NEW PRINCIPLES FOR A SAFE INTERRUPTION OF LOW CURRENTS IN HIGH-VOLTAGE HIGH-RUPTURING CAPACITY FUSES

Uwe Kaltenborn(1), Guido Hoffmann(2)

ABB Switzerland(1,2), Corporate Research, CH-5405 Baden, Switzerland
uwe.kaltenborn@ch.abb.com(1), guido.hoffmann@ch.abb.com(2)

Abstract: Based on the definition of IEC 60282-1, backup-fuses have to interrupt currents higher than the minimal breaking current. Full-range fuses have to interrupt all currents, which are able to melt the fusing element. Severe circumstances like reduced heat-transfer or external heating might trip the fuse when the actual operating current is below the minimum breaking current or the melting current. In consequence the fuse can explode. Therefore the use of fuses in severe environments with high operating temperatures like fuse canisters and cubicles for electrical switchgears can dramatically aggravate a high risk of failure. Utilizing novel concepts like high-energy materials will enable a defined temperature-dependent tripping of the fuse. Combining this technology with a novel enhanced arc quenching material will lead to an interruption of very low and critical over-currents also in fuse canisters and cubicles under severe thermal conditions.

Keywords: h.r.c. fuse, low over-currents, arc-quenching, interruption, arc-initiation

1 Introduction

Electrical high rupturing current fuses have to act as protection devices in medium voltage distribution grids. The main task is to protect critical equipment to failure currents. There are two types of failure currents: short circuit currents and over-currents. Short circuit currents have to be handled so fast that the fuse operation limits the maximum current. The current limitation of the short circuit currents will be handled by a fuse element with serial constrictions. In case of a short-circuit current all serial constrictions will melt off at nearly the same time. Due to the high number of foot-points of the serial arcs, the resulting arc-voltage is high enough to quench the arc and to interrupt the current. This technology is well proven and accepted.

The handling of over currents is much more critical. Here a complete other physical effect has to be taken into account. Due to the thermal behavior of the fuse, the fuse element will melt at the hottest point. Now the arc starts to burn and will be extended along the fuse element. To interrupt such an arc, the plasma has to be cooled to increase the electrical resistance of the arc and therewith to drive the arc-voltage above the recovery voltage. The cooling of the arc body appears by dissipating the heat of the arc into the fuse sand utilizing the melt enthalpy of the sand. A major problem occurs if the plasma of the arc is stable burning but do not reach the necessary temperature to melt the quartz sand at around 1700 °C, than the arc will not be interrupted. Due to the pressure build up inside the fuse, the fuse body will explode.

Such critical events can happen due to several reasons:

- The over current is smaller than the minimum breaking current.
- A reduced heat transfer away from the fuse leads to a tripping by overheating the fuse at currents below the minimum breaking current.
- Due to an external heat source the fuse will be heated until melting of the fuse-element at currents below the minimum breaking current.

In case of the reduced heat transfer and the overheating by an external heat source, the critical currents can be below the rated current. For a safe handling of such critical situations, new concepts were developed. By implementing High Energy Materials (HEM) a purely temperature dependent triggering of the fuse could be reached. Combining this effect with new arc quenching materials, able to cool low current arcs, an enhanced protection range towards low currents could be shown for h.r.c. fuses.

2 Temperature Depending Tripping of a Fuse

A fuse in a circuit corresponds to a significant reduction of the cross section of the electric conductor. Reducing the cross section leads to an increase of the resistance (1) and of the power dissipation (2):

$$R(\vartheta) = k\frac{\rho(\vartheta)\cdot \ell}{A} \tag{1}$$

$$P = U \cdot I = kI^2R(\vartheta) \tag{2}$$

The main part of the losses will be released as thermal losses, because of the small inductance of the fuse. In the case of an over-current, the thermal losses will depend on the square root of the current.

To melt the silver wire, a temperature of 960 °C is needed.

If the fuse has the ability to interrupt every current that is melting the fuse wire, the fuse is called a full range fuse. Common principles of full-range fuses operate with two serial fuse wires of different materials, a heating chamber or a large number of small parallel wires.

Another opportunity is the use of a thermal limiting striker. Here the external overheating of the fuse will release the striker, which can than trigger a load-break switch for a safe interruption of the current. In such a case the fuse itself does not operate as a fuse.

