Fusing Currents in Traces

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(Revision 1, July, 2015)
(See Note 8)

For a complete analysis of trace and via currents and temperatures, see Brooks and Adam, ***PCB Trace and Via Currents and Temperatures: The Complete Analysis****, Available at Amazon.com, https://www.amazon.com/PCB-Trace-Via-Currents-Temperatures/dp/1530389437/ref=la_B001IR1JBS_1_4?s=books&ie=UTF8&qid=1476216597&sr=1-4*

At the end of a seminar one of the authors was leading one day, a participant asked the following question:

> If there is a catastrophic failure of my system, a certain 1 Oz. trace will carry 40 Amps. I need it to carry that for 1 second while the system shuts down in a controlled manner. What size trace do I need?

The first person usually credited with exploring this type of problem was Sir W. H. Preece back in the 1880's. He was then a consulting engineer for the British General Post Office. At that time the Post Office was responsible for the telegraph (and later wireless telegraph) system in England. Preece was concerned with the effects of lightning strikes on telegraph systems and was searching for the best material and size for a fuse application. He published three papers [1] in the Proceedings of the Royal Society of London in the 1880's that formed the basis for his famous equation:

$$I = a * d^{3/2} \qquad \text{[Eq. 1]}$$

where d is the diameter of the wire in inches, a is a constant (10244 for copper), and I is the fusing current in Amps. A little algebra transforms this equation to:

$$I = 12277*A^{3/4} \qquad \text{[Eq. 2]}$$

where A is the cross-sectional area in square inches.

A problem (for us) with Preece's equation is that there is no variable for time. Around the 1920's (we believe) I. M. Onderdonk developed his equation that does incorporate time. As far as we can determine, Onderdonk never published his work under his own name. The earliest reference we know of is one by E. R. Stauffacher in 1928 [2]. In it he refers to Onderdonk's equation as:

$$33\left(\frac{I}{A}\right)^2 S = \log_{10}\left(\frac{\Delta T}{274}+1\right)$$ [Eq. 3]

where ΔT is the change in temperature from an ambient temperature = 40 °C. There are later publications which refer to Onderdonk's equation in a more general form:

$$33\left(\frac{I}{A}\right)^2 S = \log_{10}\left(\frac{\Delta T}{234+Ta}+1\right)$$ [Eq. 4]

where: I = the current in Amps
A = the cross-sectional area in circular mils (note 1)
S = the time in seconds the current is applied
ΔT = the rise in temperature from the ambient or initial state (see note 2)
Ta = the reference temperature in degrees C

We believe the problem motivating Onderdonk was the one described in Stauffacher's paper. Under certain conditions of dust or moisture, an arc (short circuit) may develop across an insulator supporting a high-voltage power transmission line. The wires supporting the poles and insulators must be able to carry this short-circuit current for sufficient time for the automated equipment "to clear the line."

In this paper we are going to look at the question of trace fusing currents using Onderdonk's equation and also some thermal simulation models of traces using software developed by one of the authors. Johannes Adam has written a thermal simulation program [3] [7] called TRM (Thermal Risk Management.) It 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. The program has been adapted for use in modeling individual traces under a variety of conditions.

The authors have written two other papers [3] and [4] that provide important background information for this paper. In the first, "Trace Currents and Temperatures Revisited," they look at the trace current/temperature relationships as reported in IPC 2152 [5] and then develop some equations that fit those curves. Then they develop some thermal simulation models that validate the IPC curves and equations, which then provide the basis for further explorations. This paper extends that thermal model exploration further into the question of high temperatures and fusing currents. An understanding of the material in that article will be very helpful in understanding the results described in this paper.

In their second article, the authors provide further detail about Preece and Onderdonk, including access to some other source documents. Then, in the absence of any apparent source documents for Onderdonk himself, they provide a derivation of Onderdonk's equation.

"Fusing" Time and Temperature:

It is important to understand what we mean by fusing temperature. The term is often used somewhat carelessly. When we apply current to a trace, the trace heats up. This is because of the I^2R power dissipated in the trace. This heat raises the temperature of the trace.

When sufficient heat is applied to a copper trace (or indeed, any material) to melt the trace, there are two times that need to be considered. The first, t1, is the time to raise the trace from the ambient temperature (see again note 2) to the melting temperature of the trace. The second, t2, is the time to actually melt the trace, i.e. to convert it from a solid to a liquid. The amount of heating provided during t2 is referred to as the heat of fusion (note 3.)

Even if the trace is beginning to melt, current may flow through the liquid copper. However, liquid copper has a lower electrical and thermal conductivity than does solid copper. Therefore, once the liquid starts to form, there may be an “explosive” run-away condition that follows. The circuit will “break” (i.e. current will stop flowing) only if the liquid path separates. This may do so as a result of gravity, as a result of constricting surface tension, or as a result of explosive “splattering.” Therefore, if we consider time t2 to be the time the circuit path opens, that can depend on many subtle variables.

Even a casual reading of Preece’s material makes it clear he is referring to time t1 in his experiments. Onderdonk’s equation also only refers to time t1, even though some of the sources (e.g. Stauffacher) carelessly refer to the “short-time current required to **melt** copper conductors.” (Emphasis added.)

When current is applied to a trace, the trace heats up because of the I^2R heating effects. But at the same time, the trace cools by conduction, convection, and radiation. A stable temperature is reached when the heating effects exactly equal the cooling effects. Preece slowly raised the current in his experiments until the wire began to glow. Thus there would have been significant cooling effects going on. But that doesn’t matter to us because he didn’t include as time variable into his results.

Onderdonk’s equation, on the other hand, was derived analytically and explicitly ignores any cooling effects (from conduction, convection, or radiation). Thus his equation is only valid for the first few seconds of time. Sources typically say that Onderdonk’s equation is not valid after 10 seconds. But Adam has suggested that the cooling effects can affect the results in as little as one or two seconds [6].

In this paper the term “fusing time” refers to time t1, the time for the copper to heat to the melting temperature (fusing temperature, 1083 ^{o}C).

