InterPACK '07

USING LINEAR SUPERPOSITION TO SOLVE MULTIPLE HEAT SOURCE TRANSIENT THERMAL PROBLEMS

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Outline

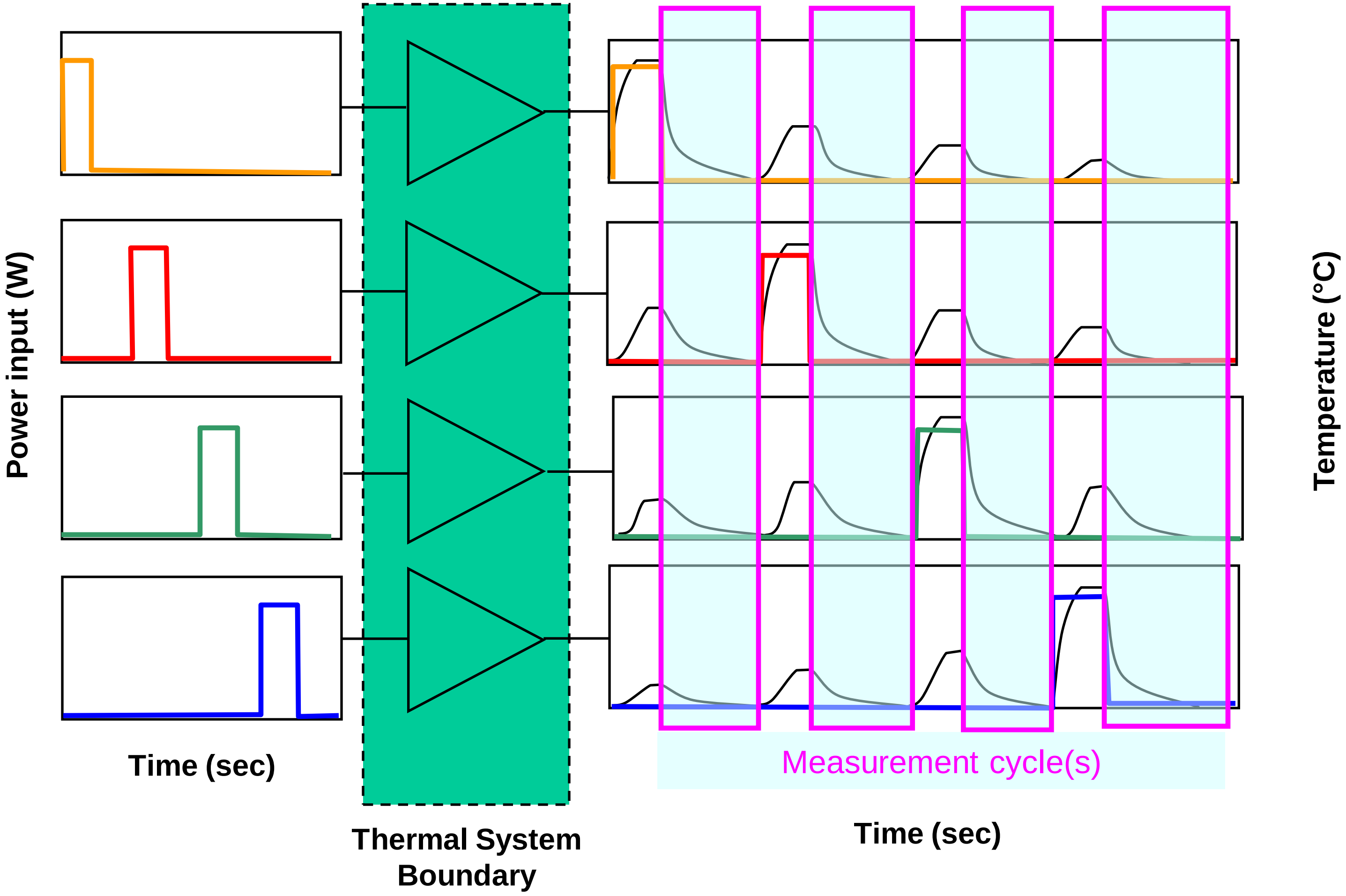
- *Setting up the Problem- Data collection*
- *Curve Fitting a R-Tau Model to Transient Data*
- *Using Linear superposition to solve Complex waveforms in Excel™*
- *Using Linear superposition to solve Complex waveforms in Electrical Spice*
- *Conclusion/ Recommendations*
- *References*

Setting up the Problem- Data collection

- Each heat source needs to be independently heated.
- Each potential measurement location needs to be monitored.
  - Measurement techniques require high speed data acquisition for multiple inputs. A method of converting voltage from a device to a temperature from a calibrated source.
  - Simulation techniques require tracking temperature locations and storing the values for later processing.
- Transient temperature data must then be converted to a transient impedance curve and fit to a R-Tau net-list.

Each heat source needs to be independently heated.

Each heat source needs to be independently measured based on the interaction of the others.



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Converting Temperature data into Thermal resistance values for R-Tau model fit.

- Temperature correction for the first millisecond can be performed for a surface flux heat source input using the square-root of time estimate.

(MIL-STD 883 method 1012, Heat Transfer, J.P Holman 5th edition)

$$Csr = \frac{2}{\sqrt{\pi * \rho * \mathrm{Cp} * \mathrm{K}}} \frac{1}{A} \qquad \frac{1}{Csr\_eff} = \frac{1}{Csr_1} + \frac{1}{Csr_2} \qquad R(time) = Csr\_eff * \sqrt{time}$$

[units °C-mm^2-√sec/W]

[units °C/W]

Definitions:

A	area of the surface being heated
L	thickness of the material
ρ	density of the material
Cp	Specific heat of the material
K	thermal conductivity of the material
Csr	square-root-of-time constant
Csr_eff	parallel combination of Csr constants
R(t)	thermal response as a function of time
sqrt(t)	square-root-of time abbreviation
C	thermal capacitance
t	time
Tau	thermal time constant

