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Current-Carrying Capacity of Fine-Line Printed Conductors

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This paper presents simple equations, along with experimentally determined parameters, to calculate the transient temperature rise of current-carrying, fine-line (~7 mils) conductors on various styles of circuit packs. The styles of circuit packs include wire wrap, double-sided, metal, bonded, and various multilayer boards. All styles of circuit packs in the BELLPAC™ system family are included. The maximum steady-state temperature rise of a nicked or constricted current-carrying conductor is also treated. The calculated transient and steady-state temperature rises agree with experimental results.

I. INTRODUCTION

Printed wiring technology presently provides the physical designer with fine-line copper conductors to interconnect integrated circuits and other components at the circuit-pack (CP) level. These fine-line conductors now have a nominal width of 7 mil, and a nominal thickness of 1.4 mil. For such relatively small conductor sizes, (~AWG39), the current-carrying capacity of the conductors becomes an important matter of concern. Can such fine-line conductors carry the required current to operate the various components on a CP without causing an excessive temperature rise? What is the temperature rise during normal current flow? If a fault occurs and a current of 10 A flows for 100 ms, will the CP be damaged? Questions of this nature are becoming very important as printed wiring technology provides finer conductors for the electrical interconnections.

Also, as large-scale integrated (LSI) circuits are introduced, the assembled CPs are becoming more expensive. Therefore, there is more incentive to protect the CP from possible damage as a result of an over current.

Some early work by W. Aung and A. J. Colucci[1] has shown that a 7.5-A current flowing through a fine-line printed conductor inside a multilayer board (MLB) can cause the MLB to break into flames in about 5 s. Also, W. T. Smith[2] reported that a current flow through a fine-line printed conductor (2.8-mils thick) should be limited to about 5 A if temperature rises are to be limited to 120°C.

Clearly, to avoid possible disaster or damage, the physical designer of electronic equipment must be able to estimate the transient temperature rise of fine-line, current-carrying conductors on all styles of circuit packs and backplanes.

During the past few years, the Bell System has introduced a modular packaging system (*BELLPAC** system[3]) for packaging electronic equipment. This system makes use of a number of CP styles that have common features suitable for computer-aided design. Fine-line printed conductors are available for use on any of the CP styles. The *BELLPAC* system project has provided us with the opportunity to study the current-carrying capacity of fine-line conductors on a variety of CP styles.

The purpose of this paper is to present some useful results concerning the current carrying capacity of fine-line conductors on various styles of CPs. The results include the transient temperature rise of a current-carrying printed conductor, and the maximum steady-state temperature rise of a conductor which may be nicked or constricted.

For the special case of a double-sided epoxy printed wiring board (flex or rigid), some results concerning the steady-state temperature rise of fine-line printed conductors have been reported in Refs. 4 and 5. Although the methods reported in these two references differ, the results agree well with one another.

A listing of the CP styles of interest in this paper, along with a short description of each is presented in Table I. Figure 1 shows the corresponding physical layups of the CP styles. These physical layups include all of the CP styles presently in the *BELLPAC* system. We shall see that the results in this paper can be applied to estimate the current-carrying capacity of fine-line conductors on any layer of any of the CP styles shown in Fig. 1.

II. BASIC EQUATIONS

2.1 General results

For a general current-carrying conductor, the conservation of heat energy requires that the average temperature rise satisfy the following differential equation:

$$I^2R_1[1 + \alpha_1\overline{\Delta T}]dt = Cd\overline{\Delta T} + \frac{\overline{\Delta T}}{R_T}dt, \qquad (1)$$

* Trademark of Western Electric.

Table I—Description of the circuit-pack styles

Circuit-Pack Style	Description
Wire wrap	Wire-wrap board for breadboarding
Extender board	6-Layer MLB, 2-pad layers, 2 signal layers, power (P) and ground (G) on inside, dedicated ground conductor between every pair of signal conductors
Double-sided (epoxy)	Double-sided, epoxy PWB
Double-sided (metal)	Double-sided, metal core, PWB
Bonded board (LAMPAC)*	Flex bonded to epoxy-coated steel
4L MLB (EXT P/G)	4-Layer MLB, 2 signal layers, P and G on outside
6L MLB (EXT P/G)	6-Layer MLB, 4 signal layers, P and G on outside
6L MLB (INT P/G)	6-Layer MLB, 2 pad layers, 2 signal layers, P and G on inside
6L MLB (INT P/G, Surface Routing)	6-Layer MLB, 4 signal layers, P and G on inside
8L MLB (INT P/G)	8-Layer MLB, 2 pad layers, 4 signal layers, P and G on inside