Assumptions and Cautions:

In this paper we are talking about the fusing temperature of PCB traces. We are not talking about fuses *per se*. So, for example, we are not talking about a commercial fuse of the type shown in Figure 1(a) nor are we talking about forming a fuse link along a PCB trace of the type shown in Figure 1(b) (although the principles we explore here probably apply equally well to Figure 1(b).) Nor are we talking about an insulated wire. Instead, we are talking about standard PCB traces of uniform width and uniform thickness over their entire length.

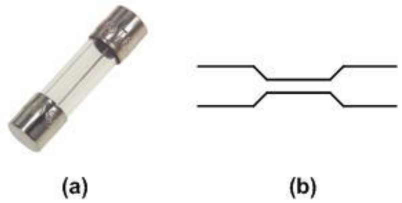


Figure 1

Types of fuses we are not considering (note 4)

In our previous paper [3] we described how to create a thermal model of a PCB trace and run a simulation with the TRM software. Two of the models we developed in that paper we continue to use here. One is a model of a 6" section of a 12" trace configured to simulate the IPC testing fixture (note 5). This model is used to check our results, as described below. The other model is of a simple 6" trace on a substrate, with pads on each end. This model is referred to in our graphs as "TRM Trace". These models range in thickness from 1 Oz. to 2 Oz., and in width from 20 mil to 200 mil. The trace model is placed on a 63 mil thick FR4 substrate.

We also developed a new model for this paper we call "TRM Fuse." It is a solid strip of copper, 200 mil long. It also varies in width from 20 to 200 mil and in thickness from 1 to 2 Oz. There is no substrate under this trace. You might envision it as a trace segment placed over a hole drilled in the board substrate material.

Thermal Model of a Fuse:

Before we look at some thermal simulations, let's convert Onderdonk's equation into a more comfortable format. We can start with Equation [4] and solve for time:

$$t = \left(\frac{1}{33.5}\right)\left[\log_{10}\left(\frac{\Delta T}{234 + T_{ref}} + 1\right) * \left(\frac{A}{I}\right)^2\right] \qquad \text{[Eq. 5]}$$

In this equation, A is still in units of circular mils. If we assume a reference temperature of 20 °C, a fusing temperature of 1083 °C, and convert this to square mils, the result is:

$$t = .0346*(A/I)^2 \qquad \text{[Eq. 6]}$$

We ran simulations of our fuse model and compared the results with Onderdonk's equation. Onderdonk's equation applies to a bare conductor under adiabatic conditions. That is, without the transfer of any heat into the surroundings. Since TRM is not designed to model a single layer structure, we modeled a copper PCB "fuse" as shown in Figure 2. Both conductor layers are copper; there is no dielectric layer. The Heat Exchange Coefficient (see [3]) was set to zero, but setting it to 10 had negligible effect on the simulation model results.

There is a subtle detail involved in running a simulation of this type. In order to get a precise measure of fusing time, the model needs to run for a period of time, calculate the temperature of the copper, adjust the resistivity of the copper to the new temperature, and then run the simulation for the next period of time. This continues until the melting point of copper (1083 degrees C) is reached. The "period of time" is called a "Step." We learned that the step size impacts the results, and that the most precise results are reached with infinitely small steps (i.e. in the limit where step approaches zero.) A step size that small results in very long calculation times. After considerable experimentation we found that setting the step to 0.1 seconds was a reasonable compromise.

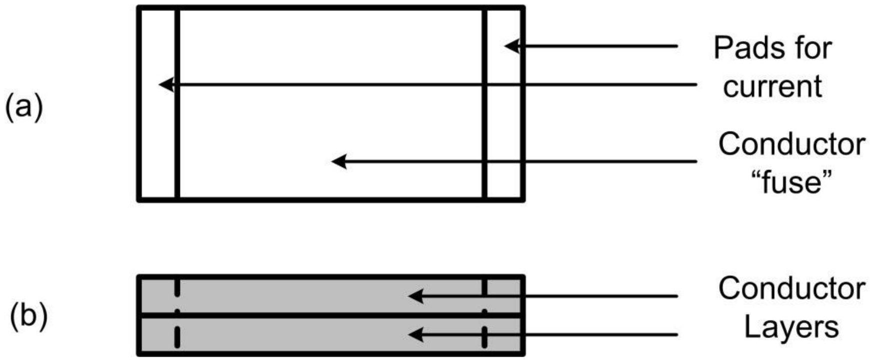


Figure 2
Fuse model for simulation.

Six different simulations were run, 1 Oz.(1.35 mil) and 2 Oz. (2.7 mil) thicknesses with widths of 20 mil, 100 mil, and 200 mil. Figure 3 plots the simulation results of the 1 Oz. 100 mil simulation along with Onderdonk’s equation. Preece’s current is also shown on the graph for reference.

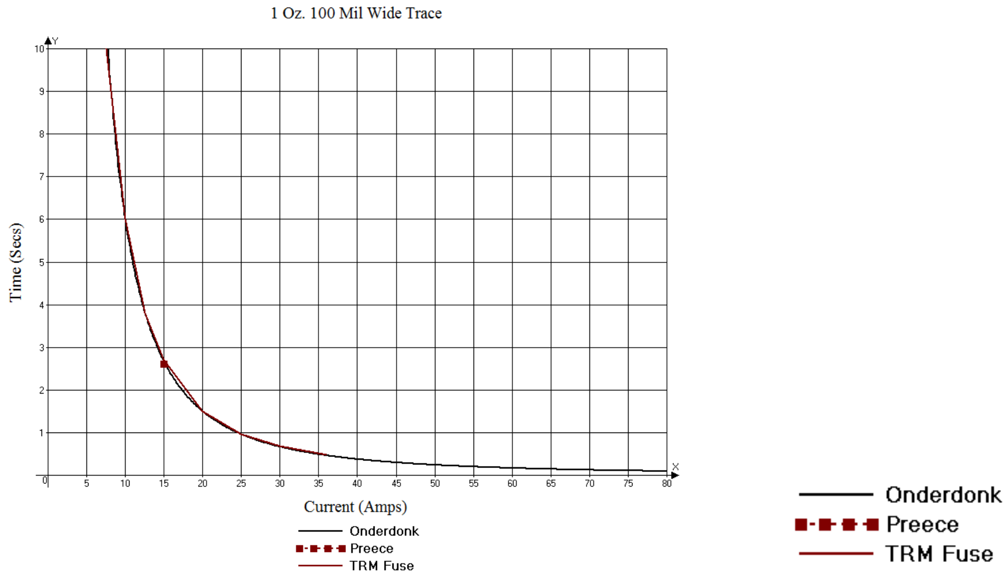


Figure 3
Fusing time vs. current for fuse model and for Onderdonk.

