including linear, logarithmic, exponential, square, and square root distributions. Each graph has a note indicating the best fit distribution.

Table 2
Correlation Coefficient Calculations

Distribution	*x* Variable	*y* Variable	*r*	r_{adj}	r^2
Exponential	Age	MAC Pressure	0.4105	0.4107	16.87%
Exponential	Age	AC HiPot	0.1194	0.1195	1.43%
Exponential	Age	Contact Resistance	0.3171	0.3173	10.07%
Linear	MAC Pressure	AC HiPot	-0.0362	-0.0362	0.13%

Divisions within Data

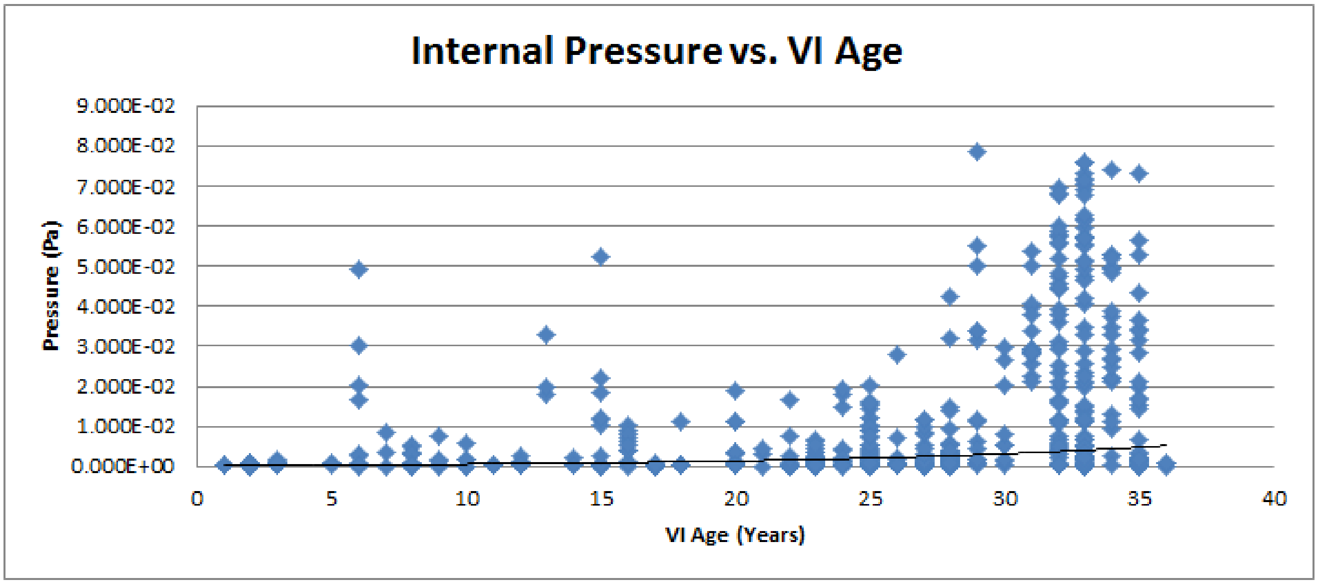
To ensure a homogeneous data set, the correlation coefficients of MAC Pressure values and the age of the vacuum interrupters for the entire sample and for subgroups designated by VI Type, MVA, Mechanism Type, and Pinch Tubes were computed. None of these divisions had a significant impact on the strength of the relationships. All results are for the VI sample as a whole.

Relationships

In addition to the MAC Pressure and VI age relationship, correlation coefficients were calculated for AC HiPot results versus VI age, Contact Resistance versus VI age, and MAC Pressure versus AC HiPot results. The strongest relationship was found to be age of the VI versus the MAC Pressure values, with an unbiased exponential correlation coefficient (r_{adj}) of 0.4107. This is a much stronger relationship than the 0.1195 r_{adj} value for AC HiPot test results versus VI age. As more time-related data becomes available we expect the individual VI curves will more closely follow the exponential change. This will lead to larger correlation coefficients.

