

Short-circuit current interruption in a low-voltage fuse with ablating walls

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SHORT-CIRCUIT CURRENT INTERRUPTION
IN A LOW-VOLTAGE FUSE WITH ABLATING
WALLS

by

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Abstract

This report describes a computer simulation study of the process of short-circuit current interruption in low-voltage fuses which have no sand filling. The current interruption process in such fuses is aided by the ablation of the wall material of the fuse which helps to cool the arc column inside the fuse.

An algorithm has been developed to solve numerically the time-dependent energy balance equation for the arc column taking into account the ablation of the wall material and the consequent pressure rise inside the fuse. The numerical algorithm is linked with the equations describing a test circuit to provide nearly 1500 A of prospective short-circuit current from a 250 V , 50 Hz source.

This study suggests that the current interruption process is dictated by the temperature distribution in the arc column immediately after the explosion of the fuse wire. The investigation reveals that the most likely reason for the successful operation of the fuse under a set of test conditions is that most of the joule heating in the arc column immediately after the explosion of the fuse wire occurs in the outer regions of the arc column close to the wall of the tube.

Results of temperature distribution in the arc column, arc voltage and current as a function of time are presented for tests with step arc currents and also for short-circuit tests and compared with experimental results.

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List of symbols

C_p	heat capacity (J/kg)
C_{pc}	heat capacity for carrier gas (J/kg)
C_{pw}	heat capacity for wall gas (J/kg)
E	axial electric field in the arc (V/m)
g	arc conductance (S)
h_w	energy per unit mass of wall material to ablate and raise to wall temperature (J/kg)
i	arc current (A)
l	length of the tube of the fuse (m)
L	inductance (H)
m	mass per unit length (kg/m)
\dot{m}	rate of mass ablating from the wall per unit length (kg/s m)
m_c	mass of a carrier gas per unit length (kg/m)
m_w	mass of wall gas per unit length (kg/m)
p	pressure (bar)
p_o	reference pressure = 1 bar (bar)
q	energy per unit time and length of arc (W/m)
q_{rad}	transparent radiation loss per unit length (W/m)
r	radial coordinate (m)
r_w	inner radius of tube (m)
R	electrical resistance (Ω)
t	time (s)
T	plasma temperature (K)
T_w	wall temperature (K)
u	net radiation emission (W/m^3)
u_a	arc voltage (V)
u_g	source voltage (V)
u_t	transparent radiation emission value (W/m^3)
v	velocity of the mass (m/s)
x	ratio number for wall gas, depending upon the relative masses in a mixture of two gasses
ψ	closing angle
κ	thermal conductivity (W/m K)
ρ	plasma density (kg/m^3)
ρ_o	plasma density at $p = 1$ bar (kg/m^3)
ρ_c	mass density of carrier gas (kg/m^3)
ρ_w	mass density of wall gas (kg/m^3)
σ	electrical conductivity (S/m)

1. Introduction

Protection of electrical equipment from damage resulting from electrical faults such as overload and short circuit is one of the major factors to be incorporated in the design of any electrical equipment or system. Electric fuses are widely used as protection devices and offer advantages such as low cost, simple design and constructional feature, and current limiting capability.

This report applies to a class of cartridge fuses, called "miniature fuses", which are normally used to protect a single apparatus or instrument or a part of it. These fuses are used at a nominal voltage of 250 V and have typical outer dimensions of 5 mm diameter × 20 mm length. The present limit on the short-circuit current is 1.5 kA which is likely to increase in future. Present dimensions, interruption ratings and test recommendations are covered by IEC-Publication 127 [19].

These small fuses consist of a thin metallic wire of tinned copper, silver or nickel stretched inside a tube made of glass, ceramic or suitable plastic. End connections to the fuse wire inside the tube are provided by means of two metallic end caps, which make the fuse a totally-enclosed protective device. When the interrupting capacity of these fuses is as high as 1.5 kA, the tube is also filled with fine-grain sand to absorb the arc energy liberated during the current interruption process and also to absorb the mechanical energy generated as a result of high-pressure development during the vaporization and arcing of the fuse wire. The requirement of sand-filling inside the tube introduces problems in their manufacture thus increasing the manufacturing cost.

One way to avoid the necessity of sand filling inside the fuse is to make the tube of the fuse out of a suitable plastic material with somewhat reduced inner diameter [1]. The polymer used to make the tube should then meet the following two important requirements: (i) it should have sufficient mechanical strength to withstand the high pressure generated within the tube; and (ii) the vapour ablated from the inner wall of the tube as a result of arcing inside the tube should have good "arc quenching" properties, comparable with those of sand-filling.

As fuses of this type operate under conditions when gas is liberated from the tube wall as a consequence of ablation, these fuses can be called "ablation-dominated" fuses. Preliminary experiments described in this report indicate that it is feasible to construct such ablation-dominated fuses up to a nominal current rating of 3 A with a short-circuit rating of 1.5 kA.

In order to obtain quantitative guide lines for the design of ablation-dominated fuses over a range of currents, it is essential to understand the mechanism of current interruption in the fuse and to be able to predict the pressure rise inside the fuse. Unfortunately, there appears to be little published literature on the behaviour of ablation-dominated fuses. Although there exist a few publications [2,3,4] on the behaviour of ablation-dominated arcs, these are not directly relevant in the context of fuse behaviour because these publications refer to arcing at very high current densities in tubes with open ends through which the plasma escapes to reduce the pressure rise inside the tube.

This report attempts to develop a quantitative understanding of the fuse behaviour on the basis of a theoretical model derived from physical principles. Owing to the non-linear nature of this time-dependent problem, a numerical solution of the differential equations describing the arc behaviour is considered. The problem considered in this study deals only with the arcing phase of the current interruption process; the prearcing phase consisting of the melting of the fusing wire and its subsequent explosion is not considered. The study reveals that the prearcing phase which acts as the initial condition for the arcing phase has a significant bearing on the interruption process.

2. Arc model

In a fuse of the type shown in Figure 1, during a fault, the fuse wire initially melts, explodes if the current is high and then an arc column is established within the tube across the end caps. The flow of current through the plasma results in joule heating within the arc and the heat is transported by thermal conduction and also by radiation, if the plasma temperature is sufficiently high, to the inner wall of the

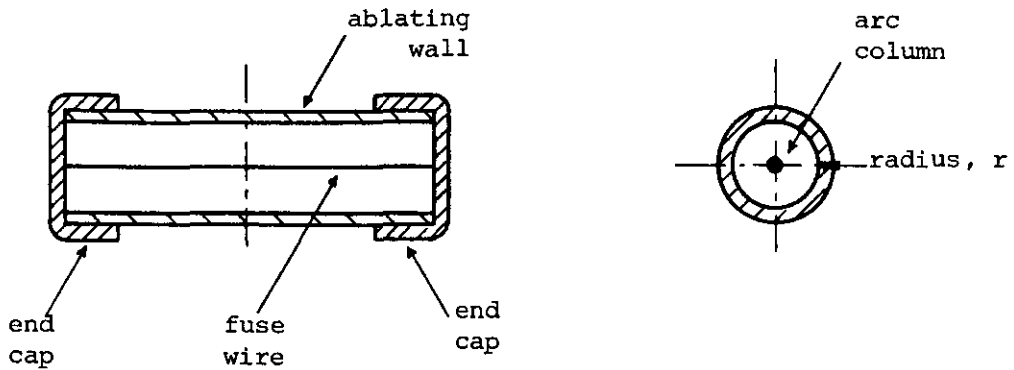


Figure 1 Fuse considered in this study.

tube. The wall material of the tube ablates and gets entrained into the arc column. As the fuse is a totally enclosed tube, the addition of wall material increases the pressure inside the tube. The entrainment of wall vapour results in a thermal convection and the convective flow is mainly in the radial direction towards the axis because the tube is cylindrically symmetric. This thermal convection may be viewed as the energy required to elevate the wall vapour to the arc temperature from its value adjacent to the wall. Thus, ablative cooling of the arc column results.

The process of arcing in a totally enclosed tube is inherently non-stationary in character. Even if the arc current is steady, continued ablation of the wall results in ever increasing pressure inside the tube until, perhaps, a mechanical failure occurs. On the theoretical level, no steady-state solution for the problem exists.

A detailed modelling of this type of arc should consider all three conservation equations, viz. mass, momentum and energy. As this is extremely difficult, in this study it is assumed that the mass liberated from the wall has negligible inertia and hence distributes itself within the arc column instantaneously. This assumption is equivalent to assuming that the pressure in the radial direction at any instant of time is uniform. This simplifying assumption allows one to discard the momentum equation.

Further, as the tube is cylindrically symmetric, it is assumed that axial variations in plasma properties are negligible. Thus we seek solutions of plasma properties in the radial direction only.

It is to be noted that at the instant the fuse wire explodes, the plasma is made up entirely of the carrier gas, which is a mixture of metal vapour and air. As time progresses, the addition of wall gas changes the composition of the plasma and the ratio of the mass of carrier gas to that of wall gas is a time-dependent function. Calculation of thermodynamic and transport properties of mixtures of gases at different temperatures and pressures is by no means simple. Hence, in this study, only variations in density and heat capacity as a function of gas-mixture ratio are considered at an approximate level. These two material properties contribute considerably towards thermal convection and the pressure rise inside the tube.

2.1. Energy-Balance Equation

Assuming that the plasma temperature T varies only along the radial coordinate r because of cylindrical symmetry, the energy balance equation [5] for the arc column can be written as

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p v \frac{\partial T}{\partial r} = \sigma E^2 + \frac{1}{r} \frac{\partial}{\partial r} (r \kappa \frac{\partial T}{\partial r}) - u \quad (1)$$

thermal storage	thermal convection	Joule heating	thermal conduction	radiation
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where E is the axial electric field in the arc column, v the velocity of the plasma in the radial direction induced by the ablation process as well as temperature changes and t the time. The material functions of the plasma are: ρ the plasma density in kg/m^3 , c_p the heat capacity in J/kg , σ the electrical conductivity in S/m , κ the thermal conductivity in W/mK and u the net radiation emission in W/m^3 . The material functions are dependent upon temperature and pressure.

The energy balance equation (1) can be interpreted in simple terms as follows: A fraction of the Joule heating as a result of electrical power input into the plasma is transported by thermal conduction; another fraction is transported as radiation; and yet another function is expended in heating the ablated wall material to plasma temperature. The remaining is used up in raising the plasma temperature, as expressed in the thermal storage term in the equation.

