A study of vacuum levels in a sample of long service vacuum interrupters

L. T. Falkingham[1] R. Reeves[1] S. Mistry[1] C. H. Gill[1]
[1]Vacuum Interrupters Limited, Rugby, UK

Abstract-
We report on the inspection and testing of 140 vacuum interrupters that had been in service with utilities. These had significantly exceeded the normal 20 year vacuum lives originally assigned by the manufacturers, but were still considered to be good, and remained in service. Our sample included interrupters of a number of different types from two manufacturers.

We found that some interrupters still had an extremely good vacuum. The majority had a slightly degraded vacuum, but we could confidently predict a further 10 or 20 years of use. A few had a poor vacuum and needed to be replaced urgently. A small number had such a poor vacuum that they failed a voltage withstand test, and were not suitable for vacuum measurement. This study concludes that although the reliability of vacuum interrupters is extremely high during the normal service life, interrupters in use for significant periods beyond this life have a significantly higher probability of vacuum failure, following the predictions of the classic "bath tub" curve of failure.

I. INTRODUCTION

Vacuum Interrupters were first used as the switching element in medium voltage switchgear about 50 years ago and today the majority of installations of medium voltage switchgear in the world use vacuum interrupters.

Manufacturers typically quote a service (vacuum) life of 20 years when supplying interrupters. This normally ties in to the manufacturer's quality programme where the worst case rise in pressure is calculated not to exceed a value of pressure which would affect the dielectric properties of the vacuum insulation. Service life of vacuum interrupters is discussed in more detail in [1].

Among the known failures of vacuum interrupters in service, the most common cause has been loss of vacuum. We would expect vacuum interrupters to follow the bathtub curve for failure, whereby there is an initial relatively high failure rate due to manufacturing faults, followed by a long period of low failure rate, followed at some point by a rising failure rate due to end-of-life mechanisms starting to work. In the early days of Vacuum Interrupters, manufacturers had no clear idea of when this will start to happen for vacuum interrupters or what the end of life mechanisms might be, although we would expect loss of vacuum to be prominent. Therefore they used worst case calculation to estimate a minimum life expectancy, which many manufacturers set at 20 years.

Today an increasing number of interrupters in service are now 30 to 40 years old and it is now possible to examine the question "how long can a vacuum interrupter remain in service without the probability of failure significantly increasing?"

In pursuit of this have been testing a large number of interrupters that had seen long service with utilities and were withdrawn temporarily from service and sent to us for examination and revalidation. All interrupters received were considered to be in good condition and fit for service by the utility. In 2009 we reported our initial results from 10 interrupters [2], which indicated that the pressure in some interrupters had degraded significantly, this was a surprising result to us, and so we decided to check a much larger sample to see if this was just a rogue sample. We have now collated the results from a much larger sample, of 140 interrupters, and we now present the results of the tests on these in order to try to provide more light on the problem outlined above.

II. THE SAMPLE OF INTERRUPTERS EXAMINED

There were 128 interrupters of three types, and a further twelve interrupters of small numbers of each type. The interrupters tested were from two different manufacturers and had been used in a number of applications with different clients.

TABLE 1. TYPES OF INTERRUPTER IN THE SAMPLE

Type	number	Manufacturer
A	80	X
B	30	X
C	18	Y
Others	12	X/Y
Total	**140**	

When interrupters are sent to us we do not normally receive full information about them. However from the circuit breaker installation dates and serial numbers we

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believe that these interrupters had all been in service for between 25 and 40 years, with the majority for more than 30 years.

III. Initial Examination

Visual inspection showed that nearly all the interrupters were in good condition. Many had coatings of anti corrosion paint or grease on the metal parts, but none showed signs of significant corrosion. Quite often the insulating ceramic was fairly dirty, but could be wiped clean with a dry cloth or with the help of water or a solvent.

One interrupter had a small chip of ceramic broken off, but it proved to be good for continued service.

A number of interrupters made by manufacturer Y had discharge markings and discolouration on their ceramics but all of these passed the tests described below.

We conclude that normal external wear and tear was not a problem for any of the interrupters.

IV. Contact Wear

We had information on contact wear for the majority of the sample (71 devices). But the wear could not be measured in 69 of the sample. In all cases we knew that the allowed wear was 3mm,

TABLE 2. Contact Wear Measurements

Indicated wear	Remaining permitted wear	Number of interrupters
0 mm	3 mm	42
0.5 mm	2.5 mm	21
1.0 mm	2.0 mm	7
2.0 mm	1.0 mm	1
	Total	**71**

It can be seen that contact wear was normally moderate. The one interrupter with contact wear of 2.0 mm later failed its vacuum test, which may or may not be related.

V. Voltage Withstand Test

We apply 10 kV dc across the VI for one minute. If there is any current flow above about 0.3 mA of field emission current, then there must be gas in the interrupter at a pressure above the critical level, and the interrupter is quite unable to withstand its service voltage and is completely unsuitable for use. It is also unsafe to proceed to the vacuum measurement. Out of the 140 in the sample, four failed this test, passing current in excess of the 10mA capability of the test unit and causing it to trip. Two of these were made by manufacturer A and two by manufacturer B.

VI. Vacuum Level Measurements

Vacuum interrupters are generally made with a vacuum level of less than 1.10^{-6} mbar, i.e. less than one billionth of atmospheric pressure. If there is a very small leak, the pressure will rise over time to the unsafe level of 1.10^{-3} mbar, or one millionth of atmospheric pressure, at which level the gas will begin to conduct, leading to an avalanche increase in current and destruction of the interrupter. Manufacturers measure the vacuum level of each interrupter before shipping them.

a. Our vacuum level measurement equipment.

