International Academic Publishers Ltd.

ICREPEC 2nd 2007

Proceedings of the 2nd International Conference on Reliability of Electrical Products and Electrical Contacts

March 28–31, 2007
Asia Gulf Hotel, Xiamen, China

Edited by
Jingqin Wang   Jingying Zhao

China Science & Technology Press

International Academic Publishers Ltd.

Proceedings of the 2nd International Conference on Reliability of Electrical Products and Electrical Contacts

March 28-31, 2007

Asia Gulf Hotel, Xiamen, China

ICREPEC 2nd 2007

Edited by

Jingqin Wang Jingying Zhao

Organized by

Electrical Products Reliability Society of Chinese Electrotechnical Society

Sponsored by

Xiamen Hongfa Electroacoustic Co., Ltd.

Hebei Electric Motor Company Limited

Beijing Machine and Equipment Institute

Suzhou Electrical Apparatus Science Research Institute Co.,Ltd.

Huanyu Group Co., Ltd.

CHINA SCIENCE & TECHNOLOGY PRESS

· Beijing ·

图书在版编目（CIP）数据

第二届电工产品可靠性与电接触国际会议论文集 / 王景芹，赵靖英编. —北京：中国科学技术出版社，2007.3
ISBN 978-7-5046-4629-3

Ⅰ.第… Ⅱ.①王… ②赵… Ⅲ.①电子产品可靠性—国际学术会议—文集 ②电接触—国际学术会议—文集 Ⅳ.TM5-53

中国版本图书馆 CIP 数据核字（2007）第 023516 号

The book has been photographically reproduced from the best available copy. The papers were not refereed but were reviewed for their technical contents. Editing was restricted to matters of format, general organization and retyping.

The editors assume no responsibility for the accuracy, completeness or usefulness of the information disclosed in this volume. Unauthorized use might infringe on privately owned patents of publication right. Please contact the individual authors for permission to reprint or otherwise use information from their papers.

ISBN 978-7-5046-4629-3
First edition 2007

Edited by Jingqin Wang, Jingying Zhao

Proceedings of the 2nd International Conference on Reliability of Electrical Products and Electrical Contacts

China Science & Technology Press
Zhong Guan Cun Nan Dajie, No. 16
Hai Dian District, Bejing 100081, China
Printed in China

CONFERENCE ORGANIZATION

CONFERENCE CHAIRMAN

Jianguo Lu

CONFERENCE HONORARY CHAIRMAN

Yansun Lu   Zhicheng Guan   J. B. P. Williamson (U.K.)

TECHNICAL PROGRAM COMMITTEE

Chairman	Yajun Chen
Vice Chairman	Jingqin Wang Liangjun Xu Guofu Zhai
Secretary-general	Taihang Du
Vice Secretary-general	Xiuping Su Youtong Fang

ORGANIZATION COMMITTEE

Chairman	Manjin Guo
Vice Chairman	Cheng Yang Delin Hu Tuoyu Wang
Secretary-general	Zhigang Li
Vice Secretary-general	Yunguang Ding Kui Li

INTERNATIONAL COMMITTEE

Chairman	Jigao Zhang	
Vice Chairman	Zhenbiao Li	Mingzhe Rong
Members	M. Braunovic (Canada)	Z. K. Chen (USA)
	Piet van Dijk (Netherland)	H. Inoue (Japan)
	N. Ben Jemaa (France)	W. Johler (Switzerland)
	Chi Leung (USA)	B. Miedziński (Poland)
	P. Slade (USA)	T. Takagi (Japan)
	R. W. Vook (USA)	Xin Zhou (USA)
Secretary-general	Yanyan Luo	
Vice Secretary-general	Lin Cheng	

PROCEEDINGS EDITORAL BOARD

Chief Editors	Jingqin Wang	Jingying Zhao
Members	Yanyan Luo	Kui Li

Table of Contents

2nd International Conference on Reliability of
Electrical Products and Electrical Contacts,
March 28-31, 2007 **(Keynote Paper)**

The Vacuum Interrupter, the High Reliability Component of Distribution Switches, Circuit Breakers and Contactors

Paul G. Slade, Wangpei Li, Stephen Mayo, R. Kirkland Smith, Erik D. Taylor
Eaton Electrical, Horseheads, NY USA
PaulGSlade@eaton.com; 1-607-796-3230

***Abstract*—The use of vacuum interrupters as the current interruption component for switches, circuit breakers, reclosers and contactors operating at distribution voltages has escalated since their introduction in the mid-1950's. This electrical product has developed a dominating position for switching and protecting distribution circuits. Vacuum interrupters are even being introduced into switching products operating at transmission voltages. Among the reasons for the vacuum interrupter's popularity are its compactness, its range of application, its low cost, its superb electrical and mechanical life and its ease of application. Its major advantage, however, is its well-established reliability. In this paper we show how this reliability has been achieved by design, by mechanical life testing and by electrical performance testing. We introduce the "sealed for life" concept for the vacuum interrupter's integrity. We discuss this in terms of what is meant by a practical leak rate for vacuum interrupters with a life in excess of 30 years. We show that a simple high voltage withstand test is an easy and effective method for monitoring the long-term vacuum integrity. Finally we evaluate the need for routine inspection of this electrical product when it is used in adverse ambients.**

***Index Terms*—vacuum interrupter, reliability, mechanical life, electrical life.**

I. Introduction

The vacuum interrupter was introduced in the 1950's as a distribution voltage, load-break switch [1]. In the late 1950's and into the 1960's the General Electric Corporation (USA) began their R&D effort to produce a vacuum interrupter that would interrupt fault currents [2]. Eaton Corporation (formerly Westinghouse) began its development of vacuum interrupters suitable for use in distribution circuit breakers and reclosers in 1960. We introduced our first designs into the US recloser market at the end of the 1960's. Thus we have had over 45 years of experience in manufacturing and applying vacuum interrupters. When the vacuum interrupter was first introduced into switching and circuit protection products the end users expressed two major concerns:

1. What is the reliability of the vacuum interrupter's performance over its service life?
2. How reliable is the vacuum vessel over its design life; i.e. will the vacuum interrupter maintain the required vacuum for the life of the switching product?

