Innovative fuse-link of high-breaking capacity with high mechanical stability

N. Kanakis*, J. Mentel*, M. Schumann*, J. Schein*, H. Ter*, A. Kunde**
*Ruhr-Universität Bochum, **Wickmann-Werke GmbH, Witten

1 Introduction

By experimental investigation it could be shown that new fuse designs ensure a high mechanical stability and high breaking capacity combined with short current cut-off times even for the requirements for HBC-fuses, which have to be capable of handling prospective short circuit currents of 1500 A.

Physical effects were used to increase the arc voltage by splitting up the arc column and generating additional cathode and anode falls, or by reducing the diameter of the arc column by the confining tube.
To generate additional cathode and anode falls, small diaphragms of Cu or Fe with an aperture of less than one millimeter were inserted in the fuse enclosure.
The reduction of the diameter of the tube and with this of the arc column resulted in a higher voltage demand because of the ohmic characteristic a of wall-stabilized arc.
It turned out that the current cut-off times can be reduced by a factor 2 to 10 and the dissipated energy by a factor 100 compared to the commonly used fuses without filler if tube diameters smaller than 1 mm were used.

2 The construction of fuses

The principal design of a conventional fuse-link is sketched in **Fig. 1**.

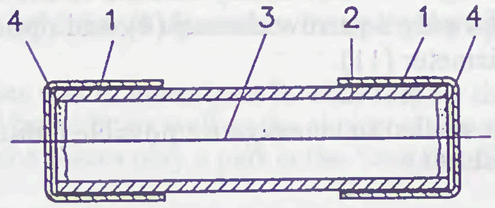
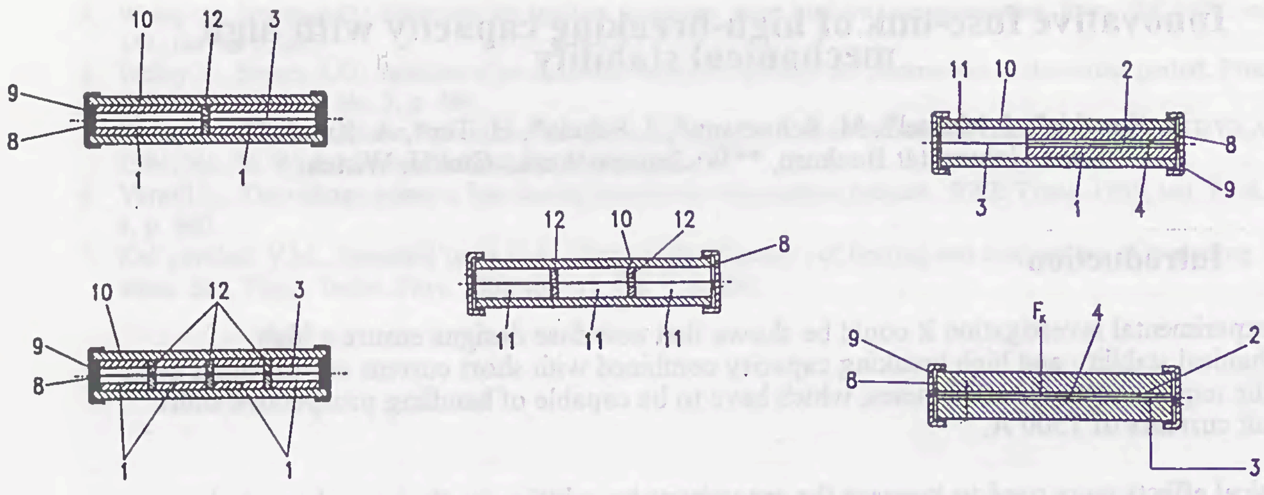


Fig. 1: The principal design of a conventional fuse-link (for details see text).

Conventional fuses which are designed to fulfil the requirements of the so-called "low breaking capacity" of 35 A, 250 V, cos θ = 1, according to the IEC 127 standard /1/, normally consist of two termination caps (1), a glass tube (2), the melting wire as current conducting element (3) and solder (4) to establish a safe and reliable electric contact to the caps.

