Modelling fuse elements using a C.A.D. software package

D.A. Beaujean, P.G. Newbery and M.G. Jayne[1]

Abstract

The short-time pre-arcing characteristics of high breaking capacity fuses are controlled by the current density in the fuse element and the thermal properties of the fuse materials. At longer operating times, the characteristics of fuses using M-effect are dominated by the rate of dissolution of the M-effect alloy through the base element material. The short-time operation is thus dependent upon the electrical and thermal properties of the fuse element, whilst for longer operating times, diffusion rates also have to be taken into account

Electrical, thermal and diffusion properties form analogous systems which may be fully described by differential equations of a similar form, and thus by a suitable change of variables, temperature rise and diffusion rates may be modelled using circuit simulation software packages.

This paper describes the modelling of fuse elements both with and without M-effect using a C.A.D. software package. At high current densities, the effects of the characteristics of the prospective current, such as circuit power factor and point on wave closing angle can be simulated, and notch temperature profiles obtained. At lower current densities, M-effect action is successfully modelled, taking into account both radial and axial heat loss to the sand filler.

1. Introduction

Many problems in engineering involve the determination of potentials existing at various points in a field, and the flow of substance between these potentials. It may be the flow of current or determination of flux in an electric or magnetic field, the determination of temperature at various points in a thermal field, the flow of liquid in a cooling system or the mass diffusion of one substance through another.

Most fields can be described mathematically by a form of Laplace's equation.

$$\nabla^2\Psi = 0 \qquad \text{...(1)}$$

Where Ψ is the scalar value of a variable in the field. Each field is of the form:

Flow Density = Constant x Potential Gradient

or Flux = Flow Rate/Area = transport property x potential gradient

The operating characteristics of electric fuses are determined by the distribution of current in the fuse element (the electric field), and the element's corresponding temperature rise (the thermal field). If the fuse design utilises M-effect, then the dissolution of the alloy through the fuse element will change the element composition and will also influence the operating characteristics (the composition field), as will the cooling effect of the sand filler (the thermal field). Electric, thermal and element composition fields are thus all active during fuse operation.

The three key variables of current, temperature and element composition form analogous systems and can be represented by partial differential equations of a similar form.

The equation for the one dimensional movement of electricity may be written as:

$$\frac{\partial^2 V}{\partial^2 x} = \rho C \frac{\partial V}{\partial t} \qquad \text{...(2)}$$

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where ρ is the resistivity, **C** the capacitance per unit volume and **V** the electric potential. This is analogous to the equation for the one dimensional conduction of heat.

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad \text{...(3)}$$

where α is the thermal diffusivity and **T** the temperature. This is also analogous to the one dimensional diffusion of mass

$$\frac{\partial^2 c}{\partial x^2} = \frac{1}{D}\frac{\partial c}{\partial t} \qquad \text{...(4)}$$

where **c** is the concentration and **D** the diffusion coefficient.

Computer aided design (CAD) packages are now available covering all fields of engineering and in particular electrical engineering, where various circuit simulation packages enable the current and voltage at various points in a network to be determined. Owing to the similarity of the physical systems active during fuse operation, a suitable change of variables allows these CAD packages to be modified to also determine the movement of heat and material in thermal and diffusion fields. A CAD package suitable for this purpose is *ASTEC 3*.[1]

2 ASTEC 3 Software.

ASTEC 3 is a powerful circuit analysis software package for performing transient, a.c. small signal and d.c. steady state simulations [1]. It is also suitable for providing solutions to differential equations and systems defined by this format can be solved. The programme uses an iterative method for solving differential equations, in which the number of iterations, accuracy of solution and the simulated duration of analysis can be specified by the user. Using *ASTEC 3*, it is also possible to perform repeated analyses using a number of different initial conditions during the analysis of a single system, the resulting data being output in tabular and/or graphical form. In addition, it has powerful modelling facilities where sub-circuits or processing elements can be described in the form of models and used independently or nested within more complex models to simulate sophisticated systems.

The simulation of a system using *ASTEC 3* proceeds in three stages:

* problem description
* simulation
* presentation of results

Each of these stages can proceed independently and may be repeated as required, thus allowing different results to be presented in a variety of formats from one simulation.