The fit is almost perfect at all levels of current. The results for all other configurations are identical to this one except for scale. The results for all configurations are provided in Appendix 1. This gives us a high degree of confidence in TRM’s ability to simulate a fuse in this kind of simulation.

Thermal Model of Two Traces:

We constructed a trace model for simulation that was a very simple PCB trace, 155 mm (approximately 6”) long. It varied in width and thickness depending on what we were testing. There were 3 mm (118 mils) between each side of the trace and the edge of the board, and the ends of the trace were 5 mm (200 mils) in from each edge. A schematic of one of the traces is shown in Figure 4, which is a figure from one of the TRM simulations.

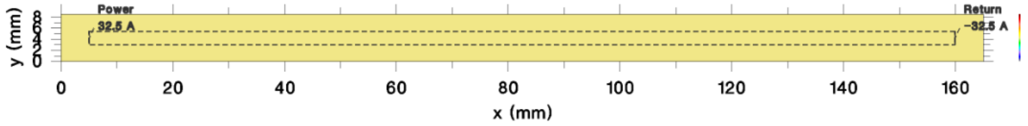


Figure 4
Schematic of our trace model for simulation.

The same six configurations as described above were run on our trace model. The 1 Oz. 100 mil wide simulation result is shown in Figure 5. (The results for all six configurations are shown in Appendix 1.)

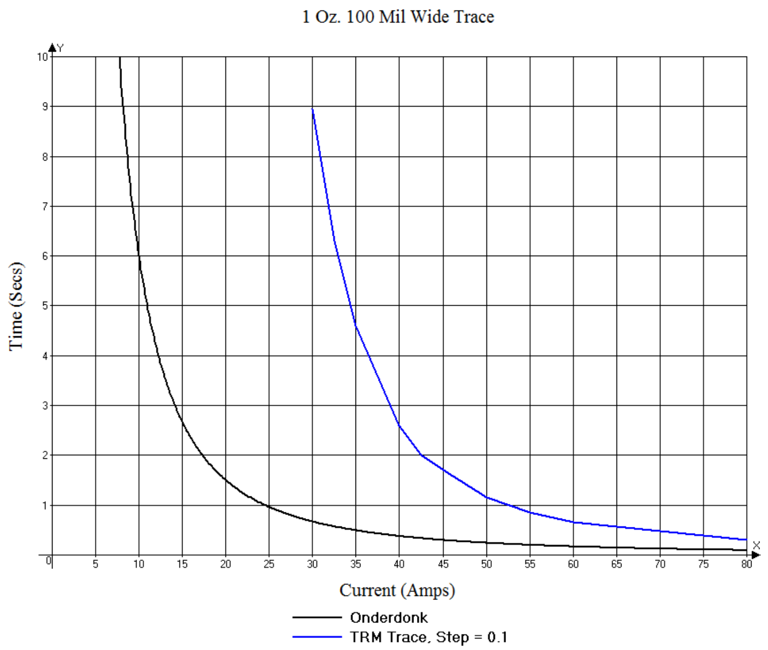


Figure 5

Fusing time vs. current for trace simulation, compared to Onderdonk’s equation.

There are three types of cooling that occurs when these traces heat --- conduction into the board material, convection into the air, and radiation away from the trace. The Heat Exchange Coefficient was set in the simulations to 10 to represent a normal situation. Subsequent testing showed that the value of the Heat Exchange Coefficient did not change the results significantly, showing that the primary cooling effect in the time frames looked at here are confined to conduction through the board material. The significant shift of the trace model simulation to the right of Onderdonk’s equation is the result of conduction of heat into the board material, thereby slowing the increase in temperature.

The dielectric material used in this simulation was FR4. Polyimide might provide slightly better heat conductivity, better cooling, and therefore slightly longer fusing times. The size of the board had no effect on the results. Placing a plane on the opposite side of the board did not affect the results. Placing a plane 12 mils under the trace layer did have an effect on the results, increasing the fusing time by 30% to 100 % depending on the current level (lower current levels, and therefore longer fusing times, resulted in higher percentage changes).

An interesting observation of these results is that at relatively high currents (and therefore at relatively short times) the curves begin to merge. This is the area where the cooling effects of the board dielectric material have not had time to “kick in.”

We also ran a simulation on the trace model we used for simulating the IPC test board (see [3].) The results were ***identical*** with those from our trace model (within less that 0.1 second at every current level.) This gives further confidence in our feeling that the fusing time is a function of trace size and board material only, and nothing else (except a closely spaced underlying plane.) This also gives further confidence in TRM’s ability to model fusing currents and times.

Short-time Effects:

Let’s look back at Equation 6 and rearrange terms:

$$t\ (I/A)^2 = .0346 \qquad \text{[Eq. 7]}$$

This says that the product on the left is a constant (see note 6.) Figure 6 plots the result of $t^*(I/A)^2$ for the various fuse model simulations. The results are the same as the Onderdonk result within reasonable measurement accuracy. There is a slight anomaly for the larger 2 Oz traces at the shortest times caused by measurement uncertainties in that region. The current levels are very high and the sensitivity to current level very low in that region for those sizes.

