Heat Sinks and Component Temperature Control
Need for Component Temperature Control

- All components, capacitors, inductors and transformers, and semiconductor devices and circuits have maximum operating temperatures specified by manufacturer.
  - Component reliability decreases with increasing temperature. Semiconductor failure rate doubles for every 10 - 15 °C increase in temperature above 50 °C (approx. rule-of-thumb).

- High component operating temperatures have undesirable effects on components.

**Capacitors**
- Electrolyte evaporation rate increases significantly with temperature increases and thus shortens lifetime.

**Magnetic Components**
- Losses (at constant power input) increase above 100 °C
- Winding insulation (lacquer or varnish) degrades above 100 °C

**Semiconductors**
- Unequal power sharing in paralleled or seriesed devices.
- Reduction in breakdown voltage in some devices.
- Increase in leakage currents.
- Increase in switching times.
Temperature Control Methods

• Control voltages across and current through components via good design practices.
  • Snubbers may be required for semiconductor devices.
  • Free-wheeling diodes may be needed with magnetic components.

• Use components designed by manufacturers to maximize heat transfer via convection and radiation from component to ambient.
  • Short heat flow paths from interior to component surface and large component surface area.

• Component user has responsibility to properly mount temperature-critical components on heat sinks.
  • Apply recommended torque on mounting bolts and nuts and use thermal grease between component and heat sink.
  • Properly design system layout and enclosure for adequate air flow so that heat sinks can operate properly to dissipate heat to the ambient.
Heat Conduction Thermal Resistance

- Generic geometry of heat flow via conduction

\[ P_{\text{cond}} \] = \[ \frac{A (T_2 - T_1)}{d} \] = \[ \frac{T_2 - T_1}{R_{\text{cond}}} \]

- Heat flow \( P_{\text{cond}} \) [W/m\(^2\)] = \[ \frac{A (T_2 - T_1)}{d} \] = \[ \frac{T_2 - T_1}{R_{\text{cond}}} \]

- Thermal resistance \( R_{\text{cond}} \) = \[ \frac{d}{[\square A]} \]
  - Cross-sectional area \( A = hb \)
  - \( \square = \text{Thermal conductivity has units of W-m}^{-1}\cdot{°C}^{-1} \) (\( \square_{\text{Al}} = 220 \text{ W-m}^{-1}\cdot{°C}^{-1} \)).
  - Units of thermal resistance are °C/W
**Thermal Equivalent Circuits**

- Heat flow through a structure composed of layers of different materials.

- Thermal equivalent circuit simplifies calculation of temperatures in various parts of structure.

- \[ T_i = P_d (R_{jc} + R_{cs} + R_{sa}) + T_a \]

- If there parallel heat flow paths, then thermal resistances of the parallel paths combine as do electrical resistors in parallel.
• Heat capacity per unit volume $C_v = \frac{dQ}{dT}$ [Joules/°C] prevents short duration high power dissipation surges from raising component temperature beyond operating limits.

• Transient thermal equivalent circuit. $C_s = C_v V$ where $V$ is the volume of the component.

• Transient thermal impedance $Z_q(t) = \frac{[T_j(t) - T_a]}{P(t)}$

\[ \bullet \quad \square = \pi R_{\square} C_s/4 = \text{thermal time constant} \]

\[ \bullet \quad T_j(t = \square) = 0.833 \, P_o \, R_{\square} \]
Application of Transient Thermal Impedance

- Symbolic response for a rectangular power dissipation pulse \( P(t) = P_0 \{ u(t) - u(t - t_1) \} \).

\[
T_j(t) = P_0 \{ Z_{q}(t) - Z_{q}(t - t_1) \}
\]

- Symbolic solution for half sine power dissipation pulse.
  - \( P(t) = P_o \{ u(t - T/8) - u(t - 3T/8) \} \); area under two curves identical.
  - \( T_j(t) = P_0 \{ Z_{q}(t - T/8) - Z_{q}(t - 3T/8) \} \)
**Z for Multilayer Structures**

- Multilayer geometry

- Transient thermal equivalent circuit

- Transient thermal impedance (asymptotic) of multilayer structure assuming widely separated thermal time constants.

