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Temperature Rise Behavior of Ag/SnO_2 Contact Materials for Contactor Applications

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***Abstract*—Critical temperature rise can be a failure mechanism for contact materials in power applications. The use of contact materials with reduced silver content to be more cost effective and the smaller sizes of devices impact this failure mode. Furthermore this effect is enforced by reductions in the volume of contact material and lower contact forces, due to energy saving by less power consumption of the driving coil.**

This paper presents influences of metal oxide content to contact resistance and temperature rise by experiments in a break-only model switch and in contactor applications. Temperature rise tests according to IEC standards show the influences of contact force on temperature rise of contactors and the effect of different switching conditions/loads on temperature rise. Therefore results of AC-3 and AC-4 standard contactor lifetime tests have been compared.

contact material; contactor; Ag/SnO_2; temperature rise; contact resistance

I. Introduction

Miniaturization, power consumption and of course cost efficiency have become the driving factors in modern power systems. This leads to switching device designs with smaller contact tips and/or usage of contact materials with reduced silver content. Furthermore devices and actuating mechanisms are miniaturized to the limit. In contactor design economizer circuits are used to reduce the power consumption while the contacts are closed. Consequently contact forces are reduced very often.

Some of the mentioned effects are influencing contact resistance and temperature rise behavior and therefore will be studied in this paper.

According to Holm [1] the total contact resistance is made up of three parts. These are film, constriction and bulk material resistance. The area of true mechanical contact between two contact tips is called a-spot. The radius α of a circular a-spot can be estimated by applying Hertzian elastic contact mechanics:

$$\alpha = \left(\frac{3 \cdot r \cdot F}{4 \cdot E} \right)^{1/3} \tag{1}$$

where r is the radius of the contact surface (so-called apparent contact area), F is the contact force and Young's modulus E. Generally, any electrical contact is believed to contain some number of a-spots, which cover a very small fraction of the contact surface.

The resultant constriction resistance R_C of a flat circular metallic contact area can be written as

$$R_C = \frac{\rho}{2\alpha} = \rho \sqrt{\frac{\pi \cdot H}{4 \cdot F}}, \tag{2}$$

where ρ is the electrical resistivity and H is the contact hardness.

A quadratic reciprocal dependency between contact resistance and contact force can be seen. The impact of a contact force reduction on switching and temperature rise behavior will be pointed out in chapter 2. The resulting a-spot area A at given contact force and material hardness can be estimated by the following equation:

$$A = \alpha^2 \cdot \pi = \frac{F}{H} \tag{3}$$

Silver tin oxide materials with reduced silver content are requested by the market for realizing cost efficient switching devices. The a-spot ratio of mechanical contact comparing Ag/SnO_2 14% to 12% metal oxide content at constant contact force results in:

$$\frac{A_{86/14}}{A_{88/12}} = \frac{H_{88/12}}{H_{86/14}} \approx 75\% \tag{4}$$

Here the influence of a higher metal oxide content on the constriction resistance of a new, unswitched contact surface can be clearly seen. Furthermore the material with higher oxide content will also provide a worse bulk resistance. The influence of these effects on contact resistance and temperature rise will be studied in chapter 3.

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II. IMPACT OF CONTACT FORCE

Energy saving devices, providing minimum power consumption, have become very important today. Therefore economizer circuits are installed on the coils of industrial contactors. Furthermore optimized magnetic circuits and lower contact forces are possibilities to realize the demands for lower power consumption. Even latching contactors, which have two operating coils, momentarily energized to close and open the contacts, are available. The influence of this tendency towards reduced contact forces on the switching behavior has been studied. Therefore the contact force of a 160 kW standard contactor has been reduced by 30% and electrical lifetime tests were performed under the following test conditions:

- $V = 400$ V
- $I_{make/break} = 1{,}140$ A
- $\cos\varphi = 1$
- $n = 167$ 1/h

During this test the contactor is loaded $6 \cdot I_r$ at make and break operation. Multiple experiments showed that these test conditions lead to results, which can be compared to a standard AC-4 test. A standard powder blended silver tin oxide material with 12 wt% total metal oxide content (SnO_2 doped with Bi_2O_3 and WO_3 additives) has been used for performing these tests.