In order to solve equation (1) two boundary conditions for temperature are required. One of the two boundary conditions is $\partial T/\partial r$ (at $r=0$) = 0 because the heat flux at the axis of a cylindrically symmetric arc should be zero. The second boundary condition is determined by the ablation process at the wall. As the wall is continuously ablating, the temperature at the wall should be equal to the vaporizing temperature of the wall material. It has been shown by Kovitya and Lowke [3] that this temperature is approximately 3000 K for perspex and alumina. We, therefore, take the second boundary condition to be at $r=r_w$, $T=T_w = 3000$ K, where r_w and T_w are the radius of the tube and the temperature of plasma at the wall respectively.

2.2. Calculation of Pressure Rise in the Tube.

As the mass of gas inside an enclosed tube with non-ablating wall remains constant, if the temperature of the plasma in the tube increases due to arcing, then the mass density of the plasma falls and hence the pressure increases. Similarly, if the temperature of plasma increases, the pressure decreases.

If the tube wall ablates, then extra mass is added to the mass of gas already present in the tube and hence the pressure increases.

The procedure to calculate the pressure inside the tube at any instant of time should therefore consider pressure changes due to mass addition as a result of wall ablation as well as those due to temperature changes. The pressure changes due to both these factors can be estimated from the mass conservation equation, which is given by

$$\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r\rho v) = 0 \quad (2)$$

In order to use this equation to estimate the pressure rise, we need to know the dependence of density on pressure. This again introduces difficulties because we need to know the dependence of gas density as a function of temperature, pressure and also the gas composition, which changes with time. For simplicity we assume that the density of the plasma is proportional to pressure. That is, if $\rho_0(T)$ is the

functional dependence of plasma density on temperature at the reference pressure of p_o , which is taken as 1 atmosphere, then the density function is given by

$$\rho(p,T) = \left(\frac{p}{p_o} \right) \rho_o(T) \quad (3)$$

The above equation still does not take into account the composition of the gas mixture inside the tube. This aspect will be discussed in subsection 2.2.3 of this report.

In order to illustrate the procedure for the calculation of pressure rise, a simple case in which the carrier gas inside the tube has the same properties as the wall gas ablated from the wall is initially considered.

This illustrative procedure is discussed in subsection 2.2.2. It is stressed that the arc model does not use this illustrative procedure; the model considers the case when the carrier gas has different properties to those of the wall gas and this case is discussed in subsection 2.2.3.

2.2.1. Rate of Mass Ablation

The rate at which the wall material is ablated and entrained into the arc column is determined by the rate at which energy is received by the wall from the arc column and the energy required for the wall material to vapourise. If q is the rate at which unit length of arc receives energy in W/m, h_w the energy required by unit mass of wall material to ablate and raise to the wall temperature in J/kg and \dot{m} the rate at which mass is liberated from unit length of the wall in kg/s m, then

$$q = \dot{m} h_w \quad (4)$$

The wall receives energy from the arc column by means of thermal conduction and transparent radiation. Hence,

$$q = - 2 \pi r \kappa \left. \frac{\partial T}{\partial r} \right|_{r=r_w} + \int_0^{r_w} u 2 \pi r dr \quad (5)$$

and can be estimated using the temperature profile in the arc column.

The value of h_w required to ablate the wall material and raise it to the wall temperature is not known accurately. Niemeyer [2] has shown for both polymer and ceramic materials, the value of h_w lies in the range of 3×10^6 to 10^7 J/kg for vapour temperatures in the range of 1000 to 5000 K. Kovitya and Lowke [3] used a value of 6.5×10^6 J/kg for their studies on ablation dominated arcs. In this study, the value of h_w was taken to be 6.5×10^6 J/kg.

2.2.2. Pressure Rise when Carrier and Wall Gases have equal Mass Densities.

Multiplying the mass conservation equation (2) by $2\pi r dr$ and integrating from $r=0$ to $r=r_w$, we get

$$\int_0^{r_w} \frac{\partial \rho}{\partial t} 2\pi r dr = - 2\pi r_w (\rho v) \Big|_{r=r_w} \quad (6)$$

The right-hand side of the above equation (6) is equal to the rate at which mass is crossing the boundary at $r=r_w$ at any instant of time and hence should be equal to the rate of mass liberation from the wall which is given by equation (4). Thus, we have

$$\dot{m} = \int_0^{r_w} \frac{\partial \rho}{\partial t} 2\pi r dr \quad (7)$$

As we have assumed in this case that the density functions for the carrier and wall gases are one and the same, we can estimate the pressure rise in the tube from equation (7) in a rather simple way. Using the assumption that density is proportional to pressure given by equation (3), we get from equation (7)

$$\frac{dp}{dt} = \frac{\dot{m} p_0}{\int_0^{r_w} \rho_0(T) 2\pi r dr} - \frac{\int_0^{r_w} p \frac{\partial \rho_0(T)}{\partial t} 2\pi r dr}{\int_0^{r_w} \rho_0(T) 2\pi r dr} \quad (8)$$

where p is in bars and the reference pressure $p_0 = 1$.

The above equation (8) gives the rate at which pressure changes within the tube and can be integrated to obtain the pressure at any instant of time t . The first term on the right-hand side of equation (8) gives the pressure rise due to mass addition, while the second term gives the pressure change due to temperature changes in the plasma within the tube.

2.2.3. Pressure Rise when Carrier and Wall Gases have different Mass Densities.

The carrier gas in an enclosed fuse will be a mixture of copper vapour (or other metallic vapour), and air.

It is very unlikely that the mass density of the wall gas will be the same as that of the carrier gas. As it is difficult to evaluate mass densities of complex gas mixtures, we use an approximate averaging procedure to calculate the density of the composite plasma consisting of carrier and wall gases.

We define the density function $\rho_o(T)$ of the composite plasma at a reference pressure p_o of 1 bar as follows:

$$\rho_o(T) = \frac{\rho_c(T) + x\rho_w(T)}{1 + x} \quad (9)$$

where $\rho_c(T)$ and $\rho_w(T)$ are the density functions at the reference pressure of the carrier gas and wall gas respectively and x is a ratio which depends upon the relative masses of the two gases. It can be seen that when $x = 0$ or when there is no wall gas, the density function of the composite plasma is equal to the density function of the carrier gas. If the mass of wall gas is large in comparison with that of the carrier gas, then x is large and $\rho_o(T) \approx \rho_w(T)$. Hence the fractional densities of the carrier and wall gases are respectively $\rho_c(T)/(1+x)$ and $x\rho_w(T)/(1+x)$.

The value of ratio x at any instant of time can be evaluated by forcing mass conservation for the two species individually. That is, if m_c and m_w are, respectively, the masses of carrier and wall gases per unit length of the plasma column at time t , then we require:

$$\text{carrier gas } m_c = \frac{p}{p_o} \int_0^{r_w} \frac{\rho_c(T)}{1+x} 2\pi r dr \quad (10)$$

$$\text{wall gas } m_w = \frac{p}{p_o} \int_0^{r_w} \frac{x \rho_w(T)}{1+x} 2\pi r dr \quad (11)$$

$$\text{Composite gas } m = m_c + m_w = \frac{p}{p_o} \int_0^{r_w} \rho_o(T) 2\pi r dr \quad (12)$$

From equations (10) and (11) we can obtain an expression for x which is

$$x = \frac{m_w}{m_c} \frac{\int_0^{r_w} \rho_c(T) 2\pi r dr}{\int_0^{r_w} \rho_w(T) 2\pi r dr} \quad (13)$$

Knowing the temperature profile in the plasma at time t and also the masses of carrier and wall gases at the same instant, the value of x can be calculated.

The pressure within the tube at any instant of time, can be estimated from the total mass conservation for the composite plasma given by equation (12). We get for pressure the expression given below:

$$p = \frac{m p_o}{\int_0^{r_w} \left\{ \frac{\rho_c(T) + x \rho_w(T)}{1+x} \right\} 2\pi r dr} \quad (14)$$

2.3. Convective Cooling

The entrainment of the ablated wall material into the arc column results in a radial convection directed from the wall to the axis of the tube. This convection results in a cooling of the outer regions of the arc column and heating the inner regions. Or, it can be viewed as the energy absorbed by the wall gas in being raised from the value of the temperature at the wall to the plasma temperature.

A detailed study of this convection requires the inclusion of the momentum conservation equation. For simplicity, we have assumed that the distribution pressure is uniform across the tube and ignored the mechanical inertia of the fluid. This assumption formed the basis of our pressure calculation which used only the mass conservation equation.

Using the mass conservation equation (2), we can estimate the value of ρv at different radial positions of the plasma inside the tube.

If the carrier and wall gases have equal mass densities, then the mass conservation (2) can be directly integrated from $r=0$ to $r=r'$, the required radial position, to give the integral given below:

$$(\rho v) \Big|_{r=r'} = - \frac{1}{r'} \int_0^{r'} \frac{\partial \rho}{\partial t} r \, dr \quad (15)$$

The above expression is not readily usable when the carrier and wall gases have unequal mass densities because the value of x also changes with time. Hence, we use the following integral which deals with mass changes up to a given radius:

$$(\rho v) \Big|_{r=r'} = - \frac{1}{r'} \frac{\partial}{\partial t} \left\{ \int_0^{r'} \rho r \, dr \right\} \quad (16)$$

For $r' = r_w$, the above integral gives:

$$2\pi r_w (\rho v) \Big|_{r'=r_w} = - \frac{\partial m}{\partial t} = - \dot{m}$$

as required by equation (7).

2.4. Joule Heating

The local joule heating of the plasma is σE^2 as shown in equation (1) and is determined by the electrical power input into the plasma. The electrical power absorbed by the arc column is derived from an electrical network external to the arc column. The external circuit may be configured to either impose a voltage across the arc column or drive a current through it. In other words, if the voltage across the arc column, u_a , is specified by the circuit, we should be able to solve the energy balance equation and solve for the current through the arc column. Or, if the current, i , through the arc column is specified by the external circuit, then we should be able to estimate the voltage across the arc column. In this study, as the external test circuit is inductive in nature, it is easier

to consider the current as the state variable for the circuit and hence we can take the current i through the arc column to be determined by the test circuit. For a specified value of arc current we can calculate the axial electric field E in the arc column using Ohm's law, which gives:

$$E = \frac{i}{\int_0^r \sigma 2\pi r dr} \quad (17)$$

As the arc column is assumed to be cylindrically symmetric, the electric field is uniform axially and the arc voltage u_a can be calculated from

$$u_a = E \ell \quad (18)$$

where ℓ is the length of the tube of the fuse.

