THE INFLUENCE OF THE TEMPERATURE COEFFICIENT (TC) ON THE SELECTIVITY OF FUSES

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INTRODUCTION Every Electrical Engineer, by choosing the proper Fuses for a given electric circuit, bases his considerations upon three well accepted characteristics of the Fuses and their assemblies as follows:

a) The Time-current characteristic. This characteristic gives the time elapsing between the moment in which the current I starts and that in which this current is interrupted by the melting of the fusible element. (blow up time). Fig. 1 shows that this characteristic is asymptotic to a vertical line defining the minimal current that causes the fusible to melt in a real finite time. This current shall be referred to as "the theoretical rated current" $I_{r.th}$. Theoretically speaking, the fusible, when flown exactly by $I_{r.th}$, would reach its melting point without trespassing it. For too obvious reasons, the "technical rated current" I_r must be considerably lower, in order to avoid both an intempestive melting and a too fast aging of the fusible. I_r and $I_{r.th}$ divide the diagram into three separate ranges. The first range $0 < I < I_r$ is called the working range. The current I can flow endlessly without causing any fuse's reaction. The second range $I_r < I < I_{r.th}$ is called the indifference gap. In this range the fuse shall, theoretically, not react, because its temperature is lower than the melting one. In practice, however, the fusible's temperature is very narrow to the melting point so that its behaviour is unpredictable being influenced by various factors, many of them random ones, such as mechanical vibrations, for instance. The third range $I > I_{r.th}$ is the most important for the Electrical Engineer. It is called the activity range. In this range every current I is connected with a finite blow up time.

b) The selectivity of Fuse's assemblies. In most of the cases the short circuit current under control, flows through many Fuses in series. Fig. 2 gives two classical examples: the case of the distribution line and the case of the switchboard. Such a Fuse's arrangement is expected to work selectively, that means that being the short circuit point as indicated in Fig. 2 only the Fuses like F_2 shall react, leaving those like F_1 intact, thus confining the disturbance to the possibly smallest number of consumers. The generally accepted solution of this problem is to increase the rated current of the Fuses going from the consumer toward the source. Superimposing the time-current characteristics of the two Fuses, as done in Fig. 3, one sees that at any current $I > I_{r.2}$ the blow up time of F_2 is as required, at least theoretically, always shorter than that of F_1.

c) The rupturing capacity of the fuse. This property expresses the Fuse's capability of extinguishing the electric arc that, unavoidably, sparks between the two remaining rods of the blown up fusible, in such a short time, so that no danger is present either for the protected circuit or for its surroundings. Since every Fuse's manufacturer guarantees a given R.C. at a given voltage, this problem is of minor concern for the Electrical Engineer being fully solved by choosing the proper Fuse among those commercially available.

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With regard to points a) and b), however, the Fuses almost never react as expected according to the above mentioned rules. Especially speaking about selectivity, it is a very intriguing experience that in most of the cases nobody can predict which Fuse will blow up first, unless their rated currents are very much different.
The present paper investigates points a) and b) in a more sophisticated way in order to explain facts and to suggest how to improve the performance of Fuses and Fuse's assemblies

THE BASIC EQUATIONS. The time-current characteristic can be mathematically derived at various degrees of sophistication.
In order to avoid unnecessary complications, that would be of no help to better understanding, the following simplifying assumptions shall be adopted

a) The surrounding's temperature has been chosen as point of reference. Therefore all the temperatures mentioned in the paper are to be understood as temperature rise above the surroundings.
b) The longitudinal transfer of heat (along the fusible element) has been disregarded. As a consequence the whole fusible element assumes a uniform temperature which is a function of current and time only.
c) The change of resistance of the fusible, due to changes in temperature has been assumed to be linear until the melting temperature θ_m. The temperature coefficient α therefore, has to be understood as a mean value over a wide range of temperature. Under this assumption the resistance of the fusible element at any temperature can be expressed by the following equations :

$$R_\theta = R_o(1 + \alpha\theta) \qquad (1$$

for materials having a positive temperature coefficient (PTC), and

$$R_\theta = \frac{R_o}{1 + \alpha\theta} \qquad (2$$

for materials having a negative temperature coefficient (NTC). Obviously both equations include the limit case $\alpha = 0$ (ZTC). Under the previous assumptions the energy balance of a PTC Fuse can be formulated as follows:

$$R_o(1 + \alpha\theta)\, I^2\, dt = hS\theta dt + cGd\theta \qquad (3$$

where:

. $R_o(1 + \alpha\theta)I^2$ represents the power in Watts, converted into heat by the current I, at temperature θ.
.. h represents the equivalent radiation constant $[\frac{W}{Deg.m^2}]$ which takes into account the heat flow through the different insulating materials.
... S represents the cooling surface of the fuse $[m^2]$.
.... c represents the specific heat of the fusible material $[\frac{W_s}{Deg.Kg}]$
..... G represents the equivalent weight of the fuse [Kg] reduced to the fusible material.

Dividing both sides of eq. 3 by hS, and taking into consideration that:

. $\frac{R_o I^2}{hS} = \theta_\infty$ has the dimension of temperature. This is the temperature to which the fusible would settle after a long time, if its resistance would stay constant at the value R_o, regardless of temperature increase.
.. $\frac{cG}{hS} = T$ has the dimension of time. It can be called the "time constant" having a particular constant value for any particular Fuse.

eq. 3 becomes:

$$\theta_\infty(1 + \alpha\theta)dt = \theta dt + Td\theta \qquad (4$$

which is easily solved, being a simple linear differential equation. At the starting moment t=0 the fusible's temperature is assumed to be θ_o depending upon previous load. Accordingly. the solution of eq.4 is :

$$\tau = \frac{t}{T} = \frac{1}{1-\alpha\theta_\infty} \ln \frac{1-(1-\alpha\theta_\infty)\frac{\theta_o}{\theta_\infty}}{1-(1-\alpha\theta_\infty)\frac{\theta_m}{\theta_\infty}} \qquad (5$$

Eq. 5 holds, as previously stated, for the PTC Fuse, including the ZTC fuse as the particular case α=0.
The blow up time is given in numerical form, being the ratio $\frac{t}{T}$.
In case of a NTC Fuse, the fundamental equation is :

$$\frac{R_o I^2}{1+\alpha\theta} dt = hS\theta dt + cGd\theta \qquad (6$$

Its solution under the same starting conditions is :

$$\tau = \frac{t}{T} = \frac{\alpha\theta_2}{\sqrt{1+4\alpha\theta_\infty}} \ln \frac{\theta_m-\theta_1}{\theta_o-\theta_1} - \frac{\alpha\theta_1}{\sqrt{1+4\alpha\theta_\infty}} \ln \frac{\theta_m-\theta_2}{\theta_o-\theta_2} \qquad (7$$

where: $\theta_1 = \frac{\sqrt{1+4\alpha\theta_\infty} - 1}{2\alpha}$ and $\theta_2 = -\frac{\sqrt{1+4\alpha\theta_\infty} + 1}{2\alpha}$ are two factors having the dimension of temperature. The mere inspection of eqs. 5 and 7 show that the blow up time is influenced by three factors: θ_m, θ_o and α. Their influence will be discussed in the next paragraphs.

THE INFLUENCE OF θ_o . θ_o is a function of the current which has flown through the fuse prior to the event of short circuit. Obviously the two limit cases are:

a) θ_o=0. A completely cold fuse. Putting θ_o=0 into eqs. 5 or 7 we obtain one time-current characteristic, which may be called "the cold characteristic".
b) the fuse, prior to the short circuit, was flown by its rated current. In this case its starting temperature was $\theta_o=\theta_m(Ir/Irth)^2$. This value of θ_o gives rise to a second characteristic which may be called "the hot characteristic".

In any other case τ is confined between these two characteristics.
Fig. 4 gives one example for a PTC fuse having $\alpha = 4.10^{-3}$.
The first consequence thereof is that a defined time-current characteristic does not exist. One can only speak about a strip, within it the blow up time is confined. Thus, calling τ_c the longest blow up time, and τ_h the shortest one, it is possible to define the deviation factor as :
DF = $(\tau_c - \tau_h)/(\tau_c + \tau_h)$, that means the maximal expectable deviation from the mean value $(\tau_c + \tau_h)/2$.