First of all the impact of contact force on the bouncing behavior of the contactor at make has been studied. Figure 1 shows the frequency of an open contact - at least one side of the contact bridge is open - and therefore arcing probability at time t after first touching of the closing contacts at t = 0. The possibility to differ between one- and two-sided bounces is given by analyzing the voltage drop across the contacts. All three phases of the contactor are analyzed separately.

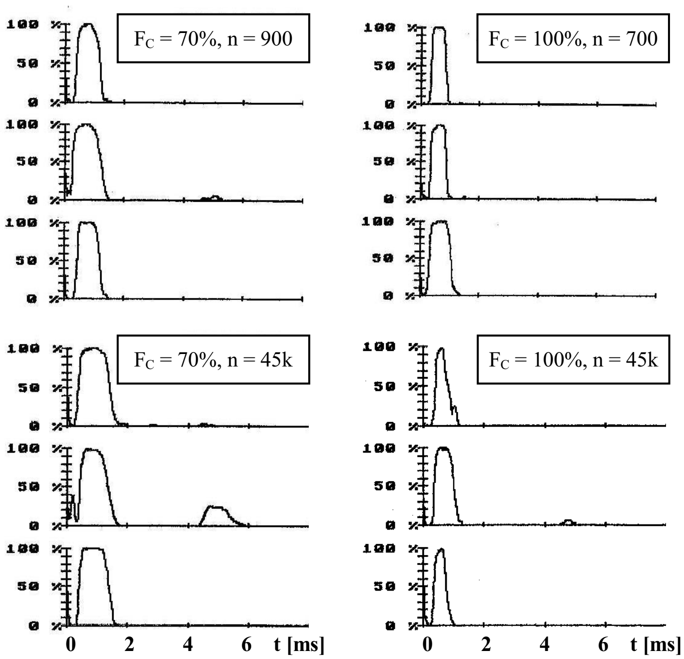

Figure 1. Bounce diagram

Bouncing behaviors seem to be similar for the new contactors (n < 1000). But, the observed primary bounces (t < 2 ms) can very often be stated as two-sided bounces for the reduced contact force contactor by further analysis of the voltage drop. In contrast to this behavior bouncing on the 100% contact force contactor is most often only one-sided. Furthermore a tendency towards secondary bounces (4 ms < t < 6 ms) can be found in the second phase of the new contactor providing the reduced contact force. This effect will even grow during electrical lifetime test (see Fig. 1, n = 45,000).

Nevertheless comparable erosion rates (Fig. 2) can be observed for both contact forces due to comparable energies at break W_{break}. This result shows that there is no significant influence of the contact spring on the opening mechanism for the tested contactor design.

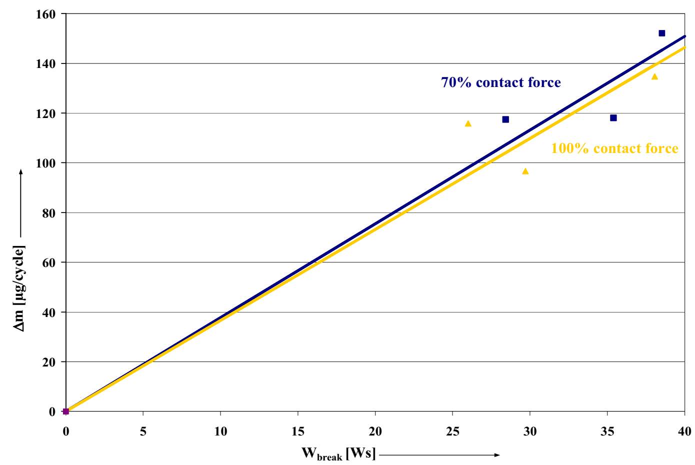

Figure 2. Erosion rates in contactor application

The calculation of energy at break for a double-breaking contactor is carried out by integrating the product of two times anode-cathode voltage drop V_{AC} and current for each phase from contacts opening until 100 V are reached:

$$W_{break} = 2 \cdot V_{AC} \int_{t_1}^{t_{100\,V}} i(t)\,dt \qquad (5)$$

The mass loss Δm is determined by weighing the contacts and calculating the average for each phase. From the computed erosion rates it can be seen, that the higher tendency towards secondary bounces at reduced contact force didn't limit the electrical lifetime. But, this effect comprises a severe risk of contact welding for higher currents at make.

