Trace Currents and Temperatures
Revisited

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April 2015
(Edit 7/20/15, note 15)

Abstract: *After reviewing the history of trace current/temperature investigations, and the theory behind trace heating, equations are fit to the current IPC 2152 temperature data. Then the results of a 3D thermal simulation model are compared to the curves and the equations. Finally, the thermal simulation model is used to look at thermal and time gradients, the sensitivity of trace temperature to such other variables as adjacent planes, adjacent traces, and material differences. The paper concludes that: (1) differences are most pronounced at higher temperatures and almost negligible at lower temperatures, (2) with one exception the IPC curves seem to be "worst case" scenarios, and (3) trace current/temperature relationships are too complex to represent with equations or graphs; thermal simulation models are required.*

1. Introduction:

The first study of the relationship between trace currents and temperature is believed to have been done in 1956. It was published by the Natural Bureau of Standards as Report # 4283 (Note 1). The empirical data were not very well controlled (because of limited resources), and the resulting charts, when published, were labeled "Tentative." The authors recommended that funding be provided for a more detailed, more carefully controlled study, but such funding was never forthcoming.

Originally, there were two sets of charts, one for external traces and one for internal traces. The empirical data only applied to the external traces. The internal trace charts were derived by de-rating the external charts by a factor of two, on the expectation that the internal traces would not cool as well as the external traces would, and would therefore be hotter.

Through the years the charts were redrawn and republished, and somewhere along the line the word "Tentative" was dropped.

Apparently they were first published as part of MIL-STD-1495 in 1973. Appendix 1 illustrates a page from one of the later versions of that standard, MIL-STD-275E, published in 1984.

Eventually the charts were published as part of an IPC standard (Note 2), IPC-D-275. Later, they were republished in IPC standard 2221 (Note 3).

These charts and standards were considered as the “Bible” for trace temperature measurements, in spite of their humble beginnings (and the fact that the assumption regarding internal traces would turn out to be quite incorrect!) They were used by most printed circuit board designers. In hindsight, the best thing they had going for them was the test of time. They apparently were appropriately conservative because few board failures were traced back to using them.

Finally, the IPC helped sponsor a very thorough study on trace currents and temperature that was released as IPC-2152, in 2009 (see end note 1). This is believed to be the best researched, best controlled, most thorough study ever made of trace currents and temperatures. The document is over 90 pages long and contains over 75 charts and tables. The results for external traces are (in my opinion) more evolutionary, than revolutionary. The IPC 2152 data result in currents approximately 25% lower than those shown in the original IPC 2221 set of curves, and they are much more detailed and complete (see Appendix 2). But the results for the internal traces are revolutionary. It turns out the internal traces cool almost as well or better than do the external traces. The IPC external 2 oz curves show higher temperatures than do the internal curves for the same traces (See Appendix 3). That is because it turns out the board materials conduct heat away from the trace better than the air does. This is the one assumption the original researchers got very wrong.

Brooks wrote his first paper on trace currents and temperatures back in 1998 (Note 4). During his investigation at that time he also uncovered a set of data published in a Design News article (Note 5) back in 1968 (which has sometimes become referred to as the DN data.)

In this paper we are taking a completely new look at the IPC 2152 data. We have been able to develop a new set of equations fitting the IPC data, been able to develop a set of thermal simulations that are consistent with the IPC data and the new equations, and therefore been able to do an extensive analysis of the sensitivities of trace temperatures to things such as trace parameters, adjacent traces, adjacent planes, and board materials. We have also been able to get new insights into the question of fusing (Note 6), how much current can a trace handle before it melts. That is the subject of a separate paper “Fusing Currents in Traces,” (Note 7).

This paper proceeds as follows:

1. **Introduction**: (this section)

2. **Background information**: The theory behind trace heating a cooling, the role of resistivity, and an expected model of the relationship. Then how we measure trace temperatures in the laboratory.

3. **IPC Trace data**: A look at the IPC trace data and a set of equations that fit the curves, comparing the equations to the expected model.

4. **Thermal Simulations**: Results of thermal simulations and models fitting the IPC trace data.

5. **Sensitivities**: The sensitivity of trace temperatures to a variety of variables such as trace parameters, board materials, adjacent traces and planes, etc.

2. Background Information:

Resistivity:

The characteristic of a material that reflects its electrical resistance is a property called "resistivity." All materials have resistivity and there are numerous tables in printed media and on the Web that provide resistivity information for the various materials (Note 8). Silver, copper, and gold, respectively, have the lowest resistivity of all elements. It is typically given by the values:

Silver	1.6×10^{-8} Ohm*m = .63 μOhm*in
Copper	1.7×10^{-8} Ohm*m = .67 μOhm*in
Gold	2.2×10^{-8} Ohm*m = .87 μOhm*in

Note: Units are Ohm-length

Resistivities of other common materials, for comparison, are (in Ohm*m):

Annealed copper	1.72×10^{-8}
Silicon	from .1 to 60
Glass	from 1.0×10^{9} to 1.0×10^{13}

Note that the resistivity of commercially available copper can depend on its particular alloy. Note also that materials like glass can be especially good insulators, i.e. their resistivities are *very* high compared to that of conductors.

As noted, the units of resistivity are Ohms-length. If we divide resistivity by the cross-sectional area of a conductor, we get units of:

Ohms-length/area = Ohms/unit length (or Ohms per unit length).

Now if we multiply that by the length of the conductor, the units become:

(Ohms/unit length) X length = Ohms (or, simply, resistance.)

So, the standard formula for the resistance of a conductor, based on its resistivity, is:

$$R = (\rho/A) * L \qquad \text{[Eq. 2-1]}$$

Where ρ (rho) is the resistivity of the conductor
A is the cross-sectional area of the conductor
L is the length of the conductor.

Thermal Coefficient of Resistivity:

Resistivity increases with temperature. Therefore, electrical resistivity *must be specified at a particular temperature*. This is usually specified as ambient, or room temperature, and is usually specified as 20°C.

The thermal coefficient of resistivity is usually represented by the symbol alpha, α. It is the factor that resistance increases with increasing temperature. Its usage is shown in Equation 2. Take the resistance of a conductor (R_{ref}) at some reference temperature (usually, but not necessarily 20°C) and multiply it by one plus alpha times the change in temperature from the reference:

$$R = R_{ref}(1+ \alpha * \Delta T) \qquad \text{[Eq. 2-2]}$$

Where R = Resistance at the desired temperature
R_{ref} = Resistance at the reference temperature (ambient)
α = thermal coefficient of resistivity at the reference temperature, and
ΔT = desired temperature – reference temperature (°C).

The thermal coefficient of resistivity for silver, copper, and gold is somewhat hard to pin down. Different sources give slightly different values. Wikipedia gives values of (Note 9):

Silver	0.0038	per degree C
Copper	0.003862	per degree C
Gold	0.0034	per degree C

Note that the thermal coefficient of resistivity for copper is very roughly 0.4 percent per degree C. Therefore, the resistance of a trace will increase by about 40% if the temperature of the trace increases by 100 degrees C.

Trace Heating Dynamics:

When current flows down a conductor, voltage is developed across the conductor because of the resistance of the conductor. Thus, by Ohm's Law (V = I*R), there is a voltage drop across the conductor. Therefore, there is power dissipated in the conductor. The power dissipated in the conductor is giver by the formula V*I, which can also be written I^2R. We regularly refer to I^2R losses when talking about power dissipated in traces or a resistor.

Power is related to temperature. So, if the I^2R losses increase (because of an increasing I or R), then the temperature would increase also. Figure 2-1 is a model of an external trace on a circuit board.

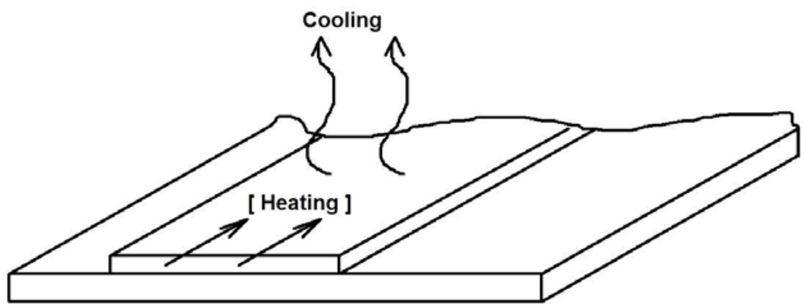


Figure 2-1
Model for trace current/temperature effects

The trace heats because of the I^2R losses caused by the current. The trace cools by convection and radiation into the air and by conduction into the board material. A stable temperature will be reached when the cooling effect just equals the heating effect. So we can speculate that the trace will increase temperature proportional to I^2R and will decrease temperature proportional to surface area (i.e. width + thickness), or:

$$\Delta T \propto \frac{I^2 R}{(w + Th)} \qquad \text{[Eq. 2-3]}$$

Where:

I = current
R = trace resistance
Th = trace thickness
w = trace width

Measuring Trace Temperature:

It is not particularly easy to measure the temperature of a trace. If, for example, you are doing a study of trace currents and temperatures (such as the IPC or Design News (DN)) studies, this is one of the major hurdles you need to overcome.

There are two techniques that are recognized as being legitimate and reliable, one based on the use of an infrared microscope and one based on measuring the change in resistance.

Use of an infrared microscope seems straightforward. You focus on a point along the trace, typically at the midpoint, and read the temperature. The major difficulty using this technique is ensuring that the surface of the trace is free of contaminants that could impact thermal reflectivity, and calibrating the microscope. Experienced technicians should be able to deal with these issues and make reliable measurements. This is the technique used in the DN study.

The other approach requires making accurate measurements of the trace's resistance at the ambient temperature and then at the elevated temperature. As noted above, the resistance of a trace increases with temperature because of the Thermal Coefficient of Resistivity. First, restating Equation 2-2:

$$R_T = R_{ref}(1 + \alpha * \Delta T) \qquad \text{[Eq. 2-4]}$$

Where:

R_T = resistance at elevated temperature
R_{Ref} = resistance at the reference temperature (ambient)
ΔT = change of temperature
α = thermal coefficient of resistivity

A little algebra gets us to the equation:

$$\Delta T = \frac{1}{\alpha}\left[\frac{R_a}{R_{\mathrm{Re}f}} - 1\right] \qquad \text{[Eq. 2-5]}$$

The major difficulty here is the accurate measurement of the resistances and the knowledge of α, the thermal coefficient of resistivity. Again, experienced test technicians should be able to overcome these difficulties.

But these two approaches measure different things! The infrared microscope approach measures the temperature at a spot on the trace, presumably at the hottest spot, the midpoint of the trace. The change in resistivity approach measures the average temperature of the entire length of the trace (because it relies on the bulk resistance of the trace.) In effect, the latter approach integrates the resistance at each individual element within the trace along the entire volume of the trace (see Figure 2-2).

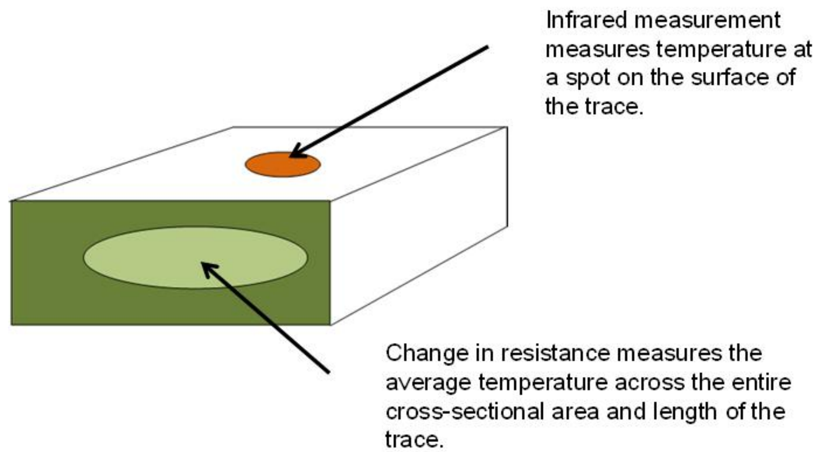


Figure 2-2
Differences in trace temperature measurement

These two approaches will yield the same results only if there are no thermal gradients along the trace. Many assume this is true, arguing that the thermal conductivity of copper is so good that no thermal gradients can develop. But consider a trace that is terminated by a reasonable heat sink at each end. One end could be connected, for example, to a plane. If there is a relatively large current running through the trace, then the midpoint of the trace could be hot, but the plane, being an effective heat sink, would result in the end of the trace being quite a bit cooler. Therefore there must be a thermal gradient along the trace.

Later on in this paper we are going to introduce a thermal simulation program. At the risk of getting a little ahead here, we are going to show some thermal images of traces illustrating the thermal gradients that can develop. Figure 2-3 illustrates the thermal profile of a 1 Oz, 200 mil wide trace carrying 15 Amps. It is 6 inches long. It has large pads at each end simulating a connection to a plane. The temperature at the midpoint of the trace is 94.7 degrees C. But the temperature at each end of the trace is only 57.9 degrees C. The mean temperature along the trace is approximately 88 degrees C.

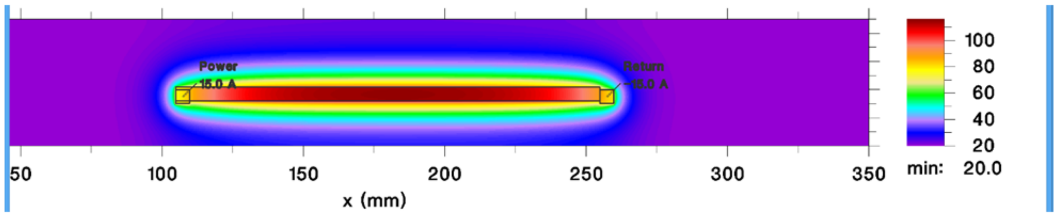


Figure 2-3
Thermal simulation of a 6 in., 1 Oz., 200 mil wide trace carrying 15 Amps.

So, one problem a board designer faces when thinking about the current carrying capacity of a trace is whether he/she is considering the mean temperature along the trace or the hottest spot on the trace. And, perhaps, where the hottest point on the trace is.

The IPC test procedure tries to avoid this problem by designing a special test fixture. The test procedure is freely downloadable from the IPC test site (Note 10). A diagram of the test fixture is shown in Figure 2-4.

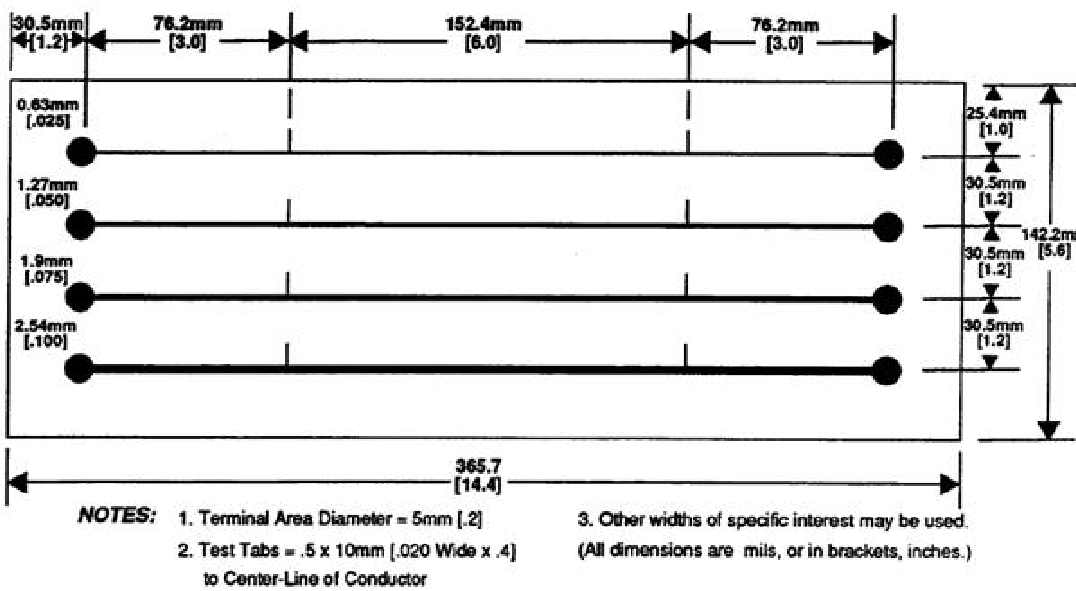


Figure 2-4
IPC test fixture for thermal testing of traces.
Source: Test procedure 2.5.4.1A

The entire test trace is 12 inches long. There are two "test tabs" (sensing points) 3 inches in from each end. So the portion of the trace actually under test is the 6 inch long center section. The test tabs are small (and presumably not thermally conducting) and carry no current. They are for measuring the resistance of the trace along that 6 inch section. The test procedure prescribes that #26 AWG magnet wire will be soldered to the test tabs. #26 magnet wire has the same cross-sectional area as a 1 Oz 153 mil wide conductor (Note 11). So our thermal model simulates this with a 153 mil wide trace connected to the end of the test tabs. The thermal result, then, of this IPC test model of a 1 Oz. 200 mil wide trace looks like Figure 2-5.