* This particular bonded board is also known as LAMPAC.

where

I = current flow through the conductor (amperes)
R_1 = resistance of the conductor at ambient temperature (ohms)
α_1 = ambient temperature coefficient (per degree C)
$= [T_1 + 234.45]^{-1}$ (a good approximation in the case of copper)
T_1 = ambient temperature (°C)
t = time duration of the current flow (seconds)
C = thermal capacity of the material heated (J/°C)
R_T = thermal resistance of the conductor on the CP style of interest (°C/W)
$\overline{\Delta T}$ = average temperature rise (°C) along the length of the conductor.

The left-hand side of eq. (1) represents the energy dissipated, and the two terms on the right-hand side represent the stored and radiated energy, respectively. More general forms of eq. (1) are discussed in Ref. 6.

Laboratory measurements show that the thermal capacity, C, is time dependent. The physical reason for this dependence is that more and more of the material is heated as time goes on. Initially, only the conductor and a small portion of the substrate and covercoat are heated.

However, if the time axis is partitioned into appropriate time intervals, it turns out that the thermal capacity, C, is approximately constant over each of the time intervals. The solution to eq. (1) in the case of three such time intervals is given by:

$$\overline{\Delta T} = \overline{\Delta T}_{ss}\,[1 - \exp\{-(R_T C_1)^{-1}(1 - I^2 R_1 R_T \alpha_1)t\}] \qquad 0 \le t \le t_1 \qquad (2)$$