Furthermore temperature rise measurements on the moveable contacts were performed for several times during the electrical lifetime test. According to Eq. 2 a rise of 20% in the contact resistance is expected for a contact force reduction of 30%. Figure 3 is showing the maximum temperature values for two different numbers of switching cycles of a 100% and 70% contact force contactor. During the test sequence the current has been increased from $1 \cdot I_r$ to $1.5 \cdot I_r$ to show the influence of decreased contact forces and increased rated currents on the temperature rise.

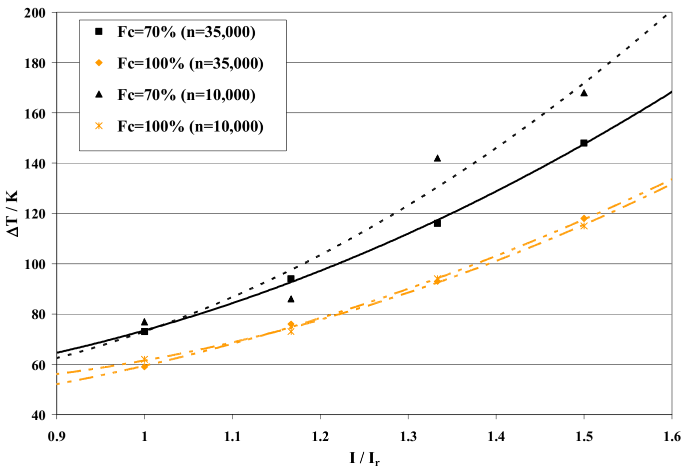

Figure 3. Temperature rise test results

Two different basic temperature levels for two different contact forces can be derived from the temperature rise tests. At rated current I_r an increase of 15 K in the maximum temperature can be seen for a contactor with a contact force reduced by 30%. Furthermore a greater variance and a tendency towards sharper temperature rise at increased currents can be stated for lower contact forces. Therefore contactor designers have to be careful by decreasing contact forces from cost saving aspects or increasing rated currents on existing contactors, if contact forces are already close to a lower limit.

III. INFLUENCE OF METAL OXIDE CONTENT

Silver metal oxide contact materials with high oxide contents are desired to produce well-priced contactors. For the following tests the tin oxide content of a powder blended and extruded material (Ag/SnO_2 SP) has been varied in a range from 4 wt% to 17 wt%. The impact of the metal oxide content (moc) on the switching performance will be shown.

The influence of tin oxide content on contactor service life has already been studied in [2]. These studies were based on Ag/SnO_2 materials doped with different contents of Bi_2O_3. Therefore the achieved results do not only depend on the total metal oxide content. They are also influenced by using Bi_2O_3 as additive.

Tests utilizing a break-only model switch were performed to show the effect of different metal oxide contents on erosion rates, arc movement and contact resistance. The electrical parameters chosen for these tests can be summarized as follows:

- $\hat{i}$ = 350 A, peak value
- B = 30 mT/kA magnetic field
- n = 1,000 cycles

The detailed kinetic parameters of the model switch have already been described in [3]. The break arc can be driven off the contact material and commutate onto arc runners by applying a magnetic field. From Fig. 4 it can be clearly seen that the lower the metal oxide content the better the arc root mobility. The dwell time of materials tested was defined by the time period from contacts opening – detected by the initial anode-cathode voltage drop – until a voltage drop of 60 V across the contacts is reached. This voltage drop is the typical value for the commutation of the breaking arc onto the arc runners taking place in the applied model switch.