3 Influencing the Tripping Temperature of a Fuse

There is one technology since more than 70 years in place, which allows a reduction of the pre-arcing time of a fuse at low over currents: the so-called M-effect after A. W. Metcalf [1]. To initiate a tripping of a fuse at lower temperatures, a piece of thin is placed on the silver based fuse element. Thin and silver are two materials able to diffuse into the other material. This diffusion leads to an Silver-Thin alloy of Ag_3Sn, which melts at 232°C. As each diffusion process is dependent on activation energy and time, the temperature of the fuse wire will be heavily influences the time of diffusion and therewith also the tripping time of the fuse as seen in Fig. 1.

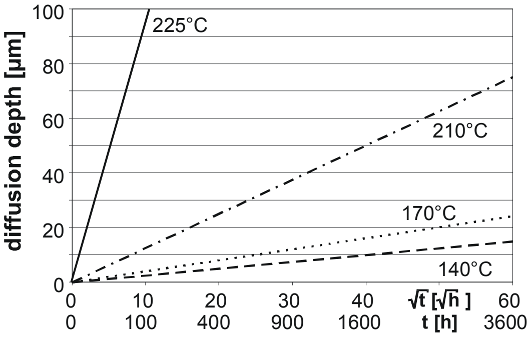


Fig. 1: Diffusion-depth over time of a silver-tin-system depending on the temperature [2]

Due to the slow diffusion speed of the M-spot at temperatures in the range of 200 to 250 °C, a method of tripping a fuse without any delay at lower temperatures would increase the triggering sensitivity of a fuse at low current switching.

3.1 High Energy Materials

Another way to influence directly the tripping of the fuse-element is the application of so-called High-Energy Materials (HEM). Such materials are able to release a high amount of thermal energy at temperatures up to 3000 K due to an exothermic chemical reaction. Such reactions can be initiated by reaching a defined temperature in the range of around 70 °C up to 250 °C. Applying such materials directly to the fuse element enables a nearly instantaneous tripping by reaching the critical temperature of the HEM.

All HEM are based on the following reaction principle (3 - 5):

$$\text{Propellant} + \text{Oxidizer} \xrightarrow{70^\circ\text{C} - 250^\circ\text{C}} \text{Initial Reaction} \quad (3)$$

$$\begin{array}{l} \text{Heat Producer} + \text{Oxidizer} \xrightarrow{\text{Initial Reaction}} \text{Melting Heat} \quad (4) \\ \hline \text{Propellant} + \text{Heat Producer} + \text{Oxidizer} \longrightarrow \text{Melting} \quad (5) \end{array}$$

The HEM can be divided by the most critical component, the propellant. There are two major groups of material, the so-called thermites and the stable nitric compounds. For the heat producer as well as for the oxidizer several chemical structures are known. In the most cases these heat producers and oxidizers can be used for both propellants. The major differences will be the burning temperature and the reaction velocity.

3.2 Thermite Based HEM

In cooperation with RUAG Munition (former Swiss Munition Enterprise Thun) several thermite based HEM were tested. A special metal/metal-oxide reaction is used, wherein the metal-oxide exists in a meta-stable condition. For this heat producing reaction, locally temperatures higher than 2000 K were measured. The initial reaction is described in formula (6):

$$\left\{\mathrm{Me^a} + \mathrm{Me^aO_y}\right\} + \mathrm{O_x} \rightarrow 2\mathrm{Me^aO_x} + \tfrac{y}{2}\mathrm{O_2} + \mathrm{Q(kJ)} \qquad (6)$$

To feed this reaction, originally oxygen from the environment was used. The materials for instance are used in applications like compact single use heaters to prepare food. In a fuse the amount of oxygen is insufficient to feed this reaction, due to the fact of the compact filling with sand. Therefore an additional oxidizer was implemented. This reaction is starting at low temperatures and produces temperatures high enough to trigger a second fast burning metal/metal-oxide reaction (7).

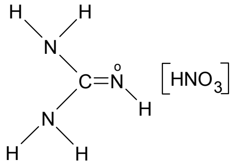
$$\mathrm{Me^b} + \mathrm{Me^cO_z} \rightarrow \mathrm{Me^bO_y} + \mathrm{Me^c} + \mathrm{Q(kJ)} \qquad (7)$$

The thermite based HEM are dissolved in an organic binder and therefore are liquefied. This liquid was applied by painting it onto the fuse element. Hardening of the HEM occurred by heating the fuse element up to temperatures around 50°C. The binder evaporates and the material is fixed.