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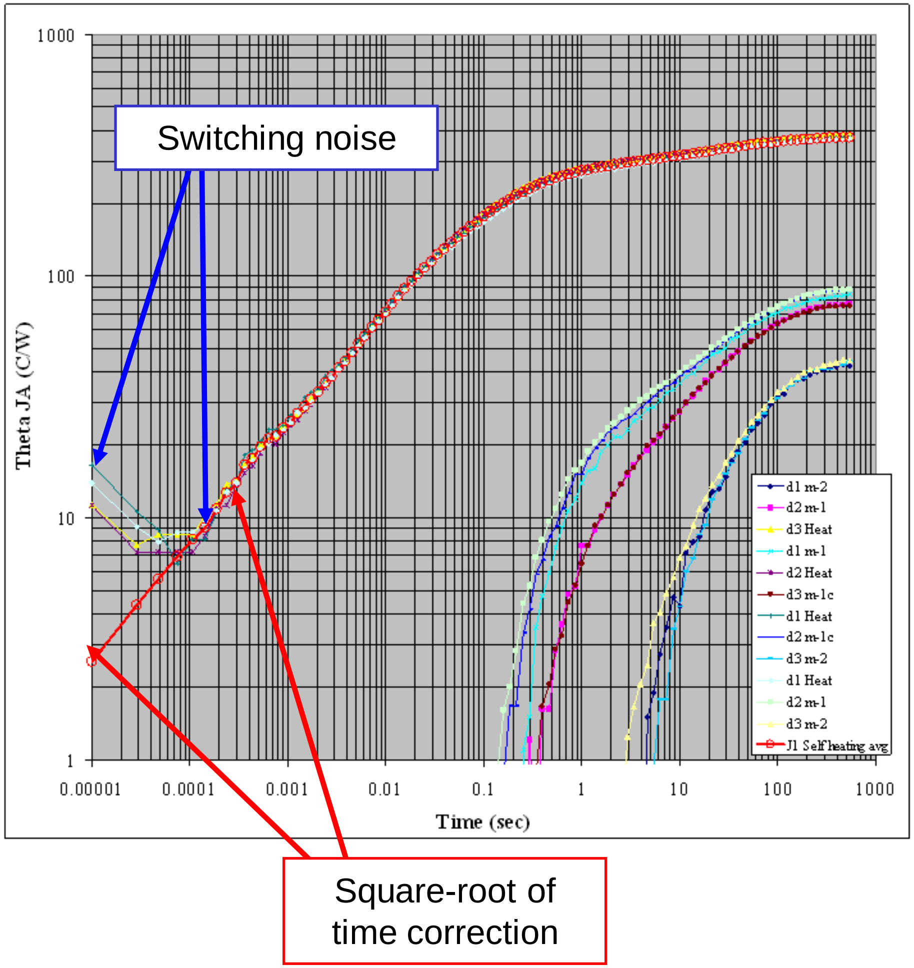
Converting Temperature data into Thermal resistance values for R-Tau model fit. (Continued)

- Measured data typically is very noisy because of the switching from a heating condition to a measurement state. This can last up to 1 millisecond or longer depending on the device characteristics.
  - We heat to steady state then switch to measurement and watch the complete cooling curve to eliminate as much noise as possible. It limits our power input to a steady state value but enhances our measurement accuracy and noise reduction.



Switching noise

Square-root of time correction

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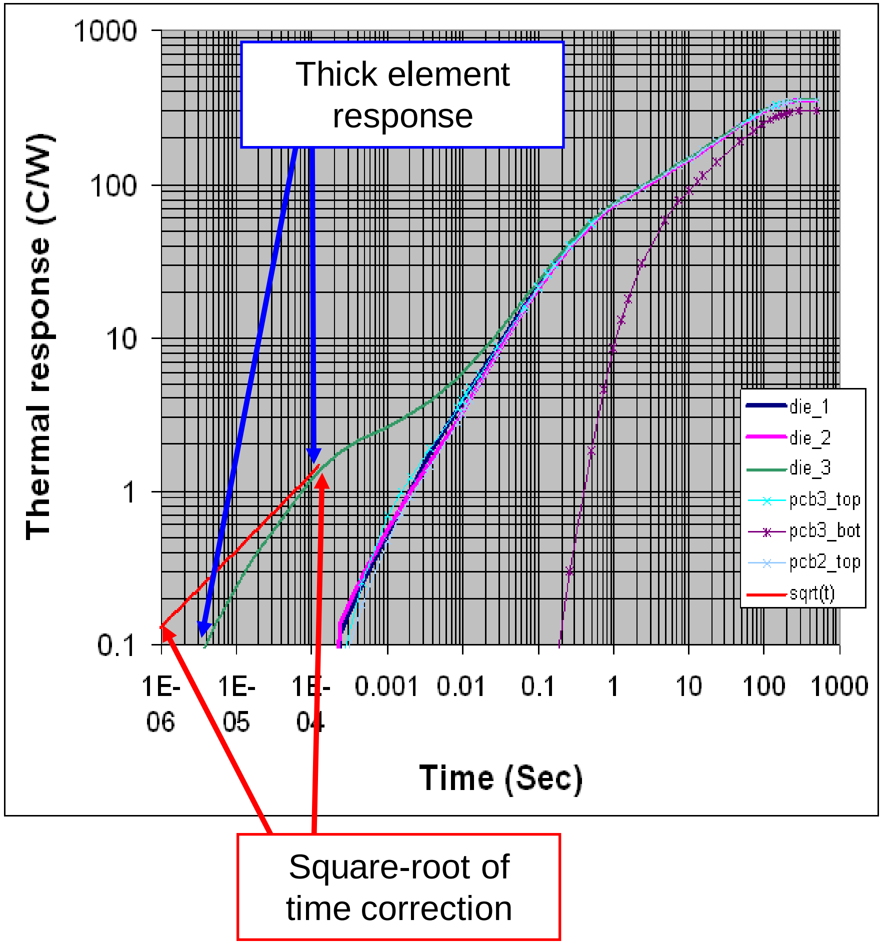
Converting Temperature data into Thermal resistance values for R-Tau model fit. (Continued)

- Simulated data typically is affected by the short time response of the elements. Elements that are too thick relative to the heat flow direction will under predict the temperature rise.
- There is a trade off between model solution time and size and temperature response. As long as we understand where this limitation begins we can correct for the discrepancies using the square-root of time estimate