After a very slow acceptance by the end user community, the products containing vacuum interrupters have gradually gained a dominant position in the distribution voltage market [3] (Fig. 1). Vacuum circuit breakers are now employed at system voltages from 1kV [4] to 145kV [5]. They can also interrupt fault currents up to 75kA and are being applied to an ever-widening range of application [6]. In this paper we will address the second concern. We will show how the design, testing and manufacture of the vacuum interrupter assure an extremely reliable product. The modern vacuum interrupter will provide excellent service throughout its design life.

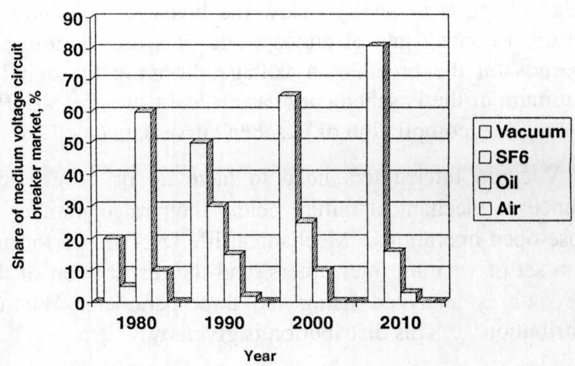


Fig.1 Sales of different medium voltage circuit breaker technologies by year.

II. Design for Life

A. Mechanical life

Vacuum circuit breakers and vacuum contactors are required to mechanically open and close for a large number of operations. A bellows made from thin stainless steel allows the contacts to open and close while retaining vacuum inside the interrupter. The fatigue performance of the bellows limits the mechanical life of the vacuum interrupter. The contact opening and closing operations stress the bellows, particularly the convolutions closest to the ends. In addition to the direct motion from the operation, the bellows oscillates after the contact motion stops, further adding to the wear on the bellows. The critical contact motion parameters that affect mechanical life are:

1. Steady state contact stroke or gap
2. Opening and closing speed
3. Motion damping at end of opening and closing stroke
4. Overshoot and rebound on opening
5. Mounting resilience
6. Contact bouncing on closing.

The mechanical life of Eaton Electrical VI's is evaluated by performing opening and closing operations on sample vacuum interrupters in a specially constructed life-test apparatus. The test apparatus is designed to simulate the operation of any mechanism that a vacuum interrupter may see in practice; e.g. that of a switch, a circuit breaker or a contactor. The opening and closing speeds reflect values recommended for use in these mechanisms. For example, a vacuum interrupter that is to be used in a vacuum circuit breaker will have its contact gap set to the circuit breaker's nominal gap, plus the gap tolerance, plus the amount of overtravel. The opening and closing speeds are adjusted towards the maximum values. This gives the maximum deflection stress on the bellows. The testing pauses after every 100 operations, opens the contacts and applies a 7.5kV AC voltage. Failure to hold off this voltage indicates that the VI has started to leak from a crack in the bellows. This voltage is generally below the breakdown voltage of the open contact gap at atmospheric pressure; therefore it depends on the breakdown voltage dropping through the minimum of the Paschen curve as air leaks into the VI. For an excellent compilation of Paschen curve data (see [7]).

Vacuum interrupters need to have no or a very low chance of mechanical failure below their rated number of close-open operations. Mechanical life tests are performed on a set of vacuum interrupters, and the distribution of the life data is analyzed using the three-parameter Weibull distribution [8]. This distribution is given by

$$f(x) = 1 - \exp\left[-\left(\frac{x - x_0}{\alpha - x_0} \right)^{\beta} \right] \qquad (1)$$

where $f(x)$ is the cumulative probability of failure, x is the mechanical life, α is the life where the fraction of $1/e$ units have failed, β is the shape parameter of the distribution, and x_0 is the threshold value. The threshold value is the value below which the probability of failure is effectively zero. Fig. 2 illustrates an example of this analysis. The plot shows the cumulative probability of failure as a function of the number of operations. The three-parameter Weibull distribution reproduces the behavior of the data, and gives a threshold value of 43,770. The

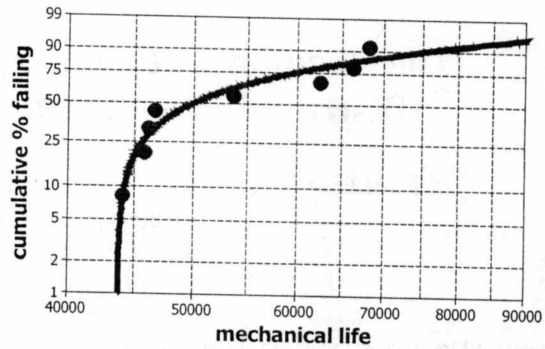


Fig.2 Cumulative percentage of vacuum interrupters experiencing mechanical failure as a function of the number of operations. These results are for a particular bellows design and circuit breaker parameters. The threshold value is 43,770 operations.

threshold value is just slightly below the lowest mechanical life measurement of 44,096.