To perform the so-called "high breaking capacity" of 1500 A, 250 V, cos φ = 0.7-0.8 /1/ the fuse-link is commonly filled with quartz-sand as an arc-extinguishing medium and the glass body (2) is replaced by a ceramic body.

The new designs for HBC-fuse-links described in this paper can do without the sand, some examples of these designs are shown in **Fig. 2**. There are two main groups:
a) the fuse-link with aperture, and b) the "Narrow-channel-fuse".



a) Fuse-links with apertures b) The „Narrow-channel-fuses“

Fig. 2: New fuse designs under investigation (for details see text).

The fuse-link with a total length of 32 mm enveloped in an outer silicate glass body (10), which is mainly used to give the entire construction a kind of mechanical stability. Inside the glass tube there are several ceramic tubes (1) of a suitable outer diameter (d_a = 4 mm) to fit inside the glass tube, and an inner diameter of 2 mm. These tube segments were separated by diaphragmes (12) of copper, quantities 1, 2, 3 or 0, having an outer diameter d_a = 4 mm and a circular hole of different diameters of 0.6 mm to 1.5 mm, by which the melting wire (3) is passed through.
In the so-called „Narrow-channel-design“ the fuse mainly consists of one or several glass tubes (1) with a small inner boring, forming a narrow channel (4), and optionally a so-called „blow-out-chamber“ with a larger diameter (11).

Different kinds of ceramic have been studied to investigate a possible influence of different thermal conductivities λ of them **(Table 1)**.

Table 1: Properties of ceramics /2/

Typ	Specification acc. to IEC 672-3 /2/	Content of Al_2O_3	Thermal conductivity λ/W/mK	porosity Pa/Vol-%
Alumina	C779	> 99%	28	0.0
Alumina/ Aluminiumsilicat	C610	> 65%	4.5	0.0
Aluminiumsilicat/ Magnesiumsilicat porous	C520		1.5	20

Commercially available round wires of 100 μm diameter made of a silver-copper-alloy have been chosen as melting elements in all experiments. The wire has been fixed by soldering to the end caps.

3 Experimental set-up

The testing of the electrical behaviour of the fuses has been performed with an electrical circuit in accordance to IEC 127 - standard /1/. The circuit has been adjusted by resistances and inductivities to establish a prospective current of 1500 A_{rms}, a power factor cos $\varphi = 0.75 - 0.77$ with a voltage of 265 V_{rms}. The circuit consists of a power tranformator, a thyristor unit which switches on the current, and by which the electrical closing angle θ can be controlled electronically.

The current has been measured by a 10 mΩ shunt, and the time dependent signals of the current i and voltage drop u_f above the fuse have been recorded by a digital oscilloscope with a vertical resolution of 12 bit and a sampling rate of 1 MHz.

Further data acquisition of the stored digital data could be carried out by normal data processing.

For interpretation of the test results the most important electrical quantities had been considered, which are:

t_s melting time	: The time from the beginning of the current flow until reaching the liquid phase of the melting wire
I_d melting current	: The maximum current amplitude occuring during the melting process
t_L arcing time	: The arc burning time
I_L arc current	: The maximum current amplitude occuring during the arcing
$t_a = t_s + t_L$	: The total switch off time
u_f	: The voltage drop across the fuse during current flow i(t)

4 The test results

4.1 Fuse-links with additional apertures for splitting up the arc

The aim of this test series was to investigate in what respect the number of apertures, various thicknesses and internal bores b_i, as well as the choice of material of the diaphragmes (metal or ceramic) and ceramic tube pieces play a part in the "switch-off-behavior" of the fuses.

A typical result of one of this series is shown in Fig 3, .4 and 5. **Fig. 3** shows the typical dependance of I_d, I_L versus the closing angle θ, **Fig. 4** the corresponding times t_S, t_L and t_a whereas **Fig. 5** shows the corresponding oscillograms $u_f(t)$ und i(t) for $\theta = 0°$ and 50°.

