ANALOG SIMULATIONS OF THE HEAT FLOW IN A HIGH VOLTAGE FUSE.

J.G.J. Sloot
Department of Electrical Engineering
Eindhoven University of Technology.

Abstract.
The heat flow in a high voltage fuse has been simulated by an electrical analog model. The design and analysis was performed interactively on the screen of a personal computer.
The model has been used to determine the melting time curve of a full range type commercial fuse.

1. Introduction.

Within high voltage fuses heat is generated by Joule-losses. In fact the functioning of the fuse depends on heat flow processes. For short circuit currents the fuse is activated when narrow parts of a silver strip reach their melting temperature.
In the overcurrent range the heating of less narrow parts often becomes dominant (for instance with the M-spot effect).
This article discusses the calculation of such thermal processes in a commercial fuse by using an electric analog model.
The method first was developed using real electric components, like resistors and capacitors, but today it is more attractive to use the the method with personal computers when graphic interaction on the screen is possible.

2. The dimensions of the fuse.

Fig 1 shows the exploded view of a commercial fuse (40 A, 12 kV) of the full range type.

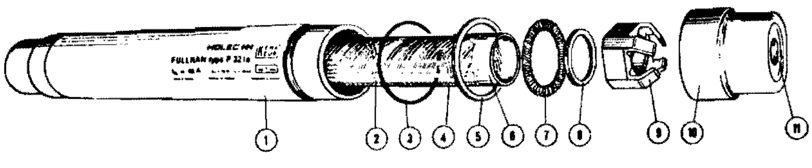

fig. 1 Exploded view of the fuse.

Within a porcellan housing, a number of parallel fuse strips (N) with thickness Λ are wounded helically with an angle β around a quartz cylinder.
The fuse strips are provided with notches (length L_{not}, heigth H_{not}) between less narrow bandparts (L_{ban}, H_{ban}).
The inner and outer space of the quartz cylinder is filled with sand.

Fig. 2 shows a part of the longitudinal cross section of a fuse slice.

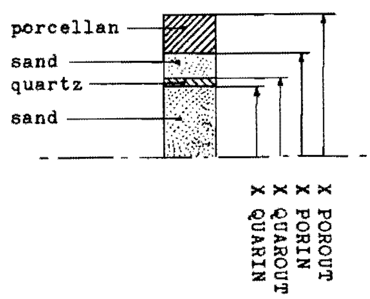

Fig. 2 Longitudinal section of the fuse.

Because of symmetry reasons, only an angular part of a slice needs to be considered (see fig. 3).

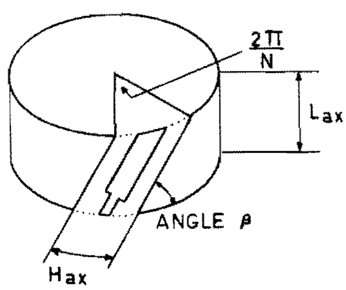

Fig. 3 Angular part of slice.

The angular part represents a fraction 1/N of the slice and corresponds with half a notch and half a band. The part has an axial length
$L_{ax} = 0.5\ (L_{not} + L_{ban})\ \sin\beta$.
(This means that the silver strip element corresponds with an outside quartz surface $L_{ax}H_{ax}$ with $H_{ax} = 2\pi Xquarout/N$).

The angular part is now further divided into pieces according to fig. 4.

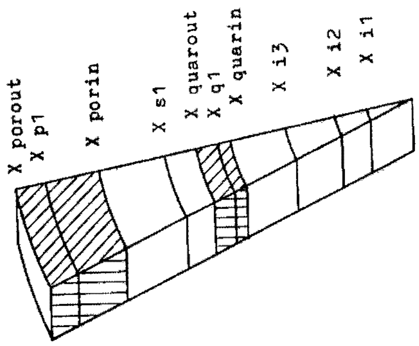

Fig. 4 Angular division of the fuse-slice.

3. The thermal model.

Joule heat is generated in the notch and the bandpart on the outside quartz surface.