2.5. Radiation Losses

As the investigation discussed in this report was based on an heuristic approach to determine the heat-loss mechanisms in the arc column during the current interruption process in a fuse, the radiation loss term was included in the energy balance equation. However, the calculations showed that if the arc temperature was as high as 12000 K for the radiation losses to be dominant then the fuse would not interrupt the current at all. This section, therefore, has been included in this report only for the sake of completeness of the problem under consideration.

A detailed treatment of radiation losses within an arc column is very complicated and requires integration of the spectral radiative intensity over space and wave length [6, 7, 8]. Such treatments have been undertaken in simple plasmas containing only Nitrogen, Argon or SF₆. In the case of ablation dominated arcs, the problem is even much more complicated owing to the presence of metal vapour and wall material in the plasma.

In a treatment of arcs in nozzle flows, Tuma and Lowke [9] use a simple procedure by using net emission of radiation u at the arc axis. Since the value of u can be negative in the outer regions of the arc column owing to strong self-absorption of radiation, they used for transparent radiation a value u_t which was taken to be 0.1 u for nitrogen plasma. It has been shown that for air plasma containing copper vapour or other metallic vapour, the value of u_t/u can be as high as 0.3 [10,11]. The model used by Tuma and Lowke [9] was an integral model with the temperature profile in the radial direction assumed to be flat. Consequently, it was simple

to introduce the approximation that the transparent radiation losses are only a small fraction of the radiation losses inside the arc column.

In a two-dimensional treatment of free-burning arcs [12] and arcs in forced convection, the values of u were arbitrarily made negative upto a certain radius and zero beyond so as to make the transparent radiation losses zero. In this study, this treatment has been refined further so that the function of radiation escaping the arc column as transparent radiation can be specified as an input parameter.

The values of net emission coefficients u for temperatures greater than 12000 K are positive and have been published for nitrogen plasma [13]. However, strong self-absorption of radiation takes place at a radius where the temperature in the plasma falls below 12000 K. In this region, the value of u is usually negative. This study chooses the negative value of u in such a way that the following condition is satisfied:

$$\frac{q_{\text{rad}}}{\int_0^{12000} u \, 2\pi r \, dr} = f, \text{ a specified fraction} \quad (19)$$

In the above expression, q_{rad} represents the transparent radiation losses escaping the arc column and is given by:

$$q_{\text{rad}} = \int_0^r u \, 2\pi r \, dr \quad (20)$$

For the plasma inside the fuse, containing a considerable amount of metal vapour, the value of f was chosen to be 0.3 [10]. The values of u were taken to be equal to those of nitrogen from the measurements of Ernst, Kopainsky and Maecker [13].

The value of u of Ernst et al. corresponds to a pressure of 1 bar. Extrapolation of these values to higher pressures has been made in this investigation by assuming that u is proportional to pressure along the lines suggested by Kovitya and Lowke [3].

2.6. Material Functions

The plasma inside the tube of the fuse consists of a mixture of carrier gas and wall gas. No attempt has been made in this study to calculate material functions of the composite plasma as a function of temperature, pressure and composition. For simplicity, we assume that only the mass density of the plasma is proportional to the pressure inside the tube. Other material functions, viz. heat capacity, thermal conductivity and electrical conductivity are assumed to be pressure independent.

The carrier gas is made up of metal vapour from the fuse wire and air. As material data for such mixtures is rare, we have taken the fuse wire to be made from copper. For a 100 microns diameter wire in a 3.2 mm diameter tube the mass ratio of copper to air is nearly 8. The values of density, heat capacity, thermal conductivity and electrical conductivity for approximately this mass ratio at a pressure of 1 bar have been taken from the publication of Shayler and Fang [14].

It is assumed that the transport properties, viz. thermal and electrical conductivities for the composite plasma, are the same as those for the carrier gas as a first-order approximation.

It can be seen from the energy balance equation (1) that the most dominant effect of ablation results from the thermal convection term which is determined by the density and heat capacity of the composite plasma. Hence, the density of the composite plasma is estimated along the lines discussed in sub-section 2.2.3 from the density functions of the carrier and wall gases. The heat capacity of the composite plasma is estimated by summing over the two component gases [Shayler and Fang, 14], the product of heat capacity and the mass fraction of the two components. That is, the heat capacity C_p of the composite plasma is given by

$$C_p = \frac{\rho_c / (1+x)}{\rho_o} C_{pc} + \frac{x\rho_w / (1+x)}{\rho_o} C_{pw} \quad (21)$$

where C_{pc} and C_{pw} are the heat capacities of carrier and wall gases respectively.

The values of mass density and heat capacity for wall gases of Perspex and Teflon have been taken from the publication of Kovitya [15].

2.7. Numerical Method

An explicit scheme using finite-differences has been used to solve the energy-balance equation (1). The region from $r=0$ to $r=r_w$ is divided into $(N-1)$ equal intervals, each interval having a width of Δr , to give N grid points at which the temperature as a function of time is evaluated. Discretizing the solution in time by choosing an appropriate small time step Δt , we seek the value of temperature at all grid points $i=1$ to N at time $t^{j+1} = t^j + \Delta t$ knowing the temperature distribution at $t=t^j$. That is, we attempt to estimate from the energy-balance equation changes in temperature, ΔT_i^j at time $t=t^j$ for all grid points $i=1$ to N . Then, at $t=t^{j+1}$ we get the temperature at all grid points from

$$T_i^{j+1} = T_i^j + \Delta T_i^j \quad (22)$$

The value of T_i^j at all grid points can be estimated from the energy-balance equation (1) by expressing the equation in a finite-difference form. The finite-difference algorithm used is based on the following formulae:

$$\Delta T_i^j = \frac{\Delta t}{\rho_i^j C_{p_i}^j} [\sigma_i^j (E^j)^2 + \frac{1}{r_i} \frac{r_i^j \kappa_i^j T_i'^j - r_{i-1}^j \kappa_{i-1}^j T_{i-1}'^j}{\Delta r} + u_i^j - \rho_i^j C_{p_i}^j v_i^j T_i'^j] \quad (23)$$

for all $i=2$ to $(N-1)$

where $T_i'^j$ is given by

$$T_i'^j = \frac{T_{i+1}^j - T_i^j}{\Delta r} \quad (24)$$

for all $i = 2$ to $(N-1)$

The boundary conditions require that $T_1^j = T_2^j$ because $\left. \frac{\partial T}{\partial r} \right|_{r=0} = 0$ and $T_N^j = T_w$, the wall temperature.

The above formulae (23) and (24) are used together with suitable integration procedures (a) to solve for the pressure within the tube (equation 14), (b) to determine the convection term (equation 16), (c) to estimate joule heating (equation 17), (d) to account for self-absorption of radiation to evaluate transparent radiation losses and (e) to link with the external circuit.

The material properties at all grid points are interpolated from reference tables.

For calculations, twenty-one radial grid points or twenty intervals were chosen. The accuracy of the solution was checked by doubling the number of intervals. The value of time step Δt required for the numerical algorithm was chosen to satisfy the von Neumann criterion [16] so that stable solutions could be obtained.

The numerical algorithm described by the formulae (equations 23 and 24) is basically an integration procedure in time in which we march forward in time to seek solutions of temperature distribution as a function of time, starting from a set of initial conditions. The set of initial conditions corresponds to a time $t = t_e$ when the fuse wire explodes to establish an arc column inside the fuse. We need to specify the pressure p , the mass of carrier gas m_c , the current i and the temperature distribution at $t = t_e$. The mass of carrier gas was taken to be equal to the sum of the masses of the copper fuse wire and the surrounding air within the fuse. The value of pressure at $t = t_e$ was estimated from the mass of carrier gas and the temperature distribution at $t = t_e$. The required conditions on current and temperature distribution are discussed in section 4.

3. Experiments

Preliminary experiments aimed at estimating the influence of wall-ablation process on arc behaviour in totally-enclosed tubes and on current-interruption process in fuses were conducted. These experiments also provided a basis for the choice of suitable initial conditions for the theoretical model and its refinement during the theoretical development.

The process of arcing in fuses during current interruption is inherently non-stationary, not only because the arc temperature is not steady but also because of the wall-ablation process which makes the pressure in the fuse to rise even if the temperature is constant. In order to gain an improved understanding of the phenomenon arcing in fuses, the following two types of experiments were conducted: (i) Fuses made from different wall materials were tested in a 50 Hz power circuit for short-circuit duty; these experiments retain the two non-stationary processes arising from unsteady current as well as the wall ablation. (ii) The response of voltage arcs in totally-enclosed tubes made from different materials to a step change in arc current was determined; these experiments characterize the non-stationary feature arising from wall-ablation alone.

3.1. Experiments with Current Steps

Experiments were conducted with tubes 50 mm in length made of perspex, teflon, p.v.c. and glass in a power source circuit development by Daalder [17]. The source circuit was modified to produce flat current pulses of current level in the range of 30 A to 100 A lasting for nearly 5 ms. Details of the experimental set-up and measurements are discussed elsewhere [18].

A typical experimental shot consisted of loading the tube with a copper wire of 100 μm diameter and holding the tube between two fixed blocks of brass which served as electrical connections to the wire inside the tube and also as seals to prevent plasma escaping the tube. The current through the wire was then initiated. Tests were conducted with tubes of different inside diameters in the range of 2 mm to 10 mm.