The problem description is an electrical circuit equivalent with component types, values and connections being entered as a net list. Dc, ac or transient conditions can be simulated. The initial values of all variables and the duration of the simulation can be set by the user.

Data output from the simulator is not confined to node voltages, but may include branch currents and component values. Furthermore the results of a simulation may be combined according to any user-defined function so that complex parameters of circuit performance can be obtained. A useful feature of the simulator package is the ease with which models can be developed and stored in personal libraries, enabling individual system simulations to be constructed.

In addition to the simulation of standard electrical circuits, *ASTEC 3* permits the solution of sets of simultaneous differential equations. This facilitates the simulation of electro-mechanical and electro-thermal systems, and enables the investigations of such operating characteristics as the temperature rise of electrical components.

ASTEC 3 software offers the possibility of modelling and hence determining the mutual relationships between the current flowing in a fuse element, the temperature rise of the element, and also, during M-effect action, the dissolution of the alloy through the element, this being modelled to a first approximation as simple diffusion.

Consider, for example, a simple one dimensional system represented by a resistor-capacitor "ladder" as shown in Fig.1. This system may also be used to represent a thermal or diffusive system, where the flow of heat or diffusing substance is simulated by the flow of electrical charge, and the potential gradient represents the temperature or concentration gradients. In other words, the flow of heat through a thermal resistance or the flow of material through a diffusive resistance is analogous to the flow of current through an electrical resistance, and any heat or material entering or leaving a system can be modelled as current sources or sinks.

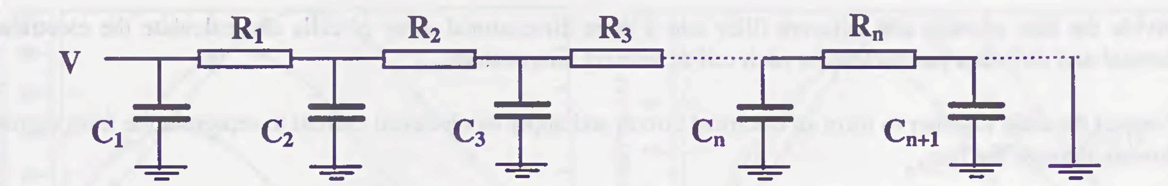

Fig.1
Modelling one dimensional systems using an R-C ladder diagram

Similarly, using the analogy between temperature in a thermal system, concentration in a diffusing system and voltage in an electrical system, it is clear that fixed temperatures or concentrations at a boundary may be modelled as voltage sources of the same value.

The *ASTEC 3* input language is based on a conventional circuit diagram with the positions of each element defined by the nodes at its connections. Electrical configurations may be used for cells in 1,2 or 3 dimensional systems. Fig.2 shows a three dimensional cell. In each cell the equivalent resistance in each direction is divided by two and resistors of such values are connected from the node at the centre of the cell to nodes at the mid-point of each side. The equivalent capacitances of value C_{Th} (thermal) and C_{Diff} (diffusion) and the optional current source representing heat (J_{Th}) or mass generation (J_{Diff}) in the cell are connected between the centre node and ground. Cells of any dimensions may be used, but in this illustration the cells are assumed to be of equal dimensions and consequently to have equal resistances in all directions.

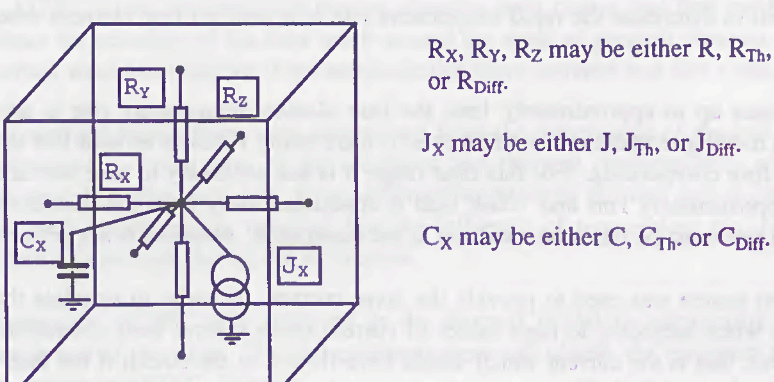

Fig.2
Modelling using three-dimensional cells

Once the cell model has been established, cells may be linked together to form one, two or three dimensional circuits, depending on the particular system being studied. Inputs to and outputs from the system to the surrounding media may also be modelled. These may, for example in the case of thermal modelling, be of the form of fixed

