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TRANSIENT TEMPERATURE RISE IN FILM RESISTORS

Henry Domingos

Clarkson College of Technology

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Transient temperature distributions in film resistors are calculated for time intervals ranging from 10 nsec to 100 μsec. A one dimensional model consisting of substrate, resistive film, and jacket is assumed. Peak temperatures are plotted for various film thicknesses, using thermal properties appropriate for resistors from four manufacturers.

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ABSTRACT

Transient temperature distributions in film resistors are calculated for time intervals ranging from 10 nsec to 100 μ sec. A one-dimensional model consisting of substrate, resistive film, and jacket is assumed. Peak temperatures are plotted for various film thicknesses, using thermal properties appropriate for resistors from four manufacturers.

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INTRODUCTION

During an Electro-Magnetic Pulse, electronic equipment is subjected to high power pulses of relatively short duration. This report is a study of EMP on discrete film resistors.

The EMP pulse is considered nominally as a constant current pulse 10 nsec to 100 μ sec in duration. Apart from dielectric breakdown, which should not be entirely ignored, the primary effect in a resistor is to produce a sharp rise in temperature of the resistive film. Any permanent changes in resistance value are the result of physical changes in or close to the film caused by the high temperature excursion. The task at hand then is to determine the temperature distribution in the resistor as a function of power level and pulse duration.

A total of 18 resistors ranging in value from 200 ohms to 30,100 ohms and power ratings from 1/10 watt to 1 watt were investigated. Most were of the metal film variety, but some were carbon film. 4 different manufacturers fabricated the original resistors.

In Section II, a general study of heat flow in layered media is undertaken. The objective is to develop general guidelines and criteria for assessing the applicability and validity of models used in later calculations. Classical solutions to heat conduction problems are given.

In Section III, the results of calculations on models which simulate the various resistors are presented. The diagrams allow one to calculate the peak temperature rise once the power level, pulse width, and resistor construction are known.

SECTION II

HEAT CONDUCTION IN MULTI-LAYERED MEDIA

In the study of temperature rise in film resistors, the problem can be accurately described for cases of interest in this investigation by the geometry shown in Figure 1. This is a one-dimensional model with Region I representing the heat-producing resistive film. Region II is the substrate, typically of ceramic or glass, and Region III is the outer jacket, usually of a thermosetting resin such as phenolic or silicone.

The basic assumption in adopting this model is that the diffusion length for heat flow during times of interest is small enough so that the cylindrical geometry of an ordinary resistor can be replaced by a one-dimensional Cartesion coordinate system. In addition, the outer boundaries of Regions II and III can be ignored. Criteria for gauging the validity of these assumptions will be developed shortly.

The partial differential equation which describes the conduction of heat in solids is

$$\frac{\partial T}{\partial t} = D \frac{\partial^2 T}{\partial x^2} + \frac{D}{k} P_o \qquad (1)$$

where T is the temperature in ^oC, t is time in seconds, x is distance in centimeters, P_o is power density in watts/cm^3 and the constants D and k are the diffusivity in cm^2/sec and the thermal conductivity of the material in watts/cm-^oC, respectively. This equation must be solved in each of the three regions separately, subject to the boundary conditions that both T and the flow of heat are continuous throughout. In addition, the temperature rise at $x = \pm \infty$ is zero. The initial condition is that the temperature throughout all three regions is equal to the ambient temperature T_o

$$T_{III}(0,t) = T_I(0,t)$$

$$T_{II}(L,t) = T_I(L,t)$$

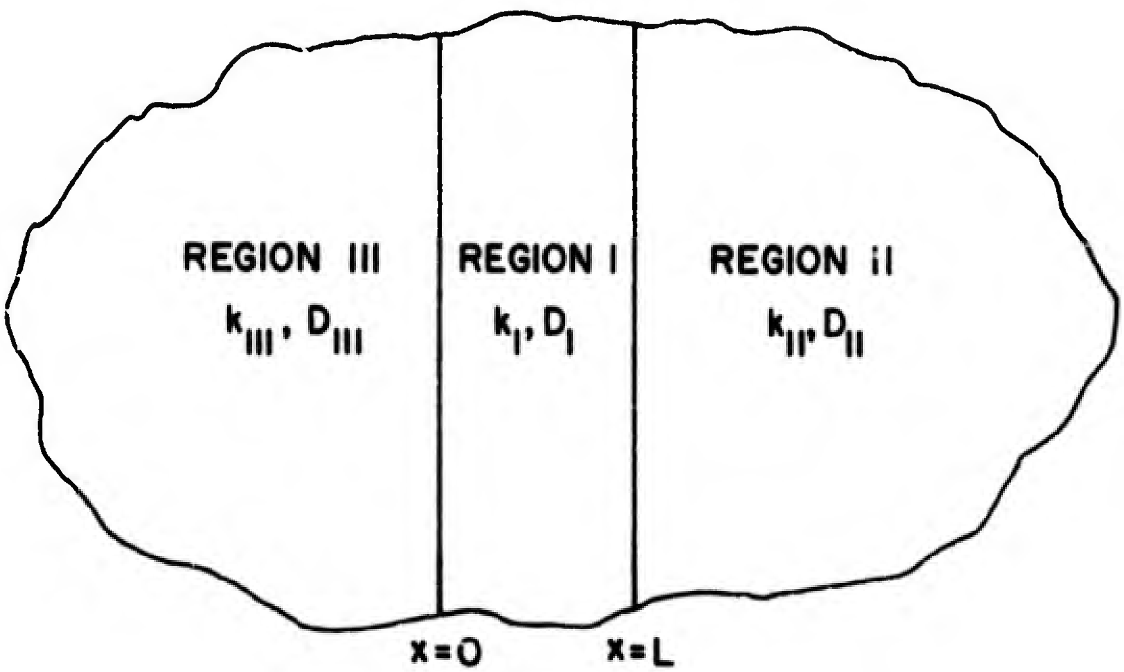

Figure 1. One-dimensional model of a film resistor. Region 1 is the resistive film, Region II is the substrate, and Region III is the insulating jacket.

$$K_{III} \frac{\partial T_{III}(0,t)}{\partial x} = K_I \frac{\partial T_I(0,t)}{\partial x}$$

$$K_{II} \frac{\partial T_{II}(L,t)}{\partial x} = K_I \frac{\partial T_I(L,t)}{\partial x}$$

$$T_{III}(-\infty,t) = T_{II}(\infty,t) = T_o$$

$$T_{III}(x,0) = T_{II}(x,0) = T_I(x,0) = T_o \qquad (2)$$

The general solution to the problem described above is quite difficult to obtain, and before describing results of numerical methods it is instructive to discuss several simplified problems for which solutions are readily obtainable.[1]

The simplest case occurs when the heat flow into Regions II and III is small enough to be neglected. This results in an adiabatic heat rise in Region I. The solution is

$$T - T_o = \frac{D}{k} P_o t \qquad (3)$$

where D and k are the thermal constants of the material comprising Region I. This answer gives an upper limit to the temperature rise in any problem, and is a good estimate of the peak temperature rise in any case where the energy transfer out of Region I is small compared with the total energy supplied. In Section III this solution will be shown to be an important limiting case.