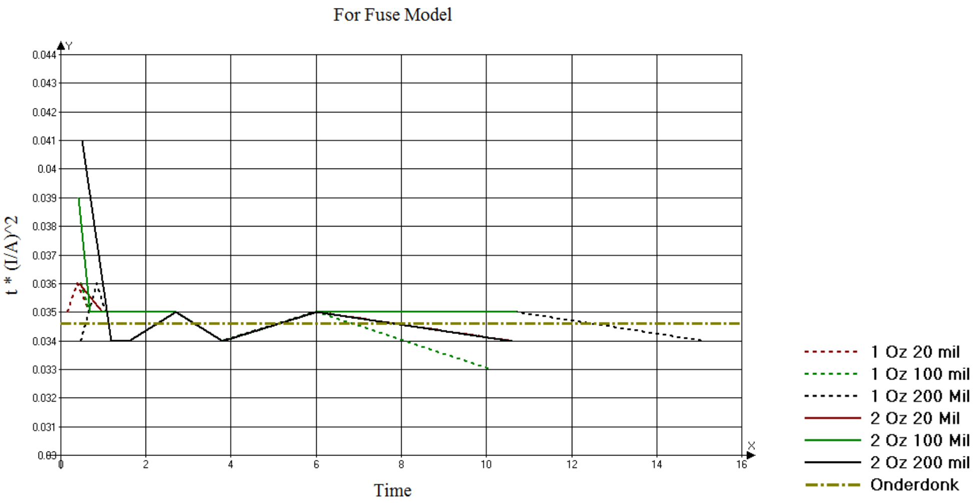


Figure 6

Plot of $t^*(I/A)^2$ for the various configuration simulations of the fuse trace.

When we plot the same term for the TRM-Trace model simulations, we get the interesting result shown in Figure 7. They are all upward sloping to the right, a clear indication of the cooling effects that are taking place with time.

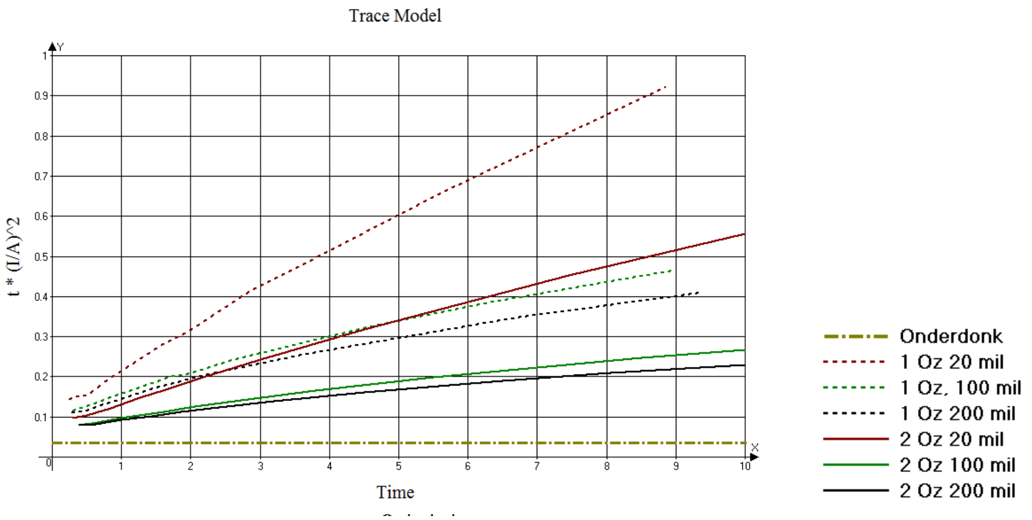


Figure 7

Plot of t*(I/A)^2 for the various configuration simulations of the trace model,.

But when we look closely at these same curves at very short times, they all seem to originate at a similar value (Figure 8.)This is not too far different from our fuse simulation. Therefore, at the first instant of time, all the trace configurations start out the same. Furthermore, except for the smallest trace (1 Oz. 20 mil), they are all at or under 0.25 during the first three seconds.

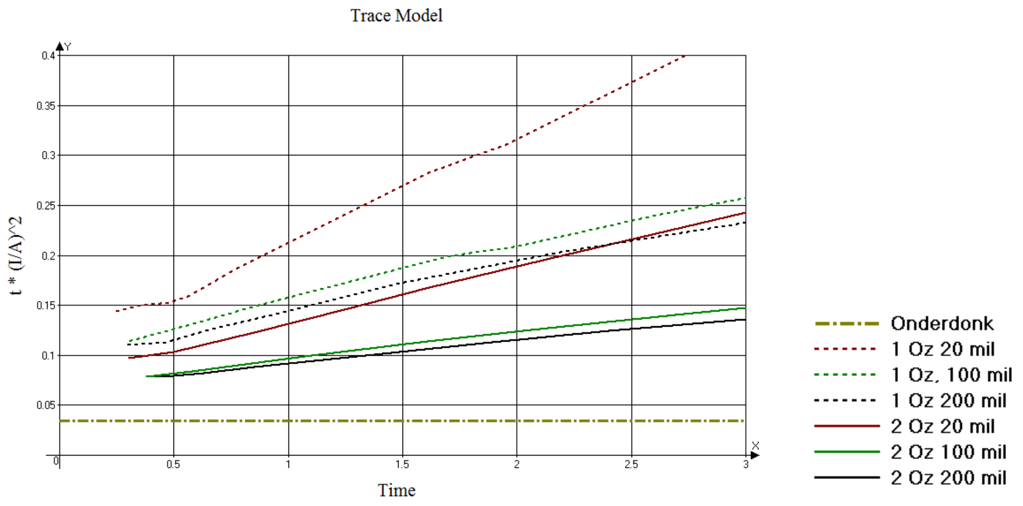


Figure 8

Plot of t*(I/A)^2 for the various configuration simulations of the regular traces at times under three seconds..

It is instructive to compare the fusing current for the traces at various times to the fusing current calculated from Onderdonk’s equation. We calculate the ratio of these two values and provide them in Table 1.