Thick element response

Square-root of time correction

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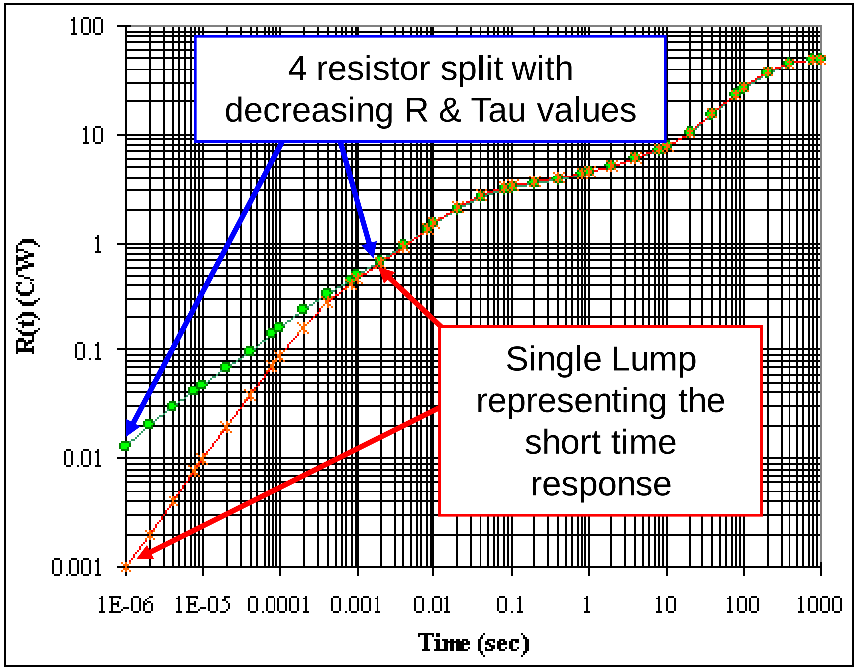
Converting Temperature data into Thermal resistance values for R-Tau model fit. (Continued)

- Understanding that the square-root of time estimates for a surface flux heat source improves the model, we can take it one step further to improve the curve fitting for a lumped parameter network.
- Lumped parameter models suffer the same problems of finite element models. A lump too large will respond too slowly to represent the actual system.
- Breaking the short time response lumps into smaller and faster responding lumps improves the accuracy of the model.
- This allows us to resize the model for quicker response if need be.



4 resistor split with decreasing R & Tau values

Single Lump representing the short time response

A Method of spliting the short time response:

R1=Csr_eff*SQRT(Tau1)
R2=Csr_eff* SQRT (Tau2)-R1
R3=Csr_eff* SQRT (Tau3)-R1-R2
R4=Csr_eff* SQRT (Tau4)-R1-R2-R3

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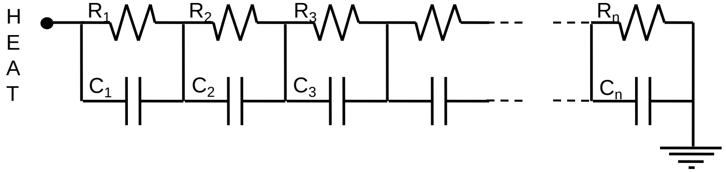
Converting Temperature data into Thermal resistance values for R-Tau model fit. (Continued)

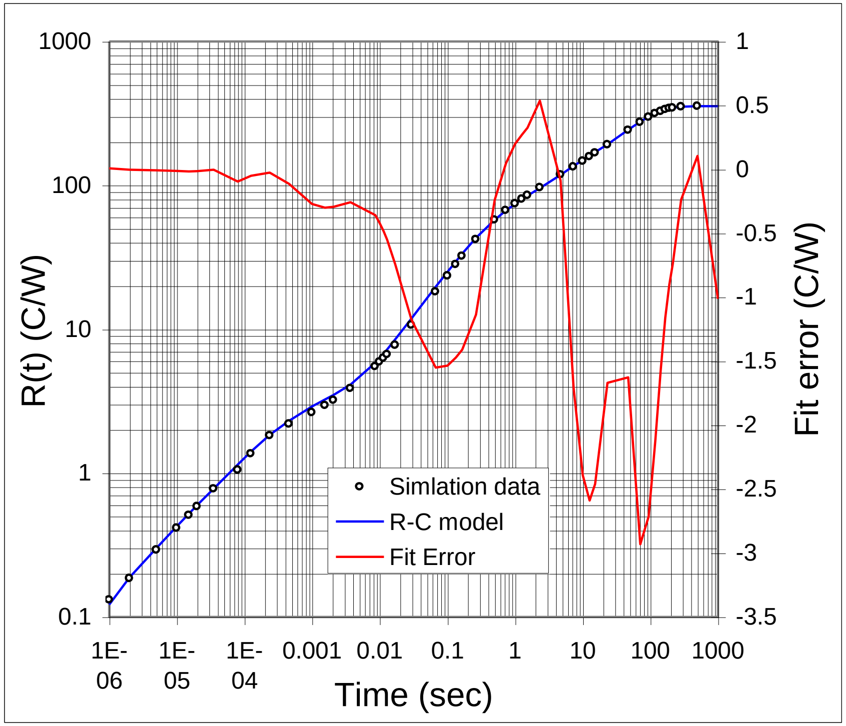
- A Foster network can be easily represented in Excel as an array formula with a combination of a few key strokes. [Control+Shift+Enter] which add the braces {} to the formula.
- Adding a fit error function to show the difference between input data and fit data helps to visualize model fit overall.



$$R(t) = \sum_{i=1}^{n} R_i \left(1 - e^{-t/tau_i}\right)$$

{=SUM(R1:R10*(1-EXP(-*t*/Tau1:Tau10)))}

$Tau_i = R_i * C_i$



Fit Error= delta between model and fit @ a particular time value

Fit error function=SQRT(SUMSQ(delta1:delta2)) Used to optimize the overall curve fit