Other solutions can be obtained whenever significant heat transfer takes place only into Region II. A special example of this type of problem occurs when the thermal conductivity and diffusivity of Region II are much greater than those of Region I; in other words the substrate acts as a very good heat sink. In the limiting case of perfect heat sinking the solution is

$$T - T_o = \frac{P_o L^2}{2k} \left[1 - \left(\frac{x}{L}\right)^2 - 4 \sum_{n=0}^{\infty} \frac{(-1)^n}{\left(\frac{(2n+1)\pi}{2}\right)^3} e^{-\left(\frac{(2n+1)\pi}{2L}\right)^2 Dt} \cos \frac{(2n+1)\pi x}{2L} \right] \quad (4)$$

For small values of time, this solution converges slowly and a more useful solution is

$$T - T_o = \frac{D P_o t}{k} \left[1 - 4 \sum_{n=0}^{\infty} (-1)^n \left\{ i^2 \operatorname{erfc} \left[\frac{(2n+1)L - x}{2\sqrt{Dt}} \right] + i^2 \operatorname{erfc} \left[\frac{(2n+1)L + x}{2\sqrt{Dt}} \right] \right\} \right] \quad (5)$$

$$\text{where } i^2 \operatorname{erfc}[\mu] = \frac{1}{4} \left\{ (1 + 2\mu^2) \operatorname{erfc}[\mu] - \frac{2}{\sqrt{\pi}} \mu e^{-\mu^2} \right\} \quad (6)$$

For very small t, the terms in the summation are small and Eq. (5) approaches Eq. (3). As t becomes very large a steady-state condition is reached where

$$T - T_o = \frac{P_o L^2}{2k} \left(1 - \frac{x^2}{L^2} \right) \quad (7)$$

Peak temperature rise occurs at $x = 0$. This can be found directly from Eq. (4) and is plotted in Figure 2.

If the thermal properties of the film and substrate are sufficiently alike so that we can take $k_I = k_{II} = k$ and $D_I = D_{II} = D$, the temperature distribution is

$$T - T_o = \frac{D}{k} P_o t \left[1 - 2 i^2 \operatorname{erfc} \left(\frac{L - x}{2\sqrt{Dt}} \right) - 2 i^2 \operatorname{erfc} \left(\frac{L + x}{2\sqrt{Dt}} \right) \right]$$

