SWITCHING PERFORMANCE OF HIGH-VOLTAGE FUSE-ELEMENTS IN DIFFERENT SOLID AND GASEOUS FILLING MEDIA

D. König, J. Trott, H.J. Müller, B. Müller

ABSTRACT

HV-fuses that are back-up fuses do not interrupt overload currents below a minimum braking current I_{mbc} because of thermal overheating caused by the overload current arcing. The rupturing capacity of the switching device High Voltage Fuse is essentially determined by the arrangement of the fuse-elements and the used filling media. Quartz sand has not proved to be the most proper medium for arc extinction during current zero in the small overload current range. However, quartz sand has proved to be the proper medium for current limiting arc extinction in the heavy fault, short-circuit current range.

The burn-back performance of fuse elements was tested with different filling media. It appears that the burn-back rate of a fuse element surrounded by electronegative gases is much higher than when surrounded by quartz sand. The significant increased arc length assists the arc extinction. In addition, the dielectric strength of electronegative gases during current zero of an overload current arc is much higher. Both features lead to a significant increase of the rupturing capacity of fuse-elements surrounded by electronegative gases, thus enabling overcurrent protection. Fuse-elements that are surrounded by electronegative gases represent in principle a current zero switching device. To obtain additionally current limitation, preference should be given to a combination of fuse-elements in electronegative gases with conventional current limiting switching device consisting of fuse-elements in quartz sand, e.g. a conventional back-up fuse.

INTRODUCTION

High Voltage fuses are in large majority so called back-up fuses. Back-up fuses provide satisfactory clearance of all currents below their maximum breaking capacity down to their minimum breaking current I_{mbc}. Currents below the minimum breaking current I_{mbc} that cause melting of the fuse element may produce the destruction of the fuse body. The low overload current arc cannot be extinguished by the filling medium due to the fact that the power loss of the arc

$$W_a = \int_0^{t_a} u_a(t) \cdot i(t)\, dt \qquad (1)$$

$W_a \hat{=}$ power loss of the arc

$t_a \hat{=}$ arcing time

$u_a \hat{=}$ arc voltage

$i \hat{=}$ arc current

leads during a significant long arcing time t_a to thermal overheating of the fuse body and thus to the mechanical destruction of the ceramic body /1/. Therefore, for safe interruption of low overload currents an early extinction of the established low overload current arc is important.

General purpose fuses according to IEC.282-1 /2/ must break currents leading to a melting time of $t_m = 1$ h. The value of 1 h-melting currents normally is below the value of minimum breaking currents I_{mbc} of back-up fuses with the same rated current. Quartz sand, due to its thermal and dielectric features, cannot give sufficient assistance to the arc extinction in the low overload current range. This applies particularly to fuses with high voltage- and high current ratings. The present report tries to point out the reasons for failure of common back-up fuses in the range below I_{mbc} and discusses an approach to solve the overload current problem. The performed investigations deal exclusively with the effects that different filling media have on arc extinction in HV fuses. Modifications of the fuse elements have not been investigated.

1 TEST ARRANGEMENT

To reproduce the breaking performance of HV fuses a test arrangement was used complying in its construction with HV fuses (Fig. 1). The fuse-element (6) is wound around a ceramic supporting core (5). The fuse body is an epoxy resin tube (1) where at both sides metal end caps (2) are glued on. Via O-rings (3) the test body can be closed gas-tight by means of additional metal flanges (4). As the investigations are restricted to the low overload current range the use of a fuse-element arrangement with notches could be omitted. Fine grained silver fuse wire of d = 0,15 mm to 0,4 mm diameter were used. In order to avoid current commutation processes between different fuse elements only one fuse wire was wound on the core. The test body (Fig. 1) was alternatively filled with quartz sand in grain size proportions of $d_g = 0,3 - 0,35$ mm (d_g = grain diameter) or with the gases air, nitrogen and sulphurhexafluoride. Prior to be filled with gas the body was evacuated to a residual pressure of p = 6 kPa.