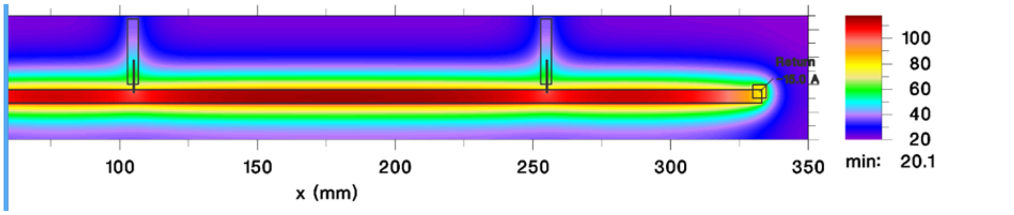


Figure 2-5
Thermal simulation of a 6 in long test section of a 1 Oz., 200 mil wide trace carrying 15 Amps using the IPC test procedure.

This result is more uniform than that for Figure 2-3. The maximum temperature is 96 degrees C but the temperature at the tabs is 84.5 degrees C. The mean temperature is closer to 94 degrees. So the IPC test procedure results in a minor difference between the hottest and the mean temperatures. Unfortunately, Figure 2-3 represents the more common case for real boards.

Figure 2-6 plots a graph of the temperature for the traces shown in Figures 2-3 and 2-5 as a function of the distance in from the left end to the midpoint. The IPC test curve is the upper curve.

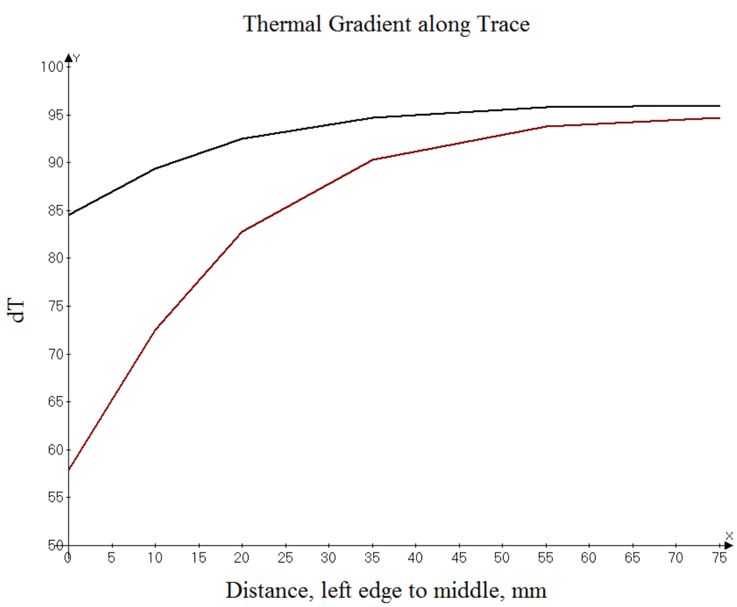


Figure 2-6
Plots of the thermal gradients in Figures 2-3 and 2-5.

3. IPC Trace Data

Reformatting the IPC Data:

A typical figure in IPC 2152 looks like Figure 3-1. These curves plot current as a function of cross-sectional area and create constant-temperature (change) curves on the graph.

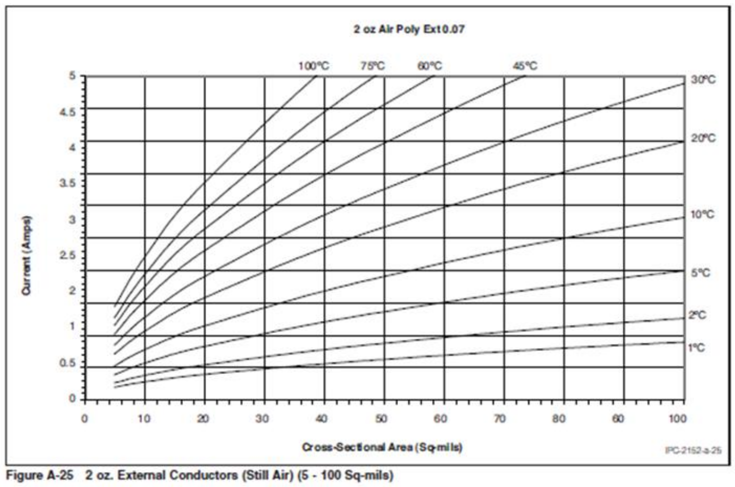


Figure 3-1
Typical curve from IPC 2152

For our purposes, we want to plot the change in temperature as a function of current and have constant-width curves on the graph. That is because our model (see Equation 2-3) is expressed this way and also because thermal simulations tend to be formulated this way. So we need to transpose the IPC data to a different format.

A convenient and efficient way to do this is through the use of a digitizing program (Note 12). Figure 3-2 illustrates the starting point.

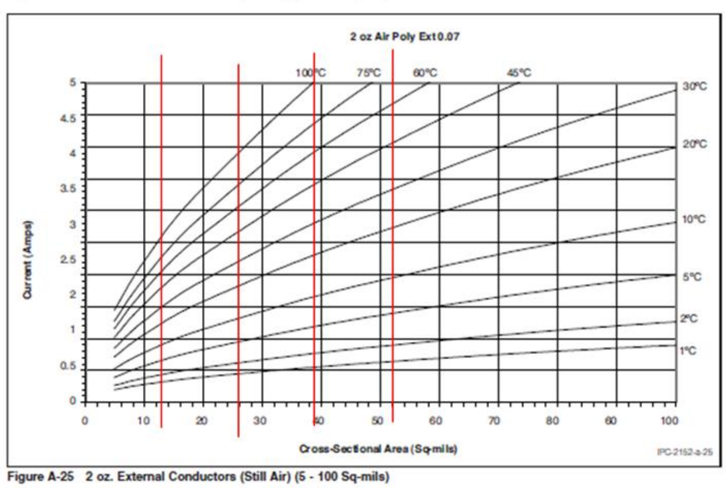


Figure 3-2
IPC Curve with constant width lines drawn.

Constant-width lines (red) are drawn at widths 5, 10, 15, and 20 mils, respectively. Then the coordinates where each line crosses each curve are recorded using the digitizer and copied to a spreadsheet. This is repeated for all relevant IPC graphs in a series. The data are all then sorted accordingly and re-graphed. The result is a graph of the type shown in Figure 3-3.

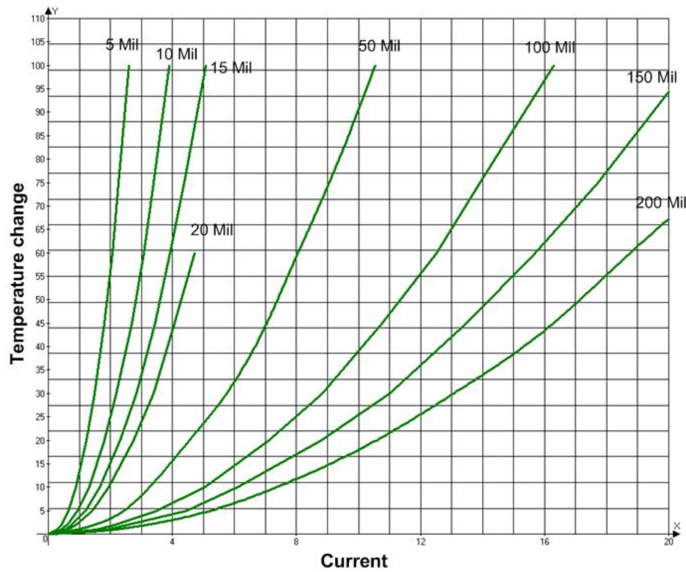


Figure 3-3
The 2 Oz. external IPC curves re-drawn to a different set of axes.

External IPC Data Equations:

The next task is to try to fit these curves with an equation. One way to do this is with a multiple regression analysis using a resource such as any current spreadsheet. Another way is to start with our model (Equation 2-3):

$$\Delta T \propto \frac{I^2 R}{(w + Th)} \qquad \text{[Eq. 2-3]}$$

Recognize that Resistance, R, is inversely proportional to area (width*thickness), so this model can also be expressed as Equation 3-1:

$$\Delta T \propto \frac{C^2}{Width^{a1} * Th^{a2}} \qquad \text{[Eq. 3-1]}$$

Where:

ΔT = Change in temperature
C =current
Width = trace width
Th = trace thickness
a1 and a2 are undetermined constants that are approximately 1.0 to 1.5

After a little work it was determined that the best fit for these curves was an equation of the form:

$$\Delta T = 215.3 * C^2 * W^{-1.15} * Th^{-1.0} \qquad \text{[Eq. 3-2]}$$

Plotting this equation onto Figure 3-3 (with the appropriate values for W and Th) gives the results shown in Figure 3-4 (solid black lines are from the IPC data, the dotted red lines are the equations.)

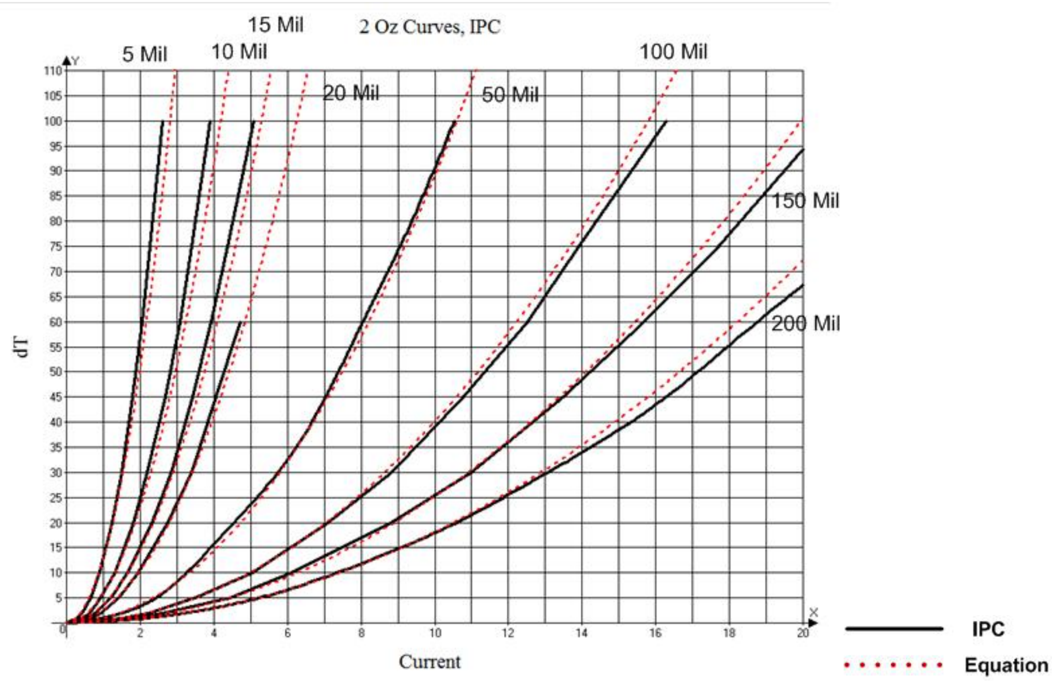


Figure 3-4
2 Oz. external IPC curves of Figure 3-3 fit with Equation 3-2

This result is impressive, but what would be even more meaningful would be if this same equation, for 2 Oz. external data, would also fit the 3 Oz. external IPC data. If that were the case, we would have a fair amount of confidence in both the IPC data and the equations.

Figure 3-5 illustrates similar results for the 3 Oz. external IPC data. The curves were generated in the same fashion as the 2 Oz. curves were, and the equation is the same, differing only in terms of the appropriate variables (width and thickness).

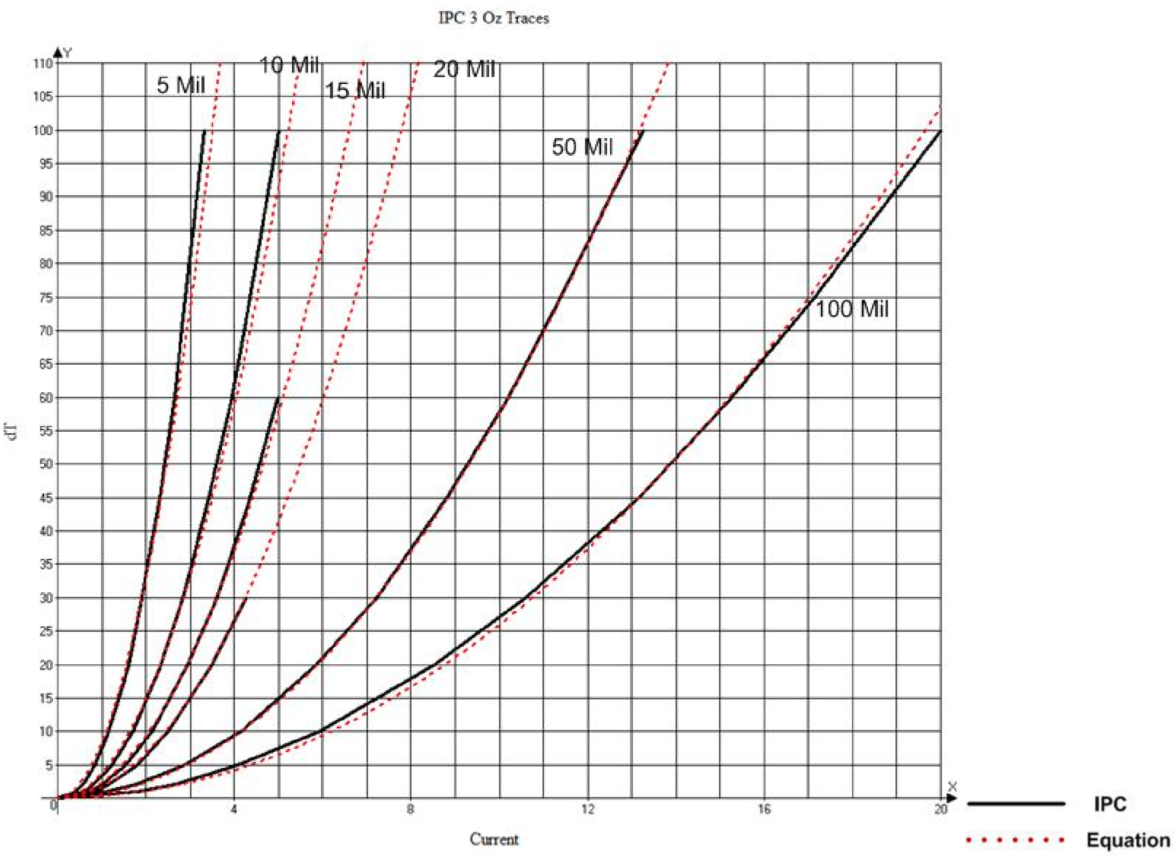


Figure 3-5
3 Oz. external IPC curves fit with Equation 3-2

The fits are obviously extremely good. This gives us very high confidence in the equations.

We can't do a similar fit test for 1 Oz. traces because there is no separate 1 Oz. external data in IPC 2152. Section 5 in IPC 2152 provides a set of charts for overall use, but they reflect a consolidation of all data, not exclusively 1 Oz. data. Similarly, there are no 1 Oz. external data charts in the Appendix. We have produced Figure 3-6, however, based on Equation 3-2. In the next section we will fit this curve with thermal simulation results for comparison with the 2 Oz. and 3 Oz. curves.

As an aside, it is worth noting that Equation 3-2 also proves that the change in temperature is not a function of current density alone, as some people might think. Since the coefficients for the width and thickness terms are different, the form factor of the trace (i.e. whether it is wider or thicker for the same cross-sectional area) matters. Although the coefficients are not exactly what we expect from our initial model (for reasons that are not exactly clear), the closeness of the fit (and the fit of the thermal models in the next section) cannot be ignored.