We have built an inverse magnetron instrument which replicates the measurement made by manufacturers. The interrupter is place in a magnetic field, which causes electrons to travel in circular paths, which increases their potential mean free paths a thousand or so times. The result is that when we apply 5kV dc across the interrupter a small pulse of current passes that peaks at a level determined by the amount of gas in the vacuum container, and then dies away. We capture this pulse, and the peak level is a measure of the vacuum level.

A more detailed description of the magnetron is given in [3] [4].

b. Temporary and permanent gases.

We do three measurements on an interrupter and then another three measurements seven days later. The first peak obtained is often quite a lot higher than the second or third ones. Some gases can be broken down by the discharge and permanently removed from the system. For example carbon dioxide might break down into free carbon and monatomic oxygen. These are very reactive and can form carbide or oxide compounds with the very clean copper surfaces in the interrupter, and so are no longer in gaseous form. Our testing can thus "pump" the temporary gases. Other gases, such as argon and molecular nitrogen may be temporarily ionized and adhered to solid surfaces, but they do not react and they are soon neutralized and return to the gaseous state. The second set of tests, after 7 days, checks that the temporary gases have not reappeared and that the pressure is not rising.

c. First pressure measurement results.

Table 2 shows the vacuum levels indicated by the first peak for all the specimens. The levels cover a wide range, four decades. We define the 10^{-5} range for example as pressures between 1.10^{-5} mbar and 9.10^{-5} mbar inclusive.

TABLE 3. FIRST PRESSURE MEASUREMENTS

Pressure	Number of interrupters
10^{-7} mbar range	31
10^{-6} mbar range	18
10^{-5} mbar range	30
10^{-4} mbar range	57
10^{-3} mbar range	4

d. *Second pressure measurement results.*

The table below shows the first measurement of the second set of three. The second and third of these measurements were similar, showing that in most cases the temporary gases had not reappeared. It can be seen that the pressures are now generally lower than in the first test, as expected.

TABLE 4. SECOND PRESSURE MEASUREMENTS

Pressure	Number of interrupters
10^{-7} mbar range	77
10^{-6} mbar range	10
10^{-5} mbar range	14
10^{-4} mbar range	37
10^{-3} mbar range	2

VII. INTERPRETATION OF THE RESULTS

Consider an interrupter which has a vacuum pressure of 1.10^{-4} mbar and which has been in service for at least 20 years. We do not know what exact pressure it had when first made, but from manufacturer's procedures we know that it would have been in the 10^{-6} mbar range or better, so a slight real or virtual leak has raised the pressure. A virtual leak might for example be gas diffusing out of slight porosities in the metal or ceramic, or contamination sealed within the device. If this leak continues, we would expect the pressure in another 20 years to be 2.10^{-4} mbar, which is still a safe pressure, so we would say that with this leak rate this interrupter would be fit for purpose for another 20 years. We are confident in doing this because we have simply replicated the manufacturer's original tests. 123 of the 140 interrupters were found to be good for at least a further 20 years.

If the measured pressure found was rather higher, at 3.10^{-4} mbar, its pressure in 20 years might be 6.10-4 mbar. Taking into account measurement errors and uncertainties, we would consider it suitable only for 10 years and state that it should be tested again after that. Nine of the interrupters came in this category.

e. *Vacuum level failure.*

If the measured pressure was in the 10^{-3} range, we would classify this as a vacuum failure, and not consider it suitable for further use. Five of the interrupters were classified as vacuum failures.

VIII. THE RESULTS SUMMARISED

The results of examination and testing of our sample are summarized in the table below.

TABLE 5. SUMMARY OF THE RESULTS

Number of interrupters tested	140	100%
Number of HT failures	4	2.9%
Number of vacuum level failures	5	3.6%
Number good for another 10 years	9	6.5%
Number good for another 20 years	122	88%

It can be seen that the vast majority of interrupters are still in serviceable condition and should be good for at least another 20 years. However there is a significant number which have either failed (2.9%) or are approaching failure (3.6%).

IX. DISCUSSION

It is clear that vacuum interrupters have given very reliable service since their introduction, with a very low probability of failures known to be due to loss of vacuum. Manufacturer's claim MTTF figures in excess of 40,000 interrupter-years during the service life, and field experience agrees with this [1]. However, once the design life is exceeded then there will come a time when the failure rates will increase. Our testing of interrupters with a life in excess of the standard 20 years shows that a much higher percentage of interrupters are not fit for service due to high vacuum pressure or even HT test failure, than would be expected during the normal 20 year service life. The fact that most pressures measured were in the 10^{-4} mbar range indicates that a form of leakage has been occurring, and that these interrupters will not have good enough vacuum forever.

Our results clearly indicate that for these interrupters the failure rate is significantly different from the failure rate during the 20 year service life period, indicating that we are seeing the upward rise predicted by the Bath tub curve model. These results consolidate those from the sample of 10 that we reported previously [2], but even a sample of 140 is still quite small if we want a statistically valid estimate of failure rates, and far too small if we wanted this broken down by interrupter type, manufacturer and service application. The difficulty is that nearly all interrupters ever made are in service and opportunities to test them and make the results publicly available are few.

We intend to continue this work as a long term study to evaluate as many interrupters as possible in order to obtain a statistical basis for predicting vacuum interrupter life expectancy.

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E-mail of the author: reeves@vil.org.uk