Tracing on the same diagram (as done in Fig. 5) two characteristic strips of two fuses having different rated current, one sees immediately the main reason for lack of selectivity. The two strips are partially superimposed. It is, therefore, meaningless to speak of selectivity as if it were an inherent property of the given fuse's assembly. One has rather to speak about Probability of selective action. (PSA). The PSA can be roughly evaluated, basing on simplifying assumptions. Fig. 6 shows a magnified portion of the superimposed strips of Fuses 1 and 2 where I represents the current flowing in Fuse 2 and the blow up time is given in its real value, instead of its numerical form. D_1 represents the width of the strip of Fuse 1 at the given current I and D_2 that of Fuse 2. D represents the width of the common portion of the two strips. As for D_2 one has to take into consideration that if Fuse 1 was "hot" at the event of the short circuit, that means that it was flown by its rated current I_{r1}, therefore the current of Fuse 1 is not I but rather $I+I_{r1}$. The hot characteristic of Fuse 1 shall be accordingly modified.

Assuming now that all the load configurations have equal probability (an assumption which is not always justified) and that any point of D is a potential point of lack of selectivity, one can conclude that the probability of the blow up time of Fuse 1 to be inside of D is D/D_1 and that of Fuse 2 is D/D_2. The total probability of having both the events simultaneously is D^2/D_1D_2. The lower limit of the PSA is therefore given by

$$PSA = 1 - \frac{D^2}{D_1 D_2} \qquad (8$$

Eq. 8 shall be considered as a rough evaluation only, because the fact that the cold characteristic of Fuse 1 is influenced by the previous load of Fuse 2 has not been taken into consideration.

THE INFLUENCE OF α AND θ_m. The influence of these two parameters may be better pointed out by a comparative example, instead of developing cumbersome equations.

As such an example, a fuse of 200 A rated current has been chosen, supposing that its theoretical rated current I_{rth} is 15% higher. The melting temperature θ_m has been taken as parameter. The maximally allowed θ_o is that reached by the fuse when flown by its rated current I_r as previously calculated. Letting α change between given limits, both in the PTC and NTC ranges, the cold and hot characteristics have been calculated. The results are given in Fig. 7. Fig. 7 shows the DF as a function of α. It is clear at the first glance that in the PTC range the DF increases with α and with the melting temperature θ_m. The opposite effect appears in the NTC range. An increase in α and in θ_m causes a decrease of the DF, thus improving the fuse as far as its accuracy is concerned. (accuracy = 1-DF).

A further parameter which influences the DF is the ratio $\beta = I_r/I_{rth}$. This ratio influences the indifference gap. The smaller β the larger the indifference gap. Recalling now that the indifference gap defines a range in which the fuse still does not react to a current which actually is exceeding its rated one, one can take β as an index of the promptness of reaction of the fuse.

On the other hand β influences the DF too. Fig. 8 shows its influence taking β as parameter. The smaller β the smaller the DF of the fuse. The consequence is that promptness and accuracy are two properties which do not go together. A good fuse for general purposes shall be based on a fair compromise between them. As Fig. 8 shows such a compromise is much easier achieved using NTC fusibles.

In order to investigate the selectivity behaviour a second fuse having a rated current of 160 A (one stage lower according to European standards), is supposed to be connected in series with the previous one.

The PSA of this arrangement has been calculated using eq. 8 assuming the same TC for the two fuses. Their time constant has also been assumed equal in order to allow the use of the numerical time instead of the real one.

The results are given in Fig. 9 for the following different cases :

Case 1 $-F_1$ = 200A PTC ; F_2 = 160A PTC.
Case 2 $-F_1$ = 200A NTC ; F_2 = 160A NTC.
Case 3 $-F_1$ = 200A PTC ; F_2 = 160A NTC.
Case 4 $-F_1$ = 200A PTC ; F_2 = 200A NTC.