The variation of the arc voltage with time was recorded using an oscilloscope. It showed the following features (Figures 2 and 3):

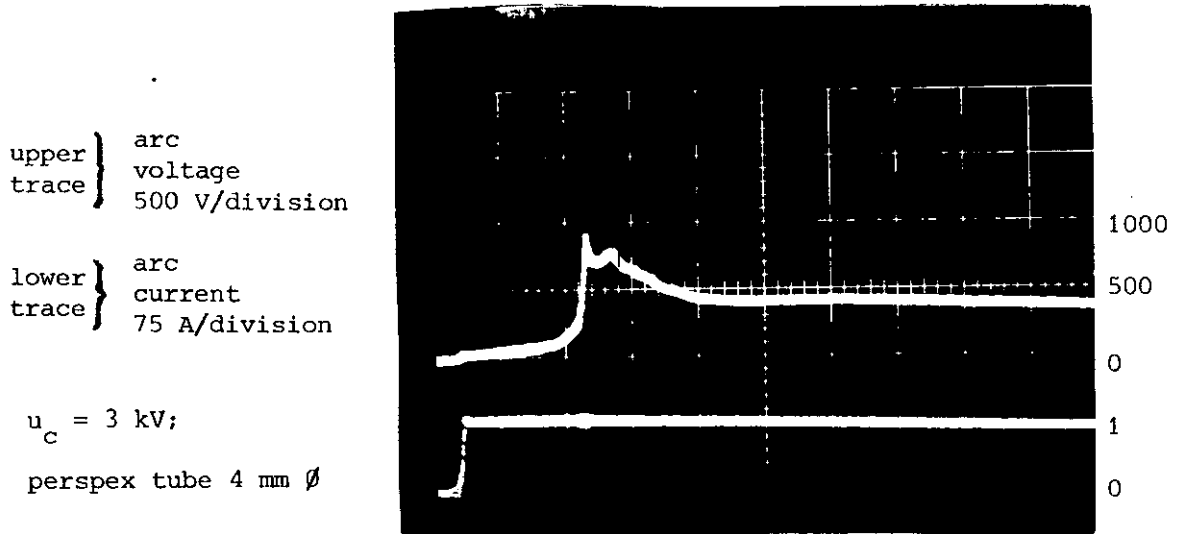


Figure 2 Typical Records of Voltage and Current obtained in the current-step study.

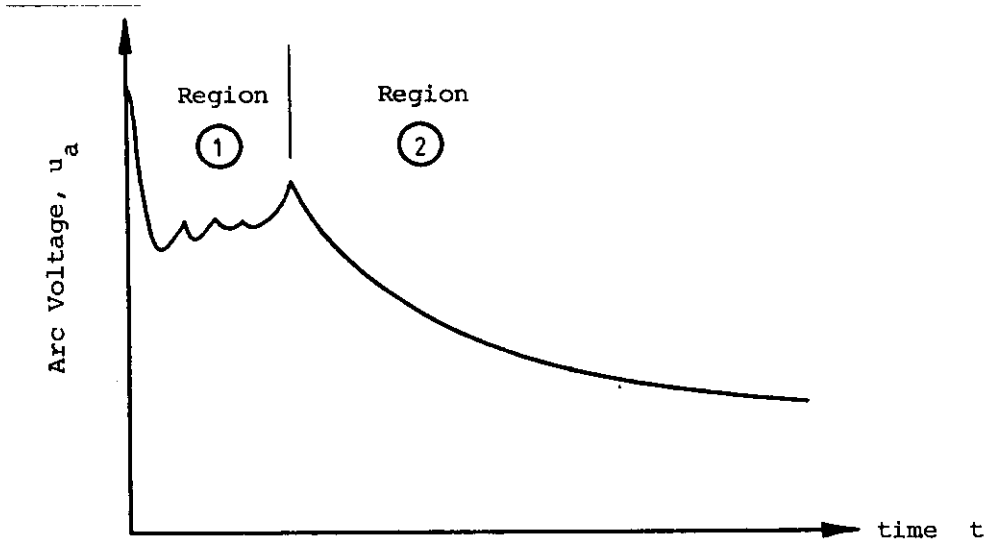


Figure 3 Typical time-variation of arc voltage in an enclosed tube after the explosion of the fuse wire.

- (i) The melting and subsequent vaporization of the fuse was characterized by a steep rise in the voltage across the tube
- (ii) for a certain duration (0.1 - 0.5 ms) (Region 1 in figure 3) after the explosion of the fuse wire, the voltage exhibited random variations with its mean value nearly constant or falling with time; and
- (iii) after this duration of somewhat random behaviour, the recorded voltage was smooth and decreased with time (region 2 in figure 3); the rate of fall of voltage was found to decrease steadily until the voltage reached nearly a constant value after 1 or 3 ms.

It was inferred from the experiments that region 1 in figure 3 corresponding to the fluctuating voltage trace corresponds to the period of establishment of an arc filling the tube from the conditions immediately after the explosion of the wire. Experiments with tubes of different materials and inside diameters showed that

- (i) the voltage recorded for the perspex tube was the highest; the other materials in the order of decreasing magnitude of voltage are :
p.v.c., teflon and glass.

(ii) the magnitude of voltage decreased if the tube diameter was increased.

These experiments show that the establishment of a well-defined arc column within a tube requires a certain duration even when the imposed current is steady and that the ablation of wall material has a significant influence on the arc voltage. Further experimentation to investigate the process of arc establishment in the tube and to measure the pressure inside the tube is essential to gain a better understanding of the behaviour of arcs in enclosed tubes and fuses.

3.2. Short-circuit Current Interruption Studies

Experiments were also conducted using fuses of standard outer dimensions in a test circuit built on IEC recommendations [19] to deliver a prospective short-circuit current of nearly 1500 A (Figure 4). Although

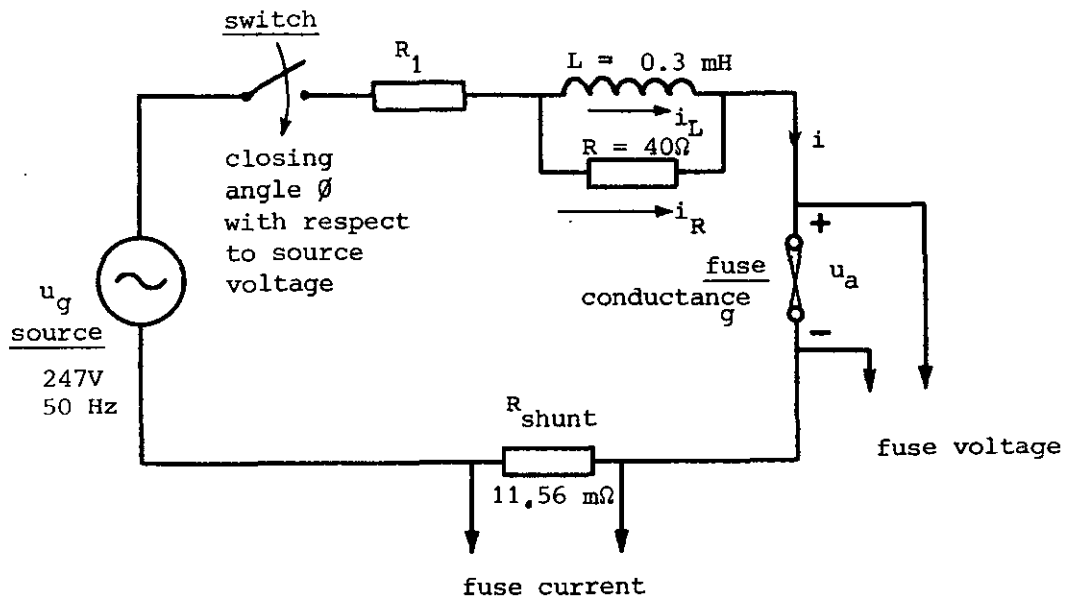


Figure 4 Test circuit used for current-interruption study.

the recommendation of the IEC on the closing angle for initiation of the circuit current relative to the source voltage is in the range of 25° to 35° , the closing angle was varied from 10° to 45° to investigate the severity of interruption duty. The current through the fuse and the voltage across it during short-circuit current interruption were recorded using a computer controlled digital recording system.

Initial experiments conducted using fuses made of a certain polymer material showed that a fuse with an inside tube diameter of 3.2 mm and a copper wire of 100 microns in diameter, interrupted the current successfully for a closing angle of 9.4° . When the diameter of the fuse wire was increased to 200 microns, the fuse failed to interrupt the current. Inspection of the fuse after the test revealed that heavy arcing inside the fuse together with the high pressure had created large holes on the end caps through which the plasma inside the tube had escaped.

Further experiments were conducted with fuses having a copper wire of diameter of 100 microns. Fuses made from perspex, teflon, p.v.c. and other materials were tested.

It was found that at a closing angle of 29° the interruption appeared to be critical. For example, the fuse made of p.v.c. developed a small hole on one of the end caps. Other fuses showed a small dimple on their end caps which might have resulted in the development of a hole.

When the closing angle was increased to 45° , all the fuses failed. The failure was not evident from the current and voltage traces recorded during the test, but was due to the failure of the end caps. But, the fuse made of teflon was found to explode during the test.

The tests appeared to show that when the fuses cleared the fault current, the current records were not significantly different for different tube materials. When a failure occurred it was mainly due to a mechanical failure resulting from arcing at the end caps and high pressure inside the tube. It was also found from tests with different closing angles that if the cut-off current for a particular closing angle was high due to high initial rate of rise of current, then the fuse failed to clear the current. This result shows that the cut-off current or the current at which the fuse wire melts, vaporizes and explodes has a significant bearing on the subsequent arcing process during current interruption; the higher the cut-off current the more severe is the short-circuit duty.

4. Results and Discussion

The arc model presented in chapter 2 was used to calculate arc properties and to predict interruption behaviour and the calculations were related to the experimental results discussed in section 3.

As mentioned previously in section 2.7, the calculation procedure relies upon specifying approximate initial conditions for the problem. The important initial conditions are the current at which the fuse wire explodes and the temperature distribution within the arc column immediately after the explosion of the fuse wire. In the case of the short-circuit test circuit using a 50 Hz power source, the current at which the fuse wire explodes is not merely determined by the fuse wire but is related to circuit parameters as well. Further the dynamic interaction between the circuit and the arc inside the fuse makes the problem complicated. Hence, initial calculations were made for the experiment using current steps. In this case, as the current remains nearly constant, the interaction of the arc with the circuit can be ignored and the current becomes a specified parameter for calculations. The choice of an appropriate distribution for temperature at the instant the fuse wire explodes, was made by comparing the calculations for different initial distributions with experimental results of arc voltage.