$$\text{for } 0 < x < L \quad (8)$$

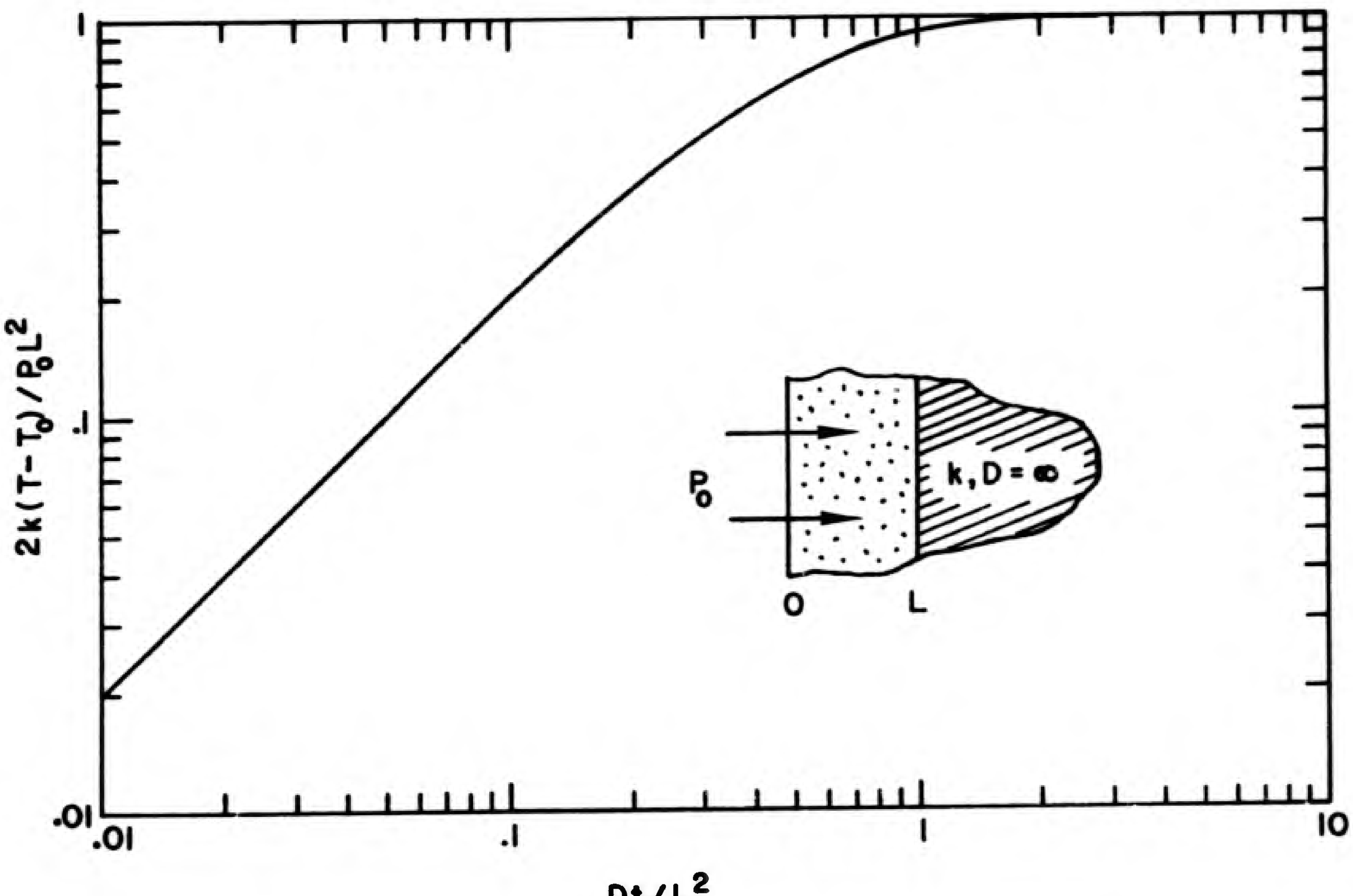

Figure 2. Peak temperature rise in a heat producing layer bounded on one face by a perfect heat sink.

and

$$T - T_o = \frac{2D}{k} P_o t \left[i^2 \operatorname{erfc}\left(\frac{x-L}{2\sqrt{Dt}}\right) - i^2 \operatorname{erfc}\left(\frac{x+L}{2\sqrt{Dt}}\right)\right] \quad \text{for } x > L \qquad (9)$$

The question sometimes arises, under what conditions can the heat producing film be regarded as infinitesimally thin? If it can be so regarded, the thermal properties of the film can be ignored. The temperature distribution which then results is due to a heat flux at $x = 0$ of F_o watts/cm^2. The solution is

$$T - T_o = \frac{2F_o}{k}\left[\left(\frac{Dt}{\pi}\right)^{1/2} e^{-\frac{x^2}{4Dt}} - \frac{x}{2} \operatorname{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)\right] \qquad (10)$$

The temperature rise at $x = 0$ from both Eq. (10) and Eq. (8) is plotted for comparision in Figure 3. The figure shows that when $\sqrt{Dt}$ is greater than about 5 L the difference in the two solutions is less than 10%. This can be used as a criterion for determining when the film can be replaced by an infinitesimally thin layer.

For long time intervals, the validity of a one dimensional approximation which ignores the finite thickness of the outer jacket can be questioned. To investigate finite distance effects, consider a surface flux of heat F_o at $x = 0$ and a boundary at $x = L$. This boundary could represent the interface between the outer jacket, say, and some other material - air or a potting compound. If the two materials are alike, so that the boundary is not a discontinuity, Eqs. (8) and (9) give the temperature distribution. If the outermost region is a perfect insulator the temperature distribution is given by

$$T - T_o = \frac{2F_o\sqrt{Dt}}{k} \sum_{n=0}^{\infty} \left\{ \operatorname{ierfc}\left[\frac{(2n+1)L - x}{2\sqrt{Dt}}\right] + \operatorname{ierfc}\left[\frac{(2n+1)L + x}{2\sqrt{Dt}}\right]\right\} \qquad (11)$$

where $\operatorname{ierfc}[\mu] = \frac{1}{\sqrt{\pi}} e^{-\mu^2} - \mu \operatorname{erfc}[\mu]$ (12)

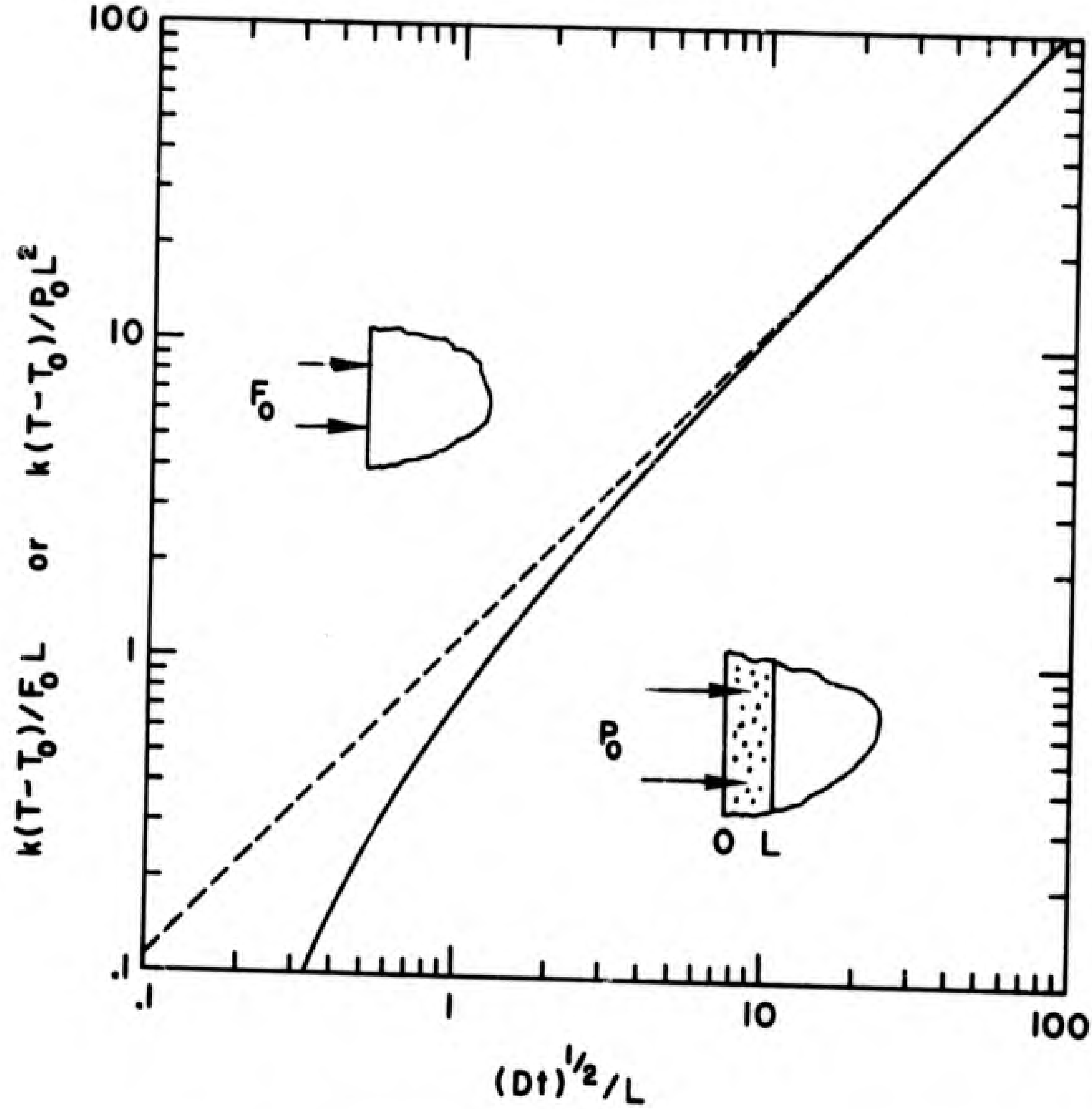

Figure 3. Peak temperature rise in a semi-infinite body. The dotted curve is for heat produced in an infinitesimally thin layer. The solid curve is for a heat-producing layer of finite thickness L.