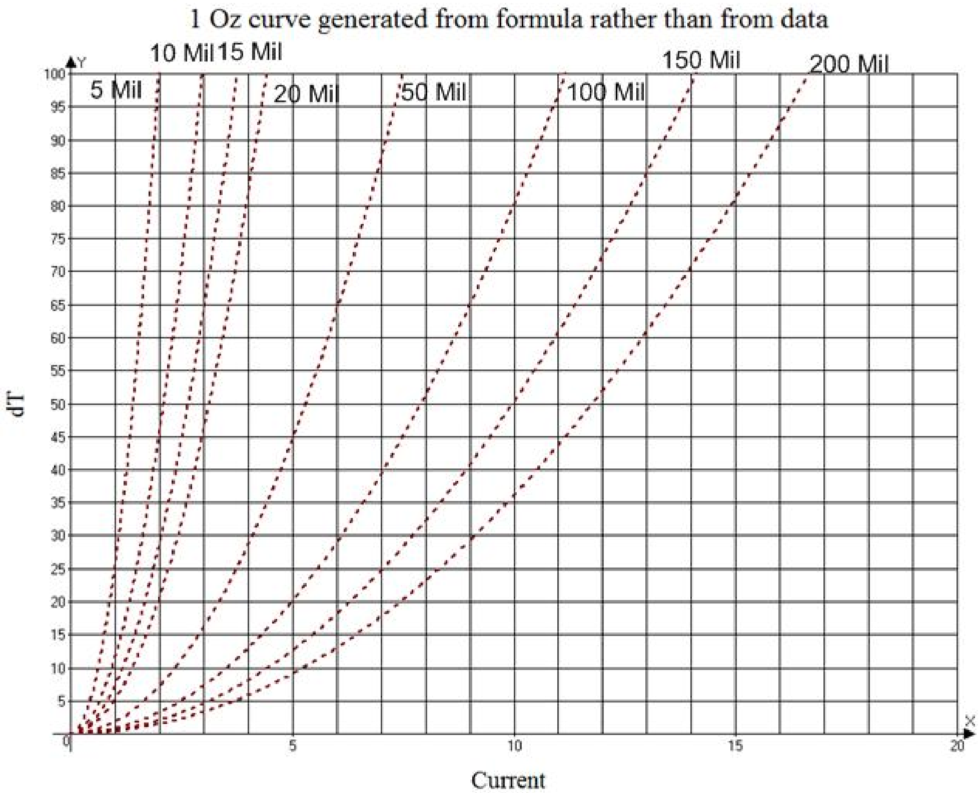


Figure 3-6
1 Oz. curves generated from Equation 3-2

Internal IPC Data Equations:

A real surprise from the IPC 2512 study and data was that the internal races actually cool *better than* the external traces do (see Appendix 3 for a comparison.) The internal traces are a little cooler than are the external traces.

Fitting the Internal IPC data does not go quite so smoothly. To save space in this paper we have put the four internal fitted curves in Appendix 4. On the surface, the curves and the fits look excellent. The problem is, in this case, the equations are not all exactly equal. They are quite close, but not exactly equal. The primary difference is in the constant term. Table 3-1 (below) provides the coefficients for the equations.

We will look at how the thermal models fit the internal data later on. At this point, my suspicion is that the differences reflect a control issue in the study (Ed. See note 15). As we will see in Section 5 the temperature of a trace is very sensitive to a variety of factors, only some of which are easily controlled. The differences here between trace widths are not nearly as great as some of the other differences we will explore in Section 5.

IPC Vacuum Data:

Traces are cooled by three effects: (a) heat conducting away from the trace through the board, (b) heat convected away from the board into the surrounding air, (c) heat radiating away from the board into "space." In a vacuum, there is no surrounding air. So heat that gets to the surface (either because the trace is on the surface or because the heat has conducted through the board to the surface) can only radiate away. This is much less efficient than convection through the air, so traces in a vacuum understandably run quite a bit hotter than otherwise. And it appears not to make too much difference whether we are talking about internal or external traces (IPC 2152 does not provide separate data for internal and external traces in a vacuum. Nor does IPC 2152 provide any 1 Oz. data for traces in a vacuum.)

The curves for traces in a vacuum (and their fitted equations) are provided in Appendix 5. Figure 3-7 illustrates the difference between some 2 Oz. external, internal and vacuum traces. The pattern is similar for all other sizes of trace.

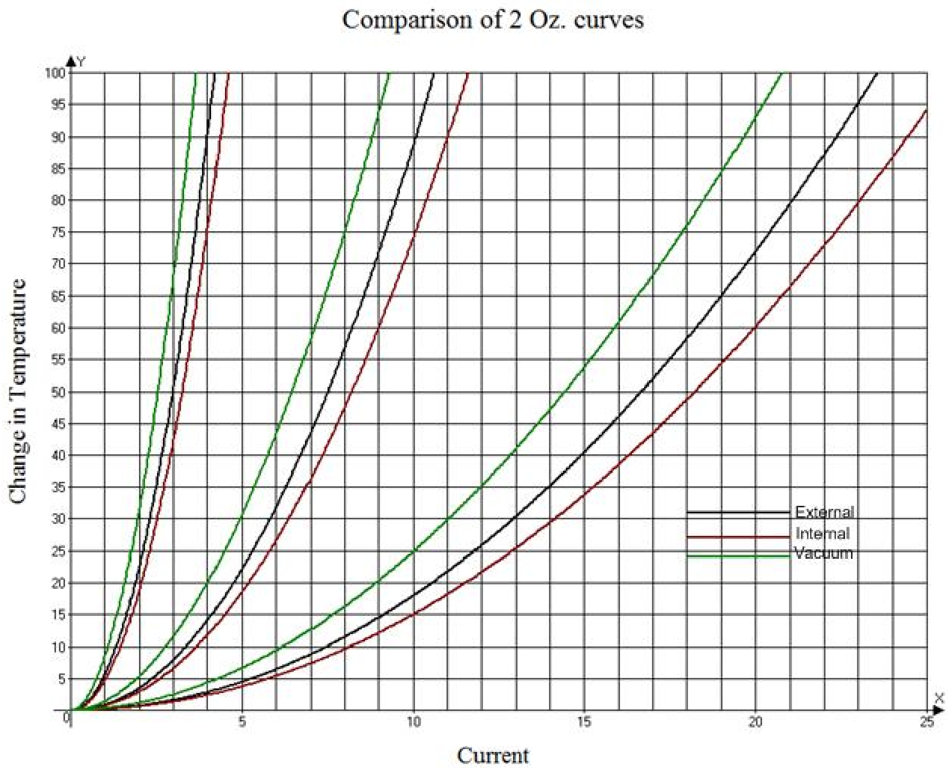


Figure 3-7
Comparison of 2 Oz. external, internal and vacuum traces
of width 10 mil, 50 mil, and 200 mil.

Table 3-1 shows the approximate equations used for fitting the curves. The complete set of equations is provided in Appendix 6.

Data	Constant	C^	W^	Th^
External				
All	215.3	2	-1.15	-1.0
Internal				
0.5 Oz.	110-130	2	-1.10	-1.52
1 Oz.	200	1.9	-1.10	-1.52
2 Oz.	300	2	-1.15	-1.52
3 Oz.	225-300	1.9	-1.15	-1.52
Vacuum				
0.5 Oz.	210-235	1.9	-1.10	1.52
2 Oz.	480	1.9	-1.10	1.52
3 Oz.	460	1.95	-1.15	1.52

Table 3-1
Coefficients for all the IPC equations

Fitting the DN Data:

In his previous paper Brooks looked at the Design News (DN) data and compared them to the IPC data. We have done that again using the techniques outlined above with little consistency between trace sizes. Furthermore, there is too little information provided in that article to construct a meaningful thermal model to study. We now believe there was, originally, too little control over the test results for there to be a meaningful analysis of that data.

4. Thermal Simulations:

Thermal Models:

The next phase of this study was to independently estimate trace currents and temperatures and compare them to the IPC results. Dr. Adam was kind enough to provide a copy of ADAM Research's TRM 1.8 simulation software for that purpose. TRM (Thermal Risk Management) was originally conceived and designed to analyze temperatures across a circuit board, taking into consideration the complete trace layout with optional Joule heating as well as various components and their own contributions to heat generation. Although it could be adapted to the measurement of an individual trace, it was not originally conceived with that use in mind. Consequently, a couple of adjustments and adaptations had to be made.

For those of us in the printed circuit board industry, a thermal model is to trace temperature calculations what a field effect model is to trace impedance calculations. And the approach is not too different. The 3-D structure is analyzed by first looking at a tiny cube within the structure. At this micro level, the computations are relatively straightforward to define. So you do the calculation for one cube, then the next cube, and then the next one --- etc. And you keep going in this iterative process until you have solved for the entire structure.

There will be a very large number of "cubes" in this analysis, and a great many calculations for each. The analysis becomes a very large matrix algebra computational problem, very difficult for an individual but perfect for a desktop computer. Any practical problem can require a large number of resources. A reasonable problem, with reasonable accuracy, can require a few minutes to an hour to solve, even with a powerful 64-bit desktop.

We will illustrate a couple of the adjustments we had to make below, as we describe one of the models. But two comments deserve mention up front. First, as mentioned in Section 2, resistance increases with temperature. So if we initiate an analysis with a certain resistivity in mind, and reach an elevated temperature, the resistance will have changed at that elevated temperature. That means the trace will be hotter than the analysis calculates. TRM runs in two selectable modes. One goes directly to a solution and one takes changing resistivity into account.

In the second mode, the program executes with initial values and reaches a solution. Then the program recalculates the resistance of the trace at the new temperature and executes (loops) a second time. And it keeps doing this. The user sets the number of loops as part of the setup. Experimentally we determined that two loops were sufficient to reach (acceptable) stability at lower temperatures and for internal traces and 4 loops (or more) were needed at higher temperatures.

Secondly, setting up a model requires defining something called the "Heat Transfer Coefficient" (HTC). This is a coefficient that defines how effectively a surface transfers heat to another medium. In this situation, it refers to how effectively the board and trace transfer heat to the surrounding air. This coefficient, found in the literature with letter h, is often not familiar to electric engineers (other than perhaps the thermal resistance Rth). However, only h provides the necessary coupling between temperature inside the board and the ambient (otherwise heat could not leave a board). In practice HTC contains the contributions of convection plus radiation. While HTC can be estimated quite well for flat and uniformly heated plates, it is not always intuitive what the value should be for a single trace on a board. But more importantly, HTC increases with temperature, and it is not at all clear how it increases for an individual trace. Here is how we attacked this problem:

We set up a model and entered a reasonable value for HTC. We solved the model and compared the result to the equations established above. We found the base value (i.e. the value of HTC for low currents and temperatures) pretty quickly. It was 10 W/m2K (Note 13). Then we solved the models at higher currents and determined what values of HTC were required to fit the equations. Higher values were expected and determined.

At lower currents (temperatures) the model results were pretty insensitive to HTC, often differing by 1 degree C or less. At higher currents (temperatures) a range of HTC from 11 to 14 only resulted in a temperature difference of around 10 degrees (in one case 20 degrees.) So the determination of the correct value for HTC was more like “tweaking” the results of the model.

The range of HTC’s needed for external and internal traces is shown in Figures 4-1 and 4-2. The range falls between the red lines.

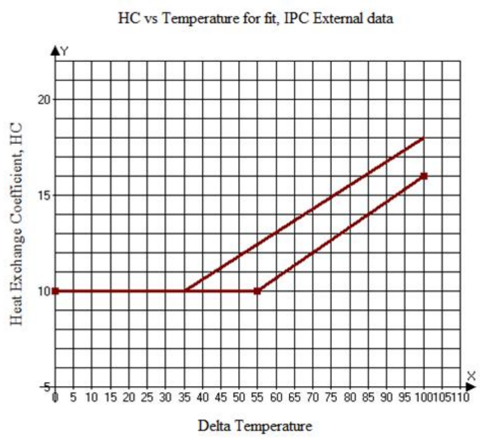


Figure 4-1
Approximate range of HTC for external traces.

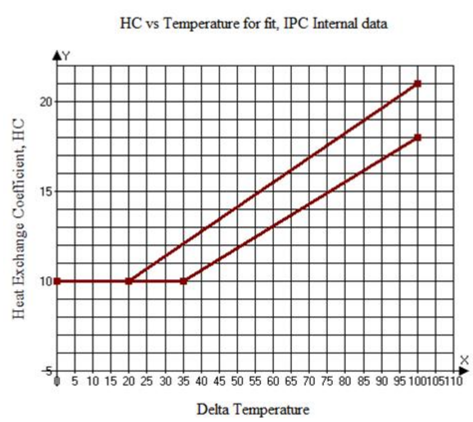


Figure 4-2
Approximate range for HTC for internal traces.

While it may seem like were somehow forcing the model to fit the data, think of the initial steps as more like *calibrating* the model. Once we knew what the predictable range was, we could then pre-set the HTC value and get acceptable results.

Running the Model:

This paper is not intended to be a tutorial on how to run a thermal model. We will go through a few of the steps just to highlight the major steps that are involved.

The first step is to define the size of the board and the default values for the materials. Figure 4-3 illustrates the default materials of copper for the conductor and FR4 for the dielectric.

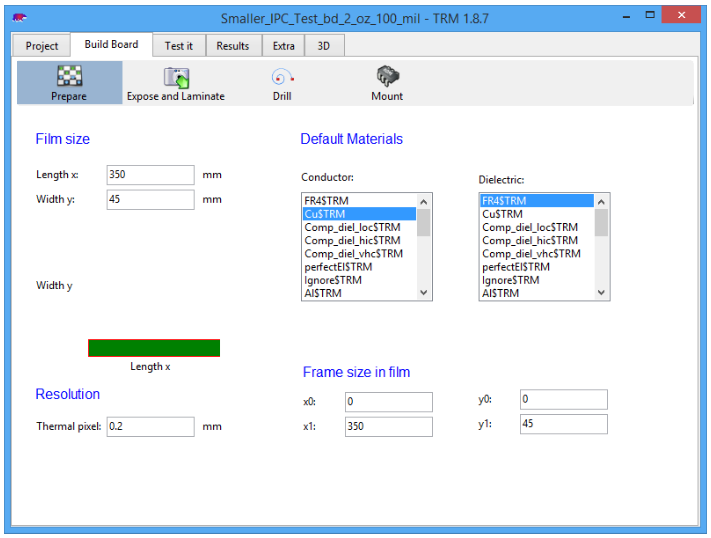


Figure 4-3
Setup screen for size and material

Then we must define the stackup. Figure 4-4 illustrates a simple, 2 Oz. single layer board, 1,600 um thick. (TRM dimensions are metric.) We use four layers of dielectric, each 400 um thick, instead of a single layer that is 1,600 thick for purely technical reasons, there is better precision in the matrix operations by doing so.

