THERMAL ANALYSIS

INTRODUCTION

Performance and reliability are strongly affected by temperature. As temperature increases, physical changes within a part are accelerated. This seldom causes immediate, catastrophic failure, but instead causes slow deterioration in a part's internal elements. These internal elements may be dielectrics, metallization areas, transistor junctions, etc. The effect is cumulative, so failure rates depend, to some extent, on the entire thermal history of the part. As a general rule of thumb, failure rate doubles for every 10^{o}C rise in temperature. In addition, many part performance ratings change as temperature increases.

Temperature changes must therefore be taken into account when designing a circuit, selecting a part, and deriving a physical circuit configuration. One method of doing this is through a thermal analysis. The purpose of this document is to introduce the procedure for performing a thermal analysis. It will provide a general procedure on how a thermal analysis should be done and the model equations used to describe conduction, convection, and radiation. It also gives the values for thermal conductivity, heat transfer coefficients, emissivity, and view factors for various materials.

It should be emphasized that a good thermal design alone is not a cure-all solution for all high electrical stress problems. Nearly all parts are thermally sensitive, but others are voltage or current sensitive. Increased reliability requires both control of part temperatures and use of parts with electrical ratings adequate for the application.

DEFINITIONS

Emissivity: The ratio of radiation intensity from a surface to the radiation intensity from a black body at the same temperature and wavelength. As applied in this document, emissivity is a measure of a surface's ability to radiate heat.

Heat Concentration: Heat dissipation expressed in Watts per unit volume (W/m^3).

Heat Dissipation: The difference between the electrical input and output of any electronic device (expressed in Watts) except where mechanical work is being accomplished (e.g., motors).

Heat Flow Rate: The power flowing along a thermal path (expressed in Watts). The symbol used for heat flow rate is (q).

Internal Temperature: The temperature of a gas, liquid, or solid at a specified location within an enclosure (^{o}C).

Point Surface Temperature: The average temperature at a specified location on a surface (^{o}C).

Thermal Conductance: The reciprocal of thermal resistance, expressed in W/^{o}C.

Thermal Resistance: The resistance to heat flow, or Θ ($^{o}C/W$).

Thermal Environment: The condition of (1) fluid type, temperature, pressure, and velocity; (2) surface temperature, configurations, and emissivities; and (3) all conductive thermal paths surrounding a device.

Module: For the purpose of this document, a module refers to the lowest practical assembly on which to perform the thermal analysis. It is usually a circuit card or assembly, but can also be a piece part (often called an LRU or SRA).

PROCEDURE

General Procedure

The following presents the general procedure for performing a thermal analysis. It is intended for users familiar with basic engineering modeling principles (especially circuit analysis) and as a refresher. It is only intended to be general information.

Step 1. Preparation: Determine the outside temperature from the equipment operating specifications. Find out what types of cooling techniques will be available and their constraints (e.g., pressures, airflow rates, etc.).

Step 2. Produce a Heat Flow Model: Find the power requirements of individual modules. From this, derive how much heat must be dissipated by each module and produce a heat flow model. This module usually takes the form of an electrical circuit analogy, as shown in Figure 1. In the analogy, electrical resistance corresponds to thermal resistance, potential difference to temperature gradients, and current flow to heat flow. Thermal resistance can be of three types: conduction, convection, and radiation. It can also include mass transfer (i.e., evaporation and condensation) which is not addressed in this document.

The model should begin with the outside, coolant, or heat sink temperature. At first, it should extend only to the module level. Additional detail is added later to extend the model to high heat producers. It does not need to extend to each individual part number. Groups of similar parts in the same general area of the module should be grouped together to simplify the calculations. Generally, a thermal analysis only extends to individual parts if they are high heat producers (e.g., voltage regulators). The model should also include heat flow from one circuit element to another.