resistors of appropriate value connected from nodes on the outside surface of the model to ground to represent heat loss at system boundaries, or fixed voltages to denote constant temperature heat sources or sinks.
For fuse pre-arcing times up to approximately 1s, only the electrical and thermal properties of the fuse need be taken into account, but for longer times fuse designs using M-effect must also take into account the diffusion of the alloy through the fuse element. Modelling the M-effect thus involves modelling all three transport properties. In order to use *ASTEC 3* to simulate such a process the electrical, thermal and diffusion processes have to be modelled, and these models then nested to ensure cross-referencing occurs during the simulation. Any variations with temperature in the electrical, thermal or diffusive properties must also be taken into account, as too must the cooling effect of the sand filler. The problem may thus be broken down into discrete stages as follows.

- Divide the fuse element and adjacent filler into a three dimensional array of cells and calculate the electrical, thermal and diffusion parameters for each cell at ambient temperature.
- Connect the cells together to form an electrical circuit and apply an electrical current to represent the fault current flowing through the fuse.
- Determine the temperature rise of each cell, taking into account the variation of resistivity and thermal conductivity with temperature and cell composition.
- Calculate the alloy diffusion depth and hence determine the alloy concentration in each cell.
- Recalculate the electrical resistance and temperature rise of each cell, the cell resistance varying with alloy concentration.
- Continue the heating/diffusion cycle until the alloy has diffused completely through the base element.

Each stage of the process is dependent upon previous conditions and thus conditional statements have to be introduced into the test program. *ASTEC 3* allows its normal analogue circuit simulation capabilities to be enhanced by the addition of user written FORTRAN sub-routines. Conditional statements may thus be easily added to the test programme.

3 Modelling Fuse Operation

3.1 Short-time Operation (up to 10ms)

ASTEC 3 was used to determine the rapid temperature rise of a notched fuse element when subjected to a high fault current.

For pre-arcing times up to approximately 1ms, the fuse element temperature rise is adiabatic and all the element restrictions reach melting temperature simultaneously, there being virtually no heat lost to either the remainder of the element or other fuse components. For this time range it is not necessary to take into account any heat losses. For times between approximately 1ms and 10ms, heat is conducted away from the restrictions to the remainder of the fuse element, and this must be taken into account in the simulation. M-effect is not active at these short times.

A constant current source was used to provide the drive current. In order to simulate the rapid temperature rise of the notch section when subjected to high values of current under typical fault conditions, the characteristics of the prospective current, that is the current which would have flowed in the circuit if the fuse were replaced with a solid link, had to be closely modelled. The prospective current is usually at power frequencies (50 or 60 Hz) and its value at any point in time is determined by both the power factor of the circuit and the point on the voltage wave at which the fault is initiated. The power factor in a fault situation is typically less than 0.15 and maximum asymmetry of the current is achieved by initiating the fault near a voltage zero. A prospective current with these characteristics may thus be represented by :

$$I = I_P\left(\sin((\omega t + \phi) - \cos^{-1}\theta) - \sin(\phi - \cos^{-1}\theta)\exp\left\{\frac{-t\omega}{\tan(\cos^{-1}\theta)}\right\}\right) \quad \text{.............................(5)}$$

where I is the instantaneous current after a time t, ω is the angular frequency of the supply, I_p is the 'steady state' peak value of the prospective current, ϕ is the point on wave switching angle in radians and θ the power factor of the circuit.

ASTEC 3 is capable of representing current sources of this type, and thus the effect of power factor and point on wave variation can be determined. Fig.3. shows the simulated applied prospective currents for different power factor values and different point-on-wave closing angles.