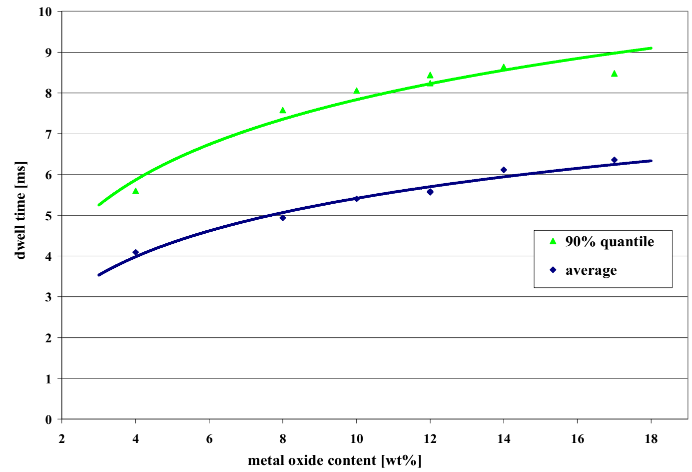

Figure 4. Dwell time against metal oxide content

Better arc root mobility and therefore shorter dwell times, consequently lead to lower energies at break stressing the contact material. Therefore material loss has to be divided by this energy for comparing the different materials. This specific erosion rate (Fig. 5) was investigated for metal oxide contents from 4% to 17%. This dependency was already examined for automotive relay applications under resistive and lamp load in [4, 5] and therefore at significantly lower breaking energies. The impact of metal oxide content on weld break forces and erosion rates of sintered Ag/SnO_2 materials for contactor applications (I = 375 A, cosφ = 0.35) was already studied in [6]. The performed lifetime tests showed a decreased contactor lifetime due to increasing erosion rates for a 20 wt% material in addition to the tendency of Fig. 5.

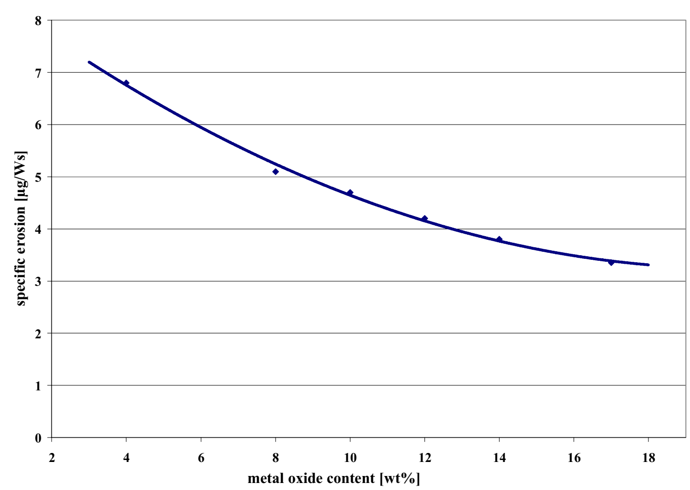

Figure 5. Specific erosion rate against metal oxide content

Better specific erosion rates for higher metal oxide contents can be observed. This behavior can be described by the following equation:

$$\frac{\Delta m}{W_{break}} \sim -\ln(moc) \qquad (6)$$

Because of longer dwell times and therefore higher breaking energies the significantly better specific erosion rates of materials providing high metal oxide contents shown in Fig. 5 must be put into perspective by the total mass loss during the experiment. The total erosion rate (Fig. 6) is only slightly decreasing with rising metal oxide content under the applied test conditions.

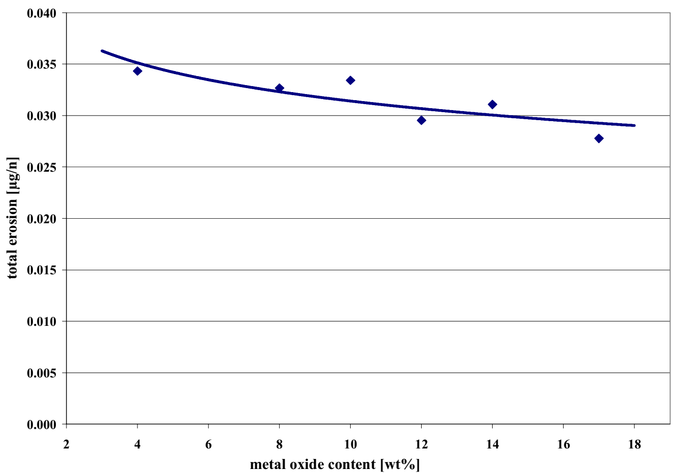

Figure 6. Total erosion rate against metal oxide content

Furthermore the advantages in erosion rates for high contents of metal oxide come along with a rise in contact resistance with increasing metal oxide content (Fig. 7). This rise in contact resistance (99% quantile) may lead to temperature rise problems in the device, if contact forces are too low.