Most vacuum interrupters are seldom operated. The electrical and mechanical wear the interrupters experience in service is usually only a small fraction of their actual capability. Table I gives an overview of the expected life for a number of common vacuum interrupter applications. In general the vacuum interrupter will certainly perform its switching and protection function for most applications in excess of the expected life of the equipment in which it resides. It is possible to develop bellows for mechanical requirements beyond the VI life given in Table I. For those applications where very frequent switching is needed, the number of operations should be monitored and a regular maintenance schedule developed. The long-term reliability of the vacuum interrupter while switching current has

TABLEI THE EXPECTED LIFE OF SWITCHING EQUIPMENT USING VACUUM INTERRUPTERS

Application	VI mechanical life [operations]	Expected operation frequency in field	Expected VI service life
Vacuum circuit breaker (VCB)	3 x 10^4	1 – 2 / year	> 40 years
Vacuum recloser	3 x 10^4	< 100 / year	> 40 years
Capacitor switching VCB	3 x 10^4	≤ 2 / day	> 40 years
Capacitor switching switch	5 x 10^4	≤ 4 /day	> 30 years
Arc Furnace VCB	3 x10^4	≤ 100 /day	< 1 year
Contactor (≥ 7.2kV)	1 x 10^6	≤ 100 /day	> 30 years
Contactor (≤ 3.3kV)	5 x 10^6	≤ 100 /day	> 30 years
Contactor: jogging (≤ 3.3kV)	5 x 10^6	≥ 100/day	< 3 years

permitted these frequent switching applications to be undertaken.

B. Electrical life

Since the first introduction of the vacuum interrupter it has demonstrated an exceptional electrical switching life. The major advantage for the contact in vacuum is that throughout its switching life the contact resistance remains nearly constant. There is no gas inside the vacuum interrupter to change the chemical composition of the contact. Slade and Smith have explored this life over the whole current range expected for vacuum interrupters that are used in vacuum circuit breakers [9]. These vacuum interrupters are designed to interrupt the diffuse vacuum arc that results during load currents switching (for currents ≤ 6kA) and the high current vacuum arc that results when switching fault currents (for currents > 6kA). In order to control the high current vacuum arc two contact structures have been successfully developed [10]. The first, named the Transverse Magnetic Field (TMF) contact, forces the high current vacuum arc to move rapidly around the periphery of the contacts. The second, called the Axial Magnetic Field (AMF) contact, forces the high current columnar vacuum arc into a high current diffuse mode.

When switching the diffuse vacuum arc that occurs when normal load currents (e.g. 630A to 3150A) are interrupted, it is important to consider the deposit of material eroded from the cathode and deposited on the anode. Schulman et al [11] have shown that when this is taken into account the effective erosion of the vacuum interrupter contacts in an ac circuit is considerably reduced. They have determined the effective erosion as a function of the contact gap <g> divided by the contact diameter <ϕ> as well as the effect of slots cut into the contact's surface. For example, a 62mm diameter Cu-Cr contact with <g>/<ϕ> and slots in 28% of the contact surfaces has an effective erosion of $13\times10^{-7}\ \mathrm{cm}^3/\mathrm{C}$. The contact life for this contact is given as a function of load current in Table II. This contact life is much larger than the 30,000 operations expected from the normal operating life of a vacuum circuit breaker. Vacuum interrupters developed for vacuum contactors have been designed with switching lives of up to 5 million electrical switching operations.

TABLE II LIFE OF A 62MM TMF CONTACT SWITCHING LOAD CURRENTS UNTIL 3MM OF EROSION IS REACHED

Circuit Current, kA rms	Switching to reach 3mm contact erosion
0.63	953,835
1.25	480,733
1.60	375,572
2.0	300,458
2,5	240,366
3.15	193,532

A 62mm diameter TMF contact switching 25kA rms has a switching life of 100 operations [9]. For currents >6kA the life of this contact is inversely proportional to the square of the current. The contact life as a function of current is shown in Fig. 3. The AMF contact of the same diameter has a much lower erosion rate for the same high current interruption. A comparison of the two contact designs is shown in Fig. 4 for a 35mm diameter Cu-Cr contact. For the AMF contact the eventual limit to the number of high current operations it can achieve is its high voltage withstand. This gradually deteriorates after about 200 high current operations as metal vapor is deposited on the interior walls of the vacuum interrupter's ceramic body [9]. It is thus possible to design vacuum interrupters to have an outstanding operating life performance, which is greatly in excess of any former and any competing interrupter technology.

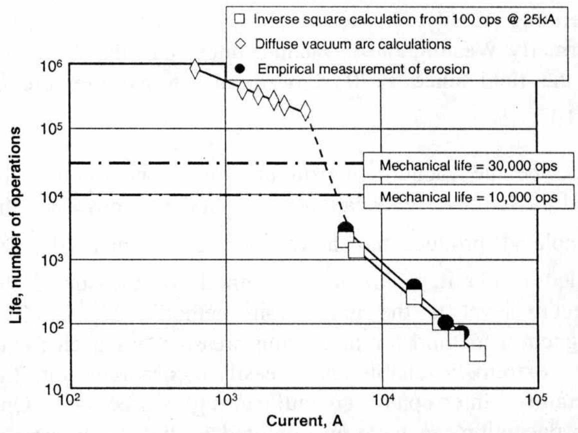


Fig. 3 The contact life vs. current (rms) curve for 62mm diameter TMF contacts inside a 102 mm diameter vacuum interrupter.