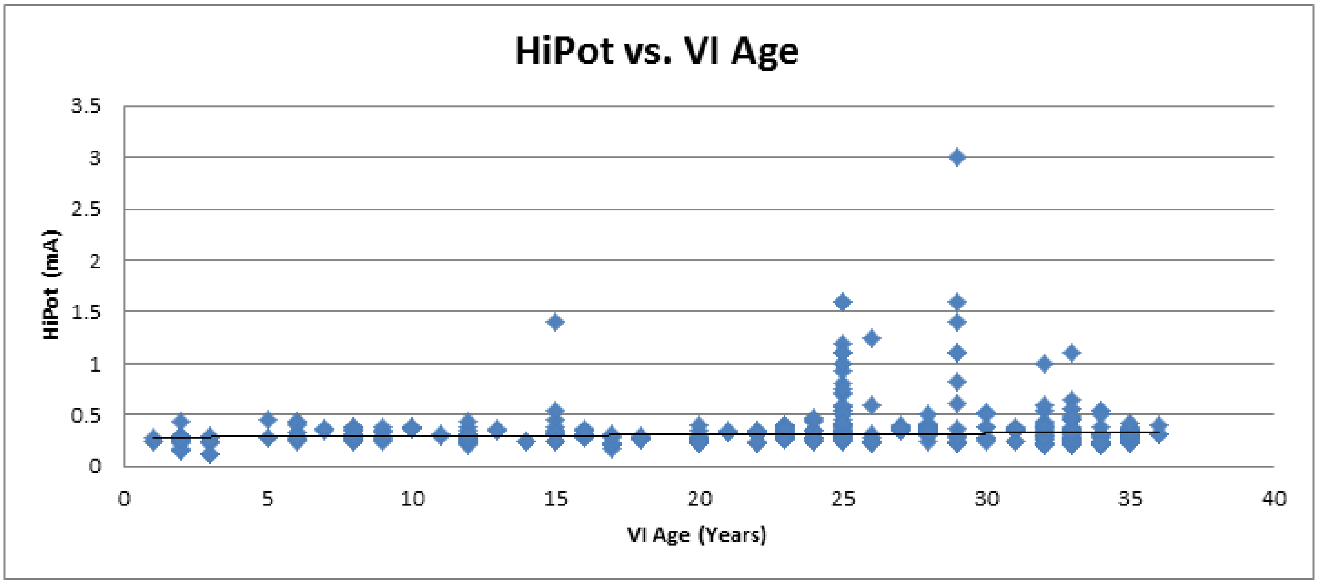
MAC Pressure and Age

In Figure 4, there is an exponential rise in pressure values over time. The increased spread in pressure values for the older VIs is expected. We believe additional tests over time of the same sample VIs will reinforce the relationship between MAC Pressure results and age. This would remove much of the variance caused by both environmental and internal variables.



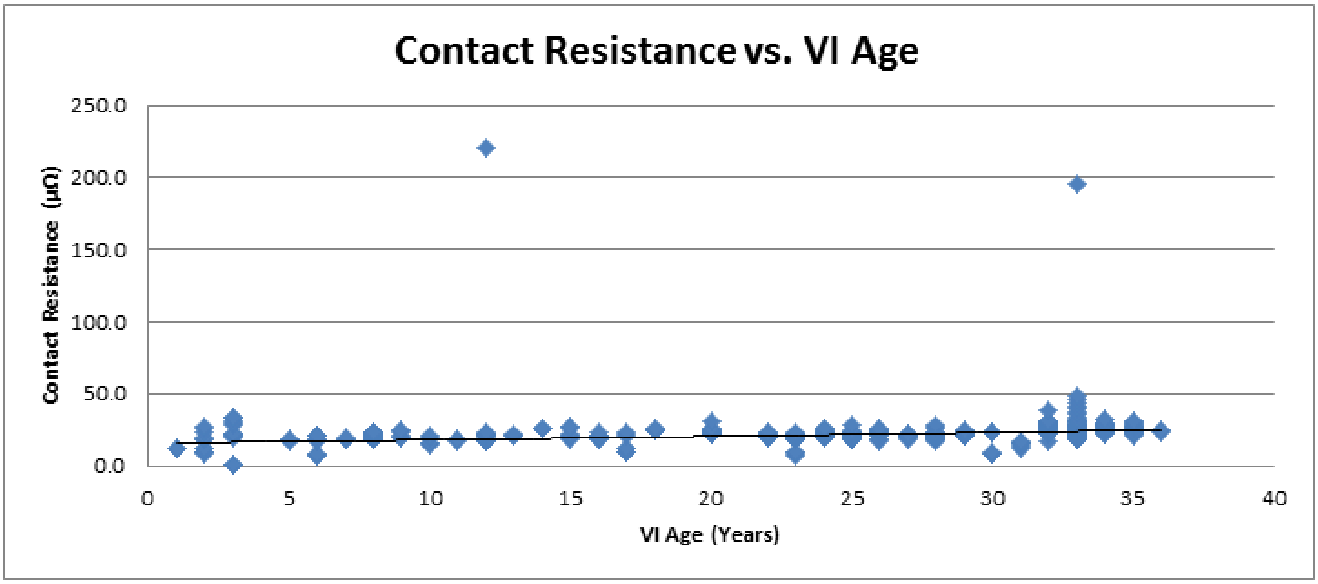
Exponential Distribution of Internal Pressure vs. VI Age where r_{adj} = 0.4107 and r^2 = 16.87%
Figure 4