		Ratio of Trace Model Current to Onderdonk Current						
				time (Seconds)				
Trace Config		Area	0.5	1	2	3	4	5
Oz.	Width							
2	20	52	3.46	3.87	4.65	5.3	5.84	6.3
1	20	26	2.24	2.45	3.03	3.53	3.83	4.2
1	100	130	2.02	2.14	2.45	2.69	3.02	3.15
1	200	260	1.88	2.04	2.37	2.62	2.77	2.97
2	200	520	1.57	1.67	1.9	2.05	2.2	2.37
2	100	260	1.51	1.63	1.82	1.98	2.1	2.2

Table 1

A very interesting result here is that, relatively speaking, narrower traces take longer to reach the fusing temperature than do wider traces. That seems, on the surface, to be counter-intuitive. But the narrower traces do cool better. Figure 9 gives us a clue as to why. The top thermal graph is from underneath the 1 Oz. 20 mil trace when it reaches the fusing temperature, The lower thermal graph is the same thing for a 2 Oz. 200 mil trace. The cooling “plume” is the dark blue area around which the trace is “shedding” heat. Comparing the area of this “plume” to the trace width illustrates that the narrower trace has, relatively speaking, a much wider plume *compared to its width* than does the wider trace. The temperature is therefore cooler under the narrower trace (720 ^{o}C compared to 952 ^{o}C.)

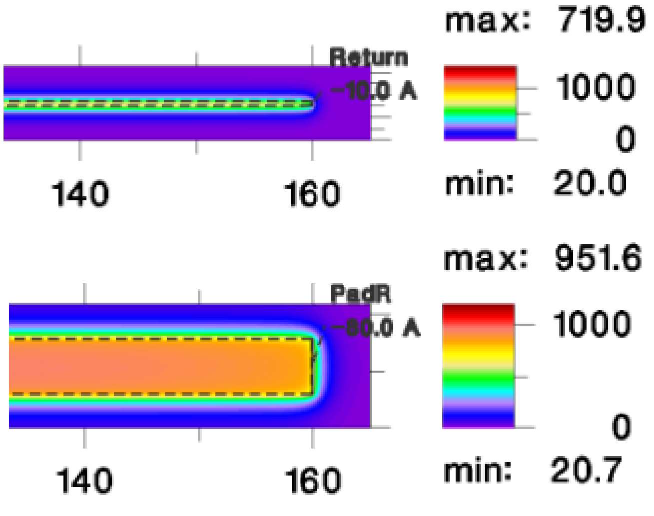


Figure 9

Comparing the thermal “plume” under two traces of differing width.

Referring back to the question first posed in this paper (how large a trace is needed to carry 40 Amps for 1 second), we can approximate an answer to that question from Figure 8 and Table 1.

> We assume the trace will be at least 100 mils wide
> Calculate $t\,(I/A)^2 < .15$, or $(1)*(40/A)^2 < 0.15$ or $(40/A)^2 < 0.15$.
> This leads to: $A > (1600/0.15)^{.5} = 103$ square mils
> A 1Oz 76 mil wide trace has an approximate area of 103 sq. mils.

We can check the answer by calculating the fusing current for this result using Onderdonk's equation and then looking at Table 1.

> Onderdonk: $t = .0346*(A/I)^2$ (From [Eq. 6])
> This leads to $I^2 = .0346(A^2)/t = .0346(103)^2$
> Leads to I = 19 Amps
> From Table 1, a 130 sq mil area trace model will have a 2.14 times greater current carrying capacity, so the current carrying capacity of the trace would be about 2.14*19 = 40.6, roughly what we wanted.

.

Final Conclusions:

Looking at the question of fusing currents on PCB traces can be very problematic. Onderdonk's equation is a reasonable place to start, and thermal simulation models suggest that the actual fusing times can be 1.5 to 6.0 times longer than Onderdonk suggests (and more considering the restrictive assumptions of the models.) But there are many, subtle variables involved. It is not really practical to solve this type of problem with a formula or graph. The use of a simulation model is almost required; and even more so if there are adjacent traces or planes that can contribute to trace cooling.

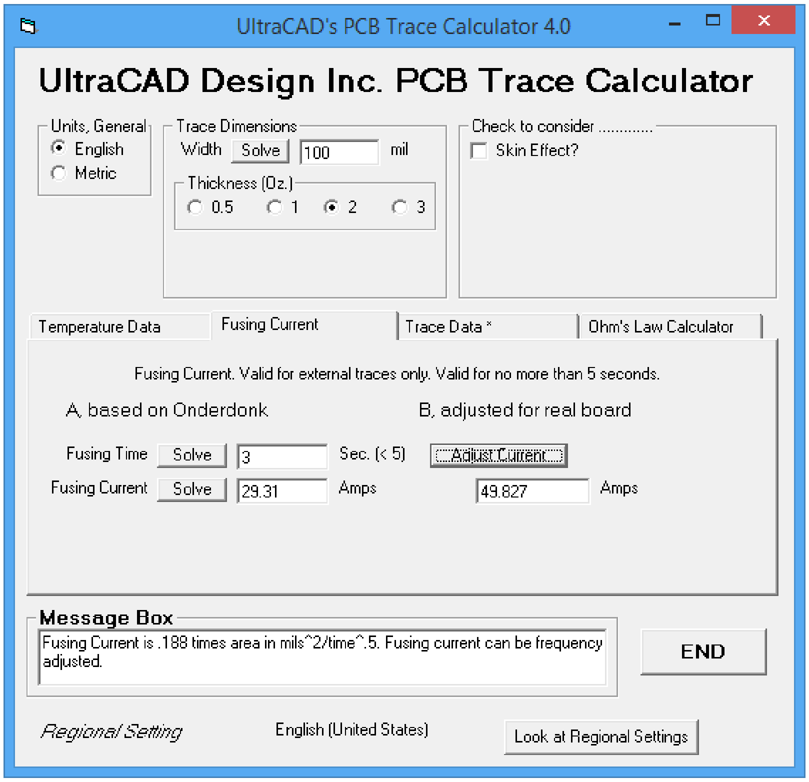
A particular problem is the knowledge of the "true" value of resistivity. According to a post on the SI-List [7], measured resistivity on fabricated boards can vary over a range of 1.7 to 2.4 uohm-cm (and more). That's a variation of some 40%! Since temperature, and therefore fusing time, is directly related to resistivity, this is a significant uncontrolled variable.

And a word of caution. If a trace fuses, it is ***never*** acceptable to repair the trace and put the board back into service. If a trace fuses, that is considered a destructive failure and the board must be removed from service. The heat from the fusing temperature may have caused any number of hidden potential problems in the material and components around that area. It may be useful to use a trace as a fuse, but doing so is a one-time event. If a replaceable fuse is required, a fusing component must be used instead.