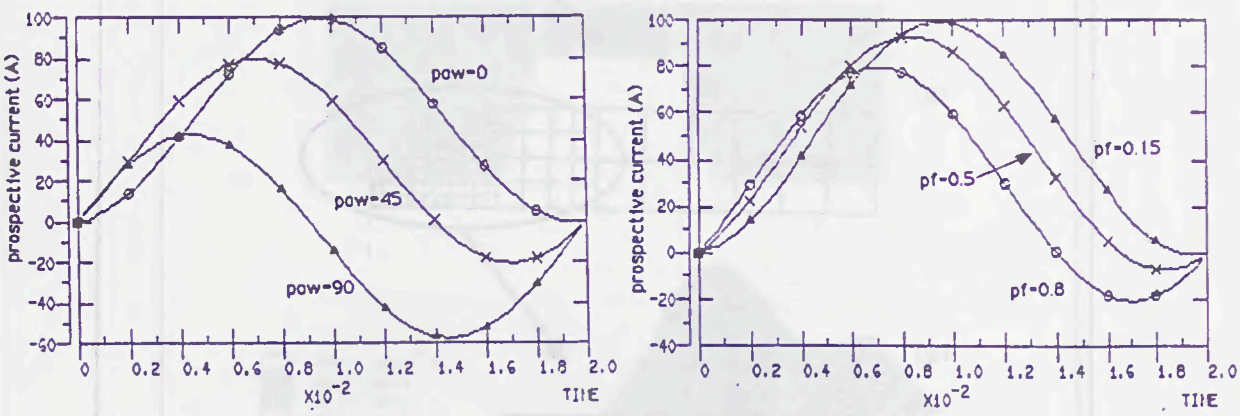

Fig.3
Variation of applied current with: (a) point on wave. (b) power factor.

A typical notched fuse element used in a medium voltage commercial fuse is shown in Fig.4. Owing to the symmetry of the design, only one quarter of the element section need be modelled, the other three sections giving identical results. Each element section was divided into a number of two dimensional cells, the current being uniform in the third dimension.

The finer the cell structure chosen, the greater the resolution and hence the more accurate the solution. Around the contour of the notch itself a fine mesh is desirable, whilst in the bulk strip where the current is more uniform a coarser mesh will suffice. *ASTEC 3* can accommodate this by allowing both coarse and fine meshes to be used in one simulation. This combines the accuracy of the finer mesh around the areas of greatest interest without the large increase in computer time which would be required if the whole section were covered in a fine mesh.

The cell resistance values at ambient temperature were determined from the dimensions of the cell and the physical properties of the element material. Integration of the electrical and thermal characteristics of the circuit was achieved by combining both models within each cell. Cross-referencing between thermal and electrical models then automatically occurs during each iterative loop, ensuring that the influence of temperature rise on resistance, and hence circuit current was taken into account during the simulation.

A simulated heat sink temperature of 20°C was achieved in the thermal model by connecting constant voltage supplies of 20 volt dc. to each end of the strip. The cell constants were calculated, the electrical mesh constructed and a computer programme written in *ASTEC 3* format.

The test current was chosen so as to cause fuse operation in approximately 10ms. Fig.5. shows the notch temperature profile obtained from the simulation after 10ms for a 250 ampere prospective current with a circuit power factor of 0.15 and a point on voltage wave closing angle of 0°. In the figure, (a) shows the temperature contour map of the notched section, (b) shows the three dimensional temperature distribution of the cells and (c) shows a smoothed three dimensional temperature profile which has been computer interpolated from the cell mid-point temperatures.