AC HiPot and Age



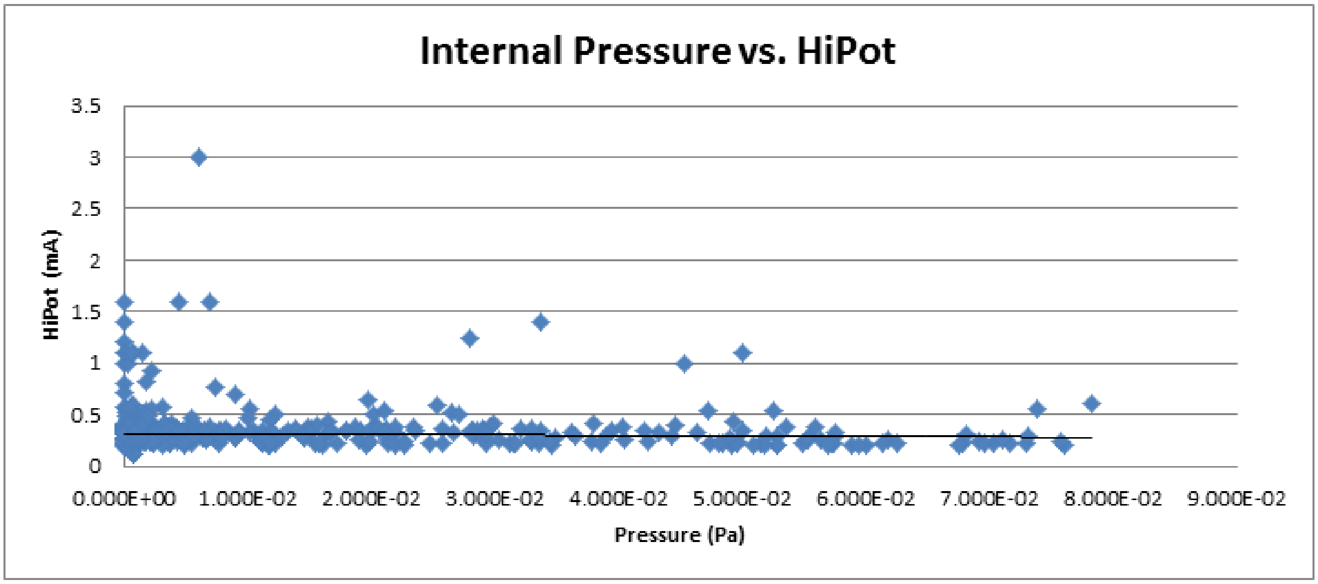
Exponential Distribution of AC HiPot vs. VI Age where r_{adi} = 0.1195 and r^2 = 1.43%
Figure 5

Contact Resistance and Age



Exponential Distribution of Contact Resistance vs. VI Age where r_{adj} = 0.3173 and r^2 = 10.07%
Figure 6

MAC Pressure and AC HiPot



Linear Distribution of Internal Pressure vs. AC HiPot where r_{adi} = -0.0362 and r^2 = 0.13%
Figure 7

SUMMARY

Tests were performed on 815 service-aged vacuum interrupters from the same manufacturer, of similar design, and of similar type with a range of manufacture dates from 1978 to 2012. The tests performed were the contact resistance, ac high-potential test, and MAC tests. After the data was compiled correlation calculations were made for the following:

- VI pressure (Pa) versus VI age
- AC leakage (mA) (HiPot) versus VI age
- Contact resistance (μΩ) versus VI age
- AC leakage(mA) (HiPot) versus VI pressure (Pa)