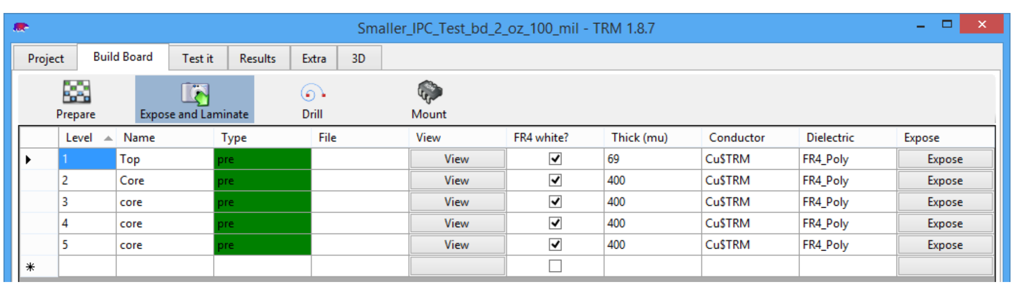
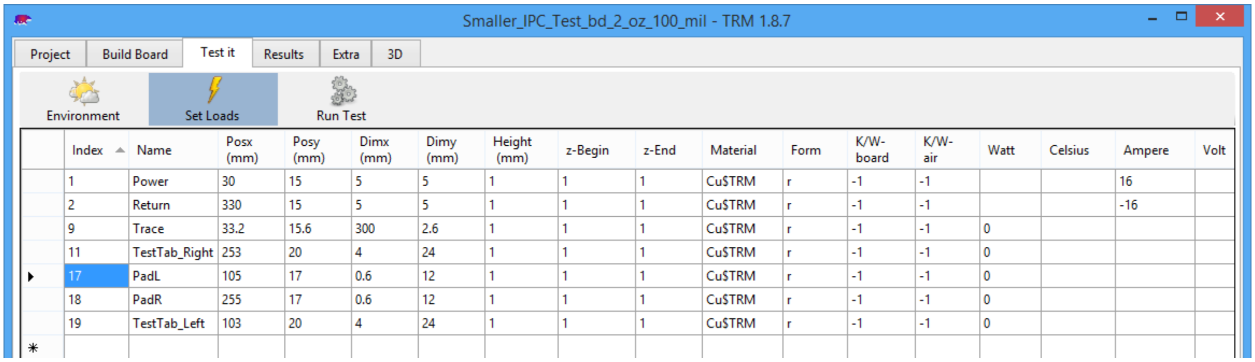


Figure 4-4
Setting up the board stackup

We then define the trace parameters. We used 'components' to enter traces and pads manually (typically the layer patterns are imported from Gerber files). First, refer back to Figure 2-4, the IPC test fixture. The elements defined in the setup of Figure 4-5 include the Power and Return pads at each end of the 12 inch long trace. Then the TestTabs, 3 inches in from each end of the trace, defining a 6 inch center test section for the model. Then the PadL and PadR pads that simulate #24 gauge magnet wire soldered to the test tabs. And finally the trace itself, 300 mm (approximately 12 inches) long. Each component in the table has a starting position (Posx,Posy), and a length dimension (Dimx,Dimy). This trace has a Dimy of 2.6 mm so it is defining a 100 mil wide trace, and the right-hand column defines that there is 16 Amps flowing through the trace.



Index	Name	Posx (mm)	Posy (mm)	Dimx (mm)	Dimy (mm)	Height (mm)	z-Begin	z-End	Material	Form	K/W-board	K/W-air	Watt	Celsius	Ampere	Volt
1	Power	30	15	5	5	1	1	1	Cu$TRM	r	-1	-1			16	
2	Return	330	15	5	5	1	1	1	Cu$TRM	r	-1	-1			-16	
9	Trace	33.2	15.6	300	2.6	1	1	1	Cu$TRM	r	-1	-1	0			
11	TestTab_Right	253	20	4	24	1	1	1	Cu$TRM	r	-1	-1	0			
17	PadL	105	17	0.6	12	1	1	1	Cu$TRM	r	-1	-1	0			
18	PadR	255	17	0.6	12	1	1	1	Cu$TRM	r	-1	-1	0			
19	TestTab_Left	103	20	4	24	1	1	1	Cu$TRM	r	-1	-1	0			

Figure 4-5
Setup parameters for a 100 mil wide, 12 inch trace with a 6 inch test section in the middle, i.e. the IPC test fixture. It is being set up to model 16Amps.

Model Results, External Traces:

Figures 4-6 through 4-8 show the result of thermal model simulations for the external traces. The thermal model results are the red boxes along each curve. The 2 Oz. and 3 Oz. traces show the results against both the IPC data (black lines) and Equation 3-2 (red dotted lines). Since there is no pure IPC 1 Oz. data, Figure 4-8 shows the simulation results only against Equation 3-2.

Because of the time required for a model simulation, We didn’t run a simulation for every curve at widely separated temperatures. Thus, the results represent what we hope is a representative sample of situations. Nevertheless, the consistency of the results gives comfort that the equations and the simulations are valid.

One point in particular needs to be emphasized: ***In all three sets of curves, there is one single equation (Equation 3-2) and one single TRM model (differing only in trace width, trace thickness, and HTC).***

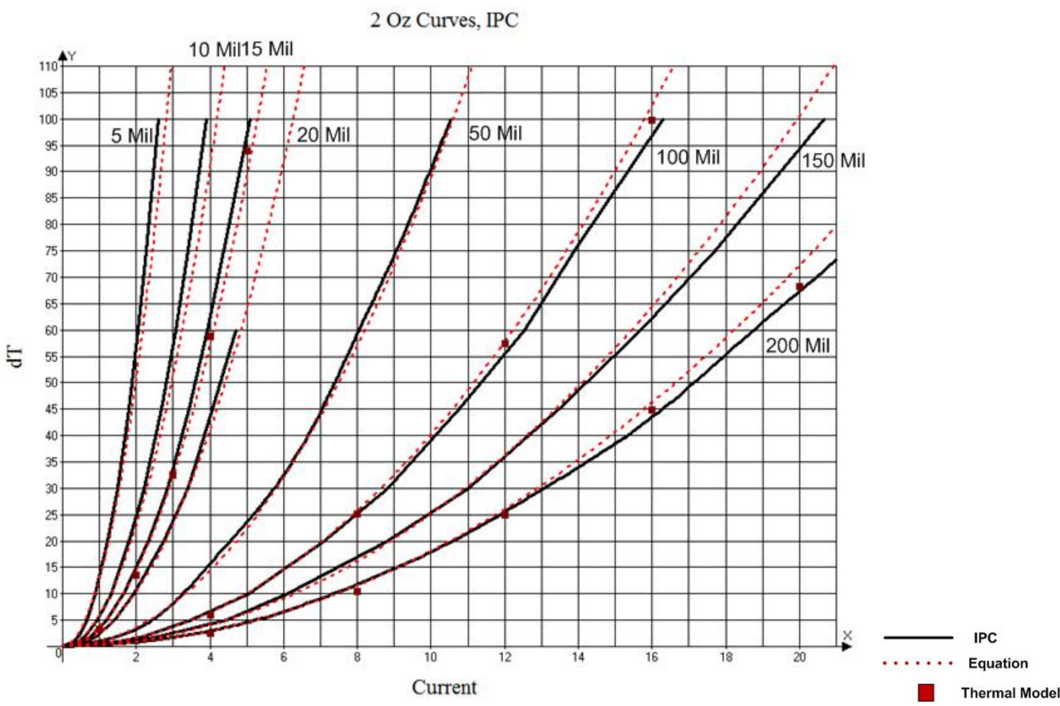


Figure 4-6
Thermal simulation results for 2 Oz. models of IPC external traces.

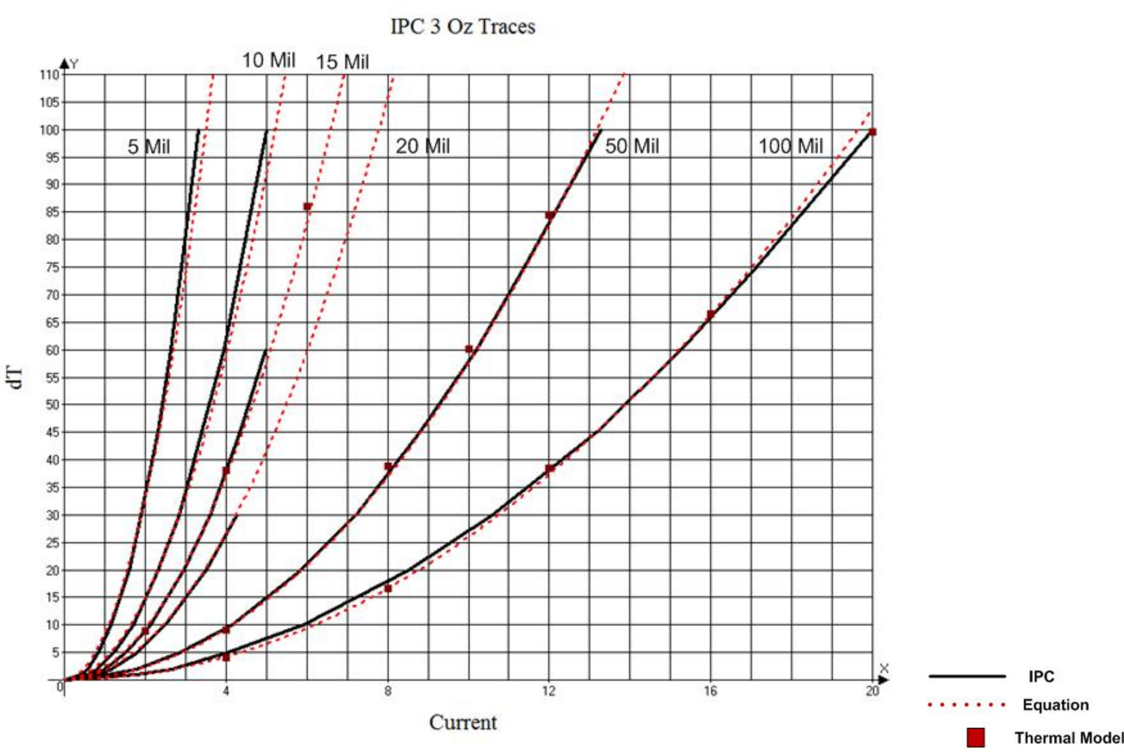


Figure 4-7
Thermal simulation results for 3 Oz. models of IPC external traces.

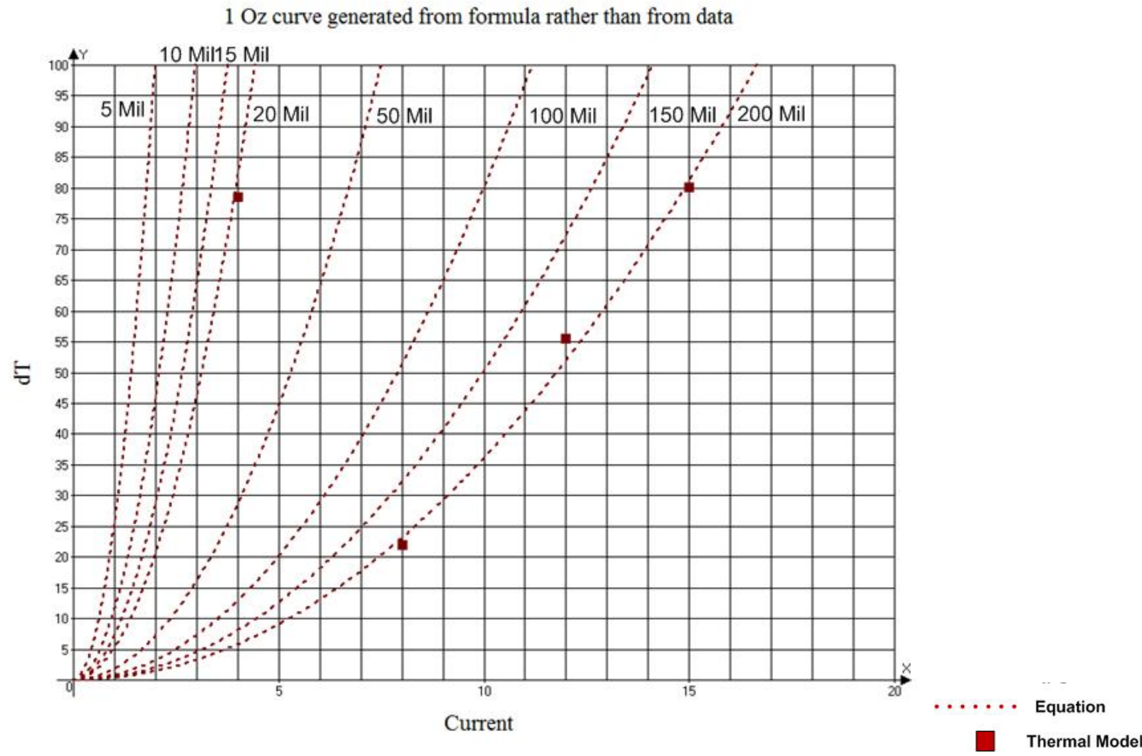


Figure 4-8
Thermal simulation results for the 1 Oz. external Equation 3-2 curves.

Model Results, Internal Traces:

Figures 4-9 through 4-11 show the result of thermal model simulations for the internal traces. The thermal model results are the red boxes along each curve.

Again, we didn't run a simulation for every curve at widely separated temperatures. Thus, the results are what we hope is a representative sample of situations. Nevertheless, the consistency of the results gives comfort that the equations and the simulations are valid.

A couple of points should be emphasized: ***The black curves are the IPC data. The equations are not entirely identical (but close, see Table 3-1). The TRM models are identical for all three sets of curves, differing only by the trace width, the trace thickness, and the HTC coefficient.***

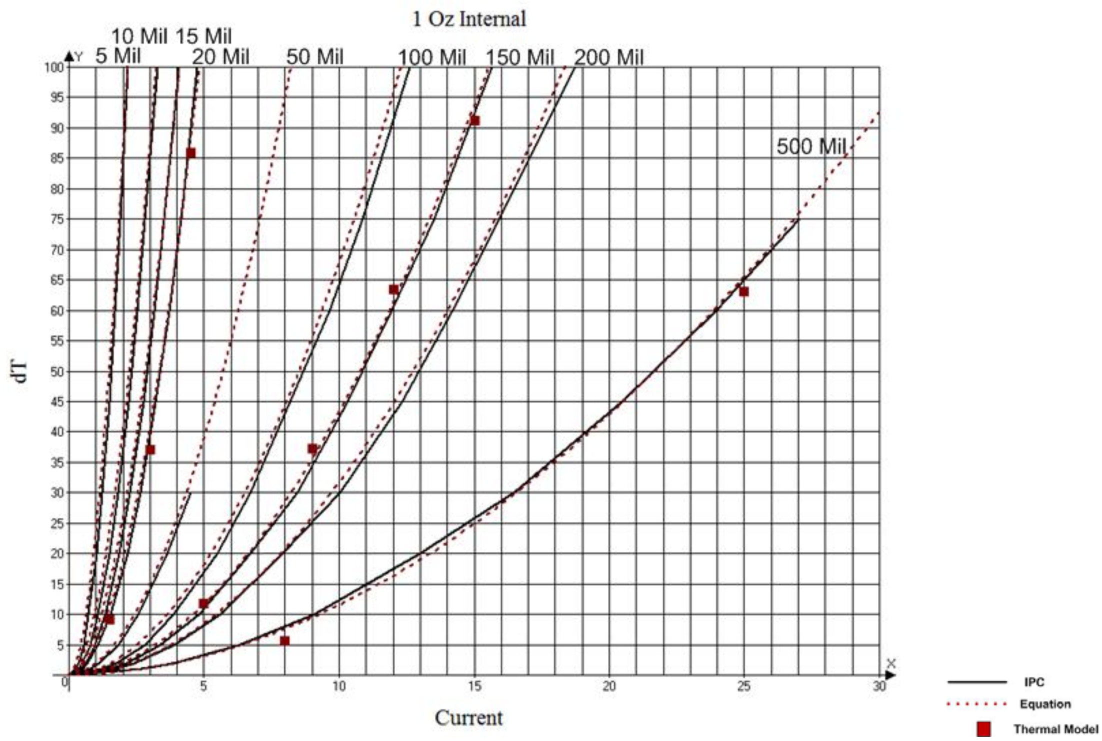


Figure 4-9
Thermal simulation results for the 1 Oz. internal traces.

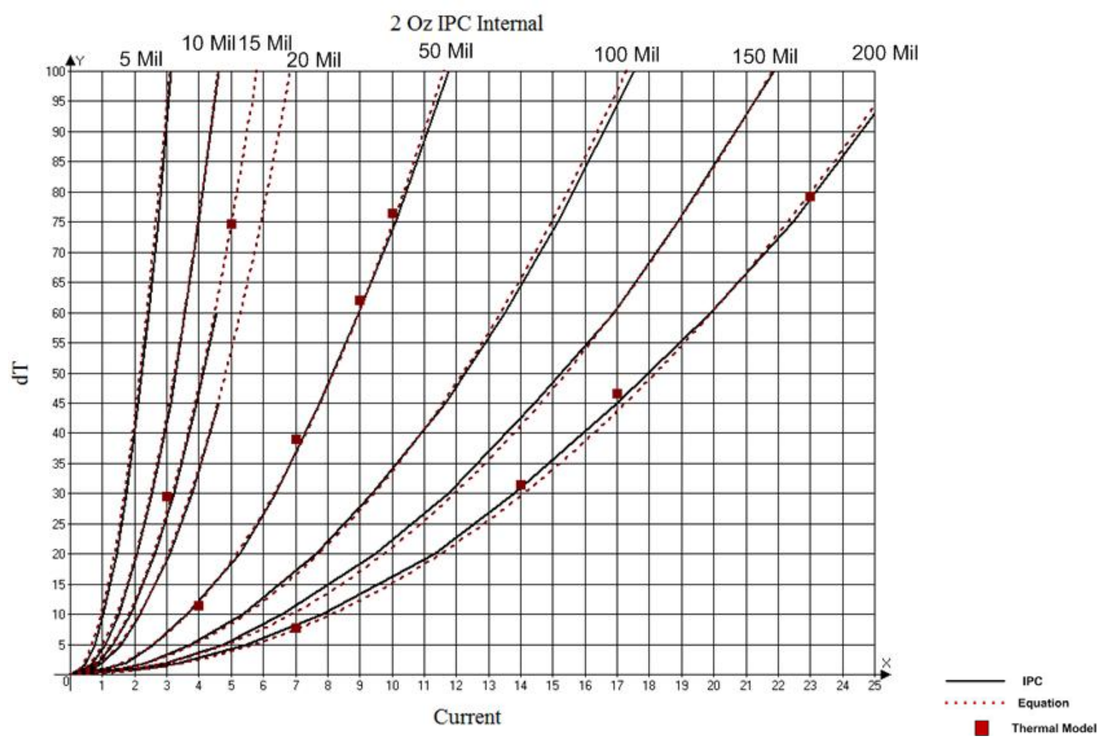


Figure 4-10
Thermal simulation results for the 2 Oz. internal traces.