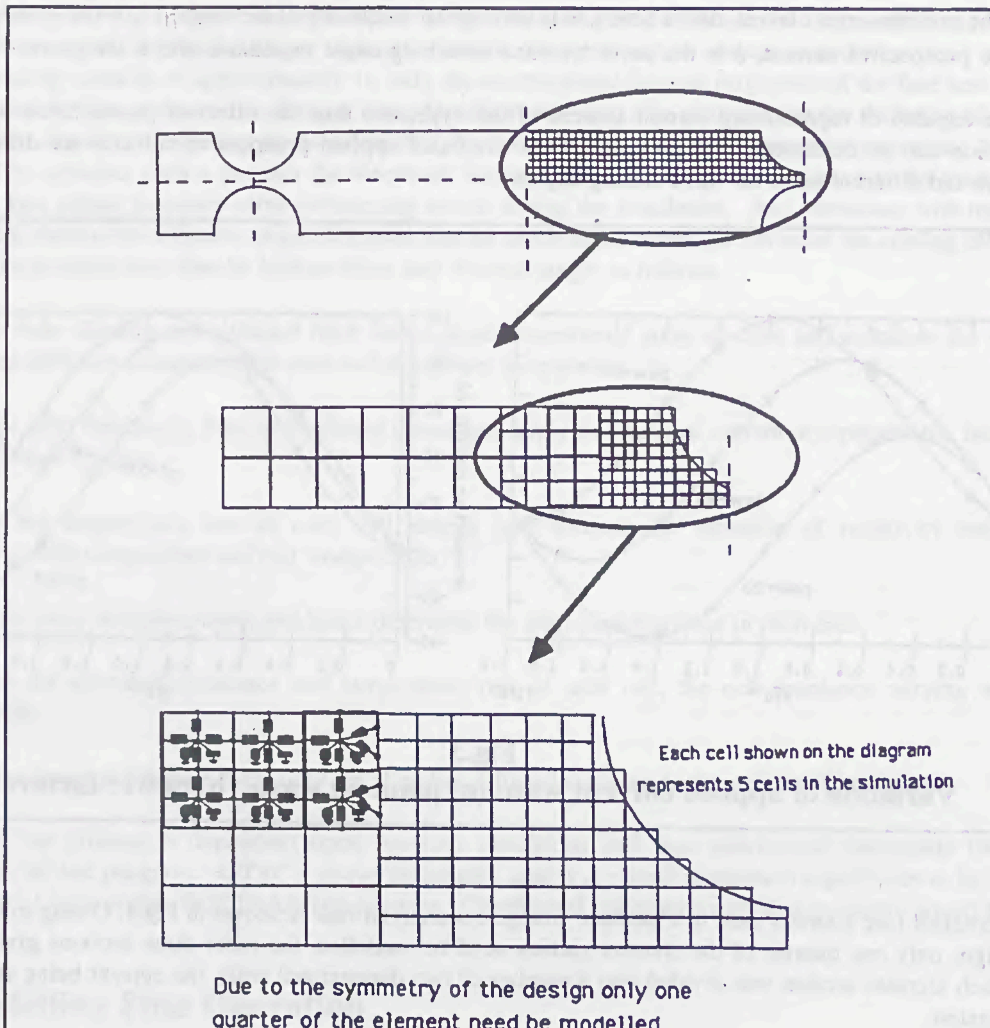

Fig.4
Modelling a fuse notch.

3.2 Medium Time Operation (10ms to 1s)

For pre-arcing times between approximately 10ms and 1s heat is conducted away from the element restrictions firstly to the remainder of the element, and then to the granular filler. To allow for this the *ASTEC 3* simulation was extended to include the cooling effect of the silica sand filler. To accommodate this, additional cells were arranged either side of the element in the thermal model to represent the filler.

The three dimensional arrangement so formed is shown in Fig.6. This three dimensional model allows the properties of the filler to be studied. The dimension of the filler cell perpendicular to the element was chosen to be several times the dimension of the element cell to enable the temperature rise at points well removed from the element to be determined. To simulate a 20°C ambient temperature, 20V voltage sources were either connected directly to the outside nodes of the filler cell, or through a suitable resistor. In the latter case the value of this resistor effectively determined the thickness of the sand filler between the element and the inside surface of the fuse barrel.

The results of the simulation including the effect of the filler for a 50 Ampere RMS current source are shown in Fig.7. As expected, the thermal time constant of the filler is very much slower than that of the silver element.