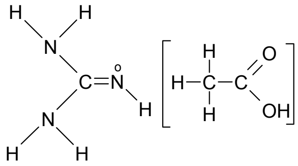
3.3 Stabilized Nitric Compounds

Several organo-nitric compounds show a good thermal stability up to temperatures above 200°C. Two of these materials are Guanidine Nitrate ($CH_6N_4O_3$) (8) with a melting point of 216°C and

Guanidine Acetate ($CH_5N_3CH_3COOH$) (9) with a melting point of 226°C.



Guanidine Nitrate (8)



Guanidine-Acetate (9)

Mixtures of these materials with common oxidizers like nitrates, chlorides or peroxides, showed no degradation for temperatures below 190°C. The reaction of these mixtures can reach temperatures up to 1500°C. To generate more heat, added magnesium shows a further increase of the released amount of heat. The reactions for a complete oxidation of Guanidine Nitrate and Guanidine Acetate is shown in (10) and (11).

$$CH_6N_4O_3 + 5O_2 \longrightarrow CO_2 + 4NO_2 + 3H_2O \tag{10}$$

$$\begin{aligned} &4(CH_5N_3CH_3COOH) + 29O_2 \\ &\qquad \longrightarrow 12CO_2 + 12NO_2 + 18H_2O \end{aligned} \tag{11}$$

The propellant / oxidizer ratio has a major influence to the reaction speed. To guarantee a complete reaction, the propellant / oxidizer ratio should be less than 1. On the other hand, the burning velocity of the mixtures has to be tuned in such a way that the sonic velocity is not reached. Otherwise the mixture will be rated as an explosive material with several safety indications.

3.4 Influence of the HEM on the Pre-Arcing Time of a Fuse

Applying the HEM to a fuse element leads to the situation that the tripping of the fuse element is purely dependent from the thermal situation inside the fuse. After igniting the HEM, a high amount of heat will be released, which melts the fuse elements. By comparing a conventional fuse element including a M-spot with the same fuse element having a HEM applied, a significant reduction of the pre-arcing could be measured. Fig. 2 shows the relation between the pre-arcing time and the applied current. The current is based on the melting current of the fuse element with M-spot.

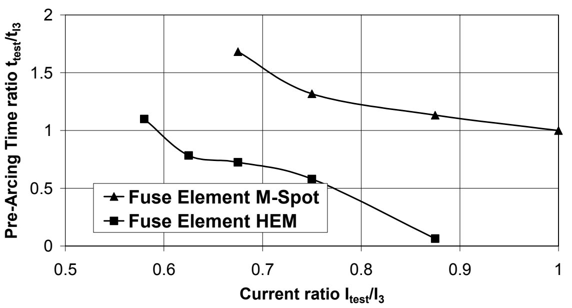


Fig. 2: Pre-arcing time versus test current of a standard fuse element with M-spot and a standard fuse element with HEM, all values related to the values of the minimal breaking current (I3 in accordance with TD 3 IEC 60282-1) of the M-Spot element

4 Arc-Quenching

After realizing a clear defined temperature dependent tripping of the fuse-element, the resulting arc must be interrupted. There are several principles available. Due to drawbacks for the known concepts, a new concept was developed and tested.

4.1 Known Principles

- Improved cooling of the arc by reduced particle size:
  Due to the fact that the melting energy of the sand is decreasing with a decreased particle size, a much more reduced particle size as used today will increase the cooling of the arc. The drawback of such a solution is the reduced ability of the sand to adsorb the metal vapor from the evaporated fuse wire after interrupting the current. Due to the hot metal gas, the dielectric recovery of the arc channel will be not sufficient to withstand the recovery voltage. A re-ignition might occur.

- Improved cooling of the arc by adding electronegative substances:
  Adding materials to the fuse sand, which are generating electronegative gases when they are heated, will also cool the arc. The electronegative gases will adsorb electrons from the arc-plasma. Such a material is PTFE, also known as Teflon®. At higher temperatures flour-gases will be generated. Beside the ecological aspect also a technical drawback has to be considered. Due to the significant difference of the specific density of quartz sand and PTFE a decomposition of both components is very likely and the availability of PTFE to the arc is not guarantied.
- Applying cooling media to the fuse wire:
  Utilizing the thermal energy to initiate a chemical reaction will also lead to a cooling effect at the arc. One example is the use of Aluminiumtrihydrate ($Al(OH)_3$). Here the energy will be used to feed the reaction of Aluminiumtrihydrate to alumina. This

will be done in two steps of oxidation: the Boehmite reaction (12) and the Alumina reaction (13) [3, 4].

$$2Al(OH)_3 + Q(kJ) \longrightarrow 2AlOOH + 2H_2O \tag{12}$$

$$2AlOOH + Q(kJ) \longrightarrow Al_2O_3 + H_2O \tag{13}$$

This reaction is mainly used as a flame retardant in filled polymers. The operating temperature for these applications is limited to maximum 150°C. For the use in fuses the maximum hot spot temperatures at the constrictions has to be taken into account, as temperatures above 170°C can be easily reached. That means that the cooling medium has to withstand such temperatures without degrading. In case of Aluminiumtrihydrate the degradation process starts between 150 and 175°C (Fig. 3). Therefore an application of such material has severe restrictions.