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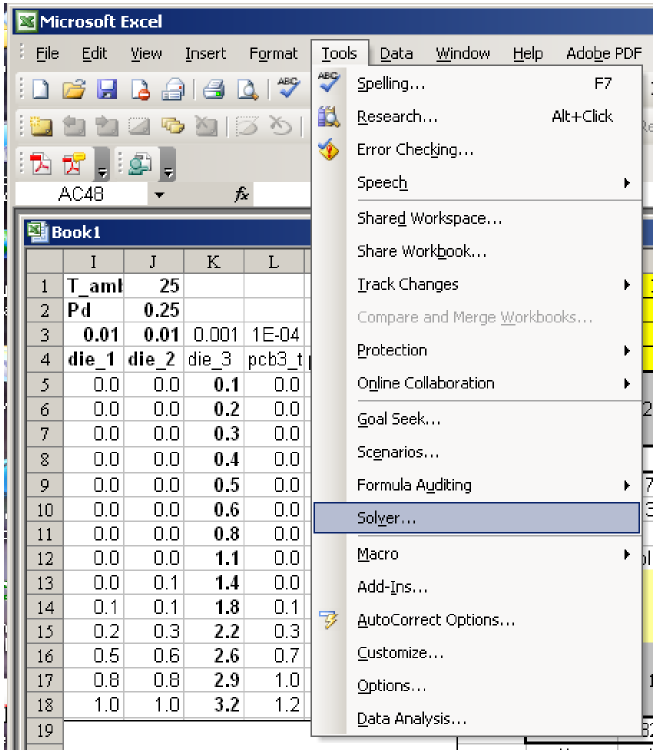
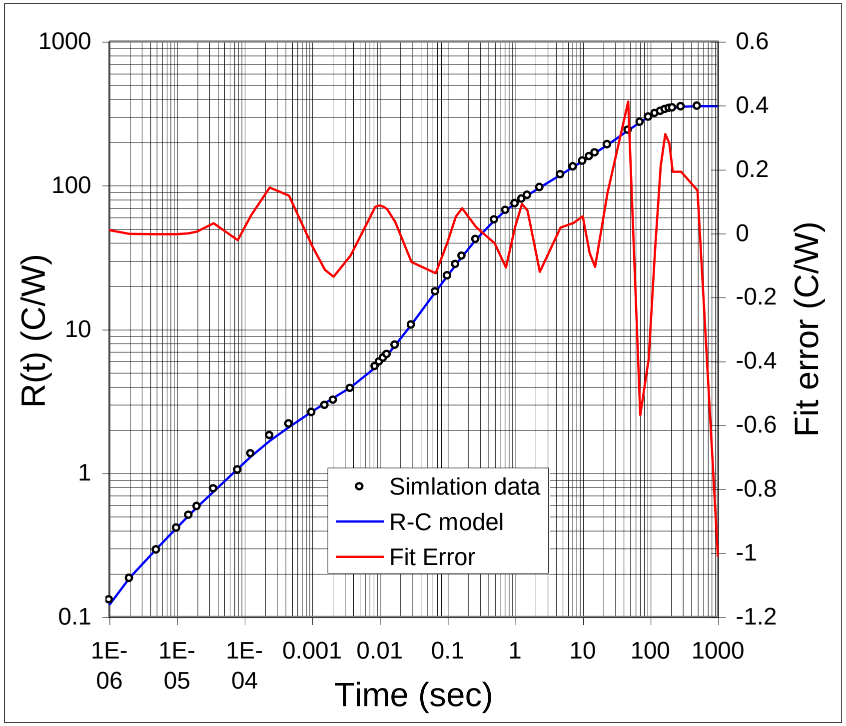
Converting Temperature data into Thermal resistance values for R-Tau model fit. (Continued)

- Using the “solver” feature in Excel can also be used to minimize the error between input data and R-C model.



	I	J	K	L
1	T_aml	25		
2	Pd	0.25		
3	0.01	0.01	0.001	1E-04
4	die_1	die_2	die_3	pcb3_t
5	0.0	0.0	0.1	0.0
6	0.0	0.0	0.2	0.0
7	0.0	0.0	0.3	0.0
8	0.0	0.0	0.4	0.0
9	0.0	0.0	0.5	0.0
10	0.0	0.0	0.6	0.0
11	0.0	0.0	0.8	0.0
12	0.0	0.0	1.1	0.0
13	0.0	0.1	1.4	0.0
14	0.1	0.1	1.8	0.1
15	0.2	0.3	2.2	0.3
16	0.5	0.6	2.6	0.7
17	0.8	0.8	2.9	1.0
18	1.0	1.0	3.2	1.2
19				



After optimization

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Final R-Tau model fit.

- Although a little manual manipulation may be required to ensure convergence as well as constraining the end points of the model.