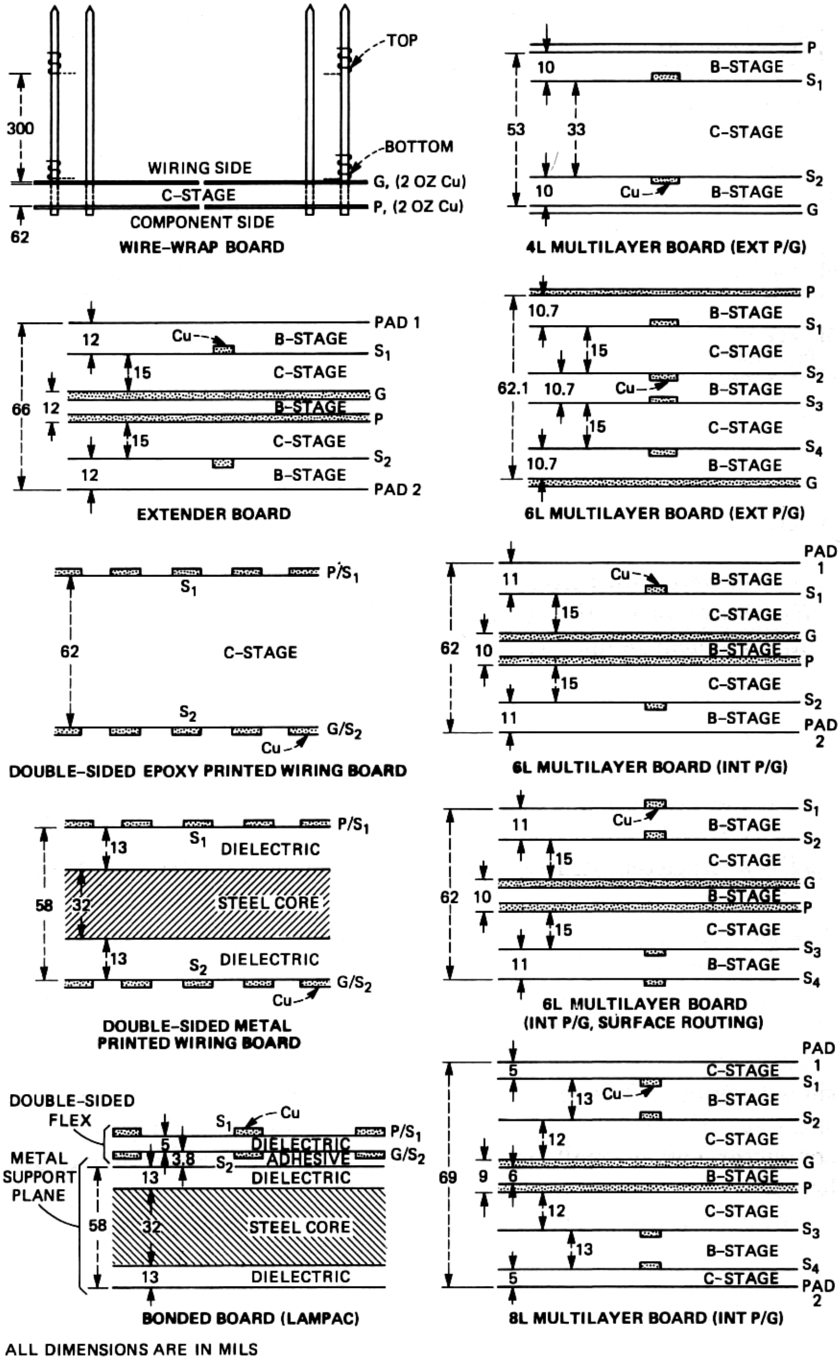

Fig. 1—Lay-ups of the various circuit-pack styles.

$$\overline{\Delta T} = \overline{\Delta T}_{ss}\left[1 - \exp\left\{-(R_T C_1)^{-1}(1 - I^2 R_1 R_T \alpha_1) \cdot \left(1 - \frac{C_1}{C_2} + \frac{C_1}{C_2}\frac{t}{t_1}\right) t_1\right\}\right] \quad t_1 \le t \le t_2 \tag{3}$$

$$\overline{\Delta T} = \overline{\Delta T}_{ss}\left[1 - \exp\left\{-(R_T C_1)^{-1}(1 - I^2 R_1 R_T \alpha_1) \cdot \left(1 - \frac{C_1}{C_2} + \frac{C_1 t_2}{C_2 t_1} - \frac{C_1 t_2}{C_3 t_1} + \frac{C_1}{C_3}\frac{t}{t_1}\right) t_1\right\}\right] \quad t_2 \le t \le \infty, \tag{4}$$

where

$\overline{\Delta T}_{ss} = \dfrac{I^2 R_1 R_T}{(1 - I^2 R_1 R_T \alpha_1)}$ = steady-state average temperature rise,

C_1 = thermal capacity during the time interval $[0, t_1]$,

C_2 = thermal capacity during the time interval $[t_1, t_2]$,

C_3 = thermal capacity during the time interval $[t_2, \infty]$.

In general, one can partition the time axis into n contiguous time intervals and obtain a set of n equations. For our purposes, $n = 3$ proved to be sufficient.

The current-carrying capacity of a conductor is limited by the permissible temperature rise of the conductor above the ambient temperature. Therefore, once the pertinent parameters are known, the above equations can be used to calculate the current-carrying capacity of a particular conductor.

In Section III, we describe the experimental method used to measure all of the pertinent parameters.

2.2 Some special cases

2.2.1 Runaway or critical current

The functional form of $\overline{\Delta T}_{ss}$ shows that a runaway or critical current, I_c, exists for which $\overline{\Delta T}_{ss} \to \infty$. That is, as $I \to I_c$, $\overline{\Delta T}_{ss} \to \infty$, and the current-carrying conductor never reaches steady-state temperature. The value of I_c is given by:

$$I_C = \frac{1}{\sqrt{R_1 R_T \alpha_1}}. \tag{5}$$

The phenomenon of runaway and the value of runaway current is consistent with our experience in the laboratory. We found that as we approached the critical value, I_c, the temperature of the conductor rises rapidly beyond the tolerable limits of the substrate and permanent damage results.

2.2.2 Small t — initial temperature rise

From eq. (2), we find that as $t \to 0$, we have

$$\overline{\Delta T} = \frac{I^2 R_1 t}{C_1}. \tag{6}$$

Notice that this result is independent of the thermal resistance R_T. That is, the initial heating process is adiabatic.

2.2.3 Large t — steady state temperature rise

From eq. (4), with $I < I_c$, we see that as $t \to \infty$ we have

$$\overline{\Delta T} = \overline{\Delta T}_{ss} = \frac{I^2 R_1 R_T}{(1 - I^2 R_1 R_T \alpha_1)}. \tag{7}$$

Equation (7) shows that the steady-state temperature rise depends on the product of the electrical resistance (a property of the conductor) and the thermal resistance (a property of the environment of the conductor). For a given current I, and ambient T_1, one can only reduce $\overline{\Delta T}_{ss}$ by reducing the product $R_1 R_T$.

III. EXPERIMENTAL DETERMINATION OF THE PARAMETERS

In order to carry out this study, appropriate test boards were designed for each CP style shown in Fig. 1. Except for the double-sided metal board, all test boards were fabricated at the Western Electric printed-circuit manufacturing plant at Richmond, Virginia. The double-sided metal board was manufactured at the Western Electric plant in Kearny, New Jersey.