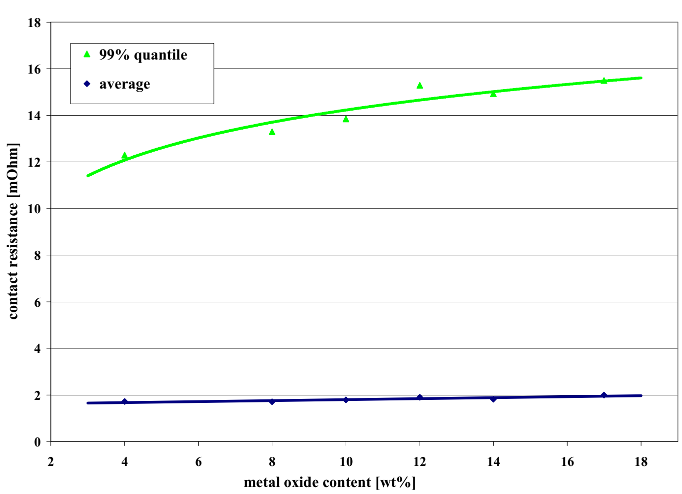

Figure 7. Contact resistance against metal oxide content

Of course the interaction of device design parameters with the material will influence these general results in a real contactor application. Therefore contactor lifetime tests have also been performed in addition to these model switch tests. The following test parameters have been chosen:

- $V = 400$ V
- $I_{make/break} = 324$ A
- $\cos\varphi = 1$
- $n = 250$ 1/h

Figure 8 shows the observed erosion rate per switching cycle during this test. Erosion behavior in contactor application shows 30% less erosion of a 14% material in comparison to a 12% material. Therefore the electrical lifetime, especially for contactors with high nominal current, can be increased by applying a contact material with higher metal oxide content (Ag/SnO_2 86/14 PMT3). Other experiments showed that the main influence of this effect can be found in the difference of the total metal oxide content of the materials. A slightly different composition of additives is needed to make the materials producible by extrusion process.

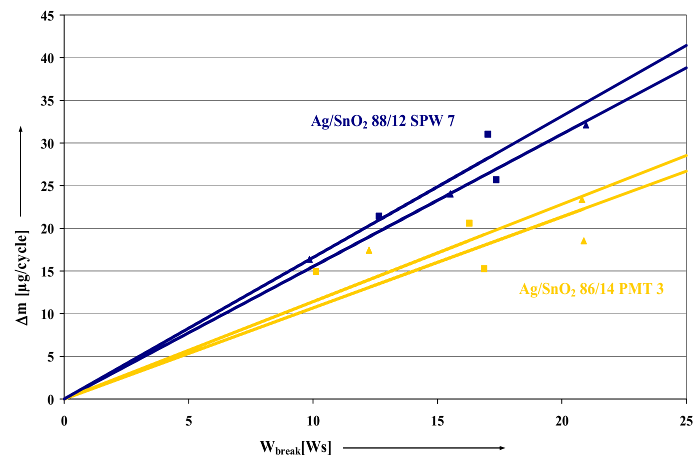

Figure 8. Erosion rates in contactor application

Furthermore temperature rise tests were performed during the electrical lifetime test. The temperature rise was measured on the contactor's contact bridges at a current $I = 100$ A. The contact bridge temperature is approximately two times the terminal temperature. After one hour constant current flow the temperature of the hottest bridge is memorized. After performing a dry switching the current is applied again. For statistics 24 cycles are recorded and analyzed. At least five such temperature rise tests are performed during the electrical lifetime test. Typical values of materials with different metal oxide contents, verified in several tests, are shown in Fig. 9.

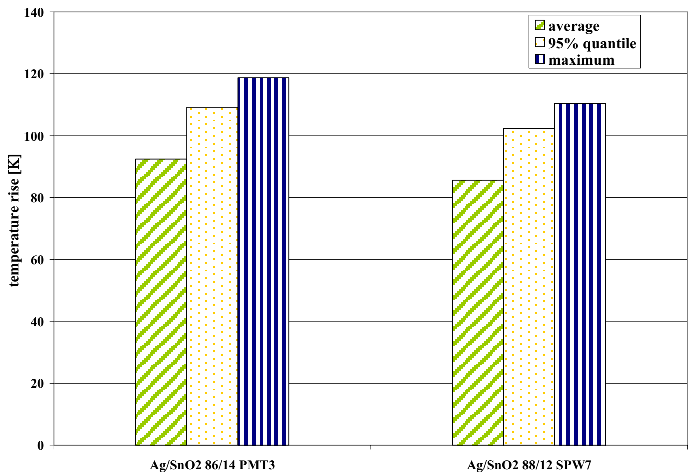

Figure 9. Temperature rise test results (contact bridge)