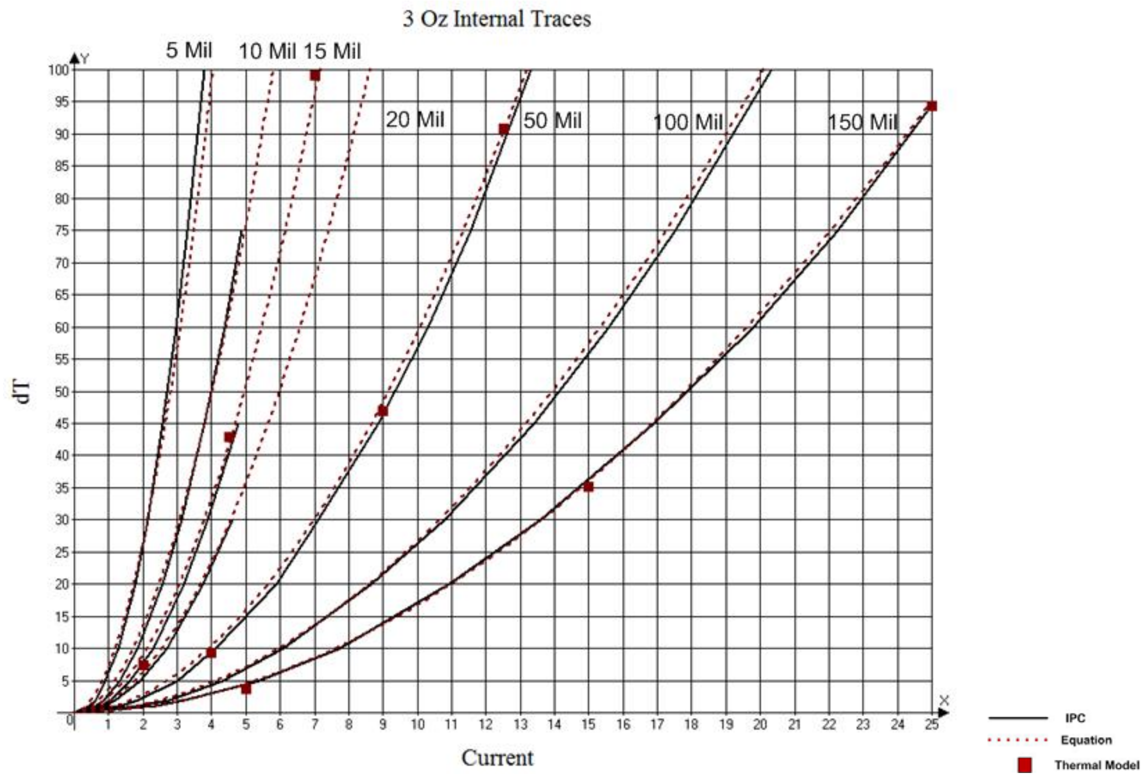


Figure 4-11
Thermal simulation results for the 3 Oz. internal traces.

Model Results, Traces in a Vacuum:

Traces in air (whether internal or external) cool by convection and by radiation. Convection and radiation convey heat (very approximately) in equal parts. If there is no air, then the board cools only by radiation. It is for this reason that traces (and boards) in a vacuum run hotter.

A couple of the vacuum traces were checked with TRM to ensure consistency. Figure 4-12 shows the results of simulation models for 100 mil wide and 200 mil wide 2 Oz. traces in a vacuum. Other vacuum trace configurations were spot checked for consistency and produced similar results.

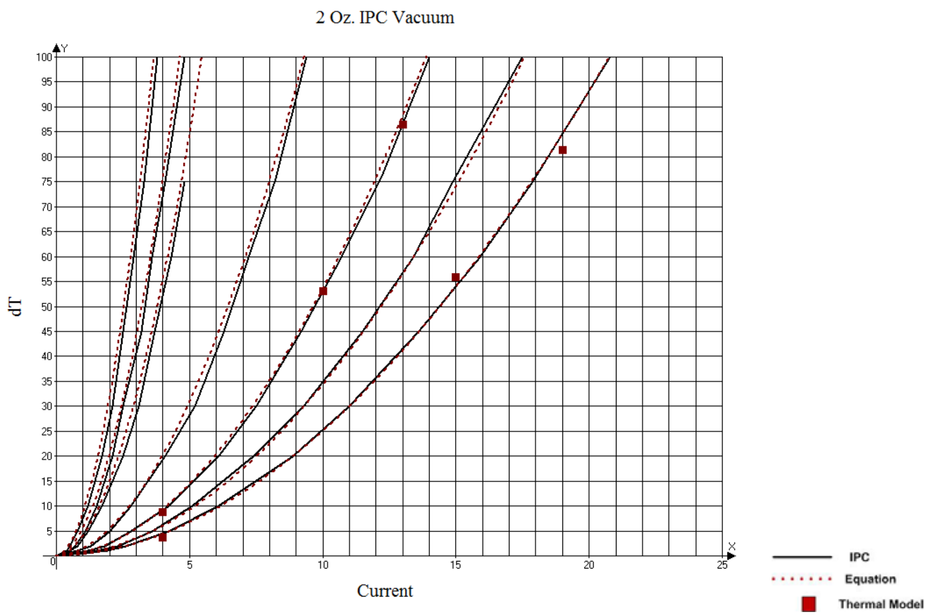


Figure 4-12
Model simulation results for 100 mil and 200 mil, 2 Oz. traces in a vacuum.

As before, the TRM models were identical except for trace width, trace thickness, and HTC. For traces in a vacuum, HTC values were in the range of 5 to 9, approximately half those for traces in air (cf. Figures 4-1 and 4-1). This is entirely consistent with expectation.

5. Sensitivities:

In Section 3 we defined a set of equations that fit the IPC curves fairly well. In Section 4 we developed a couple of thermal simulation models that also seemed to fit the IPC data fairly well. We can now use the equations and thermal simulations to look at how the trace current/temperature curves behave or might change given some changes in the environment.

Small trace width sensitivities: The current/temperature curves are very steep for narrow traces. Figure 5-1 illustrates the curves for 1 Oz., 5 and 10 mil wide internal and external traces.

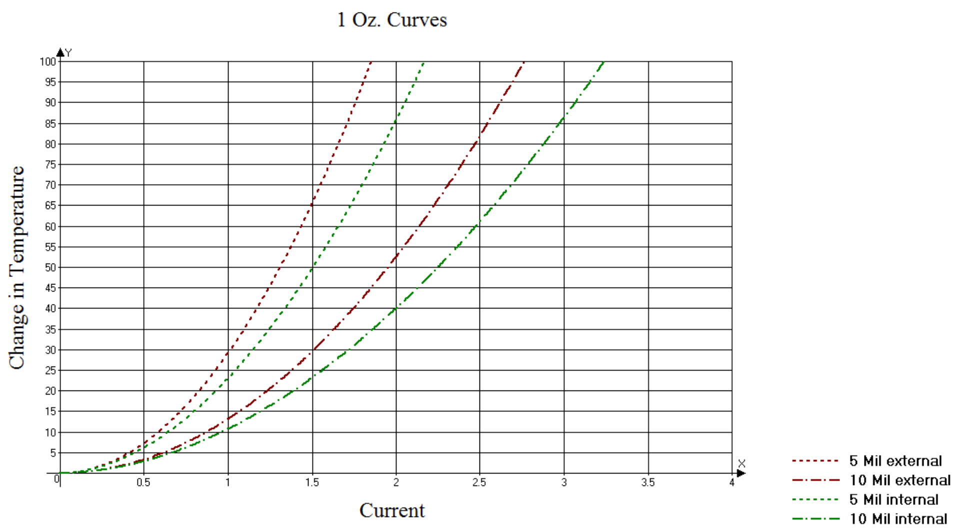


Figure 5-1
1 Oz., 5 mil and 10 mil external and internal curves

For 5 mil traces the difference between a 500 Ma current and a 1.0 Amp current is about 20 degrees C. A 1.0 Amp current has about a 25 degree temperature increase, while a 2.0 amp current has an almost 100 degree increase! The situation is only slightly better for 10 mil wide traces. As soon as we start carrying any significant currents at all, the trace temperatures increase quickly.

Figure 5-2 shows the 5 mil and 10 mil wide external traces, compared to 4 mil and 9 mil traces, respectively. Depending on how great the fabrication tolerances are, trace temperatures unexpectedly high might develop.

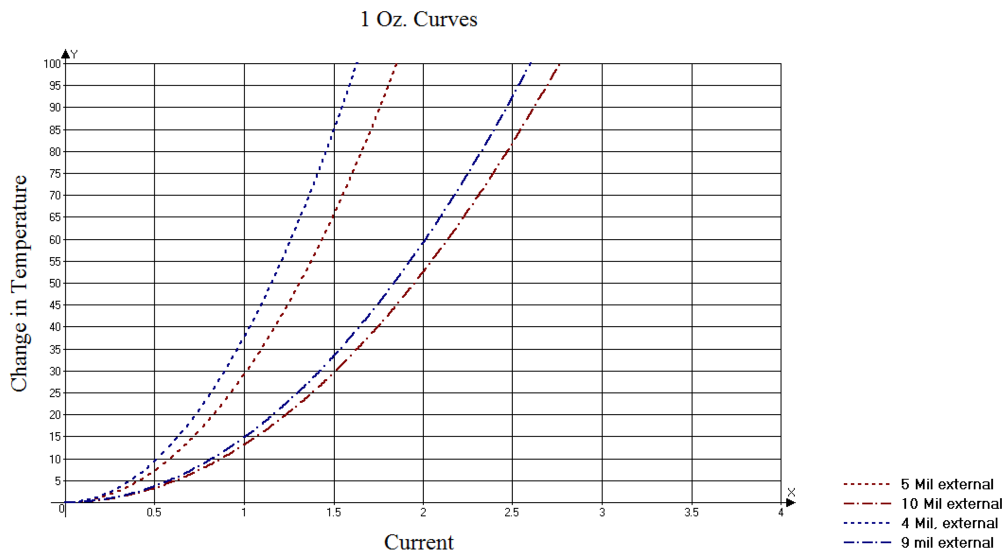


Figure 5-2
Comparing possible fabrication tolerances for 5 mil and 10 mil external traces.

The bottom line is that, if trace temperature for very narrow traces is a concern, designers might want to be particularly conservative in specifying trace widths.

Trace Length: In Section 2 we showed the results of a "typical" 6" long trace, with pads at each end, compared to the IPC test structure. The thermal simulation models suggest there is a slight difference in the change in temperature between the two cases. The model was for a 1Oz., 200 mil wide, external trace. The peak change in temperature for the IPC test arrangement is 96 degrees C while the peak change in temperature for the more "typical model is 94.7 degrees, probably not a significant difference (Note 14.).

But if we run the same model as the 6" trace shortened to 2", the temperature change drops, from 94.7 before to 81.5 for the 2" trace. If we reduce the length even further to 1", the model results show that the change in temperature drops even further to 64.6 degrees C. These results suggest that the change in temperature might well change with trace length, with shorter traces having more opportunity to shed heat through the pads at each end. By the same token, it must also be noted that the nature and size of those pads at each end will also have an impact on the change in temperature.

The conclusion is that trace length and design can have an impact on the change of temperature in a manner that is not easily predictable.

Thermal Gradients: In Figure 2-3 we showed the thermal profile of a 1 Oz., 200 mil wide, 6 inch long external trace carrying 15 Amps. If we shorten the trace, the thermal gradient is not quite so dramatic, but it still exists. Figure 5-3(a) shows the thermal gradients for the same 6 inch trace along with that for an identical trace (b) only 2 inches long. The change in the temperature for the shorter trace is 81.5 degrees C, compared to 94.7 degrees C for the longer one. But power traces are often connected to planes, which will offer additional heat sinking. Figure 5-3(c) Shows the thermal gradient for a 2” trace connected to a reference plane at each end. (The plane does not extend under the trace; we will cover that example below.) In this model the change in temperature lowers further to 60.5 degrees C.

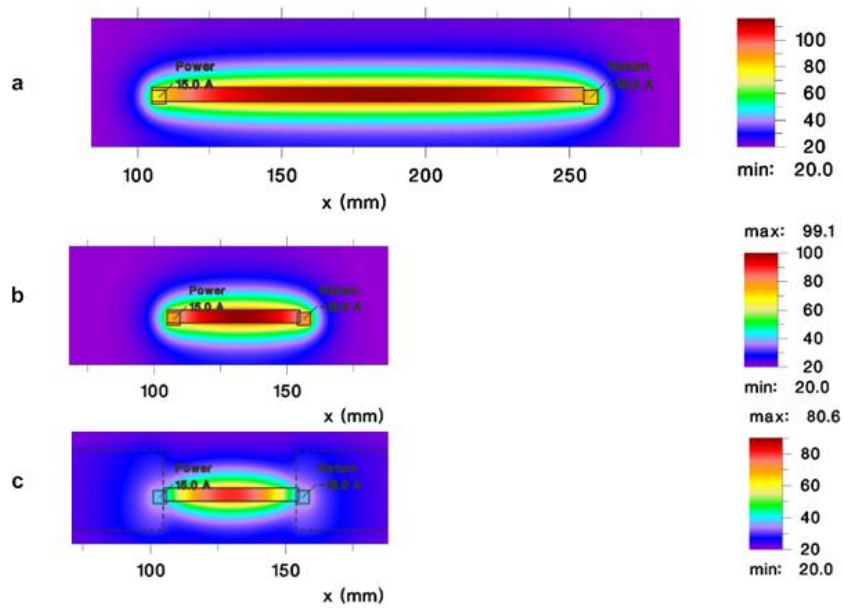


Figure 5-3
Comparing thermal profiles of 1 Oz., 200 mil wide traces carrying 15 Amps;
(a) 6 “ long, (b) 2” long, (c) 2” long with pads connected to plane.

The thermal profiles for these three examples are graphed in Figure 5-4. They are all quite different.

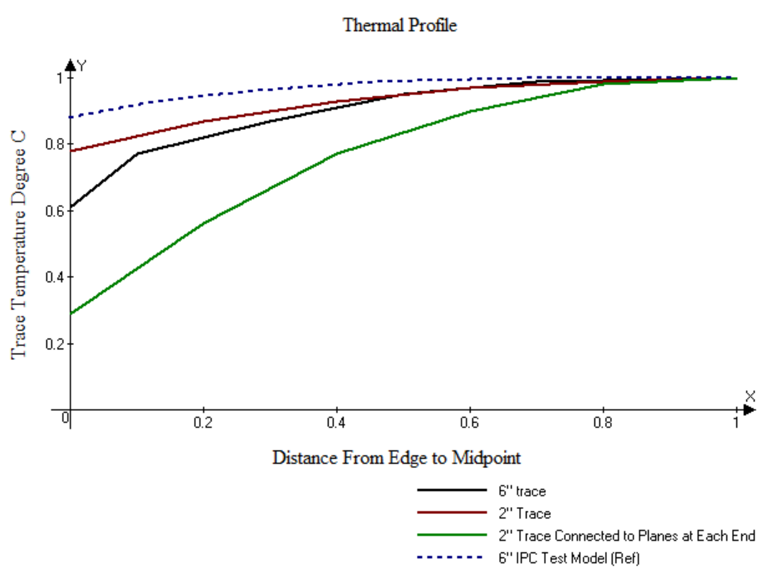


Figure 5-4
Thermal profiles of the 6” and 2” traces.