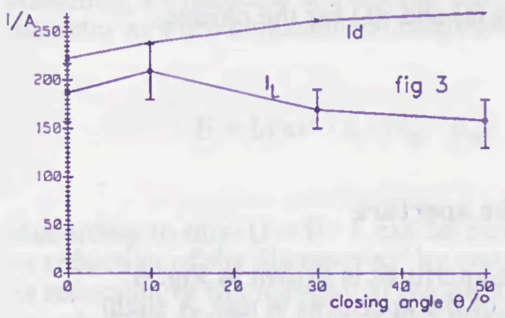


Fig. 3: Typical behaviour of currents I_d and I_L versus closing angle

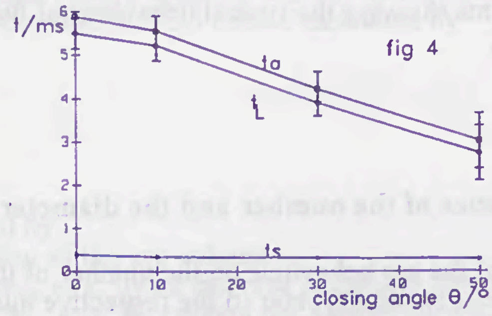


Fig 4.: The times t_S, t_L and t_a, corresponding to Fig 3.

Using a closing angle of 0°, the arc-voltage approximately reaches the value of the applied voltage (which reaches its maximum of 373 V after 5 ms) after 5.9 ms and the arc extinguishes.

For larger closing angles the begin of the current flow is delayed resulting in shorter switch-off times t_a. In this case even the dissipated energy is reduced.

The melting current I_d increases to larger switching angles since the melting phase occurs at higher current levels of the first current half-wave. In correlation with this we find a decrease of melting time t_d.

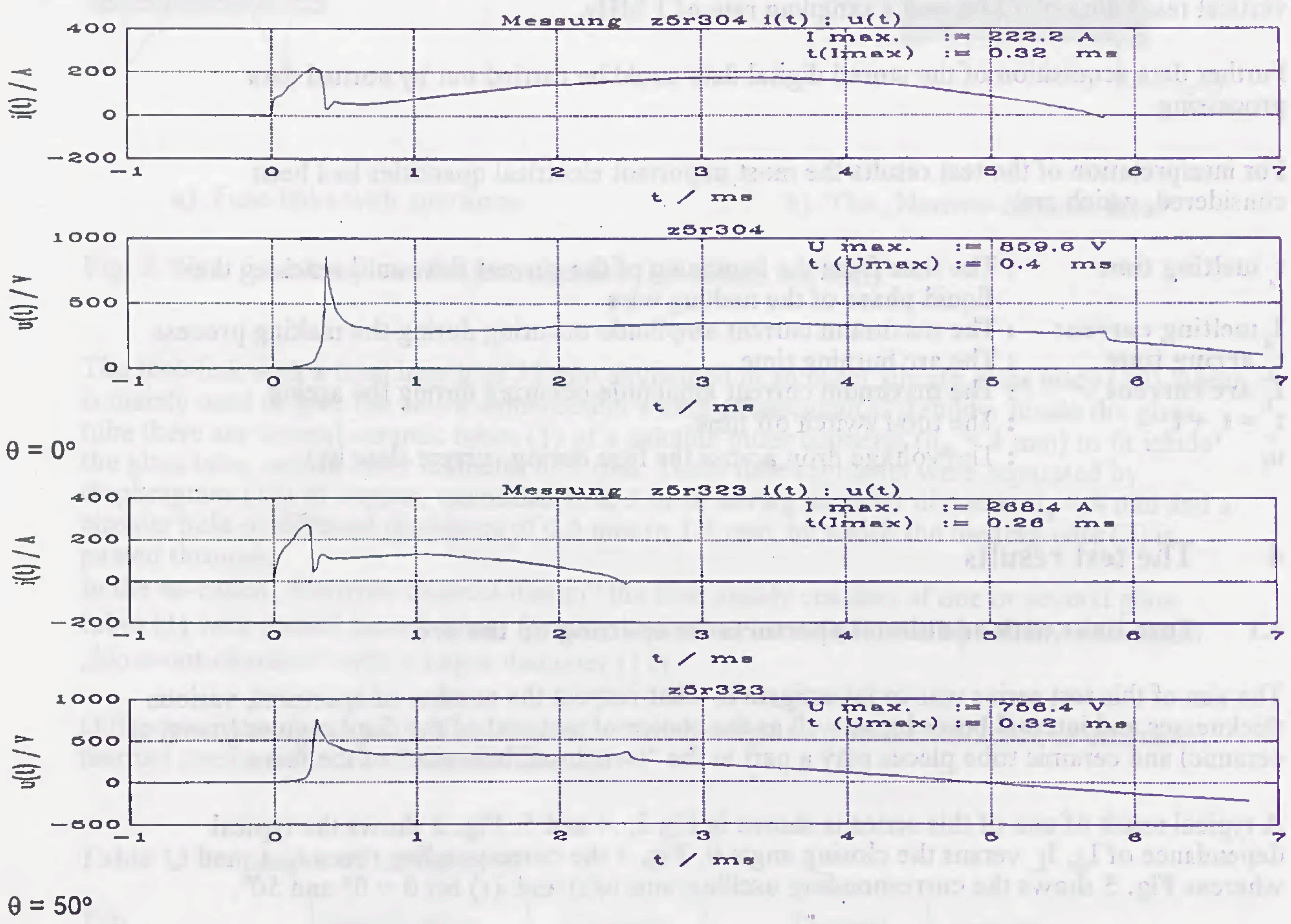
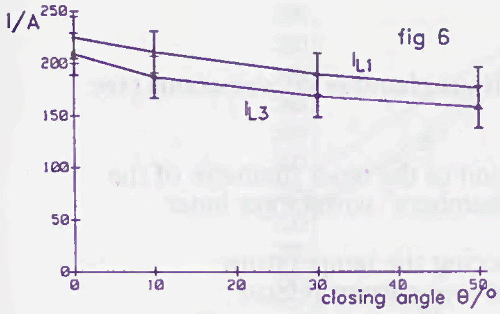