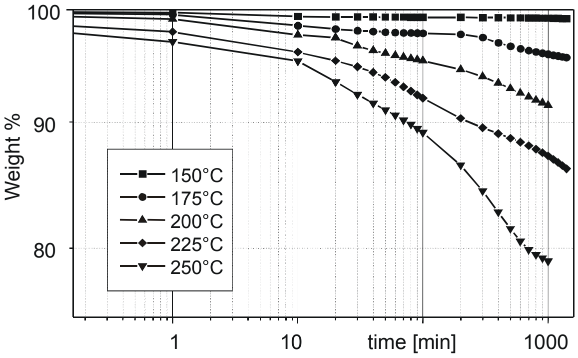


Fig. 3: Weight loss of Aluminiumtrihydrate ($Al(OH)_3$) over time dependent on the temperature

- Fast extension of the arc length:
  Another opportunity to revoke energy from the arc is the fast increase of the arc length. Applying a high number of parallel fuse elements with reduced cross-section might do this. In such a case the following restrictions has to be taken into account. If the number of parallel wires is to high, the commutation time of the arc will unacceptably increase. Another effect is the reduced distance between the wires. Due to the level of the recovery voltage a minimum insulation distance between the wires is necessary. Beside these technical issues also a production problem will occur. The resulting reduced cross-section of the single wire will make it impossible to handle such thin wires with traditional wire designs. New concepts like substrate power fuses are enablers for new design strategies dealing with a high number of parallel wires [5].

4.2 Novel Types of Arc Quenching Materials

The thermally defined tripping of a fuse has one major drawback. The energy of the burning arc will be insufficient to reach the temperature necessary to melt the extinguishing medium, the sand. By melting the sand, the energy for this process is taken away from the arc, which lead to a reduced temperature of the arc plasma. If the temperature of the plasma is low enough, the plasma channel will be quenched until implosion and the current is than interrupted. The whole effect depends on the interaction between the arc-plasma temperature and the molten volume of extinguishing medium. The volume of molten arc quenching material is than corresponding with the amount of energy taken away from the arc.

To enhance the arc-quenching effect, three possible effects can be utilized:

- Particle size:

  A reduced particle size is equivalent to an increased particle surface and therefore a reduced differential volume is needed to adsorb the same amount of energy.
- Melting point:

  A lower melting point would give the opportunity to increase the molten volume and to utilize the necessary higher energy uptake.
- Enthalpy of fusion:

  Utilizing materials with a higher fusion enthalpy will result in a higher adsorption of the arc-energy in a smaller volume of molten material.

Preferable a combination of all three opportunities should be realized. Table 1 is showing a comparison of three materials, useable as arc quenching materials. Beside the well-known quartz-sand as a reference, alumina and boric acid were chosen.

Table 1: Melting point and fusion enthalpy of different materials used as filler in AQM [6]

	SiO_2	Al_2O_3	BH_3O_3
melting point m_p [°C]	1713	2054	170
enthalpy of fusion ΔH [kJ/mol]	8.51	111.4	22.3

Alumina shows the major advantage with the high value for the enthalpy of fusion and the availability of a broad variation of commercial available grain sizes, down to nano-powders. Both effects are well compensating the higher melting point.

Boric Acid shows a reduced melting point in conjunction with a higher enthalpy of fusion. A major drawback for this material is the fact that the particle size is not controllable. Due to small difference between operating temperature and melting point, a solidification of the boric acid powder will happen.

For a real fuse-design the interruption capability of an arc-quenching material is important, but also effects like dielectric recovery after current interruption, thermal conductivity and costs are important. Considering all these boundary conditions, a direct placement of the needed amount of arc-quenching material to the potential arcing area would be the most efficient solution. For an industrial production process, this is nearly impossible. A potential solution was found by embedding the arc-quenching material into a matrix-material.

As the processing of an inorganic matrix material is rather complicated, an organic matrix material would be preferable. All carbo-organic materials might be excellent useable for an efficient low-cost process, nevertheless due to the high temperatures near the arc, those materials will be oxidized to gases and highly electrically conductive carbon black, which is than limiting the dielectric withstand voltage after the current interruption.