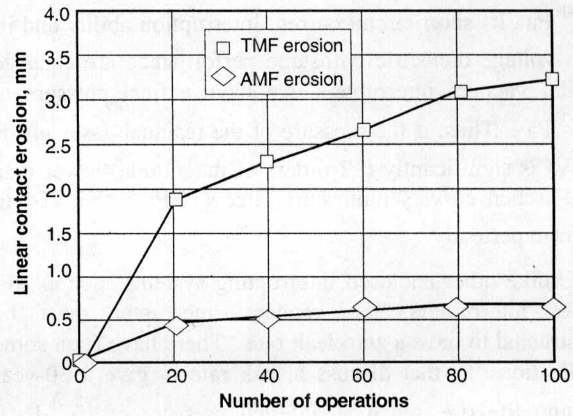


Fig. 4 Erosion of 35mm diameter TMF and AMF contacts switching 12.5kA (rms).

C. Vacuum integrity, sealed for life

In the early days of application of vacuum interrupters, there was a genuine concern about vacuum integrity. This might have been the result of the glass envelope used in the manufacture of these early vacuum interrupters. Glass is vulnerable to permeation of both Hydrogen and Helium. At that time some end users were told that the life expectancy of a vacuum interrupter was 20 years. In the last few years we have heard some utility customers replacing perfectly good vacuum interrupters in their switchgear simply because it has been 20 years since the panel boards were installed. Our own experiences of seeing our vacuum interrupters used in the field all over the world, in vastly different environments, for well over 40 years, have shown that with a proper vacuum quarantine testing carried out in the VI manufacturing plant, vacuum interrupters are "sealed for life". A VI can and should continue to be used for as long as it passes a high voltage AC withstand test, showing that it still has an acceptable vacuum. As far as we know, those vacuum interrupters we manufactured in 1968 are still operating reliably. In fact, an analysis in 1998 of an Eaton (formerly Westinghouse) vacuum interrupter that had been in the field since 1970 showed an internal pressure of 1×10^{-3} Pa.

Once the vacuum interrupters have gone through the final assembly, evacuation and brazing process, the completed product has a vacuum lower than 10^{-2} Pa sealed inside it. The usual method for measuring the vacuum level is the magnetron method [12 - 13]. The magnetron method for measuring pressure has been found to be extremely reliable and is easily incorporated into the vacuum interrupter manufacturing process. One misconception we have encountered is that the lower the residual vacuum level inside a VI, the better it will perform electrically. In fact, we have purposely manufactured and tested a vacuum interrupter with a high residual pressure of 10^{-1} Pa. Its short circuit current interruption ability and its high voltage dielectric withstand performance are equal to similar vacuum interrupters that have a final pressure of 10^{-3} Pa. Thus, if the pressure of the residual gases inside the VI is significantly (~2 orders of magnitude) lower than the Paschen curve's minimum value (10 Pa), the VI will perform perfectly.

Unlike other enclosed interrupting systems such as SF_6 puffer interrupters, the vacuum interrupter must be constructed to have a zero leak rate. There have been some publications [14] that discuss a leak rate to give a 30-year vacuum life (i.e. reach an internal pressure of 10^{-1} Pa). However, these reports do not take into consideration the unique nature of vacuum seals and vacuum leaks in an external ambient such as atmospheric air. What really matters is to determine what size of leak that can be tolerated. No one really knows the true length of time that commercial vacuum interrupters can retain a vacuum below 10^{-1} Pa. In our own experience with vacuum interrupters manufactured by Eaton Electrical (formerly Westinghouse) the field experience goes back to 1968. As far as we know, those vacuum interrupters we manufactured in 1968 are still operating reliably. A greater than 30 year life expectancy certainly imposes a very strict requirement on the leak-tightness of the vacuum interrupter envelope and all the braze joints that are exposed to the ambient. If we conservatively assume a maximum allowable vacuum interrupter pressure of 10^{-3} mbar or 10^{-1} Pa (a commonly accepted criterion), then the maximum amount of gas N_{max} allowed to leak into a vacuum interrupter of volume V_{int} is:

$$N_{max} = \Delta P \cdot V_{int} = (0.1 - P_0)V_{int} \approx 0.1 V_{int} \ \mathrm{Pa \cdot L} \quad (2)$$

where P_0 is the initial vacuum level inside the vacuum interrupter. The amount of gas that can leak into the vacuum interrupter depends upon the size of the leak.

$$N_{max} = \int_{30\ \text{years}} Q\ dt \quad (3)$$

where Q is the leak rate. The Q_{max} for a given time t is:

$$Q_{max} = \frac{\Delta P V_{int}}{t} = \frac{0.1 - P_0}{t} \frac{\mathrm{Pa \cdot L}}{\mathrm{s}} \quad (4)$$

Using Eq. (4) it is possible to calculate the Q_{max} for a 30 year life:

$$Q_{max} = \frac{N_{max}}{30\ \text{years}} = \frac{0.1}{30 \cdot 365 \cdot 24 \cdot 3600} V_{int} \frac{\mathrm{Pa \cdot L}}{\mathrm{s}} \quad (5)$$

Table III lists the maximum leak rate allowed for vacuum interrupters with volumes ranging from 0.5 to 4 Liters to reach 10^{-1} Pa as a function of time. Thus, to obtain a 30-year lifetime, the Q_{max} allowed is about 10^{-10} Pa·L/s. This is two orders of magnitude beyond the practical detection capability of 10^{-8} Pa·L/s for the typical helium leak detector [15-16]. Table III shows that the latter leak rate value would only guarantee a lifetime of about one-month. Why, then, is the practical experience by vacuum interrupter manufacturers of lifetimes in excess of 30 years? Fortunately, nature works in their favor. Leak rates of about $10^{-8} - 10^{-6}$ Pa·L/s may require a bake out to become detectable. Leak rates of about $10^{-9} - 10^{-8}$ Pa·L/s or less are most likely plugged permanently when exposed to open air at one atmosphere