Fig. 5: Oscillograms showing the typical behaviour of fuses: u_f (t) and i(t) for the closing angles 0° and 50°.

4.2 The influence of the number and the diameter of the aperture

The dependence of the arc behaviour on the number of the Cu-apertures is shown in Fig. 6 and 7.. The indices (1) and (3) refer to the respective number of the apertures in use. A slight reduction of the times ta, t_L and a decrease of the arc current I_L with the number of apertures could be observed, what is due to the additional number of cathode and anode falls on the diaphragmes. As the melting process is independent from the number of apertures, I_d and t_s are of course not affected by this.



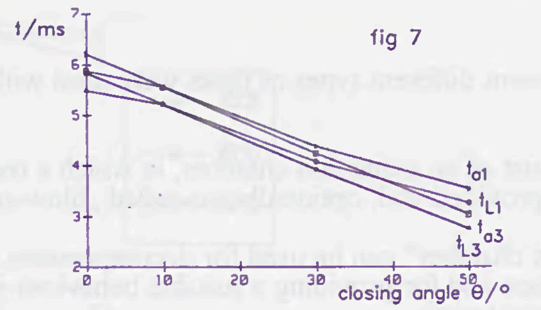


Fig. 6: The currents I_L with respect to different numbers of apertures.

Fig 7: The corresponding times t_L and t_a to Fig 6.

Further investigations showed that a variation the apertures b_i in the diameter range of 1.0 mm to 1.7 mm did not entail any significant distictions.
Relating to the thermal conductivity of the ceramic tube segments no effects were found.

The effects of the inserted apertures on the formation of additional arc spots and thereby the additional demand of voltage of the arc by several anode and cathode falls were tested. The effects of the ceramic material of the tube pieces were investigated also and it was found that the effect to the switch-off times are insignificant. The effect of a forced constriction of the arc on the switch-off times is described in the second part of this work.