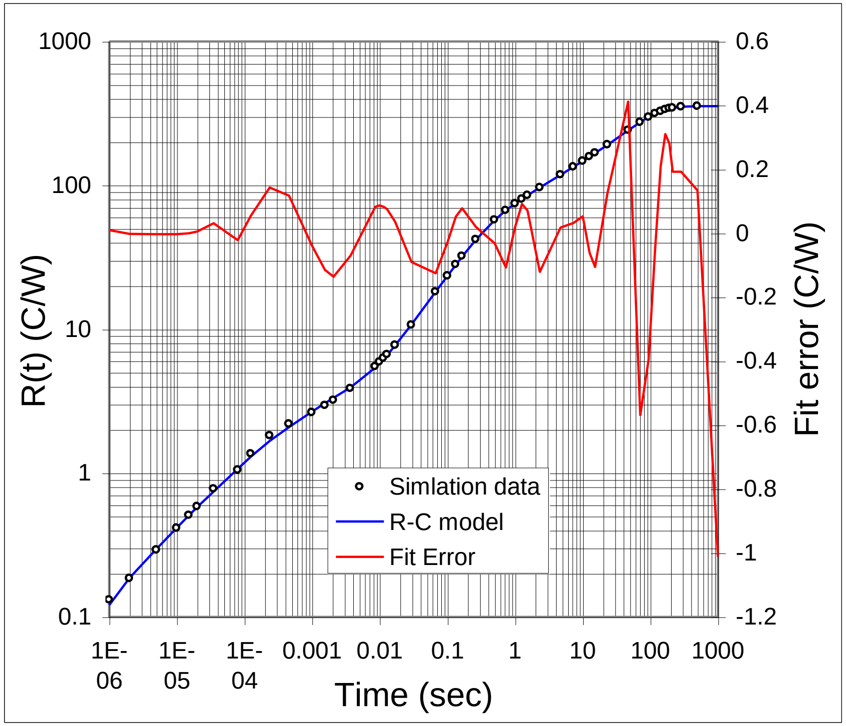
{=SUM(R1:R10*(1-EXP(-*t*/Tau1:Tau10)))}

	R's	Tau's
1	**0.13096**	**1.00E-06**
2	**0.28318**	**1.00E-05**
3	**0.89549**	**1.00E-04**
4	1.47	0.0008
5	4.93	0.036
6	40.94	0.269
7	33.27	1.348
8	43.49	6.705
9	0.010	20.604
10	229.3	67.244

Csr_eff=130.9
R1=Csr_eff*SQRT(Tau1)
R2=Csr_eff* SQRT (Tau2)-R1
R3=Csr_eff* SQRT (Tau3)-R1-R2

Subject to these Constraints
R4:R9>0.01
Tau4:Tau10>1e-6

R10=Max R(t) from data – SUM(R1:R10)



- Highlighted values are allowed to be changed by the solver. The other values are fixed by definition.
- This is then repeated for every temperature heat source.
- Non heated elements do not require the sqrt(t) correction as the first three rows show in this example.

Assembling into blocks for Superposition solution

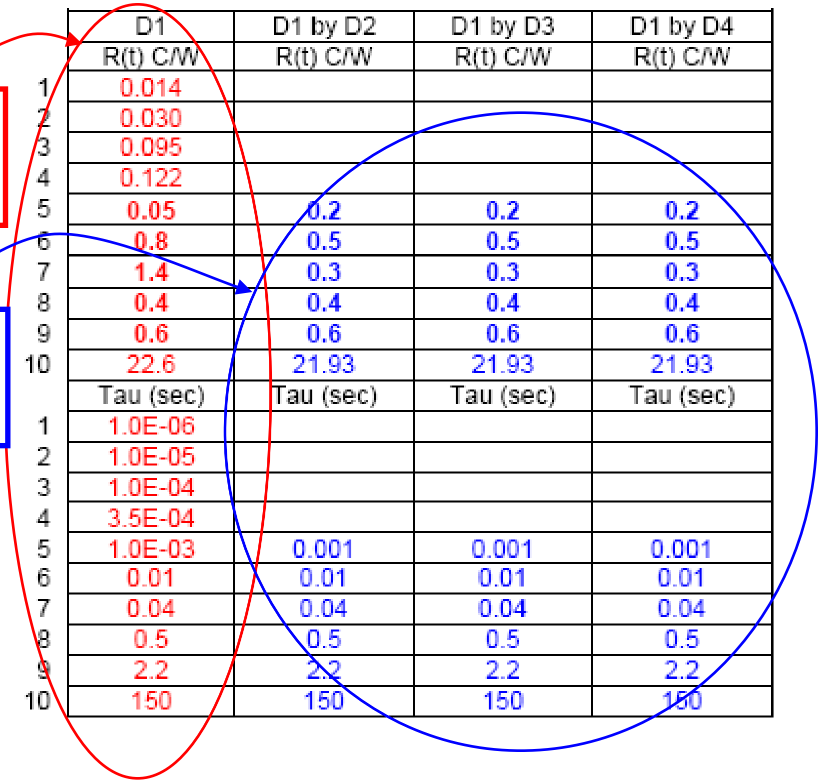
- Each block is assembled for each heat source self heating network and the networks interactions with the other heat sources.

Thermal equivalent Resistor – Capacitor networks

Self Heating Network (R-Tau)

Thermal equivalent Resistor – Capacitor networks

Interaction Heating Networks (R-Tau)