UltraCAD's PCB Trace Calculator:

UltraCAD offers a trace calculator that has been completely redesigned (to Version 4.0) as a result of the collaboration between Brooks and Adam. Figure 8 is a screen shot of the "Fusing Current" tab from that calculator. Given a trace thickness and two of any three other variables (time, current, and trace width), the calculator will solve for the third variable using Onderdonk's equation. Then pressing the “Adjust Current” button will result in the estimated “real world” current for the TRM Trace model.

For more information regarding this calculator go to www.ultracad.com .



UltraCAD's PCB Trace Calculator 4.0

UltraCAD Design Inc. PCB Trace Calculator

Units, General: ● English ○ Metric

Trace Dimensions: Width 100 mil

Thickness (Oz.): ○ 0.5 ○ 1 ● 2 ○ 3

Check to consider .... ☐ Skin Effect?

Fusing Current. Valid for external traces only. Valid for no more than 5 seconds.

A, based on Onderdonk

Fusing Time 3 Sec. (< 5)

Fusing Current 29.31 Amps

B, adjusted for real board

49.827 Amps

Message Box: Fusing Current is .188 times area in mils^2/time^.5. Fusing current can be frequency adjusted.

Regional Setting: English (United States)

Figure 8

UltraCAD’s PCB trace calculator

Notes:

1. A circular mil is the area of a circle with a diameter of one mil. The formula is $A = d^2$. The conversion from circular mils to mil^2 is π/4. Normal conversions are:

    1 mil^2 = 1.273 circular mils
    1 circular mil = .7854 mil^2
    1 m^2 = $19.736*10^8$ circular mil
    1 circular mil = $5.067*10^{-10}$ m^2 = $5.067*10^{\wedge -4}$ mm^2

2. From a thermodynamic engineering standpoint, there is a significant difference between the ambient temperature and the initial condition. For example, there could be some current-induced heating of a wire above the ambient temperature in a normal operation before a change of current is applied. In the electronic industry we are less rigorous and tend to refer to the initial temperature of the trace as the "ambient" temperature. In this paper we are assuming that the initial condition (temperature) is the same as the ambient temperature. If the initial temperature of the trace were different from the temperature around the trace, we would refer to the initial trace temperature as the "ambient" temperature.

3. See http://en.wikipedia.org/wiki/Melting_point .

4. Source of fuse picture is https://chaaad.wordpress.com/2012/02/17/fuses/

5. The design for the IPC test board is found in 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

6. Furthermore, if we let A = constant, then Equation 7 reduces to I^2t = constant. The I^2t value is an important rating in the fuse industry. See http://en.wikipedia.org/wiki/Fuse_%28electrical%29#The_I2t_value

7. The SI-List (si-list@freelist.org) is a signal integrity email forum. The referenced post was from Jeff Loyer, Signal Integrity Consulting, 7/1/15.

8. Revision 1 is the result of improved precision in the TRM simulation software and improved modeling of the fuse and trace simulations. While many of the details have changed, and improved with much better precision, the overall conclusions are fundamentally unchanged from the earlier version.

References:

[1] Preece W. H., On the Heating Effects of Electric Currents, Proc. Royal Society 36, 464-471 (1883). No. II, 43, 280-295 (1887). No. III, 44, 109-111 (1888).These documents have been made available on-line in recent years:
http://rspl.royalsocietypublishing.org/content/36/228-231/464.full.pdf+html
http://rspl.royalsocietypublishing.org/content/43/258-265/280.full.pdf+html
http://rspl.royalsocietypublishing.org/content/44/266-272/109.full.pdf+html
The problem Preece was trying to solve is explained in the 1883 article and the 10244 constant is found in the 1888 article.

[2] E. R. Stauffacher, "Short-time Current Carrying Capacity of Copper Wire," General Electric Review, Vol 31, No 6, June 1928 (Download a copy www.ultracad.com/articles/reprints/stauffacher.pdf)

[3] Douglas Brooks and Johannes Adam, "Trace Currents and Temperatures Revisited," 2015, available at http://www.ultracad.com/.

[4] Johannes Adam and Douglas Brooks, "In Search of Preece and Onderdonk," 2015, available

for download at http://www.ultracad.com/.

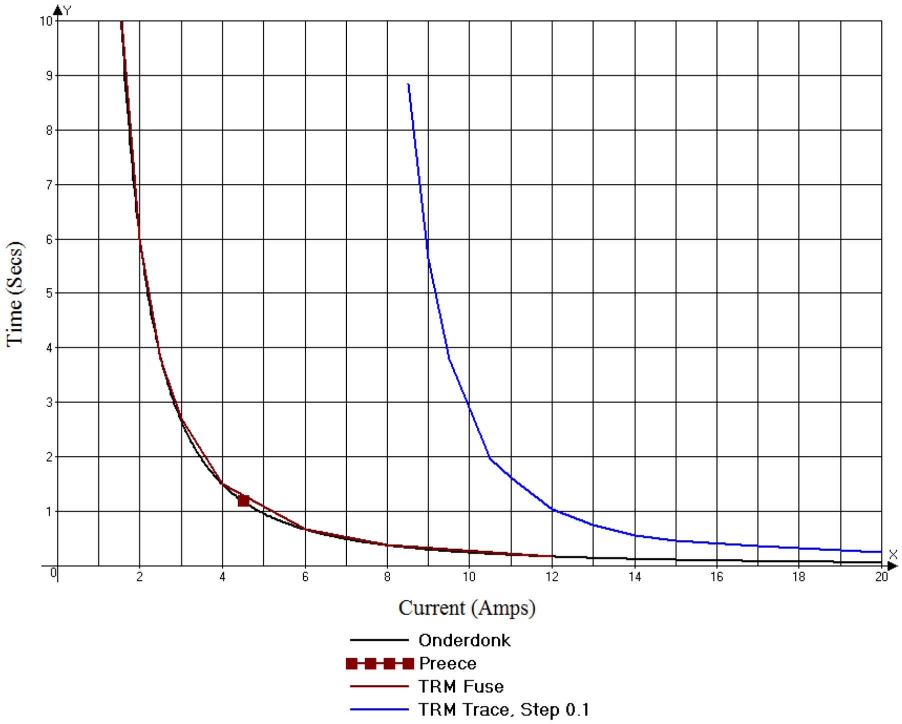
[5] IPC-2152, “Standard for Determining Current Carrying Capacity in Printed Board Design,” August, 2009, www.ipc.org.