The theme "decrease of the electrical conductance by a decrease of the diameter" and, in this context, an increased demand of voltage supporting the switch-off capacity, is sufficiently known in literature and initiated the tests with the so-called "Narrow-channel fuses".

5 Narrow-channel fuse

5.1 The physical background

Using the simplified differential Ohm's law, thereby neglecting diffusion effects and taking into account that the mobility of ions is much smaller than those of electrons ($\mu_i << \mu_e$), current density can be described by:

$$j = j_e = e \cdot N_e \cdot \mu_e \cdot E.$$

Assuming a cylindrical arc column with a radius r and a constant current density across the diameter πr^2, the longitudinal component of the electric field can be estimated by

$$E = I/(\pi r^2 \cdot e \cdot N_e \cdot \mu_e).$$

According to this $U = E \cdot l$ can be increased by
-a reduction of the diameter πr^2 by constriction of the arc column
-a reduction of the mobility of the electrons μ_e, e. g. by an increase of the gas pressure
-a reduction of the number of free electrons N_e, e. g. by cooling the plasma column.

5.2 Tests

For this experiment different types of fuses were used with various chamber combinations (see **Fig. 2b**):

-The fuses consist of an extinction chamber, in which a reduction of the inner diameter of the arc column is provided and, optionally, so-called „blow-out chambers" with larger inner diameters.
-The „blow-out chamber“ can be used for decompression, reducing the temperature near the end caps and for providing a suitable behaviour in the low-current region of the fuse characteristic.

Here, results of the most simple stage of realization, consisting exclusively of a glass tube are documented. Investigations with glass tubes with different inner diameters b_i were carried out.

Fig. 8 shows the melting and switch-off times t_s and t_a. The indices (6 and 8) refer to the different inner diameters of the tube b_i (0.6 mm and 0.8 mm).

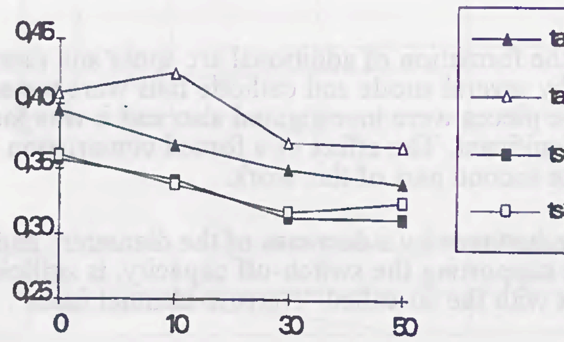


Fig. 8 Melting time t_s /ms and switch-off times t_a/ms versus the closing angle θ/°
The indices (6 and 8) refer to the different inner diameters b_i (0.6 mm and 0.8 mm)

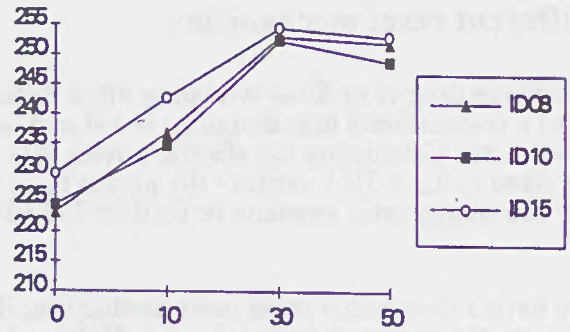
The extremely short switch-off-times t_a < 400 µs have to be pointed out; they are in the same range as the melting times t_s with approx. 350 µs.

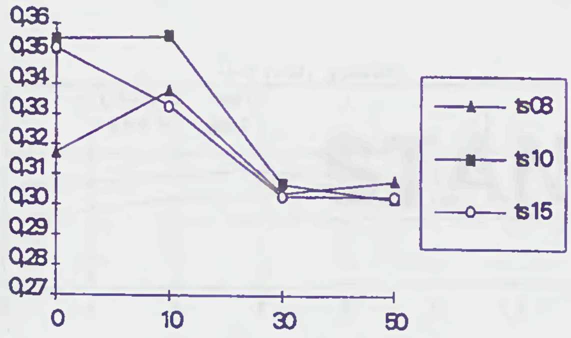
The effect of the capillary diameter is plainly recognizable. Whereas b_i does not affect melting time t_s the switch-off times t_a are distinctly shorter for internal borings of 0.6 mm (t_{a6}) than for those of 0.8 mm (t_{a8}).