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2 TEST CIRCUIT

The breaking capacity tests in the low overload current range of HV fuses were performed singlepole in a three-phase network system with a recovery voltage of U_r = 20 kV. The current setting was made by reactance regulators. A simplified equivalent circuit diagram of the test circuit is illustrated in Fig. 2. The investigated test currents are within the low overload current range of HF fuses with a rated current of I_r = 10 A. The power factor of the test circuit is cos φ = 0,125. The slope of the transient recovery voltage is du_c/dt = 220 V/µs. Thus, the test conditions are much more severe that it is required for the minimum breaking current test (test duty 3 according to IEC /2/) and cover at the same time the test specifications for the critical current (test duty 2 according to IEC /2/). The permissible tolerances for the performance of overload current breaking capacity tests are not utilized.

3 BURN-BACK PERFORMANCE OF FUSE ELEMENTS IN DIFFERENT FILLING MEDIA

During the melting period the ohmic loss on the fuse-element

$$W_m = \int_0^{t_m} R_m(t) \cdot i(t)\, dt \qquad (2)$$

W_m ≙ power dissipation of the fuse link
R_m ≙ ohmic restistance
t_m ≙ melting time

results in heating the complete fuse body /3/. Under low overload current conditions the fuse-element reaches its melting temperature right in the middle of the fuse wire and one arc is established. This arc is lenghtened along the axis of the fuse wire. As long as the low overload current keeps running, the established arc burns back. The burn-back rate of the fuse-element is depending on the fuse-element material, its geometric dimensions, the filling medium and the current rating.
Since in the performed tests fuse wires of only one type of fine grained silver were used it is possible to determine the burn-back rate in relation of the filling medium and to the current density within the fuse-element. The rupturing process was controlled in such a way that the current continued to run some few current cycles after the arc has been established until it was interrupted by the safety-switch E (see Fig. 2). By measuring the length of the partly burnt-off fuse-element (burn-back lenght ℓ) or of the fulgurite in the quartz sand and by determination of the arcing time the burn-back rate v can be calculated with

$$v = \frac{\ell}{t_a} \,. \qquad (3)$$

The test results for the filling media quartz sand, air, SF_6 are illustrated in Fig. 3. The burn-back rate is directly proportional to the current density in the fuse-element /4,5/. Hereby it is to be taken into account that the burn-back rate is determined by the distance growth of the opposite arcing foot points in both directions of the fuse-element axis starting from the melting point.

From the proportional relations given in Fig. 3 the specific burn-back volume c can be calculated in the dimension mm³/As. In Table 1 the calculated specific burn-back volumes for silver wires and the mentioned filling media are registered.

filling media	specific burn-back volume c	burn-back length ℓ t_a = 10 ms	heat conductivity λ_w	specific. heat capacity c_{vw}
quartz sand	1,4 mm³/As	11 mm	0,35 W/mK	840 J/kgK
air	8,5 mm³/As	67 mm	0,0257 W/mK	715,9 J/kgK
SF_6 (p=0,3MPa)	11,5 mm³/As	91 mm	-	608,6 J/kgK
SF_6 (p=0,1MPa)	14,5 mm³/As	115 mm	0,01778 W/mK	625,7 J/kgK

Table 1: Filling media, specific burn-back volumes and burn-back lengths at a current density of J = 792 A/mm² with fuse-elements of fine grained silver. Heat characteristic values λ_w and c_{vw} taken from /6,7/

The specific burn-back volume depends on the heat transport features of the filling medium figured in Table 1 by the thermal conductivity and the volume rated specific heat capacity of the filling medium. Media with good heat conduction (e.g. quartz sand) reduce the burn-back rate because of its cooling effect. Media with bad heat conduction (gases) on the other hand, enable quick lengthening of the arc.