Transient Response: Traces do not heat immediately. They take some time to reach temperature, sometimes a surprisingly long time. This can be a problem for people running laboratory tests of trace current/temperature relationships; they must be sure they are waiting long enough for the trace temperatures to stabilize.

Looking at the same 6” long external trace model we looked at above, Figure 5-5 shows a curve of how long it took the trace to reach a stabilized temperature of 94.6 degrees C. It takes almost 3.5 minutes for the trace to get within 90% of its final value, almost 5 minutes to get within 95% of its final value. A normalized curve for an internal trace rising to the same temperature is shown in the red dotted curve. The internal trace rises slightly more slowly than does the external trace.

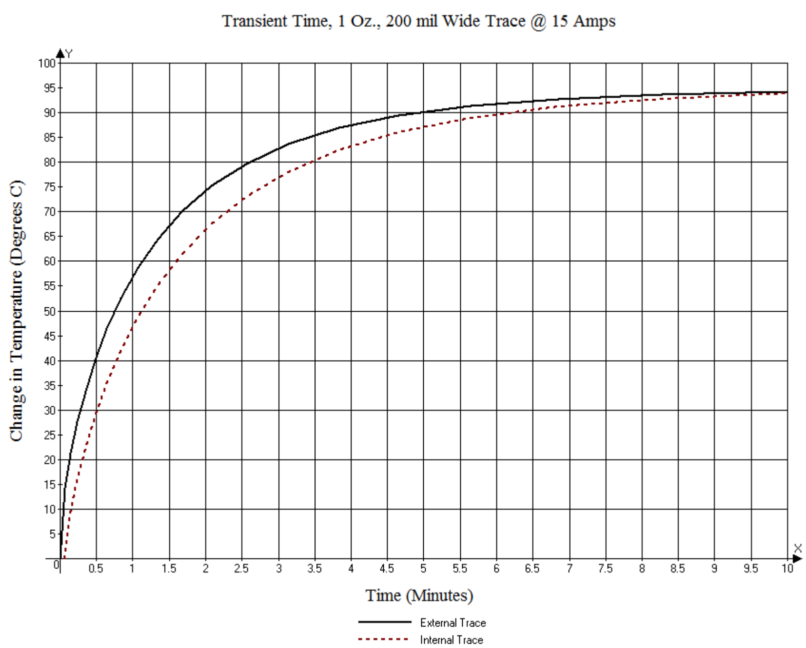


Figure 5-5
Heating time for a 1 Oz., 200 mil wide trace carrying 15 Amps.

Presence of Planes: Most of today’s boards have power planes on them. The planes play a significant role in cooling the traces above them, because the planes offer a significant conducting path away from the trace. In this section we look at two situations where planes are placed underneath our 6”, 200 mil wide, 1 Oz. trace.

First is a 1 Oz plane added to the underside of the board. For simplicity, we are simulating an unbroken plane under the entire area of the board. A real board may not have a plane covering the *entire* area. But all that is really needed to get similar results is a plane that is directly under the trace and is significantly wider than the trace itself. The resulting maximum temperature change is 47.9 degrees C.

Second is a plane that is directly under the trace layer. In this model, we are placing the plane ten mils under the trace layer, typical for today’s high-speed boards. Again, we are simulating an unbroken plane under the entire layer; but again all that is needed is a plane directly under the trace that is significantly wider than the trace itself. The resulting maximum temperature change is 33.7 degrees C (compared to 94.7 degrees C for the case without a plane).

Figure 5-6 illustrates the thermal profiles of the case where the plane is 10 mils under the trace layer, Figure 5-6(a) is the thermal profile of the trace layer, while Figure 5-6(b) is the thermal profile of the plane layer. There are two things to notice in this simulation. First, note how much wider the thermal profile is compared to other thermal profiles shown in this paper, especially Figure 5-3(a). The plane helps provide a much wider area for the heat to dissipate.

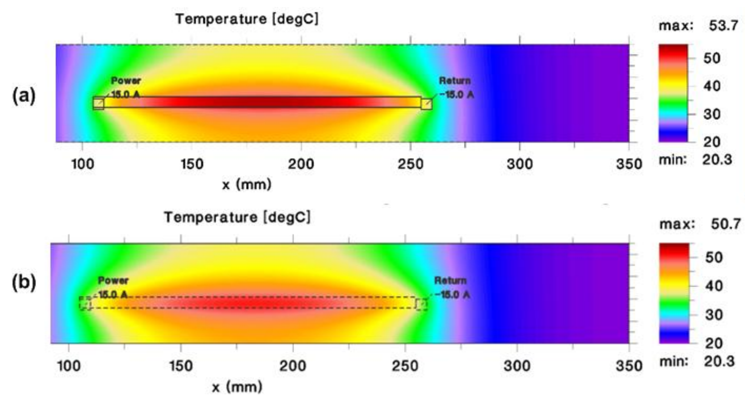


Figure 5-6
Thermal profiles of a 1 Oz., 200 mil wide trace over a plane
10 mils under the trace layer, and carrying 15 Amps.

Second, note that the plane layer itself gets warm. While the midpoint of the trace heats to 53.7 degrees (a 33.7 degree change from ambient) the plane itself directly under the midpoint heats to 48.1 degrees C. While this helps lower the temperature of the trace, it may also have implications for other, adjacent traces (something we are not considering here.)

Adjacent Trace: In most practical boards real estate is valuable. So there is almost always a trace nearby the trace we are concerned about. In this model we will add another 200 mil wide trace separated from the trace of interest by 8 mils.

The result of this model is a change of temperature of 84.9 degrees. The thermal profile is shown in Figure 5-7. Note how the adjacent trace increases in temperature to 71.5 degrees (a ΔT of 51.5), which may have other implications for the board.

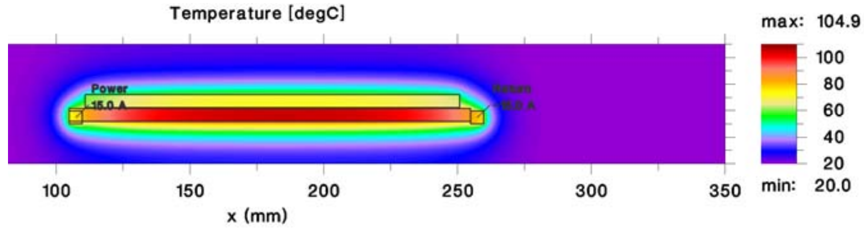


Figure 5-7
Thermal profile when there is an adjacent trace.

Naturally, these results would be influenced by how wide the adjacent trace is and how far it is from the trace of interest.

Adjacent Trace AND Internal Plane: An adjacent trace by itself heated to a ΔT of 51.5 degrees C, while the trace under investigation had a ΔT of 33.7 degrees C if there was an adjacent internal plane. If we model BOTH an adjacent trace and underlying plane, the corresponding ΔTs are 26.9 and 33.4 degrees C. Thus, the net impact of the underlying plane is to help cool the adjacent trace.

Air Flow: The effects of air blowing across a trace are very hard to simulate. It would be difficult to simulate that even if it were possible to estimate how much air moves across the trace and how fast it moves. The thing we do know is that the effect of moving air would be to increase the Heat Transfer Coefficient. We can at least indicate the trend of the effect by running a simulation at a couple of higher values of HTC.

All of the 6” trace simulations run in this section have been run with an HTC of 11 (see Figure 4-1.) If we run the same model with HTCs of 14 and 17 respectively, we get changes in temperature of 78.9 degrees C and 68.3 degrees, respectively (compared to 94.7 before).

This result, obviously, has to be taken with a large grain of salt because there is no way to meaningfully equate these results to any particular degree of air flow.

Material: All the simulations in this section have been run with the material selection set to polyimide. That is primarily because the IPC data was also taken with boards fabricated from Polyimide. Thus, all the results are directly comparable. FR4 is a more common material used in many systems, and FR4 has a lower thermal conductivity than does Polyimide. There are many grades of FR4 available, so selecting one for simulation is problematic.

Thermal conductivity in a board takes place in three dimensions. Through the board, from top to bottom, is usually referred to as the z-dimension. Parallel to the top and bottom surface is referred to as the x- and y-dimension. Thermal conductivity is different in the various dimensions. If thermal conductivity is referenced at all in a material specification, it more commonly is given for the z-dimension than for all dimensions.

FR4 boards are typically made from fiberglass embedded within epoxy. The glass conducts heat better than does the epoxy. So boards with a “tighter” weave will probably conduct heat better than those with a looser weave. Materials with tighter weaves also have higher relative dielectric constants (Er) because the Er of glass is higher than that for epoxy. Materials with tighter weaves are often used in higher speed boards where greater material homogeneity is desirable.

We ran a simulation with a board based on FR4 material of a type that might be considered a less expensive, looser weave. In that respect, we would expect a slightly higher temperature than we would with a material of more uniform quality. This probably represents a “worst case” material selection when contrasted with polyimide.

The temperature change in this simulation was 122.9 degrees C (compared to 94.7 before.)

(Edit) **Resistivity**: In this study we have assumed that resistivity is 1.7 uohm-cm. But some data exists that resistivity of traces might increase as a result of some fabrication and processing steps (see note 15). Results as high as 2.1 uohm-cm and 2.4 uohm-cm have been reported. Since the temperature of the trace is directly related to I^2R, and R is directly related to resistivity, we can expect higher resistivities to lead to higher temperatures. We ran one test of our board at 2.1 uohm-cm resistivity with a resulting change of temperature of 122 degrees C, confirming this expectation.

Summary: We have looked at many different types of simulations in this section. All started with a 1 Oz., 200 mil wide, 6" external trace, carrying 15 Amps, and a Polyimide board. The results are summarized are Table 5-1.

Simulation Condition	**ΔT**
Simple trace	94.7
Shortened to 2"	81.5
Heat sink pads (not discussed)	92.8
Bottom plane	47.9
Internal plane	33.7
Adjacent trace	84.9 (51.5)
Adjacent trace and internal plane	33.4 (26.9)
Air flow*	68.3 - 78.9
Material (FR4)	122.9
Resistivity to 2.1 uohm-cm	122.0

Table 5-1
Various results of the simulations of a 1 Oz., 200 mil wide, external trace
(* Very tenuous assumptions in this model)

There are a couple of generalizations we can make.

1. It is almost universally true that variations in results increase with temperature. That is, at low temperatures (associated with lower currents) the various parameters we have looked at here make little or no difference. At intermediate temperatures, the differences would by much milder than reported here.
2. Except for material selection (and perhaps changes in resistivity), the IPC curves generally represent a "worst case" scenario. Any other variation we introduce lowers the trace temperature, sometimes considerably so.
3. We have not addressed, in this paper, some of the more complex shapes, such as the fillets in thermal reliefs or the copper plating in drill holes. While we can speculate that the I^2R heating in these cases might be similar to other simulations, the cooling situations might be substantially more complicated.
4. The relationship between trace currents and temperatures is *very* complex. It is too complex to model with a single set of equations or curves. Since board real estate is very expensive, board designers usually want to use the smallest traces their fabricators will allow while still meeting the requirements. Optimizing board area when considering

thermal effects does not seem possible without sophisticated thermal simulation software.

6. UltraCAD's PCB Trace Calculator

UltraCAD has developed a trace calculator that can make the trace current/temperature calculations for you very easily. A screen shot is shown in Figure 6-1.

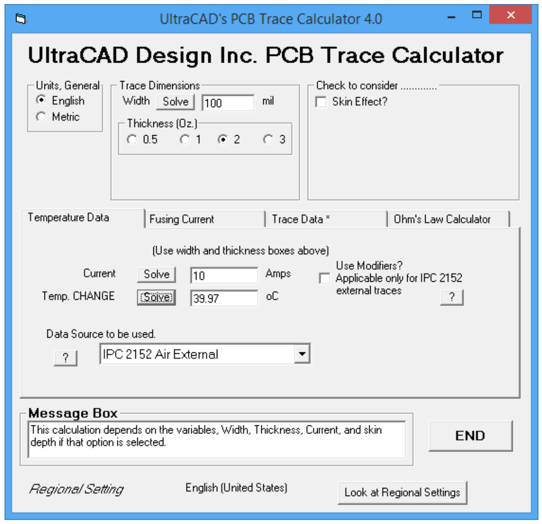


Figure 6-1
UltraCAD PCB Trace calculator, version 4.

The user enters the trace thickness and any two of the remaining three variables (trace width, current, and temperature change.) Then the user can solve for the third variable. In the example shown, for a 100 mil wide, 2 Oz. trace carrying 10 Amps, the calculated temperature change is just under 40 ^{o}C. Comparing this result with Figure 3-3 shows an almost perfect fit.

Figure 6-2 shows that the calculated temperature change for an internal trace is only 33 ^{o}C.

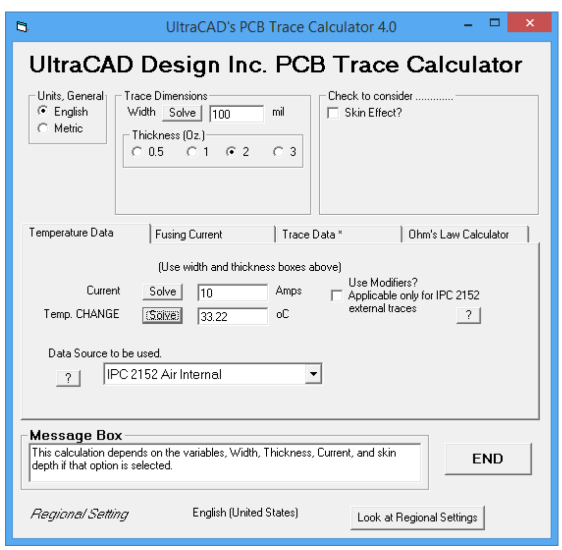


Figure 6-2
Result for an internal trace.

The calculator can also adjust the results for skin effect. If, for example, the frequency were 30 MHz, then the skin depth would significantly impact the cross-sectional area, resulting in a temperature change of almost 114 ^{o}C.

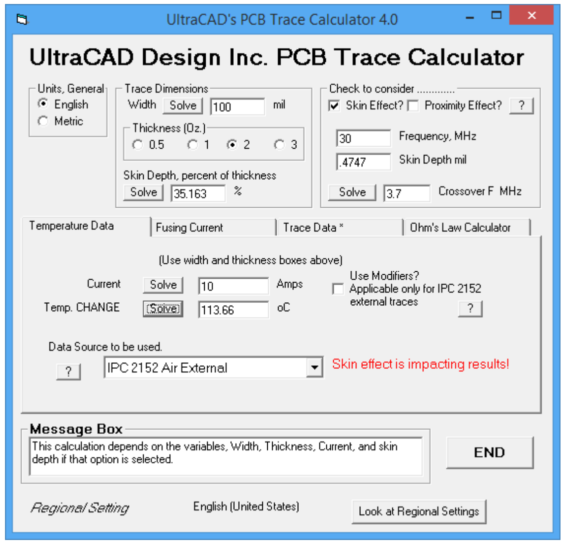


Figure 6-3
The calculator can adjust for the skin effect.

You can learn more about this calculator at www.ultracad.com.