Utilizing silicone-based polymers a work-around for the drawback of the carbo-organic materials was found. Beside the easy to handle production process an increased dielectric and thermal behavior was measured.

4.3 Current Interruption Behavior of New Arc Quenching Materials

To evaluate the arc-quenching capability, all tests were based on one standard fuse design. As a reference a standard fuse filled with quartz-sand was used. The new materials were applied directly to the fuse wire. To compare the results, the ratio of the minimal applicable testing current for a safe interruption was related to the baseline of the rated current of the used fuse design (14).

$$C = \frac{I_{test}}{I_{rated}} \qquad (14)$$

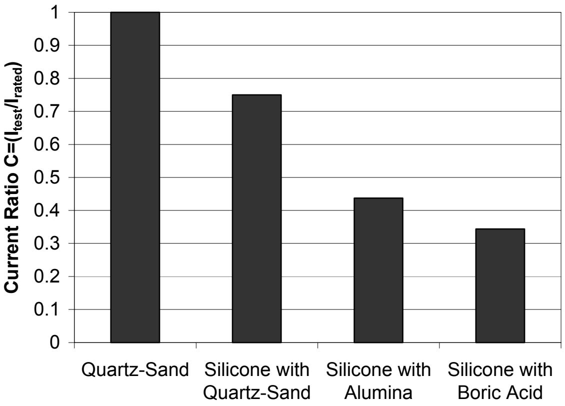


Fig. 4: Related ratio of minimal breaking current and rated current dependent on the applied arc-quenching material

In result of the tests of the minimal breaking current (TD3 in accordance to IEC 60282-1) a certain reduction of the minimal breaking current based on the current ratio (14) was measured. Also quartz-sand in a silicone matrix showed a better performance as pure fuse sand. Alumina and boric acid performed significantly better (Fig. 4).

Additional experiments were performed with ultra-fine alumina to show the influence of the particle size. Using ultra-fine alumina with particles sizes near the nano-range, lead to a further reduction of the minimal breaking current (Fig. 5).

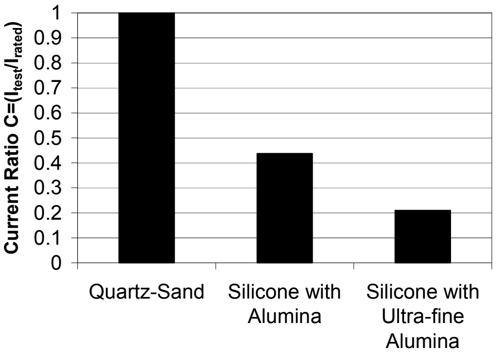


Fig. 5: Related ratio of minimal breaking current and rated current dependent on the grain size of the alumina used for the arc-quenching material

4.4 Dielectric Behavior of the New Arc Quenching Material

For the fuse-design the dielectric behavior of the arc-quenching materials is very important as well. This was measured in a needle-plan configuration as seen in Fig. 6.

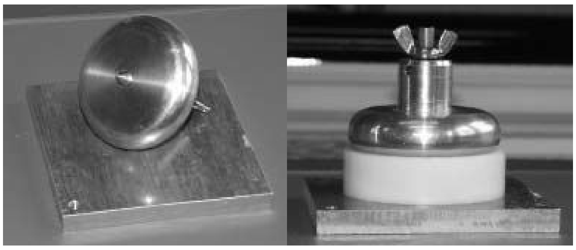


Fig. 6: Needle-Plan arrangement for the measurement of the breakdown strength of the arc quenching materials

The needle-plan setup was chosen to gain an additional safety margin compared to the real design inside a fuse. There we have the sharp edges of the fuse-element as the electrodes, which is more a needle-needle arrangement with a slightly reduced inhomogeneity of the electric field compared to a needle-plan arrangement. Mainly two materials were compared: fuse sand and alumina filled silicone. The needle was adapted to the electrode in such a way that the distance was exactly 1 cm. To realize repeatable measurements, the sand was compacted inside a PTFE-ring. In opposition to that the alumina filled silicone sampled were produced with vacuum casting including the electrode setup. For each material 10 measurements with an a. c. voltage-rise test (ΔU=1 kV/s) were performed. The average breakdown values indicated that for a strongly inhomogeneous setup quartz-sand shows twice the dielectric strength than atmospheric air, and alumina filled silicone nearly 9 times (Table 2, Fig. 7, Fig. 8).