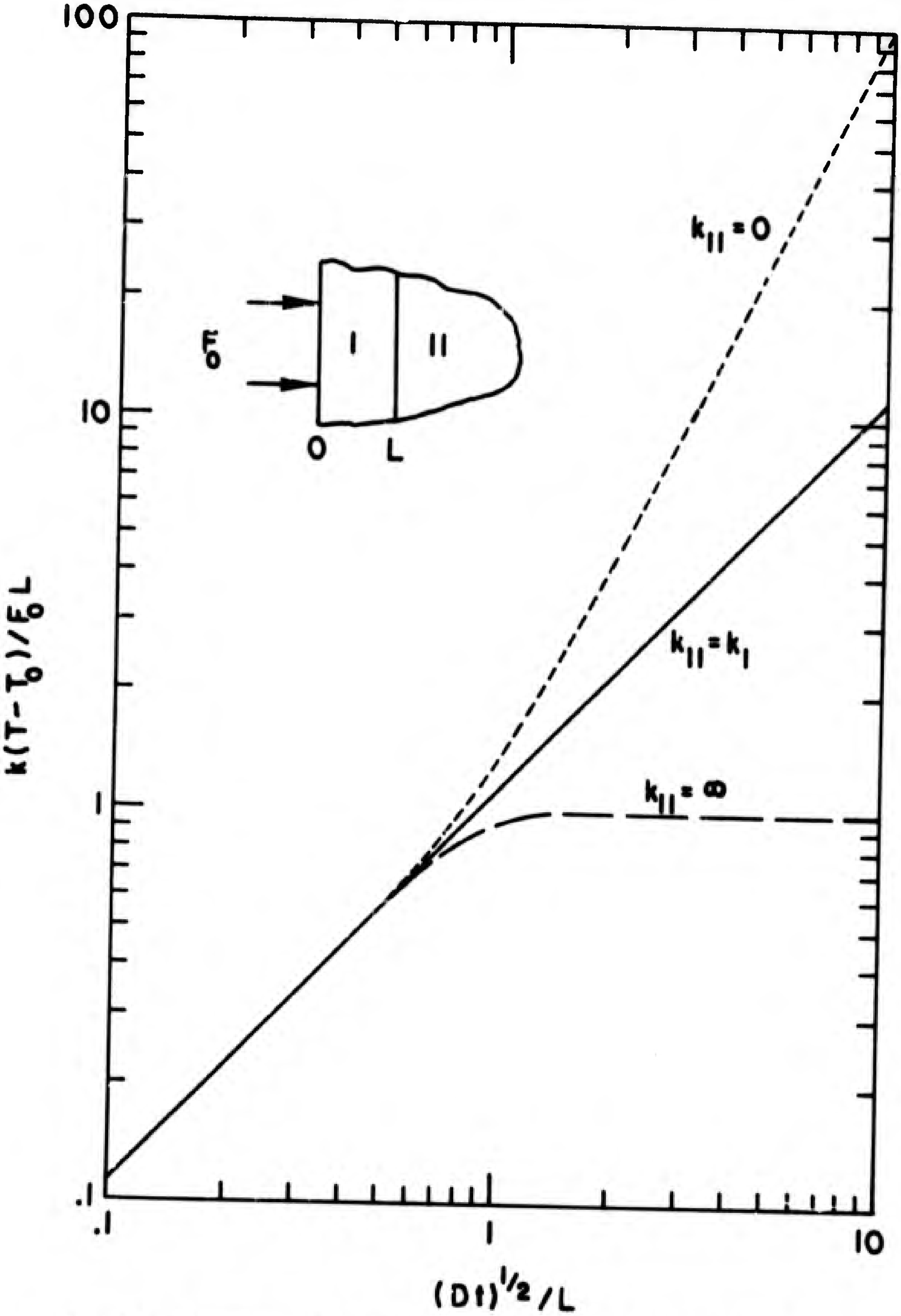

Figure 4. Peak temperature rise in a finite layer with different boundary conditions. Region II is a perfect insulator in the top curve, a perfect heat sink in the bottom curve, and has the same thermal properties as Region I in the center curve.

If, on the other hand, the outermost region is a perfect heat sink the temperature rise is given by

$$T - T_o = \frac{2 F_o \sqrt{Dt}}{k} \sum_{n=0}^{\infty} (-1)^n \left\{ \text{ierfc} \left[\frac{(2n+1) L - x}{2\sqrt{Dt}} \right] - \text{ierfc} \left[\frac{(2n+1) L + x}{2\sqrt{Dt}} \right] \right\} \quad (13)$$

Equations (8), (11), and (13) are plotted in Fig. 4 for $x = 0$. The diagram in the figure illustrates the special geometry for this particular case, and the three curves are labelled $k_{II} = 0$, $k_{II} = k_I$, and $k_{II} = \infty$ for the solutions of Eqs. (11), (8), and (13), respectively. The graph shows that a boundary has little effect on the peak temperature until $\sqrt{Dt}$ is approximately equal to L. (Of course, the temperature at points other than $x = 0$ is affected somewhat earlier.) This provides one criterion for determining the suitability of the model in Figure 1.