The inspection of Fig. 9 allows to draw some important consequences.

a) The well accepted opinion that increasing the short circuit current fuses assemblies become less selective is not sound. As far as lack of selectivity is concerned the most dangerous range is by relatively low short circuit currents. By high currents the PSA shows a slight tendency to increase.
b) The use of NTC fuses alone, can substantially improve the PSA. In our case the NTC/NTC arrangement shows an average PSA of 65%, compared with 44% of the PTC/PTC arrangement.
c) The PTC/NTC arrangement shows (at least theoretically) an enormous improvement, reaching an average PSA of > 90%.
d) The PTC/NTC combination allows even the use of two fuses of same rated current, conserving a high degree of PSA. (about 80%).

CONCLUSIONS. The previous considerations lead to some useful conclusions.
a) beside the comonly accepted differentiation of fuses according to their time constant it will be useful to differentiate them also according to their temperature coefficient. Such a differentiation will permit to fit exactly any fuse to its particular purpose.
b) As far as PTC and ZTC fuses are concerned, the author cannot predict serious difficulties. Many alloys are known to have an extremely small TC, while all the pure metals have a definitely positive TC. The realization of the NTC fuse, however, will require the solution of many very difficult problems. Some conductive materials are known to have a negative TC but none of them combines all the required properties. For instance, carbon which is a good conductor and is suitable to be worked out in form of wires, has a too small NTC (.0005 to .0009) and a too high evaporation point (about 3500 Deg.).
All the aqueous solutions of salts have a strong NTC (about .03) combined with a suitable conductivity, but their use as fusible material will require a complete new design of the fuse, because they are liquids. Even assuming to have solved the problems of design, such aqueous solutions can be used only within the limits of the critical temperature of water which is too low for obtaining good fuse's characteristics.
Glass is also among the theoretically possible NTC solutions. It has all the required properties but one. It is solid, can be extruded in form of a wire or a tube, has an extremely high NTC, it becomes as fluid as water beyond a given temperature which is enough high, but does not conduct electric current being cold.
This difficulty can be solved by a new design, so that this kind of solution seems to be promising. Other materials which behave more or less like glass, are molted salts. These materials too can lead to useful solutions after having solved design problems.
Modern chemistry can produce, nowadays, many new artificial materials. The required material really suitable for making fuses should have the strongest NTC as possible. It should be solid, ductile and a good conductor at low temperature. It should destroy itself (not necessarily melt) at a

given temperature, possibly about 1000 Deg.
To develop such a material can be an interesting challenge for people working in Physical Chemistry.

All the previous considerations have been worked out assuming that the short circuit current is constant in time.
Such an assumption can be justified by D.C. By A.C.,when the current is measured by its MSR value, this is true only when the blow up time is relatively long compared with the length of the period.

By very strong short circuit currents eqs. 4 and 6 have to be modified in order to take into consideration the variation of the current in time, thus leading to solutions different from eqs. 5 and 7. Doing so, both the cold and hot characteristics change their form, in the range of very strong currents, but all the previous considerations about accuracy and selectivity remain in force. Such a degree of sophistication seems, therefore, to be beyond the scope of the present paper.