In all cases, the physical dimensions of the printed conductors had the nominal values of length $L = 12$ in., width $W = 7$ mil, and copper thickness $t_0 = 0.5$ to 3 mil.

The experimental method used to determine the pertinent parameters is based on measuring, indirectly, the average temperature rise, $\overline{\Delta T}$, along the conductor as a function of time when a step function of current is applied. The measurement is based on the well-known resistance thermometer formula:[6,7]

$$\frac{V}{I} = R = R_1[1 + \alpha_1 \overline{\Delta T}], \tag{8}$$

where

V = voltage across the conductor,
I = magnitude of the step function of current,
R = measured resistance of the conductor.

The procedure used to measure $\overline{\Delta T}$ is as follows: The ambient temperature T_1 is recorded and R_1 is measured by means of an ac Kelvin bridge. This measurement involves a small current (100 mA or less) which causes a negligible temperature rise. Then a step function of I amperes is directed through the conductor of interest, and the resulting voltage drop, V, across the conductor is recorded as a function of time. Equation (8) is then used to deduce the corresponding $\overline{\Delta T}$ as a function of time.

To help ease the data gathering, a Kaye Instruments digistrip transmitter was used to format the data for print out and magnetic tape storage on a Texas Instruments model 733 data terminal. Subsequently, the data was transmitted (via an acoustical coupler) over the telephone line to the computation center for storage. At this point, special computer programs were used to edit the stored data and to produce the computer plots.

The procedure used to determine the constants appearing in eqs. (2), (3), and (4) is as follows: The average temperature rise is first computed from eq. (8) by using the steady state voltage value corresponding to a current flow of I amperes for a sufficiently long time (usually about 10 min). This is repeated for a number of different values of current. Then, the best value (minimum mean-square-error sense) of the product R_1R_T is determined from the measured data and eq. (7) which can be rewritten as

$$\frac{\overline{\Delta T}_{ss}}{1+\alpha_1\overline{\Delta T}_{ss}} = R_1R_TI^2. \tag{9}$$

If the left-hand side of eq. (9) is plotted as a function of I^2, the slope, R_1R_T, of the best fitting line is the quantity of interest. Since the value of R_1 is known, R_T can be determined.

According to eqs. (2), (3), and (4), a plot of the measured values of

$$Y \equiv -\ln\left[1 - \frac{\overline{\Delta T}}{\overline{\Delta T}_{ss}}\right]$$

versus time, t, yields points which tend to fit a series of approximately broken lines of positive slope. From this plot, values of t_1 and t_2 can be selected as the break points of these broken lines. In the region $0 \leq t \leq t_1$, the best value of C_1 (minimum mean-square-error sense) is determined by equating the slope of the best fitting line to the slope of the negative of the exponent in eq. (2). In a similar manner, C_2 is determined by using the measured data and the slope of the negative of the exponent in eq. (3). Finally, C_3 is determined by using the measured data and the slope of the negative of the exponent in eq. (4). At this point, all of the parameters needed in eqs. (2), (3), and (4) are known, and these equations can be used to calculate the average temperature along the conductor as a function of applied current, time, conductor resistance, and ambient temperature.

In this manner, the pertinent parameters were determined for fine-line conductors on all signal layers of all CP styles shown in Fig. 1. The resulting parameters are presented in Table II. The values of $t_1 = 0.55$ s and $t_2 = 3.55$ s were found to apply to all of the CP styles. The results were scaled to a conductor length of 12 in. and width of 7 mil by using the scaling laws $C_i \sim L$, $R_T \sim 1/L$, and $H \sim 1/W$.

The values of H listed in Fig. 2 and Table II are steady-state parameters and will be discussed in more detail in Section V.

IV. EXPERIMENTAL VERIFICATION

Figure 2 presents the experimental values of $Y(t)$ for the case of a double-sided epoxy printed wiring board (PWB) with covercoat. The parameters t_1, t_2, C_1, C_2, C_3, and R_T were determined by the methods described in Section III. The final C_i were determined by averaging the results over three different values of current.