[17]. Leak rates smaller than about 10^{-8} $\text{Pa}\cdot\text{L/s}$ are of no practical importance for the vacuum life of the typical vacuum interrupter. A leak check level to that sensitivity is enough to guarantee its vacuum integrity over its required lifetime. From the data given in Table III, it can safely be said that if a vacuum interrupter with an internal volume of 1 L does not show a pressure of 10^{-1} Pa within one month, it does not have a leak larger than 4×10^{-8} $\text{Pa}\cdot\text{L/s}$ and will, therefore be unlikely to leak further for its entire application life. This, of course, presupposes that the vacuum interrupter is not subjected to abusive handling or corrosive ambients that can generate unexpected leaks.

TABLE III MAXIMUM LEAK RATE FOR VACUUM INTERRUPTERS TO ACHIEVE A GIVEN LIFE-TIME

Internal Vacuum Interrupter Volume (L)		0.5	1	2	4
Maximum leak rate Q_{max} in Pa L/s for a life of:	30 years	0.5×10^{-10}	1.1×10^{-10}	2.1×10^{-10}	4.2×10^{-10}
	10 years	1.6×10^{-10}	3.2×10^{-10}	6.3×10^{-10}	1.3×10^{-9}
	5 years	3.2×10^{-10}	6.3×10^{-10}	1.3×10^{-9}	2.5×10^{-9}
	1 years	1.6×10^{-9}	3.2×10^{-9}	6.3×10^{-9}	1.3×10^{-8}
	1 month	1.9×10^{-8}	3.8×10^{-8}	7.6×10^{-8}	1.5×10^{-7}
	1 week	8.2×10^{-8}	1.6×10^{-7}	3.3×10^{-7}	6.6×10^{-7}
	1 day	5.8×10^{-7}	1.2×10^{-6}	2.3×10^{-6}	4.6×10^{-6}

This analysis leads to a straightforward and effective method for assessing vacuum integrity and expected life of a vacuum interrupter by measuring its high voltage withstand level. The vacuum interrupter should be opened to its design contact gap and the high voltage withstand value can be measured. The process can be illustrated using the Paschen curve. A typical vacuum interrupter can withstand a voltage of 50kV(rms) for a contact gap of 10mm and a pressure inside the vacuum interrupter of 2×10^{-2} mbar . Thus, a worst case leak or maximum leak rate , $L_{r_{max}}$ (per unit internal volume) would be :

$$L_{r_{max}} = \frac{2\times10^{-2}}{y_1}\frac{\text{mbar}}{\text{year}} \qquad (6)$$

where y_1 is the age in years since the vacuum interrupter's manufacture. A vacuum interrupter would have an unacceptable high voltage performance at a pressure of 3×10^{-2} mbar . Thus the minimum time to reach this pressure y_2 would be:

$$y_2 = \frac{3\times10^{-2}}{L_{r_{max}}} = \frac{3}{2} y_1 \text{ years} \qquad (7)$$

Now if the vacuum interrupter is tested after a time $y_2 - y_1$ and it still withstands 50kV(rms) then Eqs. 6 and 7 can be used to calculate a new minimum life for this vacuum interrupter. Table IV shows that it only takes 7 test sequences to ensure the vacuum interrupter's integrity for 30 years. In fact in our experience if a vacuum interrupter has been in the field for 5 years without showing any sign that it has a small leak, it will never leak.

TABLE IV LIFE TIME CALCULATION INTEGRITY OF A VACUUM INTERRUPTER USING A HIGH VOLTAGE WITHSTAND TEST

Withstands 50kV high voltage after y_1 years after manufacture (pressure $\leq 2 \times 10^{-2}$ bar)	Leak rate mbar/year to reach 2×10^{-2} mbar since manufacture	Years to reach 3×10^{-2} mbar after the HV withstand test	Minimum years after manufacture to reach 3×10^{-2} mbar	Years after manufacture for the next HV withstand test
1	2.0×10^{-2}	0.5	1.5	2
2	1.0×10^{-2}	1.0	3	3
3	6.7×10^{-3}	1.5	4.5	5
5	4.0×10^{-3}	2.5	7.55	8
8	2.5×10^{-3}	4	12	12
12	1.7×10^{-3}	6	18	20
20	1.0×10^{-3}	10	30	30

There are three advantages of using this high voltage test method:

1. It is relatively easy to perform.
2. The mechanism only has to be isolated from the circuit and the voltage can be applied across each vacuum interrupter in turn. The vacuum interrupter does not have to be removed from its mechanism.
3. The test also measures the insulation integrity of the circuit breaker/switch system and not just the vacuum integrity of the vacuum interrupter.

It is important to note that an insulation resistance test normally applies a test voltage of 5-10kV; this is too low to assess the vacuum integrity of VI's.

D. Ambient effects

One consequence of the vacuum interrupter's proven high reliability and its property of being maintenance free for its operating life is that it can be incorporated into sealed chambers. Once installed in such chambers the vacuum interrupters are usually inaccessible. At distribution voltages of 24kV and higher compact switchgear have been developed that surround the VI with SF_6 gas [18] or encapsulate it in a solid dielectric material such as cyclo-aliphatic epoxy [19]. Each of these developments are successful, because the vacuum interrupter is sealed for its life and does not require replacement once it has been installed.