Table 2: Average a. c. breakdown field strength of arc-quenching materials and atmospheric air

Material	Air	Quartz	Alumina filled Silicone
E [kV/cm]	~ 5	10	43.4
σ [kV/cm]	-	0.6	7

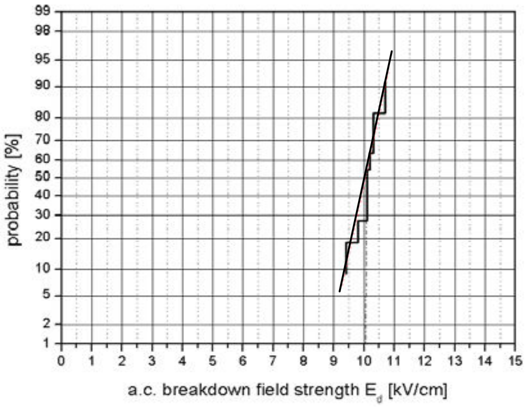


Fig. 7: Probability of the a. c. breakdown field strength of quartz sand in a needle-plan arrangement

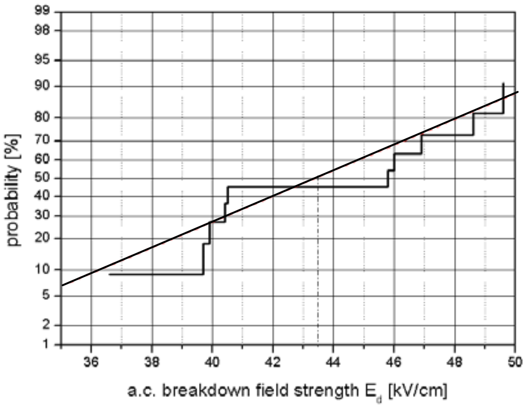


Fig. 8: Probability of the a. c. breakdown field strength of alumina filled silicone in a needle-plan arrangement

4.5 Thermal Conductivity of Arc Quenching Materials

Another important issue for the fuse-design is the thermal behavior of the arc-quenching material. The thermal conductivity and capacitance of the arc quenching material heavily influence the thermal equilibrium of the fuse link and therefore the current rating of the fuse.

The thermal conductivity was measured for quartz-sand and alumina filled silicone (Fig. 9). Due to the better conductivity of alumina compared to quartz sand, the expected result was obtained. The temperature dependency with the negative slope of alumina filled silicone is clearly dedicated to the behavior of the silicone matrix. Finally it can be concluded that the thermal behavior of the alumina filled silicone is better than for quartz-sand over the measured temperature range, which includes the nominal operating range.

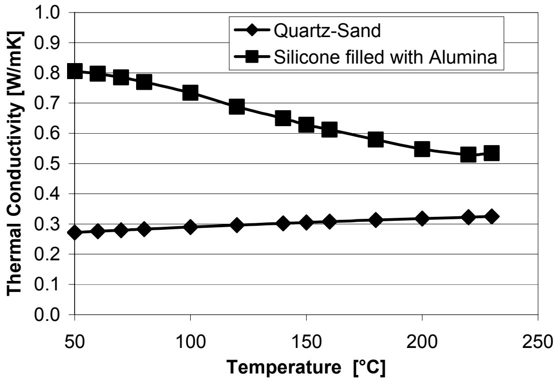


Fig. 9: Thermal conductivity of arc quenching materials dependent on the temperature

The thermal capacitance of the arc quenching material has a direct influence on the dynamic thermal behavior of the fuse-link and therewith to current-time characteristic of a fuse. A high thermal capacitance is decreasing the temperature rise at the fuse element. The measurements of the thermal capacitance (Fig. 10) were done with the Differential Scanning Calorimetry (DSC), using a temperature stabilized measuring chamber.

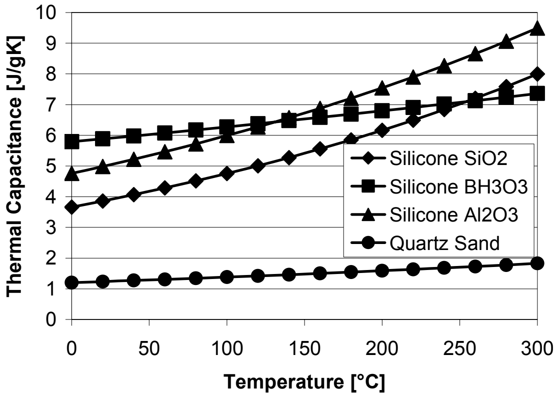


Fig. 10: Thermal capacitance of arc-quenching materials dependent on the temperature

All silicone based materials showed a significant higher thermal capacitance than the original quartz sand, whereas the alumina-filled silicone outperformed the other materials. The thermal capacitance is increasing with the temperature for all materials.