For the double-sided epoxy CP, Fig. 3 compares the experimental values of the transient temperature rise, $\overline{\Delta T}(t)$, with the corresponding theoretical values. The theoretical values were determined by using

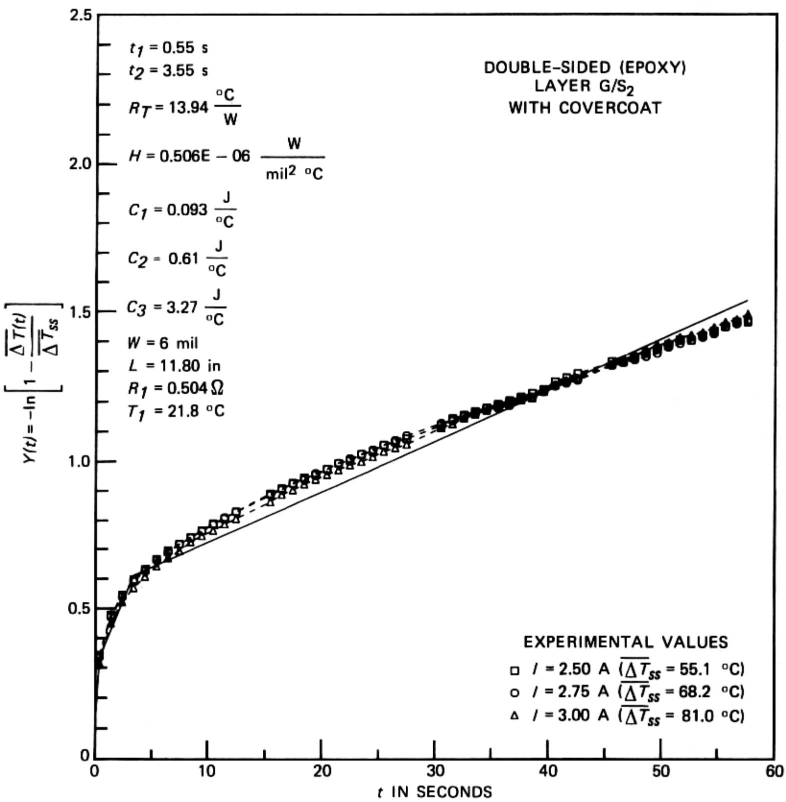

Fig. 2—Experimental values of $Y(t)$. Slopes of the broken lines determine the average thermal capacities, C_i, in the three time intervals.

Table II—Measured parameters for various circuit-pack styles (Conductor length = 1 ft, conductor width = 7 mil, and wire-wrap diameter = 10 mil)

Circuit-Pack Style*	$C_1 \frac{J}{°C}$	$C_2 \frac{J}{°C}$	$C_3 \frac{J}{°C}$	$R_T \frac{°C}{W}$	$H \frac{Watts}{mil^2\ °C}$
Wire wrap					
(Milene)†	0.118	0.170	0.265	30.5	$0.869\ 10^{-7}$
(Teflon)‡	0.150	0.259	0.406	30.2	$0.877\ 10^{-7}$
Extender board	0.121	0.697	8.71	6.32	$0.942\ 10^{-6}$
Double-sided (epoxy)	0.095	0.623	3.32	13.71	$0.434\ 10^{-6}$
Double-sided (metal)	0.052	0.305	11.22	9.00	$0.661\ 10^{-6}$
Bonded board $P/S1$	0.083	0.311	7.26	8.27	$0.720\ 10^{-6}$
(LAMPAC) $G/S1$	0.090	0.415	9.07	7.35	$0.810\ 10^{-6}$
4L MLB (EXT P/G)	0.124	1.06	3.65	11.49	$0.518\ 10^{-6}$
6L MLB (EXT P/G)					
S_1, S_4	0.124	1.06	3.65	11.49	$0.518\ 10^{-6}$
S_2, S_3	0.179	1.38	4.75	9.55	$0.623\ 10^{-6}$
6L MLB (INT P/G)					
S_1, S_2	0.121	0.697	8.71	6.32	$0.942\ 10^{-6}$
6L MLB (INT P/G, Surface Routing)					
S_1, S_4	0.076	0.443	5.59	10.47	$0.569\ 10^{-6}$
S_2, S_3	0.112	0.887	7.61	7.33	$0.812\ 10^{-6}$
8L MLB (INT P/G)					
S_1, S_4	0.076	0.438	5.01	9.70	$0.614\ 10^{-6}$
S_2, S_3	0.108	0.888	6.87	7.38	$0.806\ 10^{-6}$

* The circuit-pack styles having surface conductors were covercoated.
† Trademark of W. L. Gore & Associates, Inc.
‡ Trademark of E. I. DuPont de Nemours, Inc.

the constants t_1, t_2, C_1, C_2, C_3, R_T in eqs. (2), (3), and (4). Figure 3, shows that this method of estimating the transient temperature rise agrees with experimental results.