In further tests the effect of the internal diameter has been investigated in more detail.

Tubes made of ceramic material with different inner diameters b_i = 0.8, 1.0, 1.5 mm, surrounded by an external glass tube were tested. The results distinctly show the effect of the inner diameter (**fig. 9**).

The arc current as well as the respective arcing-time t_a diminish if the inner diameter of the tube is reduced. Stable results are achieved using b_i = 0.8 mm and times t_a less than 400 µs will be reached. If the inner diameter is larger than 1.0 mm, times are longer by an order of magnitude. Likewise this result is reproduceable. In the transition range of ≈1 mm the fuses suddenly show a varying behaviour resulting in a large scattering of the results. The average times are ≈1.5 ms; this, however, with a substantial scattering of results not considered in these figures.





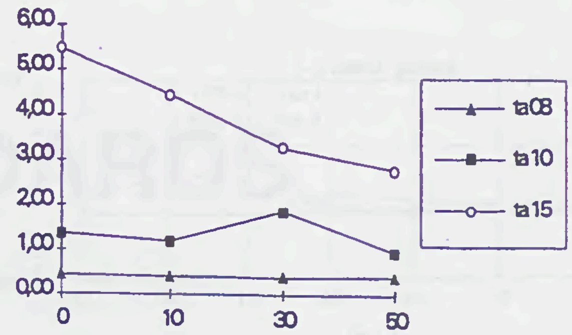


Fig. 9 Melting time t_s/ms and switch-off times t_a/ms as well as the respective currents I_d/A versus the closing angle θ/°. The indices (8, 10, 15) refer to the different boresizes b_i (0.8, 1.0 and 1.5 mm).

Evidently an inner diameter of 1 mm seems to be a kind of transition range of the "narrow-channel fuse" to the conventional fuse.

Considering the results of one internal diameter each time, the different dominating time factors become distinct (Fig 10).

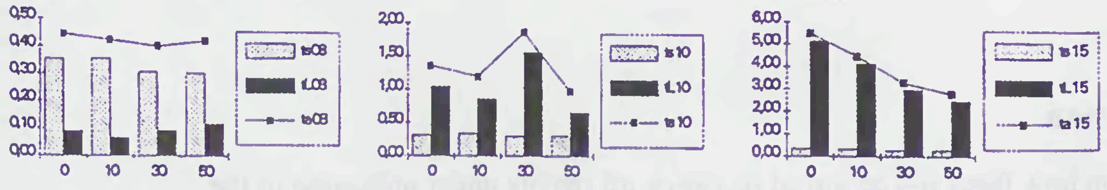


Fig 10: The influence of the different diameters b_i = 0.8, 1.0 and 1.5 mm on the time t_s, t_L, and t_a in dependence on the closing angle θ/°.

For an innner diameter of b_i = 0.8 mm the melting time is the dominant time: t_s = 0.45 ms $\approx t_L > t_a$ = 0.1 ms. For an internal diameter of 1.5 mm this relation becomes reversed and t_L is the decisive time ($t_a \approx t_L >> t_s$). For an inner diameter of 1.0 mm a transition between these two cases can be observed.

6 The energy balances in different reset mechanisms

Fig. 11 and 12 show the current i and voltage drop u_f of fuses switching off at different times. In one case arc behaviour is according to a conventional fuse design ($t_a \approx$ 5-6 ms), in the other case the fuse cuts the current off after $\approx$ 0.6 ms. Calculating the electric power $P(t) = u_f(t)\, i(t)$ and energy E, it becomes distinct that - when t_{a1}/t_{a2} = 10:1 variies - the power $P_{max1} \approx P_{max2} \approx$ (65 - 80) kVA is identical in both cases; the energy ratio amounts to E_2/E_1 = 742 kJ/4.8 kJ and therefore increases by factor 150.