Step 3. Determine Power Dissipation: From the circuit analysis, find the power dissipated by each device. For part groupings, total the power dissipation of the parts in the group. Enter these values in the thermal network developed in Step 2. Knowing the outside air temperature and thermal resistivities, work backward to find ambient temperatures. Several iterations may be needed because thermal resistivity is dependent to some extent on temperature. This step should be done during the breadboard/brassboard phase of the design.

Step 4. Measurements: Measure ambient temperatures on physical models (brassboards or circuit cards) to confirm the calculated values in Step 3. Resolve any differences by refining the thermal model.

Note: Steps.3 and 4 are very similar. Basically, they are two different methods of arriving at the same result. Step 3 uses engineering analysis to determine temperatures, and Step 4 uses actual measurements. The degree to which each is used is dependent on where the thermal analysis takes place in the design process.

Step 5. Analysis: Use part specifications to find maximum temperature ratings. Derate the maximum ratings in accordance with this manual. Use the ambient temperatures found in Step 4 to determine if parts exceed maximum ratings.

Step 6. Corrective Action: The results of the thermal analysis will indicate which parts exceed absolute maximum and derated maximum limits. Take corrective action as appropriate. The corrective action may consist of (1) using a higher rated part, (2) refining the power dissipating capability of the part, (3) changing the electrical design, or (4) changing the thermal design.

Step 7. Follow-up: After corrective action is taken, Steps 5 and 6 must be repeated to assure no additional problems were created.

Thermal Network

A simplified example of a thermal network is shown in Figure 1. The thermal resistance due to conduction, convection, and radiation are shown. For this example, an ambient external temperature of 50^{o}C and 145 W of internal power dissipation is assumed. Note that the modules can tolerate an operating ambient air temperature of almost 77^{o}C, or an internal temperature rise of 27^{o}C. Most real-world thermal networks are substantially more complicated than shown, and several computer models are available to assist the designer.