A solution to the case where the heat-producing film is very thin, but heat transfer into both Regions II and III takes place can also be readily obtained. The temperature distribution is

$$T_{II} - T_o = A\sqrt{t}\ \text{ierfc} \frac{x}{2\sqrt{D_{II} t}} \quad (14)$$

$$T_{III} - T_o = A\sqrt{t}\ \text{ierfc} \frac{x}{2\sqrt{D_{III} t}} \quad (15)$$

where

$$A = \frac{2 F_o \sqrt{D_{II} D_{III}}}{k_{II}\sqrt{D_{III}} + k_{III}\sqrt{D_{II}}} \quad (16)$$

At $x = 0$, $T_{III} = T_{II} = T$ and

$$T - T_o = 0.564\ A\sqrt{t} \quad (17)$$

In Section III, this will be shown to be another limiting case for the resistors investigated in this program.

Solutions for the general case in two and three layered media are difficult to obtain in closed form and numerical techniques are usually resorted to. Rather than presenting solutions to specific problems at this point, suffice it to say that finite difference techniques of great usefulness in solving heat conduction problems are described in references 2 and 3. In Section III the results of an analysis by this technique of heat flow in resistors will be given.

SECTION III

RESULTS AND DISCUSSION

Discrete resistors can be conveniently divided into three categories: carbon composition, metal film, and wirewound. Carbon composition resistors are inexpensive and inherently reliable, but are also the least precise and the least stable with respect to temperature changes and aging. Metal film resistors are more precise and more stable, but more costly. Where the utmost in precision and stability are required and the high cost can be justified, wirewound resistors are called for.

The resistors studied in this program are either carbon composition or metal film. The carbon types are of the film or filament variety rather than the slug or pellet construction. Thus both the carbon composition and metal film resistors, hereafter collectively referred to as film resistors, are similar in construction and can be analyzed in the same manner.

The resistors consist of a layer of carbon or a metallic compound deposited on a glass or ceramic substrate. The film is spiralled (typically several turns) to the desired resistance value. End cap and lead assemblies make contact to the film, and an outer jacket of thermosetting plastic such as a phenolic, silicone, polyester, epoxy, etc., provides electrical insulation, mechanical strength, and a barrier to contamination and moisture penetration.

For a given line of resistors, the film composition and thickness are adjusted to provide the sheet resistivity commensurate with the physical size (i.e., power rating) and resistance value. Under normal operating conditions, film thickness is of secondary importance because most of the heat is conducted through the substrate and out through the leads. The thermal conductivity of the substrate and the geometry of the end caps and leads are important under these circumstances. Under short duration, high power pulse operation the characteristics of the resistive layer become all-important; the thermal properties of the substrate and jacket are important only under certain conditions, and the caps and leads, not at all.

A total of eighteen resistors from four manufacturers were investigated. These are listed in Table I.

Table I. Resistor Values

Manufacturer	Value (ohms)	Power Rating (watts)
A	825	1/10
A	825	1/8
A	825	1/4
A	200	1/4
A	3090	1/4
B	200	1/10
B	200	1/8
B	200	1/4
C	30000	1/4
C	200	1/4
C	30000	1/2
C	200	1/2
C	820	1
C	200	1
D	30100	1/8
D	30100	1/4
D	30100	1/2
D	806	1/2

Note: Rating of resistors from Manufacturers A and B are based on 125°C ambient, while those from C and D are referred to 70°C ambient.

The manufacturers were very cooperative in providing samples as well as information not generally available on fabrication methods, materials used, material properties, dimensions, frequency response, hot spot temperatures, and pulsed power operation. Some of the samples were finished resistors whereas others were provided without the outer jacket. This allows one to determine the heat-sinking effect of the outer jacket, and allows a microscopic examination of the resistive film before and after pulsing. All companies still producing these particular resistors extended invitations to visit their facilities and one such visit was made.

Several resistors were cross-sectioned and photographed to determine substrate dimensions, jacket thickness, etc. There was good agreement with the information supplied by the manufacturers.

Thermal properties of the materials were difficult to obtain in some cases. Even when suppliers were able to give values of thermal conductivity, density, specific heat, and diffusivity, or where these could be gleaned from handbooks and technical literature, they often did not apply to the specific conditions or compositions used in resistor manufacture. Nevertheless, the values listed in Table II are considered to be good estimates. The effect of deviations from the values in the table will be discussed later in the description of results.

Table II. Thermal Characteristics of Resistor Materials

	k, thermal conductivity watts/cm-^{o}C	D, diffusivity cm^2/sec
Manufacturer A		
Substrate	0.03	0.01
Film	0.15	0.04
Jacket	0.0025	0.001
Manufacturer B		
Substrate	0.25	0.08
Film	0.25	0.1
Jacket	0.0025	0.001
Manufacturer C		
Substrate	0.013	0.006
Film	0.2	0.114
Jacket	0.0025	0.001
Manufacturer D		
Substrate	0.013	0.006
Film	0.25	0.1
Jacket	0.005	0.002

Power dissipation is of little importance in itself. The temperature rise which it induces with the attendant physical and or chemical changes is what causes permanent changes in resistance value or even catastrophic failure. Temperature distributions, calculated by the methods discussed in Section II, are thus of primary importance in investigating resistor failure.

Temperature distributions in a one-dimensional model of film resistors comprised of a thick substrate, a thin resistive film, and a thick outer jacket have been calculated by the finite difference technique referred to at the end of Section II. The initial temperature was assumed to be constant throughout the resistor at the ambient temperature. A constant power pulse was applied uniformly throughout the resistive film. Temperature as a function of time in all regions of the resistor was calculated. A typical result is shown in Figure 5.

The figure shows the temperature distribution at several instants in time in a resistor with a 10μm film thickness. At the shortest time interval shown, the temperature rise is appreciable only in the film itself. Under these conditions, the peak temperature is almost exactly given by Eq. (3). Heat gradually diffuses into the substrate and jacket and by the longest time shown in the figure, the peak temperature differs appreciably from that predicted by Eq. (3). The temperature distribution becomes noticeably skewed, due to the difference in thermal properties of the substrate and jacket. At much longer time intervals, the temperature distribution depends only on the properties of the substrate and jacket and is independent of film thickness and thermal properties. In this case the peak temperature is described accurately by Eq. (17).