This result shows how important it is to have a fuse with a rapid reset mechanism, if a high current capacity is to be achieved. However, the excess voltage ($U_{ind} \approx L\, dI/dt$), which was increased from 860 V to 1300 V, as occurring in this example, represents a disadvantage.

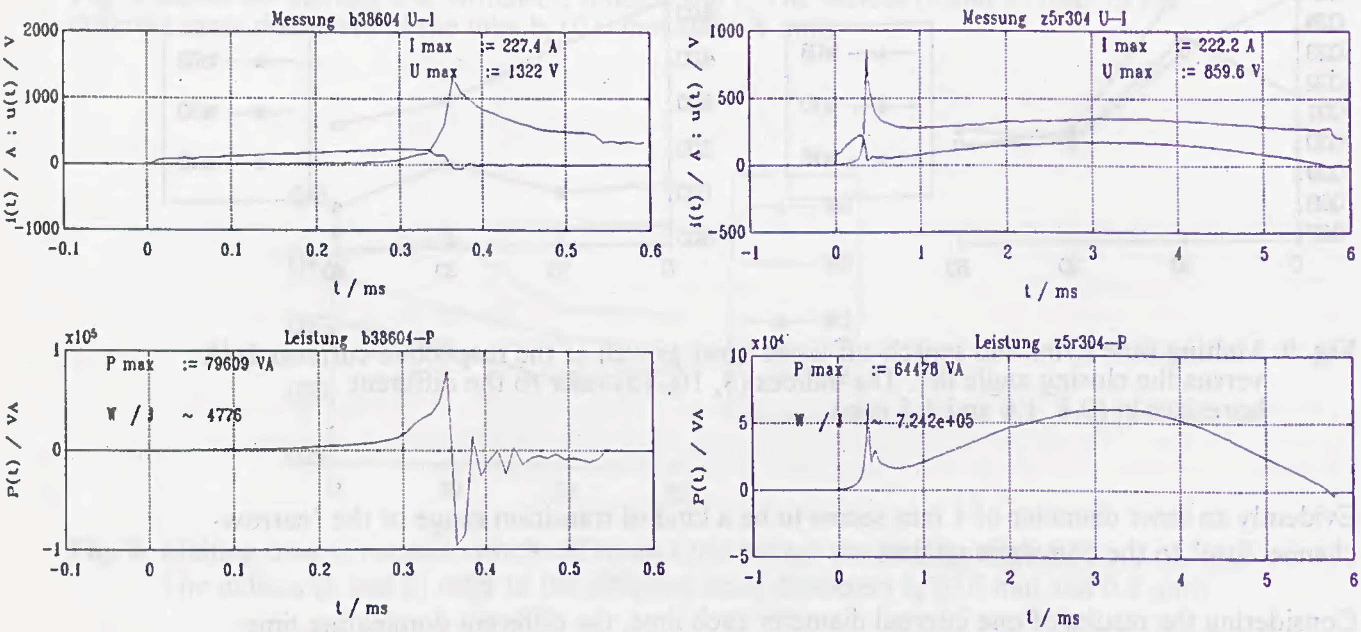


Fig 11/12: Voltage drop u_f, power P and resulting energy in accordance to different switch off times.

7 Conclusion

It could be shown how fuses will be forced to switch off rapidly under utilization of the reduction of the arc diameter and the increased demand of voltage of the arc even for miniature fuse designs.

8 References

-/1/ IEC 127-1(1988): „Miniature fuses; Part 1: Definitions for miniature fuses and general requirements for miniature-fuse-links; IEC 127-2 (1989): „Miniature fuses; Part 2: Cartridge fuse-links"

-/2/ IEC 672-3 (1984): „Specification for ceramic and glass insulating materials; Part 3: Individual materials"

DESIGN, TESTING, STANDARDS