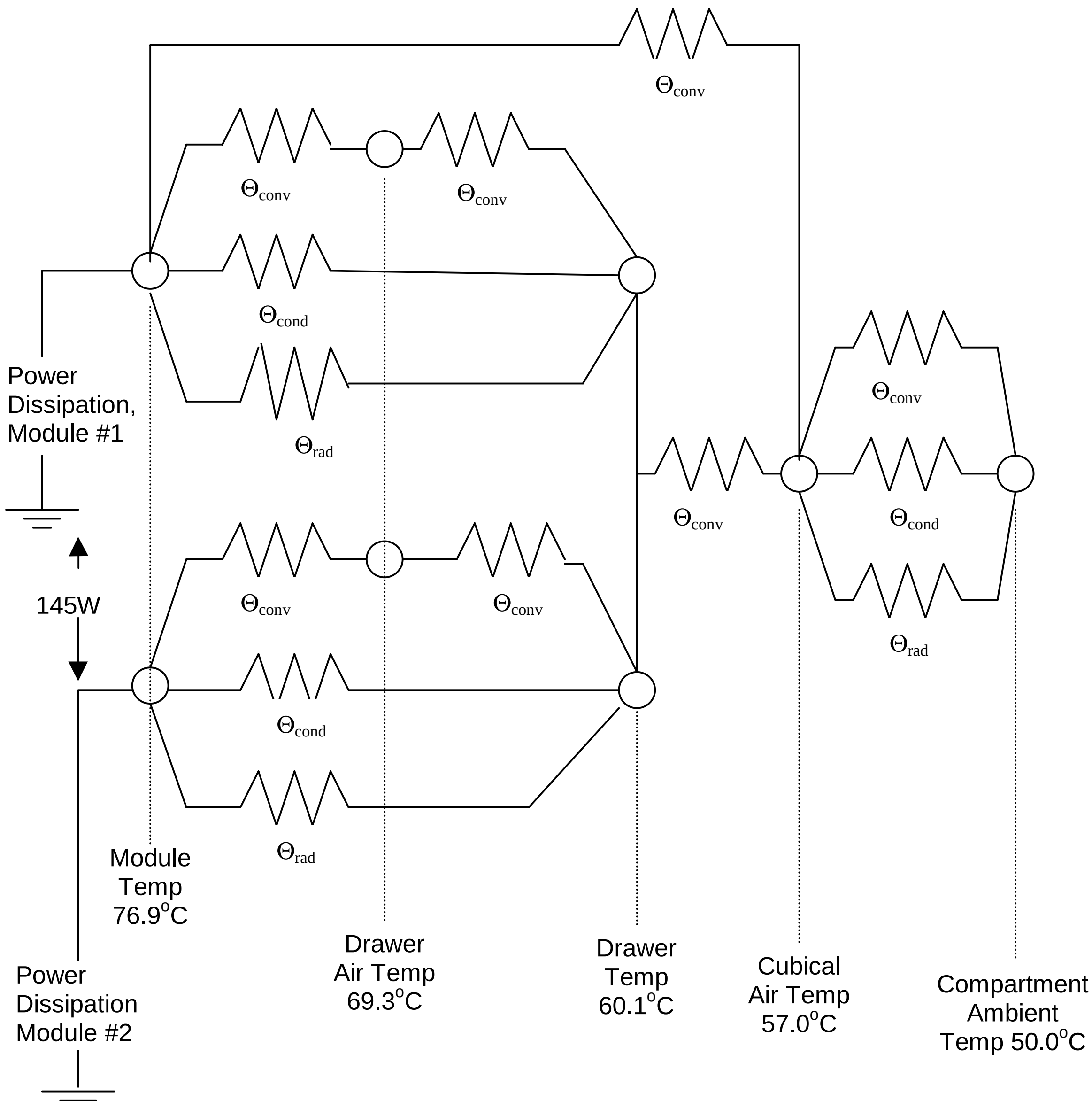

Figure 1. Electronic Cabinet Thermal Network Example

THE BASICS OF THERMAL RESISTANCE

Thermal resistance is a means to relate the case or local air temperature (ambient) surrounding a part to its power dissipation. This is important to know because nearby parts and structures may cause overheating. The classic example is a microcircuit mounted next to a wirewound power resistor. The microcircuit may not dissipate much power, but the resistor can have a hot spot temperature rise of 230°C when operating at high power. The microcircuit may therefore fail if mounted too close to the resistor.

Thermal resistance is the ratio of temperature change to power dissipation under steady state conditions. It is mathematically defined as:

$$\Theta = \frac{\Delta T}{P_D}$$

where:

Θ: Thermal Resistance ($^oC/W$)

ΔT: change in temperature (^oC)

P_D: Power Dissipation (W)

The maximum temperature a part can withstand is given as a combination of internal, case, and external temperature. The specifications of most passive parts give only an external temperature in the form of maximum ambient temperature (T_A). High heat dissipating parts may also give a case temperature (T_C) so the designer can more easily calculate the heat flow through a heat sink. For discrete semiconductors, all three ratings are given in the form of junction temperature (T_J), T_C, and T_A.

Thermal resistance of parts is expressed by their relationship to T_A, T_C, and T_J, as follows:

Θ_{JC} = Thermal Resistance, Junction to Case (discrete semiconductor)

Θ_{CA} = Thermal Resistance, Case to Ambient (any part)

Θ_{JA} = Thermal Resistance, Junction to Ambient (discrete semiconductor)

All three are related by the equation:

$$\Theta_{JA} = \Theta_{JC} + \Theta_{CA}.$$

Junction, case, and ambient temperatures are related to each other by the following:

$$T_J = T_C + P_D \Theta_{JC}$$
$$T_C = T_A + P_D \Theta_{CA}.$$

Note: This is only under steady state DC operation. Under pulsed operation, the situation changes. Temperature tends to increase faster for high frequency pulses. As frequency decreases, so does temperature. This is because the part cools while it is off. Therefore, the nature of the duty cycle makes a difference. A high duty cycle may cause device temperature to increase while a low duty cycle will cause device temperature to decrease. For devices that are repetitively switched on and off (e.g., thyristors), maximum temperature versus frequency and duty cycle information is provided in the component specification.