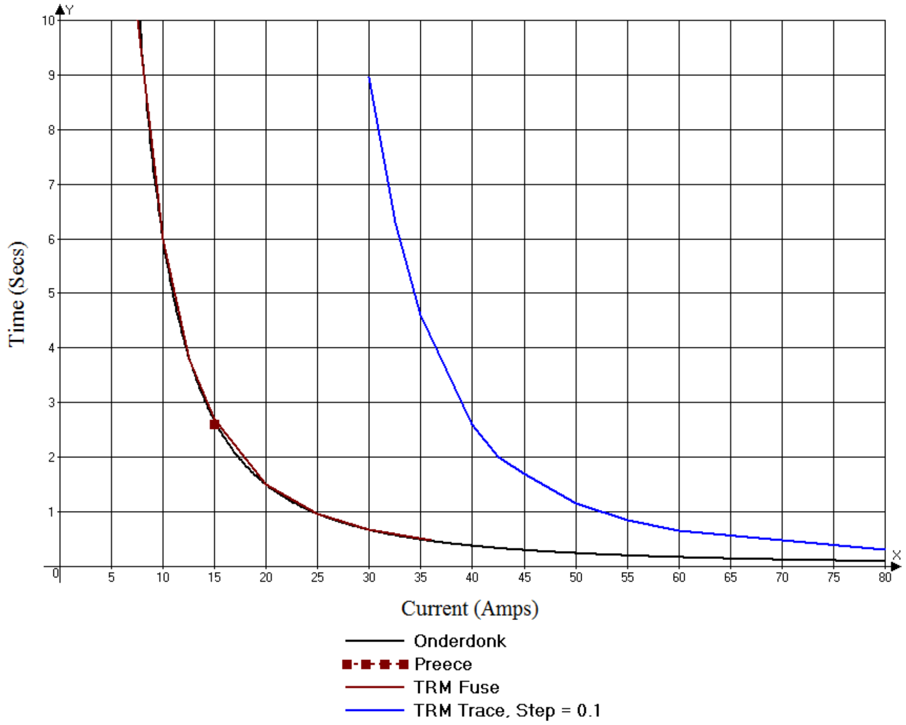
[6] Johannes Adam white paper No.10 www.adam-research.de/pdfs/TRM_WhitePaper10_AdiabaticWire.pdf

[7] Learn more about TRM at www.adam-research.com

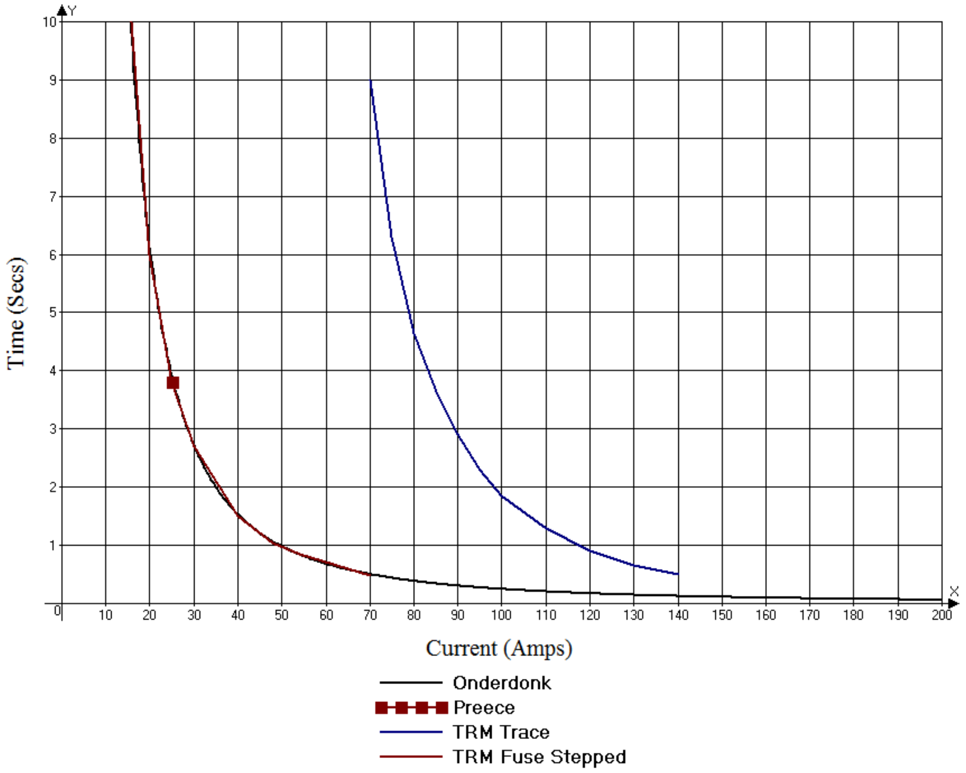
Appendix 1

Results of all six configuration simulations.