4.1. Initial Temperature Profile.

No measured temperature profile for the plasma inside the tube during the time immediately after the explosion of a fuse wire in an enclosed tube has been reported in the published literature. Hence, an heuristic approach was followed by choosing three different temperature profiles. All these profiles were chosen to satisfy the required boundary conditions at radii 0 and r_w . The three chosen profiles are shown in Figure 5 ($t = 0$) and can be seen to have temperatures larger than 3000 K for computational convenience which depends upon the availability of material properties of the plasma. However, the energy required to raise the plasma within the tube to the temperatures shown in the figure for $t = 0$ is less than 0.5 J which means at a current of 100 A and a voltage of 1000 V immediately after the explosion of the fuse wire, it would take only 5 μ s to heat up the plasma to the initial temperature distribution. Experiments on fuses (subsection 3.3.2.) show that typical interruption times are 300 μ s or more and the total energy absorbed during the interruption process is 10 J or more. As the values of time and energy

required to heat the plasma to the assumed initial temperature are small, the errors involved in the computational procedure are likely to be small. The three assumed initial temperature distributions are given below:

- (i) Elevated core, Fig. 5(a): The arc is assumed to have a thin core near the axis with the core temperature at 12000 K. Calculations show that if the core temperature is assumed to be lower, then owing to Joule heating the temperature would rise rapidly to high temperatures.
- (ii) Uniform core, Fig. 5(b): The temperature profile is assumed to be uniform radially with a value of 4000 K.
- (iii) Elevated Wall, Fig. 5(c): The temperature is assumed to be uniform at 3000 K everywhere except near the wall where the temperature is raised to 4500 K. This elevated temperature gives larger electrical conductivity near the wall and can also be viewed as an enhancement of electrical conductivity near the wall owing to the presence of copper or metal vapour near the wall rather than an elevated temperature.

In the case of the assumption of elevated core (Figure 5(a)) , the temperature at the axis of the arc increases initially and also the profile broadens to accommodate the imposed steady current which produces

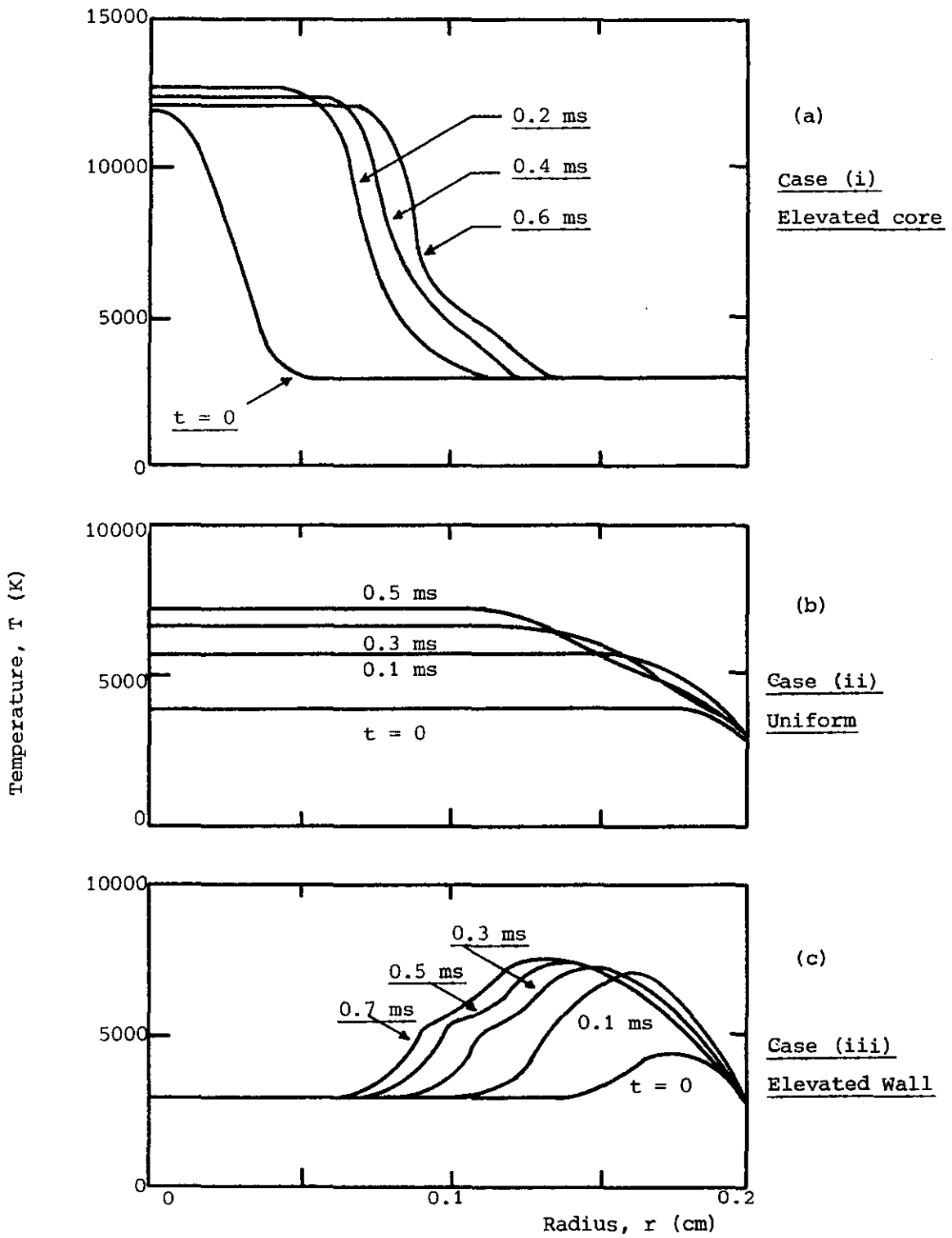


Figure 5

Calculated Radial Distribution of Temperature
in a 4.0 mm Diameter x 50.0 mm Long Perspex
Tube for a Step Current of 75A.

intense joule heating within the core. The temperature at the axis then begins to drop, but the profile continues to broaden. The broadening of the temperature profile results in an increase in the conductance of the arc column and hence the voltage across the arc drops as shown in Figure 6(a) i. The rate at which the broadening of the temperature profile occurs drops as time progresses because the ablated mass from the wall not only cools the outer boundary but also increases the mass and hence the thermal inertia of the arc column. The comparison of the calculated time variation of voltage with the experimental results for a 75 A arc column in a 4 mm diameter × 50 mm long perspex tube shows that the value of voltage is smaller than the measured value. In this case of assumption of elevated core, the ablation of the wall material is mainly due to the transparent radiation from the arc column which is small as shown by Figure 6(b). Consequently the arc cooling as well as the pressure rise are small. The voltage predicted by this initial distribution is smaller than the measured one because of an under-estimation of the ablation process. It is therefore concluded that this temperature profile is a very unlikely consequence of the explosion of the fuse wire. Calculation of short-circuit behaviour of fuses using this temperature profile also predicts that the fuse would fail to interrupt the current corresponding to test conditions of successful experimental interruption.

The assumption of uniform temperature distribution within the plasma initially produces an improvement in the predicted voltage (Figure 6(a)ii), but again appears to under-estimate the ablation process (Figure 6(b)ii). As ablative cooling of the plasma is effective only in the outer regions of the plasma, the temperature in the inner regions increases thereby increasing the conductance of the arc. The predicted voltage, therefore, is smaller than the measured value.

For wall ablation to provide arc cooling as effective as shown by the recorded voltage for an imposed steady current, it is very likely that most of the joule heating of the plasma immediately after the explosion of the fuse wire occurs in the outer region of the arc column. This mode of heating the plasma may occur if considerable amount of copper vapour is present in the outer regions near the wall of the confining tubes. If the joule heating is present only in the outer regions, then the temperature in outer regions rises while the inner region remains cooler until heat diffuses to the inner region as shown in Figure 5(c).

Initial Conditions for Temperature

- (i) Elevated core
- (ii) Uniform
- (iii) Elevated Wall
- . Experimental Results

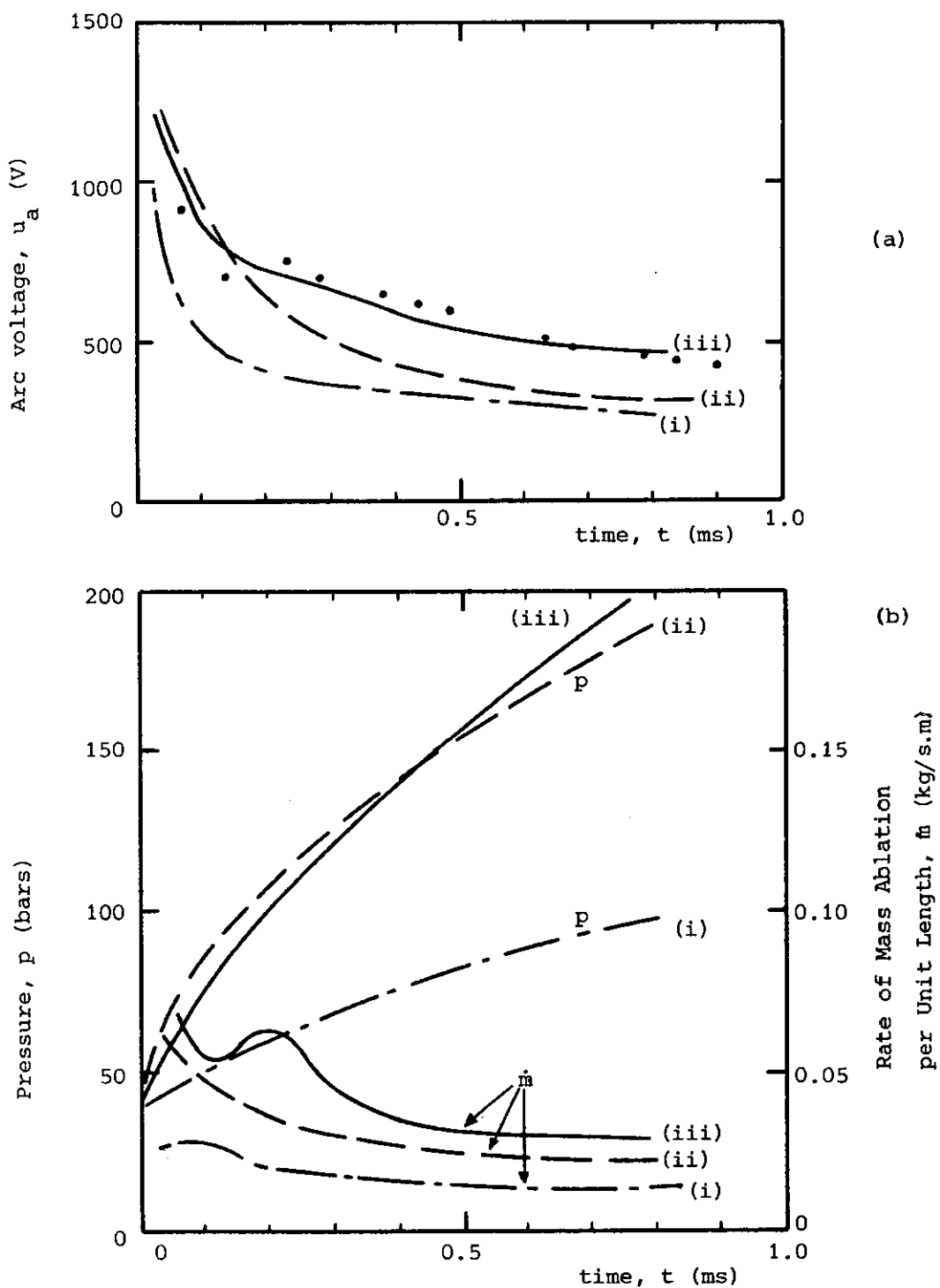


Figure 6 Calculated time-variation of pressure and
voltage of an arc in a 4.0 mm diameter
x 50 mm long perspex tube for a step
current of 75A.