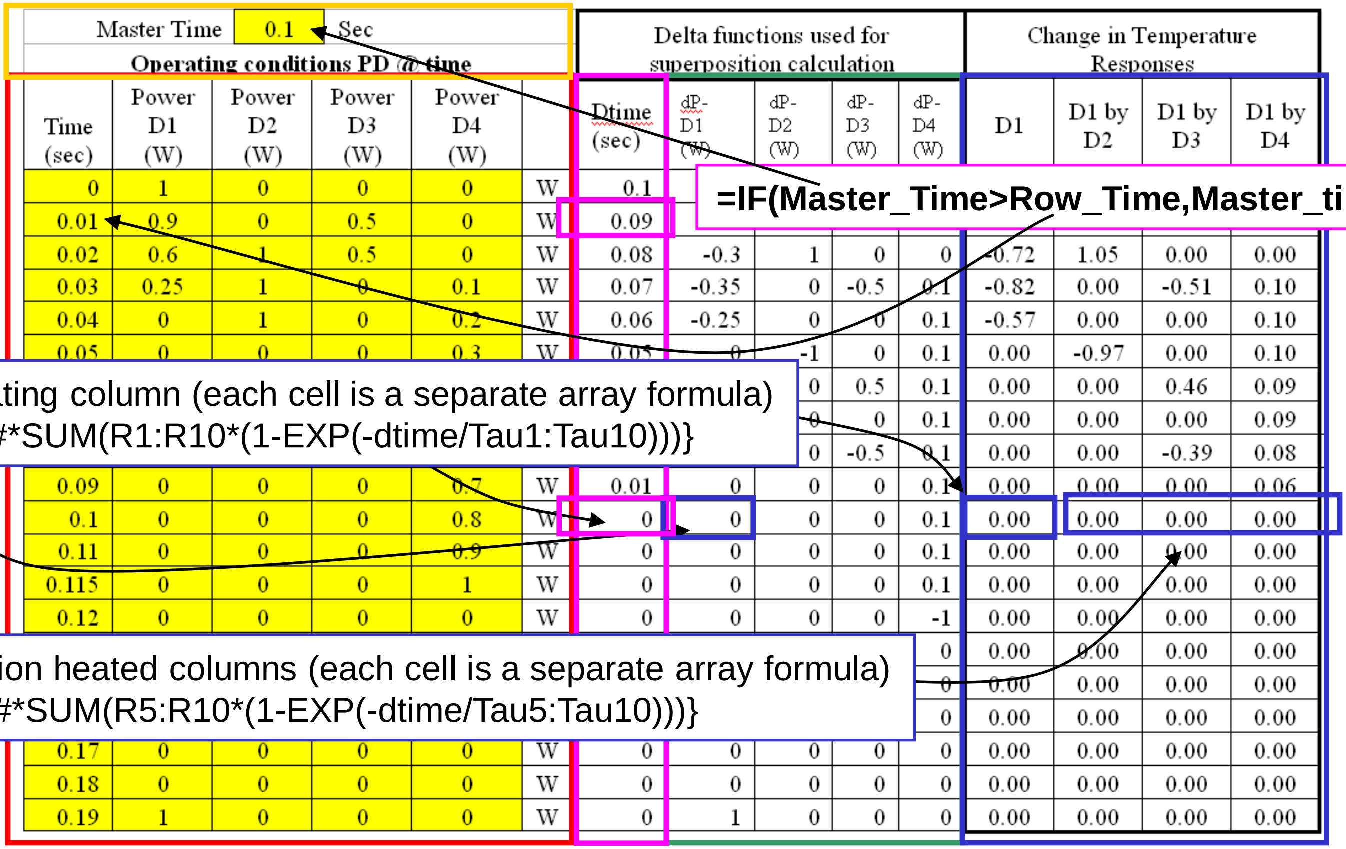


	D1	D1 by D2	D1 by D3	D1 by D4
	R(t) C/W	R(t) C/W	R(t) C/W	R(t) C/W
1	0.014			
2	0.030			
3	0.095			
4	0.122			
5	0.05	0.2	0.2	0.2
6	0.8	0.5	0.5	0.5
7	1.4	0.3	0.3	0.3
8	0.4	0.4	0.4	0.4
9	0.6	0.6	0.6	0.6
10	22.6	21.93	21.93	21.93
	Tau (sec)	Tau (sec)	Tau (sec)	Tau (sec)
1	1.0E-06			
2	1.0E-05			
3	1.0E-04			
4	3.5E-04			
5	1.0E-03	0.001	0.001	0.001
6	0.01	0.01	0.01	0.01
7	0.04	0.04	0.04	0.04
8	0.5	0.5	0.5	0.5
9	2.2	2.2	2.2	2.2
10	150	150	150	150

R-Tau FOSTER NET-LIST BLOCK FOR D1 ONLY

Organizing the sheet for transient solution

A cell for keeping track of the overall time progression of **ALL** blocks.



Master Time 0.1 Sec

Operating conditions PD @ time							Delta functions used for superposition calculation				Change in Temperature Responses			
Time (sec)	Power D1 (W)	Power D2 (W)	Power D3 (W)	Power D4 (W)		Dtime (sec)	dP-D1 (W)	dP-D2 (W)	dP-D3 (W)	dP-D4 (W)	D1	D1 by D2	D1 by D3	D1 by D4
0	1	0	0	0	W	0.1								
0.01	0.9	0	0.5	0	W	0.09								
0.02	0.6	1	0.5	0	W	0.08	-0.3	1	0	0	-0.72	1.05	0.00	0.00
0.03	0.25	1	0	0.1	W	0.07	-0.35	0	-0.5	0.1	-0.82	0.00	-0.51	0.10
0.04	0	1	0	0.2	W	0.06	-0.25	0	0	0.1	-0.57	0.00	0.00	0.10
0.05	0	0	0	0.3	W	0.05	0	-1	0	0.1	0.00	-0.97	0.00	0.10
								0	0.5	0.1	0.00	0.00	0.46	0.09
								0	0	0.1	0.00	0.00	0.00	0.09
								0	-0.5	0.1	0.00	0.00	-0.39	0.08
0.09	0	0	0	0.7	W	0.01	0	0	0	0.1	0.00	0.00	0.00	0.06
0.1	0	0	0	0.8	W	0	0	0	0	0.1	0.00	0.00	0.00	0.00
0.11	0	0	0	0.9	W	0	0	0	0	0.1	0.00	0.00	0.00	0.00
0.115	0	0	0	1	W	0	0	0	0	0.1	0.00	0.00	0.00	0.00
0.12	0	0	0	0	W	0	0	0	0	-1	0.00	0.00	0.00	0.00
										0	0.00	0.00	0.00	0.00
										0	0.00	0.00	0.00	0.00
										0	0.00	0.00	0.00	0.00
0.17	0	0	0	0	W	0	0	0	0	0	0.00	0.00	0.00	0.00
0.18	0	0	0	0	W	0	0	0	0	0	0.00	0.00	0.00	0.00
0.19	1	0	0	0	W	0	1	0	0	0	0.00	0.00	0.00	0.00

=IF(Master_Time>Row_Time,Master_time-Row_time,0)

Self heating column (each cell is a separate array formula)
{=dP-D#*SUM(R1:R10*(1-EXP(-dtime/Tau1:Tau10)))}

Interaction heated columns (each cell is a separate array formula)
{=dP-D#*SUM(R5:R10*(1-EXP(-dtime/Tau5:Tau10)))}