Similar plots have verified that this method of estimating the transient temperature rise also agrees with experimental results for all other cases of interest in this paper.

V. SOME APPLICATIONS

5.1 Steady state temperature rises

The steady-state temperature rises of fine-line printed conductors, or wire-wrap conductors, can be readily computed from eq. (7). The required values of thermal resistance, R_T, are listed in Table II for a conductor length of 1 ft, printed conductor width of 7 mil, and wire-wrap diameter of 10 mil. Also, the required values of the electrical resistance, R_1, can be computed from:

$$R_1 = \frac{\rho L}{t_0 W} \text{ (printed conductor),} \tag{10}$$

or

$$R_1 = \frac{4\rho L}{\pi D^2} \text{ (wire-wrap conductor),} \tag{11}$$

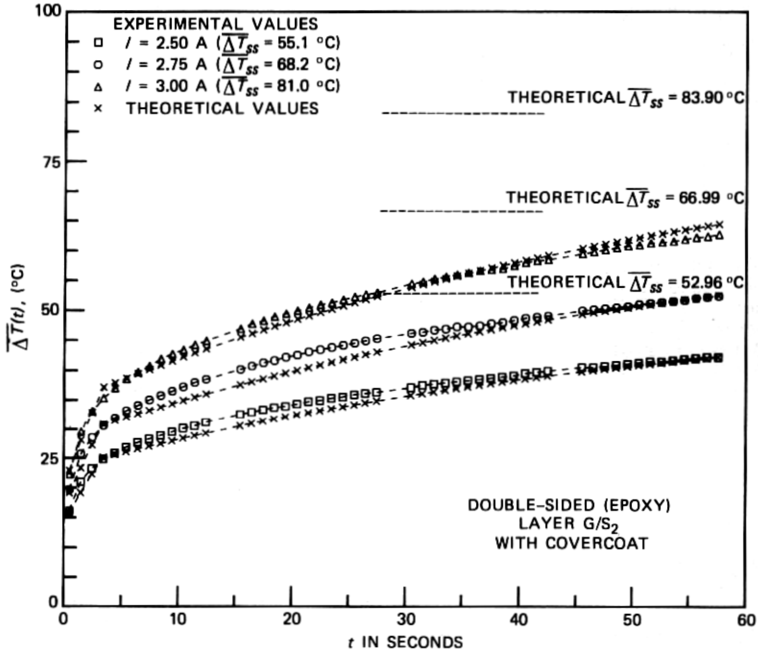

Fig. 3—Experimental values of the transient temperature rise, $\overline{\Delta T}(t)$, are compared with theoretical values.

where

$$\rho = (0.67878)10^{-3}[1 + 0.00393(T_1 - 20)] \text{ ohm-mil}$$
$$T_1 = \text{ambient temperature, °C}$$
$$L = \text{length of conductor} = 1 \text{ ft } (12{,}000 \text{ mil})$$
$$t_0 = \text{thickness of conductor, mil}$$
$$W = \text{width of conductor} = 7 \text{ mil}$$
$$D = \text{diameter of wire-wrap conductor} = 10 \text{ mil.}$$

As an example, consider a double-sided (epoxy) CP style. From Table II, we see that $R_T = 13.71°\text{C}/W$. From eq. (10), for $L = 12{,}000$ mils, $t_0 = 1.4$ mils (1 oz cu), $W = 7$ mil and $T_1 = 20°\text{C}$, we find that $R_1 = 0.8312\Omega$. For a current flow of $I = 2.5$ A, eq. (7) then yields $\overline{\Delta T}_{ss} = 98.9°\text{C}$.

For conductor lengths other than $L = 1$ ft, one can use the scaling law $R_T \sim 1/L$ to scale the values of R_T listed in Table II. Also, R_T is essentially independent of W as is shown by eq. (16) of Ref. 4.

Let us now compute the maximum steady-state temperature rise, max ΔT_c, when the same current-carrying conductor is nicked or constricted. The maximum temperature rise of such conductors was treated in Ref. 4. It was shown that the key parameter was the value of H, the coefficient of surface heat transfer. The values of H for the CP styles of interest in this paper are listed in Table II.