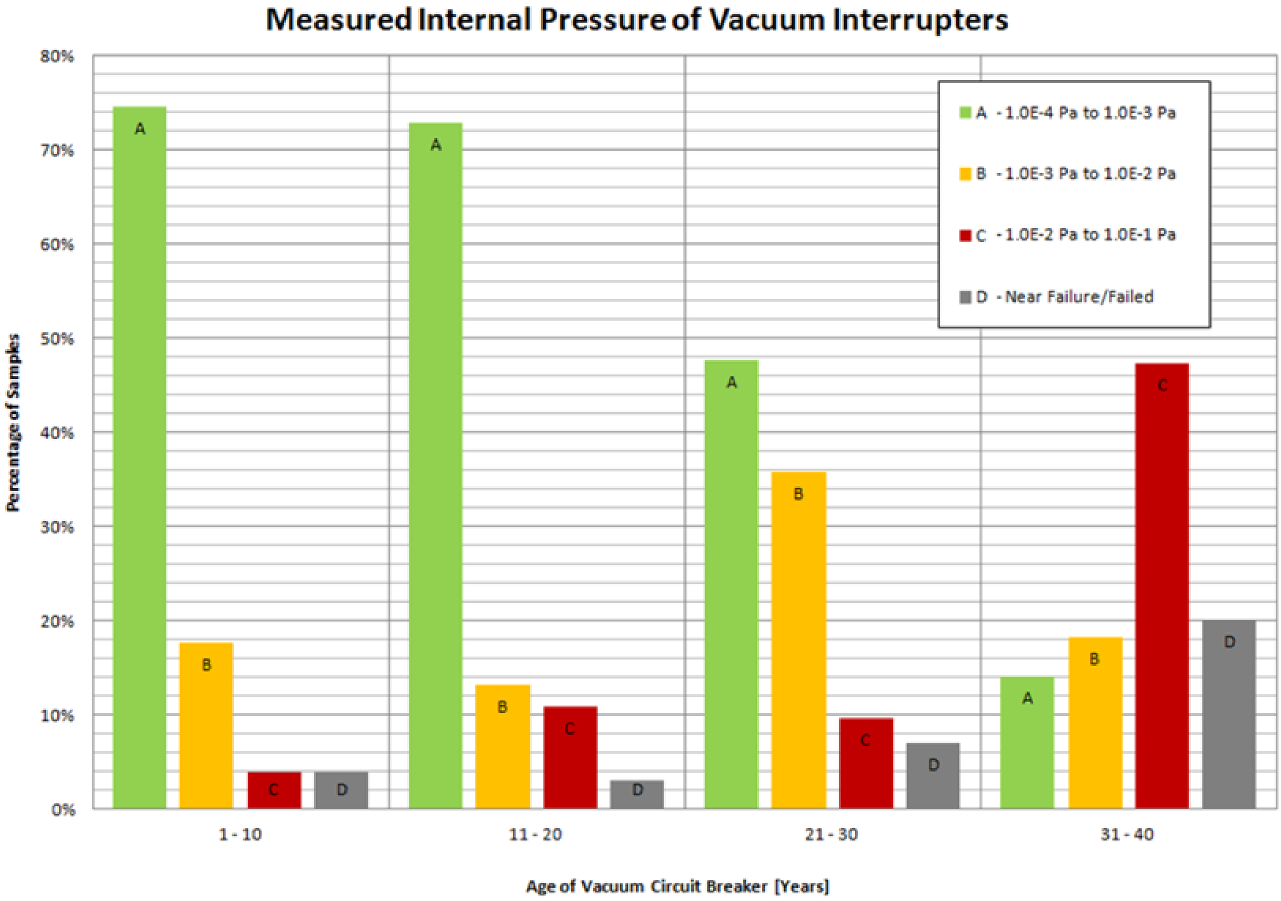
Figure 8 shows a bar graph of the VI pressures grouped by age.

Three variables were not factored into the final calculations.

Numbers of Operations: The numbers of operations were captured in the dataset and preliminary correlation calculations were made against the other variables. Based on these results it was decided not to factor numbers of operations into this study.

In-Service Ambient Conditions: There was no way to qualitatively or quantitatively include variations of in-service ambient conditions. It is possible, though by no means certain, that wide in-service temperature extremes could increase the VI leakage rate. This is being looked at and considered for a future iteration of this research.

Time-Related Data for Individual VIs: No data was available for individual VIs with respect to time prior to the present study. Our Condition Based Maintenance research has shown that inclusion of individual time-based data greatly improves the quality of the statistical analysis. We have isolated ten of the breakers from the present study to be fully reevaluated in a five year period. This will help to establish important leak rate information for the VIs being tested and provide a means for projecting failure due to internal pressure rise.