Because of its higher resistance the notch will heat the band.

On a longer time scale both will heat the quartz and the sand. The fuse is relatively long compared to the diameter, therefore it is assumed that the heatflow in the middle of the fuse is directed radially. The outside of the porcellan is cooled by convection and radiation. The governing heat equations are the following:

a. Heat sources.

The Joule heat of the band and the notch represent heat sources P_{ban} and P_{not} with:

$P_{ban} = (I/N)^2 R_{ban}$

$R_{ban} = Rb_o(1 + \alpha (T - T_o))$

$Rb_o = \rho_o \, 0.5 \, L_{ban}/(H_{ban}\Delta)$

$\rho_o = \rho (T_o)$ with ambient temperature T_o

$P_{not} = (I/N)^2 R_{not}$

$R_{not} = Rn_o (1 + \alpha (T - T_o))$

$Rn_o = \rho_o \, 0.5 \, L_{not}/(H_{not}\Delta)$

The coefficient α can be considered as a constant for the temperature range 295K - 1234K, as illustrated in fig. 5.

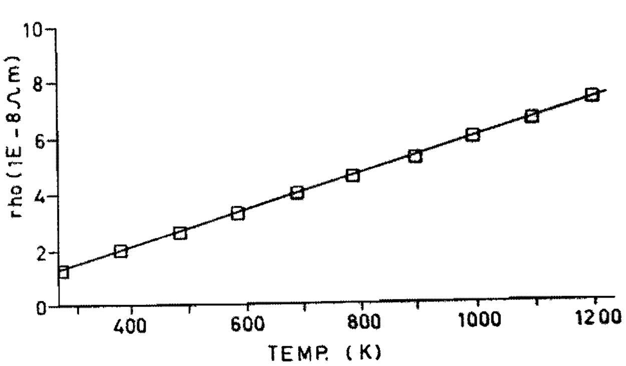

Fig. 5 Specific electrical resistivity of silver.

*: exp values [1]

curve: linear regression

$\rho = \rho_o (1 + \alpha (T - T_o))$

with T_o = 295 [K]

ρ_o = 1.51 E-8 [Ωm]

α = 0.0045 [1/K]

b. Storage of heat energy.

The Joule heat of the fuse strip results in an increase of the temperature T of the subsequent cylindrical layers with length L_{ax} between radius r_1 and r_2.

This power P_{store} can be represented by:

$$P_{store} = \gamma S \pi \, (r_2^2 - r_1^2) \, L_{ax} \, \frac{dT}{dt}/N \qquad (1)$$

with γ for the specific density and S for the specific heat.

c. Radial conduction.

The radial heatflux density can be represented by:

$$q = -\lambda \frac{dT}{dr} \qquad (2)$$

For the heat flow through a cylindrical surface it follows

$$P_{cond} = -\lambda 2\pi r L_{ax} \frac{dT}{dr}/N \qquad (3)$$

From this equation the temperature-difference between two radial positions can be calculated:

$$T_1 - T_2 = \frac{P_{con} N}{\lambda 2\pi L_{ax}} \ln\left(\frac{r_2}{r_1}\right) \qquad (4)$$

d. Convection and radiation.

The convection-losses of the porcellan surface with temperature T_w, to the surrounding at temperature T_o can be presented by Newton's law of cooling:

$$q = h(T_w - T_o) \qquad (5)$$

The heat-transfercoefficient h for horizontally positioned cylinders with a radius r less than 10 cm can be described [2] by:

$$h = 1.3 \left[\frac{T_w - T_o}{2r} \right]^{0.25} \qquad (6)$$

This gives an equation for the convective cooling:

$P_{conv}=2\pi r L_{ax} 1.3\ (2r)^{-0.25}(T_w - T_o)^{1.25}/N$ ..(7)

The radiation heatflux of the outside porcellan surface is given by the formula:

$$q = \sigma\ \epsilon_p\ (T_w^{\ 4} - T_o^{\ 4}) \qquad (8)$$

with universal radiation constant:
σ = 5.67 E-8 [W/m2K4]
emission coefficient of porcellan: ϵ_p = 0.93
surrounding temperature : T_o=295 [K]

This means a powerflow due to radiation from the surface of:

$P_{rad} = 2\pi r L_{ax}\ \sigma\ \epsilon_p\ T_o^{\ 4}[(T_w/T_o)^4 - 1]/N$.....(9)

The total cooling power flow through the outside porcellan surface part is:
$P_{conrad} = P_{conv} + P_{rad}$.