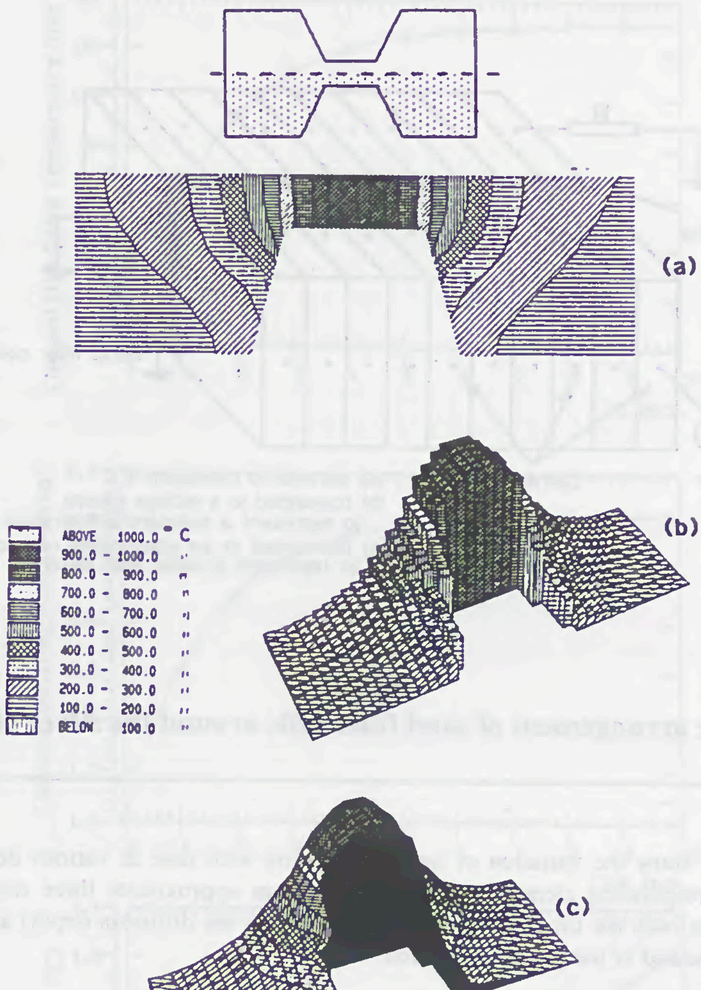

Fig.5
Notch temperature profile after 10ms.
Applied prospective current 250 amperes RMS

3.3 Long-time Operation (1s to 6h).

For pre-arcing times greater than a few seconds, heat is conducted away through the elements to the fuse end caps and connecting cables and also through the sand filler to the fuse barrel. In addition, the shape of the pre-arcing characteristic in this time range is considerably affected by the M-effect alloy dissolving through the fuse element.

A relatively coarse mesh structure was initially tried, the element and tin deposit being sub-divided into three-dimensional cells of various sizes. The area of greatest interest is the tin deposit and the adjacent section of silver element, and this area needs to have the largest number of elements. Once the model was functioning correctly, each cell was sub-divided into eight smaller cells to give a greater resolution (2%) through the thickness of the strip.

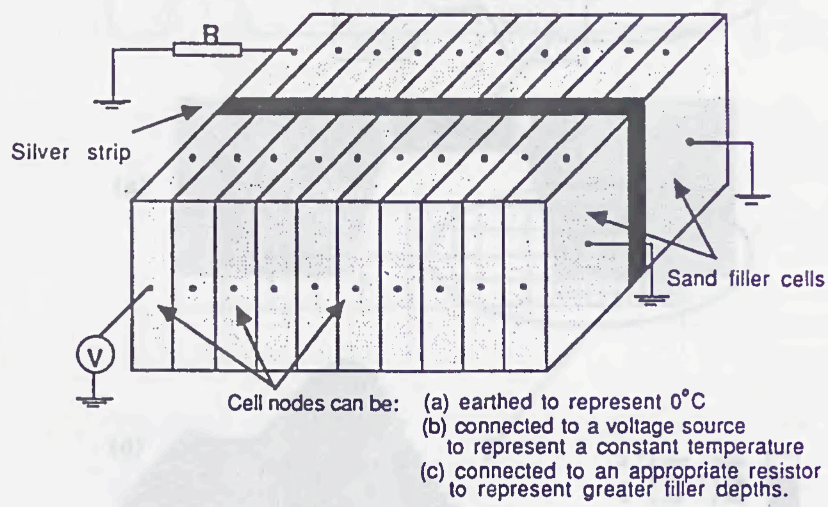

Fig.6
Schematic arrangement of sand filler cells around the silver element.

Figs.8. and 9. respectively show the variation of tin concentration with time at various depths through the silver element, and also the corresponding element temperature when an approximate three minute melting current is applied. It can be seen that both the tin concentrations (representing the diffusion depth) and element temperature both rise rapidly towards the end of the pre-arcing period.