This figure corresponds to the case of elevated-wall temperature. The voltage estimated using this initial temperature distribution compares favourably with the experimental result for the region 2 of Figure 3. Region 1 in Figure 3 which corresponds to the establishment of a well-defined arc column, however, is not explained by this assumption on initial temperature distribution.

Preliminary investigations [18] using framing photography at 35000 frames/second of the initial phase of arcing in an enclosed fuse show that the arc resides near the wall of the tube in the form of a core initially and after a certain period an arc column which fills the tube is established. This preliminary experimental test result tends to support the idea that the Joule heating occurs mainly in the outer regions of the tube initially. In reality, the joule heating is more localised than what has been assumed because the initial distribution with elevated wall temperature considers heating all around the inner wall. A treatment of this localised core near the inner wall of the tube immediately after the explosion of the fuse wire is complicated and requires solution of the energy-balance equation in two dimensions, viz. radial and azimuthal coordinates. As a first-order approximation to this complicated problem, we use the initial temperature distribution to be one of elevated-wall type for the prediction of fuse behaviour.

4.2. Arc Behaviour for Steady Arc Currents

Calculated results using the model for a 75 A arc in a 4 mm diameter \times 50 mm long tube are shown in Figure 7(a) and (b). The results of time variation of voltage after the explosion of the fuse wire for tubes made of perspex, teflon and non-ablating material show that perspex has the highest voltage followed by teflon. A tube whose wall does not ablate results in the smallest voltage. This result is consistent with experimental results.

Figure 7(b) shows the calculated variation of pressure inside the tube with time. The pressure inside a perspex tube is higher than that in a teflon tube because perspex vapour has a lower density and addition of lower density wall gas to the carrier gas results in a reduction of the carrier gas density at the reference pressure of 1 bar. The pressure in a tube of non-ablating material also increases because of

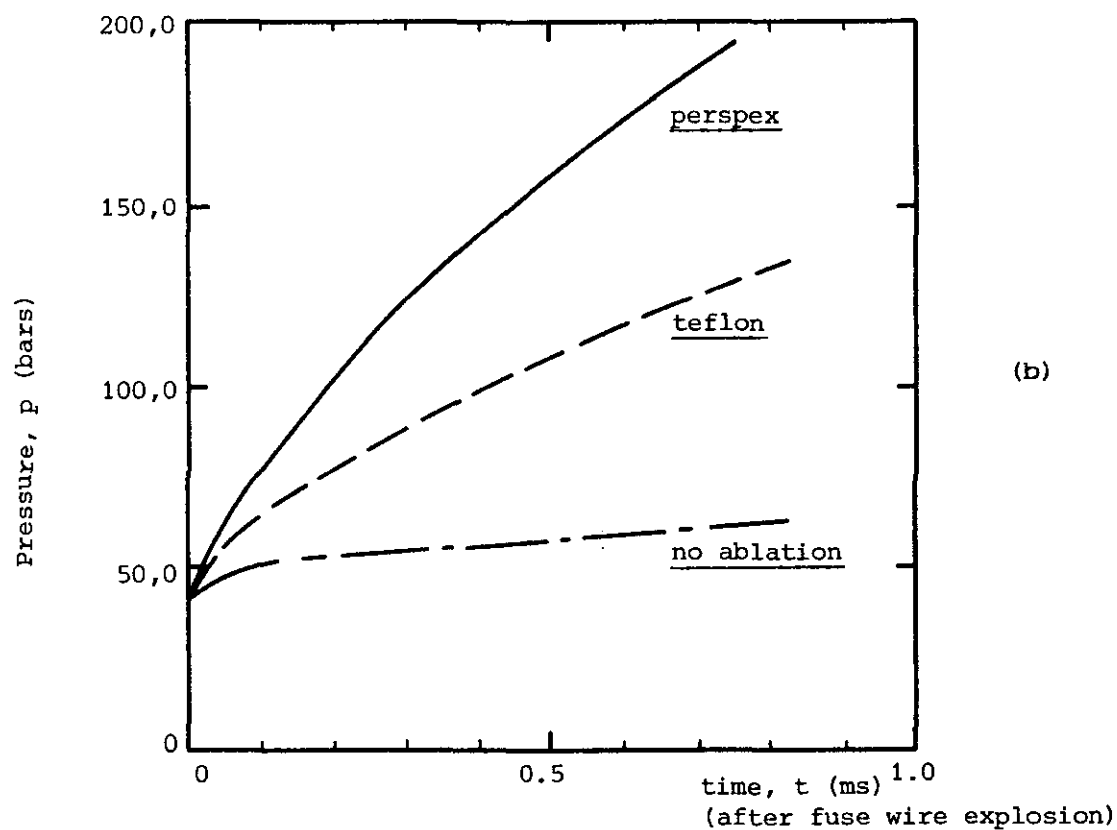
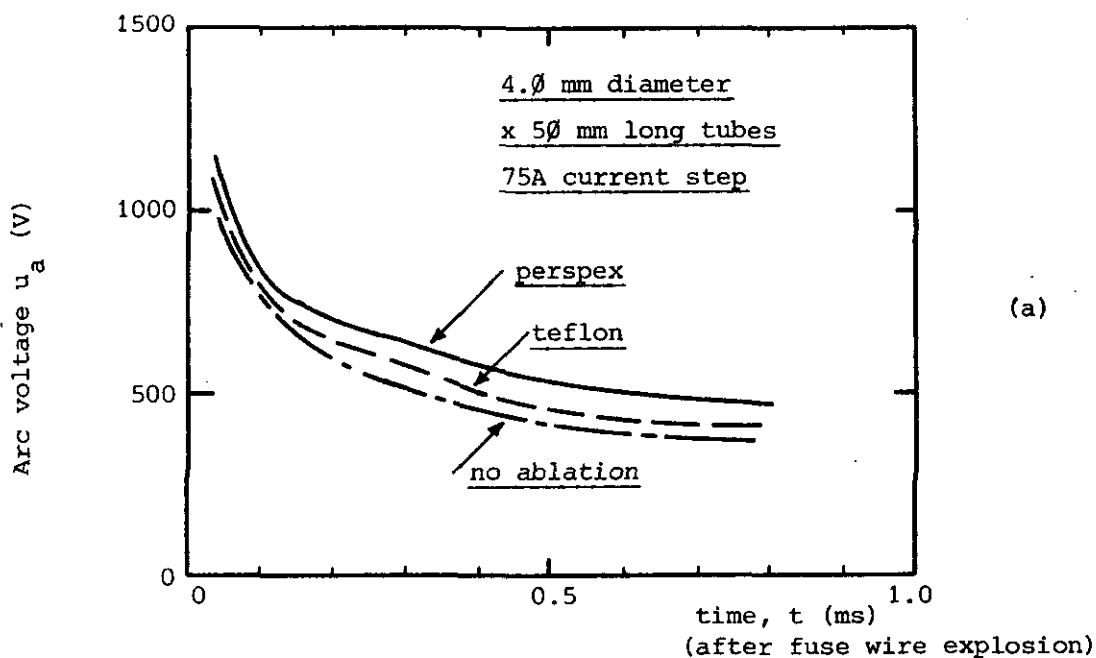


Figure 7 Calculated dependence of time-variation of arc voltage and pressure on wall material for an imposed current step of 75A.

the rise in temperature inside the tube. It is likely that the calculations overestimate the pressure inside the tube because we have assumed that the whole of the circumference of the arc gets heated and produces ablation whereas in practice the heated zone might be more localised near the wall of the tube.

4.3. Fuse Behaviour under Short-Circuit Tests

In order to predict the behaviour of fuses under short-circuit test conditions, the arc model described in section 2 has been linked with the equations describing the test circuit shown in Figure 4. The necessary circuit equations are given below:

$$i = i_L + i_R \quad (25)$$

$$L \frac{di_L}{dt} = u_g - iR_1 - i R_{\text{shunt}} - u_a \quad (26)$$

and

$$L \frac{di_L}{dt} = i_R R_2 \quad ; \quad u_a = \frac{i}{g} \quad (27)$$

where the source voltage u_g is given by

$$u_g = u_m \sin(\omega t + \psi) \quad (28)$$

ψ being the closing angle and g the arc conductance. Before closing the switch in the test circuit, the circuit currents are zero which are taken as the initial conditions.

The inclusion of the test circuit which produces 50 Hz current with superimposed transients introduces the problem of finding the current and the instant at which the fuse wire explodes. The circuit equations (25) - (28) were initially solved numerically without the inclusion of the arc model until melting of the fuse wire occurs. The initial value of conductance g of the fuse wire was estimated from the dimensions of fuse wire. The value of g was updated at each time step of integration of equation (26) by calculating approximately the temperature of the fuse wire and using the temperature coefficient of the resistance of the fuse wire. The instant at which the $i^2 t$ value reached a value corresponding to the $i^2 t$ value for melting estimated using the Mayr's constant was taken to give the instant of melting of the fuse wire. The circuit current at the instant the fuse wire melts, gives the cut-off current i_c .