As an example of the effect of a nicked or constricted conductor on steady-state temperature rise, Fig. 4 compares the computed results for a fine-line current-carrying conductor on a double-sided (epoxy) board and a 6-layer MLB (INT P/G, surface routing). At a current of $I = 2.5$ A, the nicked conductor on the double-sided board rises in temperature to about 119°C; whereas, the nicked conductor on the inside signal layer (S_2) of the 6-layer MLB rises in temperature to only 56°C.

Tabulated results for the special case $H = (0.52)10^{-6}$ (Watts/mil^2°C) were presented in Ref. 4. Since many of the values of H tabulated in Table II are close to this value, the earlier results can also be applied to many of the CP styles of interest in this paper. Also the simple relationship given as eq. (13) of Ref. 4 yields results which agree well with those presented in Fig. 4.

Table II gives the values of H when $W = 7$ mil. For conductor widths other than $W = 7$ mil, one can use the scaling law $H \sim 1/W$.

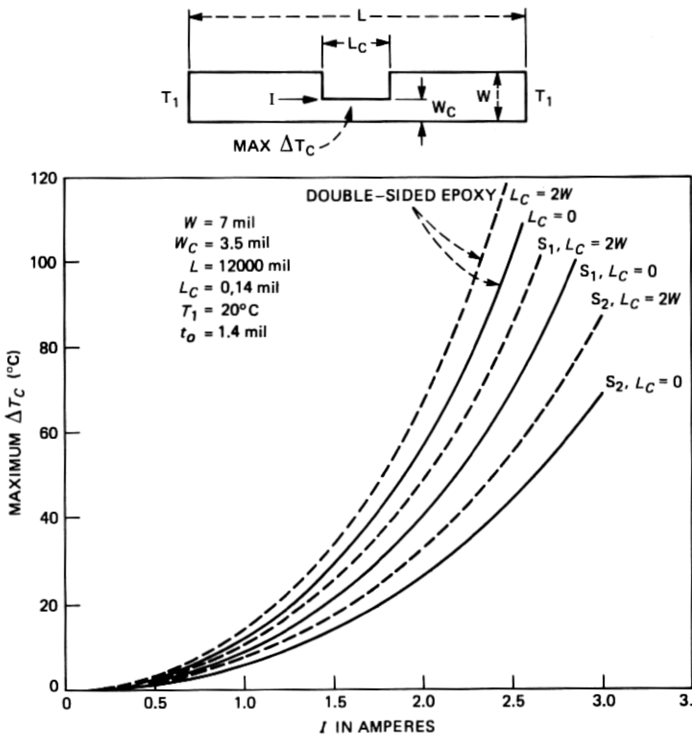

Fig. 4—The effect of a nicked or constricted conductor on the maximum steady state temperature rise.

5.2 *Transient temperature rises*

The transient temperature rises of fine-line printed conductors, or wire-wrap conductors can be computed from eqs. (2), (3), and (4). The required values of C_i and R_T are listed in Table II, also the values of t_1, and t_2 are given by $t_1 = 0.55$ s, and $t_2 = 3.55$ s, as was discussed in Section III.

An example of the transient temperature rise of a fine-line printed conductor on a double-sided CP is presented in Fig. 5. For this case, the appropriate parameters are listed in Table II as:

$$C_1 = 0.095 \frac{\text{J}}{{}^\circ\text{C}},\ C_2 = 0.623 \frac{\text{J}}{{}^\circ\text{C}},\ C_3 = 3.32 \frac{\text{J}}{{}^\circ\text{C}},\ \text{and } R_T = 13.71 \frac{{}^\circ\text{C}}{\text{Watt}}.$$

5.3 *Temperature rises resulting from fault currents*

A signal conductor on a CP normally carries a maximum current of about 0.1 A. Figure 4 shows that the temperature rise of such a current-