During the long pre-arcing times associated with M-effect action, the only effect the element notches will have on the simulation is to increase the strip resistivity and produce local hot spots along the element where the notches occur. The effect of these notches can be taken into account in the form of cells of increased resistance at regular points along the element length. Once a particular single notch configuration has been modelled, the results obtained from this simulation can be used to determine the value of these resistors. Notched sections can be successfully modelled as single coarse cells, the electrical resistance being calculated as described above, and the thermal resistance and thermal capacity calculated, taking into account the reduced element mass.

4 Conclusion.

A method has been described which enables the complex pre-arcing operation of high breaking capacity fuses to be modelled using an analogue electrical circuit simulation software package. At short pre-arcing times, time-current and temperature rise plots obtained using this method give good agreement with experimental results (within 5%) and it can be concluded that from the thermal aspects, the theory adequately describes the physical problem. At longer pre-arcing times, when M-effect is active, simple diffusion theory is used to account for the dissolution of the M-effect alloy through the underlying fuse element. Whilst diffusion theory alone cannot account for this complex process it nevertheless gives reasonable agreement with experimental results (within 30%), and provides a useful guide to the fuse design engineer.

References

[1] 'ASTEC 3 User Manual' SIA Computer Services, Rungis, France 1984.

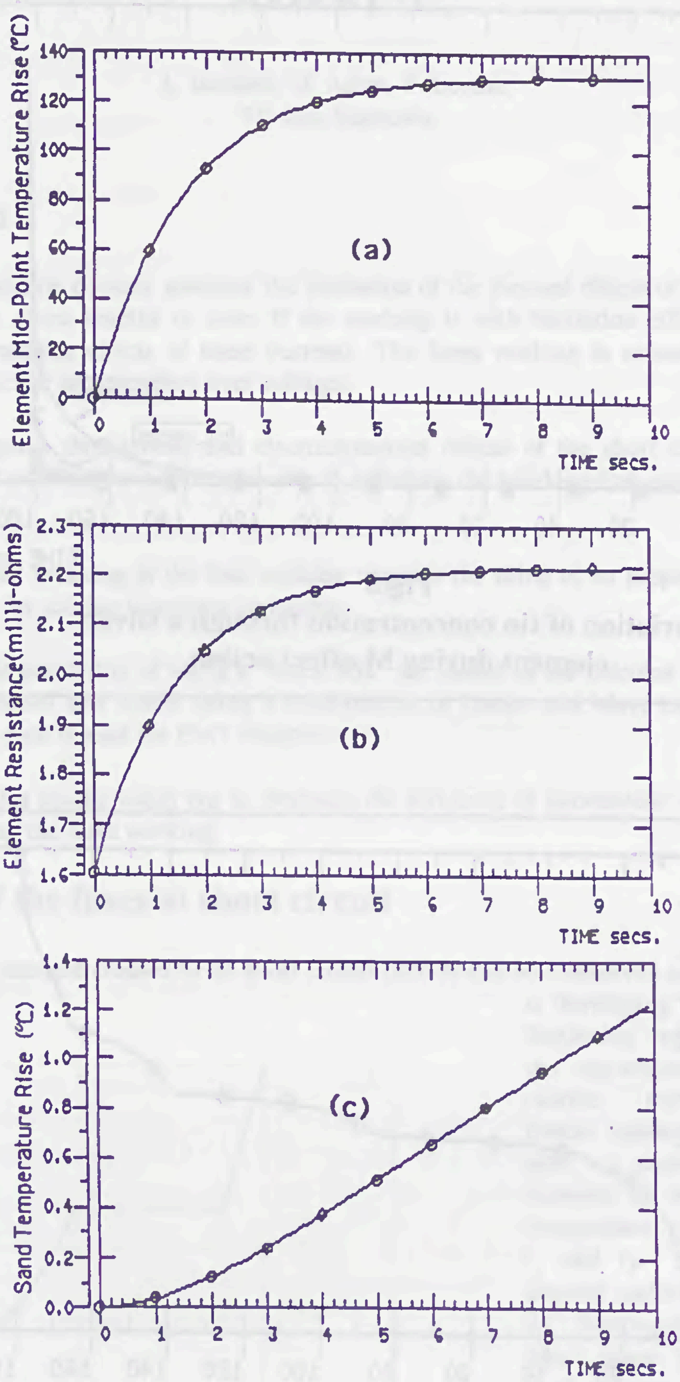

Fig.7.
Silver element surrounded with sand filler:
(a) element mid-point temperature rise
(b) element resistance variation
(c) sand temperature rise