4.6 Mechanical Implications

Due to the stiffness of the silicone matrix of the new arc-quenching materials, the increased mechanical stresses have to be taken into account. Using the Finite Element Solver ABAQUS, the displacement stresses in a standard fuse, utilizing a star-shaped winding stick and fuse-elements with constrictions, were simulated. The potential stress and the deformation of the fuse element are shown in Fig. 11.

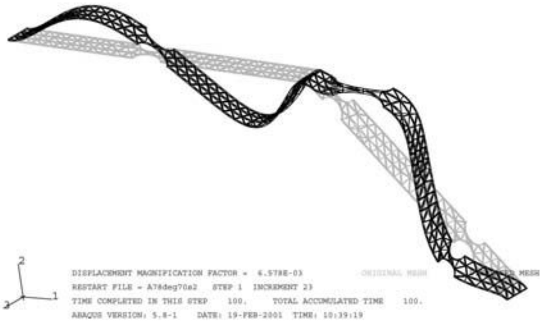


Fig. 11: FEM-simulation of the displacement of a fuse-element in a standard h.r.c. fuse (only the virgin and the stressed fuse-element shown)

Based on the simulation results (Fig. 12) a significant increase of the displacement stresses by a minimum factor of 10 was found. Two main reasons for the increased stressed were identified and simulated (Fig. 13, Fig. 14): the thickness of the arc-quenching material and the number of ribs of the winding stick.

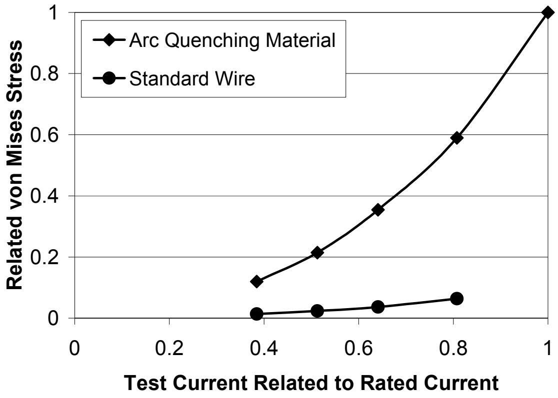


Fig. 12: Related von Mises Stress versus the related test current for a fuse-element with and without arc-quenching material (alumina filled silicone)

Due to the in-compressibility of the silicone matrix of the arc-quenching materials, a higher thickness of the applied material will lead to a higher mechanical stress (Fig. 13). A reduction of the thickness from 3 mm to one mm leads to stress reduction off 25 %.

Another topic is the number of ribs. As the ribs of the winding stick are the mechanical carrier of the wounded shape of the fuse-elements, they are also the cause for mechanical stresses (Fig. 14). By changing the numbers of ribs from 6 to 7, only a moderate increase was found by the simulation. Increasing the number of ribs to 8 led to a significant increase of the mechanical stresses. The explanation for this effect is the increased number of constrictions located directly on or near a rib, which might be specific for the chosen type of fuse-element.

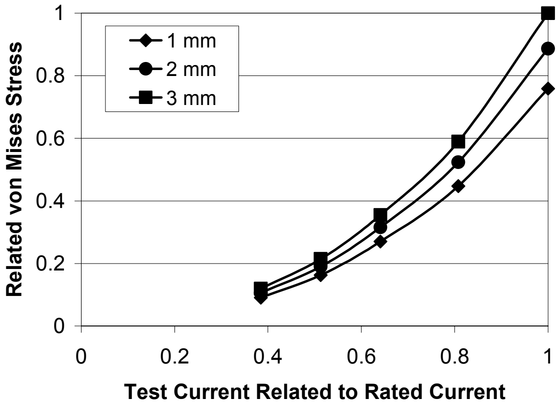


Fig. 13: Related von Mises Stress versus the related test current for fuse-elements with arc-quenching material (alumina filled silicone) of different thickness