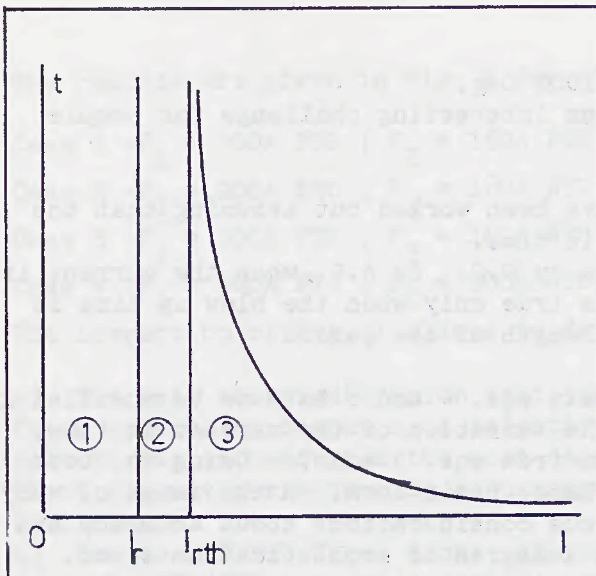

Fig. 1 Time-current characteristic

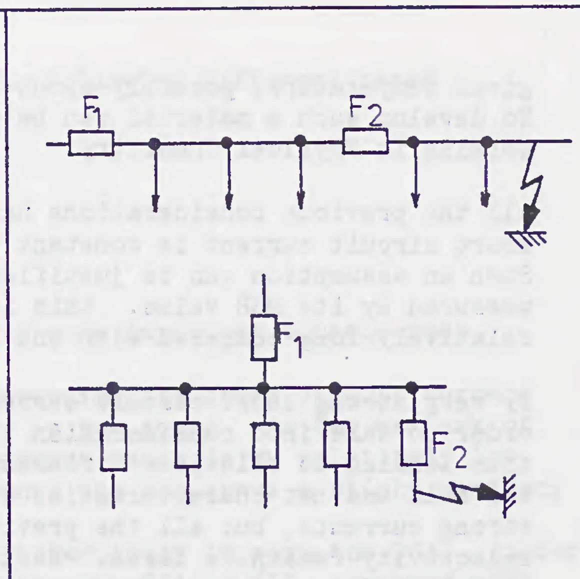

Fig. 2 Assemblies of Fuses

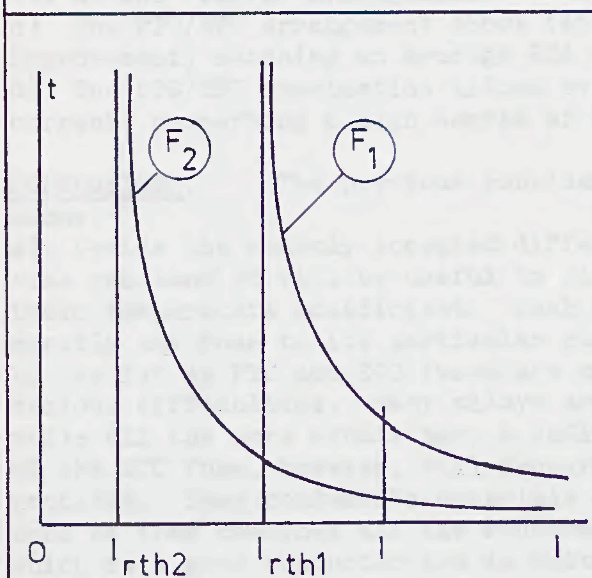

Fig. 3 Definition of selectivity