THERMAL EVALUATION AND DESIGN FOR HEAT TRANSFER

The fundamental principles used in a thermal profile analysis are presented in this section. Ideally, small temperature gradients and consistent low operating temperatures indicate that effective heat transfer techniques are being used. Two basic assumptions used in this analysis are as follows:

a. Positive heat flow is the heat flow from a high temperature region to a low temperature region, and

b. Heat emitted by a high temperature region is equal to the heat absorbed by a low temperature region.

HEAT CONDUCTION

Heat conduction is caused by molecular oscillations in solid materials and elastic impact of molecules in liquids and gases. For heat flowing through a region of constant cross sectional area, the equation for heat condition is:

$$\Theta_{cond} = \frac{\Delta T}{q}$$

where:

Θ_{Cond} = Thermal Resistance to Heat Conducted Through and Along the Region (^{o}C/W).

ΔT = Temperature Gradient Across the Conductive Path (^{o}C).

q = Heat Flow Rate Through and Along the Conductive Path (W).

Heat flow in liquids and solids is analogous to Ohm's Law for current flow in a circuit. The resistance to heat flow is analogous to the resistance to current flow in a circuit, and temperature difference is the analogous to potential difference. A second general relation for thermal resistance can be used, which is based on analogy to circuit resistance:

$$R_{Circuit} = \frac{L}{\sigma A}$$

where:

σ = Electrical Conductivity

L = circuit Path

A = Circuit Wiring cross-sectional Area

Accordingly, for heat conduction:

$$\Theta_{cond} = \frac{L}{KA}$$

where:

K = Thermal Conductivity, See Table 1 (W/^{o}C-m)

L = Conduction Path Length (m)

A = Conduction Path cross-sectional Area (m^2)

So that the equations for heat conduction are as follows:

$$\Theta_{cond} = \frac{T}{q}$$

$$\Theta_{cond} = \frac{L}{KA}.$$

Table 1. Thermal Conductivity (K) of Typical Materials[1].

Material	Thermal Conductivity		Material	Thermal Conductivity	
	W/cm-^oC	BTU/h-ft-^oF		W/cm-^oC	BTU/h-ft-^oF
Metals			Insulators		
Aluminum (pure)	2.165	0.03746	Still Air	0.0003	5 X 10^{-6}
Beryllium	1.772	0.03066	Alumina	0.276	0.00478
Beryllium Copper	1.063	0.01839	Alumina (85%)	0.118	0.00204
Brass[2]	1.22	0.0211	Beryllia (99.5%)	1.969	0.0341
Copper	3.937	0.0681	Beryllia (97%)	1.575	0.0273
Gold	2.913	0.05041	Beryllia (95%)	1.161	0.0201
Iron (pure)	0.669	0.0116	Boron Nitride[3]	0.394	0.00682
Lead	0.343	0.00594	Diamond	6.299	0.109
Magnesium	1.575	0.02725	Epoxy	0.002	30 X 10^{-6}
Molybdenum	1.299	0.02248	Conductive Epoxy[4]	0.008	100 X 10^{-6}
Monel	0.197	0.00341	Mica	0.007	100 X 10^{-6}
Nickel (pure)	0.906	0.0157	Glass	0.008	100 X 10^{-6}
Silver	4.173	0.07221	Heat Sink Compound[5]	0.004	70 X 10^{-6}
Stainless Steel 321	0.146	0.00253	Mylar	0.002	30 X 10^{-6}
Stainless Steel 410	0.240	0.00415	Phenolic	0.002	30 X 10^{-6}
Steel, Low Carbon	0.669	0.0116	Silicone Grease	0.002	30 X 10^{-6}
Tin	0.630	0.0109	Silicone Rubber	0.002	30 X 10^{-6}
Titanium	0.157	0.00272	Teflon	0.002	30 X 10^{-6}
Tungsten	1.969	0.03407	FR-4 or G-10 PWB Material	0.003	50 X 10^{-6}
Zinc	1.024	0.01772			
Semiconductors					
Gallium Arsenide	0.591	0.0102			
Silicon (pure)	1.457	0.0252			
Silicon (doped)[6]	0.984	0.0170			