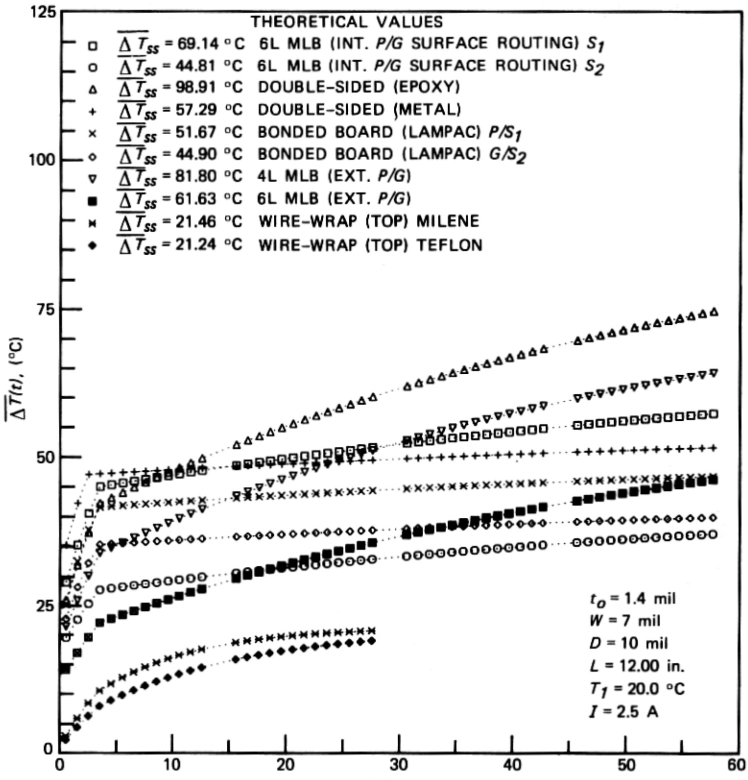

Fig. 5—Theoretical values of the transient temperature rise, $\overline{\Delta T}(t)$, are compared for different styles of circuit packs.

carrying conductor is negligible. However, a component failure or other malfunction can result in a current flow of many more amperes through the fine-line signal conductor. In this case, a circuit fuse or other over-current protection device can take many milliseconds to interrupt the flow of current. In such situations, the results in this paper can be applied to calculate the temperature rises on any layer of any of the CP styles shown in Fig. 1.

For example, consider the case of a signal conductor having the physical dimensions of $L = 1$ ft, $W = 7$ mil, and $t_0 = 1.4$ mil on a double-sided (epoxy) CP. Let us also assume that the ambient temperature is 50°C. Suppose the fault current is 10 A and the fuse or over-current protection device interrupts the fault current in 100 ms. What is the resulting temperature of the current-carrying conductor immediately before the current flow is interrupted?

From eq. (10), the electrical resistance of the conductor is $R_1 = 0.929\Omega$. From eq. (6) we find that

$$\overline{\Delta T} = \frac{I^2 R_1 t}{C_1} = \frac{(10\ A)^2(0.929\Omega)(0.1s)}{\left(0.095\ \frac{\text{J}}{°\text{C}}\right)} = 97.8°\text{C}. \tag{12}$$

The value of C_1 was taken from Table II. Thus, the temperature of the signal conductor is about 50°C + 98°C = 148°C. From some additional experimental work, we have found that the epoxy glass substrate begins to discolor at about 175°C. Thus, in our example, the substrate would not be discolored if the fault current of 10 A is interrupted in about 100 ms. Of course, in an application, one may want to restrict the conductor temperature to much less than 175°C.

It is important to notice that the same conductor temperature would result even if the length, L, of the conductor were only a few inches, since both R_1 and C_1 are proportional to L. Also, for conductor widths other than $W = 7$ mil, one can use the scaling law $C_1 \sim W$ to scale the values of C_1 listed in Table II.

5.4 Some comparative results

Figure 5 compares the transient temperature rises of fine-line printed conductors carrying a current of $I = 2.5$ A on various CP styles. In the steady state, the wire-wrap conductors exhibit the least rise in temperature (21°C); whereas, the conductor on the double-sided CP yields the highest rise in temperature (99°C).

Notice that the relative current-carrying capacity of the various CP styles depends on the duration of current flow. For example, at about $t = 5$ s, the conductor on the double-sided metal board exhibits the highest temperature rise (47°C). Interestingly, this result shows that the thermal conductivity of the dielectric resin of the metal board is somewhat less than the thermal conductivity of epoxy glass. Similarly, Fig. 5 also shows that Milene insulation has a somewhat lower thermal conductivity than Teflon insulation.

In most applications, one is usually interested in the comparative results during the steady state. In this case, the double-sided (epoxy) board is the worst from the point of view of current-carrying capacity.

Finally, notice that in all cases, the conductor temperature rises to a substantial fraction of its final value in the first five seconds.

VI. SUMMARY

This paper presents simple equations, based on the conservation of heat energy, to calculate the transient temperature rise of current-carrying, fine-line (~7 mil) conductors on various styles of circuit packs. The equations depend on various parameters which were determined experimentally. All of the styles of circuit packs in the *BELLPAC* system are included. These styles range from wire wrap to various MLBs.

The maximum steady-state temperature rise of a nicked or constricted current-carrying printed conductor is also treated.

VIII. ACKNOWLEDGMENTS

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