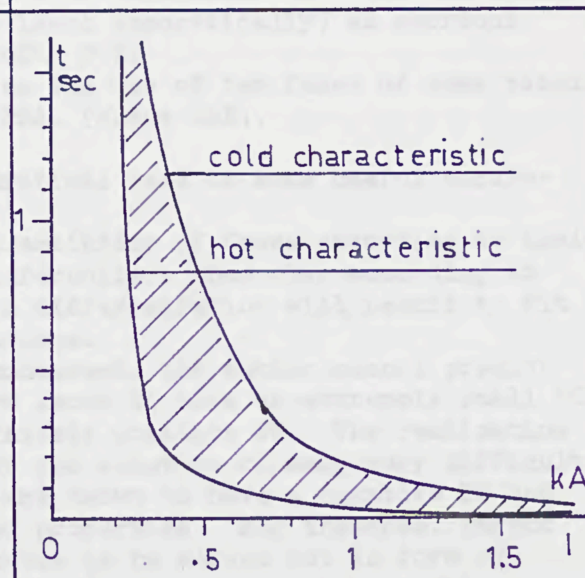

Fig. 4 Time-current strip

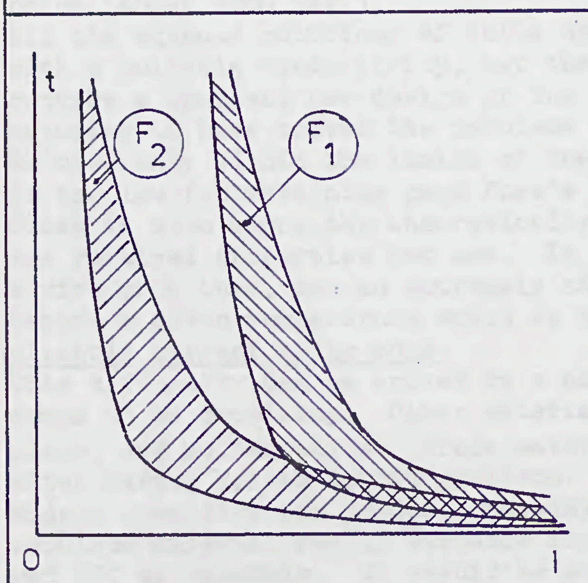

Fig. 5 Superposition of strips

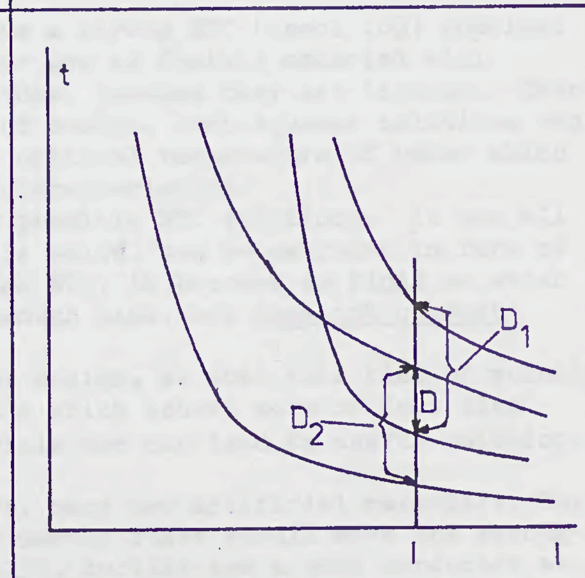

Fig. 6 Evaluation of PSA