The arcing development in the low overload current range of HV fuses can therefore be influenced by the choice of the filling medium. Quartz sand leads at small current densities to little burn-back lengths ℓ, For this reason the arc extinction below the minimum breaking current I_{mbc} is aggravated. Only if the current density is increased to such an extend that the fuse-element melts simultaneously at several points, a significant arc extension may be obtained. When gases are used as filling medium (e.g. SF_6) considerable arc lengths can already be achieved with significant smaller current densities within the time of half a current cycle.

4 INVESTIGATION OF THE DIELECTRIC STRENGTH AFTER OVERLOAD CURRENT ZERO

According to the tests described in Chaper 3 the arc length during low overload current arcs in quartz sand is only some mm in length at the first current zero after arc ignition. Since the fuse body is heated up according to Equation (1) by the power loss of the arc an early rupturing of the low overload current is important. The aim is to obtain arc extinction at the first zero of the arc current.

4.1 Current and voltage development after current zero

The low overload current arcs in HV fuses are exclusively extinguished during current zero. As arc current and arc voltage are in phase during the arcing time and the power factor of the test circuit is cos $\varphi < 1$ the arc gap is heavily stressed by the steep transient recovery voltage as soon as the current remains zero. During test performance the transient recovery voltage amounted to d_{uC}/dt = 220 V/µs.
Current and voltage development of the restriking of a low overload current arc in quartz sand and SF_6 are plotted in Fig. 4 and Fig. 5. The plots demonstrate restriking arcs directly after the first current zero. While the arc current in quartz sand is running linear through the natural zero of current, in SF_6, however, a distinct zero phase of current can be realized. The ignition voltage U_Z which is characteristic for the extinction ability of an arcing arrangement with equal arc length and equal current rating, is significantly higher in SF_6 than in quartz sand. The higher U_Z the better is the cooling of the rupturing arc /8,9/.

4.2 Dielectric strength of an arc gap caused of an overload current arc

At a current density of J = 792 A/mm² and for an arc length (burn-back length ℓ of the silver element) of ℓ = 10 mm (see Table 1) the cumulative frequency distribution of the measured ignition voltages in quartz sand was statistically calculated and is illustrated in Fig. 6. According to this 70 % of the measured ignition voltages are smaller than U_Z = 2 kV. Due to different burn-back rates v a comparison with gaseous filling media, however, is possible only on condition that the arc length is constant. This can be achieved by reducing the fuse wire length in such a way that the burn-back length per half current cycle is of the same order as in quartz sand. For measuring the ignition voltage in gaseous media the arc length is reduced to l = 10 mm by the arrangement of Fig. 7 in the fuse body. From the measured ignition voltages and accurately adjusted burn-back lengths the external ignition field strength E_Z of the arcing arrangement can be determined:

$$E_Z = \frac{U_Z}{l} \quad (4)$$

The arithmetic mean values of the ignition field strength $\bar{E}_Z$ are given in Table 2 for the tested filling media.

filling media	field strength $\bar{E}_Z$
quartz sand	1,5 ± 0,5 kV/cm
O_2 (p=0,1 MPa)	0,075 ± 0,025 kV/cm
N_2 (p=0,1 MPa)	0,075 ± 0,025 kV/cm
SF_6 (p=0,1 MPa)	3,5 ± 0,5 kV/cm
SF_6 (p=0,3 MPa)	16,0 ± 0,5 kV/cm

Table 2: Ignition field strength $\bar{E}_Z$ in dependence of the filling media at a current density of J = 792 A/mm².

According to Table 2 the dielectric strength of the same arc gap is in SF_6 higher than in quartz sand. According to Table 1 the arc in a fuse filled with SF_6 may obtain a burn-back length ℓ that is sufficient to extinguish the arc already after half a current cycle. In quartz sand, however, the burn-back rate and the ignition field strength is so small that a quick arc extinction is not possible. Only if the fuse-element melt up at increased current density at various different locations forming multiple partial arcs the burn-back performance causes the necessary length for arc extinction.