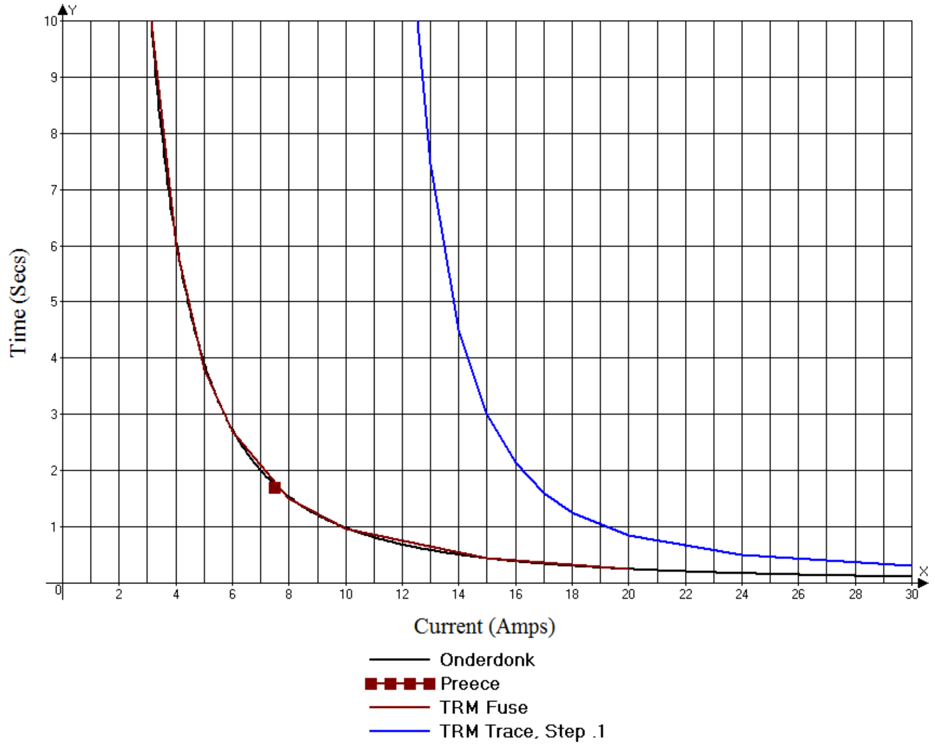

1 Oz. 20 Mil Wide Trace


1 Oz. 100 Mil Wide Trace

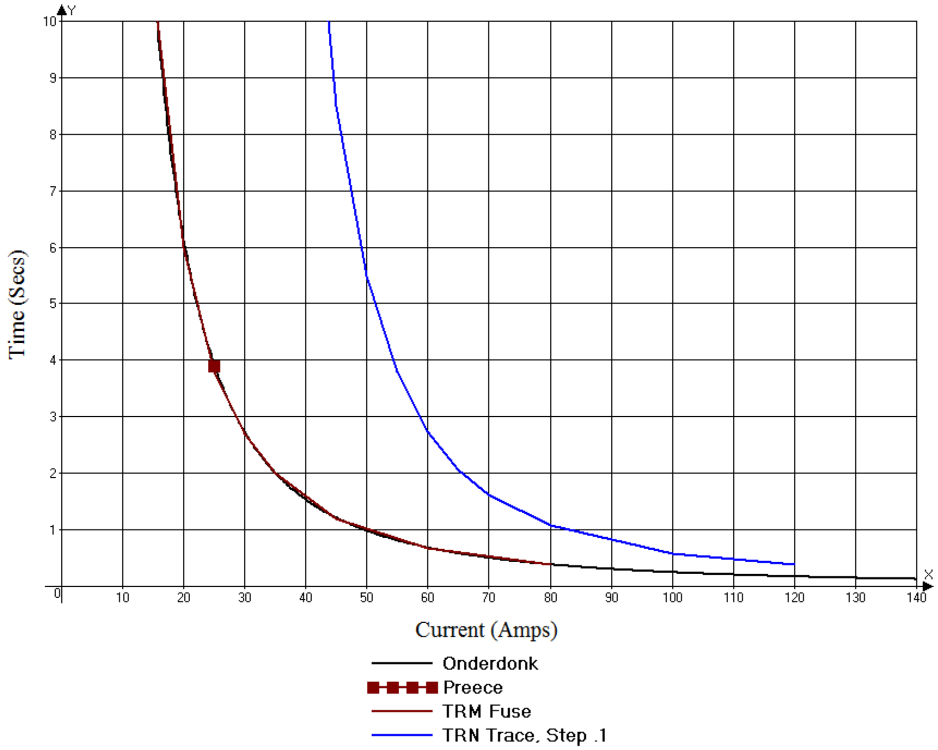
1 Oz. 200 Mil Wide Trace



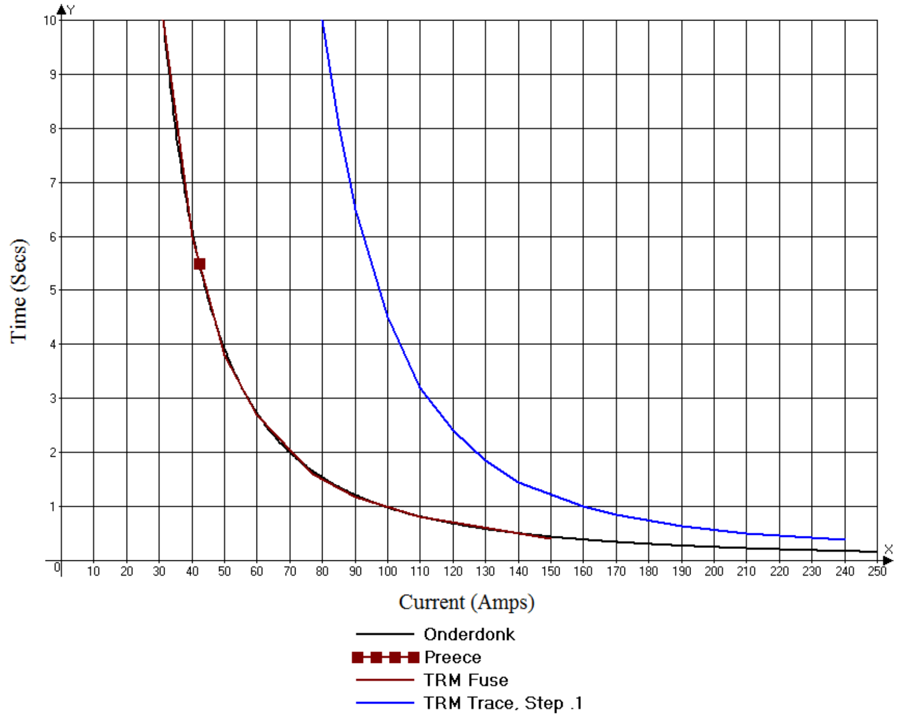
2 Oz. 20 Mil Wide Trace



2 Oz. 100 Mil Wide Trace



2 Oz. 200 Mil Wide Trace



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.