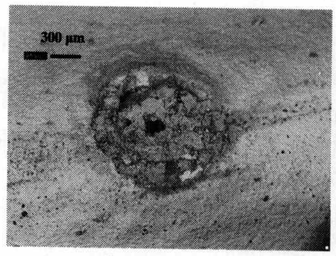
There are some characteristics of the interrupter that can lead to failure if care is not taken. Most if not all of the cases of vacuum integrity failures are caused by a new leak generated later once the vacuum interrupter has been installed as a result of either mishandling, e.g. twisting the bellows, or fatigue failures of the braze joints by inadequate mounting of the VI in the breaker or misuse of the breaker.

Vacuum interrupters are generally assembled from high purity metal, such as OFHC copper and stainless steel, which are susceptible to corrosion in certain environments. For example, in paper mills and wastewater treatment facilities, Hydrogen Sulfide gas is commonly found. The silver used in the braze joints can react readily with this gas until the integrity of the braze joint is compromised, leading to a loss of vacuum. In order to protect against this type of corrosion, many vacuum interrupter manufacturers apply a protective coating to these joints. If the VI is to be used in a corrosive environment, care must be taken to not scratch or remove this protective coating. Likewise, if the VI is to be used in a corrosive environment, it is a good idea to perform an annual visual inspection of the VI's to look for corrosion, in addition to a yearly high voltage test.

In the aftermath of the flooding caused by Hurricane Katrina in New Orleans in the U.S., it has become apparent that VI's that have been submerged are also at risk. Coastal floodwaters often contain salts, which have chlorine as one component. The stainless steel used to make the bellows and the copper component of the braze material are susceptible to chlorine-based corrosion (Fig. 5). Even if the VI is externally cleaned after being immersed, it should not be used, as chlorine-containing water can become trapped in the bellows of the interrupter leading to corrosion of the stainless steel bellows. Even relatively "clean" waters, such as municipal water supplies should not be allowed to come into contact with the interrupter, as they frequently have up to 4ppm of chlorine added to control the growth of microbes.

III. CONCLUSIONS

1. The modern vacuum interrupter using state-of-the-art processing techniques ensure a vacuum tight construction for the greater than 30 year life of the vacuum interrupter.
2. The vacuum interrupter provides a reliable maintenance-free operation for its full electrical life.



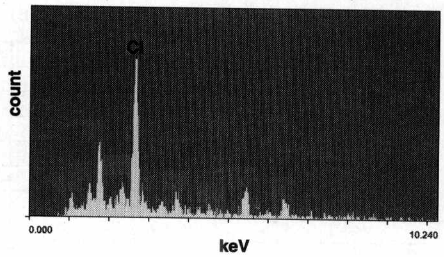


Fig. 5 Top, example of a hole in a bellows from chlorine corrosion. Bottom, the surface spectra of the area around the hole, showing the presence of chlorine.

3. The vacuum interrupter is used in long-life reclosers, vacuum circuit breakers, load break switches and contactors.
4. The vacuum interrupter can be matched to all types of operating mechanisms and its opening can be precisely controlled
5. The vacuum interrupters proven versatility will result in its continued application to an even wider role in the control and protection of electrical circuits.

REFERENCES

[1] Jennings, J., Schwagner, A., Ross, H., "Vacuum switches for power systems", Trans. A.I.E.E., Power Apparatus and Systems, Vol. 75, pp. 462-468, June 1956.

[2] Lee, T., Greenwood, A., Crouch, D., Titus, C., "Development of power vacuum interrupters, A.I.E.E. Trans. Power Apparatus and Systems, Vol. 81, pp. 629-639, February 1963.

[3] Slade, P.G., "Vacuum interrupters: the new technology for switching and protecting distribution circuits", IEEE Trans. On Industry Applications, Vol. 33, No. 6, pp. 1501-1511, Nov./Dec. 1997.

[4] Fink, H., Renz, R., "Future trends in vacuum application", Proc. 20th Intl. Symposium On Discharges and Electrical Insulation in Vacuum, Tours (France), pp. 25 – 29, July 2002.

[5] Himi, H., Takashima, T., Shinmon, Y., Umeya, E., Yanagisawa, H., "145kV vacuum circuit breakers," Proc. IEE Intl. Conf. on Developments in Distribution Switchgear, Nov. 1978.

[6] Long, W., Smith, R.K., "Are all circuit breakers created equal? Not when it comes to some generator circuits", Proc. Water Power Conference, 2003.

[7] Dakin, T., Luxa, G., Oppermann, G., Vigreux, J., Wind, G., Winkelnkemper, H., "Breakdown of gases in uniform fields: Paschen Curves for nitrogen, air and sulfur hexafluoride", Electra, No. 32, pp. 61 – 82, 1974.

[8] Bruning, A., Kasture D., Ascher, H., "Absolute vs. comparative end-of-life age", IEEE Trans. Dielectrics and Electrical Insulation, Vol. 3, No.3, pp. 567 – 576, Aug. 1996 plus a discussion in IEEE Trans. Dielectrics and Electrical Insulation, Vol. 4, No.2, pp. 241 – 247, April 1994.

[9] Slade, P. G. and Smith, R. K., "Electrical switching life of vacuum circuit breaker interrupters" Proc. 52nd IEEE Holm Conf. on Electrical Contacts, (Montreal, Canada), IEEE Cat. No. 06CH37833, pp. 32 – 37, Sept. 2006.

[10] Slade, P. G., "The vacuum interrupter contact", IEEE Trans. CHMT, Vol. CHMT-7, No. 1, pp. 25 – 32, March 1984.