5 MINIMUM BURN-BACK LENGTH OF THE FUSE WIRE FOR ARC EXTINGUISHING IN SULPHURHEXAFLUORIDE

By lengthening of the wire in Fig. 7 the ignition voltage increases. In dependence of the pressure and of the field strength $\bar{E}_Z$ of the filling media SF_6 (see Table 2) the arc is extinguished at a definite minimum burn-back length of the wire. The drawn line in Fig. 8 shows the minimum arc length of overload currents in static SF_6. Experiments with successfull arc extinction have been done with a larger arc length. Experiments without arc extinction were performed with smaller arc length. In the media SF_6 it is possible to extinguish an overload current arc during the first current zero after arc ignition by a arc length of only some cm.

SUMMARY

The low burn-back rate of low overload current arcs in quartz sand and the small dielectric strength of the achieved arc gap at current zero may lead to malfunction of HV fuses filled with quartz sand below a minimum breaking current I_{mbc}. Because if its high dielectric strength during current zero and of the high burn-back rate for low current densities, SF_6 offers the possibility to rupture low overload currents with long melting times before the fuse body failes due to thermal overheating.

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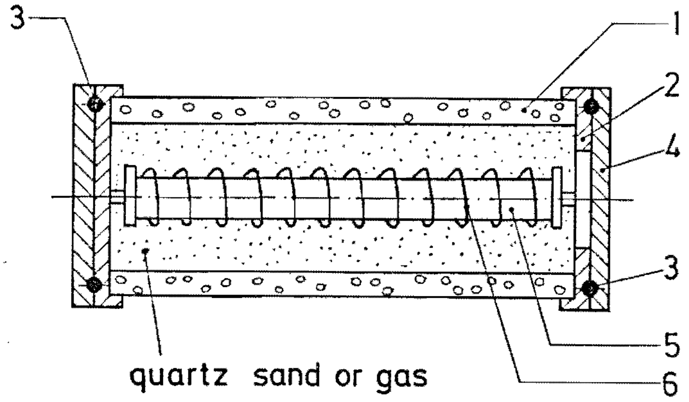

Fig. 1: Test Body

1	epoxy resin tube
2	metal end caps
3	O-rings
4	metal flanges
5	ceramic supporting core
6	fuse-element

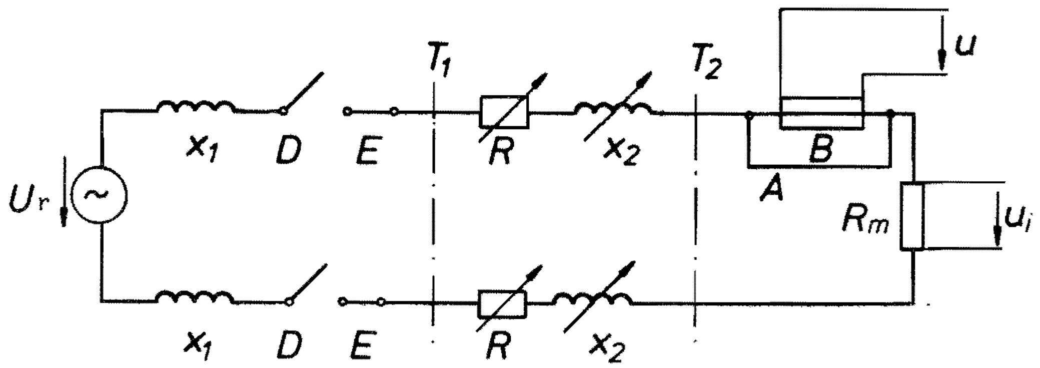

Fig. 2: Simplified equivalent circuit diagram of the test circuit

X_1; X_2	inductances	B	test arrangement
R	resistance	A	removeable short circuiter for regulationof the test current
D; E	circuit-breakers	R_m	measuring resistance
T_1; T_2	transformers		