Fig. 6 presents the calculated relation between P_{conrad} and T_w-T_o for a porcellan radius r = 27.4 mm, N = 15, L_{ax} = 3.6 mm and T_o = 295 K.
The upper curve represents the quadratic regression:

$P = A + B\ (T_w - T_o) + D\ (T_w - T_o)^2$
with A = -3.54-4, B = 4.62E-4 and D = 2.63E-6.

The validity of this equation was confirmed by some experiments, where the quartz tube was replaced by a tungsten core. The results are presented in fig. 6 by the +marks.

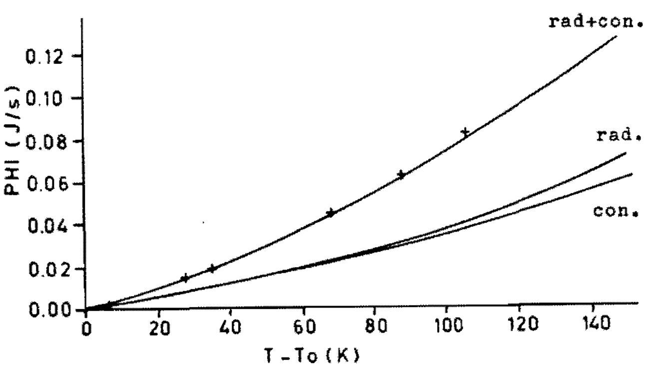

Fig. 6 The cooling power P_{conrad} of an elementary surface as a function of the temperature difference $T_w - T_o$.

The surface cooling relationship corresponds with a temperature dependent resistance, which has been plotted in Fig. 7.

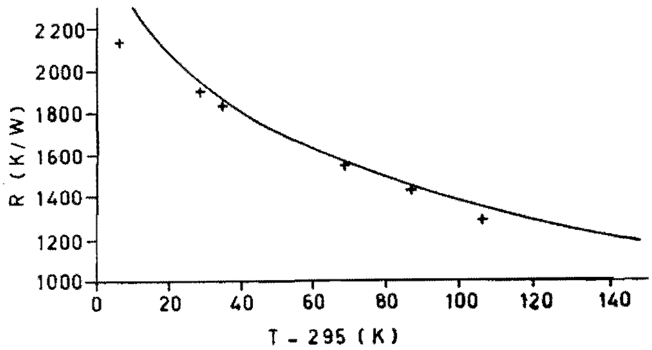

Fig. 7 The elementary surface transition resistance R_{conrad} as a function of the temperature difference with the surrounding (+ for the experimental values).

4. Analogy between thermal and electrical equations.

It is generally known that there exists a great analogy between the equations describing thermal or electrical problems.
Table 1 shows the equivalent equations and quantities:

Thermal	Electrical
storage: $P=\gamma S\pi(r_2^2 - r_1^2)\ L_{ax}(\frac{dT}{dt})/N$	$I = C\frac{dU}{dt}$
conduction: $P=\frac{\lambda 2\pi L_{ax}}{N\ \ln(r2/r1)}\ (T_1 - T_2)$	$I = \frac{U_1 - U_2}{R(1,2)}$
radiation + convection: $P=(T_w - T_o)/R_{conrad}$ with $R_{conrad}=f(T_w-T_o)$	$I = \frac{U_w - U_o}{R_{conrad}}$
heat flux: P	current: I
temperature: T	voltage: U
thermal capacitance: $\gamma S\pi(r_2 - r_1)L_{ax}/N$	capacitance: C(1,2)
thermal resistance: $\frac{N\ \ln\ (r_2/r_1)}{2\pi L_{ax}\lambda}$	electrical resistance: R(1,2)
surfaceresistance: $f(T_w - T_o)$	surface resistance: R_{conrad}

Table 1. Equivalent thermal and electrical expressions.