The results of the calculations are summarized in Figures 6, 7, and 8. The abscissa is time (or pulse duration). The ordinate is normalized peak temperature rise. Each curve represents peak temperature rise for a particular film thickness. There are three pertinent asymptotes: Eq. (3), the adiabatic case where heat diffusing out of the film is a small fraction of total heat input; Eq. (17) which corresponds to an infintesimally thin film; and Eq. (10) which is the solution for an infinitesimally thin film when there is no outer jacket. The latter asymptote

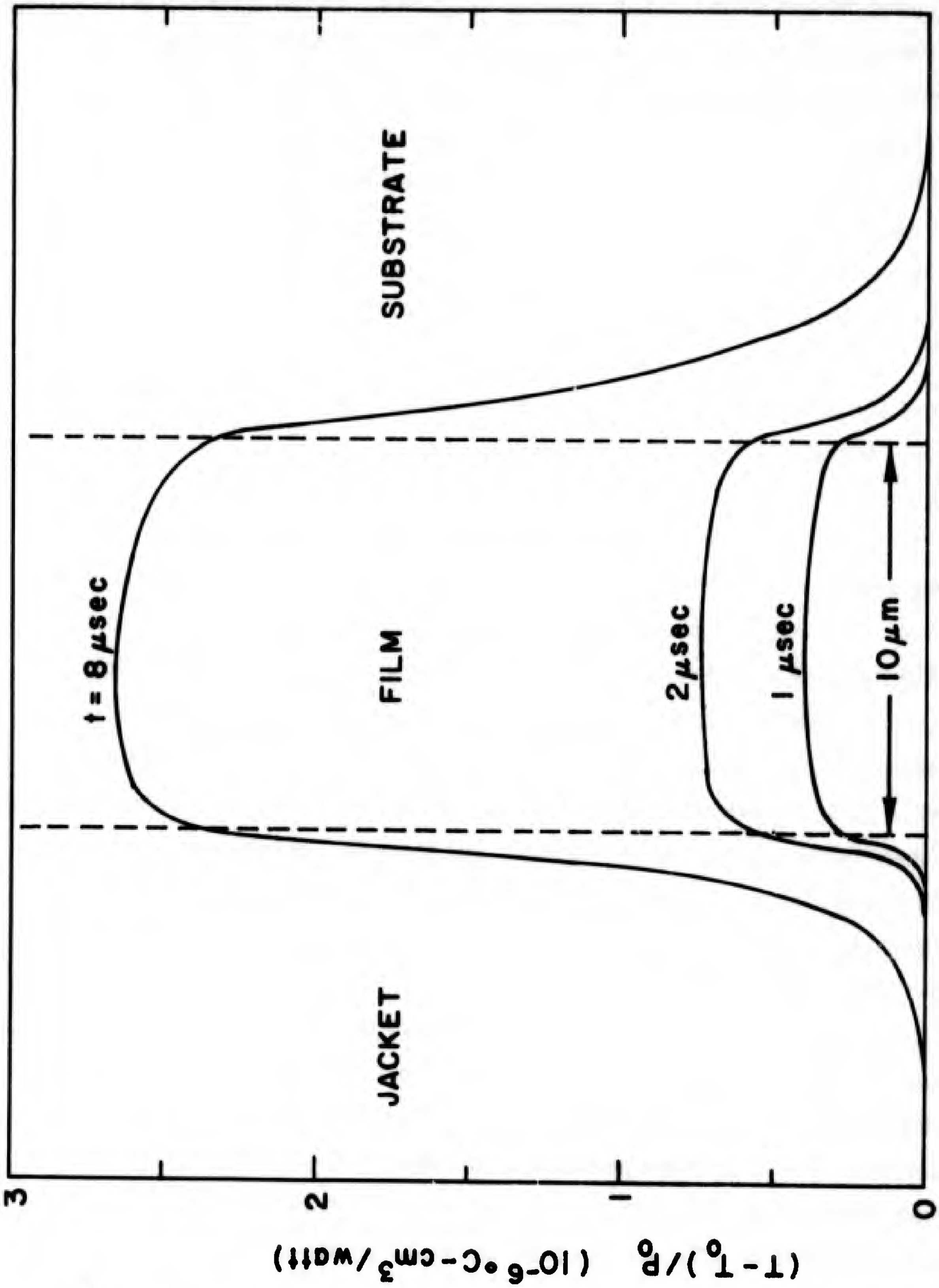

Figure 5. A typical solution for the temperature distribution in a film resistor.

is plotted in the figures to show the relative heat sinking effect of the outer jacket and to correlate experimental findings on resistor samples without jackets.

For relatively thick films, or at short time intervals, each curve coincides with the asymptote given by Eq. (3). Temperature rise then depends only on the heat capacity, ρc, of the film. In Figure 6, the adiabatic asymptote coincides with the curve for the 50 μm film for nearly 100 μsec. For thin films or for long pulse intervals, on the other hand, all curves approach Eq. (17). In Figure 7, for example, the 0.1 μm curve is the same as Eq. (17) for t greater than 0.1 μsec.

A comparison of the three figures shows that Figure 7 has the lowest temperature rise for very thin films. Furthermore, the effect of the jacket is also smallest. This can be attributed to the superior heat conduction properties of the substrate material used in these resistors. On the other hand, for a relatively thick film, where the thermal properties of the film itself dominate, Figure 6 shows the lowest temperature rise.

As an example of the use of the curves in calculating peak temperatures, consider a 50 kW, 10 μsec pulse applied to a resistor which has a film 10 μm thick, a substrate 50 mils in diameter, and a 200 mil length of film between end caps. The surface area of the cylindrical substrate is 0.20 cm^2. Assuming uniform power distribution over the surface area, the power density is 2.5×10^5 watts/cm^2. Referring to Figure 6, when t = 10 μsec and film thickness = 10 μm, the ordinate is 2.3×10^{-3} ^oC - cm^2/watt. Hence the temperature rise is 575^oC above ambient.

Caution is necessary in using the calculated results to avoid unwarranted conclusions. It is not valid to compare, say, the 50 μm curve of Figure 6 with the 50 μm curve of Figure 7 if manufacturer A's resistors are all thin film, less than 2 μm, while manufacturer B's resistors all have films 25 μm or thicker. The only fair comparison is between two products with the same resistance value and the same power rating intended for the same application.

Furthermore, temperature is not necessarily an absolute measure of hardness to high power pulses. One resistor may reach a higher temperature, but may also be capable of withstanding higher temperatures without degradation.