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Heat Sinks

• Aluminum heat sinks of various shapes and sizes widely available for cooling components.
  • Often anodized with black oxide coating to reduce thermal resistance by up to 25%.
  • Sinks cooled by natural convection have thermal time constants of 4 - 15 minutes.
  • Forced-air cooled sinks have substantially smaller thermal time constants, typically less than one minute.

• Choice of heat sink depends on required thermal resistance, $R_{qa}$, which is determined by several factors.
  • Maximum power, $P_{diss}$, dissipated in the component mounted on the heat sink.
  • Component's maximum internal temperature, $T_{j,\text{max}}$
  • Component's junction-to-case thermal resistance, $R_{jc}$.
  • Maximum ambient temperature, $T_{a,\text{max}}$.

$$R_{qa} = \frac{T_{j,\text{max}} - T_{a,\text{max}}}{P_{diss} - R_{jc}}$$

• $P_{diss}$ and $T_{a,\text{max}}$ determined by particular application.
• $T_{j,\text{max}}$ and $R_{jc}$ set by component manufacturer.
Radiative Thermal Resistance

- Stefan-Boltzmann law describes radiative heat transfer.
  
  \[ P_{\text{rad}} = 5.7 \times 10^{-8} EA \left( (T_s)^4 - (T_a)^4 \right) ; [P_{\text{rad}}] = [\text{watts}] \]

- \( E \) = emissivity; black anodized aluminum \( E = 0.9 \); polished aluminum \( E = 0.05 \)

- \( A \) = surface area \([m^2]\) through which heat radiation emerges.

- \( T_s \) = surface temperature \([\degree K]\) of component. \( T_a \) = ambient temperature \([\degree K]\).

\[
\frac{(T_s - T_a)}{P_{\text{rad}}} = R_{q,\text{rad}} = \frac{[T_s - T_a][5.7EA \{(T_s/100)^4 - (T_a/100)^4\}]}{-1}
\]

- Example - black anodized cube of aluminum 10 cm on a side. \( T_s = 120 \degree C \) and \( T_a = 20 \degree C \)

  \[
  R_{q,\text{rad}} = \frac{[393 - 293][(5.7)(0.9)(6\times10^{-2})\{(393/100)^4 - (293/100)^4\}]}{-1}
  \]

  \[
  R_{q,\text{rad}} = 2.2 \degree C/W
  \]
Convective Thermal Resistance

- \( P_{\text{conv}} = \) convective heat loss to surrounding air from a vertical surface at sea level having a height \( d_{\text{vert}} \) [in meters] less than one meter.
- \( P_{\text{conv}} = 1.34 A [T_s - T_a]^{1.25} d_{\text{vert}}^{-0.25} \)
- \( A = \) total surface area in \([\text{m}^2]\)
- \( T_s = \) surface temperature [°K] of component, \( T_a = \) ambient temperature [°K].

- \( \frac{T_s - T_a}{P_{\text{conv}}} = R_{\text{conv}}^{\text{q}} = \frac{T_s - T_a}{d_{\text{vert}}^{0.25} [1.34 A (T_s - T_a)^{1.25}]^{-1}} \)
- \( R_{\text{conv}}^{\text{q}} = d_{\text{vert}}^{0.25} \{1.34 A [T_s - T_a]^{0.25}\}^{-1} \)

- Example - black anodized cube of aluminum 10 cm on a side. \( T_s = 120 \, ^{\circ}\text{C} \) and \( T_a = 20 \, ^{\circ}\text{C} \).
- \( R_{\text{conv}}^{\text{q}} = [10^{-1}]^{0.25}([1.34] [6 \times 10^{-2}] [120 - 20]^{0.25})^{-1} \)
- \( R_{\text{conv}}^{\text{q}} = 2.2 \, ^{\circ}\text{C/W} \)
Combined Effects of Convection and Radiation

- Heat loss via convection and radiation occur in parallel.

- Steady-state thermal equivalent circuit

\[ R_{\text{sink}} = \frac{R_{\text{rad}} R_{\text{conv}}}{R_{\text{rad}} + R_{\text{conv}}} \]

- Example - black anodized aluminum cube 10 cm per side

\[ R_{\text{rad}} = 2.2 \, ^\circ\text{C/W} \quad \text{and} \quad R_{\text{conv}} = 2.2 \, ^\circ\text{C/W} \]

\[ R_{\text{sink}} = \frac{(2.2)(2.2)}{2.2 + 2.2} = 1.1 \, ^\circ\text{C/W} \]