[1] Thermal conductivity is assumed to be at room temperature
[2] Brass is assumed to be 70% Copper, 30% Zinc
[3] Hot pressed boron nitride
[4] Thermally conducting epoxy
[5] Metal oxide loaded epoxy
[6] Silicon doped to resistivity of 0.0025 Ω-cm

HEAT CONVECTION

Heat convection is the process where heat is transferred from a solid surface to a moving fluid or gas. The circulation of the fluid or gas removes heat from a warm area and transfers it to a cooler area. The equation for heat convection is as follows:

$$\Theta_{conv} = \frac{T}{q}$$

where:

$$q = h_C A_S \Delta T_S$$

and:

q = Heat Flow Rate (W).

A_S = Heated Surface area (m^2).

ΔT_S = Temperature Gradient From the Surface to the Ambient in the Near Vicinity of the Surface (^oC).

h_C = The Convection Heat Transfer Coefficient, See Table 2 (W/m^2-^oC).

The convection heat transfer coefficient (h_C) is a complex function of the fluid flow, thermal properties of the ambient near vicinity of the surface, the geometry of the system (i.e., size, shape, surface texture, etc.), as well as a function of the temperature itself. However, for most electronic components in air, h_C may be approximated by the value of 0.47 mW/cm^2-^oC (5.4 mW/in^2-^oF).

Table 2. Convection Heat Transfer Coefficients

Cooling Technique	Heat Transfer Coefficient, h_C	
	(mW/cm^2-^oC)	(mW/in^2-^oF)
Free Convection	0.28 to 0.57	3.2 to 6.7
High Altitude (70,000 feet)	Closer to 0.28	Closer to 3.2
Sea Level	Closer to 0.57	Closer to 6.7
Air Impingement	0.17 to 0.28	2.0 to 3.2
Forced Convection:		
Air over Plain fins	3.4 to 17	40 to 200
Air Over Interrupted Fins	3 to 5 Times Higher Than Plain Fins	3 to 5 Times Higher Than Plain Fins
Liquid Cooling:		
Dielectric Liquid	57 to 227	662 to 2,640
Water	280 to 5,700	3,250 to 66,200

We can then write:

$$\Theta_{conv} = \frac{\Delta T}{q} = \frac{\Delta T}{h_C A_S \Delta T_S} = \frac{1}{h_C A_S}.$$

Convection is more complicated than conduction because the convection heat transfer coefficient, h_C, is a nonlinear function of ΔT. It also varies more with temperature than thermal resistivity. However, approximate values of the temperatures are usually known. More exact values (within ±5%) can be calculated using a successive approximation method of two or three steps. This is good enough for most electronic equipment cooling designs.

Convection heat transfer coefficients are usually relatively small, so corresponding Θ_{conv} is high compared to Θ_{cond}. Instances in which conduction and convection are serially occurring, convection is usually the dominant heat transfer-limiting factor.

There are separate convection coefficients for vertical and horizontal, and top and bottom surfaces. A further expansion of the convection equation for thermal resistance can be performed using the individual surfaces. When the ambient fluid is moved by external means such as fans or pumps, the process is termed forced convection. Fluid motion due to density decreases in the heated fluid, with resultant changes in buoyancy, is termed free convection.

HEAT RADIATION

Heat radiation is a transfer of heat through electromagnetic energy. Heat travels from a warmer body (emitter) to a cooler body (heat sink), with the assumption of relatively little absorption from the air. When reaching a cooler body, the energy is either absorbed, reflected, or is transmitted through to the cooler body. The transmitted energy is usually insignificant.