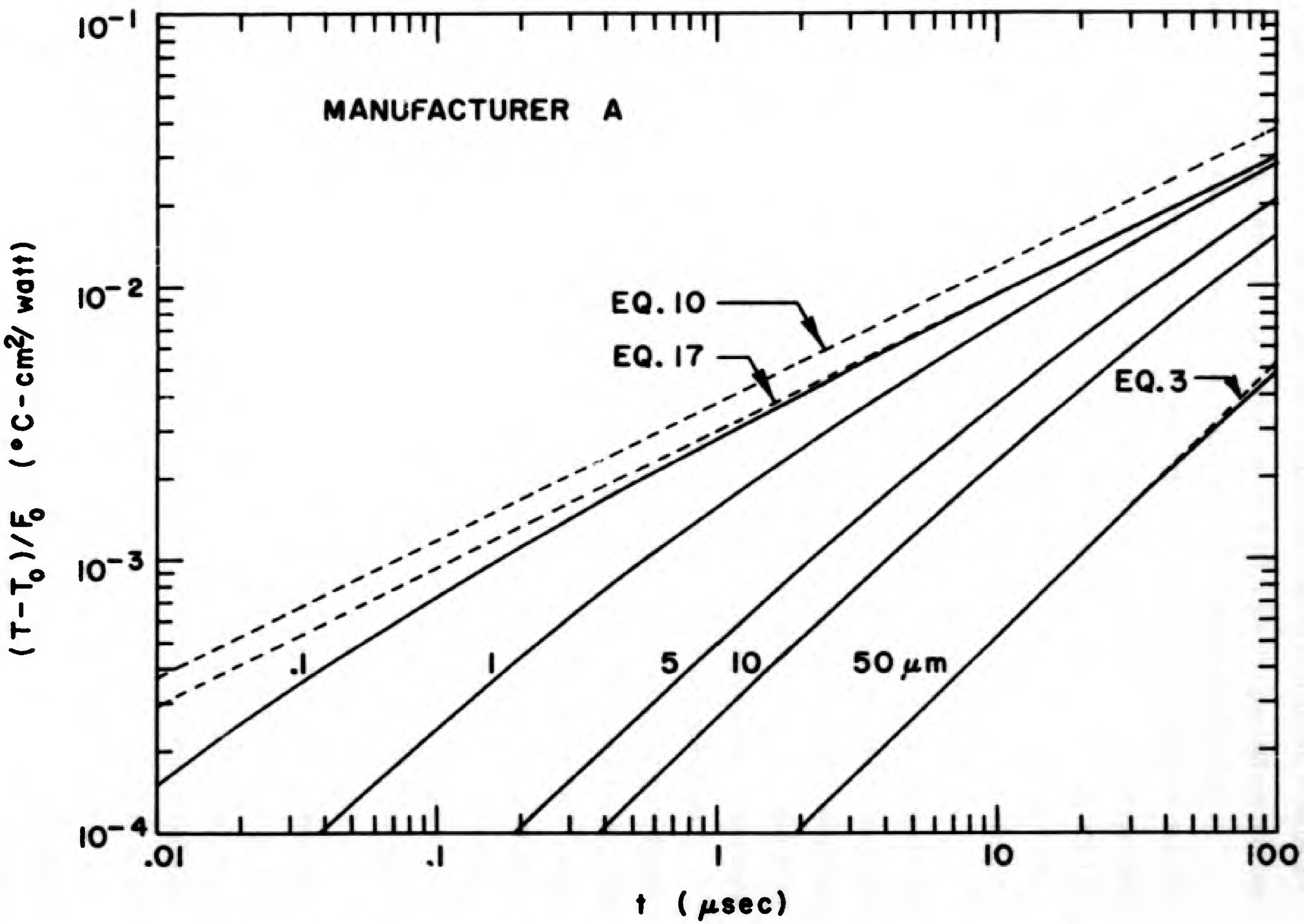

Figure 6. Peak temperature rise as a function of time in resistors produced by Manufacturer A. The parameter is film thickness. The dashed curves are asymptotic limits given by equations in Section II.