With the formulas of table 1 it was possible to calculate the equivalent circuit components for the elementary part of Fig 4.
The resulted values are listed in table 2.

Capacitances	Resistances
Ci1 = 2.6E-2	Ri12 = 1664
Ci2 = 6.0E-2	Ri23 = 741
Ci3 = 1.0E-1	Riq = 300
Cq1 = 1.1E-1	Rq1n = 429
Cqn = 2.7E-3	Rqnn = 425
Cnot = 1.4E-5	Rsnn = 1550
Csn = 2.1E-3	Rsn1 = 1700
Cs1 = 1.4E-1	Rsp = 190
Cp1 = 3.9E-1	Rpw = 72
Cw = 2.2E-1	Rq1b = 38
Cqb = 3.4E-2	Rqbb = 34
Cban = 4.9E-4	Rnb = 333
Csb = 2.6E-2	Rsbb = 123
	Rsb1 = 273
	Rqs = 103

Table 2. Equivalent component for the element in fig. 4.

5. Electrical analogon of the thermal model.

The equivalence of thermal and electrical quantities can be used to construct an electrical analogon for the discussed thermal model (see fig. 8).

An interactive computer program was developed, to calculate the values of all circuit components, after it was supplied with the fuse dimensions, the material properties and the fault current.

Voltage dependent current sources P_{not} and P_{band} have to be used for the representation of the powerflow from the notch and the band.

The convection/radiation is represented by a voltage dependent resistor CONRAD. Their description was already discussed in paragraph 3. The other component values are listed in table 2.

6. Simulation of the nominal current-situation.

The analog model was first applied to simulate the warming-up of the fuse with the nominal current (40 A) flowing.

Fig. 9 shows the calculated temperature rise of the porcellan surface, and the silver strip.

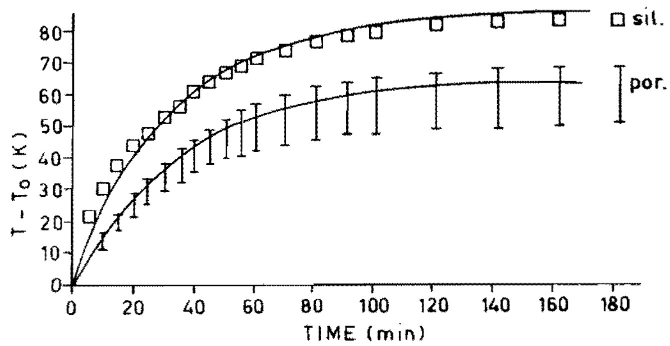

Fig. 9 Comparison of computer predictions and experimental results of temperature rises in a fuse, at a current I = 40 A

(□ = exp silver, I = exp porcellan).