[11] Schulman, M., Slade, P., Loud, L., Li, W-P, " Influence of contact geometry and current on effective erosion of Cu-Cr, Ag-WC, and Ag-Cr, vacuum contact materials", IEEE Trans. Components and Packaging Technology, Vol.22, No. 3, pp. 405 – 413, Sept. 1999.

[12] Kageyama, K., "Magnetically confined low-pressure gas discharge generated in a vacuum switch", J. Vac. Sci. Technology, Vol. 1, No. 3, pp 1522 – 1528, July-Sept. 1983.

[13] Kageyama, K., "Properties of a series cross-field discharge in a vacuum switch", J. Vac. Sci. Technology, Vol. 1, No. 3, pp 1529 – 1532, July-Sept. 1983.

[14] Okawa, M., Tsutsumi, T., Alyoshi, T., "Reliability and field experience of vacuum interrupters", IEEE Trans. on Power Delivery, Vol. PWRD 2, No. 3, pp799 – 804, July 1987.

[15] User's Manual, ASM 142/ASM 142D Helium Leak Detector, Alcatel Vacuum Products, Hingham, MA, pp. A800-801, Ed. 06/03/2005.

[16] Varian Vacuum Products Catalog, Varian Vacuum Products, Lexington, MA, p. 201, 1996.

[17] Wilson, N., and Beavis, L., Handbook of Vacuum Leak Detection, (pub. American Vacuum Soc.), p.55, 1976.

[18] Lav, C., Staley, D., Olsen, T., "Practical Design Considerations for Application of GIS MV Switchgear," IEEE Trans. Industry Applications, Vol. 40, No. 5, pp. 1427-1434, Sept/Oct 2004.

[19] Leusenkamp, M., Hilderink, J., Lenstra, K., "Field calculations on epoxy resin insulated vacuum interrupters", Proc. 17th Int. Symp. On Discharges and Electrical Insulation in Vacuum, Berkeley, U.S.A., pp. 1065 - 1069, July 1996.

Paul G. Slade (Fellow IEEE) received the B.S. and Ph.D. degrees and the Diploma of Mathematical Physics from the University of Wales, Swansea, U.K. and the M.B.A. degree from the University of Pittsburgh, PA.

He has over 40 years experience covering a wide range of problems associated with switching electric current. His research has covered electrical contact and arcing phenomena in air, vacuum, and SF_6. He has used this experience to develop new types of circuit breakers and switches. He has authored or co-authored over 90 research papers and has published the book "Electrical Contacts, Principles and Applications".

He is presently the Manager of the Vacuum Interrupter Technology Department, Eaton Electrical, Horseheads, NY. Where he is responsible for research and development, design, and applications engineering for the vacuum interrupter product.

2nd International Conference on Reliability of
Electrical Products and Electrical Contacts,
March 28-31, 2007 (Keynote Paper)

Reliability of Power Connections

Dr. Milenko Braunovic
MB Interface, 5975 Place de l'Authion, Suite 503
Montréal, Québec, Canada, H1M 2W3
E-mail: mbinterface@yahoo.com

***Abstract*—Despite the use of various preventive maintenance measures there are still a number of problem areas that can adversely affect system reliability. Also, economical constraints have pushed the designs of power connections closer to the limits allowed by the existing standards. The major parameters influencing the reliability and life of Al-Al and Al-Cu connections are identified. The effectiveness of various palliative measures are determined and misconceptions about their effectiveness are dealt in detail.**

***Index Terms*— Power connections, deterioration mechanisms, palliative measures.**

I. INTRODUCTION

The primary purpose of an electrical connection is to allow the uninterrupted passage of electrical current across the contact interface which can only be achieved if a good metal-to-metal contact is established. The processes occurring in the contact zone are complex and not fully explained within the limits of present knowledge. Although the nature of these processes may be different, they are all governed by the same fundamental phenomena, the most important being the degradation of the contacting interface and the associated changes in contact resistance, load, temperature, and other parameters of a multipoint contact.

Experimental evidence and various reports of service problems strongly suggest that reliable power connections are not obtained by routine application of established practices and methods. The degradation rate of power connectors in service cannot be determined precisely, which makes maintenance scheduling difficult.

There are two main reasons for this: first, there is a general lack of awareness of the problem, since connection deterioration is a time-related process; and second, the specific features of connection deterioration are not readily recognizable, because the failure of a power connection is usually associated with thermal runaway, thus making identification of the degradation mechanism difficult. The adverse consequences of this situation are reflected in the materials specifications for electrical joints, their usage and maintenance, and thus reliability of the entire power network.

The necessity of developing reliable electrical contact dates back to the beginning of the 19th century when the first electrical machines were used. First contacts were made of copper. As electric engineering evolved, the metal - carbon-graphite material became the most common material presently widely used in sliding contacts such as many types of electric machines and current pick-offs.

Progress in power engineering, the development of new electronic circuits and automatics and telecommunication devices prompted extensive applications of separable, breaking, and sliding contacts of new kinds such as: relay contacts, low-voltage and high-voltage electrical apparatuses, rheostats, potentiometers, electronic circuit joints etc.. Currents and voltages at which the contacts operate can vary by ten and more orders of magnitude and their operating conditions include space, vacuum and high temperatures (hundreds of centigrade.

In the 21st century electric energy still remains as one of the most basic need for civilization. A huge number of various electrical contacts is being used in the process of energy production, transmission, distribution, and usage. The trend of the extensive utilization of microprocessor devices, automatic control systems of technological processes, communication equipment, speedy electric transport, and the modular telecommunication device design increases the number of contact joints reaching thousands and tens of thousands in one article. For instance, a motherboard of a PC unit may comprise up to 20000 contacts.