VI Pressures by Age Group
Figure 8

CONCLUSIONS

We have drawn the following conclusions from our research:

1) There is a relatively close, exponential correlation between VI age and internal pressure. We believe that this correlation will be strengthened by an increase in the size of the database and inclusion of time-related data for individual breakers.
2) There is a small to moderate correlation between the contact resistance and VI age.
3) There is a minimal correlation between AC HiPot test and VI age.
4) There is very little correlation between AC HiPot leakage current results and internal pressure.

Given the proven relationship between dielectric strength (interrupting ability) and vacuum level, we are confident in offering the following:

1) The MAC test (VI internal pressure) provides excellent predictive data for determining VI continuing serviceability. The MAC test should be considered as an important tool in the breaker maintenance tool bag.

2) Contact resistance testing may provide some value as a predictive tool; however, there are two significant issues that must be accounted for.
   a) Frequent contact erosion adjustments must be accounted for. For example, the interrupter contact pressure can change with wear/interruption history.
   b) The significant differences in contact area (a 400 ampere VI versus a 3000 ampere VI) must be accounted for.
3) Since there is very little correlation between AC HiPot leakage current and VI age or vacuum level, the high-potential test is of no value in any predictive maintenance program for the VI. We recommend using the AC HiPot test for evaluating the current functioning of the VI as well as the other insulation systems in the breaker. However, the addition of the MAC test will provide a means of actually estimating the remaining vacuum life of the VI and is a valuable tool in selecting which VIs are due for replacement.

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BIOGRAPHY

A registered professional engineer, John Cadick has specialized for over four decades in electrical engineering, electrical safety, training, and management. In 1986 he founded Cadick Professional Services (forerunner to the present-day Cadick Corporation), a consulting firm in Garland, Texas. His firm specializes in electrical engineering, marine services and training, working extensively in the areas of power system design and engineering studies, condition based maintenance programs, and electrical safety. Prior to the creation of Cadick Corporation, John held a number of technical and managerial positions with electric utilities, electrical testing firms, and consulting firms. Mr. Cadick is a widely published author of numerous articles and technical papers. He is the author of the Electrical Safety Handbook as well as Cables and Wiring. His expertise in electrical engineering as well as electrical maintenance and testing coupled with his extensive experience in the electrical power industry makes Mr. Cadick a highly respected and sought after consultant in the industry.

Finley Ledbetter is the Chief Scientist for Group CBS Inc. with over thirty-five years of power systems engineering experience a member of the IEEE and past president of PEARL.

Jerod Day received his B.S. and M.S. degrees in Mechanical & Energy Engineering in 2010 and 2012, respectively, from the University of North Texas, Denton, TX. Jerod has coauthored publications including the J. Heat Transfer. He is the Vice President of Vacuum Interrupters, Inc. in Carrollton, TX which specializes in vacuum interrupter design and testing. Mr. Day has five years of field experience with medium voltage circuit breakers and switchgear.

John Toney, trained as an electrical engineer, has specialized for over thirty years in the design, development, testing and manufacture of vacuum interrupters / vacuum circuit breakers. Currently he is a design engineer for Vacuum Interrupters Inc.
His undergraduate degrees are from University of Michigan—Ann Arbor (BS in Astronomy and BSEE) and his master's degree is from Drexel University—Philadelphia (MSEE).

Finley Ledbetter III Received his B.S. degree in Electrical Engineering from The Texas Tech University in 2011. He has worked for three years at Western Electrical Services as a field service engineer earning his NETA Level II Assistant Technician certification and more recently as product manager for the Instrument group a Vacuum Interrupters Inc. Finley's responsibilities include developing new technology for Group CBS and performing field testing and demonstrations. Finley has the distinction of performing more field MAC tests than any other engineer or technician.

Gabrielle Garonzik holds a bachelor's degree in Actuarial Sciences from the University of Texas. She signed on with Cadick Corporation in 2005 developing CBM 2010, a predictive maintenance algorithm for electrical equipment. She is currently the Director of Research and Development for Cadick Corporation.

APPENDIX
Glossary

1. *Correlation Coefficient (r)*: a number between −1 and +1 calculated so as to represent the linear dependence of two variables or sets of data.
2. *Correlation Coefficient squared (r^2)*: a value which represents the fraction of the variation in one variable that may be explained by the other variable.
3. *Getter*: A deposit of reactive material that is placed inside a vacuum system for the purpose of achieving and maintaining operating vacuum levels.
4. *Vacuum Interrupter*: A current interruption device in which the interrupting contacts are enclosed in a vacuum.