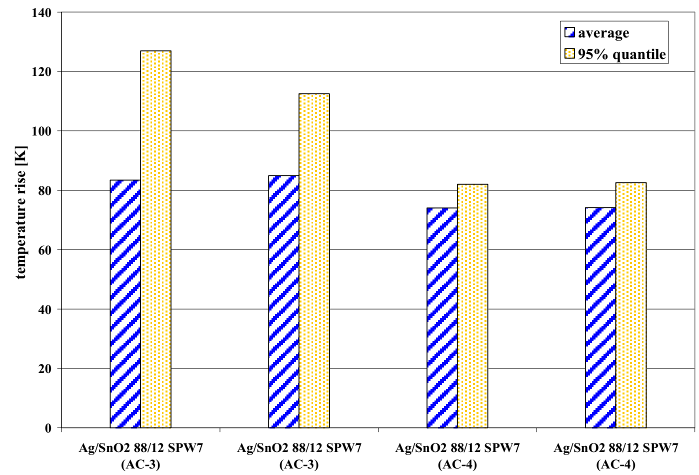

Figure 10. Temperature rise test results (contact bridge)

The temperatures on the contact bridge are approximately 7 K higher for a material containing 2% more metal oxide in this type of contactor. In this case a remarkable increase in electrical lifetime, coming along with moderate higher temperature rise values, can be achieved by applying an Ag/SnO_2 86/14 PMT3 material to the contactor.

IV. Impact of Utilization Category

The influence of switching contactors at different utilization categories, AC-3 (normal switching duty of squirrel-cage motors) and AC-4 (extreme switching duty of squirrel-cage motors), on temperature rise tests has also been studied. A 30 kW contactor applying Ag/SnO_2 88/12 SPW7 as contact material was chosen for this type of test. The temperature rise on moveable contact was measured at a tests current I = 100 A. Several temperature rise tests were performed during the electrical lifetime at different numbers of switching cycles.

During the lifetime test the contact material is stressed by bouncing arcs at make and by intensive break arcing at break. The energy levels of these effects depend on the load. Under normal switching duty (AC-3) arcing at make due to bouncing effects in combination with inrush currents dominate the material behavior. At extreme switching duty (AC-4) the high current (and therefore energy) at break dominates the contact material erosion behavior. This leads to different surface structures and material decompositions under different types of electrical loads. As a result different temperature levels can be seen for the different loads during the temperature rise test (Fig. 10).

The average temperatures of the two contactors tested at AC-3 load are 10 K higher than those switched under AC-4 load conditions. The 95% quantile of the maximum values is even 40 K higher. For contactors providing much higher/lower rated powers this effect can turn around, mainly depending on the ratio between energies at make and break – influenced by the contactor design – under the different types of load.

V. Conclusions

Silver tin oxide contact materials are widely used for industrial contactor applications. The technical requirements on these materials are influenced by actual trends in contactor design. Temperature rise is a critical failure mode for contactors in industrial application and the consequences of design changes on the contact resistance have to be considered carefully.

Therefore studies on switching behavior of contactors influenced by reduced contact forces, higher metal oxide contents and usage under different utilization categories have been performed.

Reduction of the contact force influences contactor kinematics and bouncing behavior. Though no large impact on erosion rates and lifetime under extreme switching duty (AC-4) could be seen, the influence on the bouncing behavior and the amount of energy converted in the contact material at make has to be considered at normal switching duty (AC-3) [7]. Experiments on these effects will be performed in future. Nevertheless, increasing temperatures in the device have to be considered already under AC-4 load. Critical temperature rises were observed, especially if reduced contact forces come along with increased rated currents or usage under overload.

Silver tin oxide materials with higher metal oxide content offer precious metal saving capacities to device manufacturers. Materials like Ag/SnO_2 86/14 PMT3 provide better erosion rates and therefore increased electrical lifetimes in comparison to 88/12 materials or possibilities for contact tip size reduction – approximately a 20% contact material volume reduction is possible – if slightly higher temperature rise values can be tolerated or eliminated by the design of the contactor.

Studying influences on contact resistance and temperature rise, the switching load and device kinematics have to be considered carefully. The energies converted during the make and break process by arcing have great impact on the contact material surface and therefore on the temperature rise. Reasonable tests have to include device, material and load parameters.

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