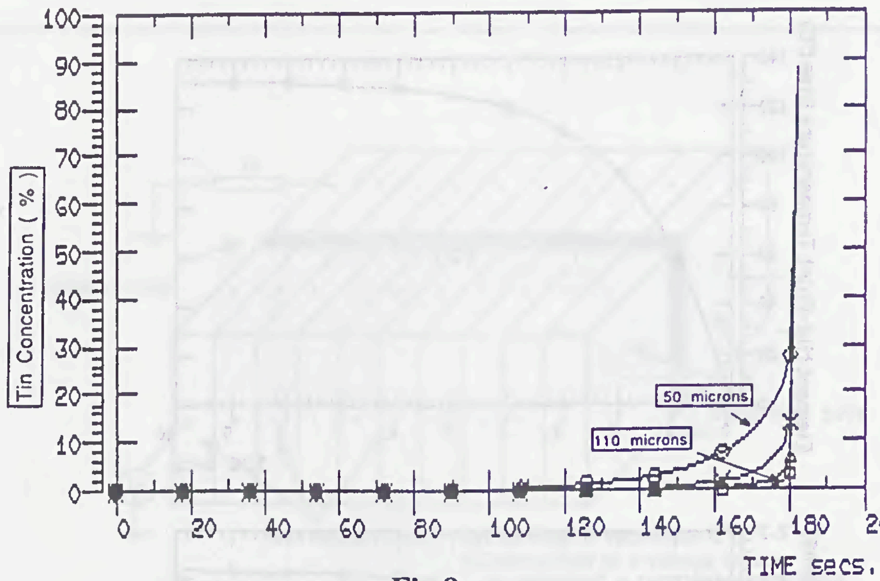

Fig.8
Variation of tin concentration through a silver element during M-effect action.

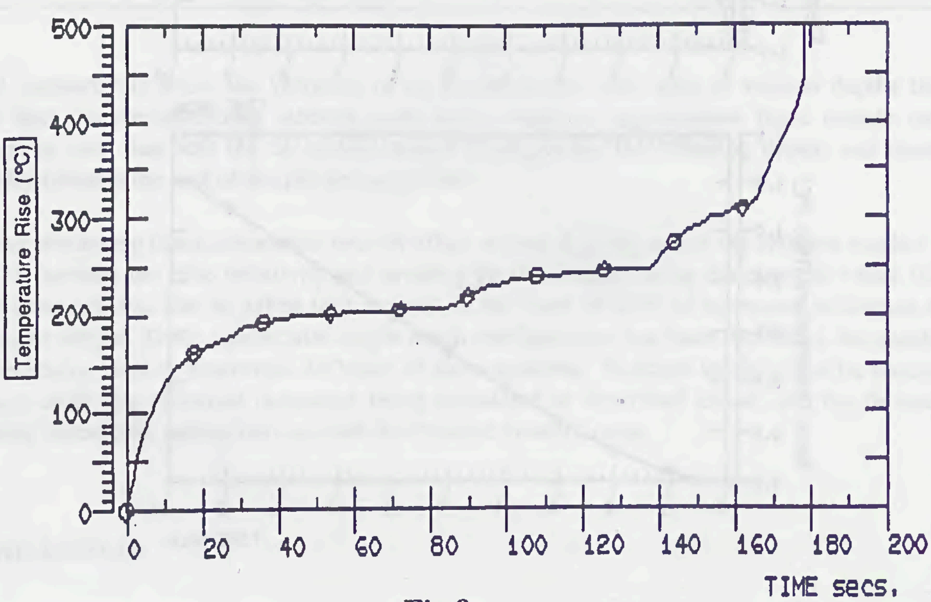

Fig.9
Simulated temperature rise of a silver element during M-effect action.