A section for power input to the heat sources

A section for Time changes

A section for power changes

A section for Temperature response calculation

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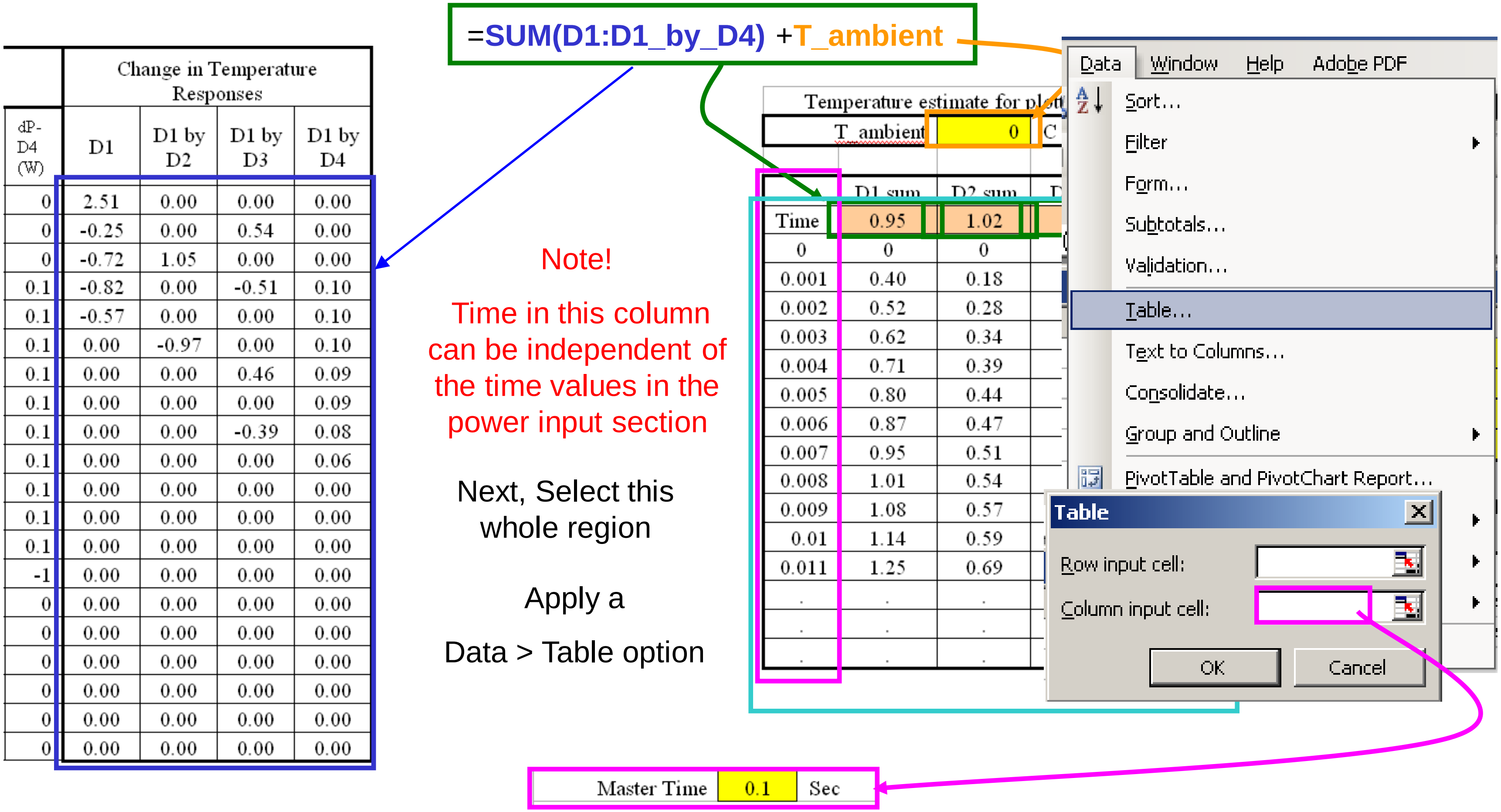
Table for plotting temperature output



=SUM(D1:D1_by_D4) +T_ambient

	Change in Temperature Responses			
dP-D4 (W)	D1	D1 by D2	D1 by D3	D1 by D4
0	2.51	0.00	0.00	0.00
0	-0.25	0.00	0.54	0.00
0	-0.72	1.05	0.00	0.00
0.1	-0.82	0.00	-0.51	0.10
0.1	-0.57	0.00	0.00	0.10
0.1	0.00	-0.97	0.00	0.10
0.1	0.00	0.00	0.46	0.09
0.1	0.00	0.00	0.00	0.09
0.1	0.00	0.00	-0.39	0.08
0.1	0.00	0.00	0.00	0.06
0.1	0.00	0.00	0.00	0.00
0.1	0.00	0.00	0.00	0.00
0.1	0.00	0.00	0.00	0.00
-1	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00
0	0.00	0.00	0.00	0.00

Note!

Time in this column can be independent of the time values in the power input section