Because of some intrinsic problems with electrical contacts such as noise, constricted current transfer across the contact interface, numerous attempts are being made to use electronic non-contact circuits as an alternative in some electrical/electronic devices.

However, the ability of these non-contact replacements may be compromised and their cost prohibitive. Consequently, any notion that in the future the application field of electrical contacts will become narrower or even obsolete is unjustified.

The variety of types of contacts and operating requirements prompted the use of a great number of conducting materials from graphite to rhenium. The world consumption of only noble metals used in the fabrication of materials and coatings for contacts is in thousands of tons. On the other hand, not only noble metals but also common contact material, such as copper, is becoming more and more deficient. Therefore, the replacement of copper with aluminum with improved connectability and reliability is an important step towards a wider use of aluminum in electrical devices.

A. Electrical contact requirements

Different types of contacts should satisfy different set of requirements depending on their stability and reliability. These problems can be addressed and solved by careful consideration of the application, design, and operating conditions of electrical contacts. Since the main function of an electrical contact is to enable transmission of the electric current from one contacting member to another with a minimal impact on the transmitted signal, the following set of requirements should be met:

- Electrical: low power losses, no signal distortion, no overheating;
- Mechanical: stable contact force during closing and opening, high wear resistance;
- Ecological: resistance to environment factors, minimal pollution to the environment under fabricating, operating, and recycling conditions;
- Ergonomic: simplicity of design and fabrication, simple maintenance repair and replacement, possibility of combining units;
- Economical: minimal content of noble and deficient non-ferrous metals.

In view of the above set of requirements, the reliability has become one of the most important characteristic of any electric/electronic device. Hence, as the requirements on the connectors increase the development process becomes substantially more complex.

B. Factors affecting reliability

One of the most important problems in providing reliability to electrical contact is the discrete nature of the interface. An electrical contact between solids is formed at discrete areas within the contacting interface and these areas (*a*-spots) are the only current conducting paths.

The formation of the real and conductive contact areas controls the reliability and efficiency of the electrical contact. These processes depend on a great number of independent or interrelated factors. The variety of the factors can be conventionally divided into the *performance* factors governed by the operating conditions and the *design-technological* factors determined by the fabrication characteristics of a contact unit. The performance factors (parameters) are divided basically into two groups: internal and external (Fig. 1).

The internal factors are the mechanical (the contact load, the type and characteristics of motion such as slip, the sliding velocity, and reciprocation) and electric (type and strength of current, operating voltages) factors. The external factors may be temperature-time variations, humidity, atmospheric pressure, effect of aerosols etc. and these are often uncontrollable. The performance factors affect the properties of contact materials and surface films, the occurrence of physical and chemical processes in the contact zone, wear particle formation thus influencing the state of the interface and, finally, the contact resistance and reliability of electrical contacts.

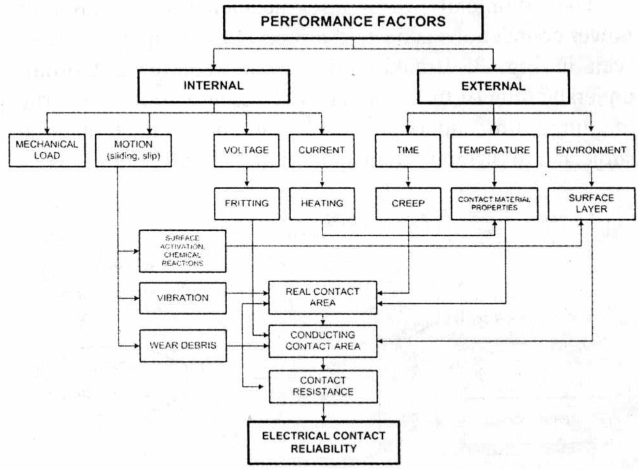


Fig. 1 Effect of performance factors on the reliability of electrical contacts

Fig.2 shows schematically the influence of the design-technological factors on the reliability and quality of electrical contacts. The selected kind of contact materials, the contact geometry, the intermediate layers separating the contacting surfaces, the quality of the deposited coatings and the contact surface microrelief determine the apparent contact area, the size, number, and distribution of contact spots. This, in its turn, influences the real and electrical contact areas, the constriction and surface film resistances, and, finally, the electrical contact reliability.

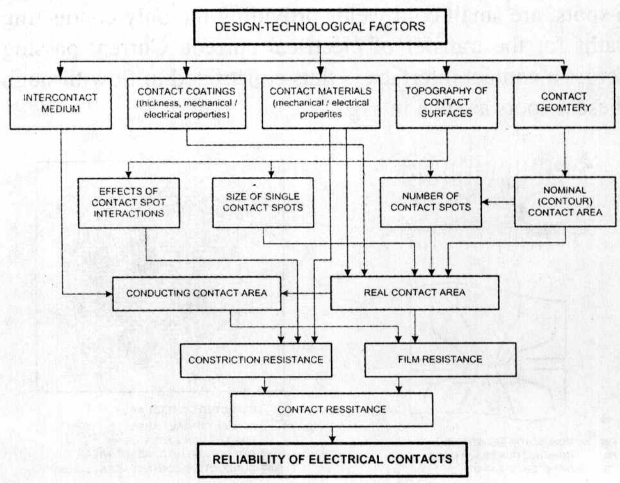


Fig. 2 Effect of design-technological factors on the performance of electrical contacts.

The widespread use of aluminium in a variety of electrical applications, has prompted numerous studies into the processes occurring in aluminium connections. Published experimental evidence and various reports of trouble in service suggest that reliable aluminium connections cannot