The amount of energy absorbed or reflected depends on the surface characteristics of the body, such as color and finish. Perfectly black bodies are defined as those that absorb all radiation, while perfectly shiny bodies reflect all radiation. The radiation characteristics of a surface are defined by a dimensionless quantity known as emissivity. A perfect absorber and emitter has an emissivity of one, and a perfect reflector has an emissivity of zero. Table 3 lists the emissivity of several common materials.

The rate of heat transfer by radiation is low when the difference in temperature between the emitting and absorbing bodies is small or the temperature of the bodies are close to room temperature. The thermal resistance due to radiation decreases rapidly as the temperature difference between the emitting and absorbing bodies increases.

This is because the heat flow rate, q_{rad}, is:

$$q_{rad} = \sigma_S e_r F_{es} A\left(Te_1^4 - Te_2^4\right)$$

where:

σ_S = Stefan-Boltzmann Constant, or 5.7 X 10^{-12} W/cm^2-^{o}K (66.2 X 10^{-12} W/in^2 ^{o}R).

$e_r = e_1 * e_2$ (Composite Emissivity), where:

e_1 = Emissivity of the Radiating Surface (See Table 3) and

e_2 = Emissivity of the Sink Surface (See Table 3).

F_{es} = View Factor (See Table 4).

A = Radiating Surface Area (cm^2).

Table 3: Emissivity Factor (F_e), Surfaces at 4^{o}C (40^{o}F)

Surface	Emissivity (e)
Silver	0.02
Aluminum (buffed)	0.03
Aluminum (dull)	0.03
Gold (plated)	0.03
Gold (vacuum deposited)	0.03
Aluminum Foil (shiny)	0.04
Aluminum (polished)	0.05
Stainless Steel (polished)	0.05
Chrome	0.08
Tantalum	0.08
Beryllium (polished)	0.09
Beryllium (milled)	0.11
Rene 41	0.11
Nickel	0.18
Titanium	0.18
Aluminum (sandblasted)	0.40
White Silicone Paint (gloss)	0.75
Black Silicone Paint (flat)	0.81
Black Vinyl Phenolic (dull)	0.84
Lamp Black	0.95
Magnesia	0.95
Grey Silicone Paint	0.96

For two non-black bodies, the relation for the net rate of exchange of radiant heat is:

$$q_{rad} = \sigma_S F_e F_{es} A(T_1 - T_2)$$

where:

F_e = Emissivity Factor

F_{es} = Physical Configuration Factor Based on the Geometry of the Situation (also called the view factor)

For the commonly occurring instance of essentially parallel planes which are large compared to their distance apart, the emissivity factor, F_e, is a composite of the emissivities of the surface and is of the form:

$$F_e = \frac{1}{1/E_1 + 1/E_2 - 1} = \frac{E_1 E_2}{E_1 + E_2 - E_1 E_2}.$$

The configuration factor, F_a, is sometimes known as the view factor (see Table 4) representative values and clarifying definition).

Table 4: View Factors (F_a) for Various Configurations

Configuration	View Factor
Infinite Parallel Planes	1.0
Body Completely Enclosed by Another Body; Internal Body Cannot See Any Part of Itself	1.0
Two Squires in Perpendicular Planes with a Common side	0.20
Two Equal, Parallel Squires Separated by Distance Equal to Side	0.19
Two Equal, Parallel Circular Disks Separated by Distance Equal in Diameter	0.18

Substituting for q_{rad}, then:

$$q_{rad} = \frac{T_e - T_S}{F_e F_a \sigma_S A(T_e - T_S)}$$

The above expression is in $^oK/W$, where Kelvin is the absolute unit of temperature. Degrees centigrade is converted to degrees Kelvin by,

$^oK = {}^oC + 273$

Since the Kelvin scale and centigrade scales are identical units except for the additive constant of 273, once the thermal resistance for radiation is determined in ^{o}K/W, the same resistance can be used for ^{o}C/W. In other words, a 1^{o}K rise is equal to a 10^{o}C rise.