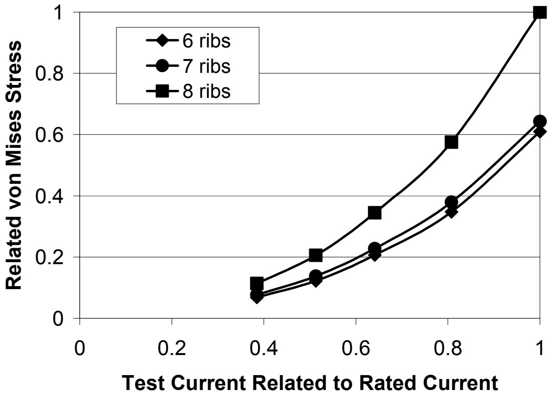


Fig. 14: Related von Mises Stress versus the related test current for fuse-elements with arc-quenching material (alumina filled silicone) dependent on the number of ribs of the winding stick

5 Combined Application of High Energy Materials and Novel Arc Quenching Materials

It was shown that the handling of low overcurrents could be improved by applying HEM for a thermally defined tripping and new arc-quenching materials. To realize such a functionality in a fuse, both effects have to be implemented without interferences. Therefore fuse-elements covered with HEM and alumina filled arc-quenching material was produced and the minimum breaking current was tested. In result (Fig. 15 and Fig. 16) no interference of both technologies could be found. Combining both methods did not influence the pre-arcing time, as well as the minimum breaking current.

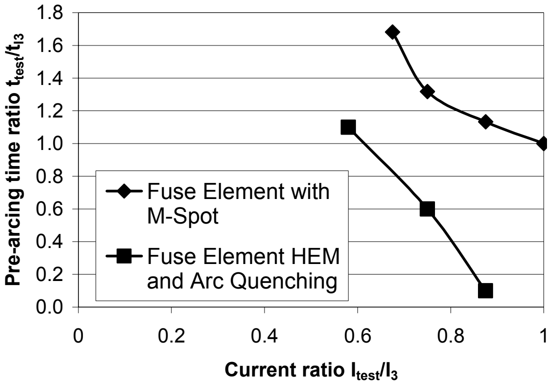


Fig. 15: Pre-arcing time versus test current of a standard fuse element with M-spot and a standard fuse element with HEM and arc quenching materials, all values related to the values of the minimal breaking current (I3 in accordance with TD 3 IEC 60282-1) of the M-Spot element

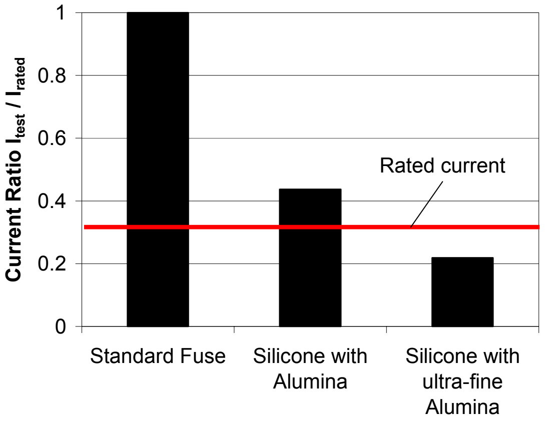


Fig. 16: Related ratio of minimal breaking current and rated current for fuses with HEM and different Arc quenching material

6 Conclusions

The interruption of low over-currents of a h.r.c. fuse was divided into two physical processes: the thermally induced tripping and the interruption of the arc. Due to the application of new materials improvements for both processes were found.

For the thermally induced tripping of a fuse, the M-spot is a well-known technology. By applying so called High-Energy Materials (HEM) based on thermites or stabilized nitric compounds, the tripping temperature and the melting time of conventional h.r.c. fuse elements could be reduced. This results in a reduced pre-arcing time. Due to the possibility of fine-tuning the behavior of the HEM, the pre-arcing I-t characteristic can by customized.

Interrupting the initiated arc is always related to the energy adsorption by the arc-quenching medium. It was again shown that new materials could improve the performance of a fuse. Inorganic fillers based on minerals, showed a better energy adsorption than conventional fuse sand. Applying these powder-like materials to a silicone-based matrix allows a direct placement of the materials to the fuse-element. The positive effect of different fillers and different grain sizes were shown. Especially arc-quenching materials based on alumina filled silicones showed a very good performance. The minimal breaking current could be reduced to values below the melting current of the fuses. This effect is very helpful for full-range fuse applications, or for fuses applied to severe thermal environments like fuse-canisters and switchgears. There the fuse is able to operate without a derating, as long as the melting temperature of the fuse element is not reached.

Beside the dielectric and the thermal behavior of the new arc-quenching materials, also the higher mechanical stresses at the fuse elements due to the new materials were simulated and discussed.

Finally successful tests with fuse elements incorporating HEM and the new arc-quenching material were performed. An interference of the two approaches was not found.

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