The value of the cut-off current and the instant of melting were used as the initial conditions for the arc model. From this instant of melting of the fuse wire, the circuit equations were solved in conjunction with the arc model. The temperature distribution in the arc column at the instant of melting of the fuse wire was taken to be of the elevated wall type. At each time step of numerical calculation, the value of current given by the circuit equations was used in the arc model to update the temperature distribution in the arc column, the conductance of the fuse and the voltage u_a across the fuse. Using the updated value of arc conductance the arc current i was updated using the circuit equations. This process was continued to estimate fuse current, fuse voltage, pressure inside the tube and the temperature distribution in the arc column, all as a function of time. There was, however, a difficulty in the determination of the exact initial condition for the current at which the fuse wire exploded. The cut-off current estimated from $i^2 t$ values was found to be higher than the value obtained experimentally. This discrepancy was due to an oversimplification in this study of the melting process in the fuse wire.

Calculated results (Figure 8) of current and voltage of the fuse as a function of time are compared with the experimental results for a fuse made of perspex tube of inner diameter 3 mm and having a copper fuse wire of 100 micron in diameter. Case (i) corresponds to the case where the cut-off current is estimated from $i^2 t$ -values. As the cut-off current in case (i) is higher than the value obtained in the experiment, it is found that intense arc heating occurs immediately after the explosion of the fuse. The arc current drops, but not significantly enough. Calculations show that at the end of 0.6 ms after the initiation of the current through the fuse, the current is still nearly 60 A and the pressure is nearly 190 bars. It is very likely that a fuse under these conditions would fail mechanically, thus failing to interrupt the current. In case (ii) we have taken the value of the cut-off current to be 185 A as obtained in the experiment. In this case, the fuse appears to interrupt the current.

Results were also obtained for current interruption by a perspex fuse with a copper wire of 100 μm in diameter at a closing angle of 10° . In this case, as the initial rate of rise of current through the fuse wire is lower than the value at a closing angle of 29° , the cut-off

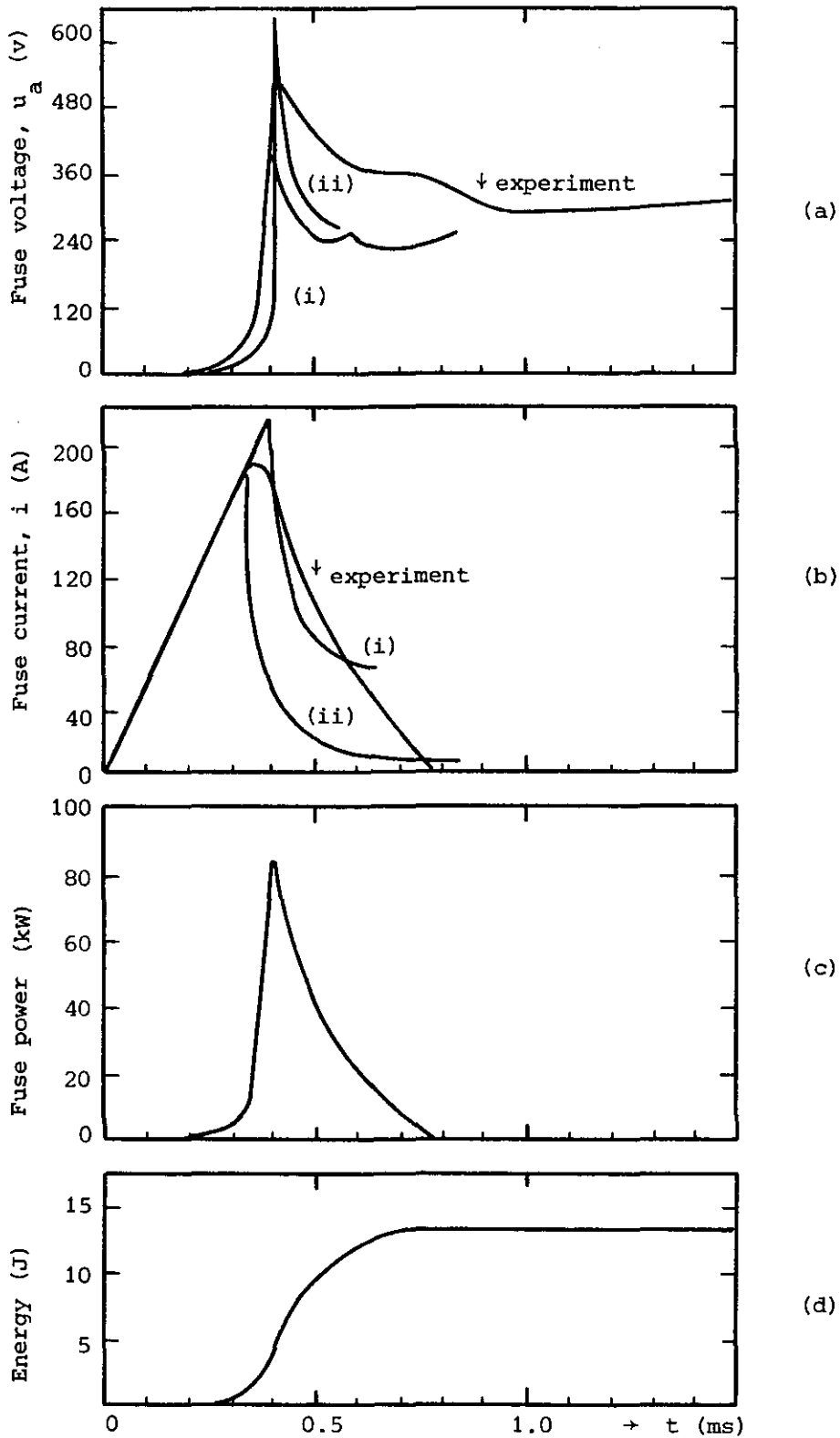


Figure 8 Measured and calculated fuse behaviour in a short-circuit test.

Perspex tube 3.00 mm diameter \times 20.00 mm long
100 μ m tinned copper wire, closing angle 29° ,
case (i) calculation using estimated cut-off current,
case (ii) cut-off current taken from the experiment.

current is lower and the fuse wire clears the fault-current. These results confirm our experimental results that while the fuse cleared the fault current at a closing angle of 9.4° , it failed to interrupt the current at a closing angle of 45° . The experiments also showed that at a closing angle of 29° , the fuse interrupted the current only marginally.

Calculated results of current, voltage and pressure for fuses made of 3 mm diameter x 20 mm long perspex tubes with different fuse wire diameters are shown in Figure 9. The values of cut-off current for these calculations have been estimated on the basis of i^2t values. It can be seen that interruption of current gets more critical as the diameter of the fuse wire is increased.

The influence of wall ablation on current interruption is shown in Figure 10. Ablation has small but important influence in reducing the value of the current through the fuse to a small value from a high initial value. Although it appears from Figure 10 that the influence of ablation is small, it is important to note that any arcing at a higher value of current for a prolonged period results in the burning of the end caps leading to an eventual failure of the fuse.

4.4. Discussion.

This study using the arc model highlights several interesting features of arc behaviour in enclosed tubes and fuses. The study reveals that in the presence of ablation from the wall of the confining tube, the arc voltage is higher than when no ablation is present and as a consequence the fault current in the circuit is brought to a small value very rapidly by the fuse. However, prolonged arcing in the presence of ablation results in an increased mass accumulation within the tube. This increased mass has two detrimental effects: (i) the pressure inside the tube increases to very high values and can result in a mechanical failure of the fuse and (ii) the increased mass inside the tube increases the thermal inertia of the arc column and hence the plasma cools much more slowly than when wall-ablation is absent. Prolonged arcing in an ablating environment should therefore be avoided for efficient current interruption.

The study also reveals that the current at which the fuse wire explodes has an important bearing on current interruption. Immediately after the explosion of the fuse wire we may assume the joule heating is balanced