Next, Select this whole region

Apply a

Data > Table option

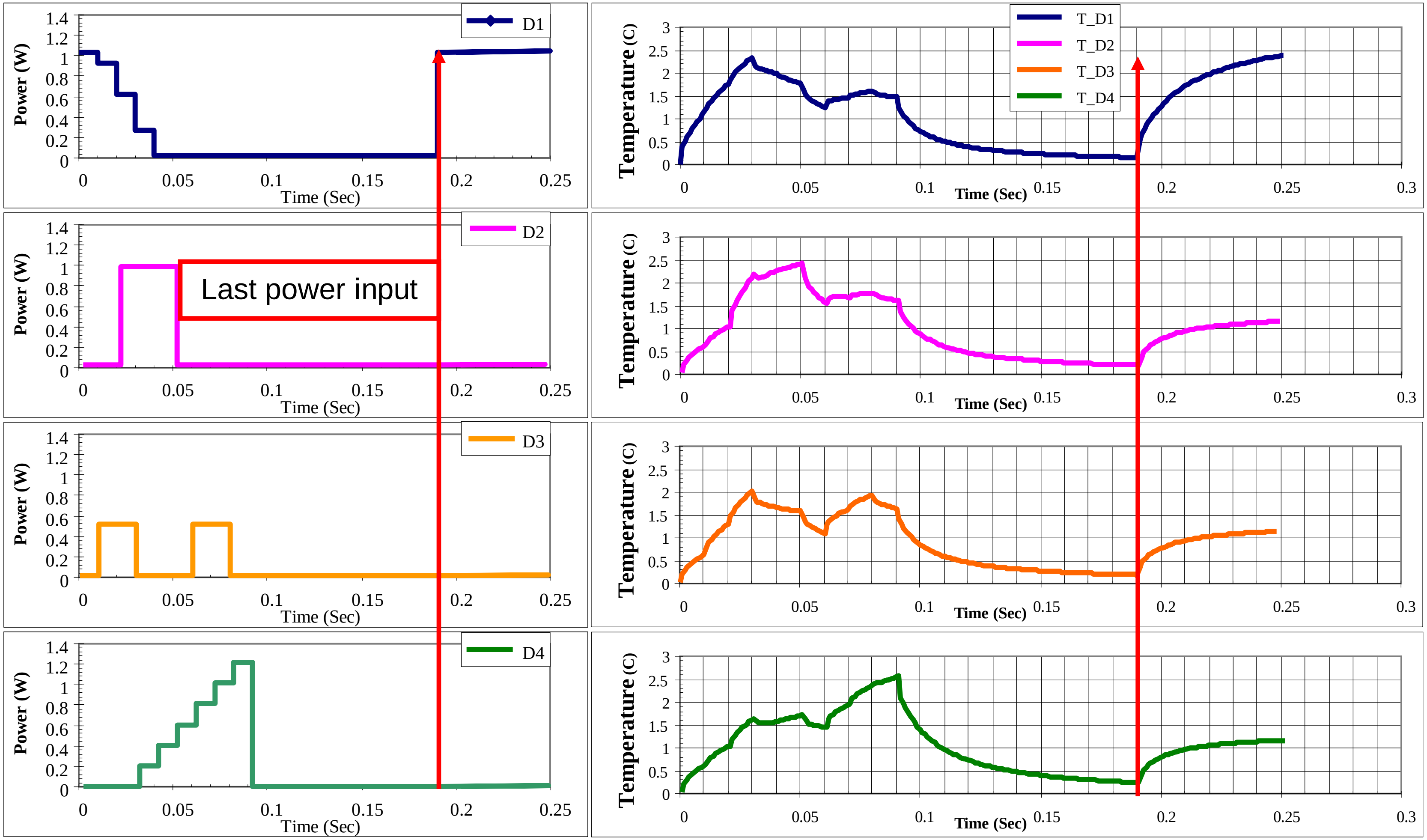
Temperature estimate for plott

T_ambient 0 C

	D1 sum	D2 sum
Time	0.95	1.02
0	0	0
0.001	0.40	0.18
0.002	0.52	0.28
0.003	0.62	0.34
0.004	0.71	0.39
0.005	0.80	0.44
0.006	0.87	0.47
0.007	0.95	0.51
0.008	1.01	0.54
0.009	1.08	0.57
0.01	1.14	0.59
0.011	1.25	0.69
.	.	.
.	.	.
.	.	.

Master Time 0.1 Sec

Final plotted Results



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Spice Thermal Simulation

- Using an electrical analogy to do thermal analysis the following rules apply:

Electrical	Thermal
Voltage (V)	Temperature difference (°C)
Current (A)	Power (W)
Resistance (Ω)	Thermal resistance (°C/W)
Capacitance (farad)	Thermal capacitance (W-sec/°C) [Tau/R]

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Components of a Spice model

Piece–wise linear current source for Power input from each source generating heat.

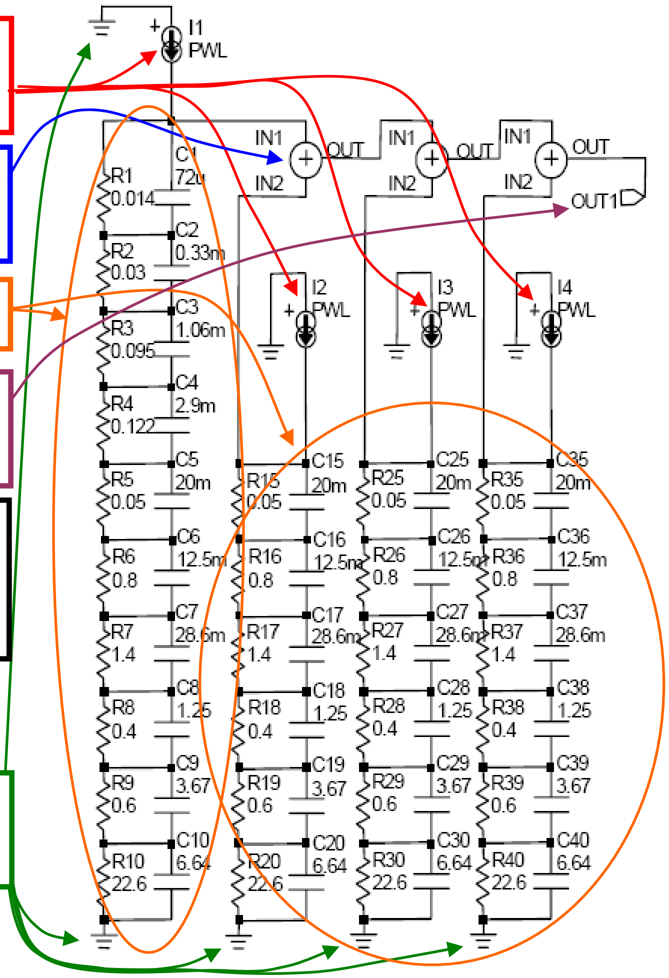
Summing tool to add voltages from the separate interaction networks with the self heating network

Thermal equivalent Resistor – Capacitor networks

The Output port (OUT1) will be where you want to monitor the temperature response

Each heat source will require a similar block in order to simulate the temperature response of the self heating effect as well as the interactions.

Thermal ground – by adding a voltage potential to the ground point ambient temperature can be added.



Conclusions

- With the right tools a Thermal R-C network can be generated from temperature data which is captured from measurements or Finite Element simulation.
- The method allows for generating complex – compact transient thermal models with several heat sources.
- Many problems can be solved using a spread sheet tool like Excel™ from Microsoft®.
- The method can also be performed using Electrical tools such as SPICE or P-SPICE. (Assuming a voltage summing tools is available in the library.)

Recommendations

- Temperature dependences of power can be added but may cause solution instability in tools such as Excel.
- Model size can get to the point of overwhelming the computational capability of the computer.(>100 networks)
- Foster Networks can be used to simulate the thermal response of a system using commonly available software tools, where as Cauer networks (which are closer to a physical lumped system) are not.
- Cauer Networks are also harder to generate physically representative lumped parameters models.

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