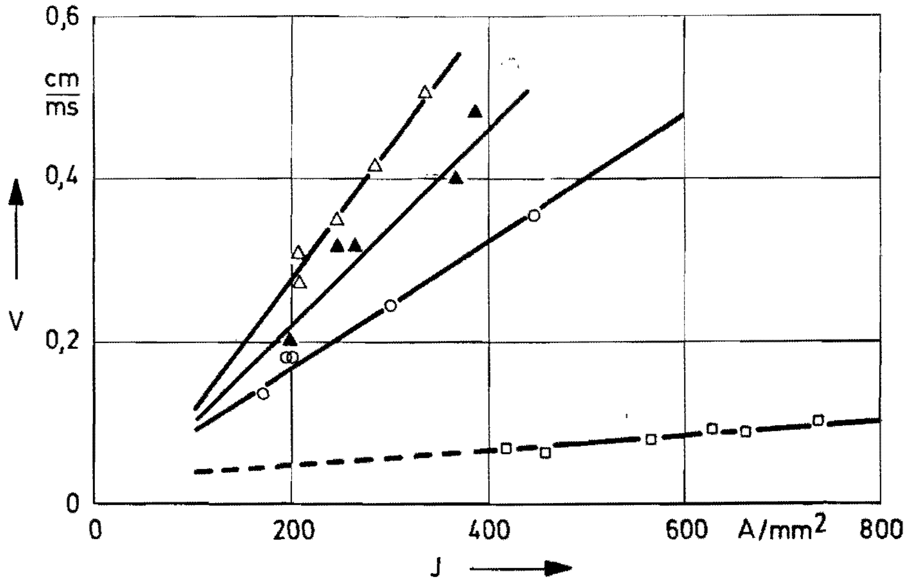

Fig. 3: Burn-back rate of silver wires in dependence of the current density in different filling media

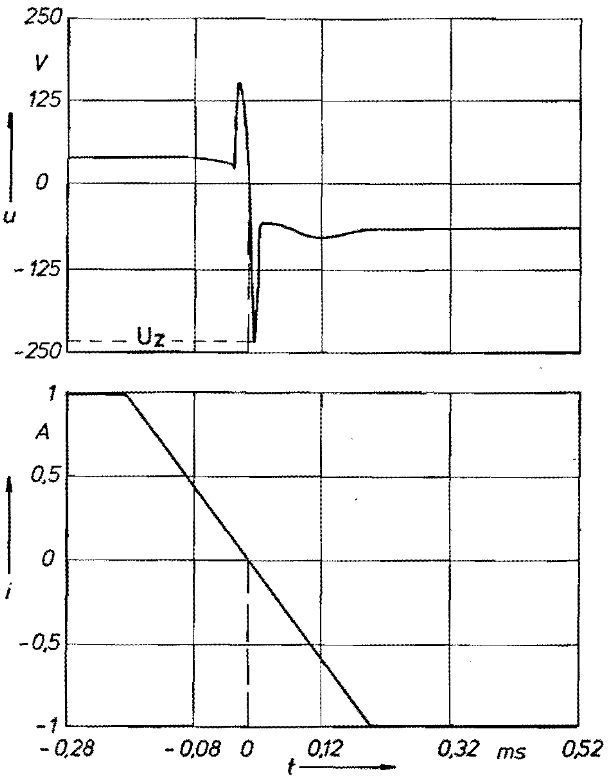

Fig. 4: Voltage and current development of a low overload current restriking arc in quartz sand

I = 14 A arc current

U_r = 20 kV rated voltage

l = 10 mm arc length

du_c/dt = 220 V/µs transient recovery voltage

U_Z = 245 V ignition voltage (neg. polarity)