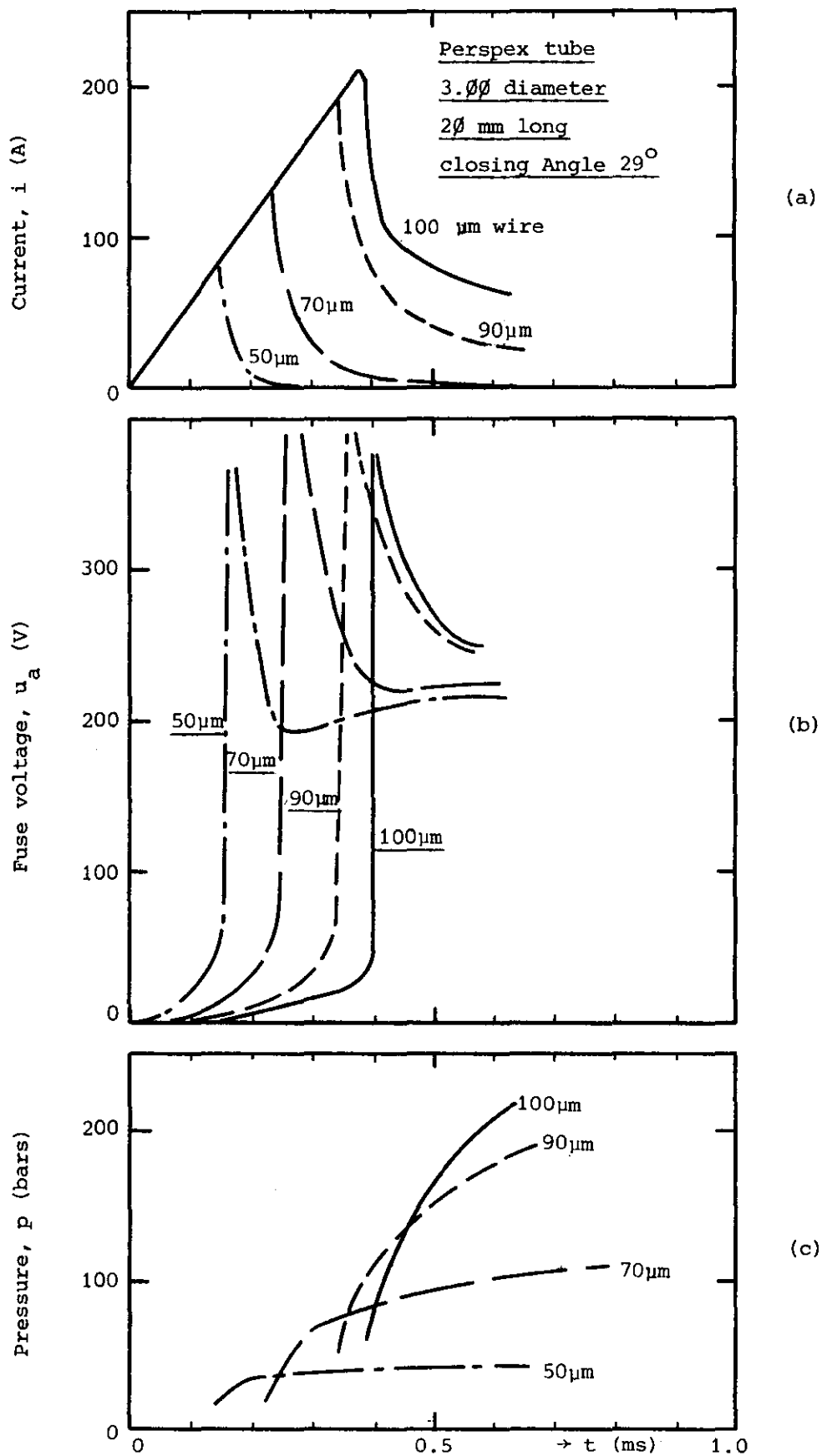


Figure 9 Calculated behaviour of fuse in a short-circuit test.

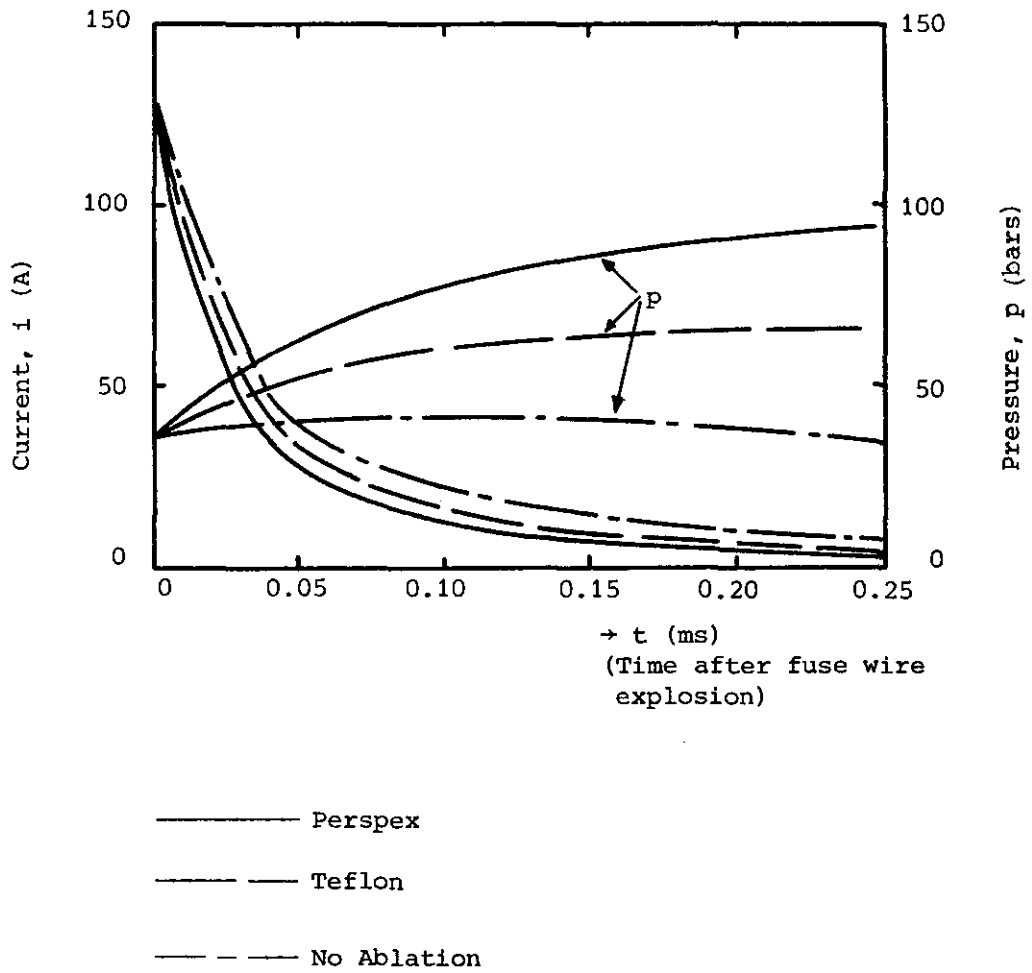


Figure 10 Fuse Behaviour: Influence of Wall material on interruption

3.0 ϕ diameter \times 20.0 mm long tube
70 μ m copper wire
closing angle 29 $^{\circ}$

by wall ablation. For a tube of radius r_w , the joule heating is proportional to $1/r_w^2$ or is a volume effect whereas ablative cooling is proportional to r_w or is a surface effect. Consequently, an increased current at the instant of explosion of the fuse wire increases the plasma temperature considerably. Further, ablative cooling is dominant only near the boundary of the arc column. If considerable heating of the inner region of the arc column occurs due to a high initial current then interruption of the current by the fuse will not result. In a short-circuit test, the rate of increase of current after the circuit current is initiated is the highest when the closing angle is equal to the power factor angle of the circuit. For a closing angle equal to the power factor angle, the cut-off current obtained for a given fuse wire is the highest. The condition agrees with switching on without d.c.-component and presents the most severe duty of short-circuit current interruption.

We have assumed in this study that the temperature profile inside the arc column immediately after the explosion of the fuse wire is one that offers enhanced conductivity near the wall of the tube so that most of the joule heating occurs near the wall initially. Although this choice of temperature profile was made on the basis of a comparison of the voltage across the arc with experimental results for steady arc currents, it is necessary to investigate further the initial period during which the establishment of a well-defined arc column takes place within the tube.

A comparison of the calculated voltage and current for short-circuit interruption with experimental results (Figure 8) reveals that the calculated current falls much more rapidly than what is obtained in the experiment. Further, the calculated voltage is smaller than the experimental value. This discrepancy is mainly due to an inadequate description of the initial state of arc development. It is likely that in a fuse the arc exists initially as a core near the wall of the tube, but expands to fill the tube if arc current persists. The arc model proposed assumes that the arc column initially is more like a ring embracing the wall of the tube. In this case, ablation is present around the whole periphery of the arc column. Thus, the current falls very rapidly. The total $i^2 t$ for arcing of the fuse predicted by the model is smaller than what is obtained in practice. On the basis of this comparison, the authors of

this report are tempted to conclude that if a fuse is manufactured with a metal layer deposition on an ablating wall instead of a fuse wire in the middle of the tube, the interruption characteristic of such a fuse in terms of the total i^2t value would be very much improved.

It is also important to note that failure of fuses of this type is due to mechanical forces resulting from pressure rise within the fuse and also arcing at the end caps. While it is important to reduce the level of current as rapidly as possible to reduce severity of arcing, it is also essential that the pressure inside the tube is not very large. In order to reduce the pressure rise, a wall material whose vapour has a large mass density can be chosen. In order to provide adequate ablative cooling, the wall gas should also have a large value of heat capacity. The wall material should also have adequate mechanical strength to withstand the mechanical stresses generated during current interruption.

5. Summary and Conclusion

A numerical model has been developed to study the behaviour of arcs in enclosed tubes and the process of current interruption in small fuses whose walls ablate as a consequence of arcing within the fuse. The model enables the determination of the temperature profile in the arc column as a function of time by solving the energy balance equation describing the arc behaviour. The model considers the phenomena of ablative cooling and estimates also the pressure within the tube of the fuse as a function of time.

One of the main difficulties of the model stems from a lack of knowledge of the temperature profile within the plasma immediately after the explosion of the fuse wire in the fuse. It is found from a comparison of the calculated results with experiments using steady arc currents that most of the joule heating in the plasma should occur in the outer region of the plasma near the wall of the confining tube. Initial experiments using framing photography tend to suggest that the joule heating appears to occur near the wall, but in a much more localised form than what has been assumed in the model. Further investigation is essential to study this initial duration of arcing in enclosed tubes.

Calculated results of voltage as a function of time for steady arc currents in tubes made of perspex and teflon agree fairly well with measured values.

Results are also obtained to estimate fuse behaviour under short-circuit test conditions. It is found that the current at which the fuse wire explodes has a significant influence upon the behaviour of the fuse. A high initial current results in a rapid heating of the plasma initially with a rapid increase in also the pressure inside the tube; the fuse under those conditions may fail to interrupt the current owing to a mechanical failure.

It is found that ablative cooling is dominant immediately after the explosion of the fuse wire and the current in a short-circuit test is brought to a small value very rapidly. However, prolonged arcing even at low currents in the presence of ablation may have a detrimental effect on the fuse behaviour because continued ablation results not only in an increase of pressure within the tube but also increases the thermal inertia of the arc column thus slowing down the process of arc cooling. The study shows that ablative cooling is dominant mainly in the outer regions of the arc column near the wall of the confining tube. If inner regions of the arc column get heated due to a large value of initial current, it is very unlikely a successful interruption will result in the presence of wall ablation.

The calculated results for short-circuit behaviour of fuses are only in approximate agreement with experimental results. It is found that the predicted current in a test circuit falls initially much more rapidly than what is obtained in practice. This discrepancy is due likely to the choice of the initial temperature profile after the explosion of the fuse wire. As the temperature profile assumed for calculations produces ablation all around the periphery of the arc column, an over-estimation of the ablative cooling during the initial stage of current interruption is very likely. In practice, both joule heating and ablative cooling near the wall of the tube might be more localised than what has been assumed in the model.

In order to produce strong ablative cooling initially during an interruption process, it is essential that the surface area of the arc

column is large and that the arc column lies close to the wall. It is therefore postulated that a fuse, which uses a metal layer deposition on an ablating wall instead of a fuse wire inside a tube, would exhibit a better short-circuit interruption characteristic in terms of reduced total i^2t -value.

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