Notes:

1. For more information, see IPC-2152, "Standard for Determining Current Carrying Capacity in Printed Board Design," August, 2009, Appendix A.7, p. 85. A copy of the original NBS chart is included there as Figure A-89, p. 86.
2. ANSI/IPC-D-275, Design Standard for Rigid Printed Boards and Rigid Printed Board Assemblies, Figure 3-4, Page 10, IPC, September, 1991
3. IPC-2221, Generic Standard on Printed Board Design, 1998, superseded by IPC-2221A, Generic Standard on Printed Board Design, May, 2003, Figure 6-4, p. 41
4. Brooks, Douglas, "Temperature Rise in PCB Traces," published on the UltraCAD website and printed in the "Proceedings of the PCB Design Conference, West," Miller Freeman, Inc., March 23-27, 1998.
5. "Printed Circuits and High Currents", Friar, Michael E. and McClurg, Roger H., Design News, Vol. 23, December 6, 1968, pp. 102-107.
6. Brooks, Douglas, "Fusing Current: When Traces Melt Without a Trace!," 1998, available at http://www.ultracad.com/article_temperature.htm
7. Brooks, Douglas and Adam, Johannes, "Fusing Currents in Traces," available for download at www.ultracad.com.
8. For two examples, see http://chemistry.about.com/od/moleculescompounds/a/Table-Of-Electrical-Resistivity-And-Conductivity.htm and http://hyperphysics.phy-astr.gsu.edu/hbase/tables/rstiv.html
9. http://en.wikipedia.org/wiki/Electrical_resistivity_and_conductivity
10. IPC-TM-650, Test Methods Manual, Number 2.5.4.1A "Conductor Temperature Rise Due to Current Changes in Conductors" available at http://www.ipc.org/test-methods.aspx

11. UltraCAD has a freeware wire gauge converter calculator available at http://www.ultracad.com/calc.htm
12. We used a program called GetData Graph Digitizer, available here: http://www.getdata-graph-digitizer.com/
13. If you would like to know more about heat transfer coefficients, start here http://en.wikipedia.org/wiki/Heat_transfer_coefficient
14. In this section many of the simulations will be performed with a single model setup, that for a 1 Oz., 200 mil wide, external trace carrying 15 Amps. A legitimate question would be what about other trace widths? The relevant condition being modeled is temperature. If we used, for example, a 50 mil wide trace, heated with current to the same temperature, most of the rest of the simulation results (thermal transients, transient times, effect of planes, etc.) would remain essentially (relatively) unchanged.
15. (Edit) For example Jeff Loyer, Signal Integrity Consulting, posted an entry on the SI-List on 7/1/15 noting that he had measured resistivities ranging from 1.7 uohm-cm to 2.4 uohm-cm, a 40% difference. Some of this variation appeared to be a result of fabrication processes. Since trace temperature is directly related to resistivity, this uncontrolled variation may have had some effect on the results.

Acknowledgement:

This paper would not have been possible without the generous encouragement and support from Johannes Adam, President of ADAM Research, www.adam-research.de, located in Leiman, Germany. Dr. Adam is specialist in electronics cooling and has written TRM (Thermal Risk Management) a thermal simulation tool for printed circuit boards *that has been adapted for this study, and Dr. Adam has made that tool available to me. I am indebted to Dr. Adam for his support and encouragement.*

Appendices

Appendix 1, copies from original MIL STD document.

MIL-STD-275E
31 December 1984

(For use in determining current carrying capacity and sizes of etched copper conductors for various temperature rises above ambient)

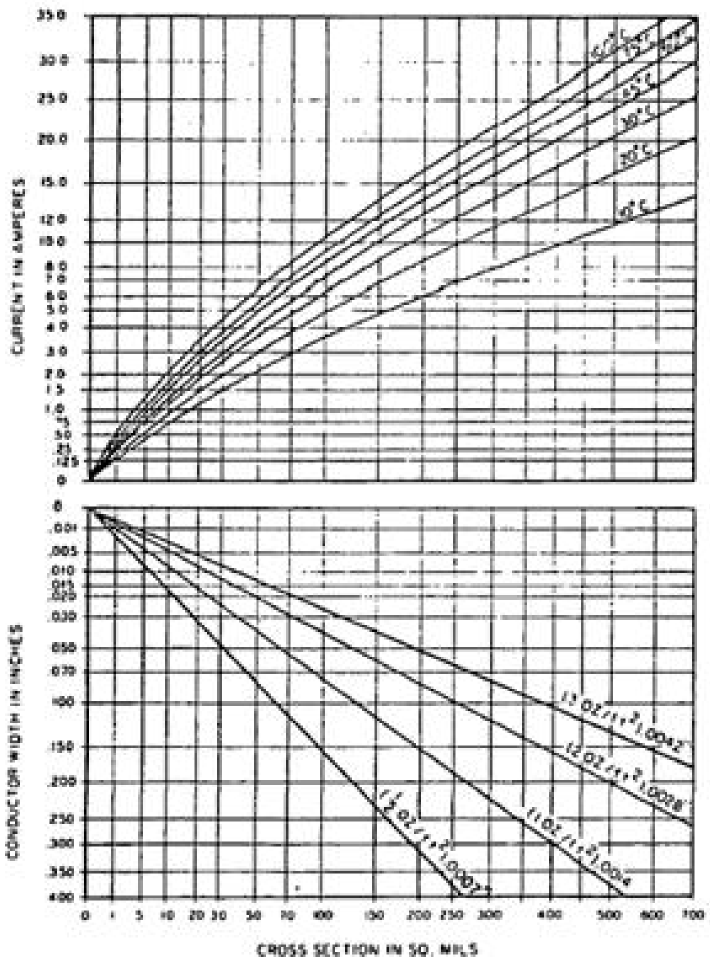


FIGURE 4a. Conductor thickness and width for type 1, type 2, and external layers of type 3 printed-wiring boards.

Source: MIL-STD-275E, Printed Wiring For Electronic Equipment, p. 34, 31 December, 1984. Downloaded from http://www.everyspec.com .

The following note appears on the cover page of this document:

MIL - STD - 275E

31 December 1984

SUPERSEDING
MIL - STD - 275D
26 APRIL 1978
MIL - STD - 1495
3 AUGUST 1973

The original internal trace curves appear a little further on in MIL-STD-275E.

Appendix 2, Comparison of IPC 2221 Curves and IPC 2152 Curves

The top set of curves is a reproduction of Figure 5-3 from IPC 2152. The bottom set of curves is a reproduction of the curves from IPC 2221. Since they are drawn on different axes, we have redrawn the bottom curve on the next page.

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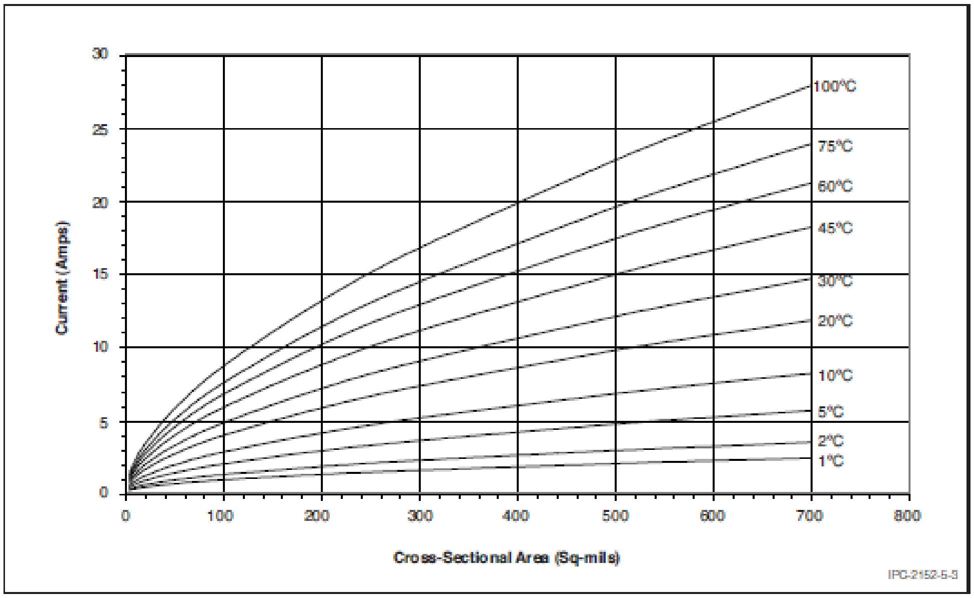

Figure 5-3 Internal and External Conductors (Still Air) (5-700 Sq-mils)

(For use in determining current carrying capacity and sizes of etched copper conductors for various temperature rises above ambient.)

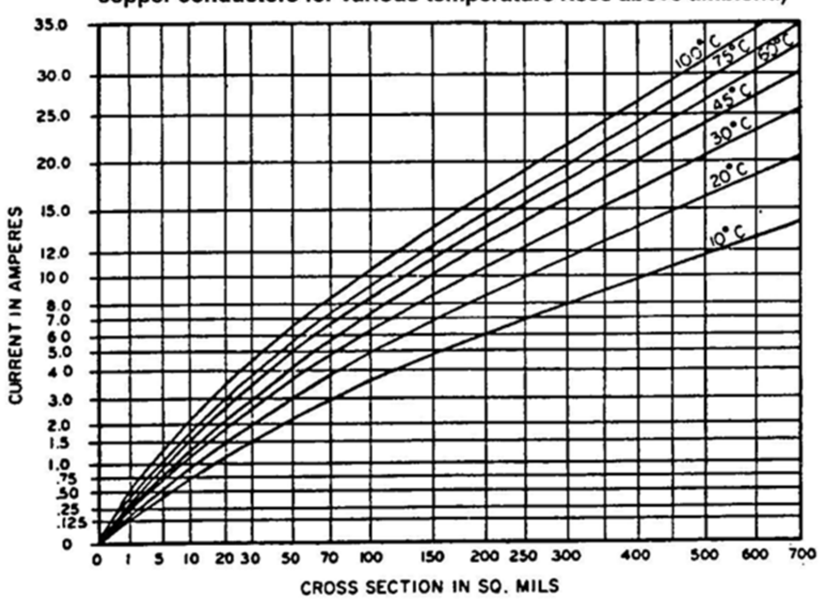

Figure A External Conductors

The top set of curves is a reproduction of Figure 5-3 from IPC 2152. The bottom set of curves is a reproduction of the curves from IPC 2221, redrawn on the same set of axes as the IPC 2152 curves.

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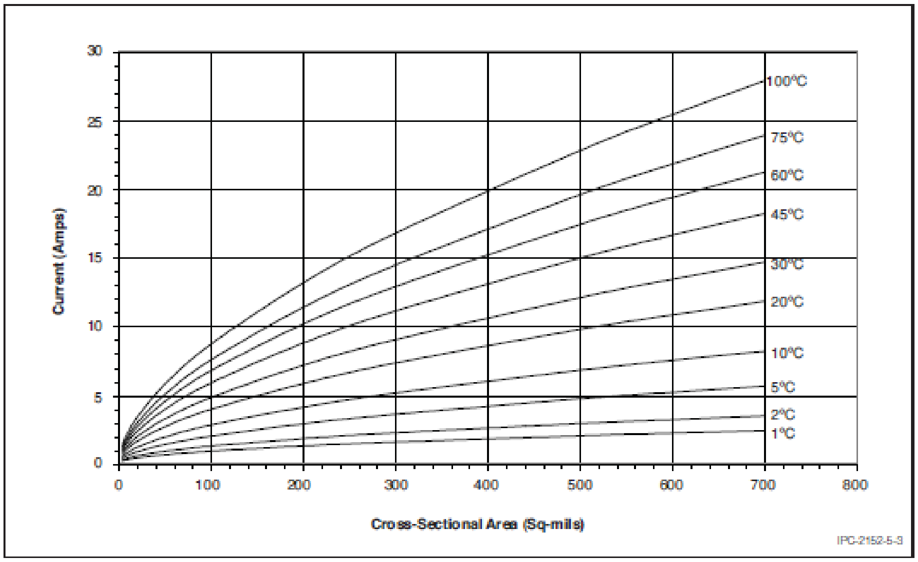
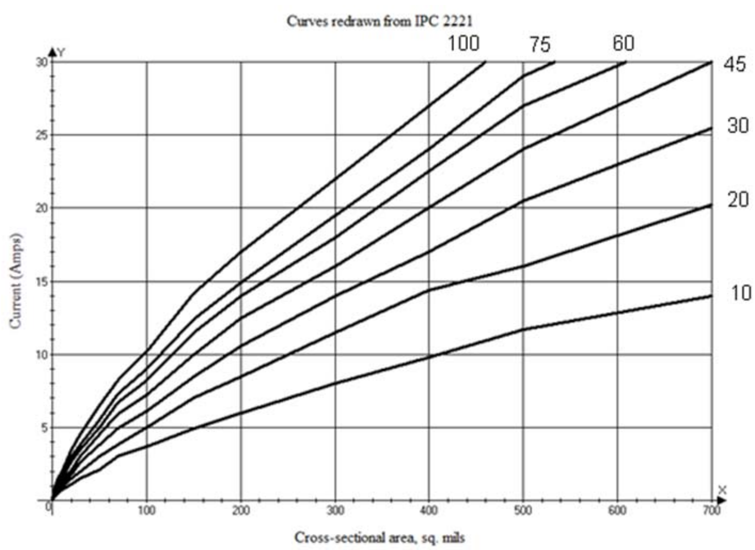


Figure 5-3 Internal and External Conductors (Still Air) (5-700 Sq-mils)



Appendix 3, Comparison of internal and external curves.

The IPC internal curves run slightly cooler than do the external curves. Figures A3-1 and A3-2 show the 2 Oz external and internal curves, respectively, from IPC 2152.

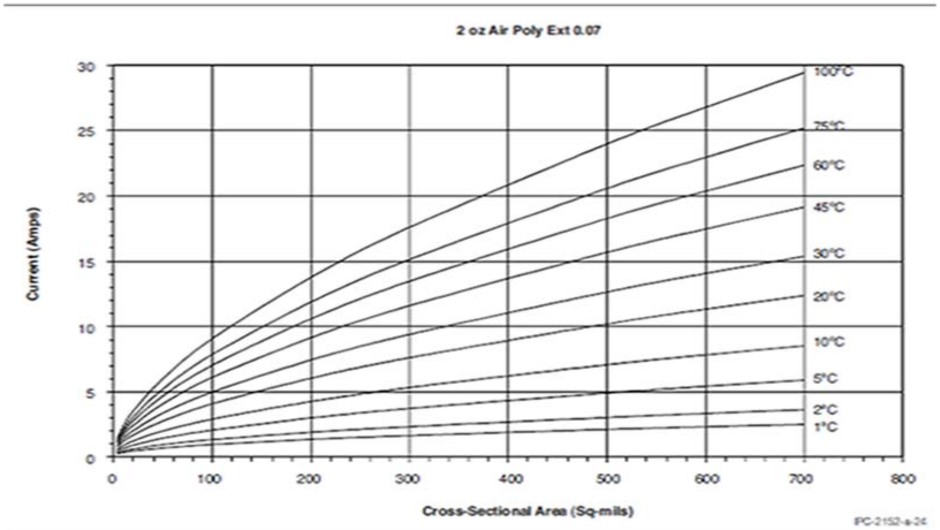


Figure A3-1
IPC 2 Oz. external curves. IPC 2152 Figure A-24, page 41.

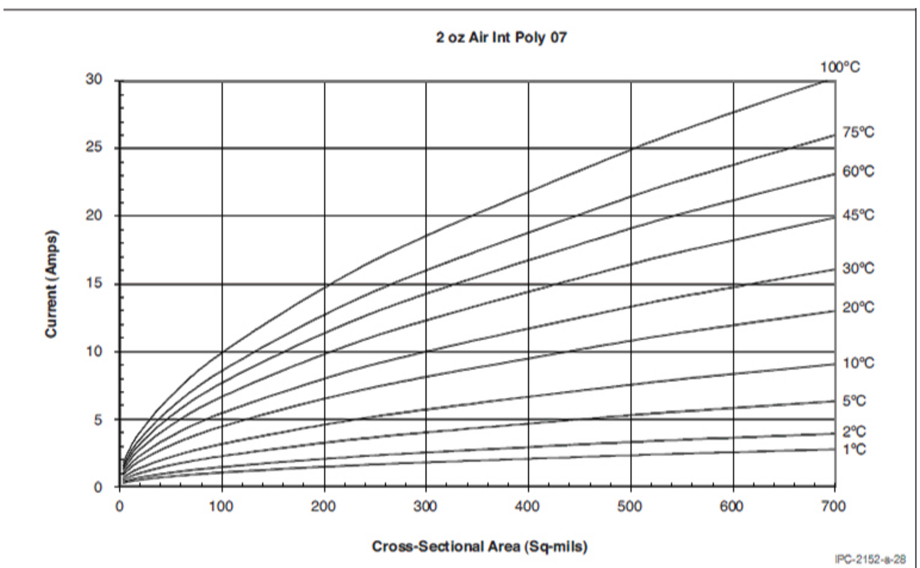


Figure A3-2
IPC 2 Oz. internal curves. IPC 2152, Figure A-28, page 44.

Note that the internal curve intersection of 500 Sq-mils and 25 Amps lies exactly on the 100 degree C curve, while the same intersection on the external lies slightly *above* the 100 degree C curve. Figure A3-3 shows the two curves in superposition.