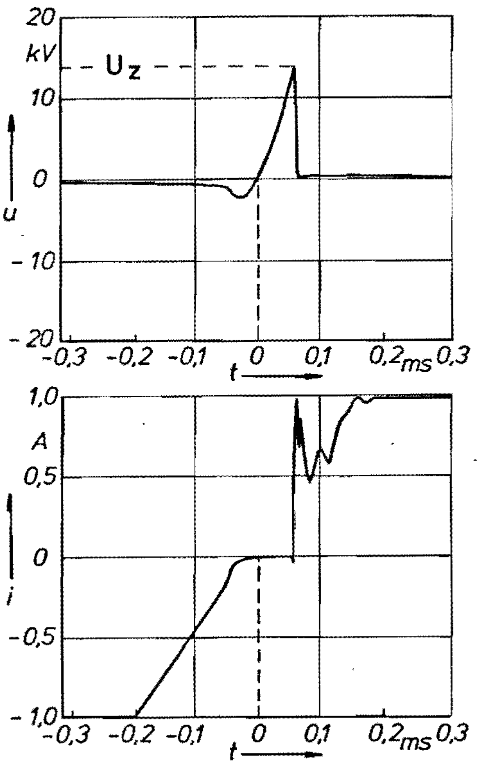

Fig. 5: Voltage and current development of a low overload current restriking arc in SF_6

I = 14 A arc current

U_r = 20 kV rated voltage

l = 10 mm arc length

du_c/dt = 220 V/µs transient recovery voltage

p = 0,3 MPa pressure of the gas

U_Z = 14 kV ignition voltage (pos. polarity)

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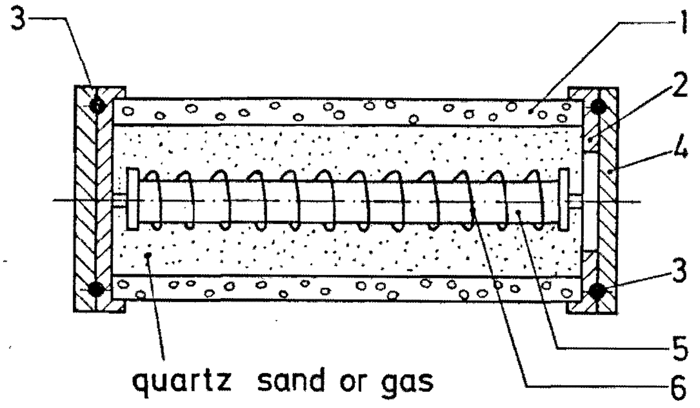

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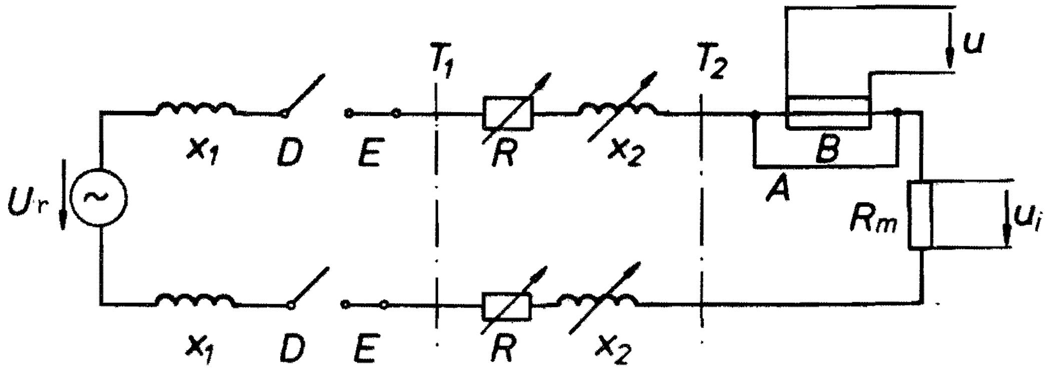

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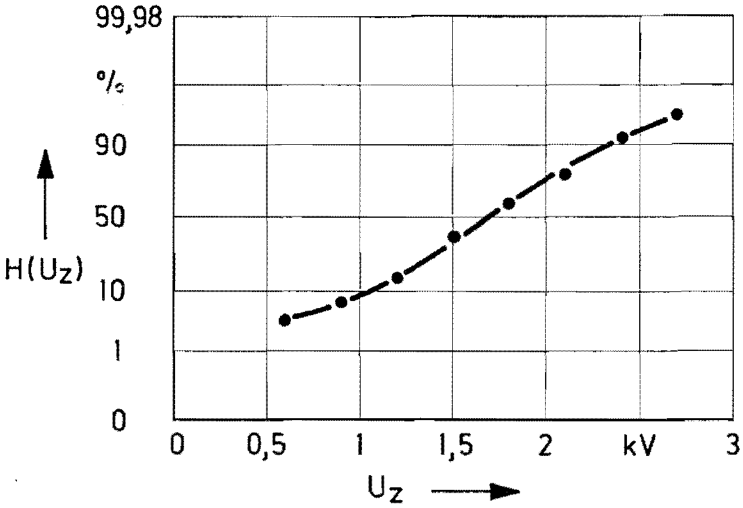

Fig. 6:

Cummulative frequency distribution of the measured ignition voltage of overload current arcs in quartz sand with a current density of J = 792 A/mm² and an arc length of ℓ = 10 mm

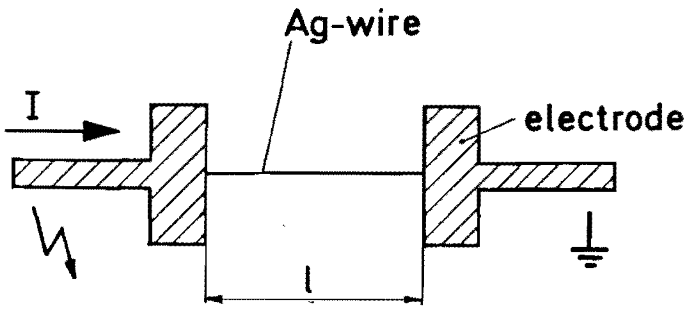

Fig. 7:

Arrangement of the fuse wire for producing a definite arc length in gaseous media

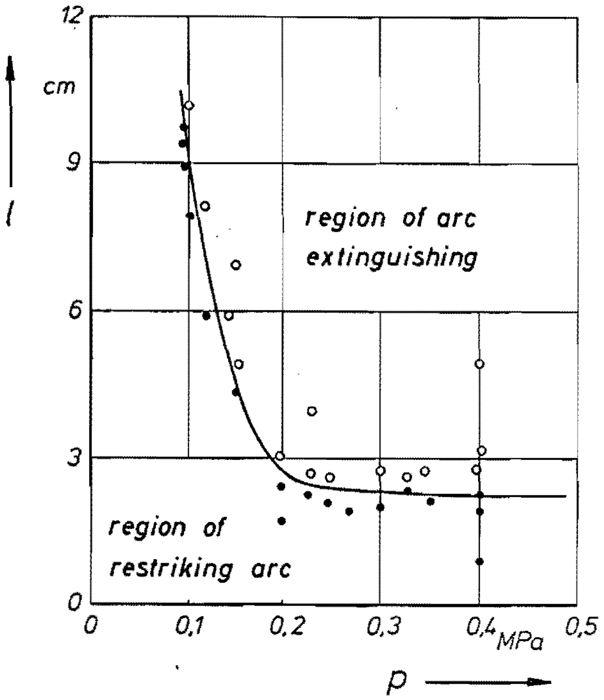

Fig. 8:

Minimum burn-back length of a wire in dependence of the pressure of SF_6

I = 14 A arc current

U_r = 20 kV rated voltage

du_c/dt = 220 V/µs transient recovery voltage