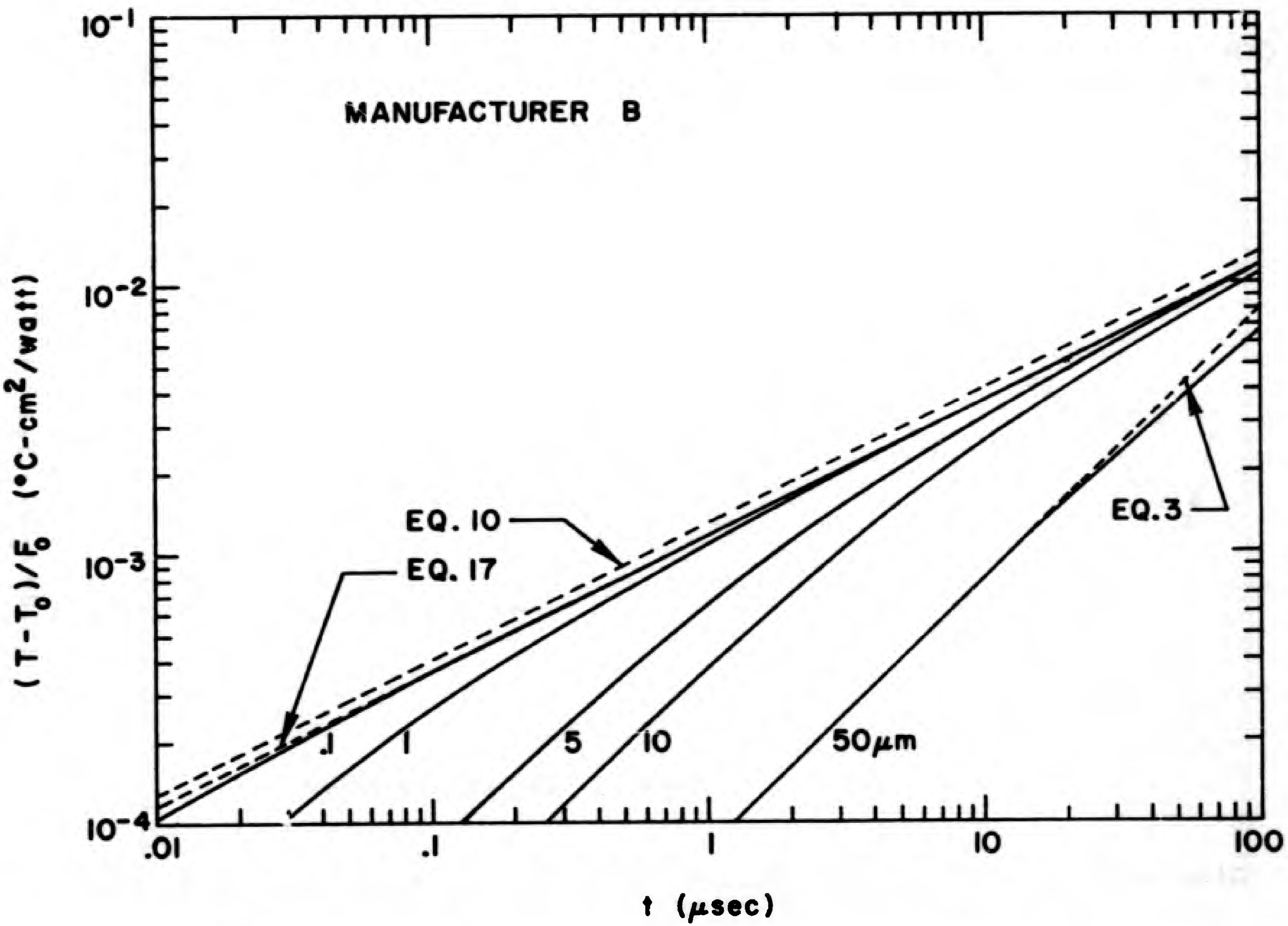

Figure 7. Peak temperature rise in resistors produced by Manufacturer B.

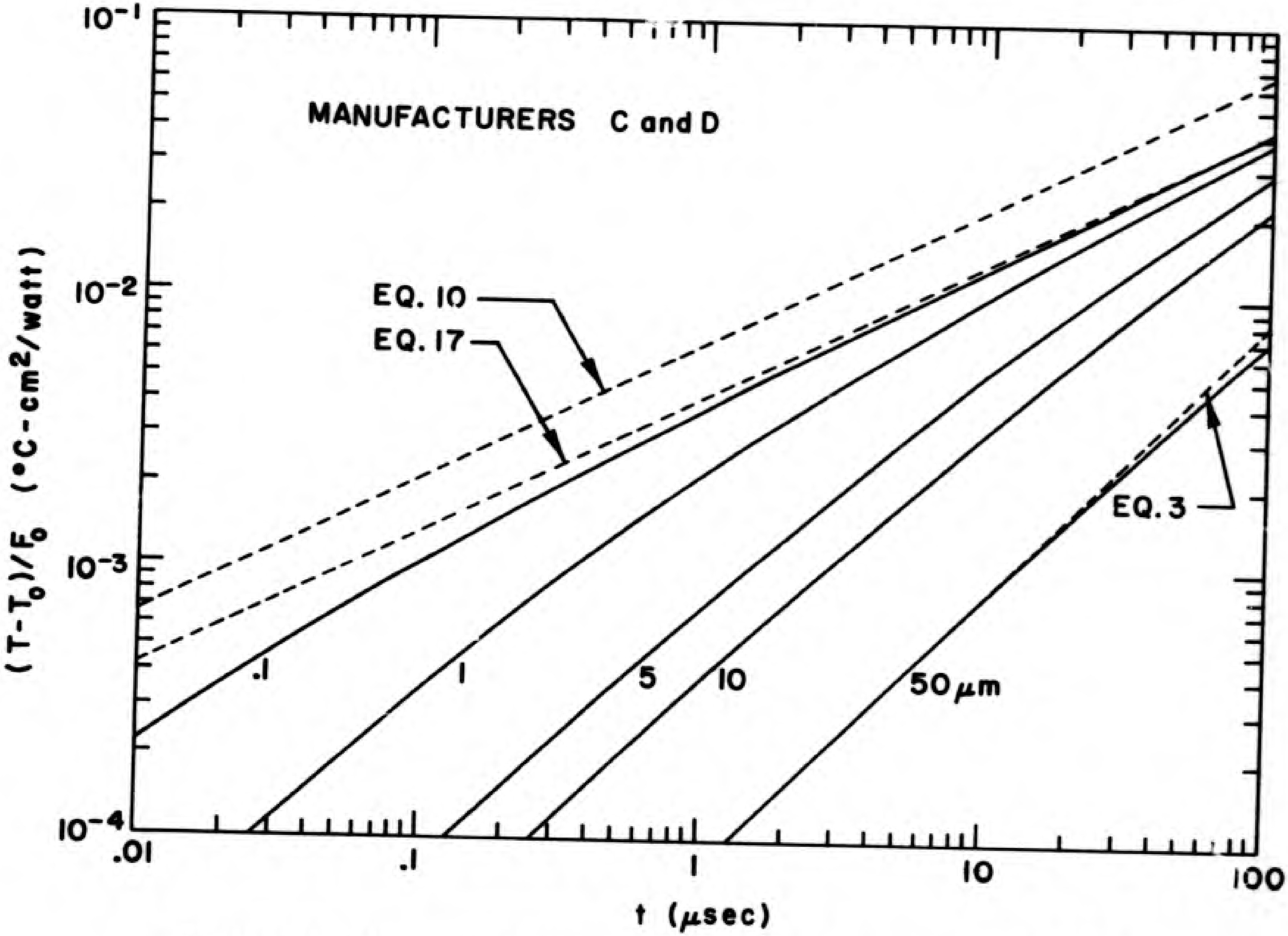

Figure 8. Peak temperature rise in resistors produced by Manufacturers C and D.

Another factor, more difficult to assess, is related to the presence of defects in the resistor. Clearly non-uniformities in the film can lead to the formation of hot spots and premature burnout. Indeed, any variation in geometry, composition, spiralling, etc., will produce an uneven power distribution and an uneven temperature distribution.

The sensitivity of the computer solutions to variations in the thermal properties listed in Table II is a legitimate concern. Fortunately, direct substitution of new values into Eqs. (3) and (17) allow one to draw new asymptotes on the figures and estimate quite accurately the corrected temperatures.

In spite of these drawbacks, the curves are accurate solutions to the heat flow problem and are able to predict peak temperature rises for the resistors studied here.

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