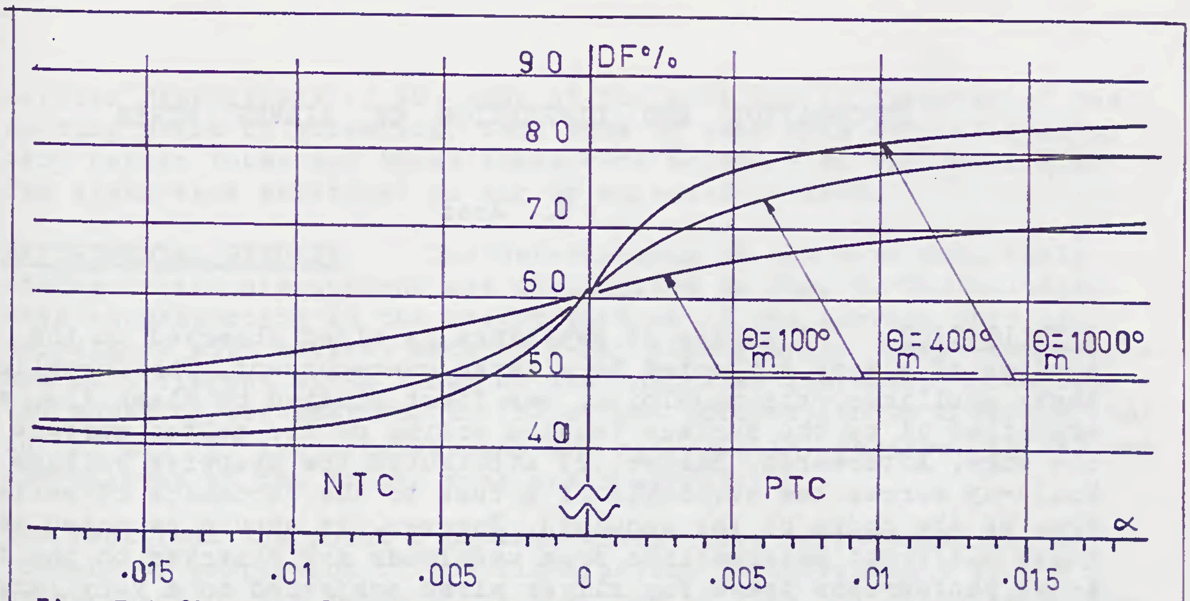

Fig. 7 Influence of α and θ_m on the DF

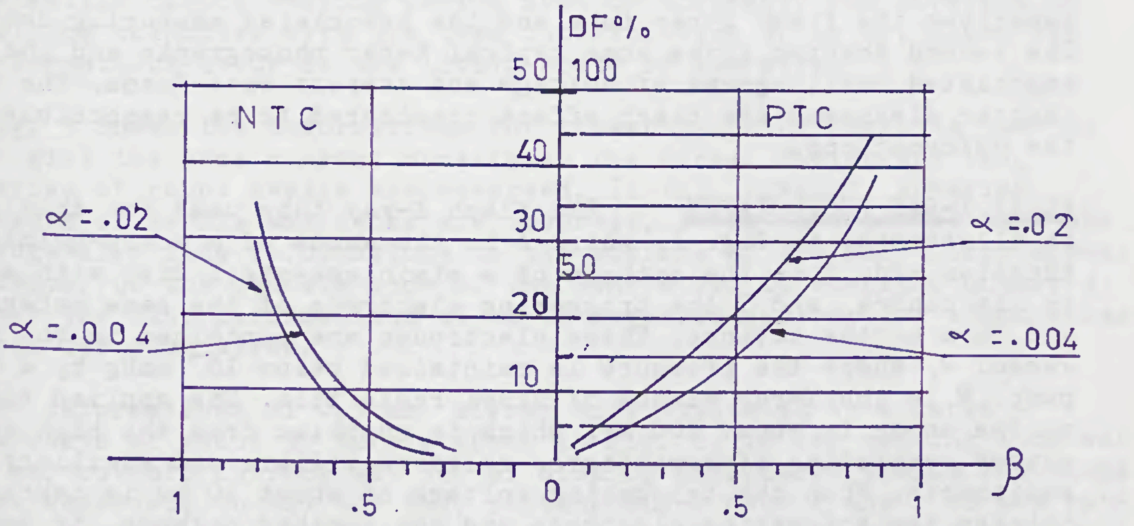

Fig. 8 Influence of β on the DF

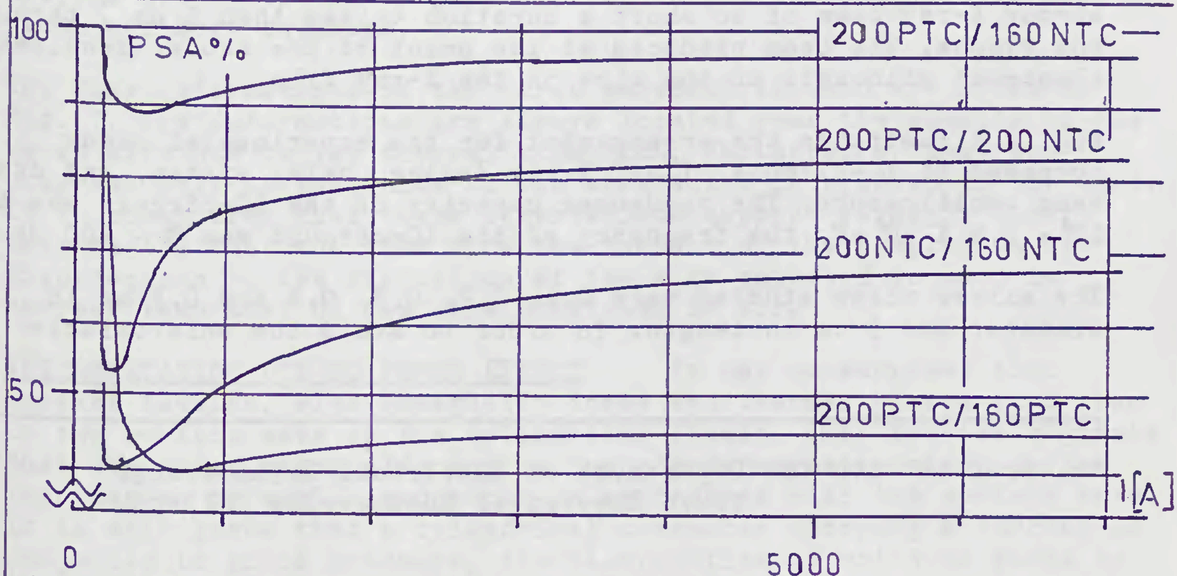

Fig. 9 PSA for different Fuse's combinations