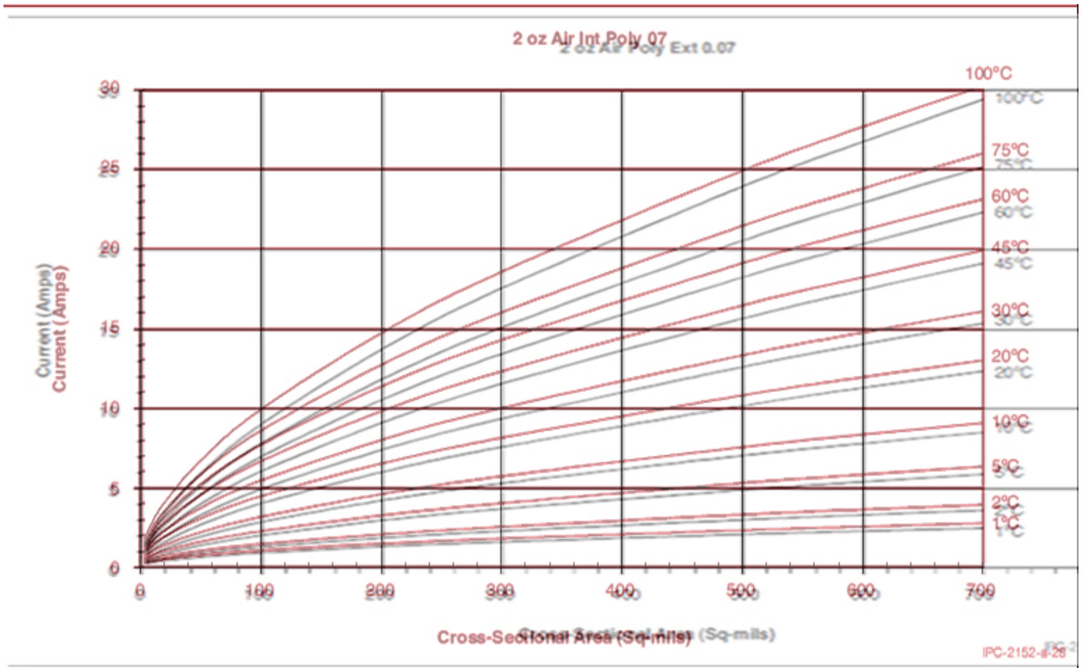


Figure A3-3
Superposition of the 2 Oz. IPC internal (red) and external (gray) curves.
Each point in the x,y plane is at a slightly higher temperature
with the external (gray) curves.

Figure A3-4 shows selected 2 Oz. curves for comparison. Note how the temperature difference is much greater for narrower curves than it is for wider curves for any given current.

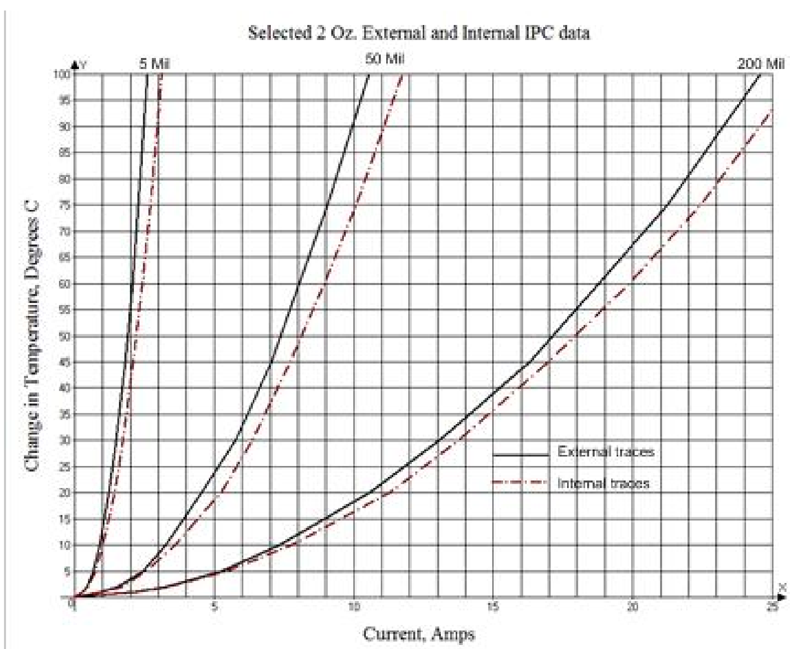
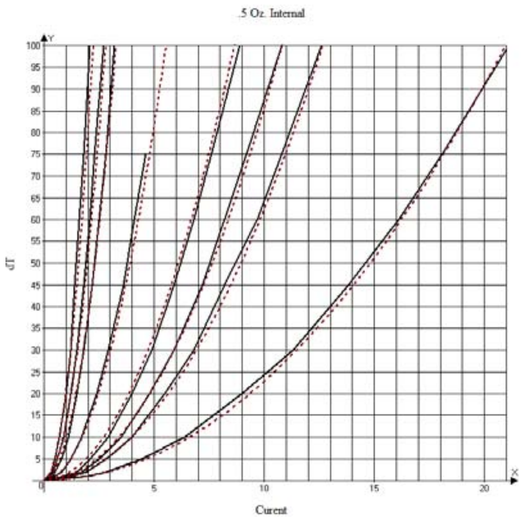
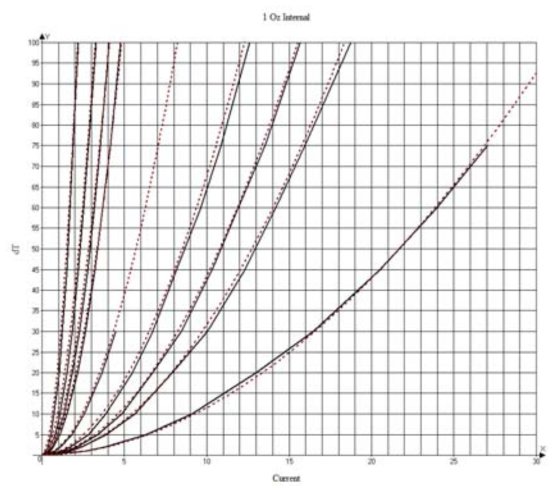


Figure A3-4
Comparison of selected internal and external 2 Oz. traces.

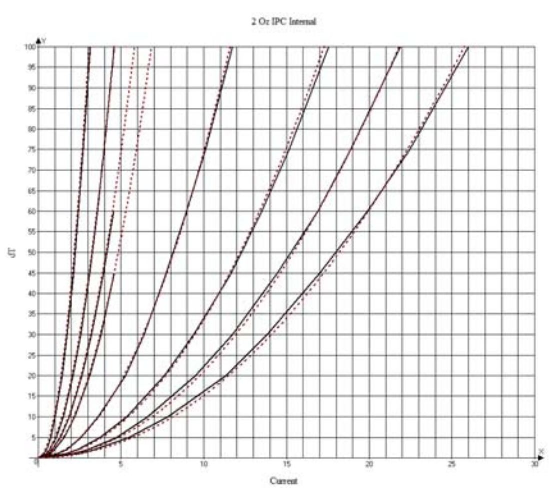
Appendix 4, Internal IPC curves fitted with equations. See Section 3.



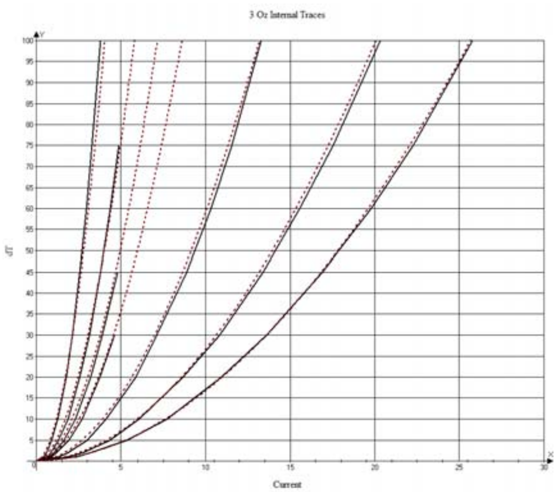
0.5 Oz. internal data fitted with equations.



1 Oz. Internal data fitted with equations.

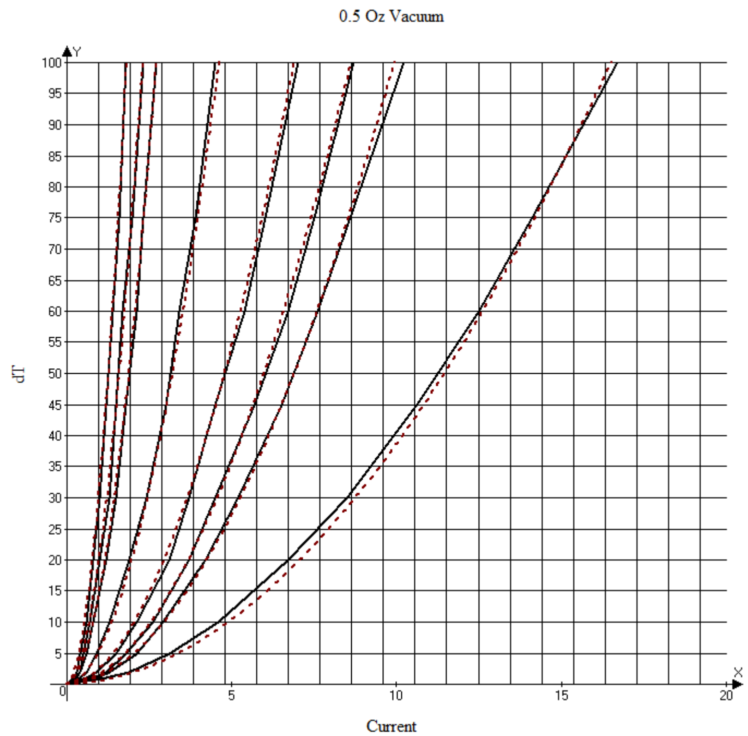


2 Oz. internal data fitted with equations

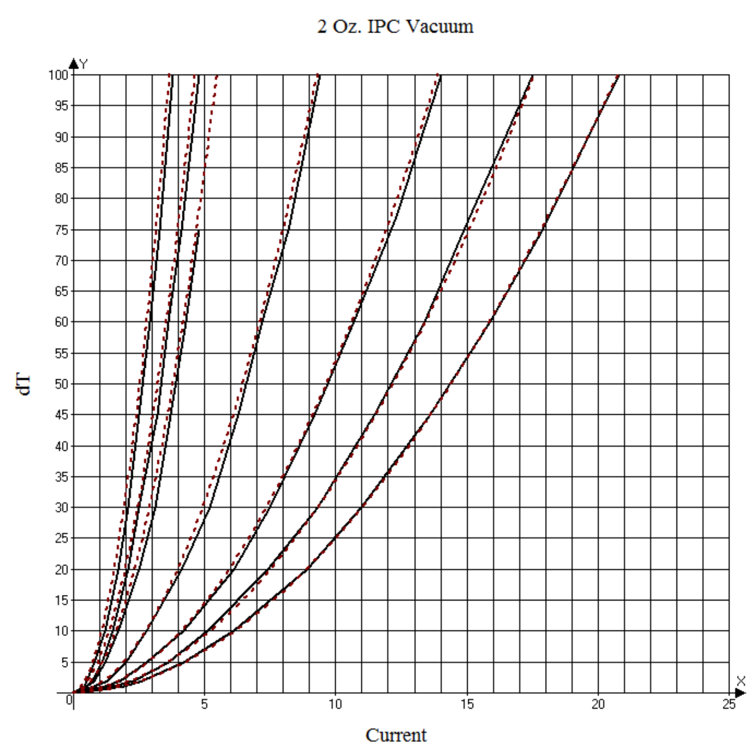


3 Oz. internal data fitted with equations.

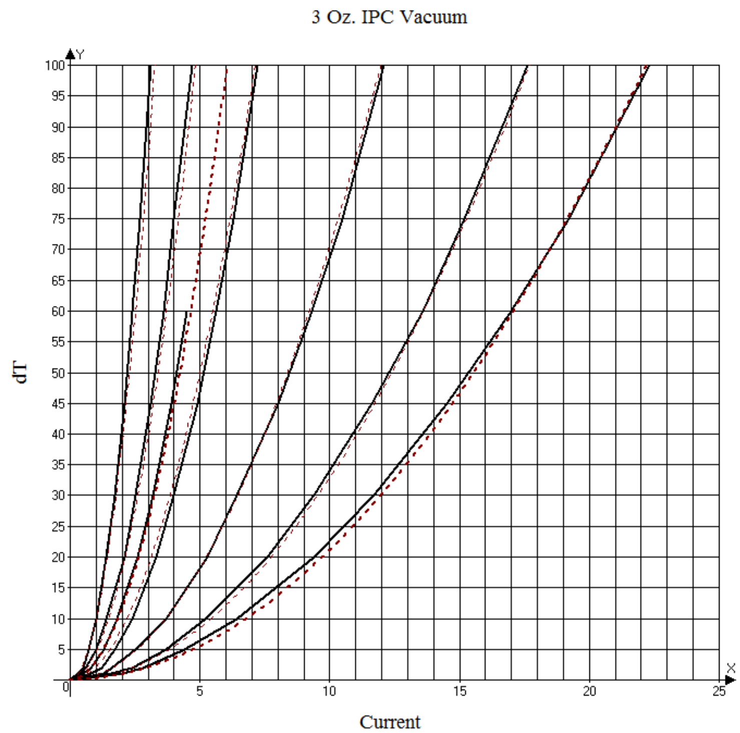
Appendix 5, IPC traces in a vacuum fitted with equations.



0.5 Oz. vacuum data fitted with equations.



2 Oz. vacuum data fitted with equations.



3 Oz. vacuum data fitted with equations.

Appendix 6, Detailed set of equations for the curves.

In the few cases where there are differences by width within a trace thickness, the differences are small and probably reflect errors, uncertainties, and variations as a result of various graphical drawings and manipulations.

Structure						
External	**dT =**	**Constant**	**W^**	**Th^**	**C^**	
All Thicknesses		215.3	-1.15	-1.00	2	
Internal						
.5 Oz		110	-1.10	-1.52	2	for 100 mil and wider
		125	-1.10	-1.52	2	50 mil
		130	-1.10	1.52	2	20 mil and smaller
1 Oz		200	-1.10	-1.52	1.9	
2 Oz		300.3	-1.15	-1.52	2	
3 Oz		300	-1.15	-1.52	1.9	for 50, 100, 150 mil
		200	-1.15	-1.52	1.9	5 Mil
		225	-1.15	-1.52	1.9	10 Mil
		240	-1.15	-1.52	1.9	15 Mil
		235	-1.15	-1.52	1.9	20 Mil
Vacuum						
.5 Oz.		210	-1.10	-1.52	1.9	100 mil and smaller
		215	-1.10	-1.52	1.9	150 mil
		225	-1.10	-1.52	1.9	200 mil
		235	-1.10	-1.52	1.9	500 mil
2 Oz.		480	-1.10	-1.52	1.9	
3 Oz		460	-1.10	-1.52	1.95	

About the authors:

Douglas Brooks received a BS and MS in EE from Stanford and a PhD from the University of Washington. He has spent most of his career in electronic manufacturing companies, rising from staff engineer to general manager and then president of his own company. He spent two short tours as a professor, first at San Diego State Univ. and then at the Univ. of Washington. His last 20 years were spent as owner of UltraCAD Design, Inc. a PCB design service bureau in Bellevue, WA. He has given seminars on signal integrity issues around the world, and his articles have appeared in numerous trade journals. Brooks has authored two books, the latest one, PCB Currents; How They Flow, How They React, published by Prentice Hall in 2013. He has three children and seven grandchildren, and is now retired with his wife in Kirkland, WA.

Johannes Adam got a doctorate in physics from University of Heidelberg, Germany, in 1989 on a thesis about numerical treatment of 3- dimensional radiation transport in moving astrophysical plasmas. He was then employed in software companies, mainly working on numerical simulations of electronics cooling at companies like Cisi Ingenierie S.A. , Flomerics. Ltd. and Mentor Graphics Corp. In 2009 he founded ADAM Research and does work as a technical consultant for electronics developing companies and as a software developer. He is the author of a simulation program called TRM (Thermal Risk Management), designed for electronics developers and PCB designers who want to solve electro-thermal problems at the board level. He is member of the German chapter of IPC (FED e.V.) and engages in its seminars about thermal topics. He is Certified Interconnect Designer (CID). He is living in Leimen near Heidelberg.