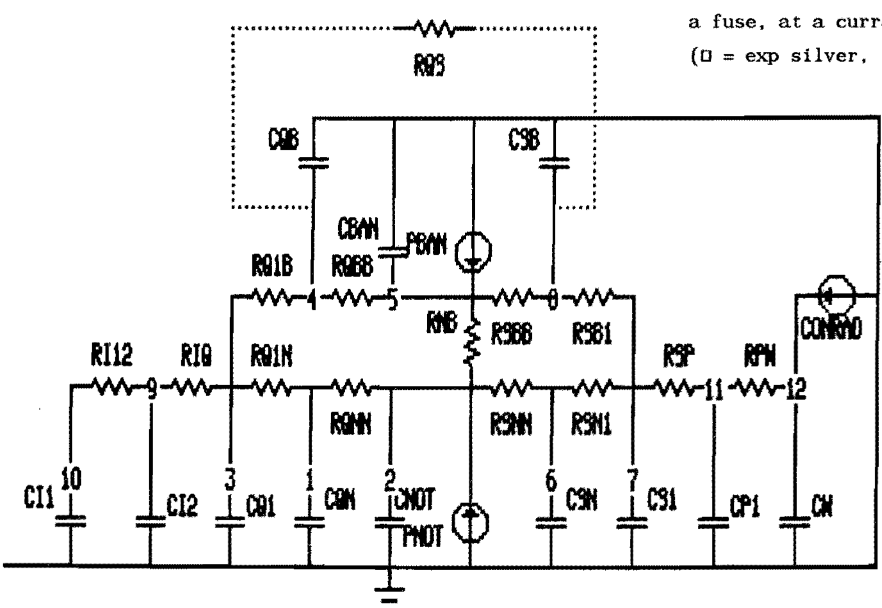

Fig. 8 Electrical analogon for a thermal elementary part.

As a verification of the validity of the model, the actual temperature-rise of the porcellan surface was also measured.
The fuse was positioned horizontally in a set-up according to the requirements of IEC 282-1.
The nominal values of the model and the experiment are reasonably in accordance with each other; this is an indication that the choice of the fractional radial losses and the value of the resistances is acceptable.
From the similarity of the dynamic curves it can be concluded that also the choice of the capacitances is acceptable.

As a raw verification of the silver curve, the experimental strip-temperature was estimated from the voltage measurements during the heating up process, by substituting these values in the resistance-relationship:

$$R(T) = R_o [1 + \alpha(T - T_o)] \ldots\ldots (10)$$

with $R = U/I$

$$\text{it follows } T(t) = T_o + (1 - \frac{U(t)}{IRO})/\alpha \ldots\ldots (11)$$

7. <u>The prediction of the fuse characteristic.</u>
Encouraged by the accordance of the dynamic situation, a prediction was made for the melting curve.
The moments were determined when either the temperature of the silver band reached 500 K, being the critical value of the M_{spot}, or the notch temperature reached its melting temperature 1234 K.
The results are presented in fig. 10 and compared with the specifications of the manufacturer.

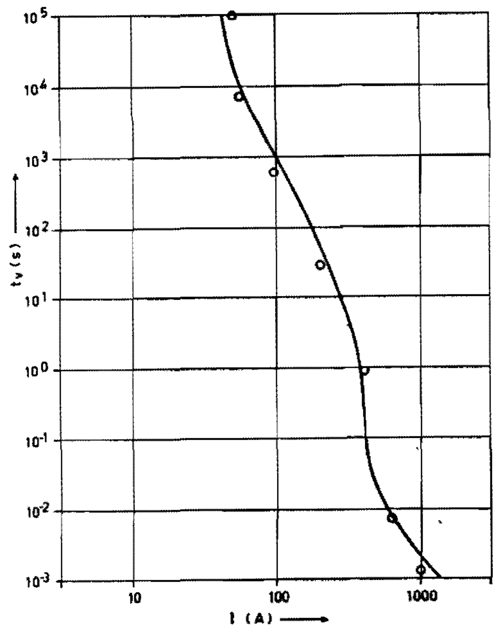

Fig. 10 The melting curve for In = 40 A.
——: specification of the manufacturer.
o : results of the analog model.

Similar agreement like fig. 10 shows for In = 40 A, was obtained for 25 A and 16 A.

<u>Conclusions.</u>
Obviously this analog model offers a valid method for the simulation of the thermal behaviour of fuses over an extended current range. With the analog model a quick impression can be got of the melting curve and this forms a powerful tool for the development engineer.
The individual influence of the silver strip dimensions, the sand, quartz and porcellan parts can be characterized separately; the effect from changes in the fuse design on the I - t characteristic can be concluded directly.
A similar calculation programm is under development for designing more classical constructions.

<u>References.</u>

[1] Tslaf, A.: Combined Properties of Conductors.
Elsevier, Amsterdam (1981).
[2] Perry, R.H. and Chilton C.H.: Chemical Engineer's Handbook, Fifth ed., Sec 